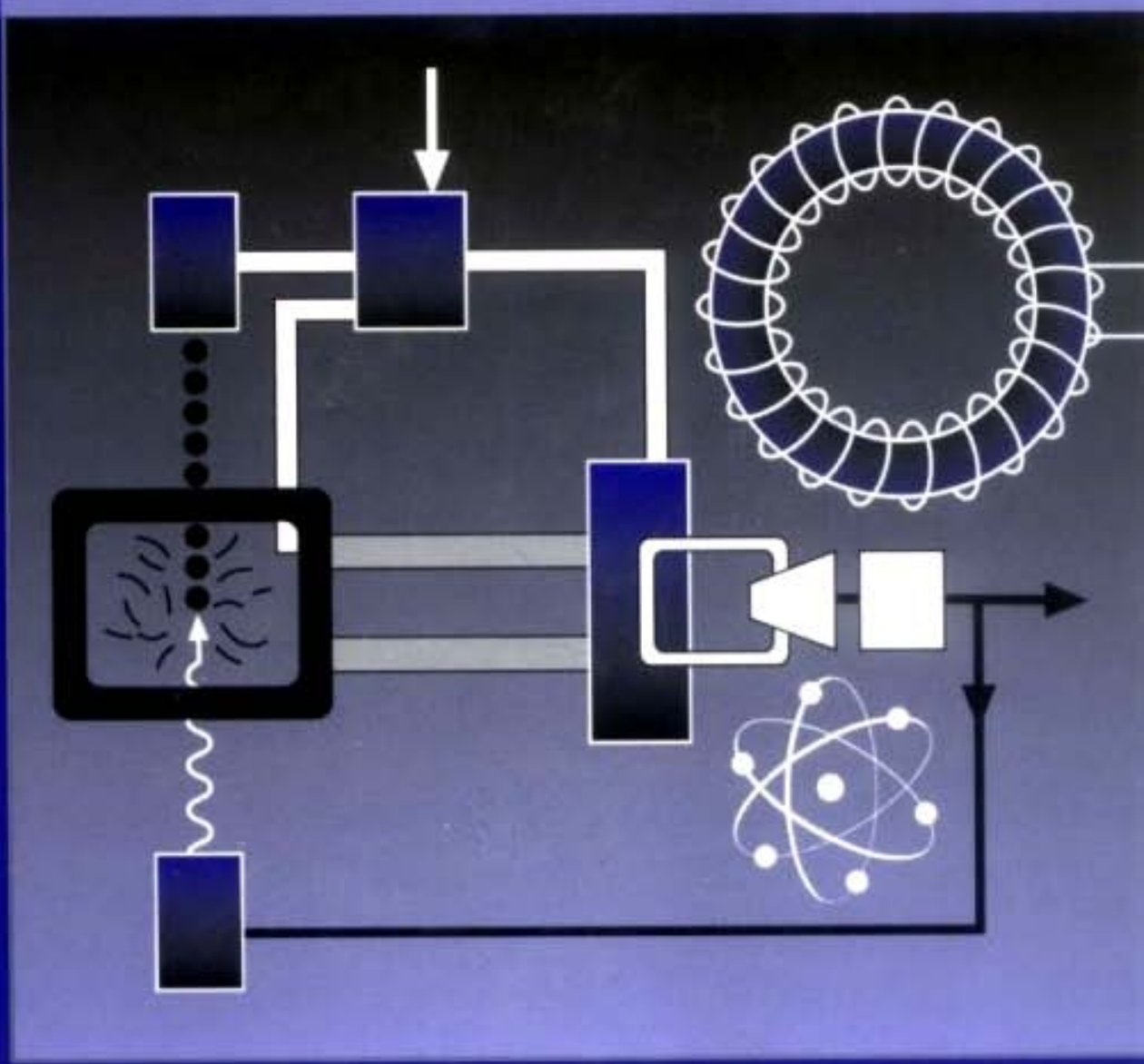
Nuclear Energy

An Introduction to the Concepts, Systems, and Applications of Nuclear Processes

Fifth Edition



Raymond L. Murray

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BUTTERWORTH HEINEMANN

To Elizabeth

Preface to the Fifth Edition

AT THE transition to the new millennium the future of nuclear energy looks brighter. Nuclear power plants worldwide have operated safely. Applications for extension of reactor operating licenses in the U.S. are in place and construction is continuing abroad.

Uses of isotopes and radiation in applications to medicine, research, and industry continue to assure human benefit. Research and development are active in the areas of controlled fusion, accelerator uses, isotope separation, space exploration, and excess weapons material disposition.

Unfortunately, progress toward solutions for the nuclear waste problem has been frustratingly slow. And there are no new orders for nuclear plants in the U.S.

Controversies surround the validity of the linear no-threshold model of the effect of low-level radiation and the anticipated consequences to climate of the buildup of greenhouse gases.

It is the author's firm belief that nuclear power will be necessary in the twenty-first century, as world population continues to grow, expectations for a better life are sought, and energy demands increase.

The phenomenon of the Internet is dramatically changing communication of information and knowledge, including education at all levels. This new edition of the book includes citations to sites on the World Wide Web in addition to references in the print media. The author has explored the Web extensively, searching for sites that are relevant, useful, and accurate. However, the reader must beware of sites that become outdated or vanish. Further comments on the Internet appear in the Appendix.

A few new Exercises are included in the fifth edition. The diskette containing programs in BASIC for use with Computer Exercises is now available free of charge on request from the author.

The author hopes that the book will continue to serve in the orientation and education of the next generation of nuclear professionals and leaders, as well as being helpful to scientists and engineers in related fields. Communication by e-mail (murray@eos.ncsu.edu) with teachers, students, and other users of the book will be most welcome.

Many persons have provided valuable ideas and information. They are recognized at appropriate points in the book. The advice and assistance of Michael Forster, Cate Rickard-Barr, and Lisa Jelly of Butterworth-Heinemann was most helpful. Special thanks are due Nancy Reid Baker for

vital computer support, for preparation of new artwork, and for formatting the final camera-ready copy. Finally, the author is grateful for the encouragement provided by his wife, Elizabeth Reid Murray.

Raleigh, North Carolina, 2000 RAYMOND L. MURRAY

Preface to the Fourth Edition

WORLD EVENTS in the early 1990s have accentuated the benefits of nuclear energy. The political revolutions in Eastern Europe and the U.S.S.R. have produced welcome relief in international tensions between the superpowers, with opportunity for the West to assist in enhancement of safety of reactors.

The end of the Cold War produced a "peace dividend" for the U.S. that can help in solving social and financial problems. Weapons and their production capability can be phased out, and there remain scores of contaminated facilities to deal with.

Military aspects of space can now be de-emphasized, with the prospect of space exploration using nuclear propulsion and nuclear power sources.

The nuclear industry has taken bold positive steps to develop new and better nuclear power reactors, while the U.S. government and states continue to attack the problem of disposal of radioactive wastes. The public appears to better recognize the need for nuclear power, but remains reluctant to accept facilities to implement it. The beneficial uses of nuclear energy continue to grow, including the application of radioisotopes and radiation to medical diagnosis, treatment, and research.

Regulatory policies in the U.S. that have hampered investment in nuclear power plants have largely been resolved by congressional action. At the same time, the laws encourage competition by alternative energy sources.

It is the author's belief that nuclear power will be necessary, as world population continues to grow, as expectations for better lives for people of the world are sought, but as the limits of energy efficiency are reached and fossil fuel resources become scarce.

Leadership in the technology of a closed fuel cycle–enrichment, new reactor construction, breeding, and reprocessing–has been assumed by countries such as France and Japan. In the U.S., expertise necessary to maintain and expand the nuclear option in the next century needs to be preserved and extended, as professionals leave or retire from the field.

The author hopes that this book will continue to serve as a useful vehicle to orient, train, and educate the next generation of professionals and leaders. The book is expected to be helpful as well for scientists and engineers in non-nuclear but related fields.

As in past editions, the level of mathematics demanded by the book is not excessive. A new feature – Computer Exercises – has been added, however, intended to enhance the appreciation of effects, trends, and

magnitudes. They use a set of computer programs available from the author on a non-proprietary, non-profit basis. These are written in the BASIC language or utilize a popular spreadsheet. Each type of program demands a minimum of expertise in computer programming, but permits calculations that go well beyond those possible or practical by use of a hand-held calculator. Some of the programs have convenient menus; others yield directly a set of numbers; still others give graphical displays.

It would have been good to be able to provide greater opportunity for the student to do creative programming and open-ended problem solving, but that was sacrificed because there is so much to learn in a field as varied and complex as nuclear technology.

The author welcomes communication with teachers and students about difficulties, errors, and suggestions for improvement of the computer programs, the exercises, and the text itself.

Those kind individuals who provided helpful comments are recognized in the pertinent sections. Special thanks are due the author's wife, Elizabeth Reid Murray, for continued encouragement and advice.

Raleigh, North Carolina, 1993 RAYMOND L. MURRAY

Preface to the Third Edition

THE ROLE of nuclear processes in world affairs has increased significantly in the 1980s. After a brief period of uncertainty, oil has been in adequate supply, but expensive for use in generating electricity. For countries without coal resources, nuclear power is a necessity, and new plants are being built.

The U.S. nuclear industry has been plagued with a combination of high construction costs and delays. The latter are attributed to actions of intervenors, to inadequate management, and to regulatory changes. No new orders for nuclear reactors have been placed, and work has been suspended on a number of plants. It appears that less than 20% of the country's electricity will be provided by nuclear power by the year 2000.

Concerns about reactor safety persist in spite of major improvements and an excellent record since TMI-2. The Chernobyl accident accentuated public fears. Concerns about waste disposal remain, even though much technical and legislative progress has been made. The threat of nuclear warfare casts a shadow over commercial nuclear power despite great differences between the two applications.

Although the ban on reprocessing of spent nuclear fuel in the United States has been lifted, economic factors and uncertainty have prevented industry from taking advantage of recycling. Spent fuel will continue to accumulate at nuclear stations until federal storage facilities and repositories are decided upon. Through compacts, states will continue to seek to establish new low-level radioactive waste disposal sites.

Progress on breeder reactor development in the United States was dealt a blow by the cancellation of the Clinch River Breeder Reactor Project, while the use of fusion for practical power is still well into the future.

Applications of radioisotopes and nuclear radiation for beneficial purposes continue to increase, and new uses of nuclear devices in space are being investigated.

Although nuclear power faces many problems, there is optimism that the next few decades will see a growing demand for reactors, to assure industrial growth with ample environmental protection. In the long term–into the 21st century and beyond–nuclear will be the only available concentrated energy source.

The challenge of being prepared for that future can be met through meticulous attention to safety, through continued research and development, and with the support of a public that is adequately informed about the technology, including a fair assessment of benefits and risks.

This book seeks to provide useful information for the student of nuclear engineering, for the scientist or engineer in a non-nuclear field, and for the technically oriented layman, each of whom is called upon to help explain nuclear energy to the public.

In this new edition, Part I Basic Concepts is only slightly changed; Part II Nuclear Systems involves updating of all chapters; Part III Nuclear Energy and Man was extensively revised to reflect the march of events. The "Problems" to be solved by the reader are now called "Exercises."

Many persons provided valuable ideas and information. They are recognized at appropriate points in the book. Special thanks are due my colleague Ephraim Stam, for his thorough and critical technical review, and to my wife Elizabeth Reid Murray, for advice, for excellent editorial suggestions, and for inspiration.

Raleigh, North Carolina, 1987 RAYMOND L. MURRAY

Preface to the Second Edition

IN THE period since *Nuclear Energy* was written, there have been several significant developments. The Arab oil embargo with its impact on the availability of gasoline alerted the world to the increasing energy problem. The nuclear industry has experienced a variety of problems including difficulty in financing nuclear plants, inflation, inefficiency in construction, and opposition by various intervening organizations. The accident at Three Mile Island raised concerns in the minds of the public and led to a new scrutiny of safety by government and industry.

Two changes in U.S. national administration of nuclear energy have occurred: (a) the reassignment of responsibilities of the Atomic Energy Commission to the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA) which had a charge to develop all forms of energy, not just nuclear; (b) the absorption of ERDA and the Federal Energy Agency into a new Department of Energy. Recently, more attention has been paid to the problem of proliferation of nuclear weapons, with new views on fuel reprocessing, recycling, and the use of the breeder reactor. At the same time, several nuclear topics have become passé.

The rapidly changing scene thus requires that we update *Nuclear Energy*, without changing the original intent as described in the earlier Preface. In preparing the new version, we note in the text and in the Appendix the transition in the U.S. to SI units. New values of data on materials are included e.g. atomic masses, cross sections, half-lives, and radiations. Some new problems have been added. The Appendix has been expanded to contain useful constants and the answers to most of the problems. Faculty users are encouraged to secure a copy of the *Solution Manual* from the publisher.

Thanks are due Dr. Ephraim Stam for his careful scrutiny of the draft and for his fine suggestions. Thanks also go to Mary C. Joseph and Rashid Sultan for capable help with the manuscript.

Raleigh, North Carolina, 1980 RAYMOND L. MURRAY

Preface to the First Edition

THE FUTURE of mankind is inextricable from nuclear energy. As the world population increases and eventually stabilizes, the demands for energy to assure adequate living conditions will severely tax available resources, especially those of fossil fuels. New and different sources of energy and methods of conversion will have to be explored and brought into practical use. The wise use of nuclear energy, based on understanding of both hazards and benefits, will be required to meet this challenge to existence.

This book is intended to provide a factual description of basic nuclear phenomena, to describe devices and processes that involve nuclear reactions, and to call attention to the problems and opportunities that are inherent in a nuclear age. It is designed for use by anyone who wishes to know about the role of nuclear energy in our society or to learn nuclear concepts for use in professional work.

In spite of the technical complexity of nuclear systems, students who have taken a one-semester course based on the book have shown a surprising level of interest, appreciation, and understanding. This response resulted in part from the selectivity of subject matter and from efforts to connect basic ideas with the "real world," a goal that all modern education must seek if we hope to solve the problems facing civilization.

The sequence of presentation proceeds from fundamental facts and principles through a variety of nuclear devices to the relation between nuclear energy and peaceful applications. Emphasis is first placed on energy, atoms and nuclei, and nuclear reactions, with little background required. The book then describes the operating principles of radiation equipment, nuclear reactors, and other systems involving nuclear processes, giving quantitative information wherever possible. Finally, attention is directed to the subjects of radiation protection, beneficial usage of radiation, and the connection between energy resources and human progress.

The author is grateful to Dr. Ephraim Stam for his many suggestions on technical content, to Drs. Claude G. Poncelet and Albert J. Impink, Jr. for their careful review, to Christine Baermann for her recommendations on style and clarity, and to Carol Carroll for her assistance in preparation of the manuscript.

Raleigh, North Carolina, 1975 RAYMOND L. MURRAY

The Author

Raymond L. Murray (Ph.D. University of Tennessee) is Professor Emeritus in the Department of Nuclear Engineering of North Carolina State University. His technical interests include reactor analysis, nuclear criticality safety, radioactive waste management, and applications of microcomputers.

Dr. Murray studied under J. Robert Oppenheimer at the University of California at Berkeley. In the Manhattan Project of World War II, he contributed to the uranium isotope separation process at Berkeley and Oak Ridge.

In the early 1950s, he helped found the first university nuclear engineering program and the first university nuclear reactor. During his 30 years of teaching and research in reactor analysis at N.C. State he taught many of our current leaders in universities and industry throughout the world. He is the author of textbooks in physics and nuclear technology and the recipient of a number of awards, including the Eugene P. Wigner Reactor Physicist Award of the American Nuclear Society in 1994. He is a Fellow of the American Physical Society, a Fellow of the American Nuclear Society, and a member of several honorary, scientific, and engineering societies.

Since retirement from the university, Dr. Murray has been a consultant for the TMI-2 Recovery Program, served as chairman of the North Carolina Radiation Protection Commission, and served as chairman of the North Carolina Low-Level Radioactive Waste Management Authority.

Contents

Part I Basic Concepts

In the study of the practical applications of nuclear energy we must take account of the properties of individual particles of matter–their "microscopic" features–as well as the character of matter in its ordinary form, a "macroscopic" (large-scale) view. Examples of the small-scale properties are masses of atoms and nuclear particles, their effective sizes for interaction with each other, and the number of particles in a certain volume. The combined behavior of large numbers of individual particles is expressed in terms of properties such as mass density, charge density, electrical conductivity, thermal conductivity, and elastic constants. We continually seek consistency between the microscopic and macroscopic views.

Since all processes involve interactions of particles, it is necessary that we develop a background of understanding of the basic physical facts and principles that govern such interactions. In Part I we shall examine the concept of energy, describe the models of atomic and nuclear structure, discuss radioactivity and nuclear reactions in general, review the ways radiation reacts with matter, and concentrate on two important nuclear processes–fission and fusion.

1

Energy

OUR MATERIAL world is composed of many substances distinguished by their chemical, mechanical, and electrical properties. They are found in nature in various physical states–the familiar solid, liquid, and gas, along with the ionic "plasma." However, the apparent diversity of kinds and forms of material is reduced by the knowledge that there are only a little over 100 distinct chemical elements and that the chemical and physical features of substances depend merely on the strength of force bonds between atoms.

In turn, the distinctions between the elements of nature arise from the number and arrangement of basic particles–electrons, protons, and neutrons. At both the atomic and nuclear levels, the structure of elements is determined by internal forces and energy.

1.1 Forces and Energy

There are a limited number of basic forces–gravitational, electrostatic, electromagnetic, and nuclear. Associated with each of these is the ability to do work. Thus energy in different forms may be stored, released, transformed, transferred, and "used" in both natural processes and man-made devices. It is often convenient to view nature in terms of only two basic entities–particles and energy. Even this distinction can be removed, since we know that matter can be converted into energy and vice versa.

Let us review some principles of physics needed for the study of the release of nuclear energy and its conversion into thermal and electrical form. We recall that if a constant force F is applied to an object to move it a distance s, the amount of work done is the product Fs. As a simple example, we pick up a book from the floor and place it on a table. Our muscles provide the means to lift against the force of gravity on the book. We have done work on the object, which now possesses stored energy (potential energy), because it could do work if allowed to fall back to the original level. Now a force F acting on a mass m provides an acceleration a, given by Newton's law $F = ma$. Starting from rest, the object gains a speed u, and at any instant has energy of motion (kinetic energy) in amount $E_k = \frac{1}{2} m u^2$. For objects falling under the force of gravity, we find that the

potential energy is reduced as the kinetic energy increases, but the sum of the two types remains constant. This is an example of the principle of conservation of energy. Let us apply this principle to a practical situation and perform some illustrative calculations.

As we know, falling water provides one primary source for generating electrical energy. In a hydroelectric plant, river water is collected by a dam and allowed to fall through a considerable distance. The potential energy of water is thus converted into kinetic energy. The water is directed to strike the blades of a turbine, which turns an electric generator.

The potential energy of a mass m located at the top of the dam is $E_p = Fh$, being the work done to place it there. The force is the weight $F = mg$, where g is the acceleration of gravity. Thus $E_p = mgh$. For example, for 1 kg and 50 m height of dam, using $g = 9.8$ m/s^2*, E_p is (1)(9.8)(50) = 490 joules (J). Ignoring friction, this amount of energy in kinetic form would appear at the bottom. The water speed would be $u = \sqrt{2E_k / m} = 31.3$ m/s.

Energy takes on various forms, classified according to the type of force that is acting. The water in the hydroelectric plant experiences the force of gravity, and thus gravitational energy is involved. It is transformed into mechanical energy of rotation in the turbine, which then is converted to electrical energy by the generator. At the terminals of the generator, there is an electrical potential difference, which provides the force to move charged particles (electrons) through the network of the electrical supply system. The electrical energy may then be converted into mechanical energy as in motors, or into light energy as in lightbulbs, or into thermal energy as in electrically heated homes, or into chemical energy as in a storage battery.

The automobile also provides familiar examples of energy transformations. The burning of gasoline releases the chemical energy of the fuel in the form of heat, part of which is converted to energy of motion of mechanical parts, while the rest is transferred to the atmosphere and highway. Electricity is provided by the automobile's generator for control and lighting. In each of these examples, energy is changed from one form to another, but is not destroyed. The conversion of heat to other forms of energy is governed by two laws, the first and second laws of thermodynamics. The first states that energy is conserved; the second specifies inherent limits on the efficiency of the energy conversion.

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* The standard acceleration of gravity is 9.80665 m/s^2. For discussion and simple illustrative purposes, numbers will be rounded off to two or three significant figures. Only when accuracy is important will more figures or decimals be used. The principal source of physical constants, conversion factors, and nuclear properties will be the *CRC Handbook of Chemistry and Physics* (see References), which is likely to be accessible to the faculty member, student, or reader.

Energy can be classified according to the primary source. We have already noted two sources of energy: falling water and the burning of the chemical fuel gasoline, which is derived from petroleum, one of the main fossil fuels. To these we can add solar energy, the energy from winds, tides, or the sea motion, and heat from within the earth. Finally, we have energy from nuclear reactions, i.e., the "burning" of nuclear fuel.

1.2 Thermal Energy

Of special importance to us is thermal energy, as the form most readily available from the sun, from burning of ordinary fuels, and from the fission process. First we recall that a simple definition of the temperature of a substance is the number read from a measuring device such as a thermometer in intimate contact with the material. If energy is supplied, the temperature rises; e.g., energy from the sun warms the air during the day. Each material responds to the supply of energy according to its internal molecular or atomic structure, characterized on a macroscopic scale by the specific heat c. If an amount of thermal energy added to one gram of the material is Q, the temperature rise, ΔT, is Q/c. The value of the specific heat for water is c = 4.18 J/g-°C and thus it requires 4.18 joules of energy to raise the temperature of one gram of water by one degree Celsius (1°C).

From our modern knowledge of the atomic nature of matter, we readily appreciate the idea that energy supplied to a material increases the motion of the individual particles of the substance. Temperature can thus be related to the average kinetic energy of the atoms. For example, in a gas such as air, the average energy of translational motion of the molecules $\overline{E}$ is directly proportional to the temperature T, through the relation $\overline{E} = \frac{3}{2} kT$, where k is Boltzmann's constant, 1.38×10^{-23} J/K. (Note that the Kelvin scale has the same spacing of degrees as does the Celsius scale, but its zero is at -273°C.)

To gain an appreciation of molecules in motion, let us find the typical speed of oxygen molecules at room temperature 20°C, or 293K. The molecular weight is 32, and since one unit of atomic weight corresponds to 1.66×10^{-27} kg, the mass of the oxygen (O_2) molecule is 5.3×10^{-26} kg. Now

$$\overline{E} = \tfrac{3}{2} (1.38 \times 10^{-23})(293) = 6.1 \times 10^{-21} \text{ J}$$

and thus the speed is

$$\upsilon = \sqrt{2\overline{E} / m} = \sqrt{2(6.14 \times 10^{-21}) / (5.3 \times 10^{-26})} \cong 479 \text{ m / s}$$

Closely related to energy is the physical entity *power*, which is the rate at which work is done. To illustrate, suppose that the flow of water in the hydroelectric plant of Section 1.1 were 2×10^6 kg/s. The corresponding energy per second is (2×10^6) (490) = 9.8×10^8 J/s. For convenience, the

unit joule per second is called the watt (W). Our plant thus involves 9.8×10^8 W. We can conveniently express this in kilowatts (1 kW = 10^3 W) or megawatts (1 MW = 10^6 W). Such multiples of units are used because of the enormous range of magnitudes of quantities in nature–from the submicroscopic to the astronomical. The standard set of prefixes is given in Table 1.1.

For many purposes we shall employ the metric system of units, more precisely designated as SI, Systeme Internationale. In this system (see References) the base units are the kilogram (kg) for mass, the meter (m) for length, the second (s) for time, the mole (mol) for amount of substance, the ampere (A) for electric current, the kelvin (K) for thermodynamic temperature and the candela (cd) for luminous intensity. However, for understanding of the earlier literature, one requires a knowledge of other systems. The Appendix includes a table of useful conversions from British to SI units.

TABLE 1.1
Prefixes for Numbers and Abbreviations

yotta	Y	10^{24}	deci	d	10^{-1}
zetta	Z	10^{21}	centi	c	10^{-2}
exa	E	10^{18}	milli	m	10^{-3}
peta	P	10^{15}	micro	m	10^{-6}
tera	T	10^{12}	nano	n	10^{-9}
giga	G	10^{9}	pico	p	10^{-12}
mega	M	10^{6}	femto	f	10^{-15}
kilo	k	10^{3}	atto	a	10^{-18}
hecto	h	10^{2}	zepto	z	10^{-21}
deca	da	10^{1}	yocto	y	10^{-24}

The transition in the U.S. from British units to the SI units has been much slower than expected. In the interests of ease of understanding by the typical reader, a dual display of numbers and their units appears frequently. Familiar and widely used units such as the centimeter, the barn, the curie, and the rem are retained.

In dealing with forces and energy at the level of molecules, atoms, and nuclei, it is conventional to use another energy unit, the *electron-volt* (eV). Its origin is electrical in character, being the amount of kinetic energy that would be imparted to an electron (charge 1.60×10^{-19} coulombs) if it were accelerated through a potential difference of 1 volt. Since the work done on 1 coulomb would be 1 J, we see that 1 eV = 1.60×10^{-19} J. The unit is of convenient size for describing atomic reactions. For instance, to remove the one electron from the hydrogen atom requires 13.5 eV of energy. However, when dealing with nuclear forces, which are very much larger than atomic forces, it is preferable to use the million-electron-volt unit (MeV). To separate the neutron from the proton in the nucleus of heavy hydrogen, for

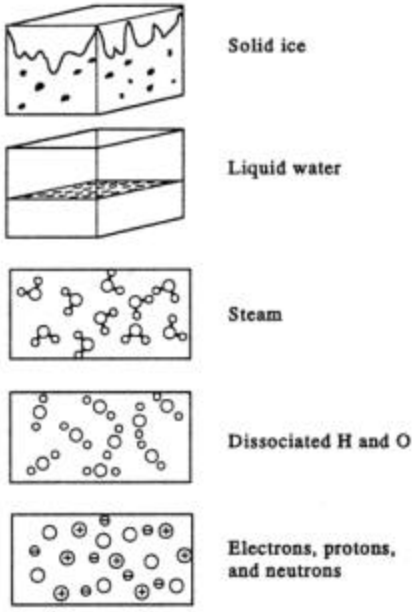

FIG. 1.1 Effect of added energy.

example, requires an energy of about 2.2 MeV, i.e., 2.2×10^6 eV.

1.3 Radiant Energy

Another form of energy is electromagnetic or radiant energy. We recall that this energy may be released by heating of solids, as in the wire of a lightbulb, or by electrical oscillations, as in radio or television transmitters, or by atomic interactions, as in the sun. The radiation can be viewed in either of two ways–as a wave or as a particle–depending on the process under study. In the wave view it is a combination of electric and magnetic vibrations moving through space. In the particle view it is a compact moving uncharged object, the photon, which is a bundle of pure energy, having mass only by virtue of its motion. Regardless of its origin, all radiation can be characterized by its frequency, which is related to speed and wavelength. Letting c be the speed of light, λ its wavelength and ν its frequency, we have $c = \lambda\nu$.† For example, if c in a vacuum is 3×10^8 m/s, yellow light of wavelength 5.89×10^{-7} m has a frequency of 5.1×10^{14} s^{-1}. X-rays and gamma rays are electromagnetic radiation arising from the interactions of atomic and nuclear particles, respectively. They have energies and frequencies much higher than those of visible light.

† We shall have need of both Roman and Greek characters, identifying the latter by name the first time they are used, thus λ (lambda) and ν (nu). The reader must be wary of symbols used for more than one quantity.

In order to appreciate the relationship of states of matter, atomic and nuclear interactions, and energy, let us visualize an experiment in which we supply energy to a sample of water from a source of energy that is as large and as sophisticated as we wish. Thus we increase the degree of internal motion and eventually dissociate the material into its most elementary components. Suppose, Fig. 1.1, that the water is initially as ice at nearly absolute zero temperature, where water (H_2O) molecules are essentially at rest. As we add thermal energy to increase the temperature to 0°C or 32°F, molecular movement increases to the point where the ice melts to become liquid water, which can flow rather freely. To cause a change from the solid state to the liquid state, a definite amount of energy (the heat of fusion) is required. In the case of water, this latent heat is 334 J/g. In the temperature range in which water is liquid, thermal agitation of the molecules permits some evaporation from the surface. At the boiling point, 100°C or 212°F at atmospheric pressure, the liquid turns into the gaseous form as steam. Again, energy is required to cause the change of state, with a heat of vaporization of 2258 J/g. Further heating, using special high temperature equipment, causes dissociation of water into atoms of hydrogen (H) and oxygen (O). By electrical means electrons can be removed from hydrogen and oxygen atoms, leaving a mixture of charged ions and electrons. Through nuclear bombardment, the oxygen nucleus can be broken into smaller nuclei, and in the limit of temperatures in the billions of degrees, the material can be decomposed into an assembly of electrons, protons, and neutrons.

1.4 The Equivalence of Matter and Energy

The connection between energy and matter is provided by Einstein's theory of special relativity. It predicts that the mass of any object increases with its speed. Letting the mass when the object is at rest be m_0, the "rest mass," and letting m be the mass when it is at speed u, and noting that the speed of light in a vacuum is $c = 3\times10^8$ m/s, then

$$m = \frac{m_0}{\sqrt{1-(u/c)^2}}.$$

For motion at low speed (e.g., 500 m/s), the mass is almost identical to the rest mass, since u/c and its square are very small. Although the theory has the status of natural law, its rigor is not required except for particle motion at high speed, i.e., when u is at least several percent of c. The relation shows that a material object can have a speed no higher than c.

The kinetic energy imparted to a particle by the application of force according to Einstein is

$$E_k = (m - m_0)\, c^2$$

(For low speeds, $u << c$, this is approximately $\frac{1}{2} m u_0^2$, the classical relation.)

The implication of Einstein's formula is that any object has an energy $E_0 = m_0c^2$ when at rest (its ''rest energy''), and a total energy $E = mc^2$, the difference being E_k the kinetic energy. Let us compute the rest energy for an electron of mass 9.1×10^{-31} kg.

$$E_0 = m_0c^2 = (9.1\times10^{-31})(3.0\times10^{8})^2 = 8.2\times10^{-14}\ \text{J}$$

$$E_0 = \frac{8.2\times10^{-14}\ \text{J}}{1.60\times10^{-13}\ \text{J/MeV}} = 0.51\ \text{MeV}$$

For one unit of atomic mass, 1.66×10^{-27} kg, which is close to the mass of a hydrogen atom, the corresponding energy is 931 MeV.

Thus we see that matter and energy are equivalent, with the factor c^2 relating the amounts of each. This suggests that matter can be converted into energy and that energy can be converted into matter. Although Einstein's relationship is completely general, it is especially important in calculating the release of energy by nuclear means. We find that *the energy yield from a kilogram of nuclear fuel is more than a million times that from chemical fuel.* To prove this startling statement, we first find the result of the complete transformation of one kilogram of matter into energy, namely, $(1\ \text{kg})(3.0\times10^{8}\ \text{m/s})^2 = 9\times10^{16}$ J. The nuclear fission process, as one method of converting mass into energy, is relatively inefficient, since the "burning" of 1 kg of uranium involves the conversion of only 0.87 g of matter into energy. This corresponds to about 7.8×10^{13} J/kg of the uranium consumed. The enormous magnitude of this energy release can be appreciated only by comparison with the energy of combustion of a familiar fuel such as gasoline, 5×10^{7} J/kg. The ratio of these numbers, 1.5×10^{6}, reveals the tremendous difference between nuclear and chemical energies.

Calculations involving Einstein's theory are made easy by use of a computer program ALBERT, described in Computer Exercise 1.A.

1.5 Energy and the World

All of the activities of human beings depend on energy, as we realize when we consider the dimensions of the world's energy problem. The efficient production of food requires machines, fertilizer, and water, each using energy in a different way. Energy is vital to transportation, protection against the weather, and the manufacturing of all goods. An adequate long-term supply of energy is therefore essential for man's survival. The world energy problem has many dimensions: the increasing cost to acquire fuels as they become more scarce; the potential for global climate change resulting from burning fossil fuels; the effects on safety and health of the

byproducts of energy consumption; the inequitable distribution of energy resources among regions and nations; and the discrepancies between current energy usage and human expectations throughout the world.

1.6 Summary

Associated with each basic type of force is an energy, which may be transformed to another form for practical use. The addition of thermal energy to a substance causes an increase in temperature, the measure of particle motion. Electromagnetic radiation arising from electrical devices, atoms or nuclei may be considered as composed of waves or of photons. Matter can be converted into energy and vice versa according to Einstein's formula $E = mc^2$. The energy of nuclear fission is millions of times as large as that from chemical reactions. Energy is fundamental to all of man's endeavors and indeed to his survival.

1.7 Exercises

1.1. Find the kinetic energy of a basketball player of mass 75 kg as he moves down the floor at a speed of 8 m/s.

1.2. Recalling the conversion formulas for temperature,

$$C = \frac{5}{9}(F - 32) \qquad F = \frac{9}{5}C + 32$$

where C and F are degrees in respective systems, convert each of the following: 68°F, 500°F, -273°C, 1000°C.

1.3. If the specific heat of iron is 0.45 J/g-°C how much energy is required to bring 0.5 kg of iron from 0°C to 100°C?

1.4. Find the speed corresponding to the average energy of nitrogen gas molecules (N_2, 28 units of atomic weight) at room temperature.

1.5. Find the power in kilowatts of an auto rated at 200 horsepower. In a drive for 4 h at average speed 45 mph, how many kWh of energy are required?

1.6. Find the frequency of a g -ray photon of wavelength 1.5×10^{-12} m.

1.7. (a) For very small velocities, show that the fractional change in mass due to relativity is

$$\Delta m/m_0 \cong (u/c)^2/2$$

Hint: use the series expansion of $(1 + x)^n$.

(b) Apply the formula to a car of mass 1000 kg moving at 20 m/s to find the increase in mass in grams.

1.8. Noting that the electron-volt is 1.60×10^{-19} J, how many joules are released in the fission of one uranium nucleus, which yields 190 MeV?

1.9. Applying Einstein's formula for the equivalence of mass and energy, $E = mc^2$, where $c = 3 \times 10^8$ m/s, the speed of light, how many kilograms of matter are converted into energy in Exercise 1.8?

1.10. If the atom of uranium-235 has mass of (235) (1.66×10^{-27}) kg, what amount of equivalent energy does it have?

1.11. Using the results of Exercises 1.8, 1.9, and 1.10, what fraction of the mass of a U-235 nucleus is converted into energy when fission takes place?

1.12. Show that to obtain a power of 1 W from fission of uranium, it is necessary to cause 3.3×10^{10} fission events per second. Assume that each fission releases 190 MeV of useful energy.

1.13. (a) If the fractional mass increase due to relativity is $\Delta E/E_0$, show that

$$u / c = \sqrt{1 - (1 + \Delta E / E_0)^{-2}} .$$

(b) At what fraction of the speed of light does a particle have a mass that is 1% higher than the rest mass? 10%? 100%?

1.14. The heat of combustion of hydrogen by the reaction $2H + O = H_2O$ is quoted to be 34.18 kilogram calories per gram of hydrogen. (a) Find how many Btu per pound this is using the conversions 1 Btu = 0.252 kcal, 1 lb = 454 grams. (b) Find how many joules per gram this is noting 1 cal = 4.18 J. (c) Calculate the heat of combustion in eV per H_2 molecule.

Computer Exercises

1.A. Properties of particles moving at high velocities are related in a complicated way according to Einstein's theory of special relativity. To obtain answers easily, the BASIC computer program ALBERT (after Dr. Einstein) can be used to treat the following quantities:

velocity
momentum
total mass-energy
kinetic energy
ratio of mass to rest mass

Given one of the above, for a selected particle, ALBERT calculates the others.

Test the program with various inputs, for example u/c = 0.9999 and T = 1 billion electron volts.

1.8 General References

Encyclopedia Britannica online
http://www.britannica.com
A new format for the venerable information source on all subjects. Use Find feature.

Grolier 2000 Multimedia Encyclopedia (CD-ROM), University of Maryland, Baltimore, 1999.

Sybil P. Parker, Editor, *McGraw-Hill Encyclopedia of* Physics, 2nd Ed., McGraw-Hill, New York, 1993.

Isaac Asimov, *Asimov's Biographical Encyclopedia of Science and Technology*, 2nd revised edition, Doubleday & Co., Garden City, NY, 1982. Subtitle: The Lives and Achievements of 1510 Great Scientists from Ancient Times to the Present Chronologically Arranged.

Frank J. Rahn, Achilles G. Adamantiades, John E. Kenton, and Chaim Braun, *A Guide to Nuclear Power Technology*: *A Resource for Decision Making*, Krieger Publishing Co., Melbourne, FL, 1991 (reprint of 1984 edition). A book for persons with some technical background. Almost a thousand pages of fine print. A host of tables, diagrams, photographs, and references.

Radiation Information Network
http://www.physics.isu.edu/radinf/index1.html

Numerous links to sources. By Bruce Busby, Idaho State University.

Scientific American Magazine
http://www.sciam.com/askexpert
Ask the expert a question on science.

American Nuclear Society publications
http://www.ans.org
Nuclear News, *Radwaste Solutions*, *Nuclear Technology*, *Nuclear Science and Engineering*, *Fusion Technology*, and *Transactions of the American Nuclear Society*.

Glossary of Terms in Nuclear Science and Technology, American Nuclear Society, La Grange Park, IL, 1986. Prepared by ANS-9, the American Nuclear Society Standards Subcommittee on Nuclear Technology and Units, Harry Alter, chairman.

Ronald Allen Knief, *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, Taylor & Francis, Bristol, PA, 1992.

Robert M. Mayo, *Introduction to Nuclear Concepts for Engineers*, American Nuclear Society, La Grange Park, IL, 1998. College textbook emphasizing nuclear processes.

William D. Ehmann and Diane E. Vance, *Radiochemistry and Nuclear Methods of Analysis*, John Wiley & Sons, New York, 1991. Covers many of the topics of this book in greater length.

David R. Lide, Editor, *CRC Handbook of Chemistry and Physics*, *80th Edition, 1999-2000*, CRC Press, Boca Raton, FL, 1999. A standard source of data on many subjects.

WWW Virtual Library
http://www.vlib.org
Links to Virtual Libraries in Engineering, Science, and other categories.

WWW Virtual Library Nuclear Engineering
http://www.nuc.berkeley.edu
Select Nuclear Links!

How Things Work
http://howthingswork.virginia.edu
Information on many subjects by Professor Louis Bloomfield.

How Stuff Works
http://www.howstuffworks.com
Brief explanations by Marshall Brain of familiar devices and concepts, including many of the topics of this book.

Internet Detective
http://www.netskills.ac.uk/TonicNG/cgi/sesame?detective
A tutorial on browsing for quality Internet information.

Scout Report Signpost
http://www.signpost.org/signpost/index.html
Select Science or Technology.

Energy Quest

http://www.energy.ca.gov/education/index.html
The Energy Story. From California Energy Commission.

1.9 References for Chapter 1

David Halliday, Jearl Walker, and Robert E. Resnick, *Fundamentals of Physics*, 5th Ed., John Wiley & Sons, New York, 1996. Classic popular textbook for college science and engineering students.

Paul A. Tipler, *Physics for Scientists and Engineers*, 4th Ed., Worth Publishers, New York, 1999. Calculus-based college textbook.

Raymond L. Murray and Grover C. Cobb, *Physics: Concepts and Consequences*. Prentice-Hall, Englewood Cliffs, NJ, 1970 (available from American Nuclear Society, La Grange Park, IL). Non-calculus text for liberal arts students.

The NIST Reference on Constants, Units, and Uncertainty
http://physics.nist.gov/cuu/
Information on SI units and physical constants.

American Physical Society
http://www.aps.org
Select Physics Internet Resources/Education Scientific Reference Sites/Fizzix is Phun. Basic concepts of physics from the viewpoint of a high school student.

Basic Physics Course
http://zebu.uoregon.edu/~kevan/found.html
A complete course given by Professor Stephen Kevan. Try the lectures of Nov. 1, 1995 (Newton's laws) and Oct. 11, 1995 (Special relativity).

Interactive Physics Problem Set
http://socrates.berkeley.edu:7521/projects/IPPS
87 problems with solutions, mainly on mechanics.

PhysLink
http://www.physlink.com
Select Reference for links to sources of many physics constants, conversion factors, and other data.

Physical Science Resource Center
http://www.psrc-online.org
Links provided by American Association of Physics Teachers. Example: Select Resource Center/Statistics & Thermodynamics/About Temperature.

James Trefil, "Greetings From the Antiworld," *Smithsonian Magazine*, June, 1998. A popular discussion of antimatter.

Albert Einstein
http://www.westegg.com/einstein
http://pbs.org/wgbh/nova/einstein
http://www.aip.org/history/einstein
Mainly about the scientist.

2

Atoms and Nuclei

A COMPLETE understanding of the microscopic structure of matter and the exact nature of the forces acting is yet to be realized. However, excellent models have been developed to predict behavior to an adequate degree of accuracy for most practical purposes. These models are descriptive or mathematical, often based on analogy with large-scale processes, on experimental data, or on advanced theory.

2.1 Atomic Theory

The most elementary concept is that matter is composed of individual particles–atoms–that retain their identity as elements in ordinary physical and chemical interactions. Thus a collection of helium atoms that forms a gas has a total weight that is the sum of the weights of the individual atoms. Also, when two elements combine to form a compound (e.g., if carbon atoms combine with oxygen atoms to form carbon monoxide molecules), the total weight of the new substance is the sum of the weights of the original elements.

There are more than 100 known elements. Most are found in nature; some are artificially produced. Each is given a specific number in the periodic table of the elements–examples are hydrogen (H) 1, helium (He) 2, oxygen (O) 8, and uranium (U) 92. The symbol Z is given to that *atomic number*, which is also the number of electrons in the atom and determines its chemical properties.

Computer Exercise 2.A describes the program ELEMENTS, which helps find atomic numbers, symbols, and names of elements in the periodic table.

Generally, the higher an element is in the periodic table, the heavier are its atoms. The *atomic weight* M is the weight in grams of a definite number of atoms, 6.02×10^{23}, which is Avogadro's number, N_a. For the example elements above, the values of M are approximately H 1.008, He 4.003, O 16.00, and U 238.0. We can easily find the number of atoms per cubic centimeter in a substance if its density r (rho) in grams per cubic centimeter is known. For example, if we had a container of helium gas with density 0.00018 g/cm^3, each cubic centimeter would contain a fraction 0.00018/4.003 of Avogadro's number of helium atoms, i.e., 2.7×10^{19}. This

procedure can be expressed as a convenient formula for finding N, the number per cubic centimeter for any material:

$$N = \frac{r}{M} N_a$$

Thus in natural uranium with its density of 19 g/cm^3, we find N = (19/238)(6.02 × 10^{23}) = 0.048 × 10^{24} cm^{-3}. The relationship holds for compounds as well, if M is taken as the molecular weight. In water, H_2O, with r = 1.0 g/cm^3 and M = 2 (1.008) + 16.00 ≅ 18.0, we have N = (1/18)(6.02 × 10^{23}) = 0.033 × 10^{24} cm^{-3}. (The use of numbers times 10^{24} will turn out to be convenient later.)

2.2 Gases

Substances in the gaseous state are described approximately by the perfect gas law, relating pressure, volume, and absolute temperature,

$$pV = nkT,$$

where n is the number of particles and k is Boltzmann's constant. An increase in the temperature of the gas due to heating causes greater molecular motion, which results in an increase of particle bombardment of a container wall and thus of pressure on the wall. The particles of gas, each of mass m, have a variety of speeds u in accord with Maxwell's gas theory, as shown in Fig. 2.1. The most probable speed, at the peak of this maxwellian distribution, is dependent on temperature according to the relation

$$u_p = \sqrt{2kT/m}\,.$$

The kinetic theory of gases provides a basis for calculating properties such as the specific heat. Using the fact from Chapter 1 that the average energy of gas molecules is proportional to the temperature, $\overline{E} = \frac{3}{2} kT$, we can deduce, as in Exercise 2.4, that the specific heat of a gas consisting only of atoms is $c = \frac{3}{2} k/m$, where m is the mass of one atom. We thus see an intimate relationship between mechanical and thermal properties of materials.

2.3 The Atom and Light

Until the 20th century the internal structure of atoms was unknown, but it was believed that electric charge and mass were uniform. Rutherford performed some crucial experiments in which gold atoms were bombarded by charged particles. He deduced in 1911 that most of the mass and positive charge of an atom were concentrated in a *nucleus* of radius only about 10^{-5} times that of the atom, and thus occupying a volume of about 10^{-15} times that of the atom. (See Exercise 2.2 and 2.11.) The new view of atoms paved

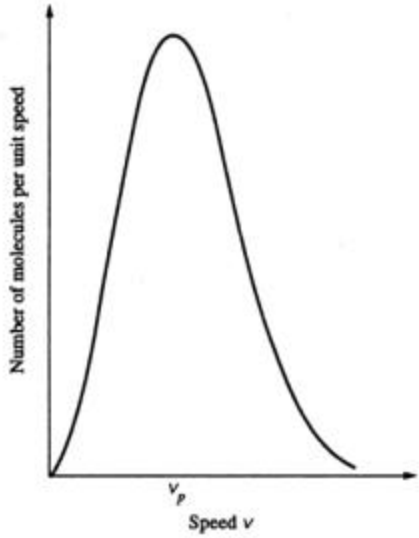

FIG. 2.1 Distribution of molecular speeds.

the way for Bohr to find an explanation for the production of light.

It is well known that the color of a heated solid or gas changes as the temperature is increased, tending to go from the red end of the visible region toward the blue end, i.e., from long wavelengths to short wavelengths. The measured distribution of light among the different wavelengths at a certain temperature can be explained by the assumption that light is in the form of photons. These are absorbed and emitted with definite amounts of energy E that are proportional to the frequency n, according to

$$E = hn,$$

where h is Planck's constant, 6.63×10^{-34} J-s. For example, the energy corresponding to a frequency of 5.1×10^{14} is (6.63×10^{-34}) (5.1×10^{14}) = 3.4×10^{-19} J, which is seen to be a very minute amount of energy.

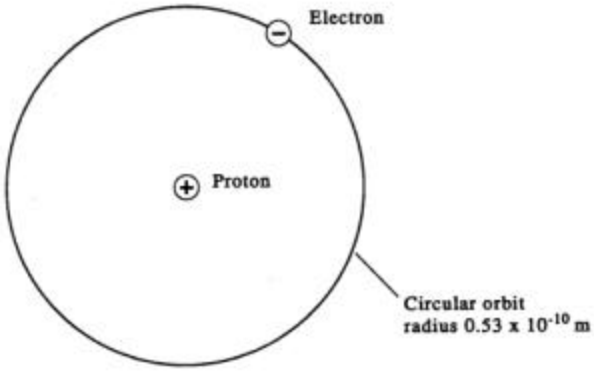

FIG. 2.2 Hydrogen atom.

The emission and absorption of light from incandescent hydrogen gas was first explained by Bohr, using a novel model of the hydrogen atom. He assumed that the atom consists of a single electron moving at constant speed in a circular orbit about a nucleus–the proton–as sketched in Fig. 2.2.

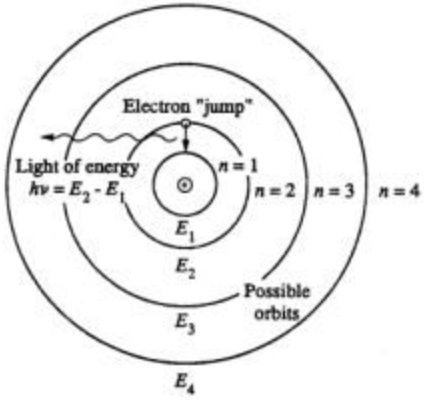

FIG. 2.3 Electron orbits in hydrogen (Bohr theory).

Each particle has an electric charge of 1.6×10^{-19} coulombs, but the proton has a mass that is 1836 times that of the electron. The radius of the orbit is set by the equality of electrostatic force, attracting the two charges toward each other, to centripetal force, required to keep the electron on a circular path. If sufficient energy is supplied to the hydrogen atom from the outside, the electron is caused to jump to a larger orbit of definite radius. At some later time, the electron falls back spontaneously to the original orbit, and energy is released in the form of a photon of light. The energy of the photon hn is equal to the difference between energies in the two orbits. The smallest orbit has a radius $R_1 = 0.53\times10^{-10}$ m, while the others have radii increasing as the square of integers (called quantum numbers). Thus if n is 1, 2, 3,..., the radius of the nth orbit is $R_n = n^2 R_1$. Figure 2.3 shows the allowed electron orbits in hydrogen. The energy of the atom system when the electron is in the first orbit is E_1 = -13.5 eV, where the negative sign means that energy must be supplied to remove the electron to a great distance and leave the hydrogen as a positive ion. The energy when the electron is in the nth orbit is E_1/n^2. The various discrete levels are sketched in Fig. 2.4.

The electronic structure of the other elements is described by the shell model, in which a limited number of electrons can occupy a given orbit or shell. The atomic number Z is unique for each chemical element, and represents both the number of positive charges on the central massive nucleus of the atom and the number of electrons in orbits around the nucleus. The maximum allowed numbers of electrons in orbits as Z increases for the first few shells are 2, 8, and 18. The chemical behavior of

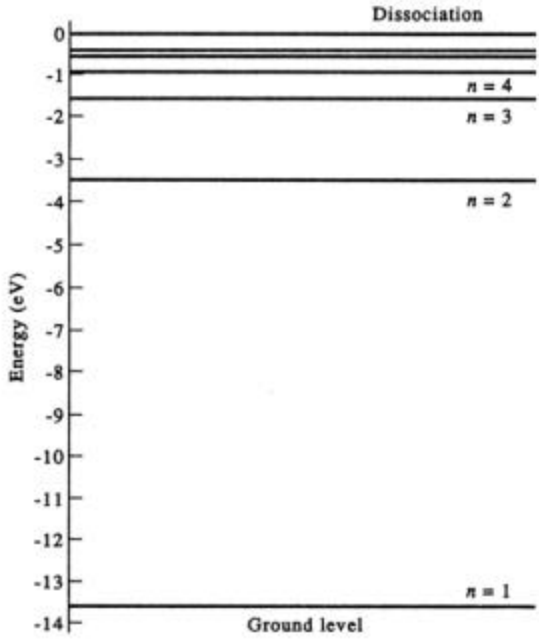

FIG. 2.4 Energy levels in hydrogen atom.

elements is determined by the number of electrons in the outermost or valence shell. For example, oxygen with $Z = 8$ has two electrons in the inner shell, six in the outer. Thus oxygen has an affinity for elements with two electrons in the valence shell. The formation of molecules from atoms by electron sharing is illustrated by Fig. 2.5, which shows the water molecule.

2.4 Laser Beams

Ordinary light as in the visible range is a mixture of many frequencies, directions, and phases. In contrast, light from a *laser* (*l*ight *a*mplified by *s*timulated *e*mission of *r*adiation) consists of a direct beam of one color and with the waves in step. The device consists of a tube of material to which energy is supplied, exciting the atoms to higher energy states. A photon of a certain frequency is introduced. It strikes an excited atom, causing it to fall back to the ground state and in so doing emit another photon of the same frequency. The two photons strike other atoms, producing four identical photons, and so on. The ends of the laser are partially reflecting, which causes the light to be trapped and to build up inside by a combination of reflection and stimulation. An avalanche of photons is produced that makes a very intense beam. Light moving in directions other than the long axis of the laser is lost through the sides, so that the beam that escapes from the end proceeds in only one direction. The reflection between the two end mirrors assures a coherent beam; i.e., the waves are in phase.

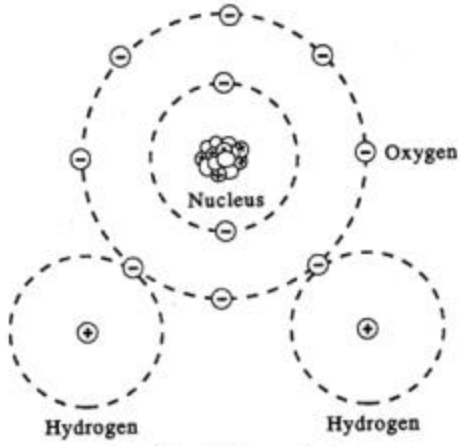

FIG. 2.5 Water molecule.

Lasers can be constructed from several materials. The original one (1960) was the crystalline gem ruby. Others use gases such as a helium-neon mixture, or liquids with dye in them, or semiconductors. The external supply of energy can be chemical reactions, a discharge produced by accelerated electrons, energetic particles from nuclear reactions, or another laser. Some lasers operate continuously while others produce pulses of energy as short as a fraction of a nanosecond (10^{-9} sec) with a power of a terawatt (10^{12} watts). Because of the high intensity, laser light if viewed directly can be hazardous to the eyes.

Lasers are widely used where an intense well-directed beam is required, as in metal cutting and welding, eye surgery and other medical applications, and accurate surveying and range finding. Newer applications are noise-free phonographs, holograms (3D images), and communication between airplane and submarine.

Later, we shall describe some nuclear applications–isotope separation (Section 9.4) and thermonuclear fusion (Section 14.4).

2.5 Nuclear Structure

Most elements are composed of particles of different weight, called isotopes. For instance, hydrogen has three isotopes of weights in proportion 1, 2 and 3–ordinary hydrogen, heavy hydrogen (deuterium), and tritium. Each has atomic number $Z = 1$ and the same chemical properties, but they differ in the composition of the central nucleus, where most of the weight resides. The nucleus of ordinary hydrogen is the positively charged proton; the deuteron consists of a proton plus a neutron, a neutral particle of weight very close to that of the proton; the triton contains a proton plus two neutrons. To distinguish isotopes, we identify the mass number A, as the total number of nucleons, the heavy particles in the nucleus. A complete

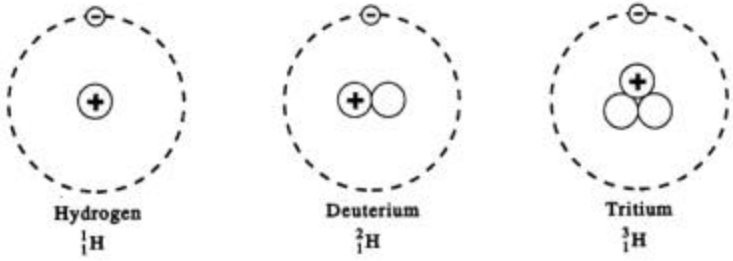

FIG. 2.6 Isotopes of hydrogen.

shorthand description is given by the chemical symbol with superscript A value and subscript Z value, e.g., $^{1}_{1}\mathrm{H}$, $^{2}_{1}\mathrm{H}$, and $^{3}_{1}\mathrm{H}$. Figure 2.6 shows the nuclear and atomic structure of the three hydrogen isotopes. Each has one electron in the outer shell, in accord with the Bohr theory described earlier.

The structure of some of the lighter elements and isotopes is sketched in Fig. 2.7. In each case, the atom is neutral because the negative charge of the Z electrons in the outer shell balances the positive charge of the Z protons in the nucleus. The symbols for the isotopes shown in Fig. 2.7 are:

$$^{1}_{1}\mathrm{H},\ ^{4}_{2}\mathrm{He},\ ^{6}_{3}\mathrm{Li},\ ^{7}_{3}\mathrm{Li},\ ^{9}_{4}\mathrm{Be},\ ^{16}_{8}\mathrm{O},\ ^{23}_{11}\mathrm{Na}.$$

In addition to the atomic number Z and the mass number A, we often need to write the neutron number N, which is, of course, $A - Z$. For the set of isotopes listed, N is 0, 2, 3, 4, 5, 8, and 12, respectively.

When we study nuclear reactions, it is convenient to let the neutron be represented by the symbol $^{1}_{0}\mathrm{n}$, implying a mass comparable to that of hydrogen, $^{1}_{1}\mathrm{H}$, but with no electronic charge, $Z = 0$. Similarly, the electron is represented by $^{0}_{-1}\mathrm{e}$, suggesting nearly zero mass in comparison with that of hydrogen, but with negative charge. An identification of isotopes frequently used in qualitative discussion consists of the element name and its A value, thus sodium-23 and uranium-235, or even more simply Na-23 and U-235.

2.6 Sizes and Masses of Nuclei

The dimensions of nuclei are found to be very much smaller than those of atoms. Whereas the hydrogen atom has a radius of about 5×10^{-9} cm, its nucleus has a radius of only about 10^{-13} cm. Since the proton weight is much larger than the electron weight, the nucleus is extremely dense. The nuclei of other isotopes may be viewed as closely packed particles of matter–neutrons and protons–forming a sphere whose volume, $\frac{4}{3}\pi R^3$, depends on A, the number of nucleons. A useful rule of thumb to calculate radii of nuclei is

$$R(\mathrm{cm}) = 1.4 \times 10^{-13} A^{1/3}.$$

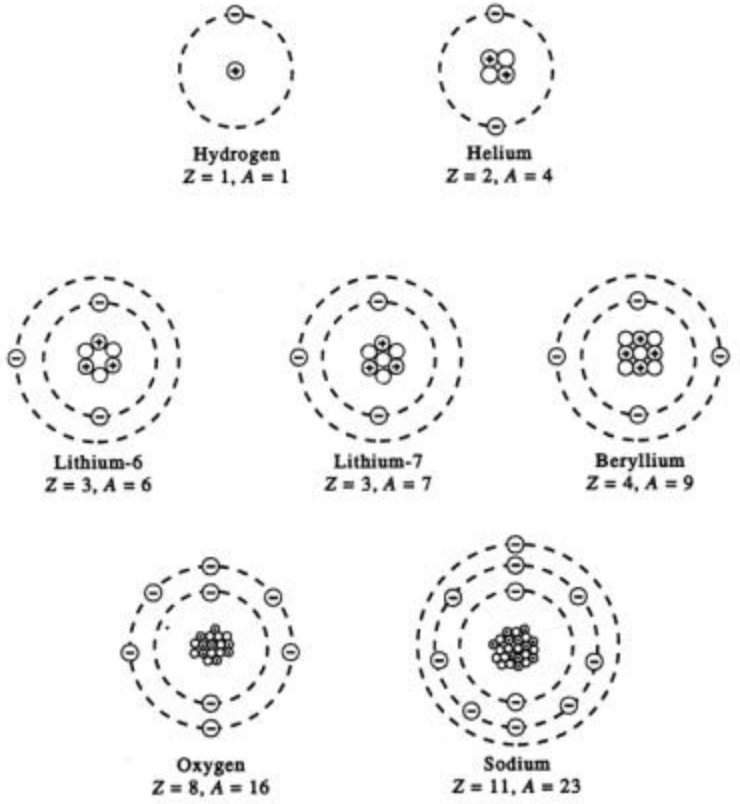

FIG. 2.7 Atomic and nuclear structure.

Since A ranges from 1 to about 250, we see that all nuclei are smaller than 10^{-12} cm.

The masses of atoms, labeled M, are compared on a scale in which an isotope of carbon ${}^{12}_{6}\mathrm{C}$ has a mass of exactly 12. For ${}^{1}_{1}\mathrm{H}$, the atomic mass is M = 1.007825, for ${}^{2}_{1}\mathrm{H}$, M = 2.014102, and so on. The atomic mass of the proton is 1.007276, of the neutron 1.008665, the difference being only about 0.1%. The mass of the electron on this scale is 0.000549. A list of atomic masses appears in the Appendix.

The atomic mass unit (amu), as 1/12 the mass of ${}^{12}_{6}\mathrm{C}$, corresponds to an actual mass of 1.66×10^{-24} g. To verify this, merely divide 1 g by Avogadro's number 6.02×10^{23}. It is easy to show that 1 amu is also equivalent to 931 MeV. We can calculate the actual masses of atoms and nuclei by multiplying the mass in atomic mass units by the mass of 1 amu. Thus the mass of the neutron is (1.008665) (1.66×10^{-24}) = 1.67×10^{-24} g.

2.7 Binding Energy

The force of electrostatic repulsion between like charges, which varies

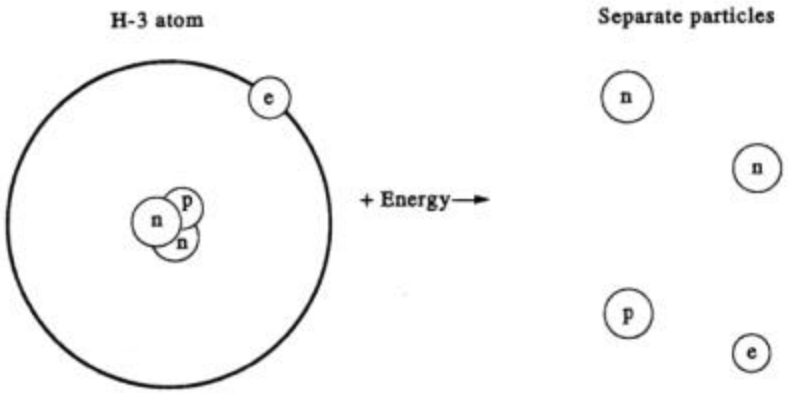

FIG. 2.8 Dissociation of tritium.

inversely as the square of their separation, would be expected to be so large that nuclei could not be formed. The fact that they do exist is evidence that there is an even larger force of attraction. The nuclear force is of very short range, as we can deduce from the above rule of thumb. As shown in Exercise 2.9, the radius of a nucleon is approximately 1.4×10^{-13} cm; the distance of separation of centers is about twice that. The nuclear force acts only when the nucleons are very close to each other, and binds them into a compact structure. Associated with the net force is a potential energy of binding. To disrupt a nucleus and separate it into its component nucleons, energy must be supplied from the outside. Recalling Einstein's relation between mass and energy, this is the same as saying that a given nucleus is lighter than the sum of its separate nucleons, the difference being the binding mass-energy. Let the mass of an atom including nucleus and external electrons be M, and let m_n and m_H be the masses of the neutron and the proton plus matching electron. Then the binding energy is

$$B = \text{total mass of separate particles} - \text{mass of the atom}$$

or

$$B = Nm_n + Zm_H - M$$

(Neglected in this relation is a small energy of atomic or chemical binding.) Let us calculate B for tritium, the heaviest hydrogen atom, ${}_1^3\mathrm{H}$. Figure 2.8 shows the dissociation that would take place if a sufficient energy were provided. Now $Z = 1$, $N = 2$, $m_n = 1.008665$, $m_H = 1.007825$, and $M = 3.016049$. Then

$$B = 2(1.008665) + 1(1.007825) - 3.016049$$

$$B = 0.009106 \text{ amu}.$$

Converting by use of the relation 1 amu = 931 MeV, the binding energy is $B = 8.48$ MeV. Calculations such as these are required for several purposes–to compare the stability of one nucleus with that of another, to find the energy release in a nuclear reaction, and to predict the possibility of

fission of a nucleus.

We can speak of the binding energy associated with one particle such as a neutron. Suppose that M_1 is the mass of an atom and M_2 is its mass after absorbing a neutron. The binding energy of the additional neutron of mass m_n is then

$$B_n = M_1 + m_n - M_2 .$$

Explanations of binding energy effects using physical logic and measured atomic masses have led to what are called "semi-empirical formulas" for binding energy. The value of B for any nuclide is calculated approximately by an expression that accounts for (a) attraction of nucleons for each other, (b) electrostatic repulsion, (c) surface tension effects, (d) the imbalance of neutrons and protons in the nucleus. Computer Exercise 2.B makes use of a program BINDING that estimates binding energy B, the internal energy per nucleon $E = -B/A$, and the atomic mass M for given mass number A and atomic number Z.

2.8 Summary

All material is composed of elements whose chemical interaction depends on the number of electrons (Z). Light is absorbed and emitted in the form of photons when atomic electrons jump between orbits. Isotopes of elements differ according to the number of nucleons (A). Nuclei are much smaller than atoms and contain most of the mass of the atom. The nucleons are bound together by a net force in which the nuclear attraction forces exceed the electrostatic repulsion forces. Energy must be supplied to dissociate a nucleus into its components.

2.9 Exercises

2.1. Find the number of carbon (${}^{12}_{6}\mathrm{C}$) atoms in 1 cm^3 of graphite, density 1.65 $\mathrm{g/cm}^3$.

2.2. Estimate the radius and volume of the gold atom, using the metal density of 19.3 $\mathrm{g/cm}^3$ and atomic weight close to 197. Assume that atoms are located at corners of cubes and that the atomic radius is that of a sphere with volume equal to that of a cube.

2.3. Calculate the most probable speed of a "neutron gas" at temperature 20°C (293K), noting that the mass of a neutron is 1.67×10^{-27} kg.

2.4. Prove that the specific heat of an atomic gas is given by $c_p = (3/2)(k/m)$, using the formula for average energy of a molecule.

2.5. Calculate the energy in electron volts of a photon of yellow light (see Section 2.3). Recall from Section 1.2 that 1 eV = 1.60×10^{-19} J.

2.6. What frequency of light is emitted when an electron jumps into the smallest orbit of hydrogen, coming from a very large radius (assume infinity)?

2.7. Calculate the energy in electron-volts of the electron orbit in hydrogen for which $n = 3$, and find the radius in centimeters. How much energy would be needed to cause an electron to go from the innermost orbit to this one? If the electron jumped back, what frequency of

light would be observed?

2.8. Sketch the atomic and nuclear structure of carbon-14, noting Z and A values and the numbers of electrons, protons, and neutrons.

2.9. If A nucleons are visualized as spheres of radius r that can be deformed and packed tightly in a nucleus of radius R, show that $r = 1.4 \times 10^{-13}$ cm.

2.10. What is the radius of the nucleus of uranium-238 viewed as a sphere? What is the area of the nucleus, seen from a distance as a circle?

2.11. Find the fraction of the volume that is occupied by the nucleus in the gold-197 atom, using the relationship of radius R to mass number A. Recall from Exercise 2.2 that the radius of the atom is 1.59×10^{-8} cm.

2.12. Find the binding energy in MeV of ordinary helium, ${}^{4}_{2}\mathrm{He}$, for which $M = 4.002603$.

2.13. How much energy (in MeV) would be required to completely dissociate the uranium-235 nucleus (atomic mass 235.043923) into its component protons and neutrons?

2.14. Find the mass density of the nucleus, the electrons, and the atom of U-235, assuming spherical shapes and the following data:

atomic radius	1.7×10^{-10} m
nuclear radius	8.6×10^{-15} m
electron radius	2.8×10^{-15} m
mass of 1 amu	1.66×10^{-27} kg
mass of electron	9.11×10^{-31} kg

Discuss the results.

2.15. Maxwell's formula for the number of molecules per unit speed is

$$n(u) = n_0 \, A u^2 \exp(-mu^2 / 2kT)$$

where n_0 is the total number of molecules and

$$A = 4p\left(\frac{m}{2p\,kT}\right)^{3/2}$$

(a) Verify by differentiation that the peak of the curve is at

$$u_p = \sqrt{2kT / m}$$

(b) Verify by integration that the average speed

$$\bar{u} = \int_0^\infty u \; n(u)\, du / n_0$$

is given by

$$\bar{u} = \sqrt{\frac{8kT}{p\,m}}\,.$$

Hint: let $mu^2/2kT = x$.

Computer Exercises

2.A. The BASIC program ELEMENTS is a miniature "expert system" that gives information on elements in the periodic table. Three related quantities are listed–atomic number, symbol for the chemical element, and its name. If one of these is input, the other two are displayed. Run the program's options, being sure to try values of Z well above 100.

2.B. The BASIC program BINDING calculates the approximate binding energy B and

atomic mass M for any nuclide, using a semi-empirical formula containing six terms dependent on atomic number Z and mass number A. Run the program on these isotopes:

$$^{16}_{8}\mathrm{O}\ ,\ ^{17}_{8}\mathrm{O}\ ,\ ^{92}_{37}\mathrm{Rb}\ ,\ ^{140}_{55}\mathrm{Cs}\ ,\ ^{235}_{92}\mathrm{U}\ ,\ ^{238}_{92}\mathrm{U}\ .$$

How do the results compare with the values listed in the Appendix?

2.10 References for Chapter 2

N. N. Greenwood and A. Earnshaw, *Chemistry of the Elements*, 2nd Ed., Butterworth-Heinemann, Oxford, 1997. Structures, properties, and reactions.

Robley D. Evans, *The Atomic Nucleus*, New York, Krieger Publishing Co., Melbourne, FL, 1982. A reprint of the McGraw-Hill 1955 classic advanced textbook containing a wealth of information on nuclei, radioactivity, radiation, and nuclear processes.

Robert M. Mayo, *Introduction to Nuclear Concepts for Engineers*, American Nuclear Society, La Grange Park, IL, 1998. Thorough discussion of the atomic nucleus.

Educational Site
http://www.lbl.gov/Education/index.html
Select ABC's of Nuclear Science; California Science Project; Glenn Seaborg: His Life & Contributions.

The Amazing World of Electrons and Photons
http://library.advanced.org/16468/gather/english.htm
Atoms, Bohr's theory, lasers, and much more, by three 16-year-old students. Part of the ThinkQuest program (see http://www.advanced.org).

Kinetic Theory of Gases: A Brief Review
http://www.phys.virginia.edu/classes/252/kinetic_theory.html
Derivations of pressure, the gas law, Maxwell's equation, etc. by Michael Fowler

How Things Work
http://howthingswork.virginia.edu
Select topic from menu.

How Stuff Works
http://www.howstuffworks.com
Try "relativity."

Nuclear Data
http://ie.lbl.gov/toi.html
Comprehensive source of information by Lawrence Berkeley Laboratory and Lunds Universitet (Sweden).

The Particle Adventure
http://www.cpepweb.org
A leisurely and light-hearted tour of quarks, antimatter, the Standard Model, interactions, and experiments.

WebElements Periodic Table of the Elements
http://www.webelements.com
Mark Winter provides information about each element.

General Chemistry
http://www.chem.ufl.edu/~chm2040/Notes
An online course of the University of Florida. By Randy Duran.

3

Radioactivity

MANY NATURALLY occurring and man-made isotopes have the property of radioactivity, which is the spontaneous disintegration (decay) of the nucleus with the emission of a particle. The process takes place in minerals of the ground, in fibers of plants, in tissues of animals, and in the air and water, all of which contain traces of radioactive elements.

3.1 Radioactive Decay

Many heavy elements are radioactive. An example is the decay of the main isotope of uranium, in the reaction

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}\ .$$

The particle released is the a (alpha) particle, which is merely the helium nucleus. The new isotope of thorium is also radioactive, according to

$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} + n$$

The first product is the element protactinium. The second is an electron, which is called the b (beta) particle when it arises in a nuclear process. The nucleus does not contain electrons; they are produced in the reaction, as discussed in Section 3.2. The third is the neutrino, symbolized by n (nu). It is a neutral particle that shares with the beta particle the reaction's energy release. On average, the neutrino carries $\frac{2}{3}$ of the energy, the electron, $\frac{1}{3}$. The neutrino has zero or possibly a very small mass, and readily penetrates enormous thicknesses of matter. We note that the A value decreases by 4 and the Z value by 2 on emission of an a particle, while the A remains unchanged but Z increases by 1 on emission of a b particle. These two events are the start of a long sequence or "chain" of disintegrations that produce isotopes of the elements radium, polonium, and bismuth, eventually yielding the stable lead isotope $^{206}_{82}\mathrm{Pb}$. Other chains found in nature start with $^{235}_{92}\mathrm{U}$ and $^{232}_{90}\mathrm{Th}$. Hundreds of "artificial" radioisotopes have been produced by bombardment of nuclei by charged particles or neutrons, and by separation of the products of the fission process.

3.2 The Decay Law

The rate at which a radioactive substance disintegrates (and thus the rate

of release of particles) depends on the isotopic species, but there is a definite "decay law" that governs the process. In a given time period, say one second, each nucleus of a given isotopic species has the same chance of decay. If we were able to watch one nucleus, it might decay in the next instant, or a few days later, or even hundreds of years later. Such statistical behavior is described by a constant property of the atom called half-life. This time interval, symbolized by t_H, is the time required for half of the nuclei to decay, leaving half of them intact. We should like to know how many nuclei of a radioactive species remain at any time. If we start at time zero with N_0 nuclei, after a length of time t_H, there will be $N_0/2$; by the time $2t_H$ has elapsed, there will be $N_0/4$; etc. A graph of the number of nuclei as a function of time is shown in Fig. 3.1. For any time t on the curve, the ratio of the number of nuclei present to the initial number is given by

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^{t/t_H}.$$

Half-lives range from very small fractions of a second to billions of years, with each radioactive isotope having a definite half-life. Table 3.1 gives several examples of radioactive materials with their emissions, product isotopes, and half-lives. The b particle energies are maximum values; on average the emitted betas have only one-third as much energy. Included in the table are both natural and man-made radioactive isotopes (also called radioisotopes). We note the special case of neutron decay according to

$$\text{neutron} \rightarrow \text{proton} + \text{electron}.$$

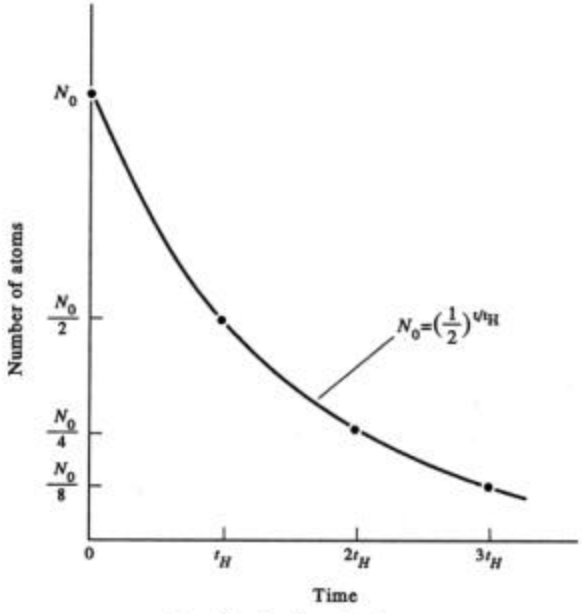

FIG. 3.1 Radioactive decay.

A free neutron has a half-life of 10.3 min. The conversion of a neutron into a proton can be regarded as the origin of beta emission in radioactive nuclei. Most of the radioisotopes in nature are heavy elements. One exception is potassium-40, half-life 1.26×10^9 y, with abundance 0.0117% in natural potassium. Others are carbon-14 and hydrogen-3 (tritium), which are produced continuously in small amounts by natural nuclear reactions. All three radioisotopes are found in plants and animals.

In addition to the radioisotopes that decay by beta or alpha emission,

TABLE 3.1
Selected Radioactive Isotopes†

Isotope	Half-life	Principal radiations (type, MeV)
Neutron	10.3 m	*b*, 0.782
Tritium (H-3)	12.32 y	*b*, 0.01860
Carbon-14	5715 y	*b*, 0.1565
Nitrogen-16	7.13 s	*b*, 4.27, 10.44; *g*, 6.129
Sodium-24	14.96 h	*b*, 1.389; *g*, 1.369, 2.754
Phosphorus-32	14.28 d	*b*, 1.710
Potassium-40	1.26×10^9 y	*b*, 1.312
Argon-41	1.82 h	*b*, 1.198; *g*, 1.294
Cobalt-60	5.271 y	*b*, 0.315; *g*, 1.173, 1.332
Krypton-85	10.73 y	*b*, 0.687; *g*, 0.514
Strontium-90	29.1 y	*b*, 0.546
Technetium-99m	6.01 h	*b*, 0.142
Iodine-129	1.7×10^7y	*b*, 0.15
Iodine-131	8.040 d	*b*, 0.606
Xenon-135	9.10 h	*b*, 0.91; *g*, 0.250
Cesium-137	30.3 y	*b*, 0.514; *g*, 0.662
Radon-222	3.8235 d	*a*, 5.490
Radium-226	1599 y	*a*, 4.784
Uranium-235	7.04×10^8 y	*a*, 4.395
Uranium-238	4.46×10^9 y	*a*, 4.196
Plutonium-239	2.411×10^4 y	*a*, 5.156

† David R. Lide, Editor, *CRC Handbook of Chemistry and Physics*, *80th Edition, 1999-2000* , CRC Press, Boca Raton, FL, 1999.

there is a large group of artificial isotopes that decay by the emission of a positron, which has the same mass as the electron and an equal but positive charge. An example is sodium-22, which decays with 2.6 y half-life into a neon isotope as

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e}\,.$$

Whereas the electron (also called negatron) is a normal part of any atom, the positron is not. It is an example of what is called an antiparticle, because its properties are opposite to those of the normal particle. Just as particles form matter, antiparticles form antimatter.

The Na-22 reaction above can be regarded as involving the conversion of a proton into a neutron with the release of a positron, using excess energy in the parent nucleus. This is an example of the conversion of energy into mass. Usually, the mass appears in the form of pairs of particles of opposite charge. The positron-electron pair is one example. As discussed in Section 5.4(c), an electron and a positron will combine and both be annihilated to form two g rays.

A nucleus can get rid of excess internal energy by the emission of a gamma ray, but in an alternate process called internal conversion the energy is imparted directly to one of the atomic electrons, ejecting it from the atom. In an inverse process called K-capture, the nucleus spontaneously absorbs one of its own orbital electrons. Each of these processes is followed by the production of X-rays as the inner shell vacancy is filled.

The formula for N/N_0 is not very convenient for calculations except when t is some integer multiple of t_H. Defining the decay constant l (lambda), as the chance of decay of a given nucleus each second, an equivalent *exponential formula* † for decay is

$$\frac{N}{N_0} = e^{-lt} \ .$$

We find that $l = 0.693/t_H$. To illustrate, let us calculate the ratio N/N_0 at the end of 2 years for cobalt-60, half-life 5.27 y. This artificially produced radioisotope has many medical and industrial applications. The reaction is

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\mathrm{e} + g,$$

where the gamma ray energies are 1.17 and 1.33 MeV and the maximum beta energy is 0.315 MeV. Using the conversion 1 y = 3.16×10^7 s, t_H = 1.67×10^8 s. Then l = 0.693/(1.67 x 10^8) = 4.15×10^{-9} s^{-1}, and since t is 6.32×10^7 s, lt is 0.262 and $N/N_0 = e^{-0.262} = 0.77$.

The number of disintegrations per second (dis/sec) of a radioisotope is called the activity, A. Since the decay constant l is the chance of decay each second of one nucleus, for N nuclei the activity is the product

$$A = l\,N.$$

For a sample of cobalt-60 weighing 1 μg, which is also 10^{16} atoms,

$$A = (4.15\times 10^{-9})\ (10^{16}) = 4.15\times 10^7 \text{ dis/sec.}$$

---

† If l is the chance one nucleus will decay in a second, then the chance in a time interval dt is $l\,dt$. For N nuclei, the change in number of nuclei is $dN = -l\,N dt$. Integrating, and letting the number of nuclei at time zero be N_0 yields the formula quoted. Note that if

$$e^{-lt} = (1/2)^{t/t_H}$$

$$lt = t/t_H \log_e 2 \text{ or } l = (\log_e 2)/t_H.$$

The unit dis/sec is called the becquerel (Bq), honoring the scientist who discovered radioactivity.

Another older and commonly used unit of activity is the curie (Ci) named after the French scientists Pierre and Marie Curie who studied radium. The curie is 3.7×10^{10} dis/sec, which is an early measured value of the activity per gram of radium. Our cobalt sample has a "strength" of $(4.15\times 10^{7}$ Bq)/$(3.7\times 10^{10}$ Bq/Ci) = 0.0011 Ci or 1.1 mCi.

The half-life tells us how long it takes for half of the nuclei to decay, while a related quantity, the mean life, t (tau), is the average time elapsed for decay of an individual nucleus. It turns out that t is $1/l$ and thus equal to t_H/0.693. For Co-60, t is 7.6 y.

Computer Exercise 3.A calculates activities using a spreadsheet and 3.B displays formulas, calculations, and a graph of decay.

3.3 Radioactive Chains

Radionuclides arise in several processes. They may be produced by the bombardment of stable nuclei by charged particles as in an accelerator or by neutrons as in a nuclear reactor. Or, they may come from other radionuclides, in which the "parent" nuclide decays and produces a "daughter" isotope. Still more generally, there may be a sequence of decays between a series of radionuclides, called a "chain," leading eventually to a stable nucleus.

Let us examine the method of calculating yields of some of these processes. The easiest case is the generation rate that is constant in time. For example, suppose that neutrons absorbed in cobalt-59 create cobalt-60 at a rate g. The net rate of change with time of the number of cobalt-60 atoms is

rate of change = generation rate – decay rate

which may be written in the form of a differential equation,

$$dN/dt = g - l\ N.$$

If the initial number is zero, the solution is

$$N = (g / l)(1 - e^{-lt}).$$

The function rises linearly at the start, then flattens out. At long times, the exponential term goes toward zero, leaving $N \cong g/l$. Numerical values of numbers of atoms and activity can be calculated using the BASIC program GROWTH, described in Computer Exercise 3.C.

In the decay of a parent radionuclide to form a daughter radionuclide, the generation rate g is an exponential function of time. Computer Exercise 3.D displays the solution of the differential equation and suggests tests of the computer program RADIOGEN for the decay of plutonium-241 into

americium-241.

Natural radioactive isotopes such as uranium-238 (4.46×10^9 y) and thorium-232 (1.4×10^{10} y) were produced billions of years ago but still persist because of their long half-lives. Their products form a long chain of radionuclides, with the emission of a particles and b particles. Those forming the uranium series are:

$$^{238}_{92}\mathrm{U},\quad ^{234}_{90}\mathrm{Th},\quad ^{234}_{91}\mathrm{Pa},\quad ^{234}_{92}\mathrm{U},\quad ^{230}_{90}\mathrm{Th},$$
$$^{226}_{88}\mathrm{Ra},\quad ^{222}_{86}\mathrm{Rn},\quad ^{218}_{84}\mathrm{Po},\quad ^{214}_{82}\mathrm{Pb},\quad ^{214}_{83}\mathrm{Bi},$$
$$^{214}_{84}\mathrm{Po},\quad ^{210}_{82}\mathrm{Pb},\quad ^{210}_{83}\mathrm{Bi},\quad ^{210}_{84}\mathrm{Po},\quad ^{206}_{82}\mathrm{Pb}.$$

Note that radium-226 (1599 y) is fairly far down the chain. The final product is stable lead-206. Because of the very long half-life of uranium-238, the generation rate of its daughters and their descendants are practically constant. Let us write $g \cong N_{238}\, l_{238}$, and apply the expression for the number of atoms at long times to the radium-226, $N_{226} \cong g/l_{226}$. Rearranging, the activities are approximately equal,

$$A_{238} \cong A_{226},$$

a condition called secular equilibrium.

3.4 Measurement of Half-Life

Finding the half-life of an isotope provides part of its identification, needed for beneficial use or for protection against radiation hazard. Let us look at a method for measuring the half-life of a radioactive substance. As in Fig. 3.2, a detector that counts the number of particles striking it is placed near the source of radiation. From the number of counts observed in a known short time interval, the counting rate is computed. It is proportional to the rates of emission of particles or rays from the sample and thus to the activity A of the source. The process is repeated after an elapsed time for

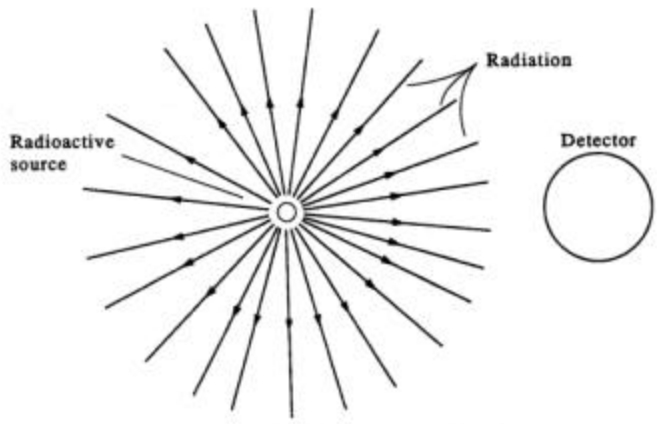

FIG. 3.2 Measurement of radiation from radioactive source.

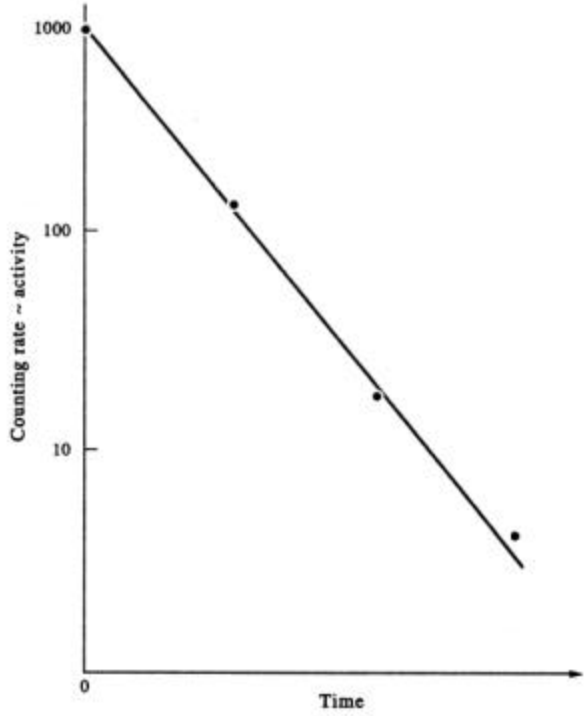

FIG. 3.3 Activity plot.

decay. The resulting values of activity are plotted on semilog graph paper as in Fig. 3.3, and a straight line drawn through the observed points. From any pairs of points on the line l and $t_H = 0.693/l$ can be calculated (see Exercise 3.8). The technique may be applied to mixtures of two radioisotopes. After a long time has elapsed, only the isotope of longer half-life will contribute counts. By extending its graph linearly back in time, one can find the counts to be subtracted from the total to yield the counts from the isotope of shorter half-life.

Activity plots cannot be used for a substance with very long half-life, e.g., strontium-90, 29.1 y. The change in activity is almost zero over the span of time one is willing to devote to a measurement. However, if one knows the number of atoms present in the sample and measures the activity, the decay constant can be calculated from $l = A/N$, from which t_H can be found.

The measurement of the activity of a radioactive substance is complicated by the presence of background radiation, which is due to cosmic rays from outside the earth or from the decay of minerals in materials of construction or in the earth. It is always necessary to measure the background counts and subtract them from those observed in the experiment.

3.5 Summary

Many elements that are found in nature or are man-made are radioactive, emitting a particles, b particles, and g rays. The process is governed by an exponential relation, such that half of a sample decays in a time called the half-life t_H. Values of t_H range from fractions of a second to billions of years among the hundreds of radioisotopes known. Measurement of the activity, as the disintegration rate of a sample, yields half-life values, of importance in radiation use and protection.

3.6 Exercises

3.1. Find the decay constant of cesium-137, half-life 30.2 y; then calculate the activity in becquerels and curies for a sample containing 3×10^{19} atoms.

3.2. Calculate the activity A for 1 g of radium-226 using the modern value of the half-life, and compare it with the definition of a curie.

3.3. The radioisotope sodium-24 ($^{24}_{11}\mathrm{Na}$), half-life 15 h, is used to measure the flow rate of salt water. By irradiation of stable $^{23}_{11}\mathrm{Na}$ with neutrons, suppose that we produce 5 micrograms of the isotope. How much do we have at the end of 24 h?

3.4. For a 1-mg sample of Na-24, what is the initial activity and that after 24 hours, in dis/sec and curies? See Exercise 3.3.

3.5. The isotope uranium-238 ($^{238}_{92}\mathrm{U}$) decays successively to form $^{234}_{90}\mathrm{Th}$, $^{234}_{91}\mathrm{Pa}$, $^{234}_{92}\mathrm{U}$, and $^{230}_{90}\mathrm{Th}$, finally becoming radium-226 ($^{226}_{88}\mathrm{Ra}$). What particles are emitted in each of these five steps? Draw a graph of this chain, using A and Z values on the horizontal and vertical axes, respectively.

3.6. A capsule of cesium-137, half-life 30.2 y, is used to check the accuracy of detectors of radioactivity in air and water. Draw a graph on semilog paper of the activity over a 10-y period of time, assuming the initial strength is 1 mCi. Explain the results.

3.7. There are about 140 grams of potassium in a typical person's body. From this weight, the abundance of potassium-40, and Avogadro's number, find the number of atoms. Find the decay constant in s^{-1}. How many disintegrations per second are there in the body? How many becquerels and how many microcuries is this?

3.8 (a) Noting that the activity of a radioactive substance is $A = l N_0 e^{-lt}$, verify that the graph of counting rate vs. time on semilog paper is a straight line and show that

$$l = \frac{\log_e (C_1 / C_2)}{t_2 - t_1}$$

where points 1 and 2 are any pair on the curve.

(b) Using the following data, deduce the half-life of an "unknown," and suggest what isotope it is.

Time (s)	Counting rate (/s)
0	200
1000	182
2000	162
3000	144
4000	131

3.9. By chemical means, we deposit 10^{-8} moles of a radioisotope on a surface and measure the activity to be 82,000 dis/sec. What is the half-life of the substance and what element is it (see Table 3.1)?

Computer Exercises

3.A. The spreadsheet Lotus 1-2-3 is convenient for calculating the amount of decay of a radioactive sample in a given time. Program DECAY 1 has input of the original number of curies and the half-life; it calculates the final number of curies. Load the program, examine its form, and look at the results for the decay in 100 y of cesium-137, half-life 30.2 y. Then change input, e.g., x = 302 y (10 half-lives), or enter figures for another radionuclide such as cobalt- 60.

3.B. The details of a calculation of radioactive decay are presented in the BASIC program DECAY. By means of a set of menus, the equations and solution can be inspected, useful numbers noted, calculations carried out, and a graph of the results viewed. Run the program, using the menus, making choices as desired. Then modify the program to handle another radionuclide.

3.C. GROWTH is a program in BASIC that calculates the number of radioactive cobalt-60 atoms and their activity, assuming a constant generation rate.

(a) Load and run the program, exploring its menus.

(b) Modify the program to calculate the growth of sodium-24 (15 h) resulting from neutron capture in sodium-23.

3.D. The number of atoms of a parent radioisotope initially is N_{p0}. At any time, the number as the result of decay is

$$N_p = N_{p0}\ E_p$$

where

$$E_p = \exp(-\lambda_p t).$$

Let k be the fraction of parents that decay into a particular daughter. Then the generation rate for the latter is

$$g = k\ N_p\ \lambda_p.$$

The solution of the differential equation

$$dN_d/dt = g - \lambda_d\ N_d$$

is

$$N_d = k\ \lambda_p\ N_{p0}\ (E_p - E_d)/(\lambda_d - \lambda_p)$$

where

$$E_d = \exp(-\lambda_d t).$$

BASIC computer program RADIOGEN uses these formulas to calculate the number of atoms N_p and N_d as a function of time and their activities. Test the program for the decay by beta emission of 10 Ci of reactor-produced plutonium-241, (14.4 y) into americium-241 (432 y), with k = l.

3.7 References for Chapter 3

Richard B. Firestone and Virginia S. Shirley, *Table of Isotopes*, 8th Ed., John Wiley & Sons, New York, 1998. Two volumes with nuclear structure and decay data for over 3,100 isotopes.

WebElements Periodic Table
http://www.webelements.com
Probably the best of its kind.

W. B. Mann, R. L. Ayres, and S. B. Garfinkel, *Radioactivity and Its Measurement*, 2nd edition, Pergamon Press, Oxford, 1980. History, fundamentals, interactions, and detectors. Serves as a supplement to NCRP Report No. 58 (q.v.). Out of print, unfortunately.

Handbook of Radioactivity Measurement Procedures, NCRP report No. 58, 2nd edition, National Council of Radiation Protection and Measurements, Bethesda, MD, 1985. A comprehensive and authoritative reference. An appendix lists radionuclides of biomedical importance.

Alfred Romer, Editor, *The Discovery of Radioactivity and Transmutation*, Dover Publications, New York, 1964. A collection of essays and articles of historical interest. Researchers represented are Becquerel, Rutherford, Crookes, Soddy, the Curies, and others.

Alfred Romer, Editor, *Radioactivity and the Discovery of Isotopes*, Dover Publications, New York, 1970. Selected original papers, with a thorough historical essay by the editor entitled, "The Science of Radioactivity 1896-1913; Rays, Particles, Transmutations, Nuclei, and Isotopes."

Robley D. Evans, *The Atomic Nucleus*, New York, Krieger Publishing Co. Melbourne, FL, 1982. Classic advanced textbook.

Merril Eisenbud and Thomas F. Gesell, *Environmental Radioactivity*, 4th edition, Academic Press, New York, 1987. Subtitle: From Natural, Industrial, and Military Sources. Includes information on the Chernobyl reactor accident.

Michael F. L'Annunziata, Editor, *Handbook of Radioactivity Analysis*, Academic Press, New York, 1998. An advanced reference of 771 pages. Many of the contributors are from commercial instrument companies.

ABC's of Nuclear Science
http://www.lbl.gov/Education/index.html
Radioactivity, radiations, and suggested experiments.

Radioactivity in Nature
http://www.physics.isu.edu/radinf/natural.htm
Facts and data on natural and manmade radioactivity and on radiation. From Idaho State University Physics Department.

Radiation and Health Physics
http://www.umich.edu/~radinfo
Select Introduction to Radiation. From University of Michigan

Radioactive Decay Series
http://www.uic.com.au/neAp2.htm
Diagrams of uranium, thorium, and actinium series. Part of an online book Nuclear Electricity, accessible from this site.

History of Radioactivity
http://www.accessexcellence.com/AE/AEC/CC
Biographies of scientists responsible for discoveries, by Genentech.

Environmental Radiation and Uranium: A Radioactive Clock
http://scifun.chem.wisc.edu/chemweek/Radiation/Radiation.html
Briefings on radiation and its effect; uranium decay series.

4

Nuclear Processes

NUCLEAR REACTIONS–those in which atomic nuclei participate–may take place spontaneously, as in radioactivity, or may be induced by bombardment with a particle or ray. Nuclear reactions are much more energetic than chemical reactions, but they obey the same physical laws–conservation of momentum, energy, number of particles, and charge.

The number of possible nuclear reactions is extremely large because there are about 2000 known isotopes and many particles that can either be projectiles or products–photons, electrons, protons, neutrons, alpha particles, deuterons, and heavy charged particles. In this chapter we shall emphasize induced reactions, especially those involving neutrons.

4.1 Transmutation of Elements

The conversion of one element into another, a process called transmutation, was first achieved in 1919 by Rutherford in England. He bombarded nitrogen atoms with α particles from a radioactive source to produce an oxygen isotope and a proton, according to the equation

$$^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} .$$

We note that on both sides of the equation the A values add to 18 and the Z values add to 9. Figure 4.1 shows Rutherford's experiment. It is difficult for the positively charged α particle to enter the nitrogen nucleus because of the electrical forces between nuclei. The α particle thus must have several MeV energy.

Nuclear transmutations can also be achieved by charged particles that are electrically accelerated to high speeds. The first such example discovered was the reaction

$$^{1}_{1}\mathrm{H} + {}^{7}_{3}\mathrm{Li} \rightarrow 2\,{}^{4}_{2}\mathrm{He} .$$

Another reaction,

$$^{1}_{1}\mathrm{H} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{13}_{7}\mathrm{N} + \gamma ,$$

yields a gamma ray and an isotope of nitrogen. The latter decays with a half-life of 10.3 min, releasing a positron, the positive counterpart of the electron.

Since the neutron is a neutral particle it does not experience electrostatic

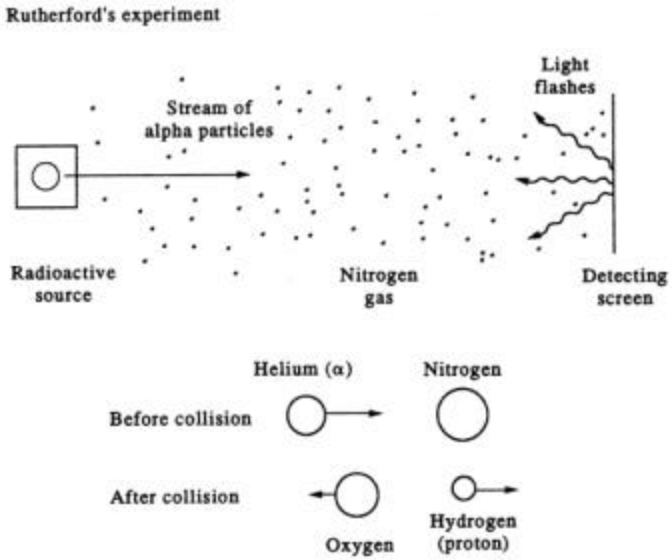

FIG. 4.1 Transmutation by nuclear reaction.

repulsion and can readily penetrate a target nucleus. Neutrons are thus especially useful as projectiles to induce reactions. Several examples are chosen on the basis of interest or usefulness. The conversion of mercury into gold, the alchemist's dream, is described by

$$ {}_{0}^{1}\mathrm{n} + {}_{80}^{198}\mathrm{Hg} \rightarrow {}_{79}^{198}\mathrm{Au} + {}_{1}^{1}\mathrm{H} . $$

The production of cobalt-60 is governed by

$$ {}_{0}^{1}\mathrm{n} + {}_{27}^{59}\mathrm{Co} \rightarrow {}_{27}^{60}\mathrm{Co} + g \ , $$

where a capture gamma ray is produced. Neutron capture in cadmium, often used in nuclear reactor control rods, is given by

$$ {}_{0}^{1}\mathrm{n} + {}_{48}^{113}\mathrm{Cd} \rightarrow {}_{48}^{114}\mathrm{Cd} + g \ . $$

A reaction that produces tritium, which may be a fuel for controlled fusion reactors of the future, is

$$ {}_{0}^{1}\mathrm{n} + {}_{3}^{6}\mathrm{Li} \rightarrow {}_{1}^{3}\mathrm{H} + {}_{2}^{4}\mathrm{He} . $$

A shorthand notation is used to represent nuclear reactions. Let an incoming particle a strike a target nucleus X to produce a residual nucleus Y and an outgoing particle b, with equation $a + X = Y + b$. The reaction may be abbreviated $X(a, b)Y$, where a and b stand for the neutron (n), alpha particle (α), gamma ray (g), proton (p), deuteron (d), and so on. For example, Rutherford's experiment can be written $^{14}\mathrm{N}(\alpha, \mathrm{p})^{17}\mathrm{O}$ and the reaction in control rods $^{113}\mathrm{Cd}(\mathrm{n}, g)^{114}\mathrm{Cd}$. The Z value can be omitted since it is unique to the chemical element.

The interpretation of nuclear reactions often involves the concept of compound nucleus. This intermediate stage is formed by the combination of a projectile and target nucleus. It has extra energy of excitation and breaks up into the outgoing particle or ray and the residual nucleus.

Later, in Section 6.1, we shall discuss the absorption of neutrons in uranium isotopes to cause fission.

The reaction equations can be used to calculate balances in properties such as mass-energy, visualizing conditions before and after. In place of the symbols, the atomic masses are inserted. Strictly, the masses of the nuclei should be used, but in most reactions, the same number of electrons appear on both sides of the equation and cancel out. In the case of reactions that produce a positron, however, either nuclear masses should be used or atomic masses with the subtraction of the mass-energy required to create an electron-positron pair, 0.0011 amu or 1.02 MeV.

4.2 Energy and Momentum Conservation

The conservation of mass-energy is a firm requirement for any nuclear reaction. Recall from Chapter 1 that the total mass is the sum of the rest mass m_o and the kinetic energy E_k (in mass units). Let us calculate the energy released when a slow neutron is captured in hydrogen, according to

$$ {}^{1}_{0}\mathrm{n} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + g \ . $$

This process occurs in reactors that use ordinary water. Conservation of mass-energy says

mass of neutron + mass of hydrogen atom =

mass of deuterium atom + kinetic energy of products.

We use accurately known masses, as given in the Appendix, along with a conversion factor 1 amu = 931.49 MeV,

$$ 1.008665 + 1.007825 \rightarrow 2.014102 + E_k, $$

from which E_k = 0.002388 amu with an energy release per capture of 2.22 MeV. This energy is shared by the deuterium atom and the gamma ray, which has no rest mass.

A similar calculation can be made for the proton-lithium reaction of the previous section. Suppose that the target nucleus is at rest and that the incoming proton has a kinetic energy of 2 MeV, which corresponds to 2/931.49 = 0.002147 amu. The energy balance statement is

kinetic energy of hydrogen + mass of hydrogen + mass of lithium

= mass of helium + kinetic energy of helium,

$$ 0.002147 + 1.007825 + 7.016004 = 2(4.002603) + E_k.. $$

Then E_k = 0.02077 amu = 19.3 MeV. This energy is shared by the two a

particles.

The calculations just completed tell us the total kinetic energy of the product particles but do not reveal how much each has, or what the speeds are. To find this information we must apply the principle of conservation of momentum. Recall that the linear momentum p of a material particle of mass m and speed u is $p = mu$. This relation is correct in both the classical and relativistic senses. The total momentum of the interacting particles before and after the collision is the same.

For our problem of a very slow neutron striking a hydrogen atom at rest, we can assume the initial momentum is zero. If it is to be zero finally, the ${}^{2}_{1}\mathrm{H}$ and g ray must fly apart with equal magnitudes of momentum $p_{\mathrm{d}} = p_g$. The momentum of a g ray having the speed of light c may be written $p_g = mc$ if we regard the mass as an effective value, related to the g energy E_γ by Einstein's formula $E = mc^2$. Thus

$$p_g = \frac{E_g}{c}.$$

Most of the 2.22 MeV energy release of the neutron capture reaction goes to the g ray, as shown in Exercise 4.5. Assuming that to be correct, we can estimate the effective mass of this g ray. It is close to 0.00238 amu, which is very small compared with 2.014 amu for the deuterium. Then from the momentum balance, we see that the speed of recoil of the deuterium is very much smaller than the speed of light.

The calculation of the energies of the two a particles is a little complicated even for the case in which they separate along the same line that the proton entered. The particle speeds of interest are low enough that relativistic mass variation with speed is small, and thus the classical formula for kinetic energy can be used, $E_k = (1/2)m_0 u^2$. If we let m be the a particle mass and u_1 and u_2 be their speeds, with p_{H} the proton momentum, we must solve the two equations

$$mu_1 - mu_2 = p_{\mathrm{H}}.$$

$$\tfrac{1}{2}mu_1^2 + \tfrac{1}{2}mu_2^2 = E_k.$$

4.3 Reaction Rates

When any two particles approach each other, their mutual influence depends on the nature of the force between them. Two electrically charged particles obey Coulomb's relation $F \sim q_1 q_2 / r^2$ where the q's are the amounts of charge and r is the distance of separation of centers. There will be some influence no matter how far they are apart. However, two atoms, each of which is neutral electrically, will not interact until they get close to one

another ($\cong 10^{-10}$ m). The special force between nuclei is limited still further ($\cong 10^{-15}$ m).

Although we cannot see nuclei, we imagine them to be spheres with a certain radius. To estimate that radius, we need to probe with another particle–a photon, an electron, or a g ray. But the answer will depend on the projectile used and its speed, and thus it is necessary to specify the apparent radius and cross sectional area for the particular reaction. This leads to the concept of cross section, as a measure of the chance of collision.

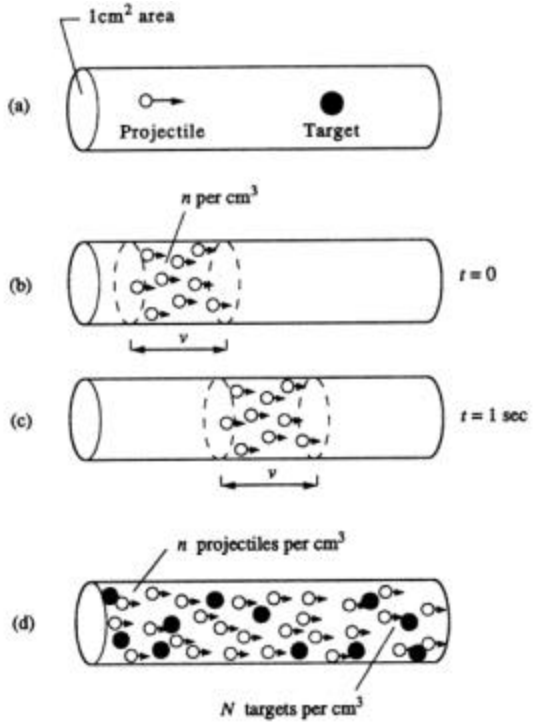

FIG. 4.2 Particle collisions.

We can perform a set of imaginary experiments that will clarify the idea of cross section. Picture, as in Fig. 4.2(a), a tube of end area 1 cm^2 containing only one target particle. A single projectile is injected parallel to the tube axis, but its exact location is not specified. It is clear that the chance of collision, labeled s (sigma) and called the microscopic cross section, is the ratio of the target area to the area of the tube, which is 1 cm^2. In Computer Exercise 4.A the programs MOVENEUT and CURRENT show graphically the flow of neutrons in a column.

Now let us inject a continuous stream of particles of speed u into the empty tube (see Fig. 4.2(b)). In a time of one second, each of the particles has moved along a distance u cm. All of them in a column of volume (1

cm^2) (u cm) = u cm^3 will sweep past a point at which we watch each second. If there are n particles per cubic centimeter, then the number per unit time that cross any unit area perpendicular to the stream direction is nu, called the current density.

Finally, Fig. 4.2(c) we fill each unit volume of the tube with N targets, each of area s as seen by incoming projectiles (we presume that the targets do not "shadow" each other). If we focus attention on a unit volume, there is a total target area of Ns. Again, we inject the stream of projectiles. In a time of one second, the number of them that pass through the target volume is nu; and since the chance of collision of each with one target atom is s, the number of collisions is $nu\ Ns$. We can thus define the reaction rate per unit volume,

$$R = nu\ Ns.$$

We let the current density nu be abbreviated by j and let the product Ns be labeled S (capital sigma), the macroscopic cross section, referring to the large-scale properties of the medium. Then the reaction rate per cubic centimeter is simply $R = jS$. We can easily check that the units of j are cm^{-2} s^{-1} and those of S are cm^{-1}, so that the unit of R is cm^{-3} s^{-1}.

In a different experiment, we release particles in a medium and allow them to make many collisions with those in the material. In a short time, the directions of motion are random, as sketched in Fig. 4.3. We shall look only at particles of the same speed u, of which there are n per unit volume. The product nu in this situation is no longer called current density, but is given a different name, the flux, symbolized by f (phi). If we place a unit area anywhere in the region, there will be flows of particles across it each second from both directions, but it is clear that the current densities will now be less than nu. It turns out that they are each nu /4, and the total current density is nu /2. The rate of reaction of particles with those in the medium can be found by adding up the effects of individual projectiles. Each

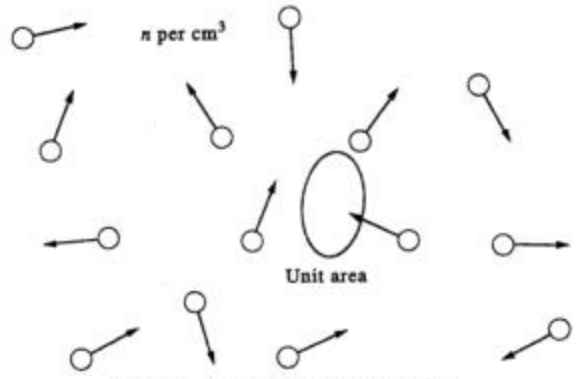

FIG. 4.3 Particles in random motion.

behaves the same way in interacting with the targets, regardless of direction of motion. The reaction rate is again $nu\,Ns$ or, for this random motion, $R = f\,S$.

The random motion of particles can be simulated mathematically by the use of random numbers, which form a collection of decimal fractions that are independent and are uniformly distributed over the range 0 -1. They are useful for the study of neutron and gamma ray processes, both of which are governed by statistics. Computer Exercise 4.B describes their generation by three small programs RANDY, RANDY1, and RANDY2.

When a particle such as a neutron collides with a target nucleus, there is a certain chance of each of several reactions. The simplest is elastic scattering, in which the neutron is visualized as bouncing off the nucleus and moving in a new direction with a change in energy. Such a collision, governed by classical physics, is predominant in light elements. In the inelastic scattering collision, an important process for fast neutrons in heavy elements, the neutron becomes a part of the nucleus; its energy provides excitation; and a neutron is released. The cross section s_s is the chance of a collision that results in neutron scattering. The neutron may instead be absorbed by the nucleus, with cross section s_a. Since s_a and s_s are chances of reaction, their sum is the chance for collision or total cross section $s = s_a + s_s$. Computer Exercise 4.A also introduces a program called CAPTURE related to neutron capture and another called HEADON describing a scattering collision of a neutron with a nucleus in which the neutron direction is exactly reversed.

Let us illustrate these ideas by some calculations. In a typical nuclear reactor used for training and research in universities, a large number of neutrons will be present with energies near 0.0253 eV. This energy corresponds to a most probable speed of 2200 m/s for the neutrons viewed as a gas at room temperature, 293 K. Suppose that the flux of such neutrons is 2×10^{12} cm^{-2}-s^{-1}. The number density is then

$$n = \frac{f}{u} = \frac{2 \times 10^{12}\ \text{cm}^{-2} - \text{s}^{-1}}{2.2 \times 10^{5}\ \text{cm/s}} = 9 \times 10^{6}\ \text{cm}^{-3}$$

Although this is a very large number by ordinary standards, it is exceedingly small compared with the number of water molecules per cubic centimeter (3.3×10^{22}) or even the number of air molecules per cubic centimeter (2.7×10^{19}). The “neutron gas” in a reactor is almost a perfect vacuum.

Now let the neutrons interact with uranium-235 fuel in the reactor. The cross section for absorption s_a is 681×10^{-24} cm^2. If the number density of fuel atoms is $N = 0.048 \times 10^{24}$ cm^{-3}, as in uranium metal, then the

macroscopic cross section is

$$S_a = N\, s_a = (0.048 \times 10^{24}\ \text{cm}^{-3})\,(681 \times 10^{-24}\ \text{cm}^{-2}) = 32.7\ \text{cm}^{-1}.$$

The unit of area 10^{-24} cm^2 is conventionally called the barn.† If we express the number of targets per cubic centimeter in units of 10^{24} and the microscopic cross section in barns, then $S_a = (0.048)\,(681) = 32.7$ cm^{-1} as above. With a neutron flux $f = 3 \times 10^{13}$ cm^{-2}-s^{-1}, the reaction rate for absorption is

$$R = f\, S_a = (3 \times 10^{13}\ \text{cm}^{-2}\text{-s}^{-1})\,(32.7\ \text{cm}^{-1}) = 9.81 \times 10^{14}\ \text{cm}^{-3}\text{-s}^{-1}.$$

This is also the rate at which uranium-235 nuclei are consumed.

The average energy of neutrons in a nuclear reactor used for electrical power generation is about 0.1 eV, almost four times the value used in our example. The effects of the high temperature of the medium (about 600°F) and of neutron absorption give rise to this higher value.

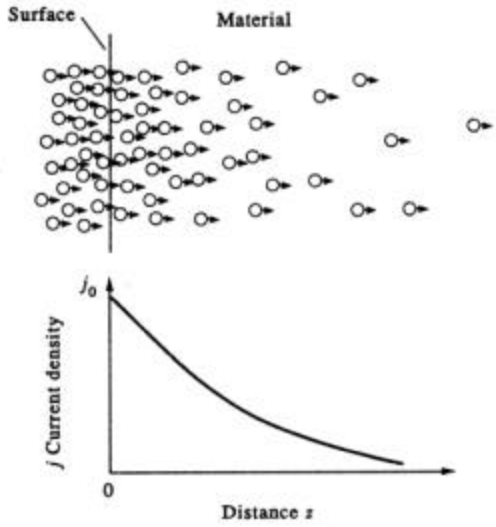

FIG. 4.4 Neutron penetration and attenuation.

4.4 Particle Attenuation

Visualize an experiment in which a stream of particles of common speed and direction is allowed to strike the plane surface of a substance as in Fig. 4.4. Collisions with the target atoms in the material will continually remove projectiles from the stream, which will thus diminish in strength with distance, a process we label *attenuation*. If the current density incident on the substance at position $z = 0$ is labeled j_0, the current of those not having

† As the story goes, an early experimenter observed that the cross section for U-235 was "as big as a barn."

made any collision on penetrating to a depth z is given by†

$$j = j_0 e^{-S z},$$

where S is the macroscopic cross section. The similarity in form to the exponential for radioactive decay is noted, and one can deduce by analogy that the half-thickness, the distance required to reduce j to half its initial value, is $z_H = 0.693/S$. Another more frequently used quantity is the mean free path l, the average distance a particle goes before making a collision. By analogy with the mean life for radioactivity, we can write‡

$$l = 1/S.$$

This relation is applicable as well to particles moving randomly in a medium. Consider a particle that has just made a collision and moves off in some direction. On the average, it will go a distance l through the array of targets before colliding again. For example, we can find the mean free path of 1 eV neutrons in water, assuming that scattering by hydrogen with cross section 20 barns is the dominant process. Now the number of hydrogen atoms is $N_{\mathrm{H}} = 0.0668 \times 10^{24}$ cm^{-3}, s_s is 20×10^{-24} cm^2, and $S_s = 1.34$ cm^{-1}. Thus the mean free path for scattering l_s is around 0.75 cm.

The cross sections for atoms interacting with their own kind at the energies corresponding to room temperature conditions are of the order of 10^{-15} cm^2. If we equate this area to πr^2, the calculated radii are of the order of 10^{-8} cm. This is in rough agreement with the theoretical radius of electron motion in the hydrogen atom 0.53×10^{-8} cm. On the other hand, the cross sections for neutrons interacting with nuclei by scattering collisions, those in which the neutron is deflected in direction and loses energy, are usually very much smaller than those for atoms. For the case of 1 eV neutrons in hydrogen with a scattering cross section of 20 barns, i.e., 20×10^{-24} cm^2, one deduces a radius of about 2.5×10^{-12} cm. These results correspond to our earlier observation that the nucleus is thousands of times smaller than the atom.

4.5 Neutron Cross Sections

The cross section for neutron absorption in materials depends greatly on the isotope bombarded and on the neutron energy. For consistent

† The derivation proceeds as follows. In a slab of material of unit area and infinitesimal thickness dz, the target area will be $Ns\,dz$. If the current at z is j, the number of collisions per second in the slab is $jNs\,dz$, and thus the change in j on crossing the layer is $dj = -jS\,dz$ where the reduction is indicated by the negative sign. By analogy with the solution of the radioactive decay law, we can write the formula cited.

‡ This relation can be derived directly by use of the definition of an average as the sum of the distances the particles travel divided by the total number of particles. Using integrals, this is $\bar{z} = \int z\,dj \,/ \int dj$.

comparison and use, the cross section is often cited at 0.0253 eV, corresponding to neutron speed 2200 m/s. Values for absorption cross sections for a number of isotopes at that energy are listed in order of increasing size in Table 4.1. The dependence of absorption cross section on energy is of two types, one called $1/u$, in which s_a varies inversely with neutron speed, the other called resonance, where there is a very strong absorption at certain neutron energies. Many materials exhibit both variations. Figures 4.5 and 4.6 show the cross sections for boron and natural uranium. The use of the logarithmic plot enables one to display the large range of cross section over the large range of energy of interest. Neutron scattering cross sections are more nearly the same for all elements and have less variation with neutron energy. Figure 4.7 shows the trend of s_s for hydrogen as in water. Over a large range of neutron energy the scattering cross section is nearly constant, dropping off in the million-electron-volt region. This high energy range is of special interest since neutrons produced by the fission process have such energy values.

TABLE 4.1
Selected Thermal Neutron Absorption Cross Sections
(in order of increasing size) †

Isotope or element	s_a (barns)
$^{4}_{2}\mathrm{He}$	$\cong 0$
$^{16}_{8}\mathrm{O}$	0.00019
$^{2}_{1}\mathrm{H}$	0.00051
$^{12}_{6}\mathrm{C}$	0.0035
Zr	0.19
$^{1}_{1}\mathrm{H}$	0.332
$^{238}_{92}\mathrm{U}$	2.7
Mn	13.3
In	197
$^{235}_{92}\mathrm{U}$	681
$^{239}_{94}\mathrm{Pu}$	1022
$^{10}_{5}\mathrm{B}$	3840
$^{135}_{54}\mathrm{Xe}$	2,650,000

†*CRC Handbook of Chemistry and Physics.*

The competition between scattering and capture for neutrons in a medium is statistical in nature. The number of scattering collisions that occur before an absorption removes the neutron may be none, one, a few, or

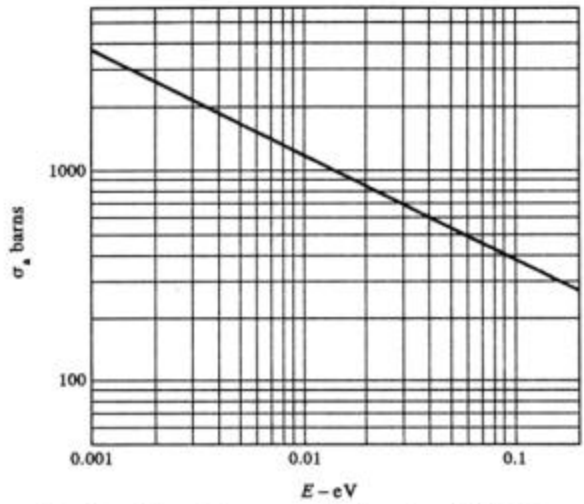

FIG. 4.5 Absorption cross section for elemental boron.

many. Computer Exercise 4.C discusses the program ABSCAT, which simulates the statistical competition.

4.6 Neutron Migration

When fast neutrons, those of energy of the order of 2 MeV, are introduced into a medium, they make inelastic or elastic collisions with nuclei. Upon each elastic collision neutrons are deflected in direction, they lose energy, and they tend to migrate away from their origin. Each neutron has a unique history, and it is impractical to keep track of all of them. Instead, we seek to deduce average behavior. First, we note that the elastic scattering of a neutron with an initially stationary nucleus of mass number A causes a reduction in neutron energy from E_0 to E and a change of direction through an angle q (theta), as sketched in Fig. 4.8. The length of arrows indicates the speeds of the particles. This example shown is but one of a great variety of possible results of scattering collisions. For each final energy there is a unique angle of scattering, and vice versa, but the occurrence of a particular E and q pair depends on chance. The neutron may bounce directly backward, $q = 180°$, dropping down to a minimum energy $a\,E_0$, where $a = (A - 1)^2/(A + 1)^2$, or it may be undeflected, $q = 0°$, and retain its initial energy E_0, or it may be scattered through any other angle, with corresponding energy loss. For the special case of a hydrogen nucleus as scattering target, $A = 1$ and $a = 0$, so that the neutron loses all of its energy in a head-on collision. As we shall see later, this makes water a useful material in a nuclear reactor.

The process of neutron scattering with energy loss is graphically

displayed by application of BASIC program SCATTER, see Computer Exercise 4.D.

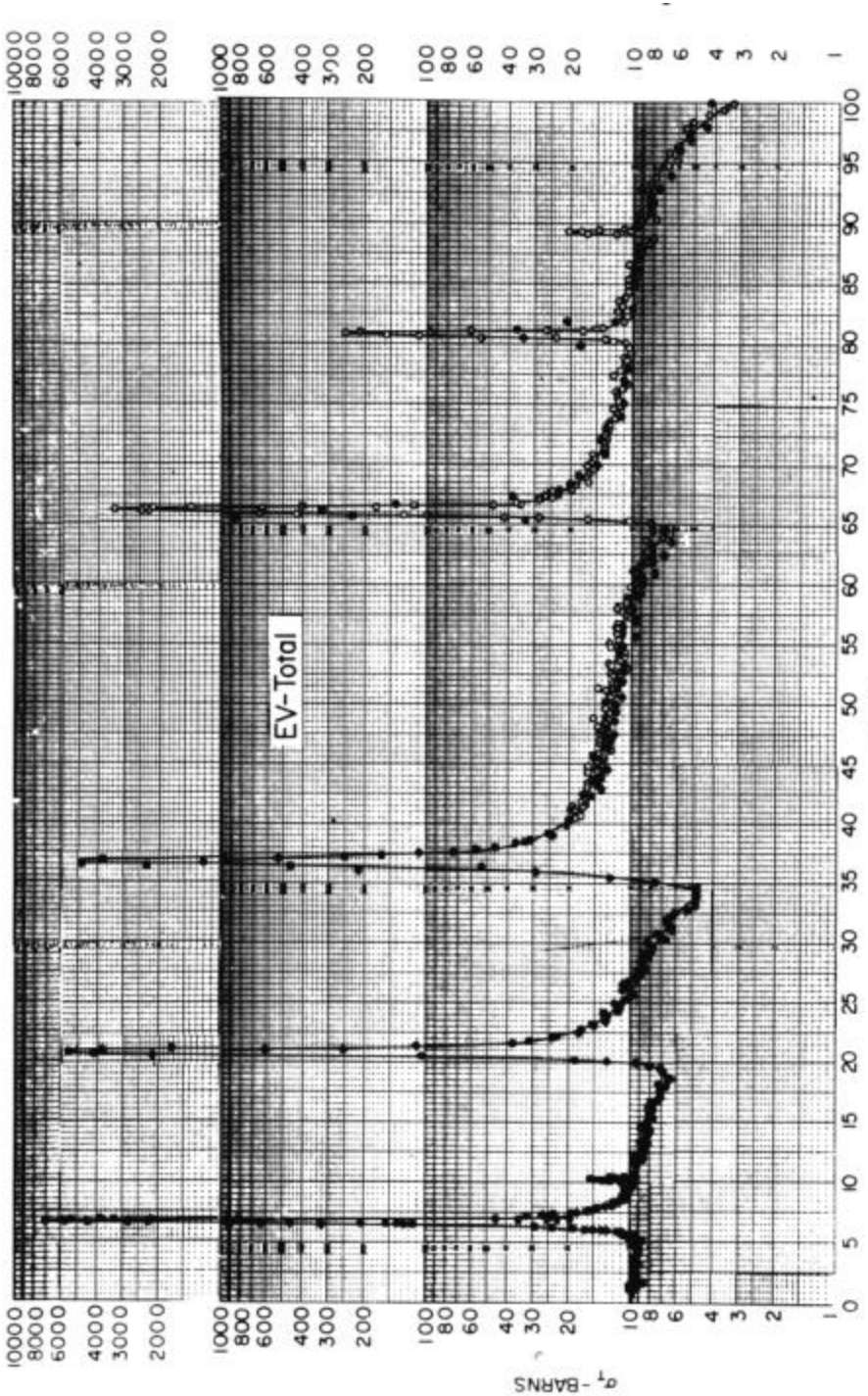

FIG. 4.6 Cross section for natural uranium.

The average elastic scattering collision is described by two quantities that depend only on the nucleus, not on the neutron energy. The first is $\overline{\cos q}$, the average of the cosines of the angles of scattering, given by

$$\overline{\cos q} = \frac{2}{3A} .$$

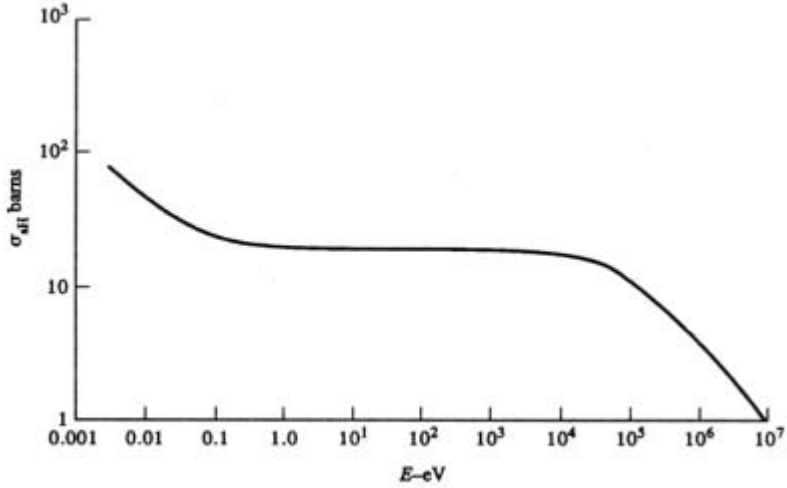

FIG. 4.7 Scattering cross section for hydrogen.

For hydrogen, it is 2/3, meaning that the neutron tends to be scattered in the forward direction; for a very heavy nucleus such as uranium, it is near zero, meaning that the scattering is almost equally likely in each direction. Forward scattering results in an enhanced migration of neutrons from their point of appearance in a medium. Their free paths are effectively longer, and it is conventional to use the transport mean free path $l_t = l_s / (1 - \overline{\cos q})$ instead of l_s to account for the effect. We note that l_t is always the larger.

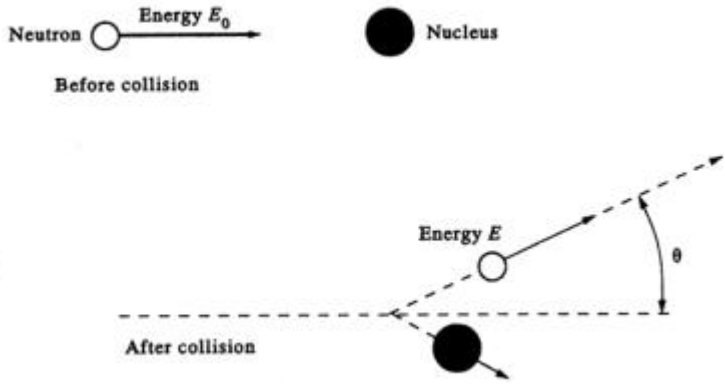

FIG. 4.8 Neutron scattering and energy loss.

Consider slow neutrons in carbon, for which s_s = 4.8 barns and N = 0.083, so that S_s = 0.4 cm^{-1} and l_s = 2.5 cm. Now $\overline{\cos q}$ = 2/(3)(12) = 0.056, 1 – $\overline{\cos q}$ = 0.944, and l_t = 2.5/0.994 = 2.7 cm.

The second quantity that describes the average collision is x (xi), the average change in the natural logarithm of the energy, given by

$$x = 1 + \frac{a \ln a}{1 - a}.$$

For hydrogen, it is exactly 1, the largest possible value, meaning that hydrogen is a good "moderator" for neutrons, its nuclei permitting the greatest neutron energy loss; for a heavy element it is $x \cong 2/(A + 2/3)$ which is much smaller than 1, e.g., for carbon, A = 12, it is 0.16.

To find how many collisions C are required on the average to slow neutrons from one energy to another, we merely divide the total change in ln E by x, the average per collision. In going from the fission energy 2×10^6 eV to the thermal energy 0.025 eV, the total change is ln (2 x 10^6) – ln(0.025) = ln(8×10^7) = 18.2. Then C = 18.2/x. For example in hydrogen, x = 1, C is 18, while in carbon x = 0.16, C is 114. Again, we see the virtue of hydrogen as a moderator. The fact that hydrogen has a scattering cross section of 20 barns over a wide range while carbon has a s_s of only 4.8 barns implies that collisions are more frequent and the slowing takes place in a smaller region. The only disadvantage is that hydrogen has a larger thermal neutron absorption cross section, 0.332 barns versus 0.0035 barns for carbon.

The statistical nature of the neutron slowing process is demonstrated in Computer Exercise 4.E, which uses program ENERGY to calculate the number of collisions to go from fission energy to thermal energy in carbon.

The movement of individual neutrons through a moderator during slowing consists of free flights, interrupted frequently by collisions that cause energy loss. Picture, as in Fig. 4.9, a fast neutron starting at a point, and migrating outward. At some distance r away, it arrives at the thermal energy. Other neutrons become thermal at different distances, depending on their particular histories. If we were to measure all of their r values and form the average of r^2, the result would be $\overline{r^2}$ = 6 t, where t (tau) is called the "age" of the neutron. Approximate values of the age for various moderators, as obtained from experiment, are listed below:

Moderator	t, age to thermal (cm^2)
H_2O	26
D_2O	125
C	364

We thus note that water is a much better agent for neutron slowing than is

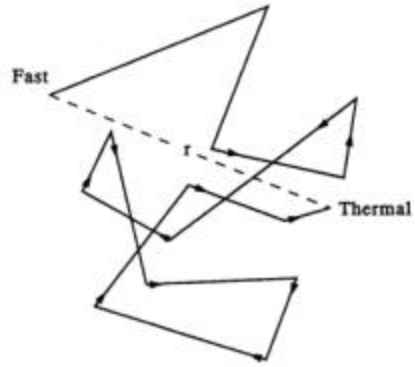

FIG. 4.9 Neutron migration during slowing.

graphite.

As neutrons slow into the energy region that is comparable to thermal agitation of the moderator atoms, they may either lose or gain energy on collision. Members of a group of neutrons have various speeds at any instant and thus the group behaves as a gas in maxwellian distribution, as was shown in Figure 2.1 and discussed in Exercise 2.15. The neutron group has a temperature T that is close to that of the medium in which they are found. Thus if the moderator is at room temperature 20°C, or 293 K, the most likely neutron speed is around 2200 m/s, corresponding to a kinetic energy of 0.0253 eV. The neutrons are said to be thermal, in contrast to fast or intermediate.

Another parameter that characterizes neutron migration while at thermal energy is the diffusion length, symbolized by L. By analogy to the slowing process, the average square distance between origin and absorption is given by $\overline{r^2} = 6\ L^2$. Approximate values of L for three moderators are listed below.

Moderator	L, Diffusion length (cm)
H_2O	2.85
D_2O	116
C	54

According to theory, $L = \sqrt{D / \Sigma_a}$, where $D = l_t /3$. This shows that the addition of an absorber to pure moderator reduces the distance neutrons travel, as expected.

The process of diffusion of gas molecules is familiar to us. If a bottle of perfume is opened, the scent is quickly observed, as the molecules of the substance migrate away from the source. Since neutrons in large numbers behave as a gas, the descriptions of gas diffusion may be applied. The flow of neutrons through a medium at a location is proportional to the way the concentration of neutrons varies, in particular to the negative of the slope of

the neutron number density. We can guess that the larger the neutron speed u and the larger the transport mean free path l_t the more neutron flow will take place. Theory and measurement show that if n varies in the z-direction, the net flow of neutrons across a unit area each second, the net current density, is

$$j = \frac{-l_t u}{3}\frac{dn}{dz}.$$

This is called Fick's law of diffusion, derived long ago for the description of gases. It applies if absorption is small compared with scattering. In terms of the flux $f = nu$ and the diffusion coefficient $D = l_t/3$, this may be written compactly $j = -D f'$ where f' is the slope of the neutron flux.

4.7 Summary

Chemical and nuclear equations have similarities in the form of equations and in the requirements on conservation of particles and charge. The bombardment of nuclei by charged particles or neutrons produces new nuclei and particles. Final energies are found from mass differences and final speeds from conservation of momentum. The cross section for interaction of neutrons with nuclei is a measure of the chance of collision. Reaction rates depend mutually on neutron flows and macroscopic cross section. A stream of uncollided particles is reduced exponentially as it passes through a medium. Neutron absorption cross sections vary greatly with target isotope and with neutron energy, while scattering cross sections are relatively constant. Neutrons are slowed readily by collisions with light nuclei and migrate from their point of origin. On reaching thermal energy they continue to disperse, with the net flow dependent on the spatial variation of flux.

4.8 Exercises

4.1. The energy of formation of water from its constituent gases is quoted to be 54,500 cal/mole. Verify that this corresponds to 2.4 eV per molecule of H_2O.

4.2. Complete the following nuclear reaction equations:

$${}_0^1\mathrm{n} + {}_7^{14}\mathrm{N} \rightarrow {}_{\ }^{\ }(\ \ )(\ \ ) + {}_1^1\mathrm{H},$$

$${}_1^2\mathrm{H} + {}_4^9\mathrm{Be} \rightarrow {}_{\ }^{\ }(\ \ )(\ \ ) + {}_0^1\mathrm{n}.$$

4.3. Using the accurate atomic masses listed below, find the minimum amount of energy an *á* particle must have to cause the transmutation of nitrogen to oxygen. (${}_7^{14}\mathrm{N}$ 14.003074, ${}_2^4\mathrm{He}$ 4.002603, ${}_8^{17}\mathrm{O}$ 16.999132, ${}_1^1\mathrm{H}$ 1.007825.)

4.4. Find the energy release in the reaction ${}_3^6\mathrm{Li}(\mathrm{n},a)\,{}_1^3\mathrm{H}$, noting the masses ${}_0^1\mathrm{n}$

1.008665, ${}^{3}_{1}\mathrm{H}$ 3.016049, ${}^{4}_{2}\mathrm{He}$ 4.002603, and ${}^{6}_{3}\mathrm{Li}$ 6.015122.

4.5. A slow neutron of mass 1.008665 amu is caught by the nucleus of a hydrogen atom of mass 1.007825 and the final products are a deuterium atom of mass 2.014102 and a g ray. The energy released is 2.22 MeV. If the g ray is assumed to have almost all of this energy, what is its effective mass in kg? What is the speed of the ${}^{2}_{1}\mathrm{H}$ particle in m/s, using equality of momenta on separation? What is the recoil energy of ${}^{2}_{1}\mathrm{H}$ in MeV? How does this compare with the total energy released? Was the assumption about the g ray reasonable?

4.6. Calculate the speeds and energies of the individual a particles in the reaction ${}^{1}_{1}\mathrm{H} + {}^{7}_{3}\mathrm{Li} \rightarrow 2\ {}^{4}_{2}\mathrm{He}$, assuming that they separate along the line of proton motion. Note that the mass of the lithium-7 atom is 7.016004.

4.7. Calculate the energy release in the reaction

$$ {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e} . $$

The atomic masses are ${}^{13}_{7}\mathrm{N}$ 13.005739, ${}^{13}_{6}\mathrm{C}$ 13.003355, and the masses of the positron and electron are 0.000549. Calculate (a) using nuclear masses, subtracting the proper number of electron masses from the atomic masses, and (b) using atomic masses with account for the energy of pair production.

4.8. Calculate the macroscopic cross section for scattering of 1 eV neutrons in water, using N for water as 0.0334×10^{24} cm^{-3} and cross sections 20 barns for hydrogen and 3.8 barns for oxygen. Find the mean free path l_s.

4.9. Find the speed u and the number density of neutrons of energy 1.5 MeV in a flux 7×10^{13} cm^{-2}-s^{-1}.

4.10. Compute the flux, macroscopic cross section and reaction rate for the following data: $n = 2 \times 10^{5}$ cm^{-3}, $u = 3 \times 10^{8}$ cm/sec, $N = 0.04 \times 10^{24}$ cm^{-3}, $s = 0.5 \times 10^{-24}$ cm^{2}.

4.11. What are the values of the average logarithmic energy change x and the average cosine of the scattering angle $\overline{\cos q}$ for neutrons in beryllium, $A = 9$? How many collisions are needed to slow neutrons from 2 MeV to 0.025 eV in Be-9? What is the value of the diffusion coefficient D for 0.025 eV neutrons if S_s is 0.90 cm^{-1}?

4.12. (a) Verify that neutrons of speed 2200 m/s have an energy of 0.0253 eV. (b) If the neutron absorption cross section of boron at 0.0253 eV is 760 barns, what would it be at 0.1 eV? Does this result agree with that shown in Fig. 4.5?

4.13. Calculate the rate of consumption of U-235 and U-238 in a flux of 2.5×10^{13} cm^{-2}-s^{-1} if the uranium atom number density is 0.0223×10^{24} cm^{-3}, the atom number fractions of the two isotopes are 0.0072 and 0.9928, and cross sections are 681 barns and 2.7 barns, respectively. Comment on the results.

4.14. How many atoms of boron-10 per atom of carbon-12 would result in an increase of 50% in the macroscopic cross section of graphite? How many ^{10}B atoms would there then be per million ^{12}C atoms?

4.15. Calculate the absorption cross section of the element zirconium using the isotopic data in the following table:

Mass number	Abundance (atom %)	Cross section (barns)
90	51.45	0.014
91	11.22	1.2
92	17.15	0.2
94	17.38	0.049

96	2.80	0.020

Compare the result with the figure given in Table 4.1.

4.16. The total cross section for uranium dioxide of density 10 g/cm^3 is to be measured by a transmission method. To avoid multiple neutron scattering, which would introduce error into the results, the sample thickness is chosen to be much smaller than the mean free path of neutrons in the material. Using approximate cross sections for UO_2 of σ_s = 15 barns and σ_a of 7.6 barns, find the macroscopic cross section $\Sigma = \Sigma_a + \Sigma_s$. Then find the thickness of target t such that t/l = 0.05. How much attenuation in neutron beam would that thickness give?

4.17. The manganese content of a certain stainless steel is to be verified by an activation measurement. The activity induced in a sample of volume V by neutron capture during a time t is given by

$$A = f\,\Sigma_a V[(1 - \exp(-\lambda t)].$$

A foil of area 1 cm^2 and thickness 2 mm is irradiated in a thermal neutron flux of 3×10^{12}/cm^2-s for 2 h. Counts taken immediately yield an activity of 150 mCi for the induced Mn-56, half-life 2.58 h. Assuming that the atom number density of the alloy is 0.087 in units of 10^{24} and that the cross section for capture in Mn-55 is 13.3 barns, find the percent of Mn in the sample.

4.18. For fast neutrons in uranium-235 metal, find the density ρ, the number of atoms per cubic centimeter N, the macroscopic cross section Σ_a and Σ_t, the transport mean free path λ_t, the diffusion coefficient D, and the diffusion length L. Note: the density of natural U (99.3% U-238) is approximately 19.05 g/cm^3; σ_c = 0.25 barns, σ_f = 1.4 barns, and σ_t = 6.8 barns (Report ANL-5800, p. 581).

4.19. When a projectile of mass m_1 and vector velocity $\mathbf{u_1}$ collides elastically with a target of mass m_2 and vector velocity $\mathbf{u_2}$, the final velocities are:

$$\mathbf{v_1} = [2\,m_2\mathbf{u_2} + (m_1 - m_2)\,\mathbf{u_1}]/(m_1 + m_2)$$

$$\mathbf{v_2} = [2\,m_1\mathbf{u_1} + (m_2 - m_1)\,\mathbf{u_2}]/(m_1 + m_2).$$

Find the velocities if $\mathbf{u_2} = 0$ and $m_2 >> m_1$. Discuss the results.

4.20. A neutron of energy E_0 collides head-on with a heavy nucleus of mass number A. Using the velocity equations of Ex. 4.19, verify that the minimum neutron energy after collision is $E_1 = \alpha E_0$, where $\alpha = [(A-1)/(A+1)]^2$. Evaluate α and x for U-238.

Computer Exercises

4.A. Several computer programs in BASIC provide visual images of neutron processes. MOVENEUT merely shows a moving particle; CURRENT gives a flow of many particles; CAPTURE allows a moving neutron to be captured by a stationary target nucleus. Run the programs to help visualize the processes. The program HEADON demonstrates an elastic collision in which neutron direction is reversed. Run the program with various choices of mass number A: 12 (carbon), 2 (deuterium), 238 (uranium), 1 (hydrogen). Note and report on differences.

4.B. Random variables are numbers between 0 and 1 that are statistically independent. They are at the heart of the method known as Monte Carlo (after the gambling casino in Monaco). The BASIC language provides such numbers by the command RND(X).

(a) Program RANDY generates and prints out a sequence of random numbers. Run the program two or three times to see results. Then delete the command RANDOMIZE TIMER and repeat. Comment on the effect.

(b) Program RANDY1 is the same as RANDY except that the average value is calculated. Run the program with increasing values of input NT, the total number of random numbers, to see what happens. What would you expect?

(c) Program RANDY2 is the same as RANDY1 except that additional statistical features are calculated. Run the program; note and comment on the results.

4.C. On the average, scattering and absorption of neutrons is determined by the macroscopic cross sections S_s, and S_a. For a given neutron, however, by chance the number of scatterings before being absorbed varies widely. The program ABSCAT uses random numbers to describe the process. Run the program several times to note the variation. Explain how the expected number of scatterings per absorption is calculated.

4.D. The computer program SCATTER in BASIC shows the general elastic collision of a neutron with a stationary nucleus, in which the neutron loses energy and moves off at an angle from the original direction, while the struck nucleus recoils in another direction. (a) Run the program several times to see the variety of final motions. (b) Change the mass ratio *A* (line 330) to 1, or 12, or 238, and observe differences.

4.E. The energy loss of a neutron in an elastic collision with a nucleus can range from zero to E_0 (1 - a). Thus there is considerable statistical variation in the number of collisions C required to go between two energies. Using random numbers, computer program ENERGY shows a set of values of C for neutron slowing in carbon between fission and thermal energies. (a) Run the program to note the variation about the average of 114 collisions; (b) Change the *A* value to 238 as for U-238 and run again; (c) Repeat for $A = 1$ as for hydrogen. (d) Make a large change in the number of histories, e.g., decrease or increase by a factor of 10, and note the effect.

4.F. Apply computer program ALBERT (See Chapter 1) to find a more accurate pair of numbers (e.g., 7 significant figures) than 2200 m/s and 0.0253 eV to describe room temperature 20°C neutrons at absolute temperature $T = 293.15$ K. Note: 1 eV= $1.60217646 \times 10^{-19}$ J and Boltzmann's constant in $E = kT$ is $1.3806503 \times 10^{-23}$ J/K. What limits the accuracy of the result?

4.9 References for Chapter 4

Hans A. Bethe, Robert F. Bacher, and M. Stanley Livingston, *Basic Bethe*: *Seminal Articles on Nuclear Physics, 1936-1937*, American Institute of Physics, 1986. Reprints of classic literature on nuclear processes.

George R. Satchler (Editor), *Introduction to Nuclear Reactions*, 2nd ed., Oxford University Press, Oxford, 1990.

Neutron Cross Sections, Vol. 1, *Neutron Resonance Parameters and Thermal Cross Sections*, S. F. Mughabghab, Part B, Z = 61 - 100, 1981; S. F. Mughabghab, M. Divadeenam, and N. E. Holden, Part A, Z = 1 - 60, 1984; Vol. 2, *Neutron Cross Section Curves*, Victoria McLane, Charles L. Dunford, and Philip F. Rose, 1988; Academic Press, New York.

Tables of thermal cross sections and resonance integrals, with uncertainties
http://ie.lbl.gov/ngdata/sig.txt.
Some of the same information as in the book above, at a web site maintained by Lawrence Berkeley Laboratory .

Donald J. Hughes, *Neutron Cross Sections*, Pergamon Press, New York, 1957. A classic reference on theory, measurements, and uses of cross sections.

National Nuclear Data Center
http://www.nndc.bnl.gov
Maintained by Brookhaven National Laboratory. Links to many sources of data.

Atomic Mass Data Center
http://csnwww.in2p3.fr
Select AMDC, AME for latest values of atomic masses.

Nuclear Data Resources (as of 1996)
http://isotopes.lbl.gov/isotopes/DataWorkshop/resources.html
Data centers: web sites, e-mail addresses, phone and fax numbers.

Raymond L. Murray, *Nuclear Reactor Physics*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1957. Elementary theory, analysis, and calculations.

John R. Lamarsh, *Introduction to Nuclear Reactor Theory,* Addison-Wesley, Reading, MA, 1972. Widely used textbook.

James J. Duderstadt and Louis J. Hamilton, *Nuclear Reactor Analysis*, John Wiley & Sons, New York, 1976. Thorough treatment.

Allan F. Henry, *Nuclear-Reactor Analysis*, MIT Press, Cambridge, MA, 1975. Advanced textbook.

5

Radiation and Materials

THE WORD "radiation" will be taken to embrace all particles, whether they are of material or electromagnetic origin. We include those produced by both atomic and nuclear processes and those resulting from electrical acceleration, noting that there is no essential difference between X-rays from atomic collisions and gamma rays from nuclear decay; protons can come from a particle accelerator, from cosmic rays, or from a nuclear reaction in a reactor. The word "materials" will refer to bulk matter, whether of mineral or biological origin, as well as to the particles of which the matter is composed, including molecules, atoms, electrons, and nuclei.

When we put radiation and materials together, a great variety of possible situations must be considered. Bombarding particles may have low or high energy; they may be charged, uncharged, or photons; they may be heavy or light in the scale of masses. The targets may be similarly distinguished, but they may also exhibit degrees of binding that range from (a) none as for "free" particles, to (b) weak, as for atoms in molecules and electrons in atoms, to (c) strong, as for nucleons in nuclei. In most interactions, the higher the projectile energy in comparison with the energy of binding of the structure, the greater is the effect.

Out of the broad subject we shall select for review some of the reactions that are important in the nuclear energy field. Looking ahead, we shall need to understand the effects produced by the particles and rays from radioactivity and other nuclear reactions. Materials affected may be in or around a nuclear reactor, as part of its construction or inserted to be irradiated. Materials may be of biological form, including the human body, or they may be inert substances used for protective shielding against radiation. We shall not attempt to explain the processes rigorously, but be content with qualitative descriptions based on analogy with collisions viewed on an elementary physics level.

5.1 Excitation and Ionization by Electrons

These processes occur in the familiar fluorescent lightbulb, in an X-ray machine, or in matter exposed to beta particles. If an electron that enters a material has a very low energy, it will merely migrate without affecting the molecules significantly. If its energy is large, it may impart energy to

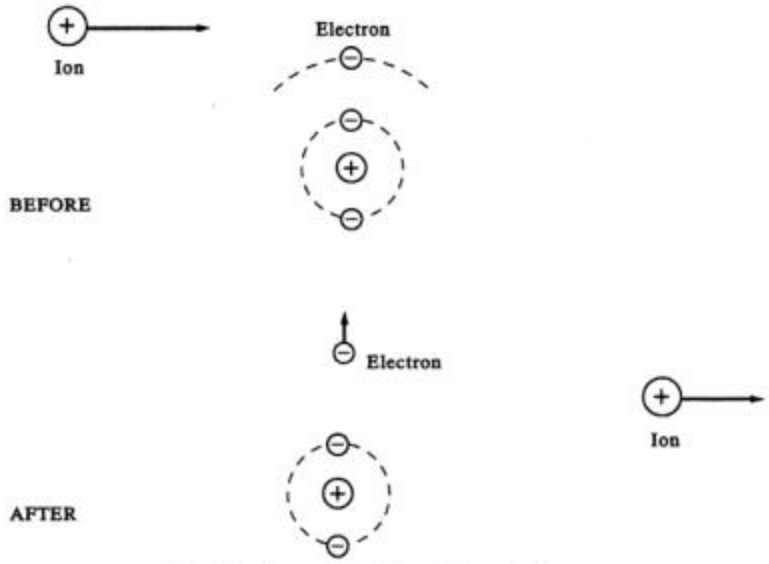

FIG. 5.1 Interaction of heavy ion with electron.

atomic electrons as described by the Bohr theory (Chapter 2), causing excitation of electrons to higher energy states or producing ionization, with subsequent emission of light. When electrons of inner orbits in heavy elements are displaced, the resultant high-energy radiation is classed as X-rays. These rays, which are so useful for internal examination of the human body, are produced by accelerating electrons in a vacuum chamber to energies in the kilovolt range and allowing them to strike a heavy element target. In addition to the X-rays due to transitions in the electron orbits, a similar radiation called bremsstrahlung (German: braking radiation) is produced. It arises from the deflection and resulting acceleration of electrons as they encounter nuclei.

Beta particles as electrons from nuclear reactions have energies in the range 0.01-1 MeV, and thus are capable of producing large amounts of ionization as they penetrate a substance. As a rough rule of thumb, about 32 eV of energy is required to produce one ion pair. The beta particles lose energy with each event, and eventually are stopped. For electrons of 1 MeV energy, the range, as the typical distance of penetration, is no more than a few millimeters in liquids and solids or a few meters in air.

5.2 Heavy Charged Particle Stopping by Matter

Charged particles such as protons, alpha particles, and fission fragment ions are classified as heavy, being much more massive that the electron. For a given energy, their speed is lower than that of an electron, but their momentum is greater and they are less readily deflected upon collision. The

mechanism by which they slow down in matter is mainly electrostatic interaction with the atomic electrons and with nuclei. In each case the Coulomb force, varying as $1/r^2$ with distance of separation r, determines the result of a collision. Figure 5.1 illustrates the effect of the passage of an ion by an atom. An electron is displaced and gains energy in an amount large compared with its binding in the atom, creating an ion. Application of the collision formulas of Ex. 4.19 leads to the energy change when a heavy particle of mass m_H and energy E_0 collides head-on with an electron of mass m_e, as approximately $4(m_e/m_H)\ E_0$. For example, for an alpha particle of 5 MeV, the loss by the projectile and the gain by the target are $4(0.000549/4.00)\ 5 = 0.00274$ MeV or 2.74 keV. The electron is energetic enough to produce secondary ionization, while hundreds of collisions are needed to reduce the alpha particle's energy by as little as 1 MeV. As the result of primary and secondary processes, a great deal of ionization is produced by heavy ions as they move through matter.

In contrast, when heavy charged particle comes close to a nucleus, the electrostatic force causes it to move in a hyperbolic path as in Figure 5.2. The projectile is scattered through an angle that depends on the detailed nature of the collision, i.e., the initial energy and direction of motion of the incoming ion relative to the target nucleus, and the magnitudes of electric charges of the interacting particles. The charged particle loses a significant amount of energy in the process, in contrast with the slight energy loss on collision with an electron. Unless the energy of the bombarding particle is very high and it comes within the short range of the nuclear force, there is a small chance that it can enter the nucleus and cause a nuclear reaction.

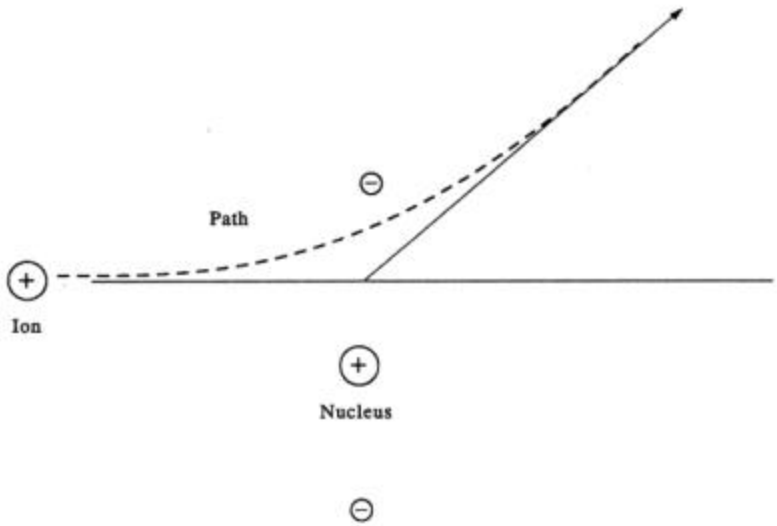

FIG. 5.2 Interaction of heavy ion with nucleus.

A measure of the rate of ion energy loss with distance traveled is the *stopping power*, symbolized by $-dE/dx$. It is also known as the linear energy transfer (LET). There are two separate components, atomic and nuclear, that add to give the total, as tabulated in the NIST web site (see References). Theoretical formulas giving the dependence on electric charges, masses, and energy are given by Mayo (see References). A related quantity is the *range*, which is the maximum distance of travel of a projectile, as it makes multiple collisions in matter. Integration of the reciprocal of the stopping power yields values of the range, also given by NIST. For example, the range of 4 MeV alpha particles in air is given as 3.147E-3 cm^2/g, and with an air density of 0.001293 g/cm^3, a distance of 2.43 cm. An alpha particle has a very small range in solid materials: a sheet of paper is sufficient to stop it and the outer layer of human skin provides protection for sensitive tissue.

5.3 Gamma Ray Interactions with Matter

We now turn to a group of three related processes involving gamma ray photons produced by nuclear reactions. These have energies as high as a few MeV. The interactions include simple scattering of the photon, ionization by it, and a special nuclear reaction known as pair production.

(a) Photon-Electron Scattering

One of the easiest processes to visualize is the interaction of a photon of energy $E = h\nu$ and an electron of rest mass m_0. Although the electrons in a target atom can be regarded as moving and bound to their nucleus, the energies involved are very small (eV) in comparison with those of typical gamma rays (keV or MeV). Thus the electrons may be viewed as free stationary particles. The collision may be treated by the physical principles of energy and momentum conservation. As sketched in Fig. 5.3, the photon is deflected in its direction and loses energy, becoming a photon of new energy $E' = h\nu'$. The electron gains energy and moves away with high speed u and total mass-energy mc^2, leaving the atom ionized. In this Compton effect, named after its discoverer, one finds that the greatest photon energy loss occurs when it is scattered backward (180°) from the original direction. Then, if E is much larger than the rest energy of the electron $E_0 = m_0c^2 =$ 0.51 MeV, it is found that the final photon energy E' is equal to $E_0/2$. On the other hand, if E is much smaller than E_0, the fractional energy loss of the photon is $2E/E_0$ (see also Exercise 5.3). The derivation of the photon energy loss in general is complicated by the fact that the special theory of relativity must be applied. The resulting formulas are displayed in computer program COMPTON, which is used in several Computer Exercises to find photon

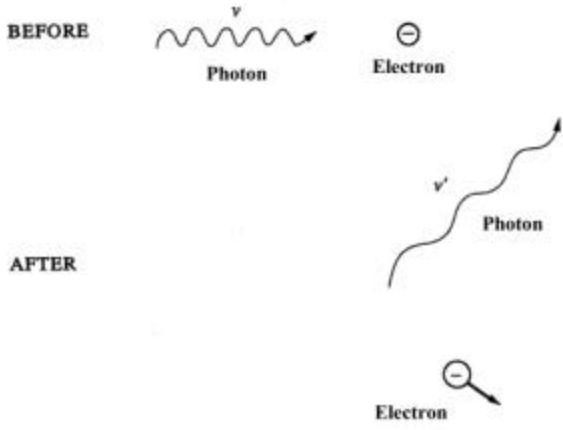

FIG. 5.3 Photon electron scattering (Compton effect).

energy losses.

The probability of Compton scattering is expressed by a cross section, which is smaller for larger gamma energies as shown in Fig. 5.4 for the element lead, a common material for shielding against X-rays or gamma rays. We can deduce that the chance of collision increases with each successive loss of energy by the photon, and eventually the photon disappears.

(b) Photoelectric Effect

This process is in competition with scattering. An incident photon of high enough energy dislodges an electron from the atom, leaving a positively charged ion. In so doing, the photon is absorbed and thus lost (see Fig. 5.5). The cross section for the photoelectric effect decreases with increasing photon energy, as sketched in Fig. 5.4 for the element lead.

The above two processes are usually treated separately even though both result in ionization. In the Compton effect, a photon of lower energy survives; but in the photoelectric effect, the photon is eliminated. In each case, the electron released may have enough energy to excite or ionize other atoms by the mechanism described earlier. Also, the ejection of the electron is followed by light emission or X-ray production, depending on whether an outer shell or inner shell is involved.

(c) Electron-Positron Pair Production

The third process to be considered is one in which the photon is converted into matter. This is entirely in accord with Einstein's theory of the equivalence of mass and energy. In the presence of a nucleus, as sketched in Fig. 5.6, a gamma ray photon disappears and two particles

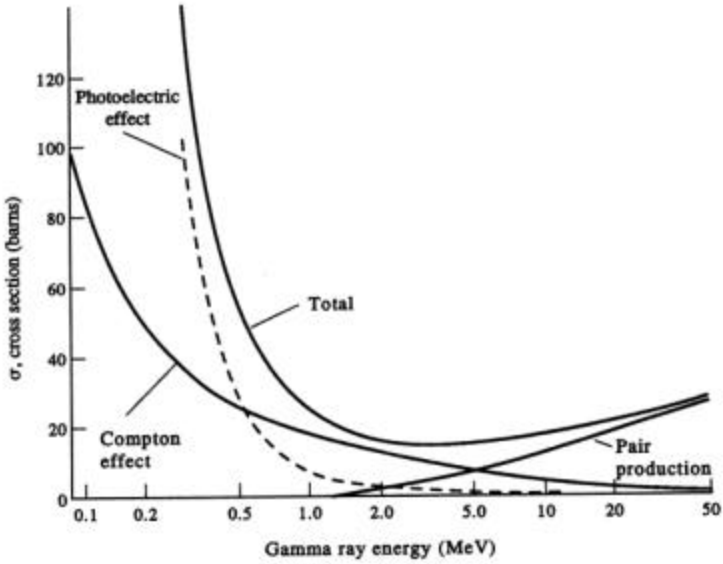

FIG. 5.4 Gamma ray cross sections in lead, Pb. Plotted from data in National Bureau of Standards report NSRDS-NSB-29.

appear–an electron and a positron. Since these are of equal charge but of opposite sign, there is no net charge after the reaction, just as before, the gamma ray having zero charge. The law of conservation of charge is thus met. The total new mass produced is twice the mass-energy of the electron, 2(0.51) = 1.02 MeV, which means that the reaction can occur only if the gamma ray has at least this amount of energy. The cross section for the process of pair production rises from zero as shown in Fig. 5.4 for lead. The reverse process also takes place. As sketched in Fig. 5.7, when an electron and a positron combine, they are annihilated as material particles, and two gamma rays of energy totaling at least 1.02 MeV are released. That there must be two photons is a consequence of the principle of momentum conservation.

Figure 5.4 shows that the total gamma ray cross section curve for lead

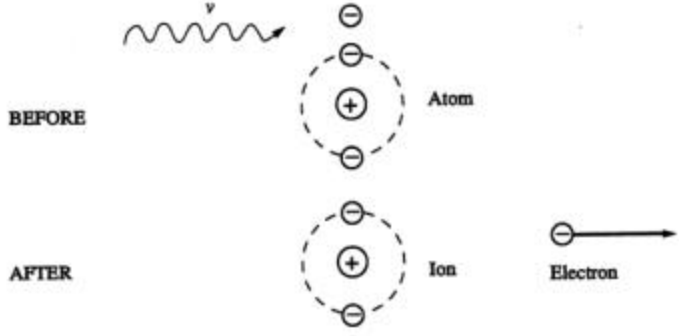

FIG. 5.5 Photoelectric effect.

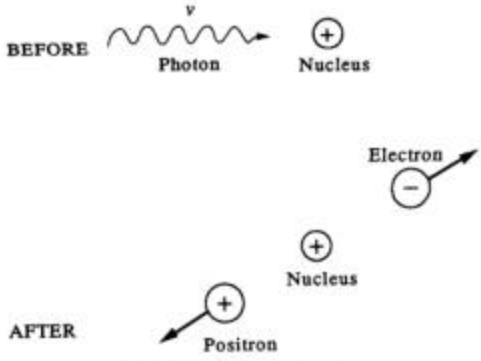

FIG. 5.6 Pair production.

(Pb), as the sum of the components for Compton effect, photoelectric effect, and pair production, exhibits a minimum around 3 MeV energy. This implies that gamma rays in this vicinity are more penetrating than those of higher or lower energy. In contrast with the case of β particles and α particles, which have a definite range, a certain fraction of incident gamma rays can pass through any thickness of material. The exponential expression e^{-Sz} as used to describe neutron behavior can be carried over to the attenuation of gamma rays in matter. One can use the mean free path $l = 1/S$ or, better, the half-thickness $0.693/S$, the distance in which the intensity of a gamma ray beam is reduced by a factor of two.

Cross section data for the interaction of photons with many elements are found in the NIST web site (see References).

5.4 Neutron Reactions

For completeness, we review again the interaction of neutrons with matter. Neutrons may be scattered by nuclei elastically or inelastically, may be captured with resulting gamma ray emission, or may cause fission. If their energy is high enough, neutrons may induce (n, p) and (n, α) reactions as well.

We are now in a position to understand the connection between neutron reactions and atomic processes. When a high-speed neutron strikes the hydrogen atom in a water molecule, a proton is ejected, resulting in chemical dissociation of the H_2O. A similar effect takes place in molecules of cells in any biological tissue. The proton in comparison with the electron is a heavy charged particle. It passes through matter, slowing and creating ionization along its path. Thus two types of neutron radiation damage take place–primary and secondary.

After many collisions, the neutron arrives at a low enough energy that it can be readily absorbed. If it is captured by the proton in a molecule of

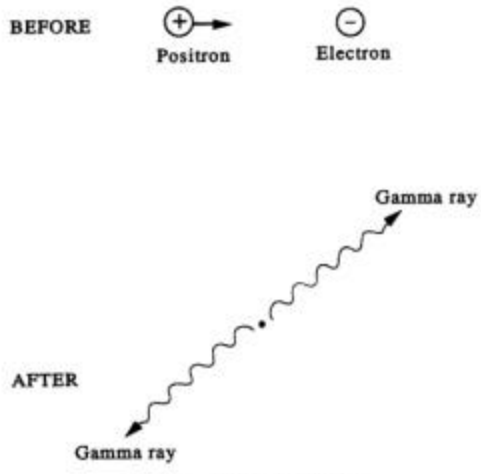

FIG. 5.7 Pair annihilation.

water or some other hydrocarbon, a gamma ray is released, as discussed in Chapter 4. The resulting deuteron recoils with energy that is much smaller than that of the gamma ray, but still is far greater than the energy of binding of atoms in the water molecule. Again dissociation of the compound takes place, which can be regarded as a form of radiation damage.

5.5 Summary

Radiation of especial interest includes electrons, heavy charged particles, photons, and neutrons. Each of the particles tends to lose energy by interaction with the electrons and nuclei of matter, and each creates ionization in different degrees. The ranges of beta particles and alpha particles are short, but gamma rays penetrate in accord with an exponential law. Gamma rays can also produce electron-positron pairs. Neutrons of both high and low energy can create radiation damage in molecular materials.

5.6 Exercises

5.1. The charged particles in a highly ionized electrical discharge in hydrogen gas−protons and electrons, mass ratio m_p/m_e = 1836−have the same energies. What is the ratio of the speeds u_p/u_e? Of the momenta p_p/p_e?

5.2. A gamma ray from neutron capture has an energy of 6 MeV. What is its frequency? Its wavelength?

5.3. For 180° scattering of gamma or X-rays by electrons, the final energy of the photon is

$$E' = \frac{1}{\frac{1}{E} + \frac{2}{E_0}} .$$

(a) What is the final photon energy for the 6 MeV gamma ray of Exercise 5.2?
(b) Verify that if $E >> E_0$, then $E' \cong E_0/2$ and if $E << E_0$, $(E - E')/E \cong 2\ E/E_0$.

(c) Which approximation should be used for a 6 MeV gamma ray? Verify numerically.

5.4. An electron-positron pair is produced by a gamma ray of 2.26 MeV. What is the kinetic energy imparted to each of the charged particles?

5.5. Estimate the thickness of paper required to stop 2 MeV alpha particles, assuming the paper to be of density 1.29 g/cm^3, about the same electronic composition as air, density 1.29 $\times$ 10^{-3} g/cm^3.

5.6. The element lead, M = 206, has a density of 11.3 g/cm^3. Find the number of atoms per cubic centimeter. If the total gamma ray cross section at 3 MeV is 14 barns, what is the macroscopic cross section S and the half-thickness 0.693/S?

5.7. The range of beta particles of energy greater than 0.8 MeV is given roughly by the relation

$$R(\text{cm}) = \frac{0.55\ E(\text{MeV}) - 0.16}{r\ (\text{g / cm}^3)}.$$

Find what thickness of aluminum sheet (density 2.7 g/cm^3) is enough to stop the betas from phosphorus-32 (see Table 3.1).

5.8. A radiation worker's hands are exposed for 5 seconds to a 3×10^8 cm^{-2} s^{-1} beam of 1 MeV beta particles. Find the range in tissue of density 1.0 g/cm^3 and calculate the amounts of charge in coulombs (C) and energy deposition in C/cm^3 and J/g. Note that the charge on the electron is 1.60×10^{-19} C. For tissue, use the equation in Ex. 5.7.

5.9 Calculate the energy gain by an electron struck head-on by an alpha particle of energy 4 MeV. How many such collisions would it take to reduce the alpha particle energy to 1 MeV?

Computer Exercises

5.A. The scattering at any angle of a photon colliding with a free electron is analyzed by the BASIC program COMPTON, after Arthur Holly Compton's theory. (a) Run the program and use the menus. (b) Find the maximum and minimum photon energies of 50 keV X-rays passing through a thin aluminum foil and making no more than one collision.

5.B. Using program COMPTON, compare the percent energy change of 10 keV and 10 MeV photons scattered at 90°. What conclusion do these results suggest?

5.C. (a) Find the fractional energy loss for a 20 keV X-ray scattered from an electron at angle 180°, and compare with $2E/E_0$. (b) Find the final energy for a 10 MeV gamma ray scattered from an electron at 180°, and compare with $E_0/2$.

5.7 References for Chapter 5

Emilio Segrè, *Nuclei and Particles*, W. A. Benjamin, New York, 1965. A classic book on nuclear theory and experiment for undergraduate physics students, written by a Nobel Prize winner.

Robert M. Mayo, *Introduction to Nuclear Concepts for Engineers*, American Nuclear Society, La Grange Park, IL, 1998. Chapter 6 is devoted to the interaction of radiation with matter.

Hans A. Bethe, Robert F. Bacher, and M. Stanley Livingston, *Basic Bethe, Seminal Articles on Nuclear Physics, 1936-1937*, American Institute of Physics, 1986. Reprints of classic literature on nuclear processes. Discussion of stopping power p. 347 ff.

National Institute of Science and Technology (NIST)
http://www.nist.gov

For stopping powers and ranges of electrons, protons and alpha particles, use Search with keyword “stopping power.”
For photon cross sections for many elements, use Search with keyword “XCOM.” Especially look for data by Berger and Hubbell.

Richard E. Faw and J. Kenneth Shultis, *Radiological Assessment: Sources and Doses*, American Nuclear Society, La Grange Park, IL, 1999. Includes fundamentals of radiation interactions.

J. Kenneth Shultis, Richard E. Faw, and Kenneth Shultis, *Radiation Shielding*, Prentice-Hall, Englewood Cliffs, NJ, 1996. Basics and modern analysis techniques.

6

Fission

OUT OF many nuclear reactions known, that resulting in fission has at present the greatest practical significance. In this chapter we shall describe the mechanism of the process, identify the byproducts, introduce the concept of the chain reaction, and look at the energy yield from the consumption of nuclear fuels.

6.1 The Fission Process

The absorption of a neutron by most isotopes involves radiative capture, with the excitation energy appearing as a gamma ray. In certain heavy elements, notably uranium and plutonium, an alternate consequence is observed–the splitting of the nucleus into two massive fragments, a process called fission. Computer Exercise 6.A provides a graphic display of the process. Figure 6.1 shows the sequence of events, using the reaction with U-235 to illustrate. In Stage A, the neutron approaches the U-235 nucleus. In Stage B, the U-236 nucleus has been formed, in an excited state. The excess energy in some cases may be released as a gamma ray, but more frequently, the energy causes distortions of the nucleus into a dumbbell shape, as in Stage C. The parts of the nucleus oscillate in a manner analogous to the motion of a drop of liquid. Because of the dominance of electrostatic repulsion over nuclear attraction, the two parts can separate, as in Stage D. They are then called fission fragments, bearing most of the energy released. They fly apart at high speeds, carrying some 166 MeV of kinetic energy out of the total of around 200 MeV released in the whole process. As the fragments separate, they lose atomic electrons, and the resulting high-speed ions lose energy by interaction with the atoms and molecules of the surrounding medium. The resultant thermal energy is recoverable if the fission takes place in a nuclear reactor. Also shown in the diagram are the prompt gamma rays and fast neutrons that are released at the time of splitting.

6.2 Energy Considerations

The absorption of a neutron by a nucleus such as U-235 gives rise to extra internal energy of the product, because the sum of masses of the two

interacting particles is greater than that of a normal U-236 nucleus. We write the first step in the reaction

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow \left(^{236}_{92}\mathrm{U}\right)^{*},$$

where the asterisk signifies the excited state. The mass in atomic mass units of (U-236)* is the sum 235.043923 + 1.008665 = 236.052588. However, U-236 in its ground state has a mass of only 236.045562, lower by 0.007026 amu or 6.54 MeV. This amount of excess energy is sufficient to cause fission. Figure 6.2 shows these energy relationships.

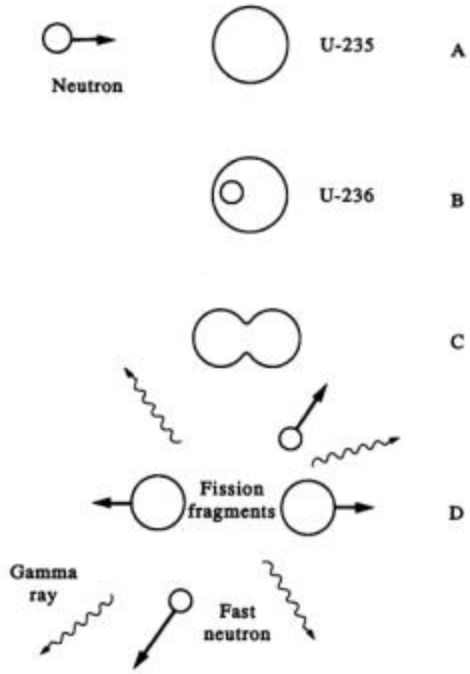

FIG. 6.1 The fission process.

The above calculation did not include any kinetic energy brought to the reaction by the neutron, on the grounds that fission can be induced by absorption in U-235 of very slow neutrons. Only one natural isotope, $^{235}_{92}\mathrm{U}$, undergoes fission in this way, while $^{239}_{94}\mathrm{Pu}$ and $^{233}_{92}\mathrm{U}$ are the main artificial isotopes that do so. Most other heavy isotopes require significantly larger excitation energy to bring the compound nucleus to the required energy level for fission to occur, and the extra energy must be provided by the motion of the incoming neutron. For example, neutrons of at least 0.9 MeV are required to cause fission from U-238, and other isotopes require even higher energy. The precise terminology is as follows: fissile materials are those giving rise to fission with slow neutrons; many isotopes are fissionable, if enough energy is supplied. It is advantageous to use fast

neutrons–of the order of 1 MeV energy–to cause fission. As will be discussed in Chapter 13, the fast reactor permits the "breeding" of nuclear fuel. In a few elements such as californium, spontaneous fission takes place. The isotope $^{252}_{98}Cf$, produced artificially by a sequence of neutron absorption, has a half-life of 2.62 y, decaying by alpha emission (96.9%) and spontaneous fission (3.1%).

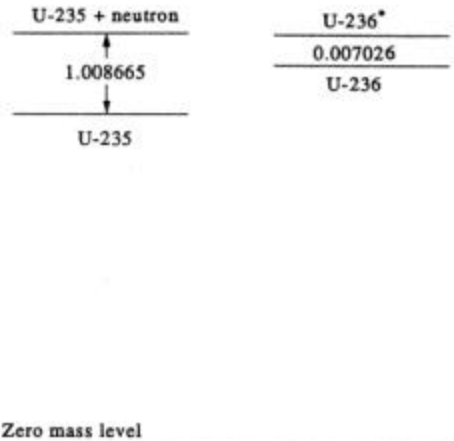

FIG. 6.2 Excitation energy due to neutron absorption.

It may be surprising that the introduction of only 6.5 MeV of excitation energy can produce a reaction yielding as much as 200 MeV. The explanation is that the excitation triggers the separation of the two fragments and the powerful electrostatic force provides them a large amount of kinetic energy. By conservation of mass-energy, the mass of the nuclear products is smaller than the mass of the compound nucleus from which they emerge.

6.3 Byproducts of Fission

Accompanying the fission process is the release of several neutrons, which are all-important for the practical application to a self-sustaining chain reaction. The numbers that appear n (nu) range from 1 to 7, with an average in the range 2 to 3 depending on the isotope and the bombarding neutron energy. For example, in U-235 with slow neutrons the average number n is 2.42. Most of these are released instantly, the so-called prompt neutrons, while a small percentage, 0.65% for U-235, appear later as the result of radioactive decay of certain fission fragments. These delayed neutrons provide considerable inherent safety and controllability in the operation of nuclear reactors, as we shall see later.

The nuclear reaction equation for fission resulting from neutron absorption in U-235 may be written in general form, letting the chemical

symbols for the two fragments be labeled F_1 and F_2 to indicate many possible ways of splitting. Thus

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{A_1}_{Z_1}F_1 + {}^{A_2}_{Z_2}F_2 + n\ {}^{1}_{0}\mathrm{n} + \text{energy}\ .$$

The appropriate mass numbers and atomic numbers are attached. One example, in which the fission fragments are isotopes of krypton and barium, is

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{90}_{36}\mathrm{Kr} + {}^{144}_{56}\mathrm{Ba} + 2{}^{1}_{0}\mathrm{n} + E\ .$$

Mass numbers ranging from 75 to 160 are observed, with the most probable at around 92 and 144 as sketched in Fig. 6.3. The ordinate on this graph is the percentage yield of each mass number, e.g., about 6% for mass numbers 90 and 144. If the number of fissions is given, the number of atoms of those types are 0.06 as large. Computer Exercise 6.B describes the program YIELD, which calculates the fission yield for several mass numbers.

As a collection of isotopes, these byproducts are called fission products. The isotopes have an excess of neutrons or a deficiency of protons in comparison with naturally occurring elements. For example, the main isotope of barium is $^{137}_{56}\mathrm{Ba}$, and a prominent element of mass 144 is $^{144}_{60}\mathrm{Nd}$. Thus there are seven extra neutrons or four too few protons in the barium

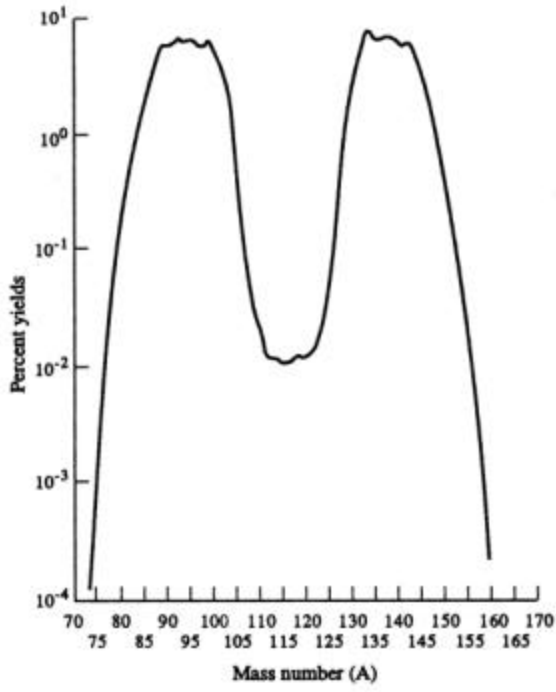

FIG. 6.3 Yield of fission products according to mass number (Courtesy of T. R. England of Los Alamos National Laboratory).

isotope from fission, and it is highly unstable. Radioactive decay, usually involving several emissions of beta particles and delayed gamma rays in a chain of events, brings the particles down to stable forms. An example is

$$^{90}_{36}\mathrm{Kr} \xrightarrow[32.3\ \mathrm{s}]{} {}^{90}_{37}\mathrm{Rb} \xrightarrow[2.6\ \mathrm{min}]{} {}^{90}_{38}\mathrm{Sr} \xrightarrow[29.1\ \mathrm{y}]{} {}^{90}_{39}\mathrm{Y} \xrightarrow[2.67\ \mathrm{d}]{} {}^{90}_{40}\mathrm{Zr}\ .$$

The hazard associated with the radioactive emanations from fission products is evident when we consider the large yields and the short half-lives.

TABLE 6.1
Energy from Fission, U-235.

	MeV
Fission fragment kinetic energy	166
Neutrons	5
Prompt gamma rays	7
Fission product gamma rays	7
Beta particles	5
Neutrinos	10
Total	200

The total energy from fission, after all of the particles from decay have been released, is about 200 MeV. This is distributed among the various processes as shown in Table 6.1. The prompt gamma rays are emitted as a part of fission; the rest are fission product decay gammas. Neutrinos accompany the beta particle emission, but since they are such highly penetrating particles their energy cannot be counted as part of the useful thermal energy yield of the fission process. Thus only about 190 MeV of the fission energy is effectively available. However, several MeV of energy from gamma rays released from nuclei that capture neutrons can also be extracted as useful heat.

The average total neutron energy is noted to be 5 MeV. If there are about 2.5 neutrons per fission, the average neutron energy is 2 MeV. When one observes many fission events, the neutrons are found to range in energy from nearly 0 to over 10 MeV, with a most likely value of 0.7 MeV. Computer Exercise 6.C discusses calculation of the fission neutron energy distribution according to a semi-empirical formula. We note that the neutrons produced by fission are fast, while the cross section for the fission reaction is high for slow neutrons. This fact serves as the basis for the use of a reactor moderator containing a light element that permits neutrons to slow down, by a succession of collisions, to an energy favorable for fission.

Although fission is the dominant process, a certain fraction of the absorptions of neutrons in uranium merely result in radiative capture, according to

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} + g\ .$$

The U-236 is relatively stable, having a half-life of 2.34×10^7 y. About 14% of the absorptions are of this type, with fission occurring in the remaining 86%. This means that h (eta), the number of neutrons produced per *absorption* in U-235 is lower than n, the number per *fission*. Thus using $n = 2.42$, h is (0.86) (2.42) = 2.07. The effectiveness of any nuclear fuel is sensitively dependent on the value of h. We find that h is larger for fission induced by fast neutrons than that by slow neutrons.

The possibility of a chain reaction was recognized as soon as it was known that neutrons were released in the fission process. If a neutron is absorbed by the nucleus of one atom of uranium and one neutron is produced, the latter can be absorbed in a second uranium atom, and so on. In order to sustain a chain reaction as in a nuclear reactor or in a nuclear weapon, the value of h must be somewhat above 1 because of processes that compete with absorption in uranium, such as capture in other materials and escape from the system. The size of h has two important consequences. First, there is a possibility of a growth of neutron population with time. After all extraneous absorption and losses have been accounted for, if one absorption in uranium ultimately gives rise to say 1.1 neutrons, these can be absorbed to give (1.1) (1.1) = 1.21, which produce 1.331, etc. The number available increases rapidly with time. Second, there is a possibility of using the extra neutron, over and above the one required to maintain the chain reaction, to produce new fissile materials. "Conversion" involves the production of some new nuclear fuel to replace that used up, while "breeding" is achieved if more fuel is produced than is used.

Out of the hundreds of isotopes found in nature, only one is fissile, ${}^{235}_{92}\mathrm{U}$. Unfortunately, it is the less abundant of the isotopes of uranium, with weight percentage in natural uranium of only 0.711, in comparison, with 99.3% of the heavier isotope ${}^{238}_{92}\mathrm{U}$. The two other most important fissile materials, plutonium-239 and uranium-233, are "artificial" in the sense that they are man-made by use of neutron irradiation of two fertile materials, respectively, uranium-238 and thorium-232. The reactions by which ${}^{239}_{94}\mathrm{Pu}$ is produced are

$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U}, $$

$$ {}^{239}_{92}\mathrm{U} \underset{23.5\,\mathrm{min}}{\rightarrow} {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}, $$

$$ {}^{239}_{92}\mathrm{Np} \underset{2.355\,\mathrm{d}}{\rightarrow} {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}, $$

while those yielding ${}^{233}_{92}\mathrm{U}$ are

$$ {}^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th}, $$

$$ {}^{233}_{90}\mathrm{Th} \underset{22.3\ \mathrm{min}}{\rightarrow} {}^{233}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}, $$

$$^{233}_{91}\mathrm{Pa} \xrightarrow[27.0\,\mathrm{d}]{} {}^{233}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e}\,.$$

The half-lives for decay of the intermediate isotopes are short compared with times involved in the production of these fissile materials; and for many purposes, these decay steps can be ignored. It is important to note that although uranium-238 is not fissile, it can be put to good use as a fertile material for the production of plutonium-239, so long as there are enough free neutrons available.

6.4 Energy from Nuclear Fuels

The practical significance of the fission process is revealed by calculation of the amount of uranium that is consumed to obtain a given amount of energy. Each fission yields 190 MeV of useful energy, which is also (190 MeV) $(1.60 \times 10^{-13}$ J/MeV) = 3.04×10^{-11} J. Thus the number of fissions required to obtain 1 W-sec of energy is $1/(3.04 \times 10^{-11}) = 3.3 \times 10^{10}$. The number of U-235 atoms consumed in a thermal reactor is larger by the factor 1/0.86 = 1.16 because of the formation of U-236 in part of the reactions.

In one day's operation of a reactor per megawatt of thermal power, the number of U-235 nuclei burned is

$$\frac{\left(10^6\,\mathrm{W}\right)\left(3.3\times10^{10}\ \text{fissions}/\mathrm{W-s}\right)(86{,}400\,\mathrm{s/d})}{0.86\ \text{fissions/absorption}}$$

$$= 3.32 \times 10^{21}\ \text{absorptions/d}\,.$$

Then since 235 g corresponds to Avogadro's number of atoms 6.02×10^{23}, the U-235 weight consumed at 1 MW power is

$$\frac{\left(3.32\times10^{21}\,\mathrm{d}^{-1}\right)(235\,\mathrm{g})}{6.02\times10^{23}} \cong 1.3\,\mathrm{g/d}\,.$$

In other words, 1.3 g of fuel is used per megawatt-day of useful thermal energy released. In a typical reactor, which produces 3000 MW of thermal power, the U-235 fuel consumption is about 4 kg/day. To produce the same energy by the use of fossil fuels such as coal, oil, or gas, millions of times as much weight would be required.

6.5 Summary

Neutron absorption by the nuclei of heavy elements gives rise to fission, in which heavy fragments, fast neutrons, and other radiations are released. Fissile materials are natural U-235 and the man-made isotopes Pu-239 and U-233. Many different radioactive isotopes are released in the fission process, and more neutrons are produced than are used, which makes

possible a chain reaction and under certain conditions "conversion" and "breeding" of new fuels. Useful energy amounts to 190 MeV per fission, requiring only 1.3 g of U-235 to be consumed to obtain 1 MWd of energy.

6.6 Exercises

6.1. Calculate the mass of the excited nucleus of plutonium-240 as the sum of the neutron mass 1.008665 and the Pu-239 mass 239.052157. How much larger is that sum than the mass of stable Pu- 240, 240.053807? What energy in MeV is that?

6.2. If three neutrons and a xenon-133 atom ($^{133}_{54}\mathrm{Xe}$) are produced when a U-235 atom is bombarded by a neutron, what is the second fission product isotope?

6.3. The total kinetic energy of the fission fragments is 166 MeV. (a) What are the energies of each if the mass ratio is 3/2? (b) What are the two mass numbers if three neutrons were released in fission? (c) What are the velocities of the fragments?

6.4. Calculate the energy yield from the reaction

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{92}_{37}\mathrm{Rb} + {}^{140}_{55}\mathrm{Cs} + 4\,{}^{1}_{0}\mathrm{n} + E$$

using atomic masses 139.917277 for cesium and 91.919725 for rubidium.

6.5. The value of h for U-233 for thermal neutrons is approximately 2.30. Using the cross sections for capture s_c = 47 barns and fission s_f = 530 barns, deduce the value of n, the number of neutrons per fission.

6.6. A mass of 8000 kg of slightly enriched uranium (2% U-235, 98% U-238) is exposed for 30 days in a reactor operating at heat power 2000 MW. Neglecting consumption of U-238, what is the final fuel composition?

6.7. The per capita consumption of electrical energy in the United States is about 50 kWh/d. If this were provided by fission with 2/3 of the heat wasted, how much U-235 would each person use per day?

6.8. Calculate the number of kilograms of coal, oil, and natural gas that must be burned each day to operate a 3000-MW thermal power plant, which consumes 4 kg/d of uranium-235. The heats of combustion of the three fuels (in kJ/g) are, respectively, 32, 44, and 50.

Computer Exercises

6.A. The fission process can be visualized by the computer program FISSION. It shows a neutron approaching a fissionable nucleus and the fragments emerging. Run the program several times, noting the variety of speeds and directions of the particles.

6.B. Program YIELD calculates the fission yield for several prominent long-lived radionuclides and their precursors by a summing process. Run the program selecting several mass numbers near the peaks near 92 and 144.

6.C. Program SPECTRUM gives a simple formula for the way fission neutrons are distributed in energy, shows a graph of the distribution, and calculates properties of the curve. Run the program using the menus.

6.7 References for Chapter 6

Basics of Nuclear Physics and Fission
http://www.ieer.org/reports/n-basics.html
Decay, binding energy, fission. By Institute for Energy and Environmental Research.

Ruth Lewin Sime, "Lise Meitner and the Discovery of Nuclear Fission," *Scientific American*, January 1998, p. 80. Contributions of the scientist who should have received the Nobel Prize. Also try AltaVista with key phrase "discovery of nuclear fission."

Emilio Segrè, "The Discovery of Nuclear Fission," *Physics Today*, July 1998, p. 38.

Hans G. Graetzer and David L. Anderson; Editor, I. Cohen, *The Discovery of Nuclear Fission*, Ayer Co., 1981. A collection of original papers with commentary. Represented are Hahn, Strassmann, Frisch, Bohr, and Fermi.

National Nuclear Data Center
http://www.nndc.bnl.gov
Links to many sources. By Brookhaven National Laboratory.

Atomic Mass Data Center
http://csnwww.in2p3.fr
Select AME, AMDC for latest published atomic mass values.

Isotopes Project
http://ie.lbl.gov/ip.html
Select Fission for data on fission product yields and on spontaneous fission. By Lawrence Berkeley National Laboratory.

Physical Science Resource Center
http://www.psrc-online.org
Select Resource Center for links to many nuclear physics topics. By American Association of Physics Teachers.

7

Fusion

WHEN TWO light nuclear particles combine or "fuse" together, energy is released because the product nuclei have less mass than the original particles. Such fusion reactions can be caused by bombarding targets with charged particles, using an accelerator, or by raising the temperature of a gas to a high enough level for nuclear reactions to take place. In this chapter we shall describe the interactions in the microscopic sense and discuss the phenomena that affect our ability to achieve a practical large-scale source of energy from fusion. Thanks are due Dr. John G. Gilligan for his comments.

7.1 Fusion Reactions

The possibility of release of large amounts of nuclear energy can be seen by comparing the masses of nuclei of low atomic number. Suppose that one could combine two hydrogen nuclei and two neutrons to form the helium nucleus. In the reaction

$$2\,{}^{1}_{1}\mathrm{H} + 2\,{}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He}\,,$$

the mass-energy difference (using atom masses) is

$$2(1.007825) + 2(1.008665) - 4.002603 = 0.030377 \text{ amu},$$

which corresponds to 28.3 MeV energy. A comparable amount of energy would be obtained by combining four hydrogen nuclei to form helium plus two positrons

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{+1}\mathrm{e}\,.$$

This reaction in effect takes place in the sun and in other stars through the so-called carbon cycle, a complicated chain of events involving hydrogen and isotopes of the elements carbon, oxygen, and nitrogen. The cycle is extremely slow, however, and is not suitable for terrestrial application.

In the "hydrogen bomb," on the other hand, the high temperatures created by a fission reaction cause the fusion reaction to proceed in a rapid and uncontrolled manner. Between these extremes is the possibility of achieving a controlled fusion reaction that utilizes inexpensive and abundant fuels. As yet, a practical fusion device has not been developed, and considerable research and development will be required to reach that goal. Let us now examine the nuclear reactions that might be employed.

There appears to be no mechanism by which four separate nuclei can be made to fuse directly, and thus combinations of two particles must be sought.

The most promising reactions make use of the isotope deuterium, ${}_1^2\mathrm{H}$, abbreviated D. It is present in hydrogen as in water with abundance only 0.015%, i.e., there is one atom of ${}_1^2\mathrm{H}$ for every 6700 atoms of ${}_1^1\mathrm{H}$, but since our planet has enormous amounts of water, the fuel available is almost inexhaustible. Four reactions are important:

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \rightarrow {}_1^3\mathrm{H} + {}_1^1\mathrm{H} + 4.03\ \mathrm{MeV}, $$

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \rightarrow {}_2^3\mathrm{He} + {}_0^1\mathrm{n} + 3.27\ \mathrm{MeV}, $$

$$ {}_1^2\mathrm{H} + {}_1^3\mathrm{H} \rightarrow {}_2^4\mathrm{He} + {}_0^1\mathrm{n} + 17.6\ \mathrm{MeV}, $$

$$ {}_1^2\mathrm{H} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1\mathrm{H} + 18.3\ \mathrm{MeV}. $$

The fusion of two deuterons–deuterium nuclei–in what is designated the D-D reaction results in two processes of nearly equal likelihood. The other reactions yield more energy but involve the artificial isotopes tritium, ${}_1^3\mathrm{H}$, abbreviated T, with the ion called the triton, and the rare isotope ${}_2^3\mathrm{He}$, helium-3. We note that the products of the first and second equations appear as reactants in the third and fourth equations. This suggests that a composite process might be feasible. Suppose that each of the reactions could be made to proceed at the same rate, along with twice the reaction of neutron capture in hydrogen

$$ {}_1^1\mathrm{H} + {}_0^1\mathrm{n} \rightarrow {}_1^2\mathrm{H} + 2.2\ \mathrm{MeV}. $$

Adding all of the equations, we find that the net effect is to convert deuterium into helium according to

$$ 4\,{}_1^2\mathrm{H} \rightarrow 2\,{}_2^4\mathrm{He} + 47.7\ \mathrm{MeV}. $$

The energy yield per atomic mass unit of deuterium fuel would thus be about 6 MeV, which is much more favorable that the yield per atomic mass unit of U-235 burned, which is only 190/235 = 0.81 MeV.

Computer Exercise 7.A permits the exploration of possible nuclear reactions for fusion.

7.2 Electrostatic and Nuclear Forces

The reactions described above do not take place merely by mixing the ingredients, because of the very strong force of electrostatic repulsion between the charged nuclei. Only by giving one or both of the particles a high speed can they be brought close enough to each other for the strong nuclear force to dominate the electrical force. This behavior is in sharp contrast to the ease with which neutrons interact with nuclei.

There are two consequences of the fact that the coulomb force between two charges of atomic numbers Z_1 and Z_2 varies with separation R according to $Z_1 Z_2/R^2$. First, we see that fusion is unlikely in elements other than those low in the periodic table. Second, the force and corresponding potential energy of repulsion is very large at the 10^{-15} m range of nuclear forces, and thus the chance of reaction is negligible unless particle energies are of the order of keV. Figure 7.1 shows the cross section for the D-D reaction. The strong dependence on energy is noted, with s_{DD} rising by a factor of 1000 in the range 10-75 keV.

Energies in the kilo-electron-volt and million-electron-volt range can be achieved by a variety of charged particle accelerators. Bombardment of a solid or gaseous deuterium target by high-speed deuterons gives fusion reactions, but most of the particle energy goes into electrostatic interactions that merely heat up the bulk of the target. For a practical system, the recoverable fusion energy must significantly exceed the energy required to operate the accelerator. Special equipment and processes are required to achieve that objective.

7.3 Thermonuclear Reactions in a Plasma

A medium in which high particle energies are obtained is the *plasma*. It consists of a highly ionized gas as in an electrical discharge created by the acceleration of electrons. Equal numbers of electrons and positively charged

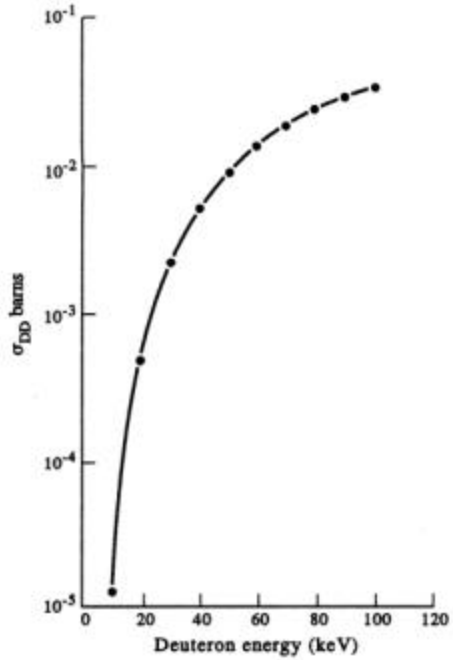

FIG. 7.1 Cross section for D–D reaction.

ions are present, making the medium electrically neutral. The plasma is often called "the fourth state of matter." Through the injection of enough energy into the plasma its temperature can be increased, and particles such as deuterons reach the speed for fusion to be favorable. The term thermonuclear is applied to reactions induced by high thermal energy, and the particles obey a speed distribution similar to that of a gas, as discussed in Chapter 2.

The temperatures to which the plasma must be raised are extremely high, as we can see by expressing an average particle energy in terms of temperature, using the kinetic relation

$$\overline{E} = \frac{3}{2}kT .$$

For example, even if $\overline{E}$ is as low as 10 keV, the temperature is

$$T = \frac{2}{3}\frac{(10^4 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV})}{1.38 \times 10^{-23} \text{ J/K}}$$

$$T = 77{,}000{,}000 \text{ K}.$$

Such a temperature greatly exceeds the temperature of the surface of the sun, and is far beyond any temperature at which ordinary materials melt and vaporize. The plasma must be created and heated to the necessary temperature under some constraint provided by a physical force. In stars, gravity provides that force, but that is not sufficient on Earth. Compression by reaction to ablation is designated as inertial confinement; restraint by electric and magnetic fields is called magnetic confinement. These methods will be discussed in Chapter 14. Such forces on the plasma are required to assure that thermal energy is not prematurely lost. Moreover, the plasma must remain intact long enough for many nuclear reactions to occur, which is difficult because of inherent instabilities of such highly charged media. Recalling from Section 2.2 the relationship $pV = nkT$, we note that even though the temperature T is very high, the particle density n/V is low, allowing the pressure p to be manageable.

The achievement of a practical energy source is further limited by the phenomenon of radiation losses. In Chapter 5 we discussed the bremsstrahlung radiation produced when electrons experience acceleration. Conditions are ideal for the generation of such electromagnetic radiation since the high-speed electrons in the plasma at elevated temperature experience continuous accelerations and decelerations as they interact with other charges. The radiation can readily escape from the region, because the number of target particles is very small. In a typical plasma, the number density of electrons and deuterons is 10^{15}, which corresponds to a rarefied gas. The amount of radiation production (and loss) increases with

temperature at a slower rate than does the energy released by fusion, as shown in Fig. 7.2. At what is called the ignition temperature, the lines cross. Only for temperatures above that value, 400,000,000 K in the case of the D-D reaction, will there be a net energy yield, assuming that the radiation is lost. In a later chapter we shall describe some of the devices that have been used to explore the possibility of achieving a fusion reactor.

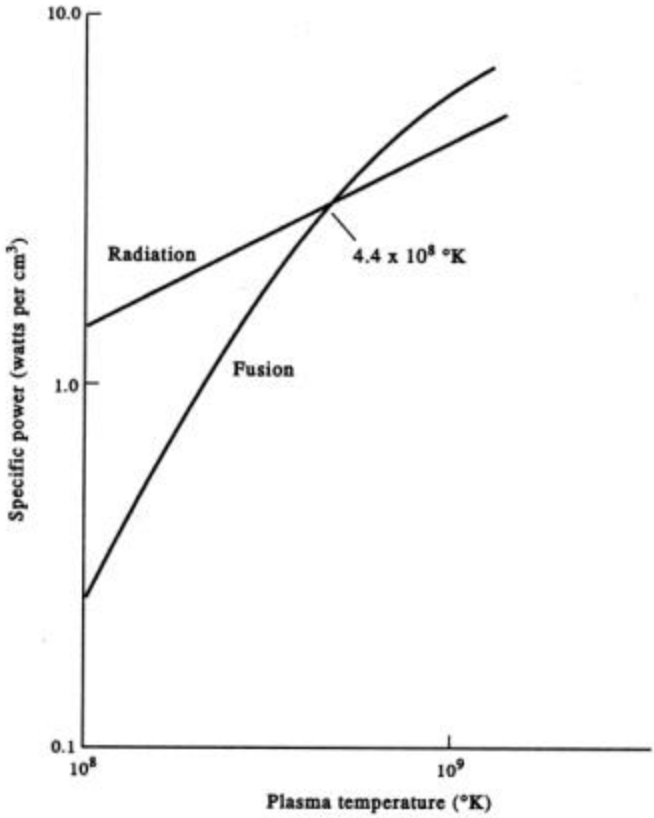

FIG. 7.2 Fusion and radiation energies.

7.4 Summary

Nuclear energy is released when nuclei of two light elements combine. The most favorable fusion reactions involve deuterium, which is a natural component of water and thus is a very abundant fuel. The reaction takes place only when the nuclei have a high enough speed to overcome the electrostatic repulsion of their charges. In a highly ionized electrical medium, the plasma, at temperatures of the order of 400,000,000 K, the fusion energy can exceed the energy loss due to radiation.

7.5 Exercises

7.1. Calculate the energy release in amu and MeV from the combination of four hydrogen atoms to form a helium atom and two positrons (each of mass 0.000549 amu).

7.2. Verify the energy yield for the reaction ${}_1^2\mathrm{H} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1\mathrm{H} + 18.3\ \mathrm{MeV}$, noting atomic masses (in order) 2.014102, 3.016029, 4.002603, and 1.007825.

7.3. To obtain 3000 MW of power from a fusion reactor, in which the effective reaction is $2{}_1^2\mathrm{H} \rightarrow {}_2^4\mathrm{He} + 23.8\ \mathrm{MeV}$, how many grams per day of deuterium would be needed? If all of the deuterium could be extracted from water, how many kilograms of water would have to be processed per day?

7.4. The reaction rate relation $nuNs$ can be used to estimate the power density of a fusion plasma. (a) Find the speed u_D of 100 keV deuterons. (b) Assuming that deuterons serve as both target and projectile, such that the effective u is $u_\mathrm{D}/2$, find what particle number density would be needed to achieve a power density of 1 kW/cm^3.

7.5. Estimate the temperature of the electrical discharge in a 120-volt fluorescent lightbulb.

7.6. Calculate the potential energy in eV of a deuteron in the presence of another when their centers are separated by three nuclear radii (Note: $E_p = kQ_1Q_2/\mathrm{R}$ where $k = 9 \times 10^9$, Q's are in coulombs, and R is in meters).

Computer Exercises

7.A. Program REACT1 displays the atomic masses for a number of light nuclides that are candidates as fusion projectiles and targets. Run the program and use Print Screen to obtain a paper copy of the table.

7.B. The reaction energy Q is the difference between masses of products and reactants. Program REACT2 calculates Q for an input of nuclei that might be involved, and obtains the approximate distribution of energy between the product nuclei. (a) Test the program using the classic D-T reaction, with A1 = 1, Z1 = 1; A2 = 2, Z2 = 1; A3 = 4, Z3 = 2; A4 = 1, Z4 = 0. (b) Try the program with a few other reactions.

7.C. Program REACT3 surveys the array of light nuclei for potential fusion reactions. Run the program to find reactions with highest reaction energy, those that are neutron-free, and those that would require the lowest temperature, based on the product of Z1 and Z2.

7.6 References for Chapter 7

(also see Chapter 14)

T. A. Heppenheimer, *The Man-Made Sun, The Quest for Fusion Power*, Little, Brown & Co., Boston, 1984. A narrative account of the fusion program of the U.S., including personalities, politics, and progress to the date of publication. Good descriptions of equipment and processes.

Robin Herman, *Fusion: The Search for Endless Energy*, Cambridge University Press, New York, 1990. A well-written and interesting account.

Robert A. Gross, *Fusion Energy*, John Wiley & Sons, New York, 1985. A readable textbook. Main emphasis is on magnetic confinement fusion.

James J. Duderstadt and Gregory A. Moses, *Inertial Confinement Fusion*, John Wiley & Sons, New York, 1982. An excellent complement to the book by Gross.

Nuclear Fusion Basics
http://www.jet.uk/fusion1.html
By JET Joint Undertaking

Educational Web Site Fusion Energy
http://fusioned.gat.com
An explanation of fusion, a glossary, and an elementary but attractive and informative slide show, “Creating a Star on Earth.” By General Atomic.

Fusion Energy Educational Web Site
http://fusedweb.pppl.gov/cpep/chart.html
Selection of information. From Princeton Plasma Physics Laboratory.

Inertial and Magnetic Confinement
http://lasers.llnl.gov/lasers/education/ed.html
Select Laser and Fusion Education for a preview of methods of obtaining high temperatures. By Lawrence Livermore National Laboratory.

Fusion Power Associates
http://fusionpower.org
A foundation that is a valuable source of information on current fusion research and political status, with links to many other sites. Fusion Program Notes appear frequently as e-mail messages.

Plasma Physics, The Science of the Fourth State of Matter
http://fusion.gat.com/PlasmaOutreach/plasmaphysics.html
An exhibit at the American Physical Society Centennial at Atlanta in 1999. Eight separate files in pdf format.

Perspectives on Plasmas
http://www.plasmas.org
All aspects of plasma science and technology.

Part II Nuclear Systems

The atomic and nuclear concepts we have described provide the basis for the operation of a number of devices, machines, or processes, ranging from very small radiation detectors to mammoth plants to process uranium or to generate electrical power. These systems may be designed to produce nuclear energy, or to make practical use of it, or to apply byproducts of nuclear reactions for beneficial purposes. In the next several chapters we shall explain the construction and operating principles of nuclear systems, referring back to basic concepts and looking forward to appreciating their impact on human affairs.

8

Particle Accelerators

A DEVICE that provides forces on charged particles by some combination of electric and magnetic fields and brings the ions to high speed and kinetic energy is called an accelerator. Many types have been developed for the study of nuclear reactions and basic nuclear structure, with an ever-increasing demand for higher particle energy. In this chapter we shall review the nature of the forces on charges and describe the arrangement and principle of operation of several important kinds of particle accelerators. In later chapters we describe some of the many applications.

8.1 Electric and Magnetic Forces

Let us recall how charged particles are influenced by electric and magnetic fields. First, visualize a pair of parallel metal plates separated by a distance d as in the sample capacitor shown in Fig. 8.1. A potential difference V and electric field $\mathscr{E} = V/d$ are provided to the region of low gas pressure by a direct-current voltage supply such as a battery. If an electron of mass m and charge e is released at the negative plate, it will experience a force $\mathscr{E}e$, and its acceleration will be $\mathscr{E}e/m$. It will gain speed, and on reaching the positive plate it will have reached a kinetic energy $\frac{1}{2}mu^2 = Ve$. Thus its speed is $u = \sqrt{2Ve/m}$. For example, if V is 100 volts, the speed of an electron ($m = 9.1 \times 10^{-31}$ kg and $e = 1.60 \times 10^{-19}$ coulombs) is found to be 5.9×10^6 m/s.

Next, let us introduce a charged particle of mass m, charge e, and speed u into a region with uniform magnetic field B, as in Fig. 8.2. If the charge enters in the direction of the field lines, it will not be affected, but if it

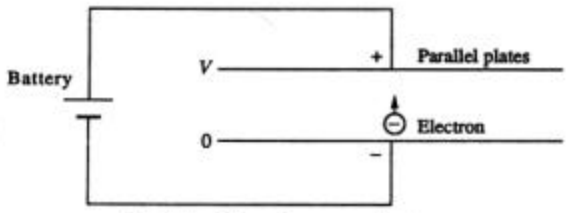

FIG. 8.1 Capacitor as accelerator.

enters perpendicularly to the field, it will move at constant speed on a circle. Its radius, called the radius of gyration, is $r = mu/eB$, such that the stronger the field or the lower the speed, the smaller will be the radius of motion. Let the angular speed be w (omega) equal to u/r. Using the formula for r, we find $w = eB/m$. If the charge enters at some other angle, it will move in a path called a helix, like a wire door spring.

Instead, let us release a charge in a region where the magnetic field B is changing with time. If the electron were inside the metal of a circular loop of wire of area A as in Fig. 8.3, it would experience an electric force induced by the change in magnetic flux BA. The same effect would take place without the presence of the wire, of course. Finally, if the magnetic field varies with position there are additional forces on charged particles.

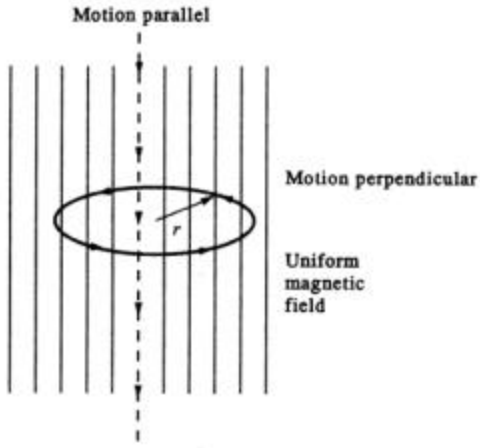

FIG. 8.2 Electric charge motion in uniform magnetic field.

8.2 High-Voltage Machines

One way to accelerate ions to high speed is to provide a large potential difference between a source of charges and a target. In effect, the phenomenon of lightning, in which a discharge from charged clouds to the earth takes place, is produced in the laboratory. Two devices of this type are commonly used. The first is the voltage multiplier or Cockroft-Walton machine, Fig. 8.4, which has a circuit that charges capacitors in parallel and discharges them in series. The second is the electrostatic generator or Van de Graaff accelerator, the principle of which is sketched in Fig. 85. An insulated metal shell is raised to high potential by bringing it charge on a moving belt, permitting the acceleration of positive charges such as protons or deuterons. Particle energies of the order of 5 MeV are possible, with a very small spread in energy.

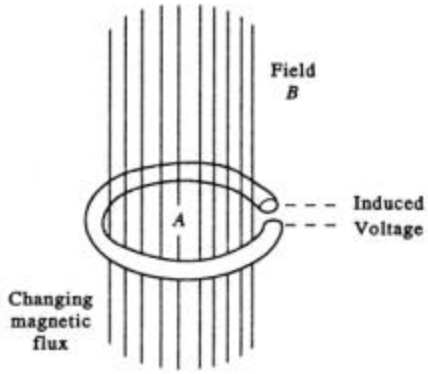

FIG. 8.3 Magnetic induction.

8.3 Linear Accelerator

Rather than giving a charge one large acceleration with a high voltage, it can be brought to high speed by a succession of accelerations through relatively small potential differences, as in the linear accelerator ("linac"), sketched in Fig. 8.6. It consists of a series of accelerating electrodes in the form of tubes with alternating electric potentials applied as shown. An electron or ion gains energy in the gaps between tubes and "drifts" without change of energy while inside the tube, where the field is nearly zero. By the time the charge reaches the next gap, the voltage is again correct for acceleration. Because the ion is gaining speed along the path down the row of tubes, their lengths ℓ must be successively longer in order for the time of flight in each to be constant. The time to go a distance ℓ is ℓ/u, which is equal to the half-period of the voltage cycle $T/2$. The linac at the Stanford

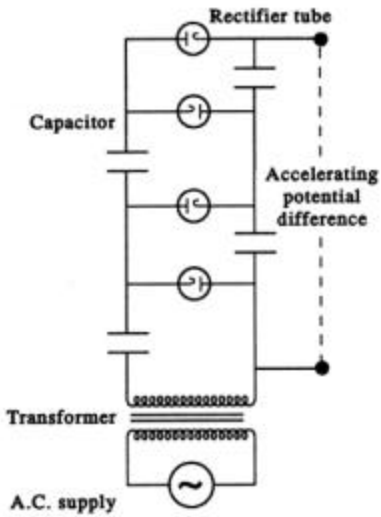

FIG. 8.4 Cockroft–Walton circuit.

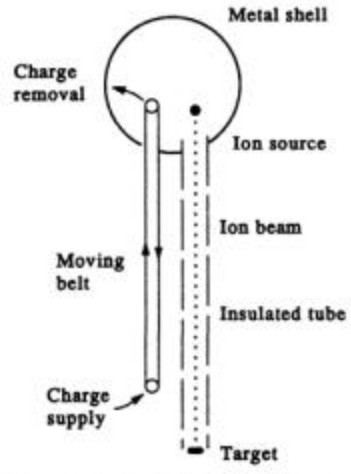

FIG. 8.5 Van de Graaff accelerator.

Linear Accelerator Center (SLAC) is two miles long. It produces electron and positron beams with energies up to 50 GeV (see References).

8.4 Cyclotron and Betatron

Successive electrical acceleration by electrodes and circular motion within a magnetic field are combined in the cyclotron, invented by Ernest O. Lawrence. As sketched in Fig. 8.7, ions such as protons, deuterons, or alpha particles are provided by a source at the center of a vacuum chamber located between the poles of a large electromagnet. Two hollow metal boxes called "dees" (in the shape of the letter D) are supplied with alternating voltages in correct frequency and opposite polarity. In the gap between dees, an ion gains energy as in the linear accelerator, then moves on a circle while inside the electric-field-free region, guided by the magnetic field. Each crossing of the gap with potential difference V gives impetus to the ion with an energy gain Ve, and the radius of motion increases according to $r = u/w$, where $w = eB/m$ is the angular speed. The unique feature of the cyclotron is that the time required for one complete revolution, $T = 2p/w$, is independent of the radius of motion of the ion. Thus it is possible to use a synchronized alternating potential of constant

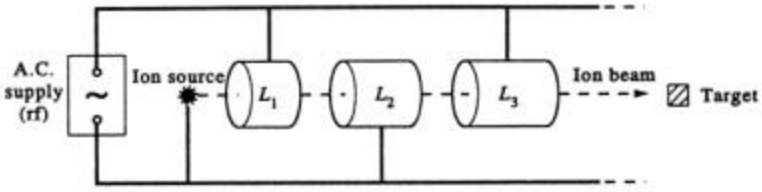

FIG. 8.6 Simple linear accelerator.

frequency n, angular frequency $w = 2pn$, to provide acceleration at the right instant.

For example, in a magnetic field B of 0.5 Wb/m^2 (tesla) the angular speed for deuterons of mass 3.3×10^{-27} kg and charge 1.6×10^{-19} coulombs is

$$w = \frac{eB}{m} = \frac{(1.6 \times 10^{-19})(0.5)}{3.3 \times 10^{-27}} = 2.4 \times 10^7 \text{ / s}$$

Equating this to the angular frequency for the power supply, $w = 2pn$, we find $n = (2.4 \times 10^7)/2p = 3.8 \times 10^6$ s^{-1}, which is in the radio-frequency range.

The path of ions is approximately a spiral. When the outermost radius is reached and the ions have full energy, a beam is extracted from the dees by special electric and magnetic fields, and allowed to strike a target, in which nuclear reactions take place.

Electrons are brought to high speeds in the induction accelerator or betatron. A changing magnetic flux provides an electric field and a force on the charges, while they are guided in a path of constant radius. Figure 8.8 shows the vacuum chamber in the form of a doughnut placed between specially shaped magnetic poles. The force on electrons of charge e is in the direction tangential to the orbit of radius r. The rate at which the average magnetic field within the loop changes is $\Delta B/\Delta t$, provided by varying the current in the coils of the electromagnet. The magnitude of the force is†

$$F = \frac{er}{2}\frac{\Delta B}{\Delta t}.$$

The charge continues to gain energy while remaining at the same radius if the magnetic field at that location is half the average field within the loop. The acceleration to energies in the million-electron-volt range takes place in the fraction of a second that it takes for the alternating magnetic current to go through a quarter-cycle.

The speeds reached in a betatron are high enough to require the use of relativistic formulas (Chapter 1). Let us find the mass m and speed u for an electron of kinetic energy $E_k = 1$ MeV. Rearranging the equation for kinetic energy, the ratio of m to the rest mass m_0 is

$$\frac{m}{m_0} = 1 + \frac{E_k}{m_0 c^2}.$$

† To show this, note that the area within the circular path is $A = p r^2$ and the magnetic flux is $F = BA$. According to Faraday's law of induction, if the flux changes by ΔF in a time Δt, a potential difference around a circuit of $V = \Delta F / \Delta t$ is produced. The corresponding electric field is $\boldsymbol{E} = V/2p r$, and the force is $e\boldsymbol{E}$. Combining, the relation quoted is obtained.

Recalling that the rest energy $E_0 = m_0c^2$ for an electron is 0.51 MeV, we find the ratio m/m_0=1 + 1/0.51 = 2.96. Solving Einstein's equation for the speed, $m/m_0 = 1/\sqrt{1-(u/c)^2}$, we find that $u = c\sqrt{1-(m_0/m)^2}$ = 0.94*c*. Thus the 1 MeV electron's speed is close to that of light, $c = 3.0 \times 10^8$ m/s, i.e., $u = 2.8 \times 10^8$ m/s. If instead we impart a kinetic energy of 100 MeV to an electron, its mass increases by a factor 297 and its speed becomes 0.999995c.

Calculations of this type are readily made by use of the computer program ALBERT, introduced in Section 1.7. Some other applications to ion motion in modern accelerators are found in Computer Exercises 8.A and 8.B.

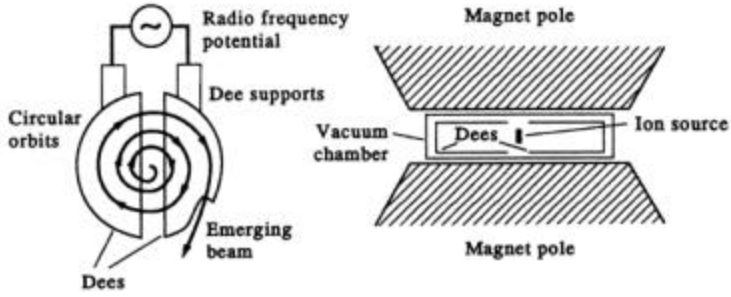

FIG. 8.7 Cyclotron.

8.5 Synchrotron and Collider

Over the past half-century, the science and engineering of accelerators has evolved dramatically, with ever-increasing beam currents and energy of the charged particles. A major step was the invention independently of the synchrotron by E. M. McMillan and V. I. Veksler. It consists of the periodic acceleration of the particles by radio-frequency electric fields, but with a time-varying magnetic field that keeps the charges on a circular path. Ions that are out of step are brought back into step; i.e., they are synchronized. Figure 8.9 shows schematically the Cosmotron, operated in the 1950s at Brookhaven National Laboratory. An ion source provides protons that are injected at 4 MeV into a vacuum chamber by a Van de Graaff accelerator. The inflector sends the charges into the magnet. There, the magnetic field rises to 1.4 tesla in one second to provide the constant radius condition $r = mu/eB$ as the protons gain energy. The field is shaped to assure proper focusing. The radiofrequency unit accelerates the particles with initial voltage 2000 V at frequency 2000 hertz. Ions at final energy 3 GeV strike an internal target to yield neutrons or mesons.

In a more modern version of synchrotron, the magnetic field that bends

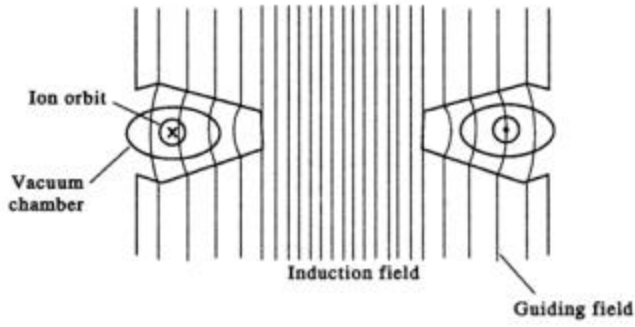

FIG. 8.8 Betatron.

the particles in a circular orbit is provided by a series of separate magnets, like beads on a necklace. In between the magnets are quadrupole (2N and 2S) magnets that provides beam focusing, helping compensate for space charge spreading.

Most of the early accelerators involved charge bombardment of a fixed target. Recently, much larger energies are achieved by causing two oppositely circulating beams to collide in what is called a storage ring. The pairs of particles used in a "collider" are (a) electrons and positrons or (b) protons and antiprotons or (c) protons and protons. The accelerating cavity of the electron-positron collider at the Thomas Jefferson Accelerator Laboratory is constructed of superconducting niobium to minimize energy losses. It provides a total energy of 4 GeV. The Large Electron Positron (LEP) collider at the European Laboratory for Particle Physics (CERN) gives particles of 110 GeV.

To reach high particle energies, a combination of accelerators of different types is used, as in the Tevatron at the Fermi National Accelerator Laboratory (Fermilab) near Chicago. The Tevatron involves a circular underground tunnel of diameter 3 m and length 6.3 km, containing the beam tube and a series of hundreds of magnets that provide ion bending. Negative hydrogen ions are first accelerated to 0.75 MeV by a Cockroft-Walton machine (Section 8.2) then raised to 200 MeV by a linear accelerator (Section 8.3). Electrons are stripped from the ions by a carbon foil, leaving protons. These are brought to 8 GeV by a small booster synchrotron. The ions are then injected into the Main Ring synchrotron and brought to 150 GeV. They are focused into short pulses and extracted to strike a copper target, creating large numbers of antiprotons. These are drawn off into a storage ring where they circulate and the beam is compressed, then transferred to an accumulator ring, and then put in the Tevatron ring. In the meanwhile a batch of protons from the Main Ring have also been put in the Tevatron ring. Along the path of that ring are 1000 superconducting magnets, using liquid nitrogen and helium for cooling. Finally, the two

countercurrent beams, of diameter about 0.1 mm, are accelerated to their peak energy of nearly 1 TeV. Detection of the byproducts of collisions is by the Collider Detector Fermilab (CDF), a complex particle tracking device. Extensive additional information with photographs is found in the Fermilab web page (see References).

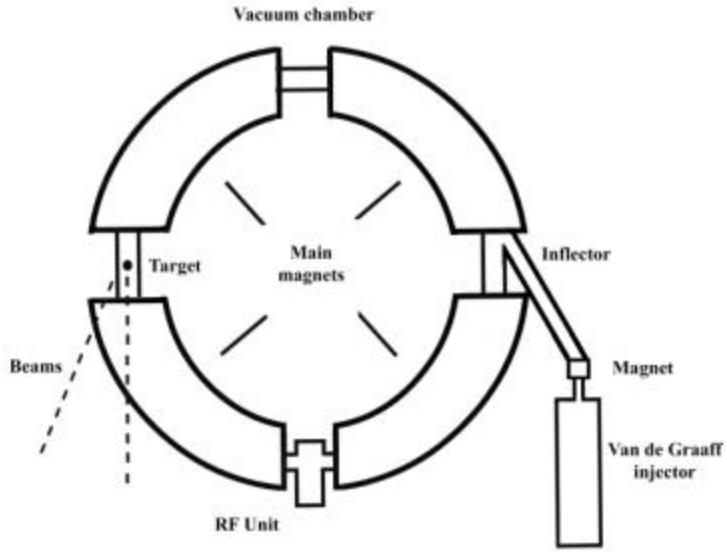

FIG. 8.9 Cosmotron. Synchrotron at Brookhaven National Laboratory.

Among the purposes of accelerators is the search for new particles in nature, which can be created only by transforming the energy of accelerated charges, in accord with Einstein's theory. Colliding high-energy beams of particles and antiparticles can create far more massive nuclear species than can simple ion bombardment of stationary targets. The reason is that a high-energy charge expends most of its energy in accelerating new particles to meet momentum conservation requirements. In contrast, when a particle collides with an antiparticle, the momentum is zero, allowing all of the energy to go into new mass.

One major accomplishment of high energy machines was the discovery of the "top" quark (see References). Its existence is crucial to the correctness of the theory called the Standard Model. According to that picture, matter is composed of leptons (electrons, neutrinos, etc.) and quarks (types "up," "down," "charm," "strange," "top," and "bottom"), along with their antiparticle forms. The up quark has a charge 2/3, the down quark -1/3. The proton is made of two ups and one down, while the neutron is two downs and one up. In the collision of protons and antiprotons, it is actually the component quarks that collide. Forces in nature are thought to be provided by the exchange of bosons, an example of which is the photon, for

electromagnetic force. There are three other forces–weak (involved in radioactivity), strong (for binding in nuclei), and gravity. The electromagnetic and weak forces are viewed as different aspects of a more general "electroweak" force. It is believed that the top quark existed in nature only in the first 10^{-16} second from the big bang that started the universe. Studies of collisions of high energy particles are intended to obtain information on the origin of mass, along with an answer why there is so much invisible mass in the universe. Also sought is a hypothetical heavy particle called the Higgs boson, which is thought to relate the vacuum of space to the existence of particles.

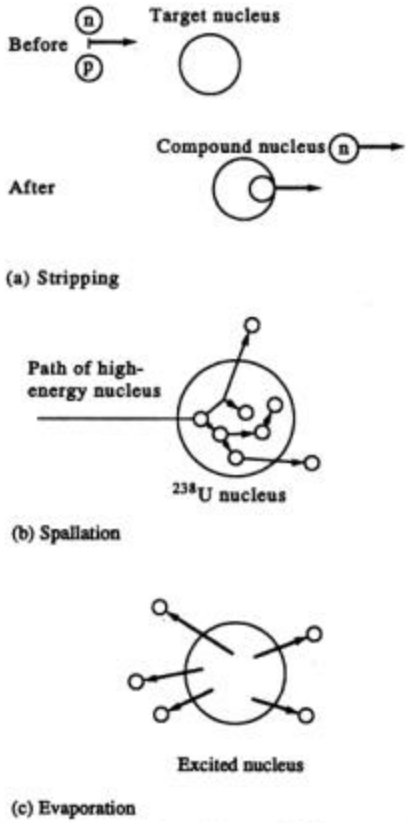

FIG. 8.10 Nuclear reactions produced by very high energy charged particles.

In the early 1990s the U.S. had started to build in Texas a large superconducting supercollider (SSC) to give a beam of 20 TeV, but the project was canceled by Congress because of excessive cost. With the demise of the SSC, a considerable part of high energy particle research by U.S. physicists was shifted to CERN, the European Laboratory for Particle Physics (see References). The U.S. Department of Energy allocated funds

to help construct the Large Hadron Collider (LHC) and the Atlas detector (see References) which will analyze the products of proton-proton collisions. The facilities are to be completed by 2005. The LHC will make use of the existing 27 km tunnel of LEP. By use of superconducting magnets and advanced accelerator technology it will be able to collide particles each of 7 TeV. Alternatively, it will handle beams of heavy ions such as lead with total energy 1250 TeV.

Two extensions of particle accelerators have opened up new opportunities for research and industrial applications. The first is synchrotron radiation (SR), based on the fact that if an electric charge is given an acceleration, it radiates light. At each of the bending magnets of a synchrotron or storage ring, experimental beams of X-rays are available. The beams are very narrow, with an angle given by E_0/E_k, the ratio of rest energy and kinetic energy. An example of an SR facility is the National Synchrotron Light Source at Brookhaven National Laboratory (see References). The second is free electron laser (FEL), in which electrons are brought to high speed in a linac and injected into a tube with magnets along its length. These provide an alternating field that accelerates the electrons to radiate photons. The light is reflected back and forth by mirrors at the ends of the tube and interacts with the circulating electrons rather than with atoms as in a conventional laser. FELs can produce frequencies ranging from infrared to gamma rays. A web page lists FELs around the world (see References).

8.6 Spallation

High-energy charged particles from an accelerator can disrupt nuclei of target materials. Experiments at California radiation laboratories showed that large neutron yields were achieved in targets bombarded by charged particles such as deuterons or protons of several hundred MeV energy. New dramatic nuclear reactions are involved. One is the stripping reaction, Fig. 8.10(a), in which a deuteron is broken into a proton and a neutron by the impact on a target nucleus. Another is the process of spallation in which a nucleus is broken into pieces by an energetic projectile. Figure 8.10(b) shows how a cascade of nucleons is produced by spallation. A third is "evaporation" in which neutrons fly out of a nucleus with some 100 MeV of internal excitation energy, see Fig. 8.10(c). The average energy of evaporation of neutrons is about 3 MeV. The excited nucleus may undergo fission, which releases neutrons, and further evaporation from the fission fragments can occur.

It has been predicted that as many as 50 neutrons can be produced by a single high-energy (500 MeV) deuteron. The large supply of neutrons can

be used for a number of purposes: (a) physics and chemistry research; (b) production of new nuclear fuel, beneficial radioisotopes, or weapons tritium; (c) burn unwanted plutonium or certain radioactive waste isotopes. Some of these applications will be discussed in later sections.

Plans have been developed for a Spallation Neutron Source (SNS) to be put into operation around the year 2005. Design and construction of the Department of Energy facility is a cooperative effort of five national laboratories (Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, and Oak Ridge). A large linear accelerator produces high speed protons to bombard a liquid mercury target. The particle energy is 1 GeV; the beam power is 1 MW; pulses are 17 ms apart. Neutrons are moderated by water and liquid hydrogen and a time-of-flight device selects neutrons of desired energy. The SNS would serve many hundreds of researchers in neutron science from the U.S. and abroad. Performance details are found in References.

8.7 Summary

Charged particles such as electrons and ions of light elements are brought to high speed and energy by particle accelerators, which employ electric and magnetic fields in various ways. In the high-voltage machines a beam of ions is accelerated directly through a large potential difference, produced by special voltage multiplier circuits or by carrying charge to a positive electrode; in the linear accelerator, ions are given successive accelerations in gaps between tubes lined up in a row; in the cyclotron, the ions are similarly accelerated but move in circular orbits because of the applied magnetic field; in the betatron, a changing magnetic field produces an electric field that accelerates electrons to relativistic speeds; in the synchrotron, both radiofrequency and time-varying magnetic field are used. High-energy nuclear physics research is carried out through the use of such accelerators. Through several spallation processes, high energy charged particles can produce large numbers of neutrons which have a variety of applications.

8.8 Exercises

8.1. Calculate the potential difference required to accelerate an electron to speed 2×10^5 m/s.

8.2. What is the proper frequency for a voltage supply to a linear accelerator if the speed of protons in a tube of 0.6 m length is 3×10^6 m/s?

8.3. Find the time for one revolution of a deuteron in a uniform magnetic field of 1 Wb/m^2.

8.4. Develop a working formula for the final energy of cyclotron ions of mass m, charge q, exit radius R, in a magnetic field B. (Use nonrelativistic energy relations.)

8.5. What magnetic field strength (Wb/m^2) is required to accelerate deuterons in a cyclotron of radius 2.5 m to energy 5 MeV?

8.6. Performance data on the Main Ring proton synchrotron of Fermilab at Batavia, Illinois (See References) were as follows:

Diameter of ring 2 km
Protons per pulse 6×10^{12}
Number of magnets 954
Initial proton energy 8 GeV
Final proton energy 400 GeV
Number of revolutions 200,000

(a) Find the proton energy gain per revolution.

(b) Find the speed of the protons at final energy using relativistic formulas of Sections 1.4 and 8.4 (or computer program ALBERT, see Chapter 1)

(c) Calculate the magnetic field at the final speed of the protons.

8.7. What is the factor by which the mass is increased and what fraction of the speed of light do protons of 200 billion-electron-volts have?

8.8. Calculate the steady deuteron beam current and the electric power required in a 500-GeV accelerator that produces 4 kg per day of plutonium-239. Assume a conservative 25 neutrons per deuteron.

8.9. Using the relativistic formulas from Section 1.4, show that for very large particle energies the fractional difference in speed from that of light, $f = (c\text{-}u)/c$, is accurately approximated by $f = (1/2)\,(m_0/m)^2$. Find f for 50 GeV electrons of rest energy 0.511 MeV.

8.10. The velocities of protons and antiprotons in the 2 km diameter Tevatron ring are practically the same as the velocity of light, 299792458 m/s. Find the time for particles of final energy 1 TeV to traverse the circumference. How much error is there in this approximation?

8.11. The synchrotron radiation loss in joules of a charge e with rest mass m_0 moving in a circle of radius R is given by Cohen (see References) as

$$\Delta E = e^2\, g\ (g^2 - 1)^{3/2}\, /(3 e_0\, R)$$

where $g = E/m_0c^2$, with $E = mc^2$ and $e_0 \cong 8.8542 \times 10^{-12}$ F/m. (a) Find an approximate formula for ΔE in keV for an electron as a function of energy in GeV and R in meters, when the speed is very close to the speed of light. (b) How much lower than the radiation from an electron is that from a proton of the same radius and energy? (c) Find a formula for the power radiated from an electron moving in a circle with speed much less than the speed of light, in terms of the acceleration.

Computer Exercises

8.A. Verify using computer program ALBERT (Chapter 1) that 1 TeV protons have a speed that appears to be the same as the velocity of light. Calculate the fractional difference between u and c using the formula derived in Ex. 8.9. Explain the discrepancy.

8.B. The electron-positron collider at Hamburg, Germany, produces 23 TeV particles.

(a) What is the ratio of the electron's total energy to its rest energy (0.510998902 MeV). Check the result using the computer program ALBERT (Chapter 1) by supplying a kinetic energy of 2.3D7 (a double precision number).

(b) If 23 TeV electrons could be induced to travel around the earth (radius 6378 km), how far behind a light beam would they arrive? See Ex. 8.9 for a useful formula.

8.9 References for Chapter 8

R. R. Wilson, "U.S. Particle Accelerators: An Historical Perspective," R. A. Carrigan, Jr., F. R. Huson, and M. Month, *The State of Particle Accelerators and High Energy Physics*, AIP Conference Proceedings No. 92, American Institute of Physics, New York, 1982.

Stanley Humphries, Jr., *Principles of Charged Particle Acceleration*, John Wiley & Sons, New York, 1986.

Waldemar H. Scharf, *Biomedical Particle Accelerators*, AIP Press, New York, 1994.

Stephen M. Shafroth and James C. Austin (Eds.), *Accelerator-Based Atomic Physics Techniques and Applications*, AIP Press, Woodbury, NY 1997.

Books on Accelerators
http://www.indiana.edu/~uspas/book.html
Lists of books by U.S. Particle Accelerator School

Stanford Linear Accelerator Center
http://www.slac.stanford.edu
Select Virtual Visitor Center

John R. Rees, "The Stanford Linear Collider," *Scientific American*, October 1990, p. 58.

Particle Physics Education Sites
http://ParticleAdventure.org/other/othersites.html
Links to many excellent web sites. Try especially
"The World of Beams": Good explanations and visual effects
"Probing Particles": Accelerators, forces, nuclear particles

R. R. Wilson, "The Batavia Accelerator," *Scientific American*, February 1974, p. 72. The forerunner of the Tevatron.

Leon M. Lederman, "The Tevatron," *Scientific American*, March 1991, page 48. Provides the history of the accelerator and its relationship to the SSC.

Fermi National Accelerator Laboratory Welcome Page
http://www.fnal.gov
Select The Laboratory; Particle Physics, Clickable Tour

The Discovery of the Top Quark
http://www.sciam.com/0997issue/0997tipton.html
Scientific American feature article by Tony M. Liss and Paul L. Tipton

Particle Accelerators Around the World
http://www-elsa.physik.uni-bonn.de/accelerator_list.html
Links to facilities sorted by location and by accelerator type

J. David Jackson, Maury Tigner, and Stanley Wojcicki, "The Superconducting Supercollider," *Scientific American*, March 1986, page 66. Discusses the reasons for the machine and describes it generally.

European Laboratory for Particle Physics (CERN)
http://www.cern.ch
Select: Scientific Programme; LHC Project

ATLAS
http://atlasinfo.cern.ch/Atlas/public/Welcome.html
Select: virtual tour

National Synchrotron Light Source
http://www.nsls.bnl.gov
Brookhaven National Laboratory

Arthur Bienenstock and Herman Winick, "Synchrotron Radiation," Sibyl P. Parker, Editor, *McGraw-Hill Encyclopedia of Physics*, New York, 1992

E. Richard Cohen, *The Physics Quick Reference Guide*, American Institute of Physics, Woodbury, NY 1995, p. 93.

WWW Virtual Library: Free Electron Laser
http://sbfel3.ucsb.edu/www/vl_fel.html
University of California at Santa Barbara

Spallation Neutron Source
http://www.ornl.gov/sns
Extensive information about features of the system and prospective applications

9

Isotope Separators

ALL OF our technology is based on materials in various forms–elements, compounds, alloys, and mixtures. Ordinary chemical and mechanical processes can be used to separate many materials into components. In the nuclear field, however, individual isotopes such as uranium-235 and hydrogen-2 (deuterium) are required. Since isotopes of a given element have the same atomic number Z, they are essentially identical chemically, and thus a physical method must be found that distinguishes among particles on the basis of mass number A. In this chapter we shall describe several methods by which isotopes of uranium and other elements are separated. Four methods that depend on differences in A are: (a) ion motion in a magnetic field, (b) diffusion of particles through a membrane, (c) motion with centrifugal force, and (d) atomic response to a laser beam. Calculations on the amounts of material that must be processed to obtain nuclear fuel will be presented, and estimates of costs will be given.

9.1 Mass Spectrograph

We recall from Chapter 8 that a particle of mass m, charge q, and speed u will move in a circular path of radius r if injected perpendicular to a magnetic field of strength B, according to the relation $r = mu/qB$. In the mass spectrograph (Fig. 9.1), ions of the element whose isotopes are to be separated are produced in an electrical discharge and accelerated through a potential difference V to provide a kinetic energy $\frac{1}{2}mu^2 = qV$. The charges move freely in a chamber maintained at very low gas pressure, guided in semicircular paths by the magnetic field. The heavier ions have a larger radius of motion than the light ions, and the two may be collected separately. It is found (see Exercise 9.1) that the distance between the points at which ions are collected is proportional to the difference in the square roots of the masses. The spectrograph can be used to measure masses with some accuracy, or to determine the relative abundance of isotopes in a sample, or to enrich an element in a certain desired isotope.

The electromagnetic process was used on uranium during World War II to obtain weapons material, using the "calutron" (after the University of California at Berkeley, where it was developed). A total of 1152 units in the "Alpha" and "Beta" processes were operated at the Y-12 Plant at Oak

Ridge, producing the enriched uranium for one atomic bomb by 1945. Since the cost of electrical power for the process is large, alternative processes such as gaseous diffusion and centrifuge are employed to produce reactor fuels. However, for over 50 years a few calutrons were maintained at Oak Ridge. These separated light stable isotopes in small quantities needed for research and for targets for accelerator-produced radioisotopes. In 1998 the system was shut down, possibly permanently (see References). It is notable that Iraq was developing its own electromagnetic process before the Gulf War (see References).

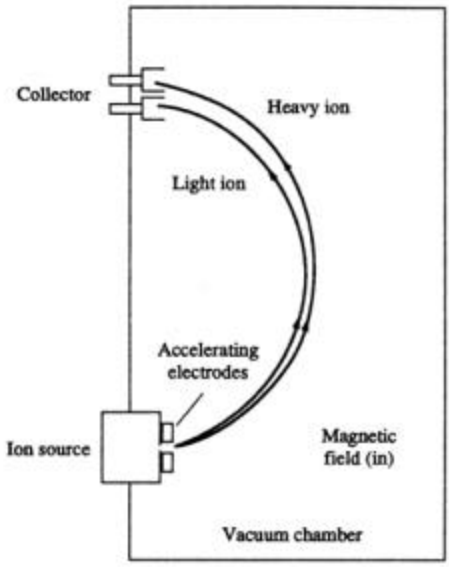

FIG. 9.1 Mass spectrograph.

9.2 Gaseous Diffusion Separator

The principle of this process can be illustrated by a simple experiment, Fig. 9.2. A container is divided into two parts by a porous membrane, and air is introduced on both sides. Recall that air is a mixture of 80% nitrogen, $A = 14$, and 20% oxygen, $A = 16$. If the pressure on one side is raised, the relative proportion of nitrogen on the other side increases. The separation effect can be explained on the basis of particle speeds. The average kinetic energies of the heavy (H) and light (L) molecules in the gas mixture are the same, $E_H = E_L$, but since the masses are different, the typical particle speed bear a ratio

$$\frac{u_L}{u_H} = \sqrt{\frac{m_H}{m_L}}\,.$$

Now the number of molecules of a given type that hit the membrane each second is proportional to nu in analogy to neutron motion discussed in Chapter 4. Those with higher speed thus have a higher probability of passing through the holes in the porous membrane, called the "barrier."

The physical arrangement of one processing unit of a gaseous diffusion plant for the separation of uranium isotopes U-235 and U-238 is shown in Fig. 9.3. A thin nickel alloy serves as the barrier material. In this "stage," gas in the form of the compound uranium hexafluoride (UF_6) is pumped in as feed and removed as two streams. One is enriched and one depleted in the compound $^{235}UF_6$, with corresponding changes in $^{238}UF_6$. Because of the very small mass difference of particles of molecular weight 349 and 352 the amount of separation is small and many stages in series are required in what is called a cascade.

Natural uranium has a small U-234 component, atom fraction 0.000055. For simplicity, we shall ignore its effect except for Exercise 9.11.

Any isotope separation process causes a change in the relative numbers of molecules of the two species. Let n_H and n_L be the number of molecules in a sample of gas. Their abundance ratio is defined as

$$R = \frac{n_L}{n_H}.$$

For example, in ordinary air $R = 80/20 = 4$.

The effectiveness of an isotope separation process is dependent on a quantity called the separation factor r. If we supply gas at one abundance ratio R, the ratio $R¢$ on the low-pressure side of the barrier is given by

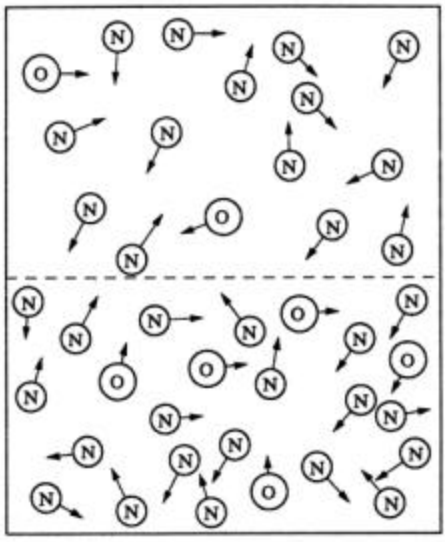

FIG. 9.2 Gaseous diffusion separation of nitrogen and oxygen.

$$R' = rR.$$

If only a very small amount of gas is allowed to diffuse through the barrier, the separation factor is given by $r = \sqrt{m_H / m_L}$, which for UF_6 is 1.0043. However, for a more practical case, in which half the gas goes through, the separation factor is smaller, 1.0030 (see Exercise 9.2). Let us calculate the effect of one stage on natural uranium, 0.711% by weight, corresponding to a U-235 atom fraction of 0.00720, and an abundance ratio of 0.00725. Now

$$R' = rR = (1.0030)\ (0.00725) = 0.00727.$$

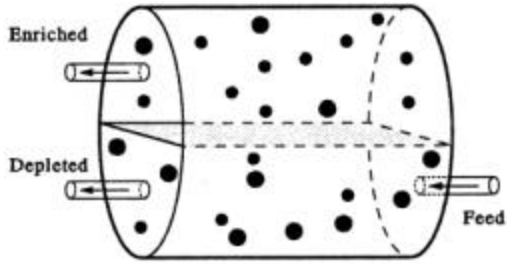

FIG. 9.3 Gaseous diffusion stage.

The amount of enrichment is very small. By processing the gas in a series of s stages, each one of which provides a factor r, the abundance ratio is increased by a factor r^s. If R_f and R_p refer to feed and product, respectively, $R_p = r^s R_f$. For $r = 1.0030$ we can easily show that 2375 enriching stages are needed to go from $R_f = 0.00725$ to highly enriched 90% U-235, i.e., $R_p = 0.9/(1–0.9) = 9$. Figure 9.4 shows the arrangement of several stages in an elementary cascade, and indicates the value of R at various points. The feed is natural uranium, the product is enriched in U-235, and the waste is depleted in U-235.

Figure 9.5 shows the gaseous diffusion uranium isotope separation plant at Portsmouth, OH. Such a facility is very expensive, of the order of a billion dollars, because of the size and number of components such as separators, pumps, valves, and controls, but the process is basically simple. The plant runs continuously with a small number of operating personnel. The principal operating cost is for the electrical power to provide the pressure differences and to perform work on the gas. The Portsmouth plant and another one at Paducah, KY are managed by the U.S. Enrichment Corp. (USEC), which is a business created by privatization of government-owned facilities (see References). USEC is participating in a program with Russia called “Megatons to Megawatts” involving dilution of highly enriched uranium to levels used in reactors.

The flow of UF_6 and thus uranium through individual stages or the whole plant can be analyzed by the use of material balances. One could

keep track of number of particles, or moles, or kilograms, since the flow is continuous. It will be convenient to use kilograms per day as the unit of uranium flow for three streams: feed (F), product (P), and waste (W), also called "tails." Then,

$$F = P + W.$$

Letting x stand for the U-235 weight fractions in the flows, the balance for the light isotope is

$$x_f F = x_p P + x_w W.$$

(A similar equation could be written for U-238, but it would contain no additional information.) The two equations can be solved to obtain the ratio of feed and product mass rates. Eliminating W,

$$\frac{F}{P} = \frac{x_p - x_w}{x_f - x_w}.$$

For example, let us find the required feed of natural uranium to obtain 1 kg/day of product containing 3% U-235 by weight. The abbreviation w/o is typically used for weight percent. Assume that the waste is at 0.3 w/o. Now

$$\frac{F}{P} = \frac{0.03 - 0.003}{0.00711 - 0.003} = 6.57$$

and thus the feed is 6.57 kg/day. We note that W is 5.57 kg/day, which shows that large amounts of depleted uranium tails must be stored for each kilogram of U-235 produced. The U-235 content of the tails is too low for use in conventional reactors, but the breeder reactor can convert the U-238

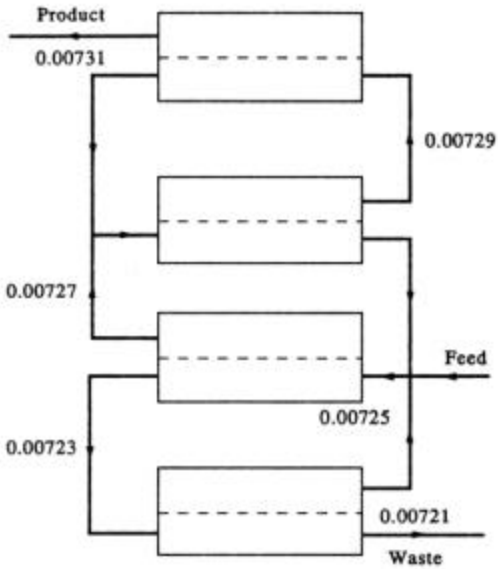

FIG. 9.4 Gaseous diffusion cascade.

FIG. 9.5 Gaseous diffusion plant at Portsmouth, OH (Courtesy U.S. Enrichment Corp.).

into plutonium, as will be discussed in Chapter 13.

The cost of enrichment is dependent in part on the energy expended, which is measured in "separative work units" (SWU, pronounced "swoo") with units in kilograms. The method of calculating SWU is reserved for Computer Exercise 9.A. By use of a program called ENRICH3, Table 9.1 was developed. The feed w/o was taken as 0.711, corresponding to an atom percent of 0.720.

TABLE 9.1
Nuclear Fuel Data

Weight percent U-235	Ratio of feed to product	Separative work units(SWU)
0.711	1.000	0
0.8	1.217	0.070
1.0	1.703	0.269
2.0	4.136	1.697
3.0	6.569	3.425
5.0	11.436	7.198
10.0	23.601	17.284
20.0	47.932	38.315
90.0	218.248	192.938

Let us use the table to find the amount of fuel needed and its cost to a utility. Assume that the fuel is to be enriched to 3 w/o. Thus each kg of fuel

contains 30 grams of U-235 and 970 grams of U-238. The natural uranium feed required for the isotope separation process is 6.569 kg or 14.48 lb. It is easy to show (Ex. 9.8) that the U weight fraction in the U_3O_8 that would contain it is 0.848. Thus our feed becomes 6.569/0.848 = 7.75 kg of the oxide, or 17.1 lb. At a typical price of $10/lb, the cost of uranium is $171.

In Column 3 of the table is found the SWU value of 3.425, and using a reasonable enrichment charge of $75/SWU, the cost is $257. Finally, there is a cost for chemical conversion of the uranium into the form used for enrichment, UF_6, of say $1.50/lb of contained U, giving an extra (14.48 lb) ($1.50/lb) = $22. The total, excluding fabrication and transportation, is thus $450/kg. To fuel a nuclear reactor rated at 1000 MWe, an electric utility may need about 60,000 lb/y, or 27,200 kg/y giving an annual fuel cost of $12.2 million. However, it can produce typically an average of 700 MW of electrical power over the 8760 hours per year, a total of 6.14×10^9 kWh. The basic fuel cost is thus 0.2 cents or 2 mills per kilowatt-hour.

The world picture on uranium enrichment has been changing in recent years, as more suppliers have appeared and U.S. utilities have diversified their sources. A large fraction of the natural uranium used in the U.S. comes from other countries such as Canada, Russia, and Australia. About half of the enrichment services are provided by USEC, with the remainder from abroad, e.g., Eurodif, Urenco, and Tenex. Details are found in DOE's Uranium Industry report (see References).

A factor that renders the future situation uncertain is the amount and speed of reduction in weapons-grade uranium in the stockpiles of the U.S. and the Commonwealth of Independent States (CIS). Conversion of highly-enriched uranium (HEU) into fuel suitable for reactor use as low-enrichment uranium (LEU) affects the supply situation significantly, including the mining and refining industries as well as the isotope separation process.

9.3 Gas Centrifuge

This device for separating isotopes, also called the ultra-centrifuge because of the very high speeds involved, has been known since the 1940s. It was tested and abandoned during World War II because materials that would withstand high rotation speeds were not available and existing bearings gave large power losses. Developments since have made centrifuges practical and economical. The centrifuge consists of a cylindrical chamber–the rotor–turning at very high speed in a vacuum as sketched in Fig. 9.6(a)).

The rotor is driven and supported magnetically. Gas is supplied and centrifugal force tends to compress it in the outer region, but thermal

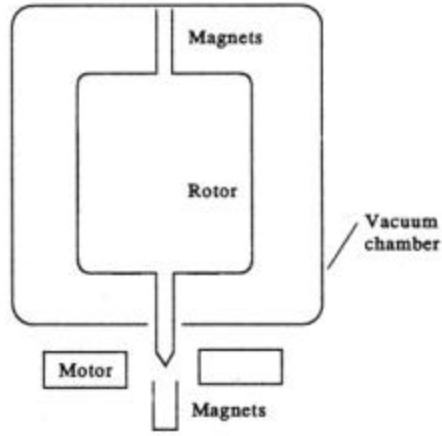

FIG. 9.6(a) Gas centrifuge.

agitation tends to redistribute the gas molecules throughout the whole volume. Light molecules are favored in this effect, and their concentration is higher near the center axis. By various means a countercurrent flow of UF_6 gas is established that tends to carry the heavy and light isotopes to opposite ends of the rotor. Depleted and enriched streams of gas are withdrawn by scoop pipes, as shown schematically in Fig. 9.6(b). More detailed diagrams are found in the References.

The theory of separation by centrifugal force starts with the formula for the gas density distribution in a gravitational field,

$$N = N_0 \exp(-mgh),$$

where the potential energy is mgh. Adapt the expression to a rotating gas, with kinetic energy at radius r being $\frac{1}{2}mu^2 = \frac{1}{2}mw^2r^2$, where w is the

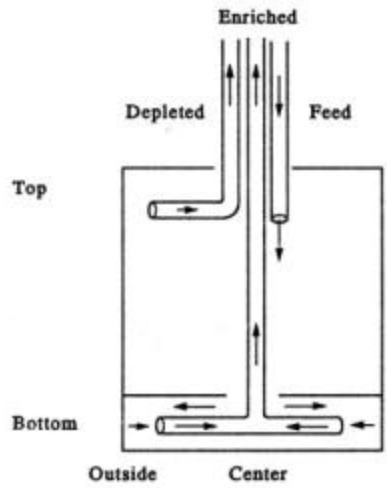

FIG. 9.6(b) Gas streams in centrifuge.

angular velocity, u/r. Apply to two gases of masses m_H and m_L to obtain the abundance ratio as a function of distance

$$R = R_0 \exp[(m_H - m_L)\, w^2\, r^2/(2kT)].$$

Note that separation depends on the difference in masses rather than on their square roots as for gaseous diffusion.

Separation factors of 1.1 or better were obtained with centrifuges about 30 cm long, rotating at a rate such that the rotor surface speed is 350 m/s. The flow rate per stage of a centrifuge is much lower than that of gaseous diffusion, requiring large numbers of units in parallel.

The electrical power consumption for a given capacity is lower, however, by a factor of 6 to 10, giving a lower operating cost. In addition, the capital cost of a centrifuge plant is lower than that of a gaseous diffusion plant. European countries have taken advantage of the lower costs of centrifuge separation to challenge the former U.S. monopoly on enrichment services. In fact, several American utilities buy fuel from Europe. Examples of facilities are the French Eurodif operated by Cogema and the three plants of Urenco, Ltd. at Capenhurst in the U.K., at Almelo in the Netherlands (see Fig. 9.7), and at Gronau in West Germany.

9.4 Laser Isotope Separation

A new and entirely different technique for separating uranium isotopes uses laser light (see Section 2.4) to selectively ionize uranium-235 atoms, which can be drawn away from uranium-238 atoms. Research and development on the process, called atomic vapor laser isotope separation (AVLIS), was done in a cooperative program between Lawrence Livermore National Laboratory and Oak Ridge National Laboratory.

An element such as uranium has a well-defined set of electron orbits, similar to those described in Section 2.3, but much more complex because there are 92 electrons. The difference in masses of the nuclei of uranium-235 and uranium-238 results in subtle differences in the electronic orbit structure and corresponding energies required to excite or ionize the two isotopes.

A laser can supply intense light of precise frequencies, and a fine-tuned laser beam can provide photons that ionize the U-235 and leave the U-238 unchanged. The ionization potential for U-235 is 6.1 volts. The method takes advantage of the intensity and unique frequency character of laser beams, to perform resonance stepwise excitation of an atom. In the AVLIS technique, three photons of around 2 eV achieve the ionization.

The virtue of the method is the almost-perfect selection of the desired isotope. Of 100,000 atoms ionized by a laser beam, all but 1 are U-235. This permits enrichment from 0.7% to 3% in a single stage rather than

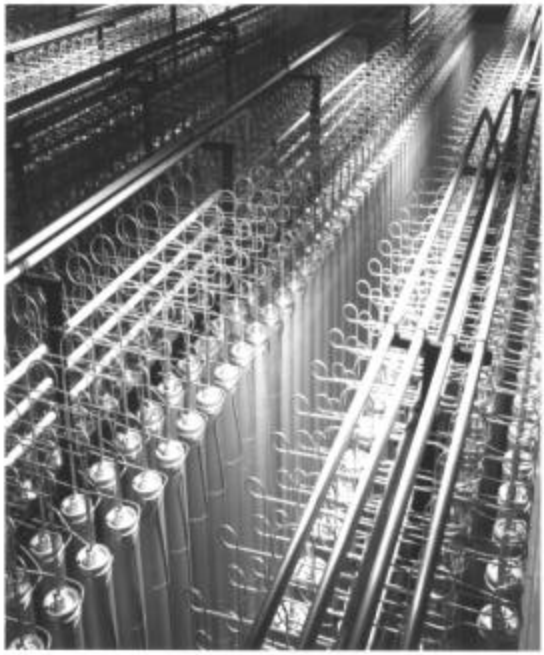

FIG. 9.7 One of the centrifuge enrichment halls of the plant at Almelo, The Netherlands. (Courtesy Urenco, Ltd.).

thousands as with gaseous diffusion. One kilogram of enriched product comes from 6 kg of natural uranium. The system sketched in Fig. 9.8 consists of several components. The first is the vaporizer, as a source of atoms, which are easier to ionize efficiently than the complex molecules. In an evacuated chamber, a stream of electrons impinges on a crucible of uranium, melting and vaporizing the metal. A high vaporization rate is achieved, even though the boiling point of uranium is 4000 K. The second is the laser light source, which involves two types of lasers. A pulsed electric current passes through a copper-vapor laser, with electric energy converted into light energy as in a fluorescent lightbulb. Its yellow-green light then energizes ("pumps") the second laser, in which a dye is dissolved in alcohol. The dye laser emits an orange-red light, which is amplified and adjusted in frequency. This laser's light irradiates the uranium vapor, and is absorbed by uranium-235 atoms, which are ionized in the three-step resonant process. It is necessary to isolate the uranium-235 ions immediately to prevent charge exchange with the unwanted uranium-238 atoms. An electric field is provided to draw the ions off to a product collector. There, the ions lose their charge and become atoms, to condense as liquid on the plates. The enriched uranium liquid is drawn off and either cast and stored as a solid or converted into uranium dioxide for use as reactor fuel. The uranium-238 atoms pass through the laser beam and

condense on the walls of the chamber, to be removed as low concentration tails.

The AVLIS was regarded as very promising, with the whole U.S. uranium separation of 5 million kg predicted to be possible with only 125 kW of laser power. However, in 1995 the laser separation technology was transferred to USEC, which concluded that the financial returns from the method would be inadequate, and in 1999 terminated the R&D program. USEC stated that alternatives such as centrifuges and the Silex process (an Australian laser method, see References) would be considered as replacements for gaseous diffusion.

Thanks are due James I. Davis of Lawrence Livermore National Laboratory and N. Haberman of the Department of Energy for some of the information in this section.

9.5 Separation of Deuterium

The heavy isotope of hydrogen ${}_1^2\mathrm{H}$, deuterium, has two principal nuclear applications: (a) as low-absorption moderator for reactors, especially those using natural uranium, and (b) as a reactant in the fusion process. The differences between the chemical properties of light water and heavy water are slight, but sufficient to permit separation of ${}_1^1\mathrm{H}$ and ${}_1^2\mathrm{H}$ by

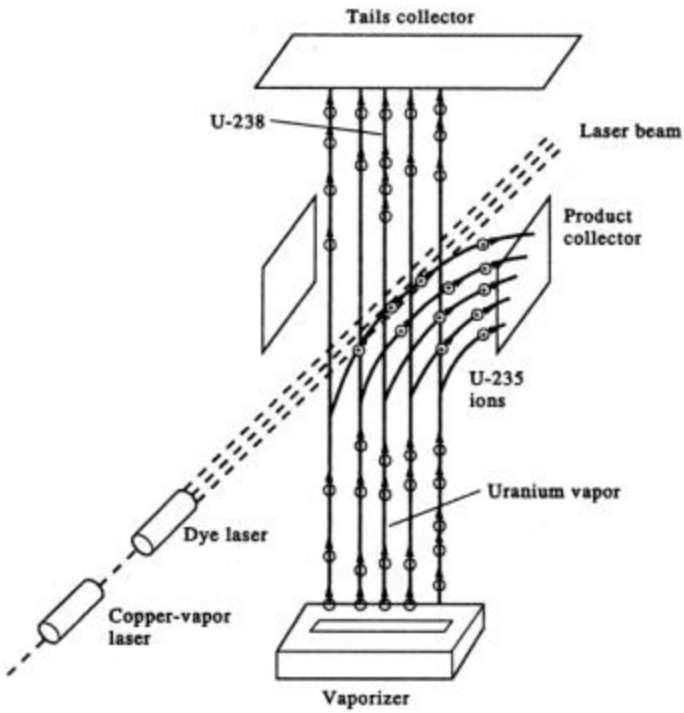

FIG. 9.8 Atomic vapor laser isotopic separation.

several methods. Among these are electrolysis, in which the H_2O tends to be more readily dissociated; fractional distillation, which takes advantage of the fact that D_2O has a boiling point about 1 degree C higher than that of H_2O; and catalytic exchange, involving the passage of HD gas through H_2O to produce HDO and light hydrogen gas.

9.6 Summary

The separation of isotopes requires a physical process that depends on mass. In the electromagnetic method, as used in a mass spectrograph, ions to be separated travel in circles of different radii. In the gaseous diffusion process, light molecules of a gas diffuse through a membrane more readily than do heavy molecules. The amount of enrichment in gaseous diffusion depends on the square root of the ratio of the masses and is small per stage, requiring a large number of stages. By the use of material balance equations, the amount of feed can be computed, and by the use of tables of separative work, costs of enriching uranium for reactor fuel can be found. An alternative separation device is the gas centrifuge, in which gases diffuse against the centrifugal forces produced by high speeds of rotation. Laser isotope separation involves the selective excitation of uranium atoms by lasers to produce chemical reactions. Several methods of separating deuterium from ordinary hydrogen are available.

9.7 Exercises

9.1. (a) Show that the radius of motion of an ion in a mass spectrograph is given by

$$r = \sqrt{\frac{2mV}{qB^2}}\,.$$

(b) If the masses of heavy (H) and light (L) ions are m_H and m_L, show that their separation at the plane of collection in a mass spectrograph is proportional to $\sqrt{m_H} - \sqrt{m_L}$.

9.2. The ideal separation factor for a gaseous diffusion stage is

$$r = 1 + 0.693\left(\sqrt{m_H / m_L} - 1\right).$$

Compute its value for $^{235}UF_6$ and $^{238}UF_6$, noting that $A = 19$ for fluorine.

9.3. (a) Verify that for particles of masses m_H and m_L the number fraction f_L of the light particle is related to the weight fractions w_H and w_L by

$$f_L = \frac{n_L}{n_L + n_H} = \frac{1}{1 + \dfrac{w_H m_L}{w_L m_H}}\,.$$

(b) Show that the abundance ratio of numbers of particles is either

$$R = \frac{n_L}{n_H} = \frac{f_L}{1 - f_L} \quad \text{or} \quad \frac{w_L / m_L}{w_H / m_H}.$$

(c) Calculate the number fraction and abundance ratio for uranium metal that is 3% U-235 by weight.

9.4. The total fuel loading of a new research reactor is 2000 kg of uranium at 20 w/o U-235. Using Table 9.1, find the amount of natural uranium feed and the SWUs required to fuel the reactor, assuming tails of 0.3 w/o.

9.5. A typical reactor using product uranium from an isotope separator at 3% enrichment burns 75% of the U-235 and 2.5% of the U-238. What percentage of the mined uranium is actually used for electrical power generation?

9.6. Find the amount of natural uranium feed (0.711% by weight) required to produce 1 kg/day of highly enriched uranium (90% by weight), if the waste concentration is 0.25% by weight. Assume that the uranium is in the form of UF_6.

9.7. How many enriching stages are required to produce uranium that is 3% by weight, using natural UF_6 feed? Let the waste be 0.2%.

9.8. Using atomic weights of uranium and oxygen in the Appendix, verify that the weight fraction of U in U_3O_8 is 0.848.

9.9. The number density of molecules as the result of loss through a barrier can be expressed as $n = n_0 \exp(-cu\ t)$ where c is a constant, u is the particle speed, and n_0 and n are values before and after an elapsed time t. If half the heavy isotope is allowed to pass through, find the abundance ratio $R'/R = r$ in the enriched gas as a function of the ratio of molecular masses. Test the derived formula for the separation of uranium isotopes.

9.10. Depleted uranium (0.3% U-235) is processed by laser separation to yield natural uranium (0.711%). If the feed rate is 1 kg/day and all of the U-235 goes into the product, what amounts of product and waste are produced per day?

9.11. Using natural uranium atom percents 99.2745 for U-238, 0.7200 for U-235, and 0.0055 for U-234, and atomic masses given in the Appendix, calculate the atomic mass of natural U and the weight percents of each isotope. Suggestion: make a table of numbers.

9.12. A utility plans to increase the enrichment of its nuclear fuel from 3 w/o to 5 w/o, achieving an increase in capacity factor from 0.70 to 0.80 as the result of longer operating cycles. Estimate costs in the two cases and determine if there is a net financial gain or loss, assuming that electricity is worth around 20 mills/kWh.

9.13. A certain country covertly builds production mass spectrographs to separate uranium isotopes. The objective is to obtain 50 kg of highly enriched uranium for a nuclear weapon, in one year of continuous operation. (a) Assuming optimistically that separation is perfect, what current of U^+ ions would be required? (b) Neglecting power needed for heating and magnets, what amount of electrical power at 50 kV is required? (c) Would the power source be difficult to conceal?

9.14. (a) Calculate the centrifugal acceleration $a = u^2/r$ in a centrifuge at radius $r = 0.1$ m with an angular speed of 5000 radians/second. By what factor is that larger than the acceleration of gravity 9.8 m/s^2? (b) Find the ratio R/R_0 for UF_6 of molecular weights 349 and 352 at 330 K, recalling $k = 1.38 \times 10^{-23}$ J/K and the mass of 1 amu $= 1.66 \times 10^{-27}$ kg.

Computer Exercises

9.A. The tails concentration of a gaseous diffusion separation process is typically 0.3 w/o. For a fixed product, e.g., 1 kg of 3 w/o fuel, study the variation of feed plus enrichment cost with the tails concentration, using (a) computer program ENRICH3 and some hand calculations, or (b) by adapting ENRICH3 to calculate costs.

9.B. Adapt computer program ENRICH3 to calculate costs as well as flows and SWU. Then, find the cost per gram of U-235 and cost per kilogram of U in product of 3 w/o, 20 w/o, and 90 w/o. Keep a constant tails assay of 0.3 w/o.

9.8 References for Chapter 9

Smyth Report on Separation of Uranium Isotopes (1945)
http://www.fas.org/nuke/hew/Smyth
Reproduction of Chapters IX-XI by Federation of American Scientists

Stelio Villani, *Isotope Separation*, American Nuclear Society, La Grange Park, IL, 1976. A monograph that describes most of the techniques for separating isotopes, including theory, equipment, and data.

Uranium Enrichment
http://www.uic.com.au/nip33.htm
Facts and figures in a briefing paper by Uranium Information Centre (Australia)

Calutrons at Oak Ridge
http://www.ornl.gov/publications/labnotes/feb95/calutron.html
Resumption of operation in 1995
http://www.ornl.gov/reporter/no1/calutron.htm
Shutdown in 1998

Iraq's quest for nuclear weapons
http://www.fas.org
Select Iraq Crisis/Iraqi Special Weapons Programs/Nuclear Programs. By Federation of American Scientists.

United States Enrichment Corporation
http://www.usec.com
Search using keywords Uranium Enrichment, AVLIS, Megatons to Megawatts, and Silex.

Donald R. Olander, "The Gas Centrifuge," *Scientific American*, August 1978, p. 37.

D. G. Avery and E. Davies, *Uranium Enrichment by Gas Centrifuge*, Mills & Boon Ltd. London, 1973. Brief discussion of concept with theory of operation.

Urenco
http://www.urenco.com/home.htm
Click on Group. Diagrams and facts from a European company.

Richard N. Zare, "Laser Separation of Isotopes," *Scientific American*, February 1977, p. 86.

Silex Systems, Ltd.
http://www.silex.com.au/overview/index.html
Select Overview. General discussion of a proprietary laser method. Click on Important Notice for a disclaimer

Jeff W. Eerkens, Editor, *Selected Papers on Laser Isotope Separation-Science and Technology*, SPIE Optical Engineering Press, Bellingham, WA, 1995. Papers on AVLIS, MOLIS (molecular laser isotope separation), CRISLA (chemical reaction by isotope selective laser activation), and others. A comprehensive review of all the methods by a researcher on laser technique.

Allen S. Krass, Peter Boskma, Boelie Elzen, and Wim A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation*, International Publication Service, Taylor & Francis, New York, 1983. A report by the Stockholm International Peace Research Institute (SIPRI).

Uranium Industry Annual 1998
http://www.eia.doe.gov/cneaf/nuclear/uia/contents.html#pre
Data on raw material, enrichment, and usage

10

Radiation Detectors†

MEASUREMENT OF radiation is required in all facets of nuclear energy–in scientific studies, in the operation of reactors for the production of electric power, and for protection from radiation hazard. Detectors are used to identify the radioactive products of nuclear reactions and to measure neutron flux. They determine the amount of radioisotopes in the air we breathe and the water we drink, or the uptake of a sample of radioactive material administered to the human body for diagnosis.

The kind of detector employed depends on the particles to be observed–electrons, gamma rays, neutrons, ions such as fission fragments, or combinations. It depends on the energy of the particles. It also depends on the radiation environment in which the detector is to be used–at one end of the scale is a minute trace of a radioactive material and at the other a source of large radiation exposure. The type of measuring device, as in all applications, is chosen for the intended purpose and the accuracy desired.

The demands on the detector are related to what it is we wish to know: (a) whether there is a radiation field present; (b) the number of nuclear particles that strike a surface per second or some other specified period of time; (c) the type of particles present, and if there are several types, the relative number of each; (d) the energy of the individual particles; and (e) the instant a particle arrives at the detector. From the measurement of radiation we can deduce properties of the radiation such as ability to penetrate matter and to produce ionization. We can also determine properties of a radioactive source, including disintegration rate, half-life, and amount of material.

In this chapter we describe the important features of a few popular types of detectors. Most of them are based on the ionization produced by incoming radiation. The detector may operate in one of two modes: (a) current, in which an average electrical flow is measured, as with an ammeter; and (b) pulse, in which the electrical signals produced by individual particles or rays are amplified and counted. A detector operating in this mode is known as a *counter*.

Since none of the five human senses will measure nuclear radiation, a

† Suggestions by Glenn F. Knoll are recognized with appreciation.

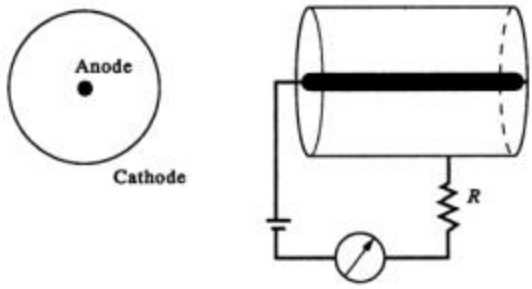

FIG. 10.1 Basic detector.

detector serves us as a "sixth sense." A detector also makes it possible to reveal the existence of amounts of material much smaller than can be found by ordinary chemical tests.

10.1 Gas Counters

Picture a gas-filled chamber with a central electrode (*anode*, electrically positive) and a conducting wall (*cathode*, negative). They are maintained at different potential, as shown in Fig. 10.1. If a charged particle or gamma ray is allowed to enter the chamber, it may produce a certain amount of ionization in the gas. The resultant positive ions and electrons are attracted toward the negative and positive surfaces, respectively. A charge moves in the local field $\mathscr{E}$ with a drift velocity $u_D = m\mathscr{E}$, where the mobility m depends on the time between collisions and the mean free path (see Section 4.6). If a magnetic field is present, charges tend to execute circular paths interrupted by collisions. When the voltage across the tube is low, the charges merely migrate through the gas, they are collected, and a current of short duration (a pulse) passes through the resistor and the meter. More generally, amplifying circuits are required. The number of current pulses is a measure of the number of incident particles that enter the detector, which is designated as an *ionization chamber* when operated in this mode.

If the voltage is then increased sufficiently, electrons produced by the incident radiation through ionization are able to gain enough speed to cause further ionization in the gas. Most of this action occurs near the central electrode, where the electric field is highest. The current pulses are much larger than in the ionization chamber because of the amplification effect. The current is proportional to the original number of electrons produced by the incoming radiation, and the detector is now called a *proportional counter*. One may distinguish between the passage of beta particles and alpha particles, which have widely different ability to ionize. The time for collection is very short, of the order of microseconds.

If the voltage on the tube is raised still higher, a particle or ray of any

energy will set off a discharge, in which the secondary charges are so great in number that they dominate the process. The discharge stops of its own accord because of the generation near the anode of positive ions, which reduce the electric field there to such an extent that electrons are not able to cause further ionization. The current pulses are then of the same size, regardless of the event that initiated them. In this mode of operation, the detector is called a *Geiger-Müller* (GM) counter. Unlike the proportional counter, the magnitude of the pulses produced by a GM counter is independent of the original number of electrons released by the ionizing radiation. Therefore the counter provides no information about the type or energy of the radiation. There is a short period, the *dead time*, in which the detector will not count other incoming radiation. If the radiation level is very high, a correction of the observed counts to yield the "true" counts must be made, to account for the dead time. In some gases, such as argon, there is a tendency for the electric discharge to be sustained, and it is necessary to include a small amount of foreign gas or vapor, e.g., alcohol, to "quench" the discharge. The added molecules affect the production of photons and resultant ionization by them.

A qualitative distinction between the above three types of counters is displayed graphically in Fig. 10.2, which is a semilog plot of the charge collected as a function of voltage. We note that the current varies over several orders of magnitude.

10.2 Neutron Detectors

In order to detect neutrons, which do not create ionization directly, it is necessary to provide a means for generating the charges that can ionize a gas. Advantage is taken of the nuclear reaction involving neutron absorption in boron

$$ {}^{1}_{0}\mathrm{n} + {}^{10}_{5}\mathrm{B} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{7}_{3}\mathrm{Li}\,, $$

where the helium and lithium atoms are released as ions. One form of *boron counter* is filled with the gas boron trifluoride (BF_3), and operated as an ionization chamber or a proportional counter. It is especially useful for the detection of thermal neutrons since the cross section of boron-10 at 0.0253 eV is large, 3840 barns, as noted in Chapter 4. Most of the 2.8 MeV energy release goes to the kinetic energy of the product nuclei. The reaction rate of neutrons with the boron in BF_3 gas is independent of the neutron speed, as can be seen by forming the product $R = nuN\sigma_a$, where σ_a varies as $1/u$. The detector thus measures the number density n of an incident neutron beam rather than the flux. Alternatively, the metal electrodes of a counter may be coated with a layer of boron that is thin enough to allow the alpha particles to escape into the gas. The counting rate in a boron-lined chamber depends

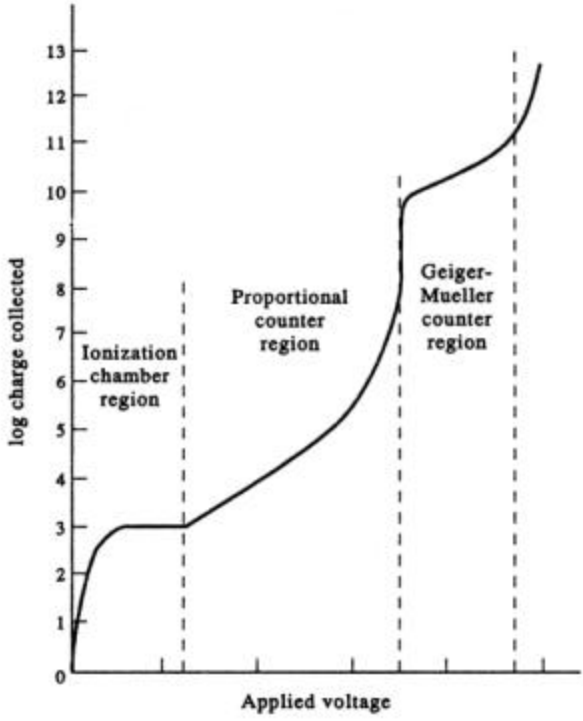

FIG. 10.2 Collection of charge in counters.

on the surface area exposed to the neutron flux.

The *fission chamber* is often used for slow neutron detection. A thin layer of U-235, with high thermal neutron cross section, 681 barns, is deposited on the cathode of the chamber. Energetic fission fragments produced by neutron absorption traverse the detector and give the necessary ionization. Uranium-238 is avoided because it is not fissile with slow neutrons and because of its stopping effect on fragments from U-235 fission.

Neutrons in the thermal range can be detected by the radioactivity induced in a substance in the form of small foil or thin wire. Examples are manganese $^{55}_{25}\mathrm{Mn}$, with a 13.3 barn cross section at 2200 m/s, which becomes $^{56}_{25}\mathrm{Mn}$ with half-life 2.58 h; and dysprosium $^{164}_{66}\mathrm{Dy}$, 1.7×10^3 barns, becoming $^{165}_{66}\mathrm{Dy}$, half-life 2.33 h. For detection of neutrons slightly above thermal energy, materials with a high resonance cross section are used, e.g., indium, with a peak at 1.45 eV. To separate the effects of thermal neutron capture and resonance capture, comparisons are made between measurements made with thin foils of indium and those of indium covered with cadmium. The latter screens out low-energy neutrons (below 0.5 eV) and passes those of higher energy.

For the detection of fast neutrons, up in the MeV range, the *proton recoil*

method is used. We recall from Chapter 4 that the scattering of a neutron by hydrogen results in an energy loss, which is an energy gain for the proton. Thus a hydrogenous material such as methane (CH_4) or H_2 itself may serve as the counter gas. The energetic protons play the same role as did α particles and fission fragments in the counters discussed previously. Nuclear reactions such as ${}^{3}_{2}\mathrm{He}(\mathrm{n},\mathrm{p}){}^{3}_{1}\mathrm{H}$ can also be employed to obtain detectable charged particles.

10.3 Scintillation Counters

The name of this detector comes from the fact that the interaction of a particle with some materials gives rise to a scintillation or flash of light. The basic phenomenon is familiar–many substances can be stimulated to glow visibly on exposure to ultraviolet light, and the images on a color television screen are the result of electron bombardment. Molecules of materials classed as phosphors are excited by radiation such as charged particles and subsequently emit pulses of light. The substances used in the scintillation detector are inorganic, e.g., sodium iodide or lithium iodide, or organic, in one of various forms–crystalline, plastic, liquid, or gas.

The amount of light released when a particle strikes a phosphor is often proportional to the energy deposited, and thus makes the detector especially useful for the determination of particle energies. Since charged particles have a short range, most of their energy appears in the substance. Gamma rays also give rise to an energy deposition through electron recoil in both the photoelectric effect and Compton scattering, and through the pair production-annihilation process. A schematic diagram of a detector system is shown in Fig. 10.3. Some of the light released in the phosphor is collected in the photomultiplier tube, which consists of a set of electrodes with photosensitive surfaces. When a photon strikes the surface, an electron is emitted by the photoelectric effect, it is accelerated to the next surface where it dislodges more electrons, and so on, and a multiplication of current is achieved. An amplifier then increases the electrical signal to a level convenient for counting or recording.

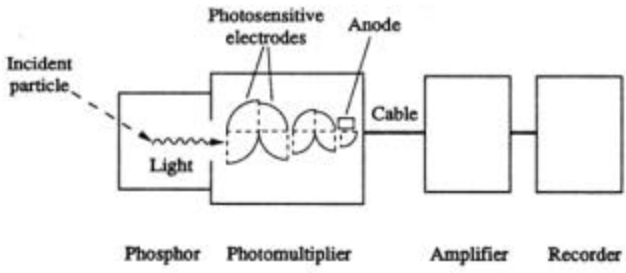

FIG. 10.3 Scintillation detection system.

Radiation workers are required to wear personal detectors called dosimeters in order to determine the amount of exposure to X- or gamma rays or neutrons. Among the most reliable and accurate types is the thermoluminescent dosimeter (TLD), which measures the energy of radiation absorbed. It contains crystalline materials such as CaF_2 or LiF which store energy in excited states of the lattice called traps. When the substance is heated, it releases light in a typical glow curve as shown in Fig. 10.4. The dosimeter consists of a small vacuum tube with a coated cylinder that can be heated by a built-in filament when the tube is plugged into a voltage supply. A photomultiplier reads the peak of the glow curve and gives values of the accumulated energy absorbed, i.e., the dose. The device is linear in its response over a very wide range of exposures; it can be used over and over with little change in behavior.

10.4 Solid State Detectors

The use of a solid rather than a gas in a detector has the advantage of compactness, due to the short range of charged particles. Also, when the solid is a semiconductor, great accuracy in measurement of energy and arrival time is possible. The mechanism of ion motion in a solid detector is unique. Visualize a crystal semiconductor, such as silicon or germanium, as a regular array of fixed atoms with their complement of electrons. An incident charged particle can dislodge an electron and cause it to leave the vicinity, which leaves a vacancy or "hole" that acts effectively as a positive charge. The electron-hole pair produced is analogous to negative and

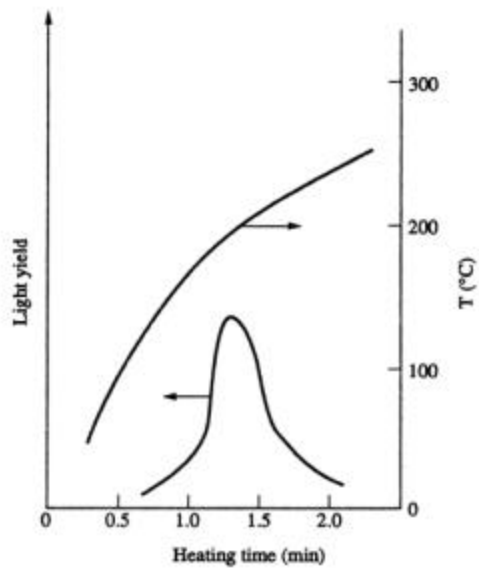

FIG. 10.4 Glow curve of the phosphor CaF_2.

positive ions in a gas. Electrons can migrate through the material or be carried along by an electric field, while the holes "move" as electrons are successively exchanged with neighboring atoms. Thus, electrons and holes are negative and positive charge carriers, respectively.

The electrical conductivity of a semiconductor is very sensitive to the presence of certain impurities. Consider silicon, chemical valence 4 (with 4 electrons in the outer shell). Introduction of a small amount of valence 5 material such as phosphorus or arsenic gives an excess of negative carriers, and the new material is called n-type silicon. If instead a valence 3 material such as boron or gallium is added, there is an excess of positive carriers, and the substance is called p-type silicon. When two layers of n-type and p-type materials are put in contact and a voltage is applied, as in Fig. 10.5, electrons are drawn one way and holes the other, leaving a neutral or "depleted" region. Most of the voltage drop occurs over that zone, which is very sensitive to radiation. An incident particle creates electron-hole pairs which are swept out by the internal electric field to register as a current pulse. High accuracy in measurement by an n-p junction comes from the fact that a low energy is needed to create an electron-hole pair (only 3 eV vs. 32 eV for an ion pair in a gas). Thus a 100 keV photon creates a very large number of pairs, giving high statistical accuracy. The collection time is very short, about a billionth of a second, allowing precise time measurements.

One way to produce a semiconductor detector with a large active volume is to introduce lithium on one surface of a heated crystal and apply an electric field. This "drifts" the Li through the volume which compensates residual p-type impurities. This detector must be kept permanently at liquid nitrogen temperature (–195.8°C), to prevent redistribution of the lithium. A preferable detector for many applications is made of an ultra-high-purity germanium, with impurity atoms reduced to 1 in about 10^{12}. A simple diode arrangement gives depletion depths of several centimeters. Such detectors still require liquid N_2 for operation, but they can be stored at room temperature.

10.5 Statistics of Counting

The measurement of radiation has some degree of uncertainty because the basic processes such as radioactive decay are random in nature. From the radioactive decay law, Section 3.2, we can say that *on the average* in a time interval t a given atom in a large collection of atoms has a chance $\exp(-\lambda t)$ of not decaying, and thus it has a chance $1 - \exp(-\lambda t)$ of decaying. Because of the statistical nature of radioactivity, however, more or less than these numbers will actually be observed in a certain time interval. There is

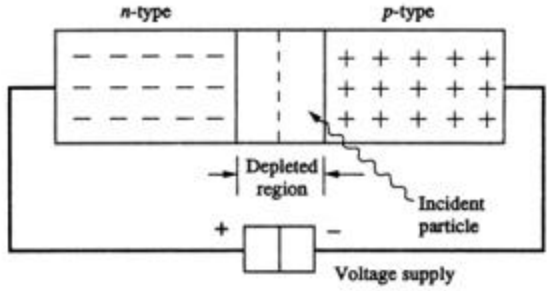

FIG. 10.5 Solid-state *n-p* junction detector.

actually a small probability that either none or all would decay. In a series of identical measurements there will be a spread in the number of counts. Statistical methods may be applied to the data to estimate the degree of uncertainty or "error." The laws of probability may be applied. As discussed in texts on statistics and radiation detection (see References), the most rigorous expression is the binomial distribution (see Exercise 10.6), which must be used to interpret the decay of isotopes of very short half-life. A simple approximation to it is the Poisson distribution (see Exercise 10.7), required for the study of low-level environmental radioactivity. A further approximation is the widely used normal or Gaussian distribution, shown in Fig. 10.6. Measured values of the number of counts x in repeated trials tend to fit the formula,

$$P(x) = \left(1/\sqrt{2p\bar{x}}\right)\exp\left(-\left(x-\bar{x}\right)^2/\left(2\bar{x}\right)\right)$$

where $P(x)$ is the probability of being in a unit range at x and $\bar{x}$ is the mean value of the counts. A measure of the width of the curve is the standard deviation, s. For this function†, $s = \sqrt{\bar{x}}$. The area under the curve between $\bar{x} + s$ and $\bar{x} - s$ is 68% of the total, which indicates that the chance is 0.68 that a given measurement will lie in that range. The figure for 95% is $\pm 2s$. It can be shown that the fractional error in count rate is inversely proportional to the square root of the total number of counts.

Since the calculation for plotting of the above statistical distribution is quite tedious, we have provided the computer program STAT, the use of which is described in Computer Exercises 10.A-10.D. Also, program EXPOIS generates simulated counting data for study using the Poisson distribution.

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† In general, for a series of trials, 1,2, 3 ,. . ., N, if count rates are x_i and the average is $\bar{x}$, the standard deviation is

$$s = \sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2/(N-1)}$$

10.6 Pulse Height Analysis

The determination of the energy distribution of nuclear particles and rays is important for identifying radioactive species. If an incoming particle deposits all of its energy in the detector, the resulting voltage signal in the external electric circuit of Fig. 10.7(a) can be used as a measure of particle energy. The particle ionizes the medium, a charge Q is produced, and a current flows, giving a time-varying voltage. If the time constant $t = RC$ of the circuit is short compared with the collection time, the voltage rises and drops to zero quickly, as in Fig. 10.7(b). If t is large, however, the voltage rises to a peak value $V_m = Q/C$, where C is the capacitance, and then because of the circuit characteristics declines slowly, as in Fig. 10.7(c). The particle energy, proportional to charge, is thus obtained by a voltage measurement.

Suppose that there are two types of particle entering the detector, say alpha particles of 4 MeV and beta particles of 1 MeV. By application of a voltage bias, the pulses caused by beta particles can be eliminated, and the remaining counts represent the number of alpha particles. The circuit that performs that separation is called a *discriminator*.

The radiation from a given source will have some variation in particle energy and thus a series of pulses due to successive particles will have a variety of heights. To find the energy distribution, a *single-channel analyzer* can be used. This consists of two adjustable discriminators and a circuit that passes pulses within a range of energy. The *multichannel analyzer* is a much more efficient and accurate device for evaluating an entire energy spectrum in a short time. Successive pulses are manipulated electronically

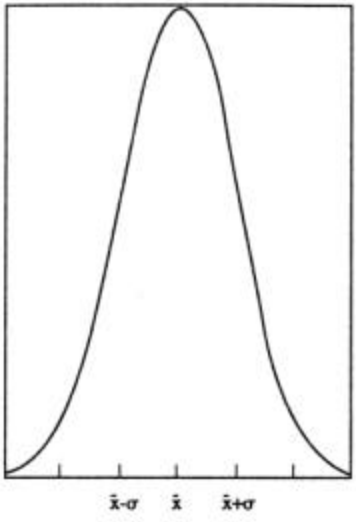
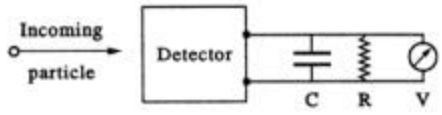
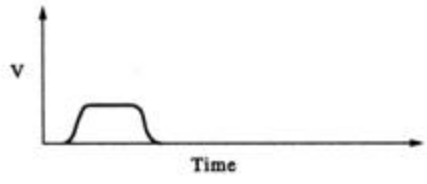


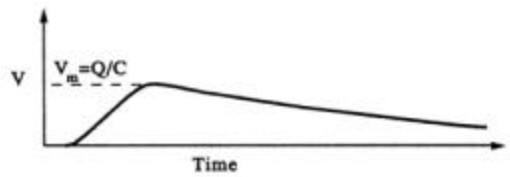
FIG. 10.6 Gaussian distribution. The area between the limits $x \pm \sigma$ is 68% of the total.



(a) Detector and electronic circuit



(b) Voltage variation with short time constant



(c) Voltage variation with long time constant

FIG. 10.7 Effect of circuit on pulse (after Knoll, see References).

and the signals stored in computer memory according to energy. The data are displayed on an oscilloscope screen or are printed out.

10.7 Advanced Detectors

A number of specialized instruments have been developed in addition to basic detectors. They are used for precise measurements of the products of high-energy nuclear collisions. Examples are :

(a) nuclear emulsion track detectors, originally used for cosmic ray studies. By application of the energy loss formula (see Section 5.2) information is obtained on particle energy, mass, and charge. Special etching techniques are used and the counting of tracks with a microscope is automated.

(b) Cerenkov counters, which measure the light produced when a particle has a speed higher than that of light in the medium. Cerenkov radiation gives the "blue glow" seen near a pool reactor core.

(c) hadron calorimeters, which measure showers of hadrons (mesons and nucleons), protons, and neutrons, produced by bombardment of materials of particles in the GeV range.

(d) neutrino detectors, consisting of large volumes of liquid or metal in

which the rare collisions resulting in a scintillation occur.

These specialized devices are discussed in the book by Kleinknecht (see References).

10.8 Summary

The detection of radiation and the measurement of its properties is required in all aspects of the nuclear field. In gas counters, the ionization produced by incoming radiation is collected. Dependent on the voltage between electrodes, counters detect all particles or distinguish between types of particles. Neutrons are detected indirectly by the products of nuclear reactions—for slow neutrons by absorption in boron or uranium-235, for fast neutrons by scattering in hydrogen. Scintillation counters release measurable light upon bombardment by charged particles or gamma rays. Solid-state detectors generate a signal from the motion of electron-hole pairs created by ionizing radiation. Pulse-height analysis yields energy distributions of particles. Statistical methods are employed to estimate the uncertainty in measured counting rates. Advanced specialized detectors are used in high-energy physics research.

10.9 Exercises

10.1. (a) Find the number density of molecules of BF_3 in a detector of 2.54 cm diameter to be sure that 90% of the thermal neutrons incident along a diameter are caught (s_a for natural boron is 760 barns).

(b) How does this compare, with the number density for the gas at atmospheric pressure, with density 3.0×10^{-3} g/cm^3?

(c) Suggest ways to achieve the high efficiency desired.

10.2. An incident particle ionizes helium to produce an electron and a He^{++} ion halfway between two parallel plates with potential difference between them. If the gas pressure is very low, estimate the ratio of the times elapsed until the charges are collected. Discuss the effect of collisions on the collection time.

10.3. We collect a sample of gas suspected of containing a small amount of radioiodine, half-life 8 days. If we observe in a period of 1 day a total count of 50,000 in a counter that detects all radiation emitted, how many atoms were initially present?

10.4. In a gas counter, the potential difference at any point r between a central wire of radius r_1 and a concentric wall of radius r_2 is given by

$$V = V_0 \frac{\ln\left(r / r_1\right)}{\ln\left(r_2 / r_1\right)},$$

where V_0 is the voltage across the tube. If r_1 = 1 mm and r_2 = 1 cm, what fraction of the potential difference exists within a millimeter of the wire?

10.5. How many electrodes would be required in a photomultiplier tube to achieve a multiplication of one million if one electron releases four electrons?

10.6. The probability of x successful events in n trials, each of which has a chance p, is given by the binomial distribution formula,

$$P(x) = n!\, p^x (1-p)^{n-x} / \left((n-x)!x!\right).$$

(a) apply to flipping a coin l, 2 and 3 times, finding the number of times the result is heads, including zero. Check by simple logic.

(b) apply to throwing a single die 1 or 2 times, finding the number of sixes. Check.

(c) repeat the above calculations using program STAT (see Computer Exercise 10.A).

10.7. For a situation in which the chance of success p is much smaller than 1, the probability of x successes in n trials in the binomial formula of Ex. 10.6 is well approximated by the Poisson formula

$$P(x) \cong \left(\bar{x}^x / x!\right)\exp\left(-\bar{x}\right),$$

where $\bar{x} = pn$ is the mean value of x. What is the value of p in throwing a single die? Find x for 1 or 2 throws of a die and calculate $P(x)$ for each case.

10.8. Counts are taken for a minute from a microcurie source of cesium-137, half-life 30.2 years. (a) Assuming one count for each 50 disintegrations, find the expected counting rate and the number of counts for the interval. (b) Find the standard deviation in the counting rate. (c) Find the probability of decay of a given atom of cesium in the 1-minute interval.

10.9. A pair of dice is thrown $n = 10$ times. (a) Verify that the chance on one throw of getting a 7 is $p = 1/6$. (b) Using the binomial distribution, find out the chance of getting a 7 exactly $x = 2$ times out of the 10. (c) Repeat using the Poisson distribution.

10.10. The cross section for absorption for low-energy neutrons of nuclides such as boron-10 varies as $1/u$, as discussed in Section 4.5. Formally, we may write

$$s_a = s_{a0}\, u_0/u$$

where s_{a0} is the cross section at $u_0 = 2200$ m/s. A boron neutron detector is placed in a neutron speed distribution $n(u)$, with n_0 as the total number of neutrons per cm^3 and N as the number of boron nuclei per cm^3. Form the total reaction rate per cm^3 by integrating over the distribution, as a generalization of the equation in Section 4.3. Discuss the result in terms of what is being measured by the detector.

Computer Exercises

10.A. Program STAT in BASIC calculates the probability distribution $P(x)$ using a choice of the Binomial, Poisson, or Gauss formulas. (a) What is the value of p for throwing a "six" with a single die? (b) Run the program with $n = 1$, 2, 5, and 10 and note the probabilities of finding 0, 1, 2, . . . sixes. (c) Assuming that Binomial is exact, comment on the apparent accuracy of the other two methods.

10.B. An alpha particle detector for surface contamination is counted for 30 one-minute intervals, with a total of 225 counts. What is the value of p? Using the Binomial and Poisson distributions in the computer program STAT, calculate $P(x)$ for $x = 0, 1, 2 \ldots, 30$. How accurate is the Poisson formula?

10.C. (a) What is the chance that any given person's birthday is today? (b) If we select 1000 people at random, using the Poisson distribution in program STAT, what is the probability that none has a birthday today? (c) Calculate $P(x)$ for $x = 0$ to 10 and plot a bar graph of the results. What is the most likely number that have a birthday today and what is the mean value? (d) Run STAT in Binomial mode for 20 people at a party and show that the chance of two people having the same birthday is almost one-half.

10.D. Computer program EXPOIS calculates "experimental" particle counting data that can be analyzed by Poisson statistics. It uses random numbers generated by BASIC using the command RND(N), where N is an assigned set of numbers. Run the program for a typical time from 10 to 30 minutes and compare the results graphically with Poisson data produced

by the program STAT (Computer Exercise 10.A).

10.10 References for Chapter 10

Philip R. Bevington and D. Keith Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 2nd Ed., McGraw-Hill, New York, 1992. An update of a classic text on statistical methods, illustrated with examples from technology. Includes computer diskette..

H. H. Ku, Editor, *Precision Measurement and Calibration-Statistical Concepts and Procedures*, National Bureau of Standards Publication 300, Volume 1, U.S. Government Printing Office, 1969.

Geoffrey G. Eichholz and John W. Poston, *Principles of Nuclear Radiation Detection*, Ann Arbor Science, Ann Arbor, MI, 1979.

Glenn F Knoll, *Radiation Detection and Measurement*, 2nd Ed., John Wiley & Sons, New York, 1989. A very comprehensive, modern, and readable text, which should be in every nuclear engineer's library.

Robley D. Evans, *The Atomic Nucleus*, New York, Krieger, 1982. Excellent treatment of statistical distributions.

Nicholas Tsoulfanidis, *Measurement and Detection of Radiation*, 2nd Ed., Taylor & Francis, Washington, DC, 1995.

K. Kleinknecht, *Detectors for Particle Radiation*, 2nd Ed., Cambridge University Press, Cambridge, U.K., 1999.

Robert L. Fleischer, *Tracks to Innovation: Nuclear Tracks in Science and Technology*, Springer-Verlag, New York, 1998.

Dennis D. Wackerly, William Mendenhall III, and Richard L. Schaeffer, *Mathematical Statistics with Applications*, Wadsworth Publishing Co., Belmont, CA, 1996.

Michael F. L'Annunziata, Editor, *Handbook of Radioactivity Analysis*, Academic Press, San Diego, 1998.

Radiation Detectors
http://www.fas.org/nuke/hew/Smyth/smythapp.html
Brief descriptions of early detectors from the Smyth Report.

Caltech Senior Physics Laboratory
http://www.pma.caltech.edu/~ph77
Nuclear measurements that prepare students for research. Valuable information provided by Guy DeRose. Select Geiger Counter.

Some commercial suppliers of nuclear radiation detectors
PerkinElmer Instruments: http://www.eggortec.com
LND, Inc.: http://Lndinc.com
Gamma Laboratories: http://www.gammalabs.com

Tutorial: Why use statistics?
http://biology.nebrwesleyan.edu/empiricist/sources/tips/Stats1.html
Definitions of various terms

Binomial and Poisson Statistics Functions
http://www.io.com/~ritter/JAVASCRP/BINOMPOI.HTM
Interactive computation. By Terry Ritter

Statistics for Engineers
http://engineering.uow.edu.au/Courses/Stats/index.html
A complete online course including practical examples. By Professor Tibor G. Rozgonyi (Australia)

The Integrator
http://integrals.wolfram.com
Interactive integration and information on math functions, e.g., gaussian distribution. From Mathematica

11

Neutron Chain Reactions

THE POSSIBILITY of a chain reaction involving neutrons in a mass of nuclear fuel such as uranium depends on (a) nuclear properties such as cross sections and neutrons per absorption (Section 6.3) and (b) the size, shape, and arrangement of the materials.

11.1 Criticality and Multiplication

To achieve a self-sustaining chain reaction, one needing no external neutron supply, a "critical mass" of uranium must be collected. To appreciate this requirement we visualize the simplest nuclear reactor, consisting of a metal sphere of uranium-235. Suppose that it consists of only one atom of U-235. If it absorbs a neutron and fissions, the resultant neutrons do nothing further, there being no more fuel. If instead we have a small chunk of uranium, say a few grams, the introduction of a neutron might set off a chain of several reactions, producing more neutrons, but most of them would escape through the surface of the body, a process called *leakage*. Such an amount of fuel is said to be "subcritical." Now if we bring together about 50 kg of U-235 metal, the neutron production balances the leakage losses, and the system is self-sustaining or "critical." The size is the critical volume and the amount of fuel is the critical mass. Neutrons had to be introduced to start the chain reaction, but the number is maintained without further additions. The term "critical mass" has become popular to describe any collection of entities large enough to operate independently.

Figure 11.1 shows the highly enriched metal assembly Lady Godiva, so named because it was "bare," i.e., had no surrounding materials. It was used for test purposes for a number of years at Los Alamos. If we add still more uranium to the 50 kg required for criticality, more neutrons are produced than are lost, the neutron population increases, and the reactor is "supercritical." Early nuclear weapons involved the use of such masses, in which the rapid growth of neutrons and resulting fission heat caused a violent explosion.

11.2 Multiplication Factors

The behavior of neutrons in a nuclear reactor can be understood through

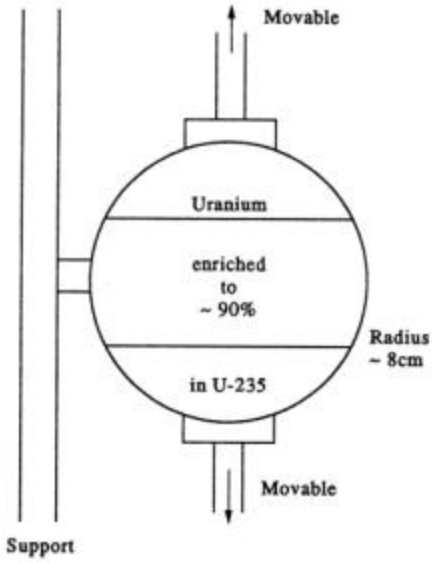


FIG. 11.1 Fast metal assembly "Lady Godiva."

analogy with populations of living organisms; for example, of human beings. There are two ways to look at changes in numbers of people: as individuals and as a group. A person is born and throughout life has various chances of fatal illness or accident. On average the life expectancy at birth might be 75 years, according to statistical data. An individual may die without an heir, with one, or with many. If on average there is exactly 1, the population is constant. From the other viewpoint, if the rates of birth and death are the same in a group of people, the population is again steady. If there are more births than deaths by 1% per year, the population will grow accordingly. This approach emphasizes the competition of process rates.

The same ideas apply to neutrons in a multiplying assembly. We can focus attention on a typical neutron that was born in fission, and has various chances of dropping out of the cycle because of leakage and absorption in other materials besides fuel. On the other hand we can compare the reaction rates for the processes of neutron absorption, fission, and leakage to see if the number of neutrons is increasing, steady, or decreasing. Each of the methods has its merits for purposes of discussion, analysis, and calculation.

For any arrangement of nuclear fuel and other materials, a single number k tells the net number of neutrons per initial neutron, accounting for all losses and reproduction by fission. If k is less than 1 the system is subcritical; if k is equal to 1 it is critical, and if k is greater than 1 it is supercritical.

The design and operation of all reactors is focused on k or on related quantities such as $dk = k - 1$, called delta-k, or dk/k, called *reactivity*,

symbolized by r. The choice of materials and size is made to assure that k has the desired value. For safe storage of fissionable material k should be well below 1. In the critical experiment, a process of bringing materials together with a neutron source present, observations on neutron flux are made to yield estimates of k. During operation, variations in k are made as needed by adjustments of neutron-absorbing rods or dispersed chemicals. Eventually, in the operation of the reactor, enough fuel is consumed to bring k below 1 regardless of adjustments in control materials, and the reactor must shut down for refueling.

We can develop a formula for k for our uranium metal assembly using the statistical approach. As in Fig 11.2 (a), a neutron may escape on first flight from the sphere, since mean free paths for fast neutrons are rather long. Another neutron (b) may make one scattering collision and then escape. Other neutrons may collide and be absorbed either (c) to form U-236 or (d) to cause fission, the latter yielding three new neutrons in this case. Still other neutrons may make several collisions before leakage or absorption takes place. The statistical nature of the process is revealed by the application of Computer Exercise 11.D, which involves the program SLOWINGS. Scattering, absorption, and escape are simulated using a Monte Carlo technique. A "flow diagram" as in Fig. 11.3 is useful to describe the various fates. The boxes represent processes; the circles represent the numbers of neutrons at each stage.

The fractions of absorbed neutrons that form U-236 and that cause fission, respectively, are the ratios of the cross section for capture s_c and fission s_f to that for absorption s_a. The average number of neutrons produced by fission is n. Now let h be the combination $n s_f / s_a$, and note that it is the number of neutrons per absorption in uranium. Thus letting ℓ be the fraction *not* escaping by leakage,

$$k = h\,\ell$$

The system is critical if $k = 1$, or $h\ell = 1$. Measurements show that h is around 2.2 for fast neutrons, thus ℓ must be 1/(2.2) = 0.45, which says that as many as 45% of the neutrons must remain in the sphere, while no more than 55% escape through its boundary.

Let us now examine more closely ℓ, the non-leakage factor, coming from the process of neutron loss through the surface of a reactor core without reflector. Leakage is dependent on scattering collisions and on the size and shape of the core. We would expect that the amount of neutron leakage depends on the ratio of surface to volume, since production occurs within the core and losses occur at the boundary. For a sphere, for example, the volume is $V = (4/3)\pi R^3$ and the surface area is $S = 4\pi R^2$, so the ratio is $S/V = 3/R$. As it turns out from the theory of neutron diffusion, the

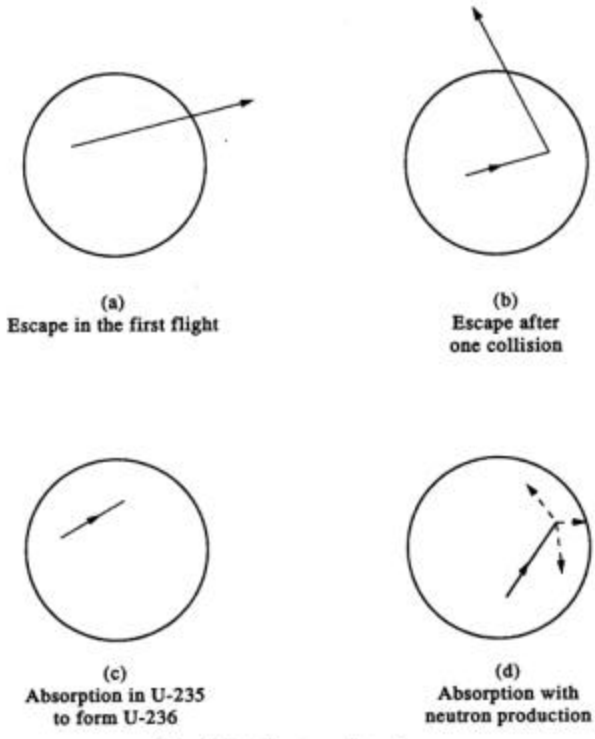


FIG. 11.2 Neutron histories.

parameter that actually applies is $B = p/R$, the square of which, B^2, is called the "buckling". It is also logical that leakage should be larger the greater the transport mean free path (recall Section 4.6), and the smaller the absorption cross section (Section 4.3). This is indeed the case, involving the use of the diffusion length, $L = \sqrt{D / \Sigma_a}$ as used in Section 4.6. The non-leakage factor for one neutron energy group in a bare reactor is thus

$$\mathscr{L} = 1/(1 + B^2 L^2).$$

Bucklings for three important shapes are as listed.

sphere, radius R: $B^2 = (p/R)^2$,

parallelepiped, L, W, H: $B^2 = (p/L)^2 + (p/W)^2 + (p/H)^2$,

cylinder, H, R: $B^2 = (p/H)^2 + (j_0/R)^2$, where $j_0 = 2.40483$.

Critical conditions for more complex situations including mixtures of fuels can be analyzed by use of program CRITICAL, discussed in Computer Exercise 11A.

The effect of flux variation with position is illustrated by Computer Exercise 11.B, dealing with the program MPDQ92.

The presence of large amounts of neutron-moderating material such as water in a reactor greatly changes the neutron distribution in energy. Fast neutrons slow down by means of collisions with light nuclei, with the result

that most of the fissions are produced by low-energy (thermal) neutrons. Such a system is called a "thermal" reactor in contrast with a system without moderator, a "fast" reactor, operating principally with fast neutrons. The cross sections for the two energy ranges are widely different, as noted in Exercise 11.4. Also, the neutrons are subject to being removed from the multiplication cycle during the slowing process by strong resonance absorption in elements such as U-238. Finally, there is competition for the neutrons between fuel, coolant, structural materials, fission products, and control absorbers.

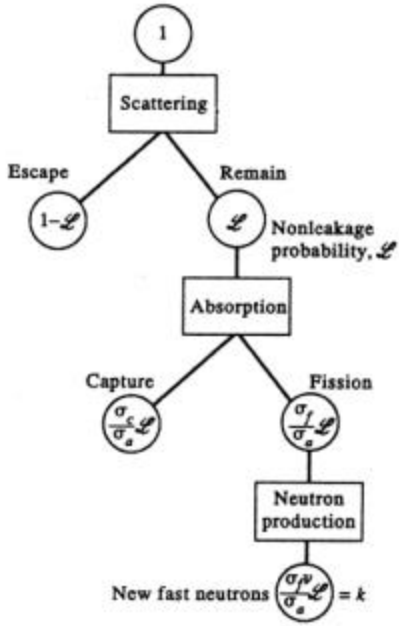


FIG. 11.3 Neutron cycle in metal assembly.

The description of the multiplication cycle for a thermal reactor is somewhat more complicated than that for a fast metal assembly, as seen in Fig. 11.4. The set of reactor parameters are (a) the fast fission factor e, representing the immediate multiplication because of fission at high neutron energy, mainly in U-238; (b) the fast nonleakage probability $\mathscr{L}_f$, being the fraction remaining in the core during neutron slowing; (c) the resonance escape probability p, the fraction of neutrons not captured during slowing; (d) the thermal nonleakage probability $\mathscr{L}_t$, the fraction of neutrons remaining in the core during diffusion at thermal energy; (e) the thermal utilization f, the fraction of thermal neutrons absorbed in fuel; and (f) the reproduction factor h, as the number of new fission neutrons per absorption in fuel. At the end of the cycle starting with one fission neutron, the number of fast neutrons produced is seen to be $e\,pfh\,\mathscr{L}_f\,\mathscr{L}_t$, which may be also

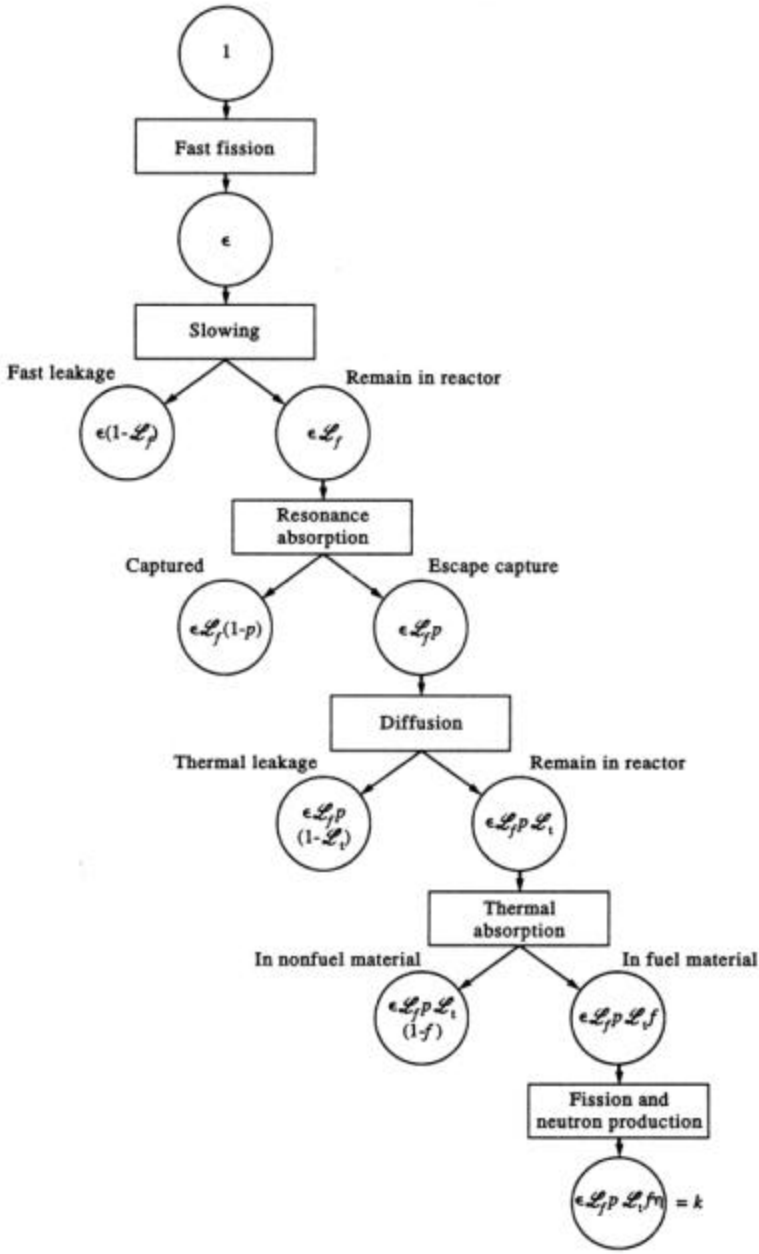


FIG. 11.4 Neutron cycle in thermal reactor.

labeled k, the effective multiplication factor. It is convenient to group four of the factors to form $k_\infty = \varepsilon p f h$, the so-called "infinite multiplication factor" which would be identical to k if the medium were infinite in extent, without leakage. If we form a composite nonleakage probability $\mathscr{L} = \mathscr{L}_f \mathscr{L}_t$ then we may write

$$k = k_\infty \mathscr{L}$$

For a reactor to be critical, k must equal 1, as before.

To provide some appreciation of the sizes of various factors, let us calculate the values of the composite quantities for a thermal reactor, for which $\varepsilon = 1.03$, $p = 0.71$, $\mathscr{L}_f = 0.97$, $\mathscr{L}_t = 0.99$, $f = 0.79$, and $\eta = 1.8$. Now $k_\infty = (1.03)(0.71)(1.8)(0.79) = 1.04$, $\mathscr{L} = (0.97)(0.99) = 0.96$, and $k = (1.04)(0.96) = 1.00$. For this example, the various parameters yield a critical system. In Section 11.4 we shall describe the physical construction of typical thermal reactors.

11.3 Neutron Flux and Reactor Power

The power developed by a reactor is a quantity of great interest for practical reasons. Power is related to the neutron population, and also to the mass of fissile material present. First, let us look at a typical cubic centimeter of the reactor, containing N fuel nuclei, each with cross section for fission σ_f at the typical neutron energy of the reactor, corresponding to neutron speed u. Suppose that there are n neutrons in the volume. The rate at which the fission reaction occurs is thus $R_f = nuN\sigma_f$ fissions per second. If each fission produces an energy w, then the power per unit volume is $p = wR_f$. For the whole reactor, of volume V, the rate of production of thermal energy is $P = pV$. If we have an average flux $\bar{f} = nu$ and a total number of fuel atoms $N_T = NV$, the total reactor power is seen to be

$$P = \bar{f} N_T \sigma_f w.$$

Thus we see that the power is dependent on the product of the number of neutrons and the number of fuel atoms. A high flux is required if the reactor contains a small amount of fuel, and conversely. All other things equal, a reactor with a high fission cross section can produce a required power with less fuel than one with small σ_f. We recall that σ_f decreases with increasing neutron energy. Thus for given power P, a fast reactor, operating with neutron energies principally in the vicinity of 1 MeV, requires either a much larger flux or a larger fissile fuel mass than does the thermal reactor, with neutrons of energy less than 0.1 eV.

The power developed by most familiar devices is closely related to fuel consumption. For example, a large car generally has a higher gasoline consumption rate than a small car, and more gasoline is used in operation at high speed than at low speed. In a reactor, it is necessary to add fuel very infrequently because of the very large energy yield per pound, and the fuel content remains essentially constant. From the formula relating power, flux, and fuel, we see that the power can be readily raised or lowered by changing the flux. By manipulation of control rods, the neutron population

is allowed to increase or decrease to the proper level.

Power reactors used to generate electricity produce about 3000 megawatts of thermal power (MWt), and with an efficiency of around 1/3, give 1000 MW of electrical power (MWe).

11.4 Reactor Types

Although the only requirement for a neutron chain reaction is a sufficient amount of a fissile element, many combinations of materials and arrangements can be used to construct an operable nuclear reactor. Several different types or concepts have been devised and tested over the period since 1942, when the first reactor started operation, just as various kinds of engines have been used–steam, internal combustion, reciprocating, rotary, jet, etc. Experience with individual reactor concepts has led to the selection of a few that are most suitable, using criteria such as economy, reliability, and ability to meet performance demands.

In this Section we shall identify these important reactor features, compare several concepts, and then focus attention on the components of one specific power reactor type. We shall then examine the processes of fuel consumption and control in a power reactor.

A general classification scheme for reactors has evolved that is related to the distinguishing features of the reactor types. These features are listed below.

(a) Purpose

The majority of reactors in operation or under construction have as purpose the generation of large blocks of commercial electric power. Others serve training or radiation research needs, and many provide propulsion power for submarines. Available also are tested reactors for commercial surface ships and for spacecraft. At various stages of development of a new concept, such as the breeder reactor, there will be constructed both a prototype reactor, one which tests feasibility, and a demonstration reactor, one that evaluates commercial possibilities.

(b) Neutron Energy

A fast reactor is one in which most of the neutrons are in the energy range 0.1-1 MeV, below but near the energy of neutrons released in fission. The neutrons remain at high energy because there is relatively little material present to cause them to slow down. In contrast, the thermal reactor contains a good neutron moderating material, and the bulk of the neutrons have energy less than 0.1 eV.

(c) Moderator and Coolant

In some reactors, one substance serves two functions–to assist in neutron slowing and to remove the fission heat. Others involve one material for moderator and another for coolant. The most frequently used materials are listed below:

Moderators	*Coolants*
light water	light water
heavy water	carbon dioxide
graphite	helium
beryllium	liquid sodium

The condition of the coolant serves as a further identification. The *pressurized water reactor* provides high-temperature water to a heat exchanger that generates steam, while the *boiling water reactor* supplies steam directly.

(d) Fuel

Uranium with U-235 content varying from natural uranium (≅0.7%) to slightly enriched (≅3%) to highly enriched (≅90%) is employed in various reactors, with the enrichment depending upon what other absorbing materials are present. The fissile isotopes $^{239}_{94}\mathrm{Pu}$ and $^{233}_{92}\mathrm{U}$ are produced and consumed in reactors containing significant amounts of U-238 or Th-232. Plutonium serves as fuel for fast breeder reactors and can be recycled as fuel for thermal reactors. The fuel may have various physical forms–a metal, or an alloy with a metal such as aluminum, or a compound such as the oxide UO_2 or carbide UC.

(e) Arrangement

In most modern reactors, the fuel is isolated from the coolant in what is called a *heterogeneous* arrangement. The alternative is a homogeneous mixture of fuel and moderator or fuel and moderator-coolant.

(f) Structural Materials

The functions of support, retention of fission products, and heat conduction are provided by various metals. The main examples are aluminum, stainless steel, and zircaloy, an alloy of zirconium.

By placing emphasis on one or more of the above features of reactors, reactor concepts are identified. Some of the more widely used or promising power reactor types are the following:

PWR (pressurized water reactor), a thermal reactor with light water at high pressure (2200 psi) and temperature (600°F) serving as moderator-

coolant, and a heterogeneous arrangement of slightly enriched uranium fuel.

BWR (boiling water reactor), similar to the PWR except that the pressure and temperature are lower (1000 psi and 550°F).

HTGR (high temperature gas-cooled reactor), using graphite moderator, highly enriched uranium with thorium, and helium coolant (1430°F and 600 psi).

CANDU (Canadian deuterium uranium) using heavy water moderator and natural uranium fuel that can be loaded and discharged during operation.

LMFBR (liquid metal fast breeder reactor), with no moderator, liquid sodium coolant, and plutonium fuel, surrounded by natural or depleted uranium.

Table 11.1 amplifies on the principal features of the above five main power reactor concepts. A description of the RBMK, exemplified by the ill-fated Chernobyl-4 reactor, appears in Section 19.6. Other reactors include the Magnox and AGR of the U. K. and several concepts that were tested but abandoned (see encyclopedia article in References).

The large-scale reactors used for the production of thermal energy that is converted to electrical energy are much more complex than the fast assembly described in Section 11.1. To illustrate, we can identify the components and their functions in a modern pressurized water reactor. Figure 11.5 gives some indication of the sizes of the various parts. To gain some appreciation of the physical arrangement of fuel in power reactors, try out the graphics programs in Computer Exercises 11.E (ASSEMBLY) and 11.F (BWRASEM).

TABLE 11.1
Power Reactor Materials

	Pressurized water (PWR)	Boiling water (BWR)	Natural U heavy water (CANDU)	High temp. gas-cooled (HTGR)	Liquid metal fast breeder (LMFBR)
Fuel form	UO_2	UO_2	UO_2	UC, ThC_2	PuO_2, UO_2
Enrichment	3% U-235	2.5% U-235	0.7% U-235	93% U-235	15 wt. % Pu-239
Moderator	water	water	heavy water	graphite	none
Coolant	water	water	heavy water	helium gas	liquid sodium
Cladding	zircaloy	zircaloy	zircaloy	graphite	stainless steel
Control	B_4C or Ag-In-Cd rods	B_4C crosses	moderator level	B_4C rods	tantalum or B_4C rods
Vessel	steel	steel	steel	prestressed concrete	steel

The fresh fuel installed in a typical PWR consists of cylindrical pellets of slightly enriched (3% U-235) uranium oxide (UO_2) of diameter about 3/8

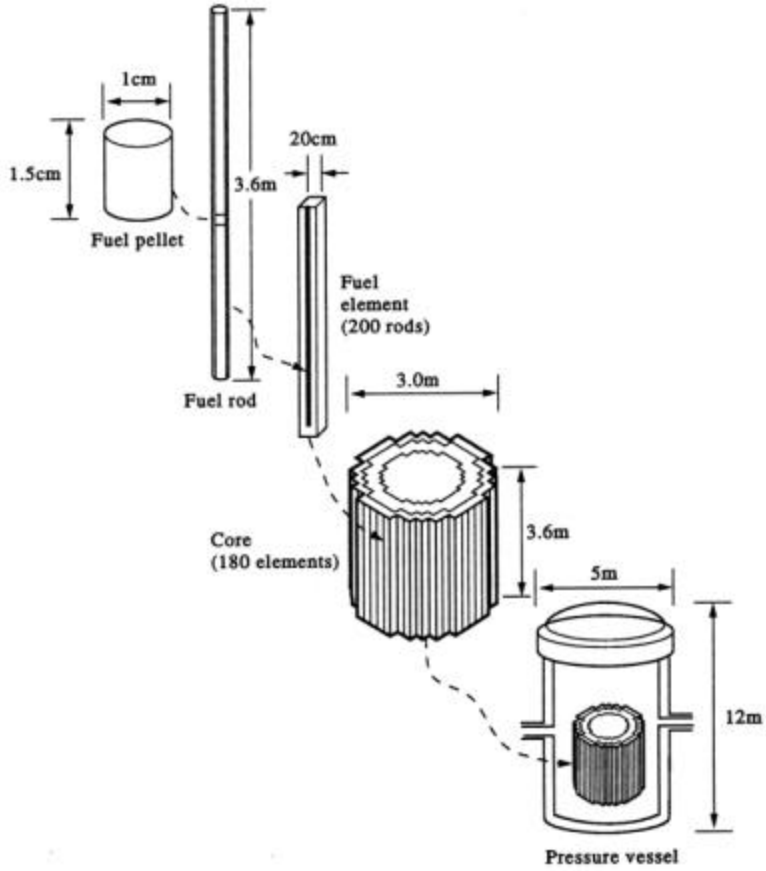


FIG. 11.5 Reactor construction.

in. (~ 1 cm) and length about 0.6 in. (~ 1.5 cm). A zircaloy tube of wall thickness 0.025 in. (~ 0.6 mm) is filled with the pellets to an "active length" of 12 ft (365 cm) and sealed to form a *fuel rod* (or pin). The metal tube serves to provide support for the column of pellets, to provide cladding that retains radioactive fission products, and to protect the fuel from interaction with the coolant. About 200 of the fuel pins are grouped in a bundle called a *fuel element* of about 8 in. (~ 20 cm) on a side, and about 180 elements are assembled in an approximately cylindrical array to form the reactor *core*. This structure is mounted on supports in a steel *pressure vessel* of outside diameter about 16 ft (~ 5 m), height 40 ft (~ 12 m) and walls up to 12 in. (~ 30 cm) thick. *Control rods*, consisting of an alloy of cadmium, silver, and indium, provide the ability to change the amount of neutron absorption. The rods are inserted in some vacant fuel pin spaces and magnetically connected to drive mechanisms. On interruption of magnet current, the rods enter the core through the force of gravity. The pressure vessel is filled with light

water, which serves as neutron moderator, as coolant to remove fission heat, and as *reflector*, the layer of material surrounding the core that helps prevent neutron escape. The water also contains in solution the compound boric acid, H_3BO_3, which strongly absorbs neutrons in proportion to the number of boron atoms and thus inhibits neutron multiplication, i.e., "poisons" the reactor. The term *soluble poison* is often used to identify this material, the concentration of which can be adjusted during reactor operation. To keep the reactor critical as fuel is consumed, the boron content is gradually reduced. A shield of concrete surrounds the pressure vessel and other equipment to provide protection against neutrons and gamma rays from the nuclear reactions. The shield also serves as an additional barrier to the release of radioactive materials.

We have mentioned only the main components, which distinguish a nuclear reactor from other heat sources such as one burning coal. An actual system is much more complex than described above. It contains equipment such as spacers to hold the many fuel rods apart; core support structures; baffles to direct coolant flow effectively; guides, seals, and motors for the control rods; guide tubes and electrical leads for neutron-detecting instruments, brought through the bottom of the pressure vessel and up into certain fuel assemblies; and bolts to hold down the vessel head and maintain the high operating pressure.

The power reactor is designed to withstand the effects of high temperature, erosion by moving coolant, and nuclear radiation. The materials of construction are chosen for their favorable properties. Fabrication, testing, and operation are governed by strict procedures.

11.5 Reactor Operation

The generation of energy from nuclear fuels is unique in that a rather large amount of fuel must be present at all times for the chain reaction to continue. In contrast, an automobile will operate even though its gasoline tank is practically empty. There is a subtle relationship between reactor fuel and other quantities such as consumption, power, neutron flux, criticality, and control.

The first and most important consideration is the energy production, which is directly related to fuel consumption. Let us simplify the situation by assuming that the only fuel consumed is U-235, and that the reactor operates continuously and steadily at a definite power level. Since each atom "burned," i.e., converted into either U-236 or fission products by neutron absorption, has an accompanying energy release, we can find the amount of fuel that must be consumed in a given period.

Let us examine the fuel usage in a simplified PWR that uses 20 w/o fuel

and operates at 100 MWe or 300 MWt, as in a test reactor or a propulsion reactor. The initial fuel loading into a single zone is 1000 kg U. We apply the rule of thumb that 1.3 grams of U-235 are consumed for each megawatt-day of thermal energy, assuming that all fissions are due to U-235. In one year, the amount of U-235 consumed is

$$(300 \text{ MWt})\ (1.3 \text{ g/MWt-day})\ (365 \text{ days}) = 1.42 \times 10^5 \text{ g},$$

or 142 kg. We see that a great deal of the original 200 kg of U-235 has been consumed, with a final enrichment of 5.8 w/o. If we carry out the calculations as in Section 9.2, the fuel cost excluding fabrication and transport is $4.28 million. The electricity produced is

$$(10^5 \text{ kW})\ (8760 \text{ h/y}) = 8.76 \times 10^8 \text{ kWh},$$

making the unit cost of fuel $(\$4.28 \times 10^6)/(8.76 \times 10^8) = \$0.0049$ or about half a mill per kWh. In Chapter 19 we shall analyze fuel cycles in a large power reactor which has several zones with different enrichments and shuts down periodically to remove, rearrange, and install fuel.

Let us continue studying the operating features of our small PWR. Since no fuel is added during the operating cycle of the order of a year, the amount to be burned must be installed at the beginning. First, the amount of uranium needed to achieve criticality is loaded into the reactor. If then the "excess" is added, it is clear that the reactor would be supercritical unless some compensating action were taken. In the PWR, the excess fuel reactivity is reduced by the inclusion of control rods and boron solution.

The reactor is brought to full power and operating temperature and pressure by means of rod position adjustments. Then, as the reactor operates and fuel begins to burn out, the concentration of boron is reduced. By the end of the cycle, the extra fuel is gone, all of the available control absorption has been removed, and the reactor is shut down for refueling. The trends in fuel and boron are shown in Fig. 11.6, neglecting the effects of certain fission product absorption and plutonium production. The graph represents a case in which the power is kept constant. The fuel content thus linearly decreases with time. Such operation characterizes a reactor that provides a "base load" in an electrical generating system that also includes fossil fuel plants and hydroelectric stations.

The power level in a reactor was shown in Section 11.3 to be proportional to neutron flux. However, in a reactor that experiences fuel consumption the flux must increase in time, since the power is proportional also to the fuel content.

The amount of control absorber required at the beginning of the cycle is proportional to the amount of excess fuel added to permit burnup for power production. For example, if the fuel is expected to go from 3% to 1.5% U-235, an initial boron atom number density in the moderator is about $1.0 \times$

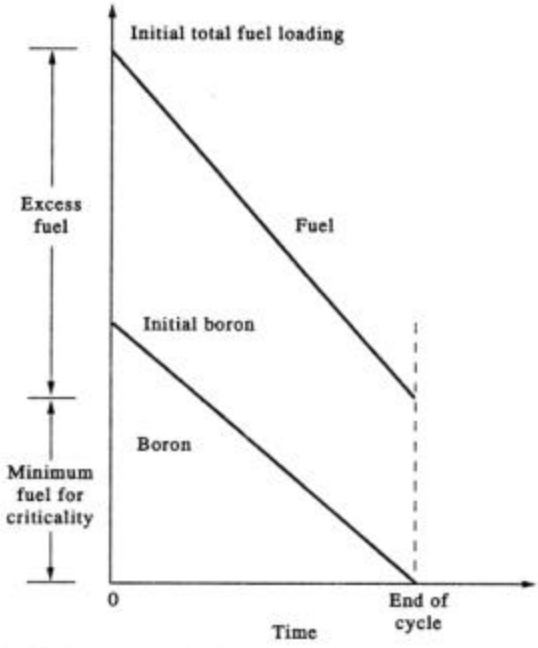


FIG. 11.6 Reactor control during fuel consumption in power reactor.

10^{-4} (in units of 10^{24}). For comparison, the number of water molecules per cubic centimeter is 0.0334. The boron content is usually expressed in parts per million (i.e., micrograms of an additive per gram of diluent). For our example, using 10.8 and 18.0 as the molecular weights of boron and water, there are $10^{6}(10^{-4})$ (10.8)/(0.0334)(18.0) = 1800 ppm.

The description of the reactor process just completed is somewhat idealized. Several other phenomena must be accounted for in design and operation.

If a reactor is fueled with natural uranium or slightly enriched uranium, the generation of plutonium tends to extend the cycle time. The fissile Pu-239 helps maintain criticality and provides part of the power. Small amounts of higher plutonium isotopes are also formed: Pu-240, fissile Pu-241 (14.4 year half-life), and Pu-242. These isotopes and those of elements farther up the periodic table are called transuranic materials or actinides. They are important as fuels, poisons, or nuclear wastes. (See Ex. 11.14).

Neutron absorption in the fission products has an effect on control requirements. The most important of these is a radioactive isotope of xenon, Xe-135, which has a cross section at 0.0253 eV of 2.65 *million* barns. Its yield in fission is high, $y = 0.06$, meaning that for each fission, one obtains 6% as many atoms of Xe-135. In steady operation at high neutron flux, its rate of production is equal to its consumption by neutron absorption. Hence

$$N_X \sigma_{aX} = N_F \sigma_{fF} y.$$

Using the ratio s_f/s_a for U-235 of 0.86, we see that the absorption rate of Xe-135 is (0.86)(0.06) = 0.05 times that of the fuel itself. This factor is about 0.04 if the radioactive decay (t_H = 9.10 hr) of xenon-135 is included (see Exercise 11.8). The time dependent variation of neutron absorption in xenon-135 is the subject of Computer Exercise 11.C, which describes the program XETR.

It might appear from Fig. 11.6 that the reactor cycle could be increased to as long a time as desired merely by adding more U-235 at the beginning. There are limits to such additions, however. First, the more the excess fuel that is added, the greater must be the control by rods or soluble poison. Second, radiation and thermal effects on fuel and cladding materials increase with life. The amount of allowable total energy extracted from the uranium, including all fissionable isotopes, is expressed as the number of megawatt-days per metric ton (MWd/tonne).† We can calculate its value for one year's operation of a 3000 MWt power reactor with initial U-235 fuel loading of 2800 kg; with an enrichment of 0.03, the *uranium* content was 2800/0.03 = 93,000 kg or 93 tonnes. Using the energy yield of (3000 MW)(365 days) ≅ 1,100,000 MWd, we find 12,000 MWd/tonne. Taking account of plutonium and the management of fuel in the core, a typical average exposure is actually 30,000 MWd/tonne. It is desirable to seek larger values of this quantity, in order to prolong the cycle and thus minimize the costs of fuel, reprocessing, and fabrication.

11.6 The Natural Reactor

Until the 1970s, it had been assumed that the first nuclear reactor was put into operation by Enrico Fermi and his associates in 1942. It appears, however, that a natural chain reaction involving neutrons and uranium took place in the African state of Gabon, near Oklo, some 2 billion years ago (see References). At that time, the isotope concentration of U-235 in natural uranium was higher than it is now because of the differences in half-lives: U-235, 7.04×10^8 years; U-238, 4.46×10^9 years. The water content in a rich vein of ore was sufficient to moderate neutrons to thermal energy. It is believed that this "reactor" operated off and on for thousands of years at power levels of the order of kilowatts. The discovery of the Oklo phenomenon resulted from the observations of an unusually low U-235 abundance in the mined uranium. The effect was confirmed by the presence of fission products.

11.7 Summary

A self-sustaining chain reaction involving neutrons and fission is

† The metric ton (tonne) is 1000 kg.

possible if a critical mass of fuel is accumulated. The value of the multiplication factor k indicates whether a reactor is subcritical (<1), critical (= 1), or supercritical (>1). The reactor power, which is proportional to the product of flux and the number of fuel atoms, is readily adjustable. A thermal reactor contains a moderator and operates on slowed neutrons. Reactors are classified according to purpose, neutron energy, moderator and coolant, fuel, arrangement, and structural material. Principal types are the pressurized water reactor, the boiling water reactor, the high-temperature gas-cooled reactor, and the liquid metal fast breeder reactor. Excess fuel is added to a reactor initially to take care of burning during the operating cycle, with adjustable control absorbers maintaining criticality. Account must be taken of fission product absorbers such as Xe-135 and of limitations related to thermal and radiation effects. About 2 billion years ago, deposits of uranium in Africa had a high enough concentration of U-235 to become natural chain reactors.

11.8 Exercises

11.1. Calculate the reproduction factor h for fast neutrons, using $s_f = 1.40$, $s_a = 1.65$, and $n = 2.60$ (ANL-5800, p.581).

11.2. If the power developed by the Godiva-type reactor of mass 50 kg is 100 watts, what is the average flux? Note that the energy of fission is $w = 3.04 \times 10^{-11}$ W-s.

11.3. Find the multiplication factors k_∞ and k for a thermal reactor with $e = 1.05$ $p = 0.75$, $\mathcal{L}_f = 0.90$, $\mathcal{L}_t = 0.98$, $f = 0.85$, and $h = 1.75$. Evaluate the reactivity r.

11.4. The value of the reproduction factor h in uranium containing both U-235 (1) and U-238 (2), is given by

$$h = \frac{N_1 s_{f1} n_1 + N_2 s_{f2} n_2}{N_1 s_{a1} + N_2 s_{a2}}.$$

Calculate h for three reactors (a) thermal, using 3% U-235, $N_1/N_2 = 0.0315$; (b) fast, using the same fuel; (c) fast, using pure U-235. Comment on the results. Note values of constants:

	Thermal	Fast
s_{f1}	586	1.40
s_{a1}	681	1.65
s_{f2}	0	0.095
s_{a2}	2.70	0.255
n_1	2.42	2.60
n_2	0	2.60

11.5. By means of the formula and thermal neutron numbers from Exercise 11.4, find h, the number of neutrons per absorption in fuel, for uranium oxide in which the U-235 atom fraction is 0.2, regarded as a practical lower limit for nuclear weapons material. Would the fuel be suitable for a research reactor?

11.6. How many individual fuel pellets are there in the PWR reactor described in the text? Assuming a density of uranium oxide of 10 g/cm^3, estimate the total mass of uranium and U-235 in the core in kilograms. What is the initial fuel cost?

11.7. The core of a PWR contains 180 fuel assemblies of length 4 m, width 0.2 m. (a) Find

the core volume and radius of equivalent cylinder. (b) If there are 200 fuel rods per assembly with pellets of diameter 0.9 cm, what is the approximate UO_2 volume fraction of the core?

11.8. (a) Taking account of Xe-135 production, absorption, and decay, show that the balance equation is

$$N_X \left(f s_{aX} + l_X \right) = f N_F s_{fF} y .$$

(b) Calculate l_x and the ratio of absorption rates in Xe-135 and fuel if f is 2×10^{13} cm^{-2}-s^{-1}.

11.9. The initial concentration of boron in a 10,000 ft^3 reactor coolant system is 1500 ppm, (the number of micrograms of additive per gram of diluent). What volume of solution of concentration 8000 ppm should be added to achieve a new value of 1600 ppm?

11.10. An adjustment of boron content from 1500 to 1400 ppm is made in the reactor described in Exercise 11.9. Pure water is pumped in and then mixed coolant and poison are pumped out in two separate steps. For how long should the 500 ft^3/min pump operate in each of the operations?

11.11. Find the ratio of weight percentages of U-235 and U-238 at a time 1.9 billion years ago, assuming the present 0.711/99.3.

11.12. Constants for a spherical fast uranium-235 metal assembly are: diffusion coefficient D = 1.02 cm; macroscopic absorption cross section S_a = 0.0795 cm^{-1}; effective radius R = 10 cm. Calculate the diffusion length L, the buckling B^2, and the non-leakage factor Λ.

11.13. The neutron flux in a reactor varies with position. In a simple core such as a bare uranium metal sphere of radius R, it varies as $f = f_c$ (sin x)/x, where $x = \pi r/R$. At the center of the sphere the flux is f_c. Calculate and plot the flux distribution for a core with radius 10 cm and central flux 5×10^{11}/cm^2-s.

11.14. A reactor is loaded with 90,000 kg of U at 3 w/o U-235. It operates for a year at 75% of its rated 3000 MWt capacity. (a) Apply the rule of thumb 1.3 g/MW-day to find the consumption of U-235. What is the final enrichment of the fuel? (b) If instead one-third of the energy came from plutonium, what would the final U-235 enrichment be? Note thermal cross sections, all in barns: U-235 s_f = 586, s_c = 95; Pu-239 s_f = 752, s_c = 270.

Computer Exercises

11.A. The evaluation of critical conditions for a variety of spherical metal assemblies can be made using the BASIC program CRITICAL. It uses a one neutron group model with cross sections deduced from early critical experiments related to weapons. CRITICAL can handle any combination of uranium and plutonium. Run the program, choosing U enrichment and Pu content. Suggested configurations:

(a) pure U-235.
(b) Godiva (93.9% U-235, experimental U-235 mass 48.8 kg).
(c) Jezebel (pure plutonium, experimental mass 16.28 kg).
(d) natural U (0.0072 atom fraction U-235, should not be possible to be made critical).
(e) depleted U (0.003 atom fraction U-235).
(f) elementary breeder reactor (Pu-239 volume 10%, depleted U).

11.B. A miniature version of a classic computer code PDQ is called MPDQ92. It finds the amount of critical control absorber in a core of the form of an unreflected slab, by solution of difference equations.

(a) Load the program and study the listing.

(b) Run the program and study the displays, then compare the results of choosing a linear or sine trial fast flux function.

(c) Using the constants given in Ex. 11.1, modify the program to calculate the critical control for a metal assembly as a slab of width 5 cm.

11.C. The amount of xenon in a reactor varies with time, especially when large changes in neutron flux occur, as at startup or shutdown. Lotus 1-2-3 program XETR (Xenon Transient) solves differential equations for the content of Iodine-135 and Xenon-135.

(a) Load the program and examine the input constants and conditions. Study the trend in the output as the reactivity r (see Section 11.2) vs. time.

(b) Use the concentrations of I-135 and Xe-135 calculated for long times after start up as initial concentrations, and set the flux equal to zero, to simulate a sudden shutdown of the reactor. Note and discuss the trend in xenon with time.

11.D. Competition among three neutron processes—scattering, absorption, and leakage—is illustrated by the program SLOWINGS. It simulates the release of a series of neutrons at the center of a carbon sphere, and using slowing theory and random numbers, finds the number of neutrons absorbed and escaping.

(a) Run the program several times to note statistical variations.

(b) Increase the absorption cross section by a factor of 200 as if considerable boron were added to the sphere, and note the effect.

11.E. The BASIC program ASSEMBLY displays a pressurized water reactor fuel assembly, an array of 14×14 fuel rods. Run the program.

11.F. The BASIC program BWRASEM displays four boiling water reactor fuel assemblies with a cross-shaped control rod between them. Run the program to inspect.

11.9 References for Chapter 11

Anthony V. Nero, Jr., *A Guidebook to Nuclear Reactors*, University of California Press, Berkeley, 1979.

Ronald Allen Knief, *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, Taylor & Francis, Bristol, PA, 1992.

Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering*, 3rd edition, Van Nostrand Reinhold, New York, 1981.

R. E. Peterson and G. A. Newby, "An Unreflected U-235 Critical Assembly," *Nuclear Science & Engineering* 1, 112 (1956). Description of Godiva.

Raymond L. Murray, "Nuclear Reactors" and "Reactor Types," in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, New York, 1996.

WWW Virtual Library: Nuclear Engineering
http://www.Nuc.Berkeley.EDU/NEadm.html
Links to nearly everything. Maintained by Jasmina Vucic.

Uranium Information Centre (Australia)
http://www.uic.com.au
Briefing papers on a variety of nuclear topics, and many links. Select "Nuclear Electricity," especially Chapter 3, Nuclear Power.

International Nuclear Safety Center
http://www.insc.anl.gov
Database on Reactor and Plant Information, Reactor Material Properties. By Argonne National Laboratory.

Nuclear Power Reactors
http://www.uilondon.org/reactor.htm

Components of a reactor. Link to RBMK (Chernobyl) reactor. By Uranium Institute.

Reactor diagrams
http://www.nrc.gov/NRC/STUDENTS/reactors.html
Colorful representations of PWR (826K)and BWR(808K) systems.

The Virtual Nuclear Tourist
http://www.cannon.net/~gonyeau/nuclear/index.htm
Comprehensive coverage of nuclear power. Explore links in Table of Contents. By Joseph Gonyeau.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

Brian R. T. Frost, *Nuclear Fuel Elements*, Pergamon Press, Oxford, 1981.

Donald R. Olander, *Fundamental Aspects of Nuclear Reactor Fuel Elements*, TID-2761l-P1, U.S. Department of Energy, Washington, DC, 1976. Also note *Solutions of Problems* by the same author in TID-2761l-P2.

George A. Cowan, "A Natural Fission Reactor," *Scientific American*, July 1976, p. 36.

The Natural Reactor
http://ibaserver.physics.isu.edu/radinf/oklo.htm
The ancient reactor in Oklo, Gabon. By Andrew Karam.
http://www.ymp.gov/about/science/geninfo/oklo.htm
Photos; relationship to nuclear wastes. By Department of Energy.

12

Nuclear Heat Energy

MOST OF the energy released in fission appears as kinetic energy of a few high-speed particles. As these pass through matter, they slow down by multiple collisions and impart thermal energy to the medium. It is the purpose of this chapter to discuss the means by which this energy is transferred to a cooling agent and transported to devices that convert mechanical energy into electrical energy. Methods for dealing with the large amounts of waste heat generated will be considered.

12.1 Methods of Heat Transmission

We learned in basic science that heat, as one form of energy, is transmitted by three methods—conduction, convection, and radiation. The physical processes for the methods are different: In *conduction*, molecular motion in a substance at a point where the temperature is high causes motion of adjacent molecules, and a flow of energy toward a region of low temperature takes place. The rate of flow is proportional to the slope of the temperature, i.e., the temperature gradient. In *convection*, molecules of a cooling agent such as air or water strike a heated surface, gain energy, and return to raise the temperature of the coolant. The rate of heat removal is proportional to the difference between the surface temperature and that of the surrounding medium, and also dependent on the amount of circulation of the coolant in the vicinity of the surface. In *radiation*, molecules of a heated object emit and receive electromagnetic radiations, with a net transfer of energy that depends on the temperatures of the body and the adjacent regions, specifically on the difference between the temperatures raised to the fourth power. For reactors, this mode of heat transfer is generally of less importance than are the other two.

12.2 Heat Generation and Removal

The transfer of heat by *conduction* in a flat plate (insulated on its edges) is reviewed. If the plate has a thickness x and cross-sectional area A, and the temperature difference between its faces is ΔT, the rate of heat flow through the plate, Q, is given by the relation

$$Q = kA\frac{\Delta T}{x},$$

where k is the conductivity, with typical units J/s-°C-cm. For the plate, the slope of the temperature is the same everywhere. In a more general case, the slope may vary with position, and the rate of heat flow per unit area Q/A is proportional to the slope or gradient written as $\Delta T/\Delta x$.

The conductivity k varies somewhat with temperature but we treat k as constant for the following analysis of conduction in a single fuel rod of a reactor (see Section 11.4). Let the rate of supply of thermal energy by fission be uniform throughout the rod. If the rod is long in comparison with its radius R, or if it is composed of a stack of pellets, most of the heat flow is in the radial direction. If the surface is maintained at a temperature T_s by the flow of coolant, the center of the rod must be at some higher temperature T_0. As expected, the temperature difference is large if the rate of heat generation per unit volume q or the rate of heat generation per unit length $q_1 = pR^2q$ is large. We can show† that

$$T_0 - T_S = \frac{q_1}{4pk},$$

and that the temperature T is in the shape of a parabola within the rod. Figure 12.1 shows the temperature distribution.

Let us calculate the temperature difference $T_0 - T_s$ for a reactor fuel rod of radius 0.5 cm, at a point where the power density is q = 200 W/cm^3. This corresponds to a linear heat rate $q_1 = pR^2q = p(0.25)\ (200) = 157$ W/cm (or 4.8 kW/ft). Letting the conductivity of UO_2 be k = 0.062 W/cm-°C, we find $T_0 - T_s$ = 200°C (or 360°F). If we wish to keep the temperature low along the center line of the fuel, to avoid structural changes or melting, the conductivity k should be high, the rod size small, or the reactor power level low. In a typical reactor there is a small gap between the fuel pin and the inside surface of the cladding. During operation, this gap contains gases, which are poor heat conductors and thus there will be a rather large temperature drop across the gap. A smaller drop will occur across the cladding which is thin and has a high thermal conductivity.

We have so far assumed that the thermal conductivity is constant. It actually varies with temperature and thus with position in the fuel pin. A more general calculation of k is possible using the program CONDUCT discussed in Computer Exercise 12A and the temperature distribution may

† The amount of energy supplied within a region of radius r must flow out across the boundary. For a unit length of rod with volume pr^2 and surface area $2pr$, the generation rate is pr^2q, equal to the flow rate $-k(dT/dr)2pr$. Integrating from r = 0, where $T = T_0$, we have $T = T_0 - qr^2/4k$). At the surface $T_s = T_0 - qR^2/4k$.

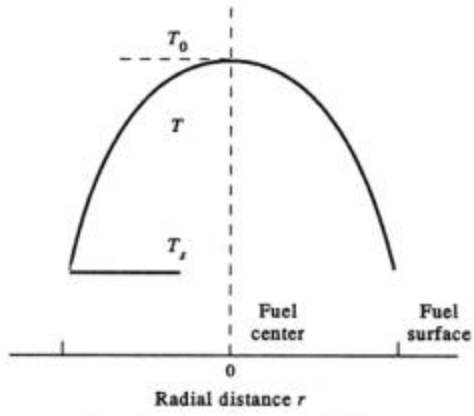


FIG. 12.1 Temperature in fuel.

be found using a program TEMPLOT in Computer Exercise 12.B.

Convective cooling depends on many factors such as the fluid speed, the size and shape of the flow passage, and the thermal properties of the coolant, as well as the area exposed and the temperature difference between surface and coolant $T_s - T_0$. Experimental measurements yield the *heat transfer coefficient h*, appearing in a working formula for the rate of heat transfer Q across the surface S,

$$Q = hS(T_s - T_0).$$

The units of h are typically W/cm^2-°C. In order to keep the surface temperature low, to avoid melting of the metal cladding of the fuel or to avoid boiling if the coolant is a liquid, a large surface area is needed or the heat transfer coefficient must be large, a low-viscosity coolant of good thermal conductivity is required, and the flow speed must be high.

As coolant flows along the many channels surrounding fuel pins in a reactor, it absorbs thermal energy and rises in temperature. Since it is the reactor power that is being extracted, we may apply the principle of conservation of energy. If the coolant of specific heat c enters the reactor at temperature T_c (in) and leaves at T_c (out), with a mass flow rate M, then the reactor thermal power P is

$$P = cM[T_c(\text{out}) - T_c(\text{in})] = cM\Delta T.$$

For example, let us find the amount of circulating water flow to cool a reactor that produces 3000 MW of thermal power. Let the water enter at 300°C (572°F) and leave at 325°C (617°F). Assume that the water is at 2000 psi and 600°F. At these conditions the specific heat is 6.06×10^3 J/kg-°C and the specific gravity is 0.687. Thus the mass flow rate is

$$M = P/(c\Delta T) = (3000 \times 10^6)/[(6.06 \times 10^3)(25)]$$
$$= 19{,}800 \text{ kg/s}.$$

This corresponds to a volume flow rate of

$$V = (19{,}800 \text{ kg/s})/(687 \text{ kg/m}^3) = 28.8 \text{ m}^3/\text{s},$$

which is also 1,730,000 liters per minute. To appreciate the magnitude of this flow, we can compare it with that from a garden hose of 40 liters/min. The water for cooling a reactor is not wasted, of course, because it is circulated in a closed loop.

The temperature of coolant as it moves along any channel of the reactor can also be found by application of the above relation. In general, the power produced per unit length of fuel rod varies with position in the reactor because of the variation in neutron flux shape. For a special case of a *uniform* power along the z-axis with origin at the bottom as in Fig. 12.2 (a), the power per unit length is $P_1 = P/H$, where H is the length of fuel rod. The temperature rise of coolant at z with channel mass flow rate M is then

$$T_c(z) = T_c(\text{in}) + \frac{P_1 z}{cM},$$

which shows that the temperature increases with distance along the channel as shown in Fig. 12.2 (b). The temperature difference between coolant and fuel surface is the same at all points along the channel for this power distribution, and the temperature difference between the fuel center and fuel surface is also uniform. We can plot these as in Fig. 12.2 (c). The highest temperatures in this case are at the end of the reactor.

If instead, the axial power were shaped as a sine function, see Fig. 12.3 (a) with $P \sim \sin(pz/H)$, the application of the relations for conduction and

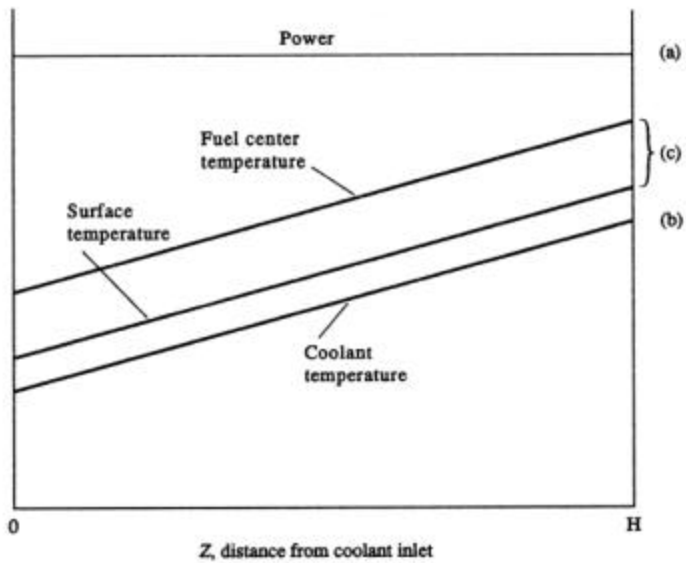


FIG. 12.2 Temperature distributions along axis of reactor with uniform power.

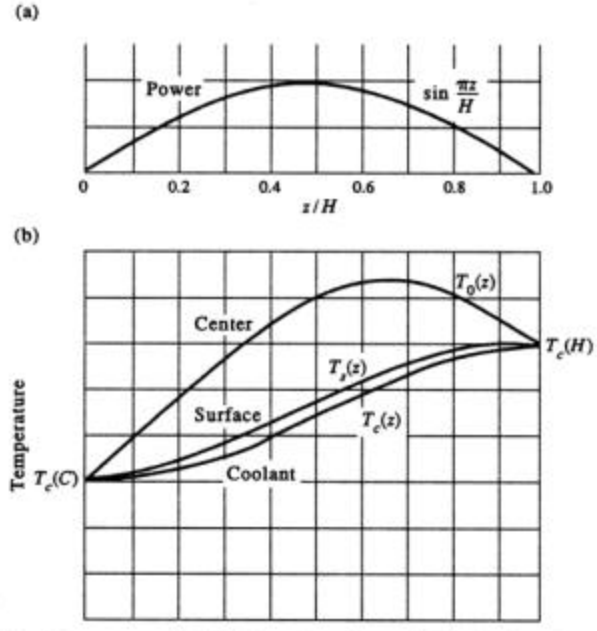


FIG. 12.3 Temperature distributions along channel with sine function power.

convection yields temperature curves as sketched in Fig. 12.3 (b). For this case, the highest temperatures of fuel surface and fuel center occur between the halfway point and the end of the reactor. In the design of a reactor, a great deal of attention is given to the determination of which channels have the highest coolant temperature and at which points on the fuel pins "hot spots" occur. Ultimately, the power of the reactor is limited by conditions at these channels and points. The mechanism of heat transfer from metal surfaces to water is quite sensitive to the temperature difference. As the latter increases, ordinary convection gives way to *nucleate boiling*, in which bubbles form at points on the surface, and eventually *film boiling* can occur, in which a blanket of vapor reduces heat transfer and permits hazardous melting. A parameter called "departure from nucleate boiling ratio" (DNBR) is used to indicate how close the heat flux is to the critical value. For example, a DNBR of 1.3 implies a safety margin of 30%. Figure 12.4 indicates maximum temperature values for a typical PWR reactor.

To achieve a water temperature of 600°F (about 315°C) requires that a very high pressure be applied to the water coolant-moderator. Figure 12.5 shows the behavior of water in the liquid and vapor phases. The curve that separates the two-phase regions describes what are called saturated conditions. Suppose that the pressure vessel of the reactor contains water at 2000 psi and 600°F and the temperature is raised to 650°F. The result will be considerable steam formation (flashing) within the liquid. The two-phase condition could lead to inadequate cooling of the reactor fuel. If instead the

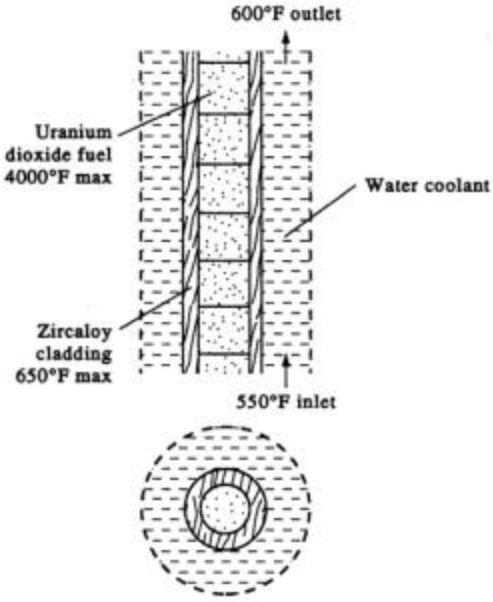


FIG. 12.4 Reactor channel heat removal.

pressure were allowed to drop, say to 1200 psi, the vapor region is again entered and flashing would occur. However, it should be noted that deliberate two-phase flow conditions are used in boiling water reactors, providing efficient and safe cooling.

12.3 Steam Generation and Electrical Power Production

Thermal energy in the circulating reactor coolant is transferred to a working fluid such as steam, by means of a heat exchanger or steam generator. In simplest construction, this device consists of a vessel partly filled with water, through which many tubes containing heated water from the reactor pass, as in Fig. 12.6. At a number of nuclear plants the steam generator has failed prematurely because of corrosion that created holes in tubes, requiring plugging or repair. In some cases replacement of the steam generator was required, with corresponding outage, cost, and loss of revenue. Details on the problem appear in an NRC Technical Issue Paper (see References). Steam from the generator flows to a turbine, while the water returns to the reactor. The conversion of thermal energy of steam into mechanical energy of rotation of a turbine and then to electrical energy from a generator is achieved by conventional means. Steam at high pressure and temperature strikes the blades of the turbine, which drives the generator. The exhaust steam is passed through a heat exchanger that serves as condenser, and the condensate is returned to the steam generator as feed water. Cooling water for the condenser is pumped from a nearby body of

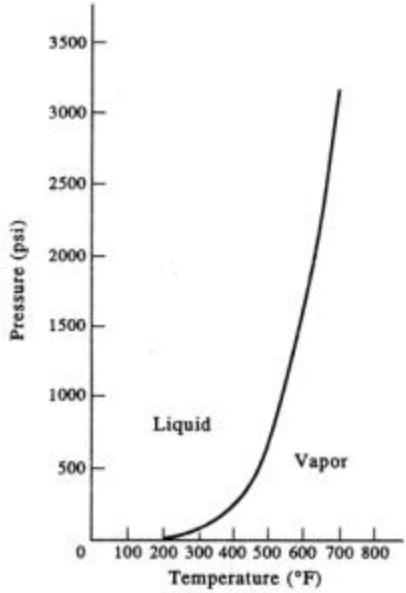


FIG. 12.5 Relationship of pressure and temperature for water.

water or cooling tower, as discussed in Section 12.4.

Figures 12.7 and 12.8 show the flow diagrams for the reactor systems of the PWR and BWR type. In the PWR, a pressurizer maintains the pressure in the system at the desired value. It uses a combination of immersion electric heaters and a water spray system to control the pressure. Figure 12.9 shows the Diablo Canyon nuclear power plant operated by Pacific Gas & Electric Co. at Avila Beach, California. The two Westinghouse PWR reactors were put into operation in 1985 and 1986.

12.4 Waste Heat Rejection

The generation of electric power by consumption of any fuel is accompanied by the release of large amounts of waste heat. For any conversion process the thermal efficiency, e, the ratio of work done to thermal energy supplied, is limited by the temperatures at which the system operates. According to the second law of thermodynamics, an ideal cycle has the highest efficiency value,

$$e = 1 - T_1/T_2,$$

where T_1 and T_2 are the lowest and highest absolute temperatures (Kelvin, °C+273; Rankine, °F+460). For example, if the steam generator produces steam at 300°C and cooling water for the condenser comes from a source at 20°C, we find the maximum efficiency of

$$e = 1 - 293/573 = 0.49.$$

The overall efficiency of the plant is lower than this because of heat loss in

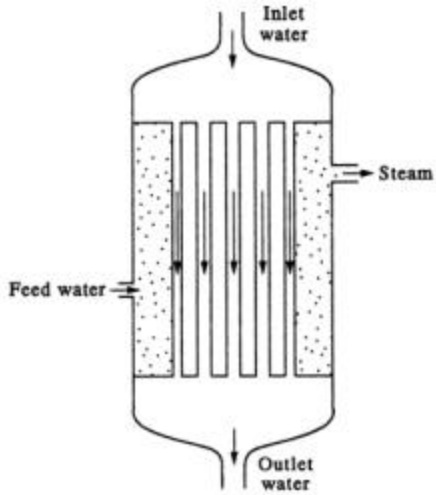


FIG. 12.6 Heat exchanger or steam generator.

piping, pumps, and other equipment. The efficiency of a typical nuclear power plant is only around 0.33. Thus twice as much energy is wasted as is converted into useful electrical energy. Fossil fuel plants can operate at higher steam temperatures, giving overall efficiencies of around 0.40.

A nuclear plant operating at electrical power 1000 MWe would have a thermal power of 1000/0.33 = 3030 MWt and must reject a waste power of P= 2030 MWt. We can calculate the condenser cooling water mass flow

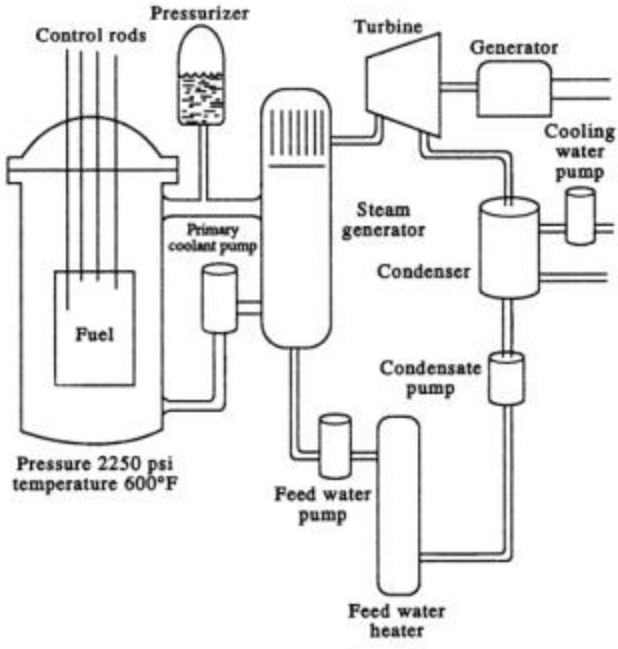


FIG. 12.7 PWR system flow diagram.

rate M required to limit the temperature rise to a typical figure of $\Delta T = 12°C$ using a specific heat of $c = 4.18 \times 10^3$ J/kg-°C,

$$M = \frac{P}{c\Delta T} = \frac{2.03\times 10^9}{(4.18\times 10^3)(12)} = 4.05\times 10^7 \text{ kg/s}.$$

This corresponds to a flow of 925 million gallons per day. Smaller power plants in past years were able to use the "run of the river," i.e., to take water from a stream, pass it through the condenser, and discharge heated water down stream. Stream flows of the order of a billion gallons a day are rare, and the larger power plants must dissipate heat by utilizing a large lake or cooling towers. Either method involves some environmental effects.

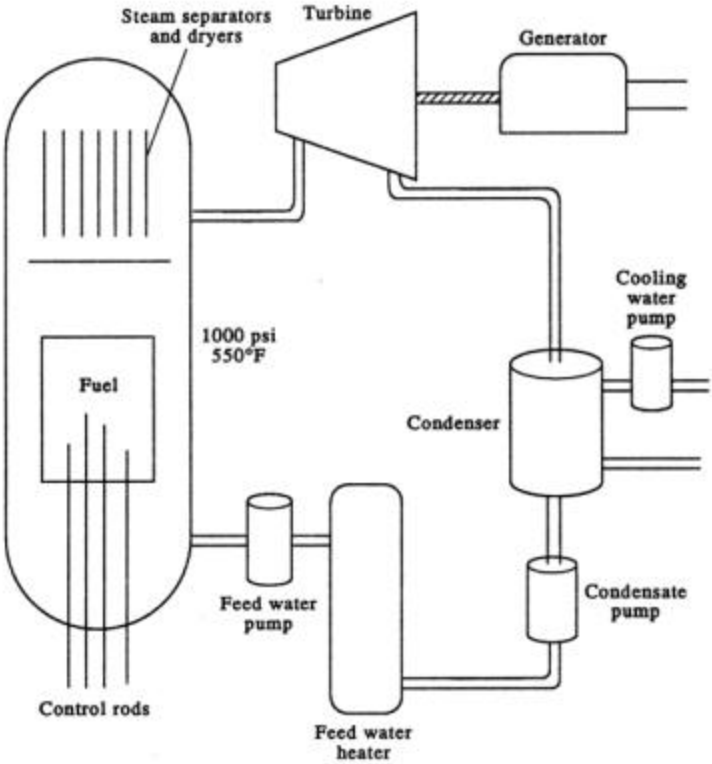


FIG. 12.8 BWR system flow diagram.

If a lake is used, the temperature of the water at the discharge point may be too high for certain organisms. It is common knowledge, however, that fishing is especially good where the heated water emerges. Means by which heat is removed from the surface of a lake are evaporation, radiation, and convection due to air currents. Regulations of the Environmental Protection Agency limit the rise in temperature in bodies of water. Clearly, the larger the lake and the wider the dispersal of heated water, the easier it is to meet

requirements. When the thermal discharge goes into a lake, the ecological effects are frequently called "thermal pollution," especially when plants and animals are damaged by the high temperatures. Other effects are the deaths of aquatic animals by striking screens, or passing through the system, or being poisoned by chemicals used to control the growth of undesirable algae.

FIG. 12.9 A nuclear power plant, Diablo Canyon, operated by Pacific Gas & Electric Co. on the coast of California (Courtesy Nuclear Energy Institute).

Many nuclear plants have had to adopt the cooling tower for disposal of waste heat into the atmosphere. In fact, the hyperboloid shape (see Fig. 12.10) is so common that many people mistake it for the reactor. A cooling tower is basically a large heat exchanger with air flow provided by natural convection or by blowers. In a "wet" type, the surface is kept saturated with moisture, and evaporation provides cooling. Water demands by this model may be excessive. In a "dry" type, analogous to an automobile radiator, the

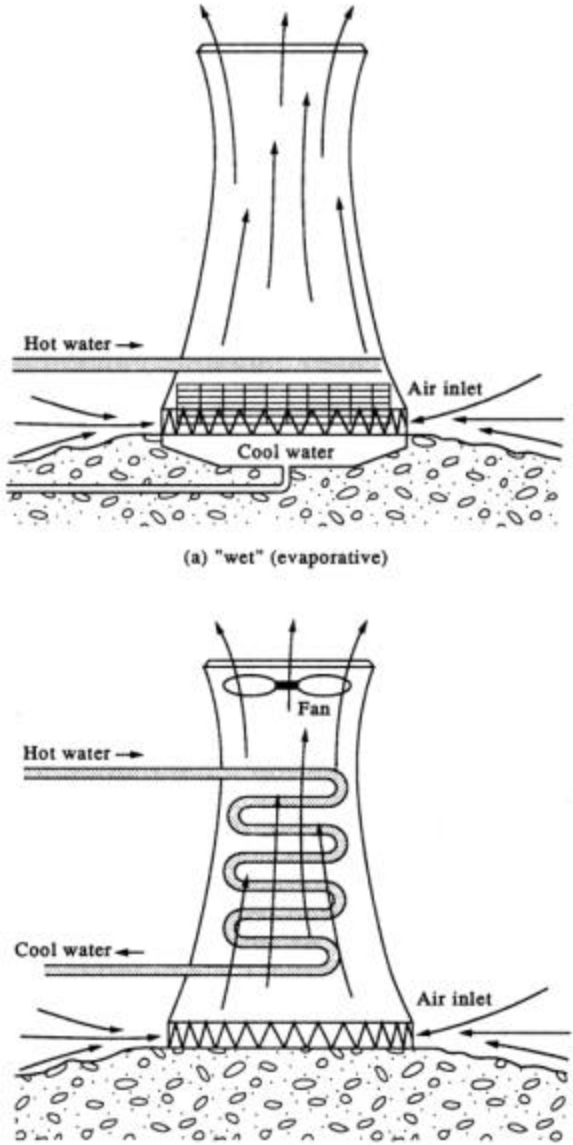


FIG. 12.10 Cooling tower (From "Thermal Pollution and Aquatic Life" by John R. Clark, *Scientific American*, March 1969).

cooling is by convection and requires more surface area and air flow. It is therefore larger and more expensive. A hybrid wet/dry cooling tower is used to minimize effects of vapor plumes in cold weather and to conserve water in hot weather.

Waste heat can be viewed as a valuable resource. If it can be utilized in

any way it reduces the need for oil and other fuels. Some of the actual or potential beneficial uses of waste heat are the following:

1. District heating. Homes, business offices, and factories of whole towns in Europe are heated in this way.
2. Production of fish. Warm water can be used to stimulate growth of the food fish need.
3. Extension of plant growth season. For colder climates, use of water to warm the soil in early Spring would allow crops to be grown for a longer period.
4. Biological treatment. Higher temperatures may benefit water treatment and waste digestion.

Each of such applications has merit, but there are two problems: (a) the need for heat is seasonal, so the systems must be capable of being bypassed in Summer or, if buildings are involved, they must be designed to permit air conditioning; and (b) the amount of heat is far greater than any reasonable use that can be found. It has been said that the waste heat from electrical plants was sufficient to heat all of the homes in the U.S. If all homes within practical distances of power plants were so heated, there still would be a large amount of unused waste heat.

A few reactors around the world have been designed or adapted to produce both electrical power and useful heat for space heating or process steam. The abbreviation CHP for combined heat and power is applied to these systems. It can be shown (see Exercise 12.11) that if half the turbine steam of a reactor with thermal efficiency 1/3 is diverted to useful purposes, the efficiency is doubled, neglecting any adjustment in operating conditions.

A practice called *cogeneration* is somewhat the reverse of waste heat utilization. A boiler used for producing steam can be connected to a turbine to generate electricity as well as provide process heat. Typical steam users are refineries, chemical plants, and paper mills. In general, cogeneration is any simultaneous production of electrical or mechanical energy and useful thermal energy, but it is regarded as a way to save fuel. For example, an oil-fired system uses 1 barrel (bbl) of oil to produce 750 kWh of electricity, and a process-steam system uses 2 bbl of oil to give 8700 lb of steam, but congeneration requires only 2.4 bbl to provide the same products.

12.5 Summary

The principal modes by which fission energy is transferred in a reactor are conduction and convection. The radial temperature distribution in a fuel pellet is approximately parabolic. The rate of heat transfer from fuel surface to coolant by convection is directly proportional to the temperature

difference. The allowed power level of a reactor is governed by the temperatures at local "hot spots." Coolant flow along channels extracts thermal energy and delivers it to an external circuit consisting of a heat exchanger (PWR), a steam turbine that drives an electrical generator, a steam condenser, and various pumps. Large amounts of waste heat are discharged by electrical power plants because of inherent limits on efficiency. Typically, a billion gallons of water per day must flow through the steam condenser to limit the temperature rise of the environment. Where rivers and lakes are not available or adequate, waste heat is dissipated by cooling towers, Potential beneficial uses of the waste thermal energy include space heating and stimulation of growth of fish and of plants. Some nuclear facilities produce and distribute both steam and electricity.

12.6 Exercises

12.1. Show that the temperature varies with radial distance in a fuel pin of radius R according to

$$T(r) = T_S + (T_0 - T_s)[1 - (r / R^2)],$$

where the center and surface temperatures are T_0 and T_s, respectively. Verify that the formula gives the correct results at $r = 0$ and $r = R$.

12.2. Explain the advantage of a circulating fuel reactor, in which fuel is dissolved in the coolant. What disadvantages are there?

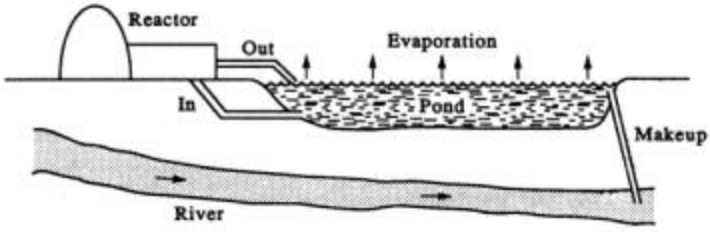
12.3. If the power density of a uranium oxide fuel pin, of radius 0.6 cm, is 500 W/cm^3, what is the rate of energy transfer per centimeter across the fuel pin surface? If the temperatures of pin surface and coolant are 300°C and 250°C, what must the heat transfer coefficient h be?

12.4. A reactor operates at thermal power of 2500 MW, with water coolant mass flow rate of 15,000 kg/s. If the coolant inlet temperature is 275°C, what is the outlet temperature?

12.5. A power reactor is operating with coolant temperature 500°F and pressure 1500 psi. A leak develops and the pressure falls to 500 psi. How much must the coolant temperature be reduced to avoid flashing?

12.6. The thermal efficiencies of a PWR converter reactor and a fast breeder reactor are 0.33 and 0.40, respectively. What are the amounts of waste heat for a 900 MWe reactor? What percentage improvement is achieved by going to the breeder?

12.7. As sketched, water is drawn from a cooling pond and returned at a temperature 14°C higher, in order to extract 1500 MW of waste heat. The heat is dissipated by water evaporation from the pond with an absorption of 2.26×10^3 J/g. How many kilograms per second of makeup water must be supplied from an adjacent river? What percentage is this of the circulating flow to the condenser?



12.8. As a rough rule of thumb, it takes 1-2 acres of cooling lake per megawatt of installed electrical capacity. If one conservatively uses the latter figure, what is the area for a 100-MWe plant? Assuming 35% efficiency, how much energy in joules is dissipated per square meter per hour from the water? Note: 1 acre = 4047 m^2.

12.9. How many gallons of water have to be evaporated each day to dissipate the waste thermal power of 2030 MWt from a reactor? Note that the heat of vaporization is 539.6 cal/g, the mechanical equivalent of heat is 4.18 J/cal, and 1 gal is 3785 cm^3.

12.10. Verify that about 1.6 kg of water must be evaporated to dissipate 1 kWh of energy.

12.11. A plant produces power both as useful steam S and electricity E from an input heat Q. Develop a formula for the overall efficiency $e¢$, expressed in terms of the ordinary efficiency $e = E/Q$ and x, the fraction of waste heat used for steam. Show that $e¢$ is 2/3 if $e = 1/3$ and $x = 1/2$. Find $e¢$ for $e = 0.4$ and $x = 0.6$.

Computer Exercises

12.A. If the thermal conductivity of UO_2 used as reactor fuel pins varies with temperature, it can be shown that the linear heat rate q_1 (W/cm) is $4p$ times the integral of k (W/cm-°C) with respect to temperature T (°C). (a) Using BASIC computer program CONDUCT which calculates the integral from 0 to T, verify that the integral is approximately 93 W/cm when T is the melting point of UO_2, 2800°C. (b) Find the linear heat rate using the maximum temperature TM = 2800°C and surface temperature TS = 315°C.

12.B. The temperature distribution within a reactor fuel pin for variable k can be calculated using the integrals of k over temperature (Exercise 12.A). In the BASIC program TEMPLOT, by specifying maximum allowed center temperature and the expected surface temperature for a fuel pellet of radius RO, the linear heat rate is calculated and used to obtain values of radius R as a function of temperature T. Test the program using typical inputs such as R = 0.5 cm, TM = 2300°C and TS = 300°C, plotting the resulting temperature distribution.

12.7 References for Chapter 12

Martin Becker, *Heat Transfer: A Modern Approach*, Plenum Press, New York, 1986. Uses spreadsheet techniques as well as analytic methods.

M. M. El-Wakil, *Nuclear Heat Transport*, American Nuclear Society, La Grange Park, IL, 1978.

William M. Kays and Michael E. Crawford, *Convective Heat and Mass Transfer*, 2nd edition, McGraw-Hill, New York, 1980.

Coolants for Nuclear Reactors
http://www.nuc.berkeley.edu/thyd/ne161/rahmed/coolants.html
Data on coolants and lists of advantages and disadvantages of various reactor types.

Joseph H. Keenan, et al. *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases/With Charts*, Krieger Publishing Co., 1992. A reprint of a classic work.

Steam Generator Tube Issues
http://www.nrc.gov/OPA/gmo/tip/tip27.htm
Technical Issue Paper by Nuclear Regulatory Commission.

Steam Generators
http://www.cannon.net/~gonyeau/nuclear/sg-mod1.htm

Photos of steam generator replacement process.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

Neil E. Todreas and Mujid S. Kazimi, *Nuclear Systems I: Thermal Hydraulic Fundamentals*; *Nuclear Systems II: Elements of Thermal Hydraulic Design*, Hemisphere Publishing Corp., New York, 1990. Advanced but understandable texts on thermal analysis. Comprehensive coverage with many numerical examples.

L. S. Tong and Joel Weisman, *Thermal Analysis of Pressurized Water Reactors*, 3rd Ed., American Nuclear Society, La Grange Park, IL, 1996. A graduate level book with principles, engineering data, and new information.

R. T. Lahey and F. J. Moody, *The Thermal-Hydraulics of a Boiling Water Nuclear Reactor*, 2nd Ed., American Nuclear Society, La Grange Park, IL, 1993. Emphasizes understanding of physical phenomena.

Nicholas P. Cheremisinoff and Paul N. Cheremisinoff, *Cooling Towers: Selection, Design and Practice*, Ann Arbor Science, Ann Arbor, MI, 1981.

G. B. Hill, E. J. Pring, and Peter D. Osborn, *Cooling Towers: Principles and Practice*, 3rd Ed., Butterworth-Heinemann, London, 1990.

R. W. Beck and Associates, *A Primer on the Rejection of Waste Heat from Power Plants*, PB-292 529, National Technical Information Service, Springfield, VA, May 1978. A report for reading by the general public, prepared for the California Energy Commission, Sacramento.

Cooling Towers
http://www.cannon.net/~gonyeau/nuclear/ct.htm
Descriptions and diagrams.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

Cooling Tower Design and Operation
http://www.cheresources.com/ctowerszz.shtml
Diagrams and theory of operation. DOS calculation program can be downloaded. By Christopher Haslego.

Marley Cooling Tower
http://www.marleyct.com/power2.htm
Typical commercial supplier.

13

Breeder Reactors

THE MOST important feature of the fission process is, of course, the enormous energy release from each reaction. Another significant fact, however, is that for each neutron absorbed in a fuel such as U-235, more than two neutrons are released. In order to maintain the chain reaction, only one is needed. Any extra neutrons available can thus be used to produce other fissile materials such as Pu-239 and U-233 from the "fertile" materials, U-238 and Th-232, respectively. The nuclear reactions yielding the new isotopes were described in Section 6.3. If losses of neutrons can be reduced enough, the possibility exists for new fuel to be generated in quantities as large, or even larger than the amount consumed, a condition called "breeding."

In this chapter we shall (a) examine the relationship between the reproduction factor and breeding, (b) describe the physical features of the liquid metal fast breeder reactor, and (c) look into the compatibility of uranium fuel resources and requirements.

13.1 The Concept of Breeding

The ability to convert significant quantities of fertile materials into useful fissile materials depends crucially on the magnitude of the reproduction factor, h, which is the number of neutrons produced per neutron absorbed in fuel. If n neutrons are produced per fission, and the ratio of fission to absorption in fuel is s_f / s_a, then the number of neutrons per absorption is

$$h = \frac{s_f}{s_a} n \, .$$

The greater its excess above 2, the more likely is breeding. It is found that both n and the ratio s_f / s_a increase with neutron energy and thus h is larger for fast reactors than for thermal reactors. Table 13.1 compares values of h for the main fissile isotopes in the two widely differing neutron energy ranges designated as thermal and fast. Inspection of the table shows that it is more difficult to achieve breeding with U-235 and Pu-239 in a thermal reactor, since the 0.07 or 0.11 neutrons are very likely to be lost by

absorption in structural materials, moderator and fission product poisons.

TABLE 13.1
Values of Reproduction Factor h

	Neutron energy	
Isotope	Thermal	Fast
U-235	2.07	2.3
Pu-239	2.11	2.7
U-233	2.30	2.45

A thermal reactor using U-233 is a good prospect, but the fast reactor using Pu-239 is the most promising candidate for breeding. Absorption of neutrons in Pu-239 consists of both fission and capture, the latter resulting in the isotope Pu- 240. If the latter captures a neutron, the fissile isotope Pu-241 is produced.

The ability to convert fertile isotopes into fissile isotopes can be measured by the conversion ratio (CR), which is defined as

$$\text{CR} = \frac{\text{fissile atoms produced}}{\text{fissile atoms consumed}}.$$

The fissile atoms are produced by absorption in fertile atoms; the consumption includes fission and capture.

We can compare values of CR for various systems. First is a "burner" fueled only with U-235. With no fertile material present, CR = 0. Second is a highly thermal reactor with negligible resonance capture, in which fuel as natural uranium, 99.28% U-238 and 0.72%U-235, is continuously supplied and consumed. Pu-239 is removed as fast as it is created. Here CR is the ratio of absorption in U-238 and U-235, and since they experience the same flux, CR is simply the ratio of macroscopic cross sections, S_{a238}/S_{a235}. Inserting the cross section ratio 2.7/681 and the atom ratio (ignoring U-234) 0.9928/0.0072, we obtain CR = 0.547. Third, we ask what conversion ratio is needed to completely consume both U isotopes in natural U as well as the Pu-239 produced? It is easy to show that CR is equal to the isotopic fraction of U-238, viz., 0.9928. Fourth, we can derive a more general relationship from the neutron cycle of Fig. 11.4. The result for initial operation of a critical reactor, before any Pu is produced, is

$$\text{CR} = S_{a\ 238}/S_{a\ 235} \grave{}+ h_{235}\, e \nu_f \quad (1 - p),$$

where h_{235} is the value for pure U-235, i.e., 2.07. For a natural U reactor with $\nu_f = 0.95$, $p = 0.9$. and $e = 1.03$, we find

$$\text{CR} = 0.547 + 0.203 = 0.750.$$

It is clear that reducing fast neutron leakage and enhancing resonance capture are favorable to the conversion process. An alternative simple formula, obtained by considerable manipulation as in Ex. 13.6, is

$$CR = h_{235}\, e - 1 - \ell$$

Where ℓ is the total amount of neutron loss by leakage and by non-fuel absorption, per absorption in U-235.

If unlimited supplies of uranium were available at very small cost, there would be no particular advantage in seeking to improve conversion ratios. One would merely burn out the U-235 in a thermal reactor, and discard the remaining U-238. Since the cost of uranium goes up as the accessible reserve decline, it is desirable to use the U-238 as well as the U-235. Similarly, the exploitation of thorium reserves is worthwhile.

When the conversion ratio is larger than 1, as in a fast breeder reactor, it is instead called the breeding ratio (BR), and the breeding gain (BG) = BR – 1 represents the extra plutonium produced per atom burned. The doubling time (DT) is the length of time required to accumulate a mass of plutonium equal to that in a reactor system, and thus provide fuel for a new breeder. The smaller the inventory of plutonium in the cycle and the larger the breeding gain, the quicker will doubling be accomplished. The technical term "specific inventory" is introduced, as the ratio of plutonium mass in the system to the electrical power output. Values of this quantity of 2.5 kg/MWe are sought. At the same time, a very long fuel exposure is desirable, e.g., 100,000 MWd/tonne, in order to reduce fuel fabrication costs. A breeding gain of 0.4 would be regarded as excellent, but a gain of only 0.2 would be very acceptable.

13.2 Isotope Production and Consumption

The performance of a breeder reactor involves many isotopes of fertile and fissionable materials. In addition to the U-235 and U-238, there is short-lived neptunium-239 (2.355 d), Pu-239 (2.411×10^4 y), Pu-240 (6537 y), Pu-241 (14.4 y), and Pu-242 (3.76×10^5 y), as well as americium and curium isotopes resulting from multiple neutron capture. The idea of a chain of reactions is evident. To find the amount of any of these nuclides present at a given time, it is necessary to solve a set of connected equations, each of the general type

$$\text{rate of change} = \text{generation rate} - \text{removal rate}$$

which is similar to the statement in Section 3.3 except that "removal" is more general than "decay" in that absorption (consumption or burnup) is included.

We can illustrate the approach to solving the balance equations as differential equations. Consider a simplified three-component system of nuclides, using a shorthand for the full names of the isotopes: 1 = U-235, 2 = U-238, and 3 = Pu-239. Because all of their radioactive half-lives are long in comparison with the time of irradiation in a reactor, true decay can be

ignored. However, it will be convenient to draw an analogy between decay and burnup. The equation for U-235 is

$$dN_1/dt = -\phi N_1 \sigma_{a1},$$

and if we let $\phi \sigma_{a1} = \lambda_{a1}$, the equation is the same as that for decay, the solution of which is

$$N_1(t) = N_{10} E_1, \text{ with } E_1 = \exp(-\lambda_{a1} t).$$

A similar solution may be written for U-238,

$$N_2(t) = N_{20} E_2, \text{ with } E_2 = \exp(-\lambda_{a2} t).$$

The growth equation for Pu-239 is

$$dN_3/dt = \gamma - \phi N_3 \sigma_{a3}, \text{ where } \gamma = \phi N_2 \sigma_{c2}.$$

where only the capture in U-238 gives rise to Pu-239, not the fission. Assuming that there is already some plutonium present when the fuel is loaded in the reactor, in amount N_{30}, the solution is

$$N_3(t) = N_{30} E_3 + N_{20} \lambda_{c2} (E_3 - E_2)/(\lambda_2 - \lambda_3),$$

where $E_3 = \exp(-\lambda_{a3} t)$. The first term on the right describes the burnup of initial Pu-239; the second term represents the net of production and consumption. Note the similarity in form of the equations to those in Computer Exercise 3.D related to parent-daughter radioactivity processes.

It is straightforward to calculate the numbers of nuclei, but time-consuming and tedious if one wishes to vary parameters such the reactor power and neutron flux level or the initial proportions of the different nuclides. To make such calculations easier, refer to Computer Exercise 13.A, in which the programs BREED and BREEDGE are applied.

A one neutron group model is not adequate to analyze the processes in a fast breeder reactor, where cross sections vary rapidly with energy. The accurate calculation of multiplication requires the use of several neutron energy groups, with neutrons supplied to the groups by fission and removed by slowing and absorption. In Computer Exercise 13.B the analysis is displayed and a simple fast reactor is computed by the program FASTR.

13.3 The Fast Breeder Reactor

Liquid metal fast breeder reactors (LMFBR) have been operated successfully throughout the world. In the United States the Experimental Breeder Reactor I at Idaho Falls was the first power reactor to generate electricity, in 1951. Its successor, EBR II, was used from 1963 to 1994 to test equipment and materials (see References). The Fermi I reactor built near Detroit was the first intended for commercial application. It was started in 1963 but was damaged by blockage of coolant flow passages and only operated briefly after being repaired.

The 400 MWt Fast Flux Test Facility (FFTF) at Richland, Washington, now shut down, did not generate electricity but provided valuable data on the performance of fuel, structural materials, and coolant (see References). After a number of years of design work and construction the U.S. government canceled the demonstration fast power reactor called Clinch River Breeder Reactor Project (CRBRP). There was a great deal of debate in the U.S. before CRBRP was abandoned. One argument for stopping the project was that increased prices of fuel, being only about one-fifth of the cost of producing electricity, would not cause converter reactors to shut down nor warrant switching to the newer technology except on a long-term basis. This political decision shifted the leadership for breeder development from the U.S. to other countries.

France took the initiative in the development of the breeder for the production of commercial electric power, in cooperation with other European countries. The reactor "Superphenix" was a full-scale pool-type breeder constructed with partial backing by Italy, West Germany, the Netherlands, and Belgium. The reactor was shut down because of sodium leaks and is unlikely to ever be restarted, in spite of the billions of dollars invested in the facility.

With the suspension of operation of Superphenix, the lead in breeder reactor development again shifted, this time to Japan, which placed its 280 MWe loop-type sodium-cooled MONJU into operation in 1993. It was part of Japan's long-range plan to construct of a number of breeders starting around 2020. However, in 1995 the reactor suffered a sodium leak (see References) and was shut down, possibly permanently in light of subsequent nuclear accidents in other facilities that raised public concerns.

The largest remaining liquid metal fast breeder reactor in the world is the BN-600 at the Beloyarskiy plant in Russia. Supplying electricity since 1981, it has operated more successfully than any other reactor in that country. Some of its pertinent features are listed in Table 13.2.

The use of liquid sodium as coolant ensures that there is little neutron moderation in the fast reactor. The element sodium melts at 208°F (98°C), boils at 1618°F (883°C), and has excellent heat transfer properties. With such a high melting point, pipes containing sodium must be heated electrically and thermally insulated to prevent freezing. The coolant becomes radioactive by neutron absorption in Na-23, producing the 15-h Na-24. Great care must be taken to prevent contact between sodium and water or air, which would result in a serious fire, accompanied by the spread of radioactivity. To avoid such an event, an intermediate heat exchanger is employed, in which heat is transferred from radioactive sodium to nonradioactive sodium.

TABLE 13.2
BN-600 liquid metal fast breeder reactor, Beloyarskiy Unit #3, Russia
From *World Nuclear Industry Handbook* (see References, INSC)

Electric power	560 MW
Sodium coolant temperatures	377 °C , 550 °C
Core fuel height	1.03 m
Core diameter	2.05 m
Vessel height, diameter	12.6 m, 12.86 m
Fuel (w/o U-235)	UO_2 (17, 21, 26)
Pin o.d.	6.9 mm
Cladding	stainless steel
Clad thickness	0.4 mm
Pin pitch (triangular)	9.82 mm
Pins per assembly	127
Number of assemblies	369
Number of B_4C rods	27
Average power density	413 kWt/l
Cycle length	5 months

Two physical arrangements of the reactor core, pumps, and heat exchanger are possible, shown schematically in Figs. 13.1 and 13.2. The "loop" type is similar to the thermal reactor system, while in the "pot" type all of the components are immersed in a pool of liquid Na. There are advantages and disadvantages to each concept, but both are practical.

In order to obtain maximum breeding ratios in the production of new fertile material, more than one fuel zone is needed. The neutron multiplying core of the breeder reactor is composed of mixed oxide (MOX) fuel as a mixture of U and Pu. Surrounding the core is a natural uranium oxide "blanket" or "breeding blanket." In early designs the blanket acted as a reflector for a homogeneous core, but modern designs involve blanket rings both inside and outside the core, rendering the system heterogeneous. The new arrangement is predicted to have enhanced safety as well.

Deployment of breeder reactors demands recycling of the plutonium. This in turn requires reprocessing, which involves physical and chemical treatment of irradiated fuel to separate uranium, plutonium, and fission products. We reserve discussion of reprocessing until Section 22.5, in connection with waste disposal. The U.S. abandoned commercial reprocessing because of concerns about the diversion of plutonium and is unlikely to resume the practice for the present generation of power reactors.

After CRBRP was canceled, the U.S. continued development of the Integral Fast Reactor (IFR) at Argonne National Laboratory (see References). The reactor had an associated fuel fabrication and reprocessing system. The fuel was an alloy of U, Pu, and Zr, converted electrochemically. The actinides, elements of atomic number 90 to 103, were recycled and burned by the fast neutrons rather than becoming long-

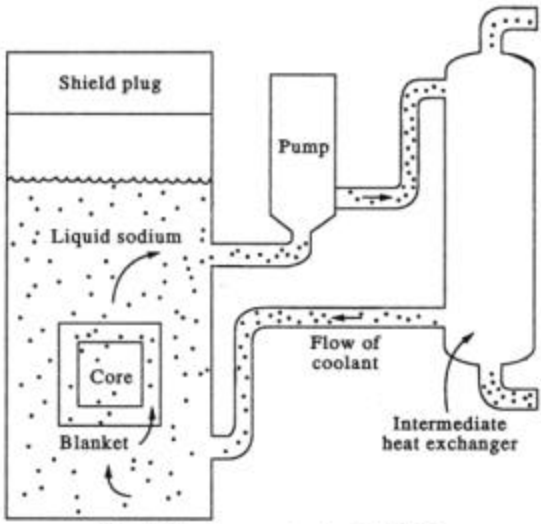


FIG. 13.1 Loop system for LMFBR.

lived radioactive wastes. The reactor was considered to be inherently or passively safe. The project was abandoned as an economic and political decision. A commercial outgrowth of the IFR was the ALMR (Advanced Liquid Metal Reactor) or PRISM, involving Argonne National Laboratory and General Electric (see References). That design project was also terminated.

Although the principal attention throughout the world has been given to the liquid metal cooled fast breeder using U and Pu, other breeder reactor concepts might someday become commercially viable. The thermal breeder reactor, using thorium and uranium-233, has always been an attractive option. One extensive test of that type of reactor was the Molten Salt

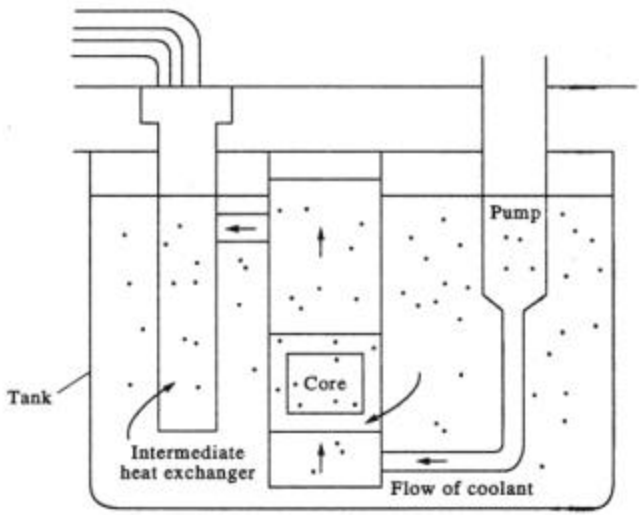


FIG. 13.2 Pot system for LMFBR.

Reactor Experiment at Oak Ridge, an outgrowth of the aircraft nuclear program of the 1960s (see Section 20.6). The MSRE demonstrated the feasibility of the circulating fuel concept, using salts of lithium, beryllium, and zirconium as solvent for uranium and thorium fluorides. Other concepts are (a) uranium and thorium fuel particles suspended in heavy water, (b) a high-temperature gas-cooled graphite-moderated reactor containing beryllium, in which the (n,2n) reaction enhances neutron multiplication.

13.4 Breeding and Uranium Resources

From the standpoint of efficient use of uranium to produce power, it is clearly preferable to employ a breeder reactor instead of a converter reactor. The breeder has the ability to use nearly all of the uranium rather than a few percent. Its impact can be viewed in two different ways. First, the demand for natural uranium would be reduced by a factor of about 30, cutting down on fuel costs while reducing the environmental effect of uranium mining. Second, the supply of fuel would last longer by the factor of 30. For example, instead of a mere 50 years for use of inexpensive fuel, we would have 1500 years. It is less clear, however, as to when a well-tested version of the breeder would actually be needed. A simplistic answer is, "when uranium gets very expensive." Such a situation is not imminent because there has been an oversupply of uranium for a number of years, and all analyses show that breeders are more expensive to build and operate than converters. A reversal in trend is not expected until some time in the 21st century. The urgency to develop a commercial breeder has lessened as the result of slower adoption of nuclear power than anticipated, with the smaller rate of depletion of resources. Another key factor is the availability in the U.S. and the former U.S.S.R of large quantities of surplus weapons plutonium, which can be used as fuel in the form of MOX.

It is useful to make a comparison of demand and reserves. On a world basis, according to Table 13.3, the annual requirement as of the year 2000 is estimated to be 64,524 tonnes. This is to be compared to the "reasonably assured resources" at cost up to $80/kg of 2,534,420 tonnes. Simple arithmetic tells us that such inexpensive resources would last only 39 years, assuming constant fuel requirements. The time would be extended if we add in other categories such as "estimated additional resources" but would be reduced if more reactors than expected went on line.

Using global figures obscures the problem of distribution. In Table 13.3 we list the top countries in the categories demand and resources. Some surprising disparities are seen. The leading potential uranium supplier, Australia, is not on the list of users, and the second supplier, Kazakhstan, is barely on that list. On the other hand, the second highest user, Japan, has

TABLE 13.3
Uranium Demand and Resources (in 1000s of tonnes)
From OECD-IAEA report (see References)

Country	Annual demand (2000 est.)	Country	Reasonably assured resources to $80/kg
United States	18.100	Australia	622.0
Japan	9.700	Kazakhstan	439.22
France	8.600	Canada	331.0
Russia	4.341	South Africa	218.30
Germany	3.000	Brazil	162.0
Korea	2.890	Namibia	156.12
Ukraine	2.820	Russia	145.0
United Kingdom	2.500	United States	110.0
Canada	1.800	Niger	69.96
Sweden	1.500	Uzbekhistan	66.21
Spain	1.240	Mongolia	61.60
Belgium	1.050	India	51.0
Taiwan	0.810	Ukraine	45.60
Brazil	0.680	Algeria	26.0
Bulgaria	0.649	France	13.46
China	0.600	Turkey	9.13
Finland	0.557	Central African Rep.	8.0
Czech Republic	0.525	Bulgaria	7.83
Slovak Republic	0.495	Portugal	7.30
Switzerland	0.479	Czech Republic	6.63
Lithuania	0.425	Gabon	6.03
Hungary	0.420	Italy	4.80
Mexico	0.257	Spain	4.65
India	0.246	Argentina	4.62
South Africa	0.200	Slovenia	2.20
Argentina	0.150	Zaire	1.80
Slovenia	0.102	Zimbabwe	1.80
Romania	0.100	Peru	1.79
Armenia	0.089	Greece	1.0
Netherlands	0.084	Hungary	0.37
Pakistan	0.065		
Kazakhstan	0.050		
Total	64.524	Total	2534.42

negligible U resources. Thus there must be a great deal of import/export trade to meet fuel needs. At some time in the future, in place of the Organization of Petroleum Exporting Countries (OPEC), there is the possibility of a "OUEC" cartel. Alternatively, it means that for assurance of uninterrupted production of nuclear power, some countries are much more interested than others in seeing a breeder reactor developed.

The resource situation for the U.S. is indicated by Table 13.4. We see that the U.S. has ample reserves in each of the categories. Not included here is the large stockpile of depleted uranium, as tails from the uranium isotope separation process. Such material is as valuable as natural uranium for use

TABLE 13.4
U.S. Uranium Reserves
From "Red Book" (see References)

Category	Cost range	Amount (1000s of tonnes)
Reasonably assured	up to $80/kg	110
	$80/kg to $130/kg	361
Estimated additional	up to $80/kg	839
	$80/kg to $130/kg	1270
Speculative	$260/kg	1340

in a blanket to breed plutonium. The principal U.S. deposits in order of size are in Wyoming, New Mexico, Colorado, Texas (coastal plain), and near the Oregon-Nevada border. The greatest concentration of estimated additional resources are in Utah and Arizona. Most of the ores come from sandstone; about 30 uranium mills are available. Exploration by surface drilling has tapered off continually since the middle 1970s when nuclear power was expected to grow rapidly. One unconventional source of uranium is marine phosphates, processed to obtain phosphoric acid.

There is considerable sentiment in the nuclear community for storing spent fuel from converter reactors rather than burying it as a waste, in anticipation of an energy shortage in the future as fossil fuels become depleted. If such a policy were adopted, the plutonium contained in the spent fuel could be recovered in a leisurely manner. The plutonium would provide the initial loading of a new generation of fast breeder reactors and the recovered uranium would serve as blanket material.

It is not possible to predict the rate of adoption of fast breeder reactors for several reasons. The capital costs and operating costs for full-scale commercial systems are not firmly established. The existence of the satisfactory LWR and the ability of a country to purchase slightly enriched uranium or MOX tends to delay the installation of breeders. It is conceivable, however, that the conventional converter reactors could be replaced by breeders in the coming century because of fuel resource limitations. It is possible that the breeder could buy the time needed to fully develop alternative sources such as nuclear fusion, solar power, and geothermal energy. In the next chapter the prospects for fusion are considered.

13.5 Summary

If the value of the neutron reproduction factor h is larger than 2 and losses of neutrons are minimized, breeding can be achieved, with more fuel produced than is consumed. The conversion ratio (CR) measures the ability

of a reactor system to transform a fertile isotope, e.g., U-238, into a fissile isotope, e.g., Pu-239. Complete conversion requires a value of CR of nearly 1. Fast breeder reactors using liquid sodium with breeding ratios (BR) greater than 1 have been built and operated, but several development programs have been canceled. One large scale breeder continues to operate in Russia. There is a great disparity between uranium resources and uranium use among the countries of the world. Application of the breeder could stretch the fission power option from a few decades to centuries.

13.6 Exercises

13.1. What are the largest conceivable values of the conversion ratio and the breeding gain?

13.2. An "advanced converter" reactor is proposed that will utilize 50% of the natural uranium supplied to it. Assuming all the U-235 is used, what must the conversion ratio be?

13.3. Explain why the use of a natural uranium "blanket" is an important feature of a breeder reactor.

13.4. Compute h and BG for a fast Pu-239 reactor if $n = 2.98$, $s_f = 1.85$, $s_c = 0.26$, and $\ell = 0.41$. (Note that the fast fission factor e need not be included.)

13.5. With a breeding ratio BR = 1.20, how many kilograms of fuel will have to be burned in a fast breeder reactor operating only on plutonium in order to accumulate an extra 1260 kg of fissile material? If the power of the reactor is 1250 MWt, how long will it take in days and years, noting that it requires approximately 1.3 g of plutonium per MWd?

13.6. (a) Using the neutron cycle, Fig. 11.4, find a formula for ℓ as defined in Section 13.1.

(b) Calculate the value of ℓ and verify that the alternative formula gives the same answer as in the text, CR = 0.750.

Computer Exercises

13.A. A breeder reactor is successful if it produces more fissionable material than it consumes. To test that possibility apply computer programs BREED and BREEDGE. The first of these uses cross sections for U-235, U-238, and Pu-239 as deduced from early critical experiments on weapons material assemblies. The second uses more modern cross sections, appropriate to a power reactor design. (a) Run the programs, varying parameters, to explore trends. (b) Use the following common input on both programs: U-235 atom fraction 0.003 (depleted U), plutonium volume fraction 0.123, fast flux 4.46×10^{15} cm^2 s^{-1}. (c) Discuss observations of trends and seek to explain in terms of assumed cross section sets.

13.B. Program FASTR solves the neutron balance equations for a fast reactor using classic 16-group Hansen-Roach cross sections prepared by Los Alamos. Those input numbers are found in the report *Reactor Physics Constants*, ANL-5800, 1963, page 568 ff. Run the program using the menus, observing input data and calculated results. Compare results for the case of pure U-235 with those obtained in Computer Exercise 11.A, using program CRITICAL.

13.7 References for Chapter 13

Karl Wirtz, *Lectures on Fast Reactors*, American Nuclear Society, La Grange Park, IL, 1976.

George A. Vendreyes, "Superphenix: A Full-Scale Breeder Reactor," *Scientific American*, March 1977, p. 26.

A. M. Judd, *Fast Breeder Reactors: An Engineering Introduction*, Pergamon Press, Oxford, 1981.

Alan E. Waltar and Albert B. Reynolds, *Fast Breeder Reactors*, Pergamon Press, New York, 1981.

C. Pierre Zaleski, "Fast Breeder Reactor Economics," in Karl O. Ott and Bernard I. Spinrad, Editors, *Nuclear Energy: A Sensible Alternative*, Plenum Press, New York and London, 1985.

EBR-II
http://www.anlw.anl.gov/anlw_history/reactors/ebr_ii.html
History of reactor with links to safety tests.

Liquid Metal Fast Breeder
http://www.ans.neep.wisc.edu/~ans/point_source/AEI/oct95/LMFBR_oct95.html
History and status as viewed by Rod Adams in issue of Atomic Energy Insights.

The Unofficial IFR Home Page
http://www.Nuc.Berkeley.EDU/ifr.html
Description provided by University of California.

Introduction to the ALMR/PRISM
http://www.nuc.berkeley.edu/~gav/almr/01.intro.html
Description provided by University of California.

Advanced Nuclear Reactors: Current Developments and Future Prospects
http://www.elsevier.co.jp
Select Engineering, Energy and Technology; Energy and Power; Nuclear Energy and Engineering; Books; Advanced Nuclear Reactors (also available in magazine *Energy*, June 1998)

BN-600 LMFBR
http://www.insc.anl.gov
Select Power Reactors/Map of World's Nuclear Power Plants/Russia/Beloyarskiy3.

Fast Neutron Reactors
http://www.ippe.rssi.ru/welcome/activity/fast_eng.html
Review of Russian reactors with link to BN-600.

Uranium 1997 Resources, Production and Demand, OECD Nuclear Energy Agency and International Atomic Energy Agency, Paris, 1998 ("Red Book"). Tabulations and analyses are based on estimates provided by the individual countries. A biennial publication.

Energy Information Administration (DOE)
http://www.eia.doe.gov/fuelnuclear.html
All about uranium, including report Uranium Industry Annual 1998.

14

Fusion Reactors

A DEVICE that permits the controlled release of fusion energy is designated as a fusion reactor, in contrast with one yielding fission energy, the fission reactor. As discussed in Chapter 7, the potentially available energy from the fusion process is enormous. The possibility of achieving controlled thermonuclear power on a practical basis has not yet been demonstrated, but progress in recent years gives encouragement that fusion reactors can be in operation in the twenty-first century. In this chapter we shall review the choices of nuclear reaction, study the requirements for feasibility and practicality, and describe the physical features of machines that have been tested. Suggestions on this chapter by John G. Gilligan are recognized with appreciation.

14.1 Comparison of Fusion Reactions

The main nuclear reactions that combine light isotopes to release energy, as described in Section 7.1, are the D-D, D-T, and D-^{3}He. There are advantages and disadvantages of each. The reaction involving only deuterium uses an abundant natural fuel, available from water by isotope separation. However, the energy yields from the two equally likely reactions are low (4.03 and 3.27 MeV). Also the reaction rate as a function of particle energy is lower for the D-D case than for the D-T case, as shown in Fig. 14.1. The quantity $\overline{su}$, dependent on cross section and particle speed, is a more meaningful variable than the cross section alone.

The D-T reaction yields a helium ion and a neutron with energies as indicated:

$$ {}_1^2\mathrm{H} + {}_1^3\mathrm{H} \rightarrow {}_2^4\mathrm{He}(3.5\,\mathrm{MeV}) + {}_0^1\mathrm{n}(14.1\,\mathrm{MeV}). $$

The cross section is large and the energy yield is favorable. The ideal ignition temperature (Section 7.3) for the D-T reaction is only 4.4 keV in contrast with 48 keV for the D-D reaction, making the achievement of practical fusion with the former far easier. One drawback, however, is that the artificial isotope tritium is required. Tritium can be generated by neutron absorption in lithium, according to the two reactions

$$ {}_3^6\mathrm{Li} + {}_0^1\mathrm{n} \rightarrow {}_1^3\mathrm{H} + {}_2^4\mathrm{He} + 4.8\,\mathrm{MeV} $$

$$^{7}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{H} + {}^{1}_{0}\mathrm{n} - 2.5\mathrm{MeV}\,.$$

The neutron can come from the D-T fusion process itself, in a breeding cycle similar to that in fission reactors. Liquid lithium can thus be used as a coolant and a breeding blanket.

The fact that the D-T reaction gives a neutron as a byproduct is a disadvantage in the operation of a fusion machine. Wall materials are readily damaged by bombardment by 14.1 MeV neutrons, requiring frequent wall replacement. Also, materials of construction become radioactive as the result of neutron capture. These are engineering and operating difficulties while the achievement of the high enough energy to use neutron-free reactions would be a major scientific challenge.

In the long run, use of the D-T reaction is limited by the availability of lithium, which is not as abundant as deuterium. All things considered, the D-T fusion reactor is the most likely to be operated first, and its success might lead to the development of a D-D reactor.

14.2 Requirements for Practical Fusion Reactors

The development of fusion as a new energy source involves several levels of accomplishment. The first is the performance of laboratory experiments to show that the process works on the scale of individual particles and to make measurements of cross sections and yields. The second is to test various devices and systems intended to achieve an energy output that is at least as large as the input, and to understand the scientific basis of the processes. The third is to build and operate a machine that will produce net power of the order of megawatts. The fourth is to refine the design and construction to make the power source economically competitive. The first of these levels has been reached for some time, and the second is in progress with considerable promise of success. The third and fourth steps remain for achievement in the 21st century.

The hydrogen bomb was the first application of fusion energy, and it is conceivable that deep underground thermonuclear explosions could provide heat sources for the generation of electricity, but environmental concerns and international political aspects rule out that approach. Two methods involving machines have evolved. One consists of heating to ignition a plasma that is held together by electric and magnetic forces, the magnetic confinement fusion (MCF) method. The other consists of bombarding pellets of fuel with laser beams or charged-particle beams to compress and heat the material to ignition, the inertial confinement (ICF) method. Certain conditions must be met for each of these approaches to be considered successful.

The first condition is achievement of the ideal ignition temperature of

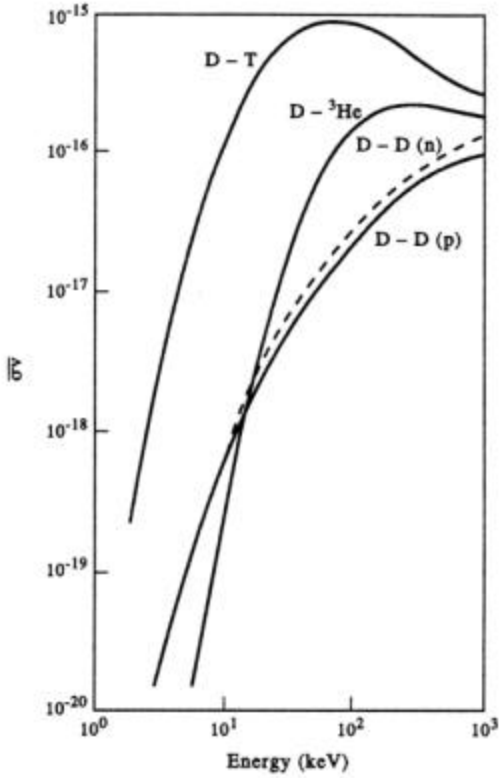


FIG. 14.1 Reaction rates for fusion reactions. The quantity $\overline{\sigma v}$, the average over a Maxwellian distribution of cross section times speed, when multiplied by particle densities gives the fusion rate per unit volume.

4.4 keV for the D-T reaction. A second condition involves the fusion fuel particle number density n and a confinement time for the reaction, t. It is called the *Lawson criterion*, and usually expressed as

$$nt \geq 10^{14}\ \mathrm{s/cm^3}.$$

A formula of this type can be derived for magnetic confinement fusion by looking at energy and power in the plasma, Suppose that the numbers of particles per cm^3 are n_D deuterons, n_T tritons, and n_e electrons. Further, let the total number of heavy particles be $n = n_D + n_T$ with equal numbers of the reacting nuclei, $n_D = n_T$, and $n_e = n$ for electrical neutrality. The reaction rate of the fusion fuel particles is written using Section 4.3 as $n_D\ n_T s\ u$, and if E is the energy yield per reaction, the fusion power density is

$$p_f = n^2 s\ uE/4,$$

proportional to the square of the ion number density.

Now the power loss rate can be expressed as the quotient of the energy content $(n_e + n_D + n_T)\ (3kT/2)$ and the confinement time t, i.e.,

$$p_1 = 3nkT/t.$$

Equating the powers and solving,

$$n\tau = \frac{12kT}{\sigma v E}.$$

Insert the ideal ignition energy of kT = 4.4 keV, the fusion energy E = 17.6 MeV, and let σv be equal to the value of $\overline{\sigma v}$ from Fig. 14.1 of around 10^{-17}. The result is 3×10^{14}, of the correct order of magnitude. The Lawson criterion, however, is only a rough rule of thumb to indicate fusion progress through research and development. Detailed analysis and experimental test are needed to evaluate any actual system.

Similar conditions must be met for inertial confinement fusion. An adequate ion temperature must be attained. The Lawson criterion takes on a little different form, relating the density ρ and the radius r of the compressed fuel pellet,

$$\rho r > 3 \text{ g/cm}^2.$$

The numerical value is set in part by the need for the radius to be larger than the range of α particles, in order to take advantage of their heating effect. For example, suppose that 1 mm radius spheres of a mixture of D and T in liquid form, density 0.18 g/cm^3, are compressed by a factor of 2500. The radius is reduced by a factor of $(2500)^{1/3}$ = 13.6, and the density is increased to (2500) (0.18) = 450 g/cm^3. Then ρr = 3.3, which meets the objective.

It is interesting to note that the factors that go into the products $n\tau$ are very different for the two types of fusion. For MCF typically $n = 10^{14}$/cm^3 and τ = 1 s, while for ICF $n = 10^{24}$/cm^3 and $\tau = 10^{-10}$ s.

The analysis of fusion reactors involves many other parameters of physics and engineering. A useful collection of formulas and methods of calculating are discussed in Computer Exercise 14.A.

Progress toward practical fusion can be measured by the parameter Q, which is the ratio of energy output to energy input. "Breakeven" is achieved if Q = 1. When ignition is reached, no energy input is required, so Q is equal to infinity.

14.3 Magnetic Confinement Machines

A number of complex MCF machines have been devised to generate a plasma and to provide the necessary electric and magnetic fields to achieve confinement of the discharge. We shall examine a few of these to illustrate the variety of possible approaches.

First, however, consider a simple discharge tube consisting of a gas-filled glass cylinder with two electrodes as in Fig. 14.2(a). This is similar to the familiar fluorescent lightbulb. Electrons accelerated by the potential

difference cause excitation and ionization of atoms. The ion density and temperature of the plasma that is established are many orders of magnitude below that needed for fusion. To reduce the tendency for charges to diffuse to the walls and be lost, a current-carrying coil can be wrapped around the tube, as sketched in Fig. 14.2(b). This produces a magnetic field directed along the axis of the tube, and charges move in paths described by a helix, the shape of a stretched coil spring. The motion is quite similar to that of ions in the cyclotron (Section 8.4) or the mass spectrograph (Section 9.1). The radii in typical magnetic fields and plasma temperatures are the order of 0.1 mm for electrons and near 1 cm for heavy ions (see Exercise 14.1). In order to further improve charge density and stability, the current along the tube is increased to take advantage of the *pinch effect*, a phenomenon related to the electromagnetic attraction of two wires that carry current in the same direction. Each of the charges that move along the length of the tube constitutes a tiny current, and the mutual attractions provide a constriction in the discharge.

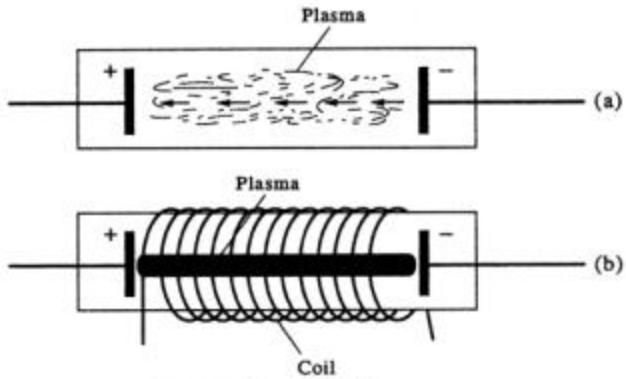


FIG. 14.2 Electrical discharges.

Neither of the above magnetic effects prevent charges from moving freely along the discharge tube, and losses of both ions and electrons are experienced at the ends. Two solutions of this problem have been tried. One is to wrap extra current-carrying coils around the tube near the ends, increasing the magnetic field there. This causes charges to be forced back into the region of weak field, i.e., to be reflected. This "mirror machine" is not perfectly reflecting. Another approach is to create endless magnetic field lines by bending the vacuum chamber and the coils surrounding it into the shape of a figure eight. An early version of this arrangement, called a "stellarator," is still being considered as a favorable system because it does not depend on internal currents for plasma confinement. It could operate continuously rather than in pulses.

A completely different solution to the problem of charge losses is to

produce the discharge in a doughnut-shaped tube, a torus, as shown in Fig. 14.3. The first successful ring-shaped fusion machine was developed by scientists of the U.S.S.R. around 1960. They called it *tokamak*, an acronym in Russian for toroid–chamber–magnet–coil. Since the tube has no ends, the magnetic field lines produced by the coils are continuous. The free motion of charges along the circular lines does not result in losses. However, there is a variation in this toroidal magnetic field over the cross section of the tube that causes a small particle migration toward the wall. To prevent such migration, a current is passed through the plasma, generating a poloidal magnetic field. The field lines are circles around the current, and tend to cancel electric fields that cause migration. Vertical magnetic fields are also employed to stabilize the plasma.

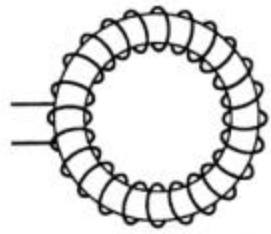


FIG. 14.3 Plasma confinement in torus.

Plasmas of MCF machines must be heated to reach the necessary high temperature. Various methods have been devised to supply the thermal energy. The first method, used by the tokamak, is resistance (ohmic) heating. A changing current in the coils surrounding the torus induces a current in the plasma. The power associated with a current through a resistance is $I^2 R$. The resistivity of a "clean" hydrogen plasma, one with no impurity atoms, is comparable to that of copper. Impurities increase the resistivity by a factor of four or more. There is a limit set by stability on the amount of ohmic heating possible.

The second method of heating is neutral particle injection. The sequence of events is as follows: (a) a gas composed of hydrogen isotopes is ionized by an electron stream; (b) the ions of hydrogen and deuterium produced in the source are accelerated to high speed through a vacuum chamber by a voltage of around 100 kV; (c) the ions pass through deuterium gas and by charge exchange are converted into directed neutral atoms; (d) the residual slow ions are drawn off magnetically while the neutrals cross the magnetic field lines freely to deliver energy to the plasma.

The third method uses microwaves in a manner similar to their application to cooking. The energy supply is a radio-frequency (RF) generator. It is connected by a transmission line to an antenna next to the plasma chamber. The waves enter the chamber and die out there, delivering

energy to the charges. If the frequency is right, resonant coupling to natural circular motions of electrons or ions can be achieved. The phrases electron (or ion) cyclotron radio-frequency, ECRF (or ICRF) come from the angular frequency of a charge q with mass m in a magnetic field B, proportional to qB/m as discussed in Section 8.1.

Since the fusion reactions burn the deuterium-tritium fuel, new fuel must be introduced to the plasma as a puff of gas, or as a stream of ions, or as particles of liquid or solid. The latter method seems best, in spite of the tendency for the hot plasma to destroy the pellet before it gets far into the discharge. It appears that particles that come off the pellet surface form a protective cloud. Compressed liquid hydrogen pellets of around 10^{20} atoms moving at 80 m/s are injected a rate of 40 per second.

The mathematical theory of electromagnetism is used to deduce the magnetic field shape that gives a stable arrangement of electric charges. However, any disturbance can change the fields and in turn affect the charge motion, resulting in an instability that may disrupt the field configuration. The analysis of such behavior is more complicated than that of ordinary fluid flow because of the presence of charges. In a liquid or gas, the onset of turbulence occurs at a certain value of the Reynolds number. In a plasma with its electric and magnetic fields, many additional dimensionless numbers are needed, such as the ratio of plasma pressure to magnetic pressure (b) and ratios to the plasma size of the mean free path, the ion orbits, and the Debye length (a measure of electric field penetration into a cloud of charges). Several of the instabilities such as the "kink" and the "sausage" are well understood and can be corrected by assuring certain conditions.

Stability of the plasma is not sufficient to assure a practical fusion reactor because of various materials engineering problems. The lining of the vacuum chamber containing the plasma is subjected to radiation damage by the 14-MeV neutrons from the D-T reaction. Also, when the plasma is disrupted, the electric forces cause "runaway electrons" to bombard the chamber wall, generating large amounts of heat. Materials will be selected to minimize the effects on what are called plasma-facing components, and reduce the frequency of need for replacement. An example is a graphite fiber composite similar to those used to protect the surface of the space shuttle on re-entry. Other possible wall materials are silicon carbide, beryllium, tungsten, and zirconium, with the latter metals possibly enriched in an isotope that does not absorb neutrons. Some self-protection of the chamber lining is provided by vaporization of materials, with energy absorbed by a "vapor shield."

The eventual practical fusion reactor will require a system to generate

tritium. As an alternative to using liquid lithium in a breeding blanket, consideration is given to a molten salt composed of fluorine, lithium, and beryllium (Li_2BeF_4 called "flibe"). The (n,2n) reaction in Be would enhance the breeding of tritium. Another possibility is the use of the ceramic lithium oxide (Li_2O).

A number of tokamaks have been built at research facilities around the world. Prominent examples are:

(a) The Tokamak Fusion Test Reactor (TFTR) at Princeton, now shut down, that achieved very high plasma temperatures.

(b) The Joint European Torus (JET) at Abingdon, England, a cooperative venture of several countries, which has employed the D-T reaction. Figure 14.4 shows the interior of JET with a person inside that provides scale.

(c) The Japanese Atomic Energy Research Institute Tokamak-60 (JT-60 Upgrade), used to study plasma physics. The National Institute for Fusion Sciences also operates the Large Helical Device, a modern stellarator.

(d) The DIII-D of General Atomic in San Diego is a modification of Doublet III. It involves science studies of turbulence, stability and interactions, along with the role of the divertor, a magnetic method of removing debris from a fusion reaction.

(e) The Alcator-C-Mod of MIT, a compact machine with high general performance.

14.4 Inertial Confinement Machines

Another approach to practical fusion is ICF, which uses very small pellets of a deuterium and tritium mixture as high-density gas or as ice. The pellets are heated by laser light or by high-speed particles. They act as miniature hydrogen bombs, exploding and delivering their energy to a wall and cooling medium. Figure 14.5 shows a quarter coin with some of the spheres. Their diameter is about 1/50 of a millimeter (smaller than the periods on this page). To cause the thermonuclear reaction, a large number of beams of laser light or ions are trained on a pellet from different directions. A pulse of energy of the order of a nanosecond is delivered by what is called the "driver." The mechanism is believed to be as follows: the initial energy evaporates some material from the surface of the microsphere, in a manner similar to the ablation of the surface of a spacecraft entering the earth's atmosphere. The particles that are driven off form a plasma around the sphere which can absorb further energy. Electrons are conducted through the sphere to heat it and cause more ablation. As particles leave the surface, they impart a reaction momentum to the material inside the sphere,

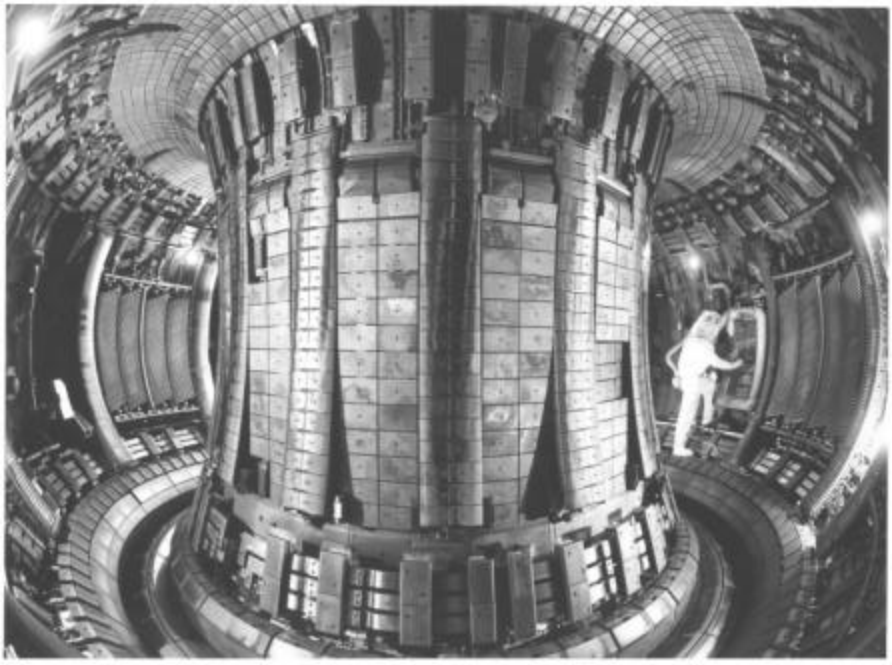


FIG. 14.4 Interior of tokamak fusion reactor Joint European Torus). at Culham, U.K. (Courtesy JET, Joint European Torus).

just as a space rocket is propelled by escaping gases. A shock wave moves inward, compressing the D-T mixture to many thousands of times normal density and temperature. At the center, a spark of energy around 1 keV sets off the thermonuclear reaction. A burn front involving alpha particles moves outward, consuming the D-T fuel as it goes. Energy is shared by the neutrons, charged particles, and electromagnetic radiation, all of which will eventually be recovered as thermal energy. Consistent numbers are: 1 milligram of D-T per pellet, 5 million joules driver energy, an energy gain (fusion to driver) of about 60, and a frequency of 10 bursts per second.

In an alternative indirect method of heating, laser light or ions bombard the walls of a pellet cavity called a hohlraum, producing X-rays that drive the pellet target. One advantage besides high energy efficiency is insensitivity to focus of the illuminating radiation.

The energy released in the series of microexplosions is expected to be deposited in a layer of liquid such as lithium that is continuously circulated over the surface of the container and out to a heat exchanger. This isolation of the reaction from metal walls is expected to reduce the amount of material damage. Other candidate wall protectors are liquid lead and flibe. It may not be necessary to replace the walls frequently or to install special resistant coatings. Figure 14.6 shows a schematic arrangement of a laser-fusion reactor.

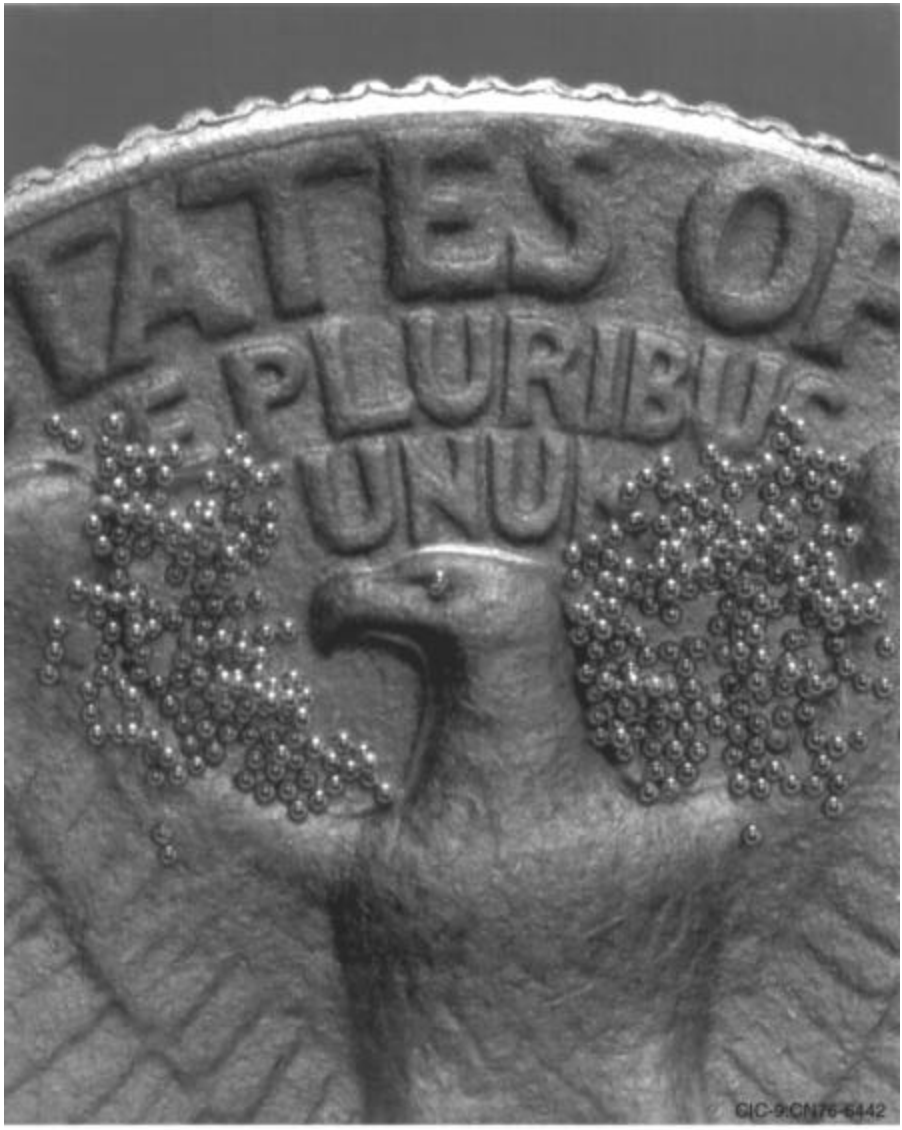


FIG. 14.5 Gold microshells containing high pressure D-T gas for use in laser fusion (Courtesy Los Alamos National Laboratory, No. CN 76-6442).

Research on inertial confinement fusion is carried out at several locations in the U.S.:

(a) Lawrence Livermore National Laboratory operates Nova, which uses a neodymium-glass laser, with ten separate beams. Nova can deliver 40 kJ of 351-nm light in a 1-ns pulse. It is the first ICF machine to exceed the Lawson criterion. LLNL is also the site of the National Ignition Facility (NIF), which has a dual purpose. The first is to provide information on target physics for the U.S. research program in inertial

confinement fusion. The second is to simulate conditions in thermonuclear weapons as an alternative to underground testing actual devices (also see Chapter 26). NIF will have 192 beamlines focused on a target fuel capsule. The design permits either direct or indirect heating. It is expected to be operational by the year 2005. One beamline called Beamlet has been tested successfully. For additional information see References.

(b) Los Alamos National Laboratory has two laser facilities–the excimer (excited molecular) laser Aurora, containing F and Kr gases, and a CO_2 laser, Antares.

(c) Sandia National Laboratories first demonstrated with its Particle Beam Fusion Accelerator (PBFA) that targets could be heated with a proton beam. The equipment was converted into the Z-accelerator, which uses a pulse of current to create a powerful pinch effect (see Section 14.3). The energy from the electrical discharge goes into accelerating electrons that create X-rays that heat the DT capsules. Power levels of near 300 trillion watts have been achieved (see References).

(d) Lawrence Berkeley National Laboratory tests methods of accelerating heavy ions such as potassium to serve as driver for ICF.

(e) General Atomics provides inertial fusion targets–spheres and hohlraums–for other laboratories.

A number of conceptual inertial fusion reactor designs have been developed by national laboratories, universities, and companies, in order to highlight the needs for research and development. These designs are

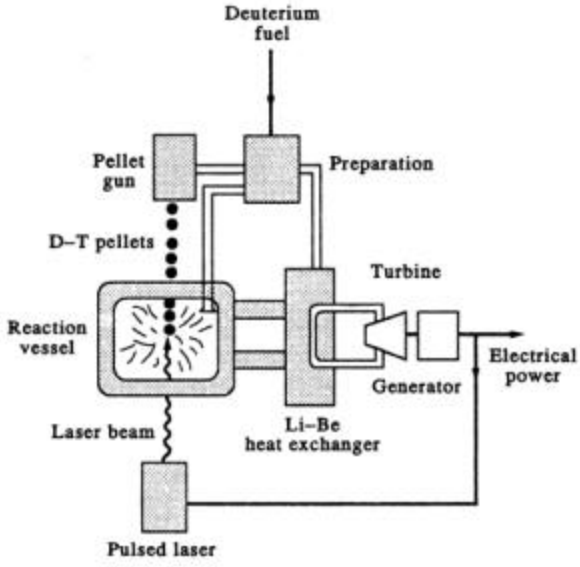


FIG. 14.6 Laser-fusion reactor.

intended to achieve power outputs comparable to those of fission reactors. They include both laser-driven and ion-driven devices. Examples are HIBALL-II (University of Wisconsin), HYLIFE-II and Cascade (Lawrence Livermore), Prometheus (McDonnell Douglas), and OSIRIS and SOMBRERO (W. J. Shafer). A considerable gap remains between performance required in these designs and that obtained in the laboratory to date.

14.5 Other Fusion Concepts

Over the years since 1950 when research on fusion was begun in earnest there have been many ideas for processes and systems. One was the "hybrid" reactor with a fusion core producing 14-MeV neutrons that would be absorbed in a uranium or thorium blanket, producing new fissile material. It was proposed as a stepping-stone to pure fusion, but appears unlikely to be considered.

Out of the approximately 100 fusion reactions with light isotopes, there are some that do not involve neutrons. If a "neutron-free" reaction could be harnessed, the problems of maintenance of activated equipment and disposal of radioactive waste could be eliminated. One example is proton bombardment of the abundant boron isotope, according to

$$ {}_1^1\mathrm{H} + {}_5^{11}\mathrm{B} \rightarrow 3\ {}_2^4\mathrm{He} + 8.68\ \mathrm{MeV}. $$

Since $Z = 5$ for boron, the electrostatic repulsion of the reactants is five times as great as the for D-T reaction, resulting in a much lower cross section. The temperature of the medium would have to be quite high. On the other hand, the elements are abundant and the boron-11 isotope is the dominant one in boron.

Another neutron-free reaction uses the rare isotope helium-3,

$$ {}_1^2\mathrm{H} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He}\,(3.6\ \mathrm{MeV}) + {}_1^1\mathrm{H}\,(14.7\ \mathrm{MeV}). $$

The D-^{3}He electrostatic force is twice as great as the D-T force, but since the products of the reaction are both charged, energy recovery would be more favorable. The process might be operated in such a way that neutrons from the D-D reaction could be minimized. This would reduce neutron bombardment to the vacuum chamber walls. A D-^{3}He fusion reactor thus could use a permanent first wall, avoiding the need for frequent replacement and at the same time reducing greatly the radioactive waste production by neutron activation.

The principal difficulty with use of the reaction is the scarcity of ^{3}He. One source is the atmosphere, but helium is present only to 5 parts per million by volume of air and the helium-3 content is only 1.4 atoms per million of helium. Neutron bombardment of deuterium in a reactor is a

preferable source. The decay of tritium in nuclear weapons could be a source of a few kilograms a year, but not enough to sustain an electrical power grid. Extraterrestrial sources are especially abundant but of course difficult to tap. Studies of moon rocks indicate that the lunar surface has a high ^{3}He content as the result of eons of bombardment by solar wind. Its ^{3}He concentration is 140 ppm in helium. It has been proposed that mining, refining, and isotope separation processes could be set up on the moon, with space shuttle transfer of equipment and product. The energy payback is estimated to be 250, the fuel cost for fusion would be 14 mills/kWh, and the total energy available is around 10^7 GWe-y. If space travel is further perfected, helium from the atmospheres of Jupiter and Saturn could be recovered in almost inexhaustible amounts.

A fusion process that is exotic physically but might be simple technically involves muons, negatively charged particles with mass 210 times that of the electron, and half-life 2.2 microseconds. Muons can substitute for electrons in the atoms of hydrogen, but with orbits that are 210 times smaller than the normal 0.53×10^{-10} m (see Exercise 14.5). They can be produced by an accelerator and directed to a target consisting of a deuterium-tritium compound such as lithium hydride. The beam of muons interacts with deuterons and tritons, forming DT molecules, with the muon playing the same role as an electron. However, the nuclei are now close enough together that some of them will fuse, releasing energy and allowing the muon to proceed to another molecule. Several hundred fusion events can take place before the muon decays. The system would appear not to need complicated electric and magnetic fields or large vacuum equipment. However, the concept has not been tested sufficiently to be able to draw conclusions about its feasibility or practicality.

Two researchers in 1989 reported the startling news that they had achieved fusion at room temperature, a process called “cold fusion.” The experiments received a great deal of media attention because if the phenomenon were real, practical fusion would be imminent. Their equipment consisted of a heavy water electrolytic cell with cathode of metal palladium, which can absorb large amounts of hydrogen. They claimed that application of a voltage resulted in an enormous energy release. Attempts by others to confirm the experiments failed, and cold fusion is not believed to exist. Under certain conditions, there may be a release of large amounts of stored chemical energy, and research is continuing.

A scientific breakthrough whose effect is not yet determined is the discovery of materials that exhibit electrical superconductivity at relatively high temperatures, well above that of liquid helium. Fusion machines using superconducting magnets will as a minimum be more energy-efficient.

14.6 Prospects for Fusion

Research on controlled thermonuclear processes has been under way for over 40 years at several national laboratories, universities, and commercial organizations. The results of the studies include an improved understanding of the processes, the ability to calculate complex magnetic fields, the invention and testing of many devices and machines, and the collection of much experimental data. Over that period, there has been an approach to breakeven conditions, but progress has been painfully slow, involving decades rather than years. Various reasons have been suggested for this. First and probably most important is the fact that fusion is an extremely complex process from both the scientific and engineering standpoints. Second are policy decisions, e.g., emphasis on fundamental plasma physics rather than building large machines to reveal the true dimensions of the problem. In the case of inertial confinement fusion, the U.S. security classification related to weapons inhibited free international exchange of research information. Finally, there have been inconsistencies in funding allocations.

Figure 14.7(a) shows accomplishments of the MCF machines being tested. The plots give the Lawson criterion product of number density n and confinement time t as a function of ion temperature T expressed as an energy in keV. Also noted on the diagram are the goals of breakeven and ignition. Although breakeven has been achieved, there still is a considerable way to go to approach ignition.

Figure 14.7(b) shows the progress by ICF machines. The plot relates the ion temperature to the product of density and radius as discussed in section 14.2. OMEGA is expected to come near ignition and NIF to exceed it.

Predictions have repeatedly been made that practical fusion was only 20 years away. Two events provide some encouragement that the elusive 20-year figure might be met. The first is the discovery of a new tokamak current. As noted earlier, current flow in the plasma is induced by the changing external magnetic field. Since that field cannot increase indefinitely, it would be necessary to shut down and start over. In 1971 it had been predicted that there was an additional current in a plasma, but not until 1989 was that verified in several tokamaks. That “bootstrap” current amounts to up to 80 per cent of the total, such that its contribution would allow essentially continuous operation.

The second event was a breakthrough in late 1997 in fusion energy release. Most fusion research had been conducted with the D-D reaction rather than the D-T reaction, to avoid the complication of contamination of equipment by radioactive tritium. At the Joint European Torus (JET) in England tritium was injected as a neutral beam into a plasma. A series of

records was set, ultimately giving 21 MJ of fusion energy, a peak power of 16 MW, and a ratio of fusion power to input power of 0.65. These results greatly exceeded those from D-D reactions.

The progress in tokamak performance over the years prompted planning for a large machine, the International Thermonuclear Experimental Reactor (ITER). A design was developed under the auspices of the International Atomic Energy Agency, by collaboration of four major participants–the U.S., the European Community, Russia, and Japan. Some of the features of the design were a large plasma volume of roughly elliptical shape, a blanket to absorb neutron energy, and a divertor to extract the energy of charged particles produced and the helium ash. Selected parameters were:

major plasma radius	8.14 m
minor plasma radius	2.80 m
magnetic field	5.7 T
plasma current	21 MA
fusion power	1500 MW
burn time	1300 s
average temperature	12 keV

The construction cost was estimated to be eight billion dollars, which was deemed excessive, leading to a scaled-down version of the technical objectives and the cost. Construction of the smaller version may be problematic for a variety of reasons: (a) concern that a tokamak might never reach ignition because of instabilities; (b) opinion that funding should go to other fusion concepts, especially small systems; (c) the unwillingness of utilities to undertake such an advanced power concept; (d) economic difficulties in Japan and Russia, and budget constraints in the U.S. For details, see References.

Most of the R&D on magnetic fusion has been focused on the tokamak mode. Disenchantment with the ITER project resulted in a change in U.S. fusion program, as supported by DOE's Office of Fusion Energy Sciences. Recommendations for a more fundamental research program that emphasized plasma processes were made by the Fusion Energy Sciences Advisory Committee (FESAC). Also, in a broadened research program other concepts are being considered, identified by terms such as compact stellarator, spherical torus, reversed field pinch, spheromak, field reversed configuration, floating multipole, electric tokamak, and z-pinch. Brief descriptions of these systems are found in a 1998 workshop (see References). Some consideration is also being given to electric confinement of a plasma. The U.S. fusion R&D program is going through a process of self-assessment to determine what approaches have the best chance of success.

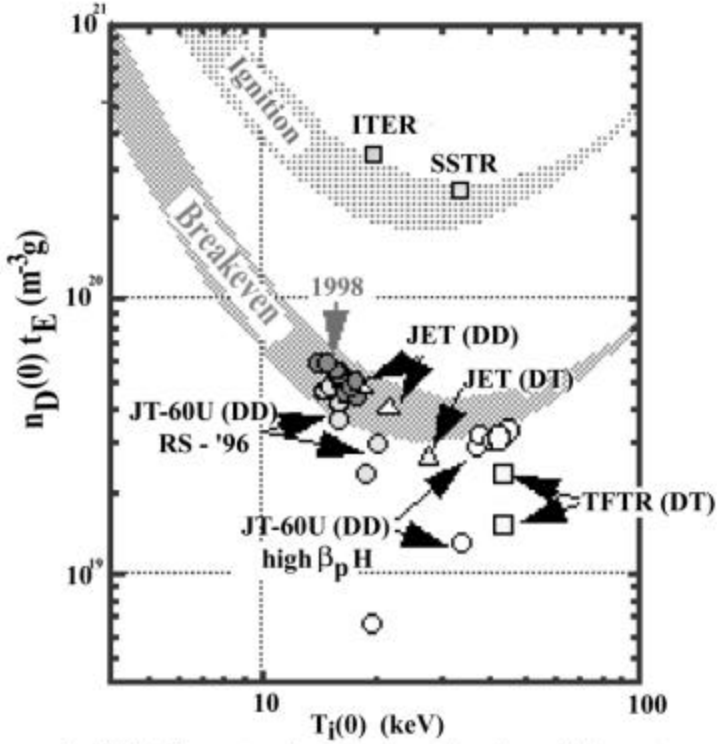


FIG. 14.7(a) Progress towards a practical magnetic confinement fusion reactor. (Courtesy Japan Atomic Energy Research Institute. Thanks are due Robert Heeter).

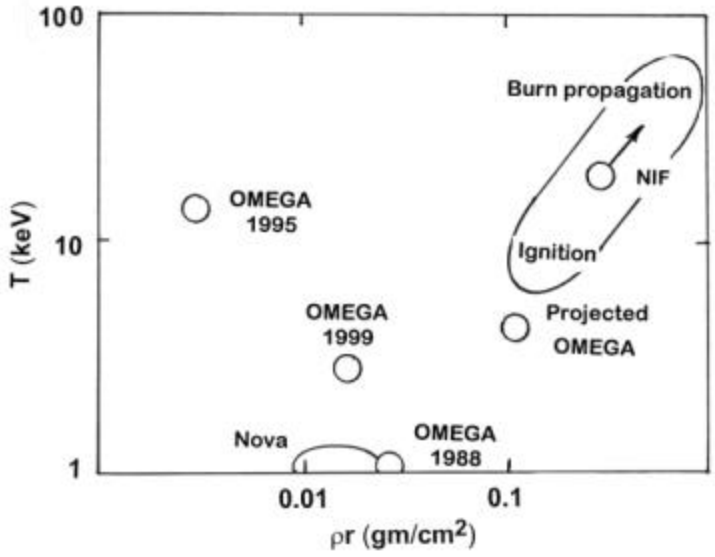


FIG. 14.7(b) Progress towards a practical inertial confinement fusion reactor (Courtesy Lawrence Livermore National Laboratory. Thanks are due John Soures and Alan Wootton.)

It appears that practical fusion reactors still will not be available soon unless there is an unanticipated breakthrough or a completely new idea arises that changes the prospects dramatically. There is yet much to understand about plasma processes and a great deal of time is required to carry out research, development, and testing of a system that will provide competitive electric power.

From time to time, the wisdom of pursuing a vigorous and expensive research program in controlled fusion has been questioned, in light of the uncertainty of success in achieving affordable fusion power. An excellent answer is the statement attributed by Robin Herman (see References) to the fusion pioneer Lyman Spitzer, "A fifty percent probability of getting a power source that would last a billion years is worth a great deal of enthusiasm."

14.7 Summary

A fusion reactor, yet to be developed, would provide power using a controlled fusion reaction. Of the many possible nuclear reactions, the one that will probably be employed first involves deuterium and tritium (produced by neutron absorption in lithium). A D-T reactor that yields net energy must exceed the ignition temperature of around 4.4 keV and have a product nt above about 10^{14}, where n is the fuel particle number density and t is the confinement time. Several experimental machines have been tested, involving an electrical discharge (plasma) that is constrained by electric and magnetic fields. One promising fusion machine, the tokamak, achieves magnetic confinement in a doughnut-shaped structure. Research is also under way on inertial confinement, in which laser beams or charged particle beams cause the explosion of miniature D-T pellets. A neutron-free reaction involving deuterium and helium-3 would be practical if the moon could be mined for helium.

14.8 Exercises

14.1. Noting that the radius of motion R of a particle of charge q and mass m in a magnetic field B is $R = mu/qB$ and that the kinetic energy of rotation in the x-y plane is $(1/2)mu^2 = kT$, find the radii of motion of electrons and deuterons if B is 10 Wb/m^2 and kT is 100 keV.

14.2. Show that the effective nuclear reaction for a fusion reactor using deuterium, tritium, and lithium-6 is

$$ {}^{2}_{1}\mathrm{H} + {}^{6}_{3}\mathrm{Li} \rightarrow 2\ {}^{4}_{2}\mathrm{He} + 22.4\ \mathrm{MeV}\,. $$

14.3. Verify the statement that in the D-T reaction the ${}^{4}_{2}\mathrm{He}$ particle will have 1/5 of the energy.

14.4. (a) Assuming that in the D-D fusion reaction the fuel consumption is 0.151 g/MWd (Exercise 7.3), find the energy release in J/kg. By how large a factor is the value larger or smaller than that for fission?

(b) If heavy water costs \$100/kg, what is the cost of deuterium per kilogram?

(c) Noting 1 kWh = 3.6×10^6 J, find from (a) and (b) the energy cost in mills/kWh.

14.5. (a) Using the formula for the radius of the smallest electron orbit in hydrogen,

$$R = \left(10^7 / m\right)\left(\hbar / ec\right)^2$$

where $\hbar = h / 2\pi$ and the basic constants in the Appendix, verify that R is 0.529×10^{-10} m.

(b) Show that the rest energy of the muon, 105.66 MeV, is approximately 207 times the rest energy of the electron.

(c) What is the radius of the orbit of the muon about hydrogen in the muonium atom?

(d) The lengths of the chemical bonds in H_2 and in other compounds formed from hydrogen isotopes are all around 0.74×10^{-10} m. Estimate the bond in molecules where the muon replaces the electron.

(e) How does the distance in (d) compare with the radii of the nuclei of D and T (see Section 2.6)?

Computer Exercise

14.A. Computer program FUSION is a collection of small modules that calculate certain parameters and functions required in the analysis of a plasma and a fusion reactor. Among the properties considered are the theoretical fusion reaction cross sections, the maxwellian distribution and characteristic velocities, the impact parameter for 90° ion scattering, the Debye length, cyclotron and plasma frequencies, magnetic field parameters, and electrical and thermal conductivities. Explore the modules using the menus provided and the sample input numbers.

14.9 References for Chapter 14

(also see Chapter 7)

T. Kenneth Fowler, *The Fusion Quest*, Johns Hopkins University Press, Baltimore, 1997. Highly readable, non-mathematical treatment of both MCF and ICF, and discussion of the virtues of fusion reactors. Formulas and numbers appear in an Appendix.

T. J. Dolan, *Fusion Research*, Pergamon Press, New York, 1982.

Weston M. Stacey, *Fusion: An Introduction to the Physics and Technology of Magnetic Confinement Fusion*, John Wiley & Sons, New York, 1984.

John D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*, AIP Press, Springer-Verlag, New York, 1998. A technical description of ICF history, theory, design, and expectations. Contains many formulas, calculations, diagrams, and graphs.

J. Raeder, et al., *Controlled Nuclear Fusion: Fundamentals of Its Utilization for Energy Supply*, John Wiley & Sons, Ltd., Chichester, England, 1986. Mathematics of the process, descriptions, and assessment of resource needs and economic practicality.

Keishiro Niu, *Nuclear Fusion*, Cambridge University Press, Cambridge, England, 1989. Treats both magnetic confinement by tokamaks and inertial confinement by lasers and ions. Includes discussion of reactors.

R. Stephen Craxton, Robert L. McCrory, and John M. Soures, "Progress in Laser Fusion," *Scientific American*, August 1986, p. 68.

E. Greenspan, "Fusion-Fission Hybrid Reactors," in *Advances in Nuclear Science and Technology*, Vol. 16, Jeffrey Lewins and Martin Becker, Editors, Plenum Press, New York, 1984.

J. Rand McNally, Jr., K. E. Rothe, and R. D. Sharp, "Fission Reactivity Graphs and Tables for Charged Particle Reactions," ORNL/TM-6914, August 1979. A set of fusion data on 31 light isotopes, including $\overline{su}$ and other averages, and a summary of reactions.

General Atomics Fusion Program
http://fusion.gat.com
Select DIII-D Program and ICF Program.

Robert W. Conn, Valery A. Chuyanov, Nobuyuki Inoue, and Donald R. Sweetman, "The International Thermonuclear Experimental Reactor," *Scientific American*, April 1992, p. 103.

International Thermonuclear Experimental Reactor
http://www.iter.org

Magnetic Fusion: The DOE Fusion Energy Sciences Program
http://www.cnie.org/nle/eng-22.html
Congressional Research Service brief.

U.S. Fusion Energy Sciences Program
http://wwwofe.er.doe.gov
Includes links to fusion research activities around the world.

JET Joint Undertaking
http://www.jet.uk/old_default.html
Download pdf file Jet & Fusion Energy in the Next Millennium. Note that since January 1, 2000, JET facilities operate under EFDA, the European Fusion Development Agreement.

Sandia National Laboratories
http://www.sandia.gov/pulspowr/PPT.html
Select High Energy Density and Inertial Confinement Fusion.

LLNL's Laser Programs
http://www-lasers.llnl.gov
Select National Ignition Facility.

Innovative Confinement Concepts Workshop 1998
http://www.FusionScience.ORG/ICC98/
Download reports on concepts in pdf.

Issues in Science and Technology, Summer 1997, pp. 53-64 and Fall 1997, pp. 5-9.
Contrasting opinions as to the best direction for the fusion R&D.

Fusion Power Associates
http://fusionpower.org
Source of information on latest technical and political developments.

Terry Kammash, Editor, *Fusion Energy in Space Propulsion*, Progress in Astronautical and Aeronautics, Vol. 67, AIAA, Washington, 1995. Composite discussion of space and fusion, including use of antimatter and terraforming Mars.

Robin Herman, *Fusion: The Search for Endless Energy*, New York, Cambridge University Press, 1990.

Part III Nuclear Energy and Man

The discovery of nuclear reactions that yield energy, radioisotopes, and radiation is of major significance in that it showed the possibility of both enormous human benefit and world destruction. It is thus understandable that nuclear energy is a controversial subject. Many have deplored its initial use for military purposes, while others regard the action as necessary under the existing circumstances. Some believe that the discovery of nuclear energy should somehow have been avoided, while others hold that the revelation of natural phenomena is inevitable. Many uninformed persons see no distinction between nuclear weapons and nuclear reactors, while most recognize that the two are very different applications of the same force. A few scientists would abandon the use of nuclear power on the basis of risks, but many knowledgeable persons believe it to be a necessary national and world energy source.

The variety of viewpoints on nuclear energy is but a part of a larger picture–the growth in concern about science and technology, which are claimed by some to be the source of many problems in advanced countries. Such a reaction stems from the observation of the extent of waste release and effects on the environment and health. Doubtless there exists a sequence of scientific discovery, commercial exploitation, and a new environmental problem. It does not follow that the studies should not have been made, but that they should have been accompanied by consideration of side-effects and prevention of future harm. Beneficial technology should be encouraged but the environmental and social costs should be assessed and made known. Finally, preoccupation with industrial byproducts among people of advanced countries must not thwart the aspirations of the rest of the world to have health, freedom from drudgery, and a standard of living made possible by high technology.

Decisions as to the uses of science are subject to ethical and moral criteria; but science itself, as a process of investigation and a body of information that is developed, must be regarded as neutral. Every natural resource has mixed good and evil. For example, fire is most necessary and welcome for warmth in our homes and buildings, but can devastate our forests. Water is required for survival of every living being but in the form of a flood can ruin our cities and land. Drugs can help cure diseases but can incapacitate or kill us. Explosives are valuable for mining and construction but are also a tool of warfare. So it is with nuclear energy. On one hand, we have the benefits of heat and radiation for many human needs; on the other,

the possibility of bombs and radioactive fallout. The key to application for benefit or detriment lies in man's decisions, and the fear of evil uses should not preclude good uses.

In Part III we shall review the history of nuclear energy, examine its hazards and the means available for protection, and describe some of the many peaceful applications of nuclear energy to the betterment of mankind. Finally, we shall discuss the role of nuclear energy in the long-term survival of our species.

15

The History of Nuclear Energy

THE DEVELOPMENT of nuclear energy exemplifies the consequences of scientific study, technological effort, and commercial application. We shall review the history for its relation to our cultural background, which should include man's endeavors in the broadest sense. The author subscribes to the traditional conviction that history is relevant. Present understanding is grounded in recorded experience, and while we cannot undo errors, we can avoid them in the future. It is to be hoped that we can establish concepts and principles about human attitudes and capability that are independent of time, to help guide future action. Finally, we can draw confidence and inspiration from the knowledge of what man has been able to accomplish.

15.1 The Rise of Nuclear Physics

The science on which practical nuclear energy is based can be categorized as classical, evolving from studies in chemistry and physics for the last several centuries, and modern, that related to investigations over the last hundred years into the structure of the atom and nucleus. The modern era begins in 1879 with Crookes' achievement of ionization of a gas by an electric discharge. Thomson in 1897 identified the electron as the charged particle responsible for electricity. Roentgen in 1895 had discovered penetrating X-rays from a discharge tube, and Becquerel in 1896 found similar rays–now known as g rays–from an entirely different source, the element uranium, which exhibited the phenomenon of radioactivity. The Curies in 1898 isolated the radioactive element radium. As a part of his revolutionary theory of motion, Einstein in 1905 concluded that the mass of any object increased with its speed, and stated his now-famous formula $E = mc^2$, which expresses the equivalence of mass and energy. At that time, no experimental verification was available, and Einstein could not have foreseen the implications of his equation.

In the first third of the twentieth century, a host of experiments with the various particles coming from radioactive materials led to a rather clear understanding of the structure of the atom and its nucleus. It was learned from the work of Rutherford and Bohr that the electrically neutral atom is constructed from negative charge in the form of electrons surrounding a central positive nucleus, which contains most of the matter of the atom.

Through further work by Rutherford in England around 1919, it was revealed that even though the nucleus is composed of particles bound together by forces of great strength, nuclear transmutations can be induced; e.g., the bombardment of nitrogen by helium yields oxygen and hydrogen.

In 1930, Bothe and Becker bombarded beryllium with α particles from polonium and found what they thought were γ rays but which Chadwick in 1932 showed to be neutrons. A similar reaction is now employed in nuclear reactors to provide a source of neutrons. Artificial radioactivity was first reported in 1934 by Curie and Joliot. Particles injected into nuclei of boron, magnesium, and aluminum gave new radioactive isotopes of several elements. The development of machines to accelerate charged particles to high speeds opened up new opportunities to study nuclear reactions. The cyclotron, developed in 1932 by Lawrence, was the first of a series of devices of ever-increasing capability.

15.2 The Discovery of Fission

During the 1930s, Enrico Fermi and his co-workers in Italy performed a number of experiments with the newly discovered neutron. He reasoned correctly that the lack of charge on the neutron would make it particularly effective in penetrating a nucleus. Among his discoveries was the great affinity of slow neutrons for many elements and the variety of radioisotopes that could be produced by neutron capture. Breit and Wigner provided the theoretical explanation of slow neutron processes in 1936. Fermi made measurements of the distribution of both fast and thermal neutrons and explained the behavior in terms of elastic scattering, chemical binding effects, and thermal motion in the target molecules. During this period, many cross sections for neutron reactions were measured, including that of uranium, but the fission process was not identified.

It was not until January 1939 that Hahn and Strassmann of Germany reported that they had found the element barium as a product of neutron bombardment of uranium. Frisch and Meitner made the guess that fission was responsible for the appearance of an element that is only half as heavy as uranium, and that the fragments would be very energetic. Fermi then suggested that neutrons might be emitted during the process, and the idea was born that a chain reaction that releases great amounts of energy might be possible. The press picked up the idea, and many sensational articles were written. The information on fission, brought to the United States by Bohr on a visit from Denmark, prompted a flurry of activity at several universities, and by 1940 nearly a hundred papers had appeared in the technical literature. All of the qualitative characteristics of the chain reaction were soon learned–the moderation of neutrons by light elements,

thermal and resonance capture, the existence of fission in U-235 by thermal neutrons, the large energy of fission fragments, the release of neutrons, and the possibility of producing transuranic elements, those beyond uranium in the periodic table.

15.3 The Development of Nuclear Weapons

The discovery of fission, with the possibility of a chain reaction of explosive violence, was of especial importance at this particular time in history, since World War II had begun in 1939. Because of the military potential of the fission process, a voluntary censorship of publication on the subject was established by scientists in 1940. The studies that showed U-235 to be fissile suggested that the new element plutonium, discovered in 1941 by Seaborg, might also be fissile and thus also serve as a weapon material. As early as July 1939, four leading scientists–Szilard, Wigner, Sachs, and Einstein–had initiated a contact with President Roosevelt, explaining the possibility of an atomic bomb based on uranium. As a consequence a small grant of $6000 was made by the military to procure materials for experimental testing of the chain reaction. Before the end of World War II, a total of $2 billion had been spent, an almost inconceivable sum in those times. After a series of studies, reports, and policy decisions, a major effort was mounted through the U.S. Army Corps of Engineers under General Groves. The code name "Manhattan District" (or "Project") was devised, with military security mandated on all information.

Although a great deal was known about the individual nuclear reactions, there was great uncertainty as to the practical behavior. Could a chain reaction be achieved at all? If so, could Pu-239 in adequate quantities be produced? Could a nuclear explosion be made to occur? Could U-235 be separated on a large scale? These questions were addressed at several institutions, and design of production plants began almost concurrently, with great impetus provided by the involvement of the United States in World War II after the attack on Pearl Harbor in December 1941 by the Japanese. The distinct possibility that Germany was actively engaged in the development of an atomic weapon served as a strong stimulus to the work of American scientists, most of whom were in universities. They and their students dropped their normal work to enlist in some phase of the project.

As it was revealed by the Alsos Mission (see References), a military investigation project, Germany had actually made little progress toward an atomic bomb. A controversy has developed as to the reasons for its failure (see References). There is evidence that an overestimate was made of the critical mass of enriched uranium–as tons rather than kilograms–with the conclusion that such amounts were not achievable.

The Manhattan Project consisted of several parallel endeavors. The major effort was in the U.S., with cooperation from the United Kingdom, Canada, and France.

An experiment at the University of Chicago was crucial to the success of the Manhattan Project and also set the stage for future nuclear developments. The team under Enrico Fermi assembled blocks of graphite and embedded spheres of uranium oxide and uranium metal into what was called a "pile." The main control rod was a wooden stick wrapped with cadmium foil. One safety rod would automatically drop on high neutron level; one was attached to a weight with a rope, ready to be cut with an axe if necessary. Containers of neutron-absorbing cadmium-salt solution were ready to be dumped on the assembly in case of emergency. On December 2, 1942, the system was ready. The team gathered for the key experiment as in Figure 15.1, an artist's recreation of the scene. Fermi calmly made calculations with his slide rule, and called for the main control rod to be withdrawn in steps. The counters clicked faster and faster until it was necessary to switch to a recorder, whose pen kept climbing. Finally, Fermi closed his slide rule and said, "The reaction is self-sustaining. The curve is exponential."

This first man-made chain reaction gave encouragement to the possibility of producing weapons material, and was the basis for the construction of several nuclear reactors at Hanford, Washington. By 1944, these were producing plutonium in kilogram quantities.

At the University of California at Berkeley, under the leadership of Ernest O. Lawrence, the electromagnetic separation "calutron" process for isolating U-235 was perfected, and government production plants at Oak Ridge, Tennessee, were built in 1943. At Columbia University, the gaseous diffusion process for isotope separation was studied, forming the basis for the present production system, the first units of which were built at Oak Ridge. At Los Alamos, New Mexico a research laboratory was established under the direction of J. Robert Oppenheimer. Theory and experiment led to the development of the nuclear weapons, first tested at Alamogordo, New Mexico, on July 16, 1945, and later used at Hiroshima and Nagasaki in Japan.

The brevity of this account fails to describe adequately the dedication of scientists, engineers, and other workers to the accomplishment of national objectives, or the magnitude of the design and construction effort by American industry. Two questions are inevitably raised. Should the atom bomb have been developed? Should it have been used? Some of the scientists who worked on the Manhattan Project have expressed their feeling of guilt for having participated. Some insist that a lesser

FIG. 15.1 The first man-made chain reaction, December 2, 1942. Painting *The Birth of the Atomic Age* by Gary Sheahan, courtesy Chicago Historical Society).

demonstration of the destructive power of the weapon should have been arranged, which would have been sufficient to end the conflict. Many others believed that the security of the United States was threatened and that the use of the weapon shortened World War II greatly and thus saved a large number of lives on both sides. In the ensuing years the buildup of nuclear weapons continued in spite of efforts to achieve disarmament. The dismantlement of excess weapons will require many years. It is of some comfort, albeit small, that the existence of nuclear weapons has served for several decades as a deterrent to a direct conflict between major powers.

The discovery of nuclear energy has a potential for the betterment of mankind through fission and fusion energy resources, and through radioisotopes and their radiation for research and medical purposes. The benefits can outweigh the detriments if mankind is intelligent enough not to use nuclear weapons again.

15.4 Reactor Research and Development

One of the first important events in the U.S. after World War II ended was the creation of the United States Atomic Energy Commission. This civilian federal agency was charged with the management of the nation's nuclear programs, including military protection and development of peaceful uses of the atom. Several national laboratories were established to continue nuclear research, at sites such as Oak Ridge, Argonne (near Chicago), Los Alamos, and Brookhaven (on Long Island). A major objective was to achieve practical commercial nuclear power through research and development. Oak Ridge first studied a gas-cooled reactor and later planned a high-flux reactor fueled with highly enriched uranium alloyed with and clad with aluminum, using water as moderator and coolant. A reactor was eventually built in Idaho as the Materials Testing Reactor. The submarine reactor described in Section 20.1 was adapted by Westinghouse Electric Corporation for use as the first commercial power plant at Shippingport, Pennsylvania. It began operation in 1957 at an electric power output of 60 MW. Uranium dioxide pellets as fuel were first introduced in this pressurized water reactor (PWR) design.

In the decade of the 1950s several reactor concepts were tested and dropped for various reasons (see References). One used an organic liquid diphenyl as a coolant on the basis of a high boiling point. Unfortunately, radiation caused deterioration of the compound. Another was the homogeneous aqueous reactor, with a uranium salt in water solution that was circulated through the core and heat exchanger. Deposits of uranium led to excess heating and corrosion of wall materials. The sodium-graphite reactor had liquid metal coolant and carbon moderator. Only one

commercial reactor of this type was built. The high-temperature gas-cooled reactor, developed by General Atomics, has not been widely adopted, but is a potential alternative to light water reactors by virtue of its graphite moderator, helium coolant, and uranium-thorium fuel cycle.

Two other reactor research and development programs were under way at Argonne over the same period. The first program was aimed at achieving power plus breeding of plutonium, using the fast reactor concept with liquid sodium coolant. The first electric power from a nuclear source was produced in late 1951 in the Experimental Breeder Reactor, and the possibility of breeding was demonstrated. The second program consisted of an investigation of the possibility of allowing water in a reactor to boil and generate steam directly. The principal concern was with the fluctuations and instability associated with the boiling. Tests called BORAX were performed that showed that a boiling reactor could operate safely, and work proceeded that led to electrical generation in 1955. The General Electric Company then proceeded to develop the boiling water reactor (BWR) concept further, with the first commercial reactor of this type put into operation at Dresden, Illinois in 1960.

On the basis of the initial success of the PWR and BWR, and with the application of commercial design and construction know-how, Westinghouse and General Electric were able, in the early 1960s, to advertise large-scale nuclear plants of power around 500 MWe that would be competitive with fossil fuel plants in the cost of electricity. Immediately thereafter, there was a rapid move on the part of the electric utilities to order nuclear plants, and the growth in the late 1960s was phenomenal. Orders for nuclear steam supply systems for the years 1965-1970 inclusive amounted to around 88 thousand MWe, which was more than a third of all orders, including fossil fueled plants. The corresponding nuclear electric capacity was around a quarter of the total United States capacity at the end of the period of rapid growth.

After 1970 the rate of installation of nuclear plants in the U.S. declined, for a variety of reasons: (a) the very long time required–greater than 10 years–to design, license, and construct nuclear facilities; (b) the energy conservation measures adopted as a result of the Arab oil embargo of 1973-74, which produced a lower growth rate of demand for electricity; and (c) public opposition in some areas. The last order for nuclear plants was in 1978; a number of orders were canceled; and construction was stopped prior to completion on others. The total nuclear power capacity of the 104 U.S. reactors in operation by 2000 was 98,030 MW, representing more than 20% of the total electrical capacity of the country. In other parts of the world there were 330 reactors in operation with 252,412 MW capacity.

This large new power source was put in place in a relatively brief period of 40 years following the end of World War II. The endeavor revealed a new concept–that large-scale national technological projects could be undertaken and successfully completed by the application of large amounts of money and the organization of the efforts of many sectors of society. The nuclear project in many ways served as a model for the U.S. space program of the 1960s. The important lesson that the history of nuclear energy development may have for us is that urgent national and world problems can be solved by wisdom, dedication, and cooperation.

For economic and political reasons, there developed considerable uncertainty about the future of nuclear power in the United States and many other countries of the world. In the next section we shall discuss the nuclear controversy, and later describe the dimensions of the problem and its solution in coming decades.

15.5 The Nuclear Controversy

The popularity of nuclear power decreased during the decades of the 1970s and 1980s, with adverse public opinion threatening to prevent the construction of new reactors. We can attempt to analyze this situation, explaining causes and assessing effects.

In the 1950s nuclear power was heralded by the Atomic Energy Commission and the press as inexpensive, inexhaustible, and safe. Congress was highly supportive of reactor development, and the general public seemed to feel that great progress toward a better life was being made. In the 1960s, however, a series of events and trends raised public concerns and began to reverse the favorable opinion.

First was the youth movement against authority and constraints. In that generation's search for a simpler and more primitive or "natural" life style, the use of wood and solar energy was preferred to energy based on the high technology of the "establishment." Another target for opposition was the military-industrial complex, blamed for the generally unpopular Viet Nam War. A 1980s version of the anti-establishment philosophy advocated decentralization of government and industry, favoring small locally controlled power units based on renewable resources.

Second was the 1960s environmental movement, which revealed the extent to which industrial pollution in general was affecting wildlife and human beings, with its related issue of the possible contamination of air, water, and land by accidental releases of radioactivity from nuclear reactors. Continued revelations about the extent of improper management of hazardous chemical waste had a side-effect of creating adverse opinion about radioactive wastes.

Third was a growing loss of respect for government, with public disillusionment becoming acute as an aftermath of the Watergate affair. Concerned observers cited actions taken by the AEC or the DOE without informing or consulting those affected. Changes in policy about radioactive waste management from one administration to another resulted in inaction, interpreted as evidence of ignorance or ineptness. A common opinion was that no one knew what to do with the nuclear wastes.

A fourth development was the confusion created by the sharp differences in opinion among scientists about the wisdom of developing nuclear power. Nobel prize winners were arrayed on both sides of the argument; the public understandably could hardly fail to be confused and worried about where the truth lay.

The fifth was the fear of the unknown hazard represented by reactors, radioactivity, and radiation. It may be agreed that an individual has a much greater chance of dying in an automobile accident than from exposure to fallout from a reactor accident. But since the hazard of the roads is familiar, and believed to be within the individual's control, it does not evoke nearly as great concern as does a nuclear event.

The sixth was the association between nuclear power and nuclear weapons. This is in part inevitable, because both involve plutonium, employ the physical process of fission with neutrons, and have radioactive byproducts. On the other hand, the connection has been cultivated by opponents of nuclear power, who stress the similarities rather than the differences.

As with any subject, there is a spectrum of opinions. At one end are the dedicated advocates, who believe nuclear power to be safe, badly needed, and capable of success if only opposition can be reduced. A large percentage of physical scientists and engineers fall in this category, believing that technical solutions for most problems are possible.

Next are those who are technically knowledgeable but are concerned about the ability of man to avoid reactor accidents or to design and build safe waste facilities. Depending on the strength of their concerns, they may believe that consequences outweigh benefits.

Next are average citizens who are suspicious of government and who believe in "Murphy's law," being aware of failures such as Love Canal, Three Mile Island, the 1986 space shuttle, and Chernobyl. They have been influenced as well by strong antinuclear claims, and tend to be opposed to further nuclear power development, although they recognize the need for continuous electric power generation.

At the other end of the spectrum are ardent opponents of nuclear power who actively speak, write polemics, intervene in licensing hearings, lead

demonstrations, or take physical action to try to prevent power plants from coming into being.

There is a variety of attitudes among representatives of the news and entertainment media–newspapers, magazines, radio, television and movies–but there is an apparent tendency toward skepticism. Nuclear advocates are convinced that any incident involving reactors or radiation is given undue emphasis by the media. They believe that if people were adequately informed they would find nuclear power acceptable. This view is only partially accurate, for two reasons: (a) some technically knowledgeable people are strongly antinuclear; and (b) irrational fears cannot be removed by additional facts. Many people have sought to analyze the phenomenon of nuclear fear, but the study by Weart (see References) is one of the best.

The eventual public acceptance of nuclear power will have to be based on the realization that it is a necessary part of the world's energy supply and the recognition of an extended record of safe, reliable, and economic performance.

15.6 Summary

A series of investigations in atomic and nuclear physics in the period 1879-1939 led to the discovery of fission. New knowledge was developed about particles and rays, radioactivity, and the structures of the atom and the nucleus. The existence of fission suggested that a chain reaction involving neutrons was possible, and that the process had military significance. A major national program was initiated in the U.S. during World War II. The development of uranium isotope separation methods, of nuclear reactors for plutonium production, and of weapons technology culminated in the use of atomic bombs to end the war.

In the post-war period emphasis was placed on maintenance of nuclear protection and on peaceful applications of nuclear processes under the U.S. Atomic Energy Commission. Four reactor concepts–the pressurized water, boiling water, fast breeder, and gas-cooled–evolved through work by national laboratories and industry. The first two concepts were brought to commercial status in the 1960s.

Support for nuclear power has waned since the early days, but sustained safe and economical operation may restore public confidence.

15.7 References for Chapter 15

Historical Figures in Nuclear Science
http://www.accessexcellence.org/AE/AEC/CC
Biographies of Roentgen, Becquerel, the Curies, and Rutherford. By Genentech.

Henry De Wolfe Smyth, "Atomic Energy For Military Purposes," *Reviews of Modern Physics*, Vol. 17, No. 4, 1945, pp. 351-471. The "Smyth Report," the first unclassified account of the nuclear effort of World War II. Readily understood technical information and administrative history of the Manhattan Project. See also the book version, listed below.

Henry De Wolfe Smyth, *Atomic Energy for Military Purposes*, Princeton University Press, Princeton, NJ. 1945. Reprinted by AMS Press, New York, 1978 and reprinted with additional commentary by Stanford University Press, 1989.

The Smyth Report online
http://sun00781.dn.net/nuke/hew/Smyth
Preface, selected chapters, and appendices.

Federation of American Scientists
http://www.fas.org
Search on Manhattan Project.

"The Italian Navigator Has Landed in the New World"
http://www.lanl.gov/worldview/welcome/history/08_chicago-reactor.html
Brief account of the first chain reaction.

Robert Jungk, *Brighter than a Thousand Suns*, Harcourt Brace & Co., New York, 1958. A very readable history of nuclear developments from 1918 to 1955, with emphasis on the atomic bomb. Based on conversations with many participants.

Lt. General Leslie R. Groves, *Now It Can be Told*, Harper & Row, New York, 1962. The account of the Manhattan Project by the person in charge.

The History of the United States Atomic Energy Commission by Richard G. Hewlett and Oscar E. Anderson, Jr., The New World, Vol. I, 1939/1946; Richard G. Hewlett and Francis Duncan; Atomic Shield, Vol. II, 1947/1952, U.S. Atomic Energy Commission, Washington DC 1972. The first volume starts with the discovery of fission and covers the Manhattan Project in great detail.

The United States Department of Energy, 1977-1994
http://www.etde.org/html/doe/about/history/doehist.html#ZZ0
Includes material from 1939 on. By Terrence R. Fehner and Jack M. Holl.

Nuclear Age Timeline
http://www.em.doe.gov/timeline
Events from the Pre-40's to the 90's, with sources of additional information

Nuclear Technology Milestones: 1942-1998
http://www.nei.org
Search on Timeline. By Nuclear Energy Institute.

Raymond L. Murray, "The Etymology of 'Scram'," *Nuclear News*, August 1988. An article on the origin of the word based on correspondence with Norman Hilberry, the Safety Control Rod Axe Man in the Chicago experiment.

Boris T. Pash, *The Alsos Mission*, New York, Universal Publishing & Distribution Corp., 1970. This book, long out of print, describes the adventures of the military unit that entered Germany in World War II to find out about the atom bomb effort.

Samuel A. Goudsmit, *Alsos*, New York, Henry Schuman, Inc., 1947. Reprinted in 1983 by Tomash Publishers and American Institute of Physics, with a new introduction by R. V. Jones and supplemental photographs. The technical leader of the Alsos mission describes his experiences and assessment of the German atom bomb program.

Mark Walker, *German National Socialism and the Quest for Nuclear Power, 1939-1949*, Cambridge, 1989.

Mark Walker, "Heisenberg, Goudsmit, and the German Atomic Bomb," *Physics Today*, January 1990, p. 52. This article prompted a series of letters to the editor in the issues of May 1991 and February 1992.

Sir Frank Charles, *Operation Epsilon: The Farm Hall Transcripts*, University of California Press, Berkeley, 1993. Recorded conversations among German scientists captured at the end of World War II.

Paul Lawrence Rose, *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture*, University of California Press, Berkeley, 1998. Very thorough investigation with voluminous bibliography. Believes that the critical mass was overestimated by error.

Stephane Groueff, *Manhattan Project*, Little, Brown & Co., Boston, 1967. Subtitle: The Untold Story of the Making of the Atomic Bomb. The author had the advantage of the many books and articles written in the 20-year period after the end of World War II. He also based his work on interviews with the many participants still living. The book was praised by both General Leslie Groves and AEC commissioner Glenn Seaborg.

Nuell Pharr Davis, *Lawrence and Oppenheimer*, Simon & Schuster, New York, 1968 (Also available in paperback from Fawcett Publications). The roles of the two atomic leaders, Ernest O. Lawrence and J. Robert Oppenheimer, and their conflict are described The book presents an accurate portrayal of the two men.

Bertrand Goldschmidt, *The Atomic Complex*, American Nuclear Society, La Grange Park, IL, 1982. A technical and political history of nuclear weapons and nuclear power. The author participated in developments in the U.S. and France.

Richard Rhodes, *The Making of the Atomic Bomb*, Simon & Schuster, New York, 1986. A detailed fascinating account of the Manhattan Project.

Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb*, Simon & Schuster, New York, 1995. Research and development by both the U.S. and U.S.S.R. Describes espionage.

John W. Simpson, *Nuclear Power from Underseas to Outer Space*, American Nuclear Society, La Grange Park, IL 1995. Personalized technical history of nuclear submarine, early nuclear power, and nuclear rocket by a Westinghouse executive.

Frank G. Dawson, *Nuclear Power: Development and Management of A Technology*, University of Washington Press, Seattle, 1976. Covers nuclear power development and regulations from 1946 to around 1975.

Raymond L. Murray, "Nuclear Reactors" and "Reactor Types," in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, New York, 1996.

The Virtual Nuclear Tourist
http://www.cannon.net/~gonyeau/nuclear/index.htm

A wealth of information with links to history sites. By Joseph Gonyeau.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

Spencer R. Weart, *Nuclear Fear: A History of Images*, Harvard University Press, 1988. An analysis of attitudes toward nuclear power.

Stephen Hilgartner, Richard C. Bell, and Rory O'Connor, *Nukespeak*, Sierra Club Books, San Francisco, 1982. Subtitle: Nuclear Language, Visions, and Mindset. The book is dedicated to George Orwell, whose language "Newspeak" in the book *1984* is now defined in *Webster's Collegiate* as "propagandistic language marked by ambiguity and contradictions." *Nukespeak* italicizes the many euphemisms of nuclear technology and politics.

Bernard L. Cohen, *Before It's Too Late*, Plenum Press, New York, 1983. Subtitle: A Scientist's Case FOR Nuclear Energy. Discusses risks on nuclear power and public perception of them. Provides data designed to refute antinuclear claims.

Histories of National Laboratories

Oak Ridge
http://www.ornl.gov/ORNLReview/rev25-34/contents.html
Gopher menu for 1992 article.

Los Alamos
http://www.lanl.gov/worldview/welcome/history.html#50
A series of articles by Robert Seidel, and links to other accounts.

Lawrence Berkeley
http://www-library.lbl.gov/Seaborg/65th-anniv/complete.html
A lecture with slides by Glenn Seaborg.

Lawrence Livermore
http://www.llnl.gov/llnl/02about-llnl/history.html
Includes interview with Edward Teller.

Argonne
http://www.anl.gov/OPA/history
Emphasis on a long series of reactors.

Pacific Northwest
http://www.pnl.gov/main/welcome/history.html
Since creation in 1965.

Brookhaven
http://www.bnl.gov/bnlweb/history.html
Includes timeline of major events.

Idaho Engineering & Environmental
http://www.inel.gov/about/history/history.html
From prehistory to present.

Sandia
http://www.sandia.gov/50years/hilights.htm
Six-decade timeline.

16

Biological Effects of Radiation

ALL LIVING species are exposed to a certain amount of natural radiation in the form of particles and rays. In addition to the sunlight, without which life would be impossible to sustain, all beings experience cosmic radiation from space outside the earth and natural background radiation from materials on the earth. There are rather large variations in the radiation from one place to another, depending on mineral content of the ground and on the elevation above sea level. Man and other species have survived and evolved within such an environment in spite of the fact that radiation has a damaging effect on biological tissue. The situation has changed somewhat by the discovery of the means to generate high-energy radiation, using various devices such as X-ray machines, particle accelerators, and nuclear reactors. In the assessment of the potential hazard of the new man-made radiation, comparison is often made with levels in naturally occurring background radiation.

We shall now describe the biological effect of radiation on cells, tissues, organs, and individuals, identify the units of measurement of radiation and its effect, and review the philosophy and practice of setting limits on exposure. Special attention will be given to regulations related to nuclear power plants.

A brief summary of modern biological information will be useful in understanding radiation effects. As we know, living beings represent a great variety of species of plants and animals; they are all composed of cells, which carry on the processes necessary to survival. The simplest organisms such as algae and protozoa consist of only one cell, while complex beings such as man are composed of specialized organs and tissues that contain large numbers of cells, examples of which are nerve, muscle, epithelial, blood, skeletal, and connective. The principal components of a cell are the *nucleus* as control center, the *cytoplasm* containing vital substances, and the surrounding *membrane*, as a porous cell wall. Within the nucleus are the *chromosomes*, which are long threads containing hereditary material. The growth process involves a form of cell multiplication called *mitosis*–in which the chromosomes separate in order to form two new cells identical to the original one. The reproduction process involves a cell division process called *meiosis*–in which germ cells are produced with only half the

necessary complement of chromosomes, such that the union of sperm and egg creates a complete new entity. The laws of heredity are based on this process. The genes are the distinct regions on the chromosomes that are responsible for inheritance of certain body characteristics. They are constructed of a universal molecule called DNA, a very long spiral staircase structure, with the stairsteps consisting of paired molecules of four types (see References). Duplication of cells in complete detail involves the splitting of the DNA molecule along its length, followed by the accumulation of the necessary materials from the cell to form two new ones. In the case of man, there are 46 chromosomes, containing about four billion of the DNA molecule steps, in an order that describes each unique person.

16.1 Physiological Effects

The various ways that moving particles and rays interact with matter discussed in earlier chapters can be reexamined in terms of biological effect. Our emphasis previously was on what happened to the radiation. Now, we are interested in the effects on the medium, which are viewed as "damage" in the sense that disruption of the original structure takes place, usually by *ionization*. We saw that energetic electrons and photons are capable of removing electrons from an atom to create ions; that heavy charged particles slow down in matter by successive ionizing events; that fast neutrons in slowing impart energy to target nuclei, which in turn serve as ionizing agents; and that capture of a slow neutron results in a gamma ray and a new nucleus. The distinction is made between low LET (electrons and gamma rays) and high LET (alpha particles and neutrons).

As a good rule of thumb, 32 eV of energy is required on average to create an ion pair. This figure is rather independent of the type of ionizing radiation, its energy, and the medium through which it passes. For instance, a single 4-MeV alpha particle would release about 10^5 ion pairs before stopping. Part of the energy goes into molecular excitation and the formation of new chemicals. Water in cells can be converted into free radicals such as H, OH, H_2O_2, and HO_2. Since the human body is largely water, much of the effect of radiation can be attributed to the chemical reactions of such products. In addition, direct damage can occur, in which the radiation strikes certain molecules of the cells, especially the DNA that controls all growth and reproduction. Turner (see References) displays computer-generated diagrams of ionization effects.

The most important point from the biological standpoint is that the bombarding particles have energy, which can be transferred to atoms and molecules of living cells, with a disruptive effect on their normal function.

Since an organism is composed of very many cells, tissues, and organs, a disturbance of one atom is likely to be imperceptible, but exposure to many particles or rays can alter the function of a group of cells and thus affect the whole system. It is usually assumed that damage is cumulative, even though some accommodation and repair takes place.

The physiological effects of radiation may be classified as *somatic*, which refers to the body and its state of health, and *genetic*, involving the genes that transmit hereditary characteristics. The somatic effects range from temporary skin reddening when the body surface is irradiated, to a life shortening of an exposed individual due to general impairment of the body functions, to the initiation of cancer in the form of tumors in certain organs or as the blood disease, leukemia. The term "radiation sickness" is loosely applied to the immediate effects of exposure to very large amounts of radiation. The genetic effect consists of mutations, in which progeny are significantly different in some respect from their parents, usually in ways that tend to reduce the chance of survival. The effect may extend over many generations.

Although the amount of ionization produced by radiation of a certain energy is rather constant, the biological effect varies greatly with the type of tissue involved. For radiation of low penetrating power such as α particles, the outside skin can receive some exposure without serious hazard, but for radiation that penetrates tissue readily such as X-rays, gamma rays, and neutrons, the critical parts of the body are bone marrow as blood-forming tissue, the reproductive organs, and the lenses of the eyes. The thyroid gland is important because of its affinity for the fission product iodine, while the gastrointestinal tract and lungs are sensitive to radiation from radioactive substances that enter the body through eating or breathing.

If a radioactive substance enters the body, radiation exposure to organs and tissues will occur. However, the foreign substance will not deliver all of its energy to the body because of partial elimination. If there are N atoms present, the physical decay rate is λN and the biological elimination rate is $\lambda_b N$. The total rate is $\lambda_e N$, where the effective decay constant is

$$\lambda_e = \lambda + \lambda_b.$$

The corresponding relation between half-lives is

$$1/t_e = 1/t_H + 1/t_b.$$

For example, iodine-131 has an 8-day physical half-life and a 4-day biological half-life for the thyroid gland. Thus its effective half-life is 2 2/3 days.

16.2 Radiation Dose Units

A number of specialized terms need to be defined for discussion of

biological effects of radiation. First is the absorbed *dose* (D). This is the amount of energy in joules imparted to each kilogram of exposed biological tissue, and it appears as excitation or ionization of the molecules or atoms of the tissue. The SI unit of dose is the *gray* (Gy) which is 1 J/kg. To illustrate, suppose that an adult's gastrointestinal tract weighing 2 kg receives energy of amount 6×10^{-5} J as the result of ingesting some radioactive material. The dose would be

$$D = (6 \times 10^{-5} \text{ J})/(2 \text{ kg}) = 3 \times 10^{-5} \text{ J/kg}$$
$$= 3 \times 10^{-5} \text{ Gy}.$$

An older unit of energy absorption is the *rad*, which is 0.01 J/kg, i.e., 1 Gy = 100 rads. The above dose to the GI tract would be 0.003 rads or 3 millirads.

The biological effect of energy deposition may be large or small depending on the type of radiation. For instance a rad dose due to fast neutrons or alpha particles is much more damaging than a rad dose by X-rays or gamma rays. In general, heavy particles create a more serious effect than do photons because of the greater energy loss with distance and resulting higher concentration of ionization. The *dose equivalent* (*H*) as the biologically important quantity takes account of those differences by scaling the energy absorption up by a *quality factor* (*QF*), with values as in Table 16.1.

TABLE 16.1
Quality Factors
(NRC 10CFR20, see References)

X-rays, gamma rays, beta particles	1
Thermal neutrons (0.025 eV)	2
Neutrons of unknown energy	10
High energy protons	10
Heavy ions, including alpha particles	20

Thus

$$H = (D)(QF).$$

If the *D* is expressed in Gy, then *H* is in *sieverts* (Sv); if the *D* is in rads, then *H* is in *rems*. Suppose that the gastrointestinal tract dose were due to plutonium, an alpha particle emitter. The equivalent dose would then be (20) $(3 \times 10^{-5}) = 6 \times 10^{-4}$ Sv or 0.6 mSv. Alternatively, the *H* would be (20)(0.003) = 0.06 rems or 60 millirems. In scientific research and the analysis of biological effects of radiation the SI units gray and sievert are used; in nuclear plant operation, rads and rems are more commonly used. Summarizing, conversion factors commonly needed:

1 gray (Gy) = 100 rads
0.01Gy = 1 rad

1 sievert (Sv) = 100 rems
10 mSv = 1 rem
1 mSv = 100 mrems
10 μSv = 1 mrem.

The great variety of radioactivity and radiation units is confusing, and a source of much time and effort to convert between systems. Although it would be desirable to switch completely to the newer units, it is unrealistic to expect it to happen. The U.S. at least will long be burdened with a dual system of units. We will frequently include the newer units in parentheses. As a memory device, let sieverts be $ and rems be ¢.

Computer Exercise 16.B makes use of the program RADOSE to conveniently translate numbers from a technical article.

The long-term effect of radiation on an organism also depends on the rate at which energy is deposited. Thus the *dose rate*, expressed in convenient units such as rads per hour or millirems per year, is used. Note that if dose is an energy, the dose rate is a power.

We shall describe the methods of calculating dosage in Chapter 21. For perspective, however, we can cite some typical figures. A single sudden exposure that gives the whole body of a person 20 rems (0.2 Sv) will give no perceptible clinical effect, but a dose of 400 rems (4 Sv) will probably be fatal; the typical annual natural radiation exposure of the average citizen including radon is 295 millirems; medical and dental applications give another 54, with all other sources 11, giving a total of 360 millirems (3.6 Sv). Fig. 16.1 shows the distribution by percentages. Earlier literature on radiation protection cited typical annual dose figures of 100 mrems (0.1 rem), but in recent times the effect of radon amounting to around 200 mrems/y has been included. Computer Exercise 16.A addresses the buildup

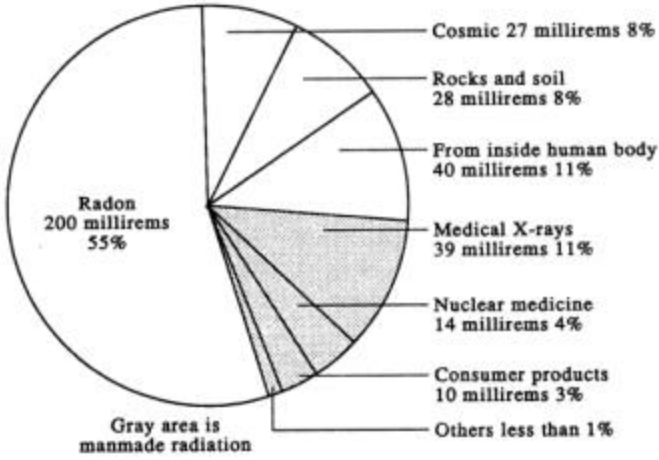


FIG. 16.1 Annual average radiation exposure to an individual in the U.S. The total is 360 millirems (NCRP 93, 1988).

of radon in an enclosed space without ventilation.

There is a wide variation of annual dose around the world. According to Eisenbud (see References, Chapter 3) in countries such as India and Brazil the presence of thorium gives exposures of about 600 mrems/y, and many waters at health spas give rates that are orders of magnitude higher.

The amounts of energy that result in biological damage are remarkably small. A gamma dose of 400 rems, which is very large in terms of biological hazard, corresponds to 4 J/kg, which would be insufficient to raise the temperature of a kilogram of water as much as 0.001°C. This fact shows that radiation affects the function of the cells by action on certain molecules, not by a general heating process.

16.3 Basis for Limits of Exposure

A typical bottle of aspirin will specify that no more than two tablets every four hours should be administered, implying that a larger or more frequent "dose" would be harmful. Such a limit is based on experience accumulated over the years with many patients. Although radiation has medical benefit only in certain treatment, the idea of the need for a limit is similar.

As we seek to clean up the environment by controlling emissions of waste products from industrial plants, cities, and farms, it is necessary to specify water or air concentrations of materials such as sulfur or carbon monoxide that are below the level of danger to living beings. Ideally, there would be zero contamination, but it is generally assumed that some releases are inevitable in an industrialized world. Again, limits based on knowledge of effects on living beings must be set.

For the establishment of limits on radiation exposure, agencies have been in existence for many years. Examples are the International Commission on Radiological Protection (ICRP), and the National Council on Radiation Protection and Measurements (NCRP). Their general procedure is to study data on the effects of radiation and to arrive at practical limits that take account of both risk and benefit of using nuclear equipment and processes.

Extensive studies of the survival of colonies of cells exposed to radiation have led to the conclusion that double-strand breaks in DNA are responsible for cell damage. Hall (see References) shows diagrams of various types of breaks. Much of the research was prompted by the need to know the best way to administer radiation for the treatment of cancer. A formula for the number of breaks N as a function of dose D is

$$N = aD + bD^2$$

where the first term refers to the effect of a single particle, the second to

that of two successive particles. This is the so-called linear-quadratic model. The fraction S of the cells surviving a dose D is deduced to be

$$S = \exp(-pN)$$

where p is the probability that a break causes cell death. The formula is somewhat analogous to that for radioactive decay or the burnup of an isotope. Cell survival data are fitted to graphs where near zero dose, the curve is linear.

There have been many studies of the effect of radiation on animals other than man, starting with early observations of genetic effects on fruit flies. Small mammals such as mice provide a great deal of data rapidly. Since controlled experiments on man are unacceptable, most of the available information on somatic effects comes from improper practices or accidents. Data are available, for example, on the incidence of sickness and death from exposure of workers who painted radium on luminous-dial watches or of doctors who used X-rays without proper precautions. The number of serious radiation exposures in the nuclear industry is too small to be of use on a statistical basis. The principal source of information is the comprehensive study of the victims of the atomic bomb explosions in Japan in 1945. Continued studies of effects are being made (see RERF in References). The incidence of fatalities as a function of dose is plotted on a graph similar to Fig. 16.2a where the data are seen to lie only in the high dosage range. In the range below 10 rads, there is no statistical indication of any increase in incidence of fatalities over the number in unexposed populations. The nature of the curve in the low dose range is unknown, and one could draw the curves labeled “unlikely” and “likely” as in Fig. 16.2b. The use of the linear-quadratic model for effect vs. dose leads to the curve labeled “likely,” but in order to be conservative, i.e., to overestimate effects of radiation in the interests of providing protection, organizations such as NCRP (see References) support a linear extrapolation through zero, the “assumed” linear no threshold (LNT) curve. Other organizations such as the American Nuclear Society and BELLE (see References) believe that there is insufficient evidence for such assumptions. Critics such as RSH (see References) believe that the insistence on conservatism and the adoption by the NRC of the LNT recommendation causes an unwarranted expense for radiation protection. The ethics of using the LNT is called into question by one writer (see References).

There is evidence that the biological effect of a given dose administered almost instantly is greater than if it were given over a long period of time. In other words, the hazard is less for low dose rates, presumably because the organism has the ability to recover or adjust to the radiation effects. If, for example (see Exercise 16.2), the effect actually varied as the square of

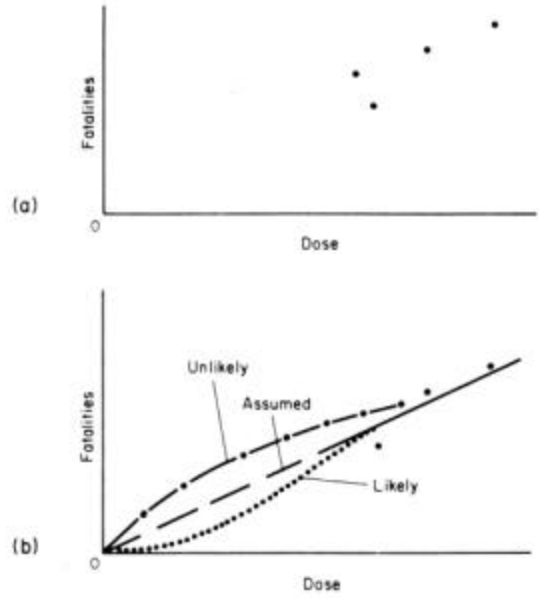


FIG. 16.2 Radiation hazard analysis.

the dose, the linear curve would overestimate the effect by a factor of 100 in the vicinity of 1 rem. Although the hazard for low dose rates is small, and there is no clinical evidence of permanent injury, it is *not* assumed that there is a threshold dose, i.e., one below which no biological damage occurs. Instead, it is assumed that there is always some risk. The linear hypothesis is retained, in spite of the likelihood that it is overly conservative.

The basic question then faced by standards-setting bodies is "what is the maximum acceptable upper limit for exposure?" One answer is zero, on the grounds that any radiation is deleterious. The view is taken that it is unwarranted to demand zero, as both maximum and minimum, because of the benefit from the use of radiation or from devices that have potential radiation as a byproduct.

The limits adopted by the Nuclear Regulatory Commission for use starting January 1, 1994 are 5 rems/y (0.05 Sv/y) for total body dose of adult occupational exposure. Alternative limits for worker dose are 50 rems/y (0.5 Sv/y) to any individual organ or tissue other than the eye, 15 rems/y (0.15 Sv/y) for the eye, and 50 rems/y (0.5 Sv/y) to the skin or any extremity. In contrast, the limits for individual members of the public are set at 0.1 rems/y (1 mSv/y), i.e., 2 percent of the worker dose. These figures take account of all radiation sources and all affected organs.

For the special case of the site boundary of a low-level radioactive waste disposal facility, NRC specifies a lower figure for the general public, 25 mrems/y (0.25 mSv/y), and for a nuclear power plant, a still lower 3

mrems/y (0.03 mSv/y).

The occupational dose limits are considerably higher than the average U.S. citizen's background dose of 0.36 rems/y, while those for the public are only a fraction of that dose. The National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation analyzes new data and prepares occasional reports, such as BEIR V (see References). In the judgment of that group, the lifetime increase in risk of a radiation-induced cancer fatality for workers using the official dose limits is 8×10^{-4} per rem, and the NRC and other organizations assume half of that figure, 4×10^{-4} per rem. However, since the practice of maintaining doses as low as reasonably achievable (ALARA) in nuclear facilities keeps doses well below the limit, the increase in chance of cancer is only a few percent. Measured dose figures have decreased considerably over the years, as reported by the Institute of Nuclear Power Operations. Table 16.2 shows the trend.

TABLE 16.2
Median Radiation Dose in Nuclear Power Plants

Year	Dose (man-rems per unit)
1984	591
1986	344
1988	320
1990	331
1992	251
1994	217
1996	162
1998	119

For the general public, the radiation exposure from nuclear power plants is negligible in comparison with other hazards of existence.

It has been said that knowledge about the origins and effects of radiation is greater than that for any chemical contaminant. The research over decades has led to changes in acceptable limits. In the very early days, soon after radioactivity and X-rays were discovered, no precautions were taken, and indeed radiation was thought to be healthful, hence the popularity of radioactive caves and springs that one might frequent for health purposes. Later, reddening of the skin was a crude indicator of exposure. Limits have decreased a great deal in recent decades, making the older literature outdated. A further complication is the development cycle: research and analysis of effects; discussion, agreement, and publication of conclusions as by ICRP and NCRP; and proposal, review, and adoption of rules by an agency such as the U.S. Nuclear Regulatory Commission (NRC). This cycle requires considerable time. For example, recommendations made in 1977 were not put into effect until 1994, leaving some later suggested

modifications in limbo. The time lag can sometimes be different for various applications, leading to apparent inconsistencies.

16.4 Sources of Radiation Dosage

The term "radiation" has come to imply something mysterious and harmful. We shall try to provide here a more realistic perspective. The key points are that (a) people are more familiar with radiation than they believe; (b) there are sources of natural radiation that parallel the man-made sources; and (c) radiation can be both beneficial and harmful.

First, solar radiation is the source of heat and light that supports plant and animal life on earth. We use its visible rays for sight; the ultraviolet rays provide vitamin D, cause tanning, and produce sunburn; the infrared rays give us warmth; and finally, solar radiation is the ultimate source of all weather. Man-made devices produce electromagnetic radiation that is identical physically to solar, and has the same biological effect. Familiar equipment includes microwave ovens, radio and TV transmitters, infrared heat lamps, ordinary lightbulbs and fluorescent lamps, ultraviolet tanning sources, and X-ray machines. The gamma rays from nuclear processes have higher frequencies and thus greater penetrating power than X-rays, but are no different in kind from other electromagnetic waves.

In recent years, concern has been expressed about a potential cancer hazard due to electromagnetic fields (EMF) from 60 Hz sources such as power lines or even household circuits or appliances. Biological effects of EMF on lower organisms have been demonstrated, but research on physiological effects on humans is inconclusive, and is continuing. More recently, concerns have arisen about the possibility of brain tumors caused by cell phone use.

Human beings are continually exposed to gamma rays, beta particles, and α particles from radon and its daughters. Radon gas is present in homes and other buildings as a decay product of natural uranium, a mineral occurring in many types of soil. Neutrons as a part of cosmic radiation bombard all livings things.

If is often said that all nuclear radiation is harmful to biological organisms. There is evidence, however, that the statement is not quite true. First, there appears to be no increase in cancer incidence in the geographic areas where natural radiation background is high. Second, in the application of radiation for the treatment of disease such as cancer, advantage is taken of differences in response of normal and abnormal tissue. The net effect in many cases is benefit to the patient. Third, it is possible that the phenomenon of *hormesis* occurs with small doses of radiation. The medical term refers to positive effects of small amounts of substances such as

hormones or enzymes that would be harmful at high doses. The topic is of broader interest in that there are toxic agents, drugs, and natural products that give paradoxical effects. The organizations BELLE and RSH (see References) are dedicated to investigating the phenomenon. A book by Luckey (see References) is devoted to the subject. In Chapter 21 we will discuss radiation protective measures and the application of regulatory limits on exposure.

16.5 Summary

When radiation interacts with biological tissue, energy is deposited and ionization takes place that causes damage to cells. The effect on organisms is somatic, related to body health, and genetic, related to inherited characteristics. Radiation dose equivalent as a biologically effective energy deposition per gram is usually expressed in rems, with natural background giving about 0.36 rem/y. Exposure limits are set by use of data on radiation effects at high dosages with a conservative linear hypothesis applied to predict effects at low dose rates. Such assumptions have been questioned.

16.6 Exercises

16.1. A beam of 2-MeV alpha particles with current density 10^6 cm^{-2}-s^{-1}, is stopped in a distance of 1 cm in air, number density 2.7×10^{19} cm^{-3}. How many ion pairs per cm^3 are formed? What fraction of the targets experience ionization?

16.2. If the chance of fatality from radiation dose is taken as 0.5 for 400 rems, by what factor would the chance at 2 rems be overestimated if the effect varied as the square of the dose rather than linearly?

16.3. A worker in a nuclear laboratory receives a whole-body exposure for 5 minutes by a thermal neutron beam at a rate 20 millirads per hour. What dose (in mrads) and dose equivalent (in mrems) does he receive? What fraction of the yearly dose limit of 5000 mrems/y for an individual is this?

16.4. A person receives the following exposures in millirems in a year: 1 medical X-ray, 100; drinking water 50; cosmic rays 30; radon in house 150; K-40 and other isotopes 25; airplane flights 10. Find the percentage increase in exposure that would be experienced if he also lived at a reactor site boundary, assuming that the maximum NRC radiation level existed there.

16.5. A plant worker accidentally breathes some stored gaseous tritium, a beta emitter with maximum particle energy 0.0186 MeV. The energy absorbed by the lungs, of total weight 1 kg, is 4×10^{-3} J. How many millirems dose equivalent was received? How many millisieverts? (Note: The average beta energy is one- third of the maximum).

16.6. If a radioisotope has a physical half-life t_H and a biological half-life t_b, what fraction of the substance decays within the body? Calculate that fraction for 8-day I-131, biological half-life 4 days.

Computer Exercises

16.A. A room with concrete walls is constructed using sand with a small uranium content, such that the concentration of radium-226 (1599 y) is 10^6 atoms per cm^3. Normally, the room

is well-ventilated so the gaseous radon-222 (3.82 d) is continually removed, but during a holiday the room is closed up. Using the parent-daughter computer program RADIOGEN (Chapter 3), calculate the trend in air activity due to Rn-222 over a week's period, assuming that half of the radon enters the room. Data on the room: 10 ft x 10 ft x 10 ft, walls 3 in. thick.

16.B. A mixture of radiation and radioactivity units are used in an article on high natural doses (*IAEA* Vol. 33, No. 2, 1991, p. 36), as follows:

(a) average radiation exposure in the world, 2.4 mSv/y.
(b) average radiation exposure in S.W. India, 10 mGy/y.
(c) high outdoor dose in Iran, 9 mrems/h.
(d) radon concentration at high altitudes in lran, 37 kBq/m^3.
(e) radon concentration in Czech houses, 10 kBq/m^3.
(f) high outdoor dose in Poland, 190 nGy/h.

Using the computer program RADOSE, which converts numbers between units, find what the numbers mean in the familiar U.S. units mrems/y or pCi/1.

16.7 References for Chapter 16

DNA Structure
http://www.accessexcellence.org/AE/AEC/CC
Genentech's Access Excellence Classical Collection. Explains the role of radioactive labeling and displays the structure of DNA.

Bruce Alberts, Dennis Bray, Alexander Johnson, Julian Lewis, Martin Raff, Keith Roberts, and Peter Walter, *Essential Cell Biology: An Introduction to the Molecular Biology of the Cell*, Garland Publishing, New York, 1997. Highly recommended. Stunning diagrams and readable text.

Jacob Shapiro, *Radiation Protection*, 3rd edition, Harvard University Press, Cambridge MA, 1990. Subtitle: A Guide for Scientists and Physicians. A very readable textbook.

Herman Cember and Herbert Cember, *Introduction to Health Physics*, McGraw-Hill, New York, 1996. Thorough and up-to-date information and instruction. Contains many illustrative calculations and tables of data. Also see Herman Cember and Thomas E. Johnson, The Health Physics Solutions Manual, PS&E Publications, 1999.

Eric J. Hall, *Radiobiology for the Radiologist*, J. B. Lippincott Co., Philadelphia, 1994. An authoritative work that explains DNA damage, cell survival curves, and radiotherapy techniques.

K. H. Chadwick and H. P. Leenhouts, *The Molecular Theory of Radiation Biology*, Springer-Verlag, Berlin, 1981. Develops formulas for DNA damage and cell survival.

James E. Turner, *Atoms, Radiation, and Radiation Protection*, John Wiley & Sons, New York, 1995. Shows Monte Carlo electron tracks in water to illustrate radiation effects.

W. R. Hendee and F. M. Edwards, Eds, *Health Effects of Exposure to Low-Level Radiation*, Institute of Physics Publishing, Bristol, 1996. An overview of radiation physics and biology and the science of risk estimation and radiation protection.

Edward Pochin, *Nuclear Radiation Risks and Benefits*, Clarendon Press, Oxford, 1983. Sources of radiation and biological effects, including cancer and damage to cells and genes.

Eric J. Hall, *Radiation and Life*, 2nd edition, Pergamon Press, New York, 1984. Discusses natural background, beneficial uses of radiation, and nuclear power. The author urges greater control of medical and dental X rays.

David W. Lillie, *Our Radiant World*, Iowa State University Press, Ames, 1986. A qualitative discussion of the sources and effects of radiation.

Arthur C. Upton, "The Biological Effects of Low-Level Ionizing Radiation," *Scientific American*, February 1982, p. 41. Describes the mechanism of biological damage and compares risks from radiation with risks from other situations or activities e.g., smoking or driving. Also discusses errors in perception of risk.

Bernard Schleien, Lester A. Slayback, Jr., and Brian Kent Birky, Editors, *Handbook of Health Physics and Radiological Health*, 3rd Ed., Williams & Wilkins, Baltimore, 1998. A greatly expanded version of a classical document of 1970.

Health Effects of Exposure to Low Levels of Ionizing Radiation: BEIR V, Committee on the Biological Effects of Ionizing Radiation, National Research Council, National Academy Press, Washington, DC, 1990. A report on the state of knowledge about radiation effects, with special attention to genetic effects and cancer. An update of the study *BEIR III* in 1980.

Radiation and Health Physics
http://www.umich.edu/~radinfo
Many links. By University of Michigan Student Chapter of the Health Physics Society.

Radiation Dose and Biological Effects
http://www.hps.org
Select Public Information, Radiation Facts for pdf files. From Health Physics Society.

Health Effects of Low-Level Radiation
http://www.ans.org
Select Search, Public Position Statements. American Nuclear Society.

Annual Report 1998, Institute of Nuclear Power Operations, Atlanta. Data on performance indicators.

Biological Effects of Low-Level Exposure (BELLE)
http://www.belleonline.com
Public health program to investigate, inform, and communicate.

Radiation, Science, and Health (RSH)
http://cnts.wpi.edu/RSH/index.html
Advocates use of scientific information on radiation matters
Zbigniew Jaworowski, "Radiation Risk and Ethics," *Physics Today*, September 1999, page 24. The article prompted a number of Letters in the April 2000 issue, page 11.

T. D. Luckey, *Radiation Hormesis*, CRC Press, Boca Raton, FL, 1991. Description of book appears at http://www.crcpress.com, with search on Luckey.

National Council on Radiation Protection and Measurements
http://www.ncrp.com
Select Publications or Documents in Review.

Biological Effects of Radiation
http://www.nrc.gov/NRC/EDUCATE/REACTOR/06-BIO/toc.html
Information from NRC.

Standards for Protection Against Radiation
http://www.nrc.gov/NRC/CFR/PART020/index.html
Part 20 of the Code of Federal Regulations–Energy.

Health Effects from Exposure to Ionizing Radiation
http://www.epa.gov/radiation/ionize2.htm
Environmental Protection Agency Fact Sheet

Richard Wilson, "Resource Letter EIRLD-1: Effects of Ionizing Radiation at Low Doses," *American Journal of Physics* 67, pp. 372-377 (1999). Puts radiation risks into perspective.

Repair Mechanisms of Radiation-Induced DNA Damage
http://www.swcc.nl/SWCNews/articles/9902/Repair.html
Relationship of cancer treatment lore to molecular effects. Article by Ad van den Berg and Roland Kanaar.

Radiation Effects Research Foundation (RERF)
http://www.rerf.or.jp/eigo/experhp/rerfhome.htm
Select Radiation Effects/Basics about Radiation/How radiation affects. Also see comprehensive review of RERF at http://www.eh.doe.gov/ihp/rerf.

17

Information from Isotopes

The applications of nuclear processes can be divided into three basic classes–military, power, and radiation. In a conference† shortly after the end of World War II the famous physicist Enrico Fermi discussed potential applications of radioisotopes. He then said, "It would not be very surprising if the stimulus that these new techniques will give to science were to have an outcome more spectacular than an economic and convenient energy source or the fearful destructiveness of the atomic bomb."

Perhaps Fermi would be surprised to see the extent to which radioisotopes have become a part of research, medicine, and industry, as described in the following sections.

Many important economic and social benefits are derived from the use of isotopes and radiation. The discoveries of modern nuclear physics have led to new ways to observe and measure physical, chemical, and biological processes, providing the strengthened understanding so necessary for man's survival and progress. The ability to isolate and identify isotopes gives additional versatility, supplementing techniques involving electrical, optical, and mechanical devices.

Special isotopes of an element are distinguishable and thus traceable by virtue of their unique weight or their radioactivity, while essentially behaving chemically as do the other isotopes of the element. Thus it is possible to measure amounts of the element or its compounds and trace movement and reactions.

When one considers the thousands of stable and radioactive isotopes available and the many fields of science and technology that require knowledge of process details, it is clear that a catalog of possible isotope uses would be voluminous. We shall be able here only to compare the merits of stable and radioactive species, to describe some of the special techniques, and to mention a few interesting or important applications of isotopes.

† Enrico Fermi, "Atomic Energy for Power," in *Science and Civilization, The Future of Atomic Energy*, McGraw-Hill, New York, 1946.

17.1 Stable and Radioactive Isotopes

Stable isotopes, as their name suggests, do not undergo radioactive decay. Most of the isotopes found in nature are in this category and appear in the element as a mixture. The principal methods of separation according to isotopic mass are electromagnetic, as in the large-scale mass spectrograph; and thermal-mechanical, as in the distillation or gaseous diffusion processes. Important examples are isotopes of elements involved in biological processes, e.g., deuterium and oxygen-18. The main advantages of stable isotopes are the absence of radiation effects in the specimens under study, the availability of an isotope of a chemical for which a radioactive species would not be suitable, and freedom from necessity for speed in making measurements, since the isotope does not decay in time. Their disadvantage is the difficulty of detection.

Radioactive isotopes, or radioisotopes, are available with a great variety of half-lives, types of radiation, and energy. They come from three main sources—charged particle reactions in an accelerator, neutron bombardment in a reactor, and separated fission products. Among the principal sources of stable and longer-lived isotopes are the U. S. Department of Energy (see References), MDS Nordion of Canada, and Russia. A number of cyclotrons that generate radioisotopes are located at hospitals. The main advantages of using radioisotopes are ease of detection of their presence through the emanations, and the uniqueness of the identifying half-lives and radiation properties. We shall now describe several special methods involving radioisotopes and illustrate their use.

17.2 Tracer Techniques

The tracer method consists of the introduction of a small amount of an isotope and the observation of its progress as time goes on. For instance, the best way to apply fertilizer containing phosphorus to a plant may be found by including minute amounts of the radioisotope phosphorus-32, half-life 14.28 days, emitting 1.7 MeV beta particles. Measurements of the radiation at various times and locations in the plant by a detector or photographic film provides accurate information on the rate of phosphorus intake and deposition. Similarly, circulation of blood in the human body can be traced by the injection of a harmless solution of radioactive sodium, Na-24, 14.96-hour half-life. For purposes of medical diagnosis, it is desirable to administer enough radioactive material to provide the needed data, but not so much that the patient is harmed.

The flow rate of many materials can be found by watching the passage of admixed radioisotopes. The concept is the same for flows as diverse as blood in the body, oil in a pipeline, or pollution discharged into a river. As

sketched in Fig. 17.1, a small amount of radioactive material is injected at a point, it is carried along by the stream, and its passage at a distance d away at time t is noted. In the simplest situation, the average fluid speed is d/t. It is clear that the half-life of the tracer must be long enough for detectable amounts to be present at the point of observation but not so long that the fluid remains contaminated by radioactive material.

In many tracer measurements for biological or engineering purposes, the effect of removing the isotope by other means besides radioactive decay must be considered. Suppose, as in Fig. 17.2, that liquid flows in and out of a tank of volume V (cm^3) at a rate u (cm^3/s). A tracer of initial amount N_0 atoms is injected and assumed to be uniformly mixed with the contents. Each second, the fraction of fluid (and isotope) removed from the tank is u/V, which serves as a flow decay constant l_f for the isotope. If radioactive decay were small, the counting rate from a detector would decrease with time as $\exp(-l_f t)$. From this trend, one can deduce either the speed of flow or volume of fluid, if the other quantity is known. If both radioactive decay and flow decay occur, the exponential formula may also be used but with the effective decay constant $l_e = l + l_f$. The composite effective half-life then can be found from the relationship

$$1/t_e = 1/t_H + 1/t_f$$

This formula is seen to be of the same form as the one developed in Section 16.1 for radioactive materials in the body. Here, the flow half-life takes the place of the biological half-life.

Soon after Watson and Crick explained the structure of DNA in 1951, tracers P-13 and S-35 were used to prove that genes were associated with DNA molecules. Tritium-labeled thymidine, involved in the cell cycle, was synthesized. The field of molecular biology expanded greatly since then, leading to the Human Genome Project (see References), an international effort to map the complete genetic structure of human beings, involving chromosomes, DNA, genes, and protein molecules. Its purpose is to find which genes cause various diseases and to enable gene therapy to be applied. Part of the complex process of mapping is hybridization, in which a particular point on the DNA molecule is marked by a radioactive or fluorescent label.

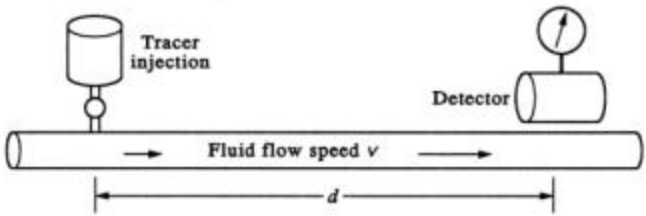


FIG. 17.1 Tracer measurement of flow rate.

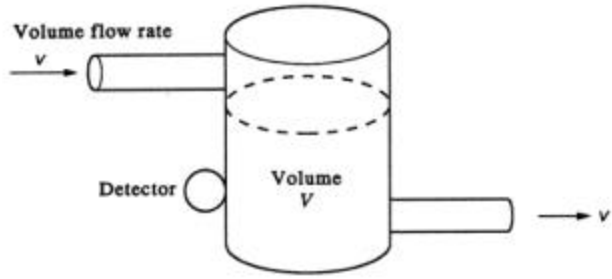


FIG. 17.2 Flow decay.

An outgrowth of genetic research is DNA fingerprinting, a method of identifying individual persons, each of which (except for identical twins) has a unique DNA structure. In one of the techniques a radioactive P-32 "probe" provides distinguishing marks on an X-ray film (see References). The process is used in crime investigation and court cases to help establish guilt or innocence, and to give evidence in paternity disputes.

17.3 Radiopharmaceuticals

Radionuclides prepared for medical diagnosis and therapy are called radiopharmaceuticals. They include a great variety of chemical species and isotopes with half-lives ranging from minutes to weeks, depending on the application. They are generally gamma-ray emitters. Prominent examples are technetium-99 (6.01 h), iodine-131 (8.04 d), and phosphorus-32 (14.28 d).

A radionuclide generator is a long-lived isotope that decays into a short-lived nuclide used for diagnosis. The advantage over using the short-lived isotope directly is that speed or reliability of shipment is not a factor. As needed, the daughter isotope is extracted from the parent isotope. The earliest example of such a generator was radium-226 (1599 y), decaying into radon-222 (3.82 d). The most widely used one is molybdenum-99 (65.9 h) decaying to technetium-99m (6.01 h). The Tc-99m is said to be "milked" from the Mo-99 "cow." Tc-99m is the most widely used radioisotope in nuclear medicine because of its favorable radiations and half-life.

Several iodine isotopes are employed. One produced by a cyclotron is I-123 (13.2 h). The accompanying isotopes I-124 (4.18 d) and I-126 (13.0 d) are undesirable impurities because of their energetic gamma rays. Two fission products are I-125 (59.4 d) and I-131 (8.04 d).

Table 17.1 illustrates the variety of radionuclides used, their chemical forms, and the organs studied.

Specialists in radiopharmaceuticals are called radiopharmacists, who are concerned with the purity, suitability, toxicity, and radiative characteristics of the radioactive drugs they prepare.

TABLE 17.1
Radiopharmaceuticals used in Medical Diagnosis

Radionuclide	Compound	Use
Technetium-99m	Sodium pertechnate	Brain scanning
Hydrogen-3	Tritiated water	Body water
Iodine-131	Sodium iodide	Thyroid scanning
Gold-198	Colloidal gold	Liver scanning
Chromium-51	Serum albumin	Gastrointestinal
Mercury-203	Chlormerodrin	Kidney scanning
Selenium-75	Selenomethionine	Pancreas scanning
Strontium-85	Strontium nitrate	Bone scanning

17.4 Medical Imaging

Administering a suitable radiopharmaceutical to a patient results in a selective deposit of the radioactive material in the tissue or organ under study. The use of these radionuclides to diagnose malfunctions or disease is called "medical imaging." About 20 million diagnostic nuclear medicine studies are performed each year in the U.S. In imaging, a photographic screen or a detector examines the adjacent area of the body, and receives an image of the organ, revealing the nature of some medical problem. A scanner consists of a sodium iodide crystal detector, movable in two directions, a collimator to define the radiation, and a recorder that registers counts in the sequence of the points it observes. In contrast, an Anger scintillation camera is stationary, with a number of photomultiplier tubes receiving gamma rays through a collimator with many holes, and an electronic data processing circuit.

The Anger camera provides a view of activity in the form of a plane. The introduction of computer technology has made possible more sophisticated displays, including three-dimensional images. Such a process is called tomography, of which there are several types. The first is Single Photon Emission Computer Tomography (SPECT), which has a rotating camera that takes a series of planar pictures of the region containing a radionuclide. A sodium iodide crystal detects uncollided photons from the radioactive source and produces electric signals. Data from 180 different angles are processed by a computer to give 2D and 3D views of the organ. SPECT is used especially for diagnosis of the heart, liver, and brain. The second is Positron Emission Tomography (PET), in which a positron-emitting radiopharmaceutical is used. Three important examples are oxygen-15 (2 min), nitrogen-13 (10 min), and carbon-11 (20 min). They are isotopes of elements found in all organic molecules, allowing them to be used for many biological studies and medical applications, especially heart disease. A fourth, fluorine-18 (110 min), is especially important in brain

studies, in which there is difficulty getting most chemicals through what is called the blood brain barrier. In contrast, F-18 forms a compound that acts like glucose, which can penetrate brain tissue and show the location of a disease such as stroke or cancer. The isotopes are produced by a cyclotron on the hospital site and the targets are quickly processed chemically to achieve the desired labeled compound. The gamma rays released in the annihilation of the positron and an electron are detected, taking advantage of the simultaneous emission (coincidences) of the two gammas and their motion in opposite directions. The data are analyzed by a computer to give high-resolution displays. PET scans are analogous to X-ray computerized axial tomography (CT) scans, but better for some purposes. Figure 17.3 compares the ability of CT and PET to locate a brain tumor.

An alternate diagnostic method that is very popular and does not involve radioactivity is Magnetic Resonance Imaging (MRI). It takes advantage of the magnetic properties of atoms in cells. Formerly it was called nuclear magnetic resonance (NMR), but physicians adopted the new name to avoid the association with anything "nuclear." There are approximately 900 MRI units in the U.S. References are included for the interested reader.

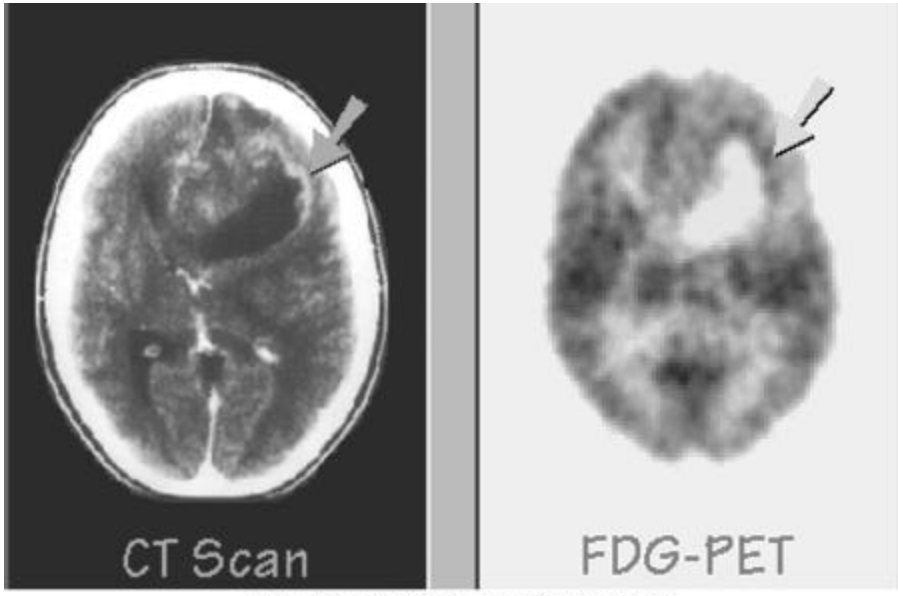


FIG. 17.3 CT and PET scans of a brain tumor
(Courtesy Lawrence Berkeley National Laboratory).

17.5 Radioimmunoassay

Radioimmunoassay, discovered in 1960 by Yalow and Berson, is a chemical procedure using radionuclides to find the concentration of biological materials very accurately, in parts per billion and less. It was

developed in connection with studies of the human body's immune system. In that system a protective substance (antibody) is produced when a foreign protein (antigen) is introduced. The method makes use of the fact that antigens and antibodies also react. Such reactions are involved in vaccinations, immunizations, and skin tests for allergies.

The object is to measure the amount of an antigen present in a sample containing an antibody. The latter has been produced previously by repeatedly immunizing a rabbit or guinea pig and extracting the antiserum. A small amount of the radioactively labeled antigen is added to the solution. There is competition between the two antigens, known and unknown, to react with the antibody. For that reason the method is also called competitive binding assay. A chemical separation is performed, and the radioactivity in the products is compared with those in a standard reaction. The method has been extended to many other substances including hormones, enzymes, and drugs. It is said that the amounts of almost any chemical can be measured very accurately, because it can be coupled chemically to an antigen.

The method has been extended to allow medical imaging of body tissues and organs. Radiolabeled antibodies that go to specific types of body tissue provide the source of radiation. As noted in Section 18.1, the same idea applies to radiation treatment. The field has expanded to include many other diagnostic techniques not involving radioactivity (see References).

17.6 Dating

There would appear to be no relationship between nuclear energy and the humanities such as history, archaeology and anthropology. There are, however, several interesting examples in which nuclear methods establish dates of events. The carbon dating technique is being used regularly to determine the age of ancient artifacts. The technique is based on the fact that carbon-14 is and has been produced by cosmic rays in the atmosphere (a neutron reaction with nitrogen). Plants take up CO_2 and deposit C-14, while animals eat the plants. At the death of either, the supply of radiocarbon obviously stops and the C-14 that is present decays, with half-life 5715 y. By measurement of the radioactivity, the age within about 50 y can be found. This method was used to determine the age of the Dead Sea Scrolls, as about 2000 y, making measurements on the linen made from flax; to date documents found at Stonehenge in England, using pieces of charcoal; and to verify that prehistoric peoples lived in the United States, as long ago as 9000 y, from the C-14 content of rope sandals discovered in an Oregon cave. Carbon dating proved that the famous Shroud of Turin was made from flax in the 14th Century, not from the time of Christ.

Even greater accuracy in dating biological artifacts can be obtained by direct detection of carbon-14 atoms. Molecular ions formed from ${}^{14}_{6}\mathrm{C}$ are accelerated in electric and magnetic fields and then slowed by passage through thin layers of material. This sorting process can measure 3 atoms of ${}^{14}_{6}\mathrm{C}$ out of 10^{16} atoms of ${}^{12}_{6}\mathrm{C}$. Several accelerator mass spectrometers are in operation around the world (see References).

The age of minerals in the earth, in meteorites, or on the moon can be obtained by a comparison of their uranium and lead contents. The method is based on the fact that Pb-206 is the final product of the decay chain starting with U-238, half-life 4.46×10^9 y. Thus the number of lead atoms now present is equal to the loss in uranium atoms, i.e.,

$$N_{\mathrm{Pb}} = (N_{\mathrm{U}})_0 - N_{\mathrm{U}} ,$$

where

$$N_{\mathrm{U}} = (N_{\mathrm{U}})_0 e^{-lt}.$$

Elimination of the original number of uranium atoms $(N_{\mathrm{U}})_0$ from these two formulas gives a relationship between time and the ratio $N_{\mathrm{Pb}}/N_{\mathrm{U}}$. The latest value of the age of the earth obtained by this method is 4.55 billion years.

For intermediate ages, thermoluminescence (heat and light) is used. Radiation shifts electrons in atoms to higher orbits (Section 2.3) while heating causes electrons to drop back. Thus the firing of clay in ancient pottery "starts the clock." Over the years, traces of radioactive U and Th cause a cumulative shifting, which is measured by heating and observing the light emitted. An elementary but entertaining account of the applications of this technique is provided by Jespersen and Fitz-Randolph (see References).

For the determination of ages ranging from 50,000 to a few million years, an argon method can be employed. It is based on the fact that the potassium isotope K-40 (half-life 1.26×10^9 y) crystallizes in materials of volcanic origin and decays into the stable argon isotope Ar-40. An improved technique makes use of neutron bombardment of samples to convert K-39, a stable isotope of potassium, into Ar-39. This provides a substitute for measuring the content of K. These techniques, described by Taylor and Aitken (see References) are of special interest in relation to the possible collision of an asteroid with the earth 65 million years ago, and the establishment of the date of the first appearance of man. Dating methods are used in conjunction with activation analysis, described in the next section.

17.7 Neutron Activation Analysis

This is an analytical method that will reveal the presence and amount of minute impurities. A sample of material that may contain traces of a certain

element is irradiated with neutrons, as in a reactor. The gamma rays emitted by the product radioisotope have unique energies and relative intensities, in analogy to spectral lines from a luminous gas. Measurements and interpretation of the gamma ray spectra, using data from standard samples for comparison, provide information on the amount of the original impurity.

Let us consider a practical example. Reactor design engineers may be concerned with the possibility that some stainless steel to be used in moving parts in a reactor contains traces of cobalt, which would yield undesirable long-lived activity if exposed to neutrons. To check on this possibility, a small sample of the stainless steel is irradiated in a test reactor to produce Co-60, and gamma radiation from the Co-60 is compared with that of a piece known to contain the radioactive isotope. The "unknown" is placed on a Pb-shielded large-volume lithium-drifted germanium Ge(Li) detector used in gamma-ray spectroscopy as noted in Section 10.4. Gamma rays from the decay of the 5.27-y Co-60 give rise to electrons by photoelectric absorption, Compton scattering, and pair production. The electrons produced by photoelectric absorption then give rise to electrical signals in the detector that are approximately proportional to the energy of the gammas. If all the pulses produced by gamma rays of a single energy were equal in height, the observed counting rate would consist of two perfectly sharp peaks at energy 1.17 MeV and 1.33 MeV. A variety of effects causes the response to be broadened somewhat as shown in Fig. 17.4. The location of the peaks clearly shows the presence of the isotope Co-60 and the heights tell how much of the isotope is present in the sample. Modern electronic circuits can process a large amount of data at one time. The multichannel analyzer accepts counts due to photons of all energy and displays the whole spectrum graphically. The Idaho National Engineering and Environmental Laboratory (INEEL) maintains a web site database on gamma ray spectroscopy (see References).

When neutron activation analysis is applied to a mixture of materials, it is necessary after irradiation to allow time to elapse for the decay of certain isotopes whose radiation would "compete" with that of the isotope of interest. In some cases, prior chemical separation is required to eliminate interfering isotope effects.

The activation analysis method is of particular value for the identification of chemical elements that have an isotope of high neutron absorption cross section, and for which the products yield a suitable radiation type and energy. Not all elements meet these specifications, of course, which means that activation analysis supplements other techniques. For example, neutron absorption in the naturally occurring isotopes of carbon, hydrogen, oxygen and nitrogen produces stable isotopes. This is

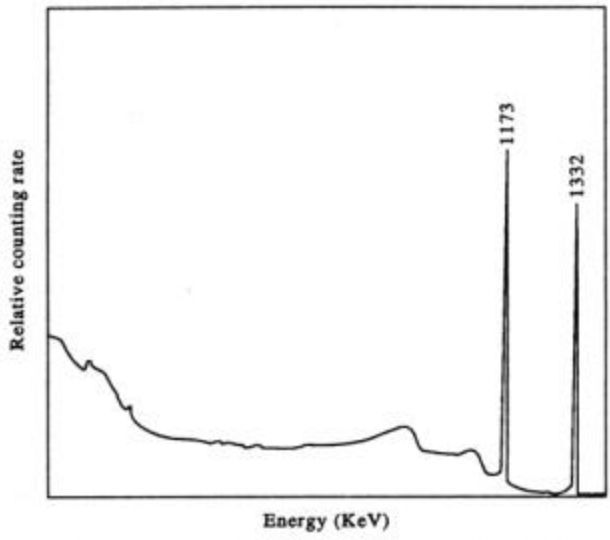


FIG. 17.4 Analysis of gamma rays from cobalt-60. (Courtesy of Jack N. Weaver of North Carolina State University).

fortunate, however, in that organic materials including biological tissue are composed of those very elements, and the absence of competing radiation makes the measurement of trace contaminants easier. The sensitivity of activation analysis is remarkably high for many elements. It is possible to detect quantities as low as a millionth of a gram in 76 elements, a billionth of a gram in 53, or even as low as a trillionth in 11.

Prompt gamma neutron activation analysis (PGNAA) is a variant on the method just described. PGNAA measures the capture gamma ray from the original (n, *g*) reaction resulting from neutron absorption in the element or isotope of interest, instead of measuring gammas from new radioactive species formed in the reaction. The distinction between NAA and PGNAA is shown in Fig. 17.5, which shows the series of reactions that can result from a single neutron.

Because the reaction rate depends on the neutron cross section, only a relatively small number of elements can be detected in trace amounts. The detection limits in ppm are smallest for B, Cd, Sm, and Gd (0.01-0.1), and somewhat higher for Cl, Mn, In, Nd, and Hg (1-10). Components that can readily be measured are those often present in large quantities such as N, Na, Al, Si, Ca, K, and Fe. The method depends on the fact that each element has its unique prompt gamma ray spectrum. The advantages of PGNAA are that it is non-destructive, it gives low residual radioactivity, and the results are immediate.

A few of the many applications of neutron activation analysis are now described briefly.

(a) *Textile manufacturing*. In the production of synthetic fibers, certain

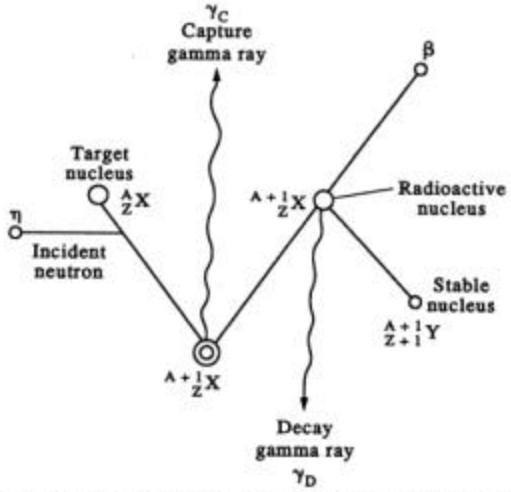


FIG. 17.5 Nuclear reactions involved in neutron activation analysis (PGNAA). (Courtesy of Institute of Physics).

chemicals such as fluorine are applied to improve textile characteristics, such as the ability to repel water or stains. Activation analysis is used to check on inferior imitations, by comparison of the content of fluorine or other deliberately added trace elements.

(b) *Petroleum processing*. The "cracking" process for refining oil involves an expensive catalyst that is easily poisoned by small amounts of vanadium, which is a natural constituent of crude oil. Activation analysis provides a means for verifying the effectiveness of the initial distillation of the oil.

(c) *Crime investigation*. The process of connecting a suspect with a crime involves physical evidence that often can be accurately obtained by NAA. Examples of forensic applications are: the comparison of paint flakes found at the scene of an automobile accident with paint from a hit-and-run driver's car; the determination of the geographical sources of drugs by comparison of trace element content with that of soils in which plants are grown; verification of theft of copper wire using differences in content of wire from various manufacturers; distinguishing between murder and suicide by measurement of barium or antimony on hands; and tests for poison in a victim's body. The classic example of the latter is the verification of the hypothesis that Napoleon was poisoned, by activation analysis of arsenic in hair samples.

(d) *Authentication of art work*. The probable age of a painting can be found by testing a small speck of paint. Over the centuries the proportions of elements such as chromium and zinc used in pigment have changed, so that forgeries of the work of old masters can be detected.

An alternative method of examination involves irradiation of a painting

briefly with neutrons from a reactor. The radioactivity induced produces an autoradiograph in a photographic film, so that hidden underpainting can be revealed.

It was desired to determine the authenticity of some metal medical instruments, said to be from Pompeii, the city buried by the eruption of Vesuvius in A.D. 79. PGNAA was applied, and using the fact that the zinc content of true Roman artifacts was low, the instruments were shown to be of modern origin.

(e) *Diagnosis of disease*. Medical applications (see References) include accurate measurements of the normal and abnormal amounts of trace elements in the blood and tissue, as indicators of specific diseases. Other examples are the determination of sodium content of children's fingernails and the very sensitive measurement of the iodide uptake by the thyroid gland.

(f) *Pesticide investigation*. The amounts of residues of pesticides such as DDT or methyl bromide in crops, foods, and animals are found by analysis of the bromine and chlorine content.

(g) *Mercury in the environment.* The heavy element mercury is a serious poison for animals and human beings even at low concentrations. It appears in rivers as the result of certain manufacturing waste discharges. By the use of activation analysis, the Hg contamination in water or tissues of fish or land animals can be measured, thus helping to establish the ecological pathways.

(h) *Astronomical studies*. Measurement by NAA of the variation in the minute amounts of iridium (parts per billion) in geological deposits led to some startling conclusions about the extinction of the dinosaurs some 65 million years ago. A large meteorite, 6 km in diameter, is believed to have struck the earth and to have caused atmospheric dust that reduced the sunlight needed by plants eaten by the dinosaurs. The theory is based on the fact that meteorites have a higher iridium content than the Earth. The sensitivity of NAA for Ir was vividly demonstrated by the discovery that contact of a technician's wedding ring with a sample for only two seconds was sufficient to invalidate results.

Evidence is mounting for the correctness of the idea. Large impact craters and buried structures have been discovered in Yucatan and Iowa. They are surrounded by geological debris whose age can be measured by the K-Ar method (see Section 17.6 and References).

(i) *Geological applications of PGNAA*. Oil and mineral exploration in situ of large-tonnage, low-grade deposits far below the surface has been found to yield better results than does extracting small samples. In another example, measurements were made on the ash on the ground and particles

in the atmosphere from the 1980 Mount St. Helens volcano eruption. Elemental composition was found to vary with distance along the ground and with altitude. Many other examples of the use of PGNAA are found in the literature (see References).

An alternative and supplement to NAA and PGNAA is X-ray fluorescence spectrometry. It is more accurate for measuring trace amounts of some materials. The method consists of irradiating a sample with an intense X-ray beam to cause target elements to emit characteristic line spectra, i.e., to fluoresce. Identification is accomplished by either (a) measurements of the wavelengths by diffraction using a single crystal, comparison with a standard, and analysis by a computer, or (b) use of a commercial low-energy photon spectrometer, a semiconductor detector. The sensitivity of the method varies with the element irradiated, being lower than 20 ppm for all elements with atomic number above 15. The time required is much shorter than for wet chemical analyses, making the method useful when a large number of measurements are required.

17.8 Radiography

The oldest and most familiar beneficial use of radiation is for medical diagnosis by X-rays. These consist of high-frequency electromagnetic radiation produced by electron bombardment of a heavy-metal target. As is well known, X-rays penetrate body tissue to different degrees depending on material density, and shadows of bones and other dense materials appear on the photographic film. The term "radiography" includes the investigation of internal composition of living organisms or inanimate objects, using X-rays, gamma rays, or neutrons.

For both medical and industrial use, the isotope cobalt-60, produced from Co-59 by neutron absorption, is an important alternative to the X-ray tube. Co-60 emits gamma rays of energy 1.17 MeV and 1.33 MeV, which are especially useful for examination of flaws in metals. Internal cracks, defects in welds, and nonmetallic inclusions are revealed by scanning with a cobalt radiographic unit. Advantages include small size and portability, and freedom from the requirement of an electrical power supply. The half-life of 5.27 y permits use of the device for a long time without need for replenishing the source. On the other hand, the energy of the rays is fixed and the intensity cannot be varied, as is possible with the X-ray machine.

Other isotopes that are useful for gamma-ray radiography are: (a) iridium-192, half-life 73.8 d, photon energy around 0.4 MeV, for thin specimens; (b) cesium-137 (30.2 y), because of its long half-life and 0.662 MeV gamma ray; (c) thulium-170, half-life 128.6 d, emitting low-energy gammas (0.052, 0.084, 0.16 MeV), useful for thin steel and light alloys

because of the high cross section of the soft radiation.

The purpose of radiography using neutrons is the same as that using X-rays, namely to examine the interior of an opaque object. There are some important differences in the mechanisms involved, however, X-rays interact principally with the electrons in atoms and molecules, and thus are scattered best by heavy high-*Z* elements. Neutrons interact with nuclei and are scattered according to what isotope is the target. Hydrogen atoms have a particularly large scattering cross section. Also, some isotopes have very high capture cross section; e.g., cadmium, boron, and gadolinium. Such materials are useful in detectors as well. Figure 17.6 shows the schematic arrangement of a thermal neutron radiography unit, where the source can be a nuclear reactor, a particle accelerator, or a radioisotope. Exposure times are least for the reactor source because of the large supply of neutrons; they are greatest for the isotopic source. A typical accelerator reaction using neutrons is the (d,n) reaction on tritium or beryllium.

Several of the radioisotopes sources use the (g,n) reaction in beryllium-9, with gamma rays from antimony-124 (60.20 d), or the (a,n) reaction with alpha particles from americium-241 (432 y) or curium-242 (163 d). An isotope of the artificial element 98, californium-252, is especially useful as a neutron source. It decays usually (96.9%) by a-particle emission, but the other part (3.1%) undergoes spontaneous fission releasing around 3.5 neutrons on average. The half-lives for the two processes are 2.73 y and 85.5 y, respectively. An extremely small mass of Cf-252 serves as an abundant source of neutrons. These fast neutron sources must be surrounded by a light-element moderator to thermalize the neutrons.

Detection of transmitted neutrons is by the small number of elements that have a high thermal neutron cross section and which emit secondary radiation that readily affects a photographic film and record the images. Examples are boron, indium, dysprosium, gadolinium, and lithium. Several neutron energy ranges may be used–thermal, fast and epithermal, and "cold" neutrons, obtained by passing a beam through a guide tube with

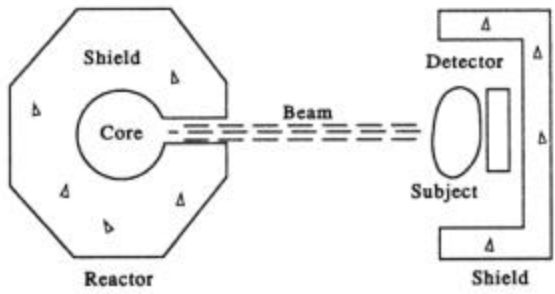


FIG. 17.6 Schematic diagram of a thermal neutron radiography unit. Source can be an accelerator, a reactor, or a radioisotope.

reflecting walls that select the lowest energy neutrons of a thermal distribution.

Examples of the use of neutron radiography are:

(a) Inspection of reactor fuel assemblies prior to operation for defects such as enrichment differences, odd-sized pellets, and cracks.

(b) Examination of used fuel rods to determine radiation and thermal damage.

(c) Inspection for flaws in explosive devices used in the U.S. space program. The devices served to separate booster stages and to trigger release of re-entry parachutes. Items are rejected or reworked on the basis of any one of ten different types of defects.

(d) Study of seed germination and root growth of plants in soils. The method allows continued study of the root system without disturbance. Root diameters down to 1/3 mm can be discerned, but better resolution is needed to observe root hairs.

(e) "Real-time" observations of a helicopter gas turbine engine at Rolls-Royce, Ltd. Oil flow patterns using cold neutrons are observable, and bubbles, oil droplets, and voids are distinguishable from normal density oil.

17.9 Radiation Gauges

Some physical properties of materials are difficult to ascertain by ordinary methods, but can be measured easily by observing how radiation interacts with the substance. For example, the thickness of a layer of plastic or paper can be found by measuring the transmitted number of beta particles from a radioactive source. The separated fission product isotopes strontium-90 (29.1 y, 0.546 MeV beta particle) and cesium-137 (30.2 y, 0.514 MeV beta particle) are widely used for such gauging.

The density of a liquid flowing in a pipe can be measured externally by detection of the gamma rays that pass through the substance. The liquid in the pipe serves as a shield for the radiation, and attenuation of the beam dependent on macroscopic cross section and thus particle number density.

The level of liquid in an opaque container can be measured readily without the need for sight glasses or electric contacts. A detector outside the vessel measures the radiation from a radioactive source mounted on a float in the liquid.

Portable gauges for measurement of both moisture and density are available commercially. A rechargeable battery provides power for the electronics involving a microprocessor. Gamma rays for density measurements in materials such as soil or asphalt paving are supplied by a

cesium-137 source. For operation in the direct-transmission mode, a hole is punched into the material being tested and a probe rod with radioactive source in its end is inserted. A Geiger-Müller gamma ray detector is located at the base of the instrument, as shown in Fig. 17.7a. A typical calibration curve for the instrument is shown in Fig. 17.7b. Standard blocks of test material using various amounts of magnesium and aluminum are used to determine the constants in an empirical formula that relates density to counting rate. If the source is retracted to the surface, measurements in the back-scattering mode can be made. The precision of density measurements is 0.4% or better. For moisture measurements by the instrument, neutrons of average energy 4.5 MeV are provided by an americium-beryllium source. A particles of around 5 MeV from americium-241, half-life 432 y, bombard beryllium-9 to produce the reaction $^{9}Be(\alpha, n)^{12}C$. Neutrons from the source, located in the center of the gauge base, migrate through the material and slow down, primarily with collisions with the hydrogen atoms in the contained moisture. The more water that is present, the larger is the thermal neutron flux in the vicinity of the gauge. The flux is measured by a thermal-neutron detector consisting of a helium-3 proportional counter, in which the ionization is created by the products of the reaction $^{3}He(n,p)^{3}H$ (σ_a = 5330 barns). Protons and tritons (hydrogen-3 ions) create the ionization measured in the detector. The gauge is calibrated by using laminated sheets of the hydrocarbon polyethylene and of magnesium. The moisture content can be measured to about 5% in normal soil. The device requires correction if there are significant amounts of absorbers such as iron, chlorine, or boron in the ground, or if there are hydrogenous materials other than water present.

A newer portable nuclear gauge† measures both water and cement in a fresh concrete mix. One probe contains a Cf-252 source, with the fast neutrons thermalized in hydrogen, and measured by a He-3 detector. The other probe has an Am-241 source, with the gamma rays absorbed by the photoelectric effect, mainly in calcium in the cement. A counter notes the amount of reduction in gammas. A calibration of the instrument is made with several water and cement combinations in the vicinity of the target mix, and correlated with compressive strengths tests. Field studies and a Monte Carlo computer simulation were used in the evaluation of the device by the Civil Engineering Research Foundation (see References).

Several nuclear techniques are employed in the petroleum industry. In the drilling wells, the "logging" process involves the study of geologic features. One method consists of the measurement of natural gamma radiation. When the detector is moved from a region of ordinary radioactive rock to one containing oil or other liquid, the signal is reduced. A neutron

† Troxler Model 4430 Water/Cement Gauge.

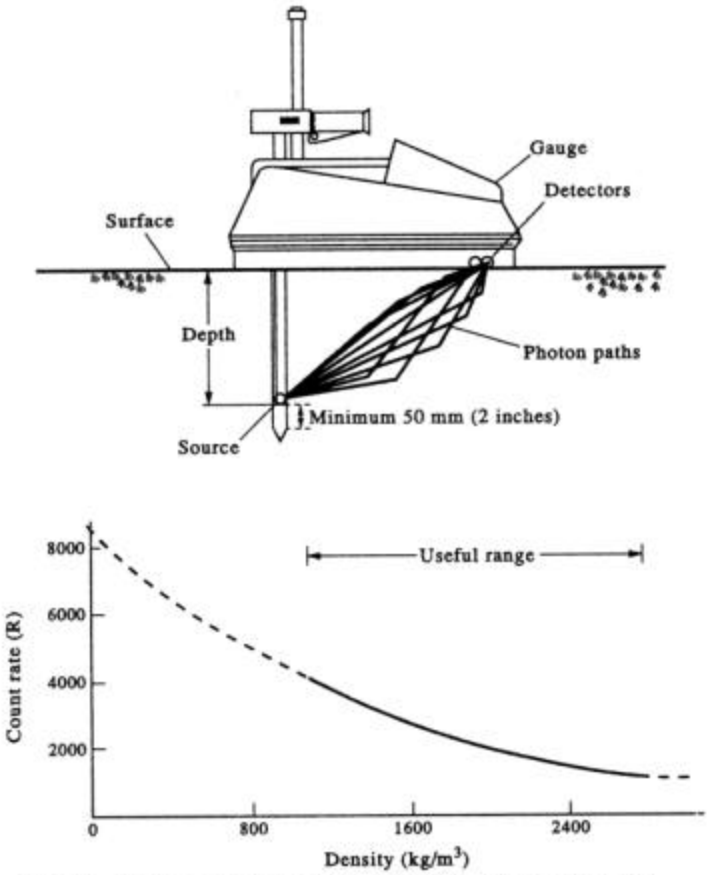


FIG. 17.7 Direct-transmission radiation gauge to measure soil density. (Courtesy of Troxler Electronic Laboratories, Inc.)

moisture gauge is adapted to determine the presence of oil, which contains hydrogen. Neutron activation analysis of chemical composition is performed by lowering a neutron source and a gamma ray detector into the well.

17.10 Summary

Radioisotopes provide a great deal of information for human benefit. The characteristic radiations permit the tracing of processes such as fluid flow. Pharmaceuticals are radioactively tagged chemicals used in hospitals for diagnosis. Scanners detect the distribution of radioactivity in the body and form images of diseased tissue. Radioimmunoassay measures minute amounts of biological materials. The dates of archaeological artifacts and of rock formations can be found from carbon-14 decay data and the ratios of uranium to lead and of potassium to argon. The irradiation of materials with neutrons gives rise to unique prompt gamma rays and radioactive decay

products, allowing measurement of trace elements for many applications. Radiography employs gamma rays from cobalt-60 or neutrons from a reactor, accelerator, or californium-252. Radiation gauges measure density, thickness, ground moisture, water/cement ratios, and oil deposits.

17.11 Exercises

17.1. A radioisotope is to be selected to provide the signal for arrival of a new grade of oil in an 800-km-long pipe line, in which the fluid speed is 1.5 m/s. Some of the candidates are:

Isotope	Half-life	Particle, energy (MeV)
Na-24	14.96 h	*b*, 1.389; *g*, 1.369, 2.754
S-35	87.2 d	*b* ,0.167
Co-60	5.27 y	*b*, 0.315; *g*, 1.173, 1.332
Fe-59	44.5 d	*b*, 0.273, 0.466; *g*, 1.099, 1.292

Which would you pick? On what basis did you eliminate the others?

17.2. The radioisotope F-18, half-life 1.83 h, is used for tumor diagnosis. It is produced by bombarding lithium carbonate (Li_2CO_3) with neutrons, using tritium as an intermediate particle. Deduce the two nuclear reactions.

17.3. The range of beta particles of energy 0.53 MeV in metals is 170 mg/cm^2. What is the maximum thickness of aluminum sheet, density 2.7 g/cm^3, that would be practical to measure with a Sr-90 or Cs-137 gauge?

17.4. The amount of environmental pollution by mercury is to be measured using neutron activation analysis. Neutron absorption in the mercury isotope Hg-196, present with 0.15% abundance, activation cross section 3×10^3 barns, produces the radioactive species Hg-197, half-life 2.67 days. The smallest activity for which the resulting photons can be accurately analyzed in a river water sample is 10 dis/sec. If a reactor neutron flux of 10^{12} cm^{-2}-s^{-1} is available, how long an irradiation is required to be able to measure mercury contamination of 20 ppm (μg/g) in a 4 milliliter water test sample?

17.5. The ratio of numbers of atoms of lead and natural uranium in a certain moon rock is found to be 0.05. What is the probable age of the sample?

17.6. The activity of C-14 in a wooden figure found in a cave is only 3/4 of today's value. Estimate the date the figure was carved.

17.7. Examine the possibility of adapting the uranium-lead dating analysis to the potassium-argon method. What would be the ratio of Ar-40 to K-40 if a deposit were 1 million years old? Note that only 10.72 percent of K-40 decay yields Ar-40, the rest going into Ca-40.

17.8. The age of minerals containing rubidium can be found from the ratio of radioactive Rb-87 to its daughter Sr-87. Develop a formula relating this ratio to time.

17.9. It has been proposed to use radioactive krypton gas of 10.73 y half-life in conjunction with film for detecting small flaws in materials. Discuss the concept, including possible techniques, advantages, and disadvantages.

17.10. A krypton isotope $^{81m}_{36}Kr$ of half-life 13.1 seconds is prepared by charged particle bombardment. It gives off a gamma ray of 0.19 MeV energy. Discuss the application of the isotope to the diagnosis of emphysema and black-lung disease. Consider production, transportation, hazards, and other factors.

17.11. Tritium (^3_1H) has a physical half-life of 12.32 years but when taken into the human body as water it has a biological half-life of 12.0 days. Calculate the effective half-life of tritium for purposes of radiation exposure. Comment on the result.

17.12. Using half-life relationship as given in Section 17.2, calculate the effective half-life of

californium-252.

17.13. The spontaneous fission half-life of Cf-252 is 85.5 y. Assuming that it releases 3.5 neutrons per fission, how much of the isotope in micrograms is needed to provide a source of strength of 10^7 neutrons per second? What would be the diameter of the source in the form of a sphere if the Cf-252 had a density as pure metal of 20 g/cm^3?

17.14. Three different isotopic sources are to be used in radiography of steel in ships as follows:

Isotope	Half-life	Gamma energy (MeV)
Co-60	5.27 y	1.25 (ave.)
Ir-192	73.8 d	0.4 (ave.)
Cs-137	30.2 y	0.66

Which isotope would be best for insertion in pipes of small diameter and wall thickness? For finding flaws in large castings? For more permanent installations? Explain.

17.15. The number of atoms of a parent isotope in a radionuclide generator such as Mo-Tc given by $N_p = N_{p0}E_p$, where $E_p = \exp(-\lambda_p t)$, with N_{p0} as the initial number of atoms. The number of daughter atoms for zero initially is

$$N_d = k\lambda_p N_{p0}(E_p - E_d)/(\lambda_d - \lambda_p)$$

where k is the fraction of parents that go into daughters and $E_d = \exp(-\lambda_d t)$.

(a) Find the ratio of Tc-99m atoms to Mo-99 atoms for very long times, using $k = 0.87$.

(b) What is the percent error in using the ratio found in (a) if it takes one half-life of the parent to ship the fresh isotope to a laboratory for use?

17.16. Pharmaceuticals containing carbon-14 (5715 y) and tritium (12.32 y) are both used in a biological research laboratory. To avoid an error of greater than 10% in counting beta particles, as a result of accidental contamination of C-14 by H-3, what must be the upper limit on the fraction of atoms of tritium in the sample? Assume that all betas are counted, regardless of energy.

17.17. The atom fraction of C-14 in carbon was approximately 1.2×10^{-12} prior to bomb tests. How many counts per minute would be expected from a 1 gram sample of carbon? Discuss the implications of that number.

Computer Exercise

17.A. Recall the computer program RADIOGEN (see Computer Exercise 3D) giving activities of parent and daughter isotopes.

(a) Apply to the radionuclide generator of Section 17.3 using half-lives 65.9 h for Mo-99 and 6.01h for Tc-99m, with $k = 0.87$. Carry the calculations out to at least 66 hours in steps of one hour.

(b) From the formula in Computer Exercise 3D, show that the ratio of activities of daughter to parent at very long times is

$$A_d/A_p = k/(1 - \lambda_p/\lambda_b).$$

(c) Find out how much error there is in using the formula of (b) rather than the ratio calculated by RADIOGEN, if it takes exactly one half-life of Mo-99 to ship the generator to a laboratory for use.

17.12 References for Chapter 17

Biology Links
http://mcb.harvard.edu/BioLinks.html
Harvard University Department of Molecular and Cellular Biology.

DOE Information Bridge
http://www.osti.gov/bridge
Search on “A Vital Legacy” for atoms in biology. 4807K pdf file.

S. James Adelstein and Frederick J. Manning, Eds., *Isotopes for Medicine and the Life Sciences*, National Academy Press, Washington, 1995. Describes sources of stable and radioactive isotopes and recommends a national dedicated accelerator.

Medical Isotopes Production
http://www.sandia.gov
Search on "molybdenum-99"

DOE Isotope Production and Distribution
http://www.ornl.gov.isotopes/catalog.html
Catalog with prices.

Human Genome Project Information
http://www.ornl.gov/hgmis
Reports that can be read or downloaded include "Primer on Molecular Genetics" and "To Know Ourselves."

Genentech's Access Excellence Classical Collection
http://www.accessexcellence.com/AE/AEC/CC
"A Visit with Dr. Francis Crick," "DNA Structure," and "Restriction Nucleases."

Basics of DNA Fingerprinting
http://www.biology.washington.edu/fingerprint/dnaintro.html
Class project by Kate Brinton and Kim-An Lieberman.

Use of DNA Fingerprinting in Forensic Science
http://www.esva.net/~dbowling/Dna.htm
High school term paper by Donald Bowling.

M. Krawczak and J. Schmidtke, *DNA Fingerprinting*, 2nd Ed., Springer Verlag, New York, 1998. Genetics background, applications to forensics, and legal and ethical aspects.

Guidebook on Radioisotope Tracers in Industry, International Atomic Energy Agency, Vienna, 1990. Methodology, case studies, and trends.

John Harbert and Antonio F. G. da Rocha, *Textbook of Nuclear Medicine*, Volume I: Basic Science, Volume II: Clinical Applications, 2nd edition, Lea & Febiger, Philadelphia, 1984. Volume I contains good descriptions of radionuclide production, imaging, radionuclide generators, radiopharmaceutical chemistry, and other subjects. Volume II give applications to organs.

Gopal B. Saha. *Fundamentals of Nuclear Pharmacy*, 4th ed., Springer, New York, 1997. Instruments, isotope production, and diagnostic and therapeutic uses of radiopharmaceuticals. Reflects the continued growth of the field.

Introduction to MRI
http://128.227.164.224/mritutor/index.html
Elementary tutorial by Ray Ballinger.

The Basics of MRI
http://www.cis.rit.edu/htbooks/mri/bmri.htm
Comprehensive treatment by Dr. Joseph P. Hornak.

Medical Physics and Bioengineering Resources
http://bach.medphys.ucl.ac.uk/inset/resource.htm
List of textbooks, videos, slides, and CD's. By University College London.

Fred A. Mettler, Jr. and Milton J. Guiberteau, *Essentials of Nuclear Medicine Imaging*, 4th Ed., Philadelphia, W. B. Saunders Co., 1998. After presenting background on radioactivity, instruments, and computers, the book describes the methods used to diagnose and treat different tissues, organs, and systems of the body.

Ramesh Chandra, *Introductory Physics of Nuclear Medicine*, 4th ed., Lea & Febiger, Philadelphia, 1992. Intended for resident physicians. Covers scintillation cameras and computer tomography.

Marshall Brucer, *A Chronology of Nuclear Medicine 1600-1989*, Heritage Publications, St. Louis, 1990. Interesting and informative discussion with abundant references.

T. Chard, *An Introduction to Radioimmunoassay and Related Techniques*, Elsevier, Amsterdam, 1995. Concept, principles, and laboratory techniques. Immunoassays in general, labeling techniques, and commercial services.

Christopher P. Price and David J. Newman, Editors, *Principles and Practices of Immunoassay*, Stockton Press, New York, 1991. A great variety of immunoassay techniques.

Herman W. Knoche, *Radioisotopic Methods for Biological and Medical Research*, Oxford University Press, New York, 1991. Includes mathematics of radioimmunoassay and isotope dilution.

G. Choppin, J. Rydberg, and J. O. Liljenzin, *Radiochemistry and Nuclear Chemistry*, 2nd Ed.., Butterworth-Heinemann, Oxford, 1995. Includes chapters on isotope uses in chemistry and on nuclear energy.

Radiocarbon Web-info
http://c14.sci.waikato.ac.nz/webinfo/applic.html
Links to many applications of C-14 dating, by T. Higham.

Robert E. M. Hedges and John A. J. Gowlett, "Radiocarbon Dating by Accelerator Mass Spectrometry," *Scientific American*, January 1986, p. 100.

Accelerator Mass Spectrometry
Woods Hole: http://ams245.whoi.edu
Lunds Universitet: http://www.fysik.lth.se/NuclearPhysics/ams/index.html
Application to carbon dating.

James Jespersen and Jane Fitz-Randolph, *Mummies, Dinosaurs, Moon Rocks: How We Know How Old Things Are*, Atheneum Books for Young Readers, New York, 1996.

Sheridan Bowman, Ed., *Science and the Past*, University of Toronto Press, Toronto, 1991. Qualitative technical treatment of dating with emphasis on the artifacts.

R. E. Taylor and Martin J. Aitken, Eds., *Chronometric Dating in Archaeology*, Plenum Press, New York, 1997. Principle, history, and current research for a number of dating techniques. Articles are written by experts in the methods.

K. Heydorn, *Neutron Activation Analysis for Clinical Trace Element Research*, Vols. I & II,CRC Press, Boca Raton, FL, 1984.

North Carolina State University's Nuclear Science Center
http://www.ne.ncsu.edu/NRP/services.html
Services for radioisotope production, neutron activation analysis, and neutron radiography.

INEEL Gamma-Ray Spectrometry Center
http://id.inel.gov/gamma
Display of spectra and decay schemes.

Zeev B. Alfassi and Chien Chung, Eds., *Prompt Gamma Neutron Activation Analysis*, CRC Press, Boca Raton, FL, 1995. Includes *in vivo* measurements of elements in the human body and *in situ* well-logging in the petroleum industry.

The Medical Radiography Home Page
http://home.earthlink.net/~terrass/radiography/medradhome.html
Internet resources by Richard Terrass of Massachusetts General.

R. Halmshaw, *Industrial Radiology, Theory and Practice*, 2nd Ed., Chapman & Hall, London, 1995. Principles and equipment using X-rays, gamma rays, neutrons, and other particles. Computers and automation in quality control and non-destructive testing.

J. C. Domanus, Ed., *Practical Neutron Radiography*, Kluwer, Dordrecht, 1992. Sources, collimation, imaging, and applications, e.g., nuclear fuel.

A. A. Harms and D. R. Wyman, *Mathematics and Physics of Neutron Radiography*, D. Reidel, Dordrecht, Holland, 1986. Highly technical reference.

X-ray WWW Server
http://xray.uu.se
Links to synchrotron radiation facilities.

Kevin L. D'Amico, Louis J. Terminello, and David K. Shuh, *Synchrotron Radiation Techniques in Industrial, Chemical, and Materials, Science*, Plenum Press, New York, 1996. Selected papers from two conferences.

Water/Cement Gauge
http://www.cerf.org/hitec/news/troxler.htm
Description of tests of a nuclear gauge.

18

Useful Radiation Effects

Radiation in the form of gamma rays, beta particles, and neutrons is being used in science and industry to achieve desirable changes. Radiation doses control offending organisms including cancer cells and harmful bacteria, and sterilize insects. Local energy deposition can also stimulate chemical reactions and modify the structure of plastics and semiconductors. Neutrons and X-rays are used to investigate basic physical and biological processes. In this chapter we shall briefly describe some of these interesting and important applications of radiation. For additional information on the uses around the world, proceedings of international conferences can be consulted. Thanks are due Albert L. Wiley, Jr., MD, PhD for suggestions on the subject of nuclear medicine.

18.1 Medical Treatment

The use of radiation for medical therapy has increased greatly in recent years, with millions of treatments given patients annually. The radiation comes from teletherapy units in which the source is at some distance from the target, or from isotopes in sealed containers implanted in the body, or from ingested solutions of radionuclides.

Doses of radiation are found to be effective in the treatment of diseases such as cancer. In early times, X-rays were used, but they were supplanted by cobalt-60 gamma rays, because the high energy (1.17 and 1.33 MeV) photons penetrated tissue better and could deliver doses deep in the body, with a minimum of skin reaction. In modern nuclear medicine, there is increasing use of accelerator-produced radiation in the range 4-35 MeV for cancer treatment.

Treatment of disease by implantation of a radionuclide is called interstitial brachytherapy ("brachys" is Greek for "short"). A small radioactive capsule or "seed" is imbedded in the organ, producing local gamma irradiation. The radionuclides are chosen to provide the correct dose. In earlier times, the only material available for such implantation was α-emitting radium-226 (1599 years). Most frequently used today are iridium-192 (73.8 days), iodine-125 (59.4 days), and palladium-103 (17.0 days). Examples of tumor locations where this method is successful are the head and neck, breast, lung, and prostate gland. Other isotopes sometimes

used are cobalt-60, cesium-137, tantalum-182, and gold-198. Intense fast neutron sources are provided by californium-252. For treatment of the prostate, 40-100 "rice-sized" seeds, (4.5 mm long and 0.81 mm diameter) containing a soft-gamma emitter, Pd-103, are implanted with thin hollow needles (see References). Computerized tomography and ultrasound aid in the implantation.

One sophisticated device for administering cancer treatment uses a pneumatically controlled string of cesium-137 impregnated glass beads encapsulated in stainless steel, of only 2.5 mm diameter. Tubes containing the beads are inserted in the bronchus, larynx, and cervix.

Success in treatment of abnormal pituitary glands is obtained by charged particles from an accelerator, and beneficial results have come from slow neutron bombardment of tumors in which a boron solution is injected. Selective absorption of chemicals makes possible the treatment of cancers of certain types by administering the proper radionuclides. Examples are iodine-125 or iodine-131 for the thyroid gland and phosphorus-32 for the bone. However, there is concern in medical circles that use of iodine-131 to treat hyperthyroidism could cause thyroid carcinoma, especially in children.

Relief from rheumatoid arthritis is obtained by irradiation with beta particles. The radionuclide dysprosium-165 (2.33 hr) is mixed with ferric hydroxide, which serves as a carrier. The radiation from the injected radionuclide reduces the inflammation of the lining of joints.

Table 18.1 shows some of the radionuclides used in treatment.

TABLE 18.1
Radionuclides Used in Therapy

Radionuclide	Disease treated
P-32	Leukemia
Y-90	Cancer
I-131	Hyperthyroidism
	Thyroid cancer
Sm-153	
Re-186	Bone cancer pain
Re-188	
Au-198	Ovarian cancer

A great deal of medical research is an outgrowth of radioimmunoassay (See Section 17.5). It involves monoclonal antibodies (MAbs), which are radiolabeled substances that have an affinity for particular types of cancer, such as those of the skin and lymph glands. The diseased cells are irradiated without damage to neighboring normal tissue. The steps in this complex procedure start with the injection into mice of human cancer cells, as antigens. The mouse spleen, a part of the immune system, produces antibodies through the lymphocyte cells. These cells are removed and blended with myeloma cancer cells, to form new cells called hybridoma. In

a culture, the hybridoma clones itself to produce the MAb. Finally, a beta-emitting radionuclide such as yttrium-90 is chemically bonded to the antibody.

A promising treatment for cancer is boron neutron capture therapy (BNCT). A boron compound that has an affinity for diseased tissue is injected, and the patient is irradiated with neutrons from a reactor. Boron-10, with abundance 20 percent in natural boron, strongly absorbs thermal neutrons to release lithium-7 and helium-4 ions. An energy of over two MeV is deposited locally because of the short range of the particles. The technique was pioneered in the 1950s by Brookhaven National Laboratory, but the program was suspended from 1961 to 1994 and terminated in 1999. Research is continuing at other locations, however (see References). A compound BPA was found that localized boron better and thermal neutrons were replaced by intermediate energy neutrons, with favorable results. A single treatment with BNCT is as effective as many conventional radiation-chemotherapy sessions. The method has been found to be effective in treatment of malignancies such as melanoma (skin) and glioblastoma multiforme (brain). The discovery of monoclonal antibodies opens up new possibilities for large scale use of BNCT.

The mechanism of the effects of radiation is known qualitatively. Abnormal cells that divide and multiply rapidly are more sensitive to radiation than normal cells. Although both types are damaged by radiation, the abnormal cells recover less effectively. Radiation is more effective if the dosage is fractionated; i.e., split into parts and administered at different times, allowing recovery of normal tissue to proceed.

Use of excess oxygen is helpful. Combinations of radiation, chemotherapy, and surgery are applied as appropriate to the particular organ or system affected. The ability to control cancer has improved over the years, but a cure based on better knowledge of cell biology is yet to come.

18.2 Radiation Preservation of Food

The ability of radiation treatment to eliminate insects and microorganisms from food has been known for many years. Significant benefits to the world's food supply are beginning to be realized, as a number of countries built irradiation facilities†. Such application in the U.S. has been slow because of fears related to anything involving radiation.

Spoilage of food before it reaches the table is due to a variety of effects: sprouting as in potatoes, rotting due to bacteria as in fruit, and insect infestation as in wheat and flour. Certain diseases stem from

† Thanks are due FoodTechnology Service in Mulberry, Florida, for extensive literature on food irradiation.

microorganisms that contaminate food. Examples are the bacteria Salmonella, found in much of poultry products, and the parasite Trichinae that infest some pork. The National Centers for Disease Control state that food-borne illnesses affect millions of people in the U.S. each year, with thousands of deaths.

Various treatments are conventionally applied to preserve food, including drying, pickling, salting, freezing, canning, pasteurization, sterilization, the use of food additives such as nitrites, and until they were banned, the application of fumigants such as ethylene dibromide (EDB). Each treatment method has its advantages, but nitrites and EDB are believed to have harmful physiological effects.

On the other hand, research has shown that gamma radiation processing can serve as an economical, safe, and effective substitute and supplement for existing treatments. The shelf-life of certain foods can be extended from days to weeks, allowing adequate time for transportation and distribution. It has been estimated that 20 to 50 percent of the food supplied to certain countries is wasted by spoilage that could be prevented by radiation treatment. The principal sources of ionizing radiation that are suitable for food processing are X-rays, electrons from an accelerator, and gamma rays from a radionuclide. Much experience has been gained from the use of cobalt-60, half-life 5.27 years, with its two gamma rays of energy 1.17 MeV and 1.33 MeV. The largest supplier of cobalt-60 is a Canadian firm, MDS Nordion, formerly part of Atomic Energy of Canada, Ltd. The isotope is prepared by irradiating pure cobalt-59 target pellets with neutrons in the CANDU reactors of Ontario Hydro. The targets are disassembled, and shipped for processing into double layer capsules of about 10 Ci each. Another attractive isotope is cesium-137, gamma ray 0.662 MeV, because of its longer half-life of 30.2 years, and its potential availability as a fission product. A considerable amount of cesium-137 has been separated at Hanford, Washington, as a part of the radioactive waste management strategy. Arrangements for loans of capsules from the Department of Energy to industrial firms have been made. Additional cesium-137 could be obtained through limited reprocessing of spent reactor fuel.

Many people are concerned about the use of irradiated products because of the association with nuclear processes. The first worry is that the food might become radioactive. The concern is unfounded since there is no detectable increase in radioactivity at the dosages and particle energies of the electrons, X-rays, or gamma rays used. Even at higher dosages than are planned, the induced radioactivity would be less than that from natural amounts of potassium-40 or carbon-14 in foods. Another fear is that hazardous chemicals may be produced. Research shows that the amounts of

unique radiolytic products (URP) are small, less than those produced by cooking or canning, and similar to natural food constituents. No indication of health hazard has been found, but scientists recommend continuing monitoring of the process. A third concern is that there would be a loss in nutritional value. Some loss in vitamin content occurs, just as it is in ordinary cooking. Research is continuing on the effects of radiation on nutritional value. It appears that the loss is minor at the low dose levels used. On various food products, there are certain organoleptic effects (taste, smell, color, texture); but these are a matter of personal reaction, not of health. Even these effects can be eliminated by operating the targets at reduced temperatures. The astronauts of the Apollo missions and the space shuttle have dined regularly on treated foods while in orbit. They were enthusiastic about the irradiated bread and meats. Many years ago, some scientists in India reported that consumption of irradiated wheat caused polyploidy, an increase in cell chromosomes. Extensive studies elsewhere disproved the finding.

Finally, it has been suggested that radiation might induce resistance of organisms, just as with pesticides and antibiotics, but the effect appears not to occur. The difference is attributed to the fact that there is a broad effect on enzymes and compounds.

The radiation dosages required to achieve certain goals are listed in Table 18.2. Note that 1 gray (Gy) is 100 rads.

TABLE 18.2
Doses To Achieve Beneficial Effects

Effect	Dose (Gy)
inhibit sprouting of potatoes and onions	60-150
eliminate trichina in pork	200-300
kill insects and eggs in fruits	200-500
disinfect grain, prolong berry life	200-1000
delay ripening of fruit	250-350
eliminate salmonella from poultry	1000-3000

The main components of a multi-product irradiation facility that can be used for food irradiation on a commercial basis are shown in Fig. 18.1. Important parts are: (a) transfer equipment, involving conveyors for pallets, which are portable platforms on which boxes of food can be loaded; (b) an intense gamma ray source, of around a million curies strength, consisting of doubly encapsulated pellets of cobalt-60; (c) water tanks for storage of the source, with a cooling and purification system; and (d) a concrete biological shield, about 2 meters thick. In the operation of the facility, a rack of cobalt rods is pulled, up out of the water pool and the food boxes are exposed as they pass by the gamma source. Commercial firms providing irradiation equipment and carrying out irradiations, mainly for sterilization of medical supplies, are RTI, Inc. of Rockaway, NJ, MDS Nordion of Kanata Ontario,

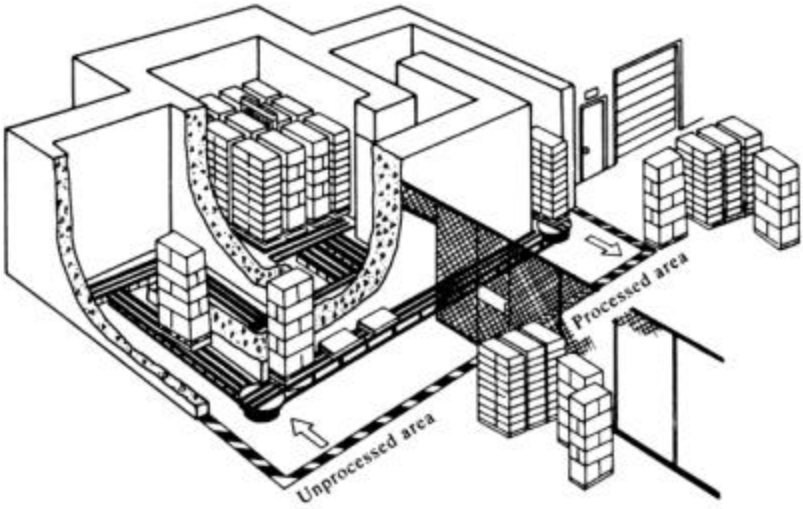


FIG. 18.1 Gamma irradiation facility of Radiation Technology, Inc., at Haw River, NC. Pallets containing boxes of products move on a computer-controlled conveyor through a concrete maze past a gamma-emitting screen.

Canada, Food Technology Service, Inc. of Mulberry, FL, Isomedix, Inc. of Whippany, NJ, and SteriGenics International of Fremont, CA.

A number of experimental facilities and irradiation pilot plants have been built and used in some 70 countries. Some of the items irradiated have been grain, onions, potatoes, fish, fruit, and spices. The most active countries in the development of large-scale irradiators have been the U.S., Canada, Japan, and the former U.S.S.R.

Table 18.3 shows the approvals for irradiation as issued by the U.S. Food and Drug Administration. Limitations are typically set on dosages to foodstuffs of 1 kilogray (100 kilorads) except for dried spices, not to exceed 30 kGy (3 Mrads).

TABLE 18.3
Approvals by the Food and Drug Administration for Use of Irradiated Substances
(Source: *FDA Consumer*, November 1990, p. 11)

Product	Purpose of irradiation	Dose (krad)	Date
Wheat and powder	Disinfest insects	20-50	1963
White potatoes	Extend shelf life	5-15	1965
Spices, seasonings	Decontaminate	3000	1983
Food enzymes	Control insects	1000	1985
Pork products	Control trichinae	30-100	1985
Fresh fruits	Delay spoilage	100	1986
Enzymes	Decontaminate	1000	1986
Dried vegetables	Decontaminate	3000	1986
Poultry	Control salmonella	300	1990

Note: 1 krad = 10 Gy.

Labeling of the packages to indicate special treatment is required, using a phrase such as “treated with radiation.” In addition, packages will exhibit

the international logo, called a radura, shown in Figure 18.2. The symbol's solid circle represents an energy source; the two petals signify food; the breaks in the outer circle mean rays from the energy source.

FIG. 18.2 International logo to appear on all irradiated food.

Final rules on red meat irradiation as a food additive were issued by FDA in December 1997 and by USDA in December 1999 (see References). The action was prompted in part by the discovery of the bacterium *E.coli* contamination of hamburger by an Arkansas supplier. Some 25 tons of meat were recalled and destroyed. The new rule cites statistics on outbreaks of disease and numbers of deaths related to beef. Maximum permitted doses for meat are 4.5 kGy (450 krads) as refrigerated and 7.0 kGy (700 krads) as frozen. Over 80 technical references are cited, on all aspects of the subject.

Approval to irradiate does not guarantee that it actually will be done, however. Many large food processors and grocery chains tend to shy away from the use of irradiated food products, believing that the public will be afraid of all of their products. Obviously, people will not have much opportunity to find treated foods acceptable if there are few products on the market. Advantage of that reluctance is taken by anti-irradiation activists, who claim that the companies have deemed the process unsafe. In contrast, enthusiastic endorsement of food irradiation is provided by organizations such as World Health Organization, American Medical Association, American Diatetic Association, International Atomic Energy Agency, Grocery Manufacturers of America, and many others (see References).

18.3 Sterilization of Medical Supplies

Ever since the germ theory of disease was discovered, effective methods of sterilizing medical products have been sought. Example items are medical instruments, plastic gloves, sutures, dressings, needles, and syringes. Methods of killing bacteria in the past include dry heat, steam under pressure, and strong chemicals such as carbolic acid and gaseous ethylene oxide. Some of the chemic als are too harsh for equipment that is to

be re-used, and often the substances themselves are hazardous. Most of the above methods are batch processes, difficult to scale up to handle the production needed. More recently, accelerator-produced electron beams have been introduced and preferred for some applications.

The special virtue of cobalt-60 gamma-ray sterilization is that the rays penetrate matter very well. The item can be sealed in plastic and then irradiated, assuring freedom from microbes until the time they are needed in the hospital. Although the radioactive material is expensive, the system is simple and reliable, consisting principally of the source, the shield, and the conveyor. A typical automated plant requires a source of around 1 MCi.

18.4 Pathogen Reduction

In the operation of public sewage treatment systems, enormous amounts of solid residues are produced. In the U.S. alone the sewage sludge amounts to six millions tons a year. Typical methods of disposal are by incineration, burial at sea, placement in landfills, and application to cropland. In all of these there is some hazard due to pathogens–disease-causing organisms such a parasites, fungi, bacteria, and viruses. Experimental tests of pathogen reduction by cobalt-60 or cesium-137 gamma irradiation have been made in Germany and in the U.S. The program in the U.S. was part of the Department of Energy's studies of beneficial uses of fission product wastes, and was carried out at Sandia Laboratories and the University of New Mexico. Tests of the effectiveness of radiation were made, and the treated sludge was found to be suitable as a feed supplement for livestock, with favorable economics. However, no use of those results was made in the U.S. Apparently, the only large-scale application of sewage sludge irradiation is in Argentina, in the large city of Tucuman (see References). It is conceivable that the time is not yet ripe in the U.S. and Europe for such application of radiation. It took a number of years to adopt recycling of household wastes.

18.5 Crop Mutations

Beneficial changes in agricultural products are obtained through mutations caused by radiation. Seeds or cuttings from plants are irradiated with charged particles, X-rays, gamma rays, or neutrons; or chemical mutagens are applied. Genetic effects have been created in a large number of crops in many countries. The science of crop breeding has been practiced for many years. Unusual plants are selected and crossed with others to obtain permanent and reproducible hybrids. However, a wider choice of stock to work with is provided by mutant species. In biological terms, genetic variability is required.

Features that can be enhanced are: larger yield, higher nutritional content, better resistance to disease, and adaptability to new environments, including higher or lower temperature of climate. New species can be brought into cultivation, opening up sources of income and improving health.

The leading numbers of mutant varieties of food plants that have been developed are as follows: rice 28, barley 25, bread wheat 12, sugar cane 8, and soybeans 6. Many mutations of ornamental plants and flowers have also been produced, improving the income of small farmers and horticulturists in developing countries. For example, there are 98 varieties of chrysanthemum. The International Atomic Energy Agency since its creation in 1957 has fostered mutation breeding through training, research support, and information transfer. The improvement of food is regarded by the IAEA as a high-priority endeavor in light of the expanding population of the world.

More recently, the application of genetic engineering to improve crops and foodstuffs has drawn a great deal of criticism, especially in Europe, and a deep-seated conflict with the U.S. over use of biotechnology will be difficult to resolve.

18.6 Insect Control

To suppress the population of certain insect pests the sterile insect technique (SIT) has been applied successfully. The standard method is to breed large numbers of male insects in the laboratory, sterilize them with gamma rays, and release them for mating in the infested area. Competition of sterile males with native males results in a rapid reduction in the population. The classic case was the eradication of the screwworm fly from Curaçao, Puerto Rico, and the southwestern U.S. The flies lay eggs in wounds of animals and the larvae feed on living flesh and can kill the animal if untreated. After the numbers were reduced in the early 1960s, flies came up from Mexico, requiring a repeat operation. As many as 350 million sterile flies were released each week, bringing the infestations from 100,000 to zero. The annual savings to the livestock industry was around $100 million.

The rearing of large numbers of flies is a complex process, involving choice of food, egg treatment, and control of the irradiation process to provide sterilization without causing body damage. Cobalt-60 gamma rays are typically used to give doses that are several times the amounts that would kill a human being.

SIT has been used against several species of mosquito in the U.S. and India, and stopped the infestation of the Mediterranean fruit fly in

California in 1980.

The discovery of a screwworm infestation in Libya in 1988 prompted international emergency action by the United Nations Food and Agriculture Organization, the International Atomic Energy Agency, and others (see References). Arrangement were made for the fly factory in Mexico to supply millions of radiation-sterilized males to Libya. There, light aircraft dropped them in a grid pattern, starting in 1990. Within five months the screwworm was eradicated, thus protecting African wildlife as a whole.

The technique was effective on the island of Zanzibar, part of Tanzania, in combating the tsetse fly (see References). The insect is a carrier of trypanosomiasis, a livestock disease, and of sleeping sickness, which affects humans. Prior pesticide use made SIT feasible, and within four years, by 1996, there were no flies left.

SIT can potentially control *Heliothis* (American bollworm, tobacco budworm, and corn earworm) and other pests such as ticks and the gypsy moth. Other related techniques include genetic breeding that will automatically yield sterile males.

18.7 Applications in Chemistry

Radiation chemistry refers to the effect of high-energy radiation on matter, with particular emphasis on chemical reactions. Examples are ion-molecule reactions, capture of an electron that leads to dissociation, and charge transfer without a chemical reaction when an ion strikes a molecule. Many reactions have been studied in the laboratory, and a few have been used on a commercial scale. For a number of years, Dow Chemical used cobalt-60 radiation in the production of ethyl bromide (CH_3CH_2Br), a volatile organic liquid used as an intermediate compound in the synthesis of organic materials. The application terminated for reasons of cost and safety. As catalysts, gamma rays have been found to be superior in many cases to chemicals, to the application of ultraviolet light, and to electron bombardment.

Various properties of polymers such as polyethylene are changed by electron or gamma ray irradiation. The original material consists of long parallel chains of molecules, and radiation damage causes chains to be connected, in a process called cross-linking. Irradiated polyethylene has better resistance to heat and serves as a good insulating coating for electrical wires. Fabrics can be made soil-resistant by radiation bonding of a suitable polymer to a fiber base.

Highly wear-resistant wood flooring is produced commercially by gamma irradiation. Wood is soaked in a monomer plastic, encased in aluminum, and placed in a water pool containing a cesium-137 source of

661 keV photons. The process of polymerization takes place throughout the wood. The molecular structure is changed so that the surface cannot be scratched or burned.

A related process has been applied in France to the preservation of artistic or historic objects of wood or stone. The artifact is soaked in a liquid monomer and transferred to a cobalt-60 gamma cell where the monomer is polymerized into a solid resin.

18.8 Transmutation Doping of Semiconductors

Semiconductor materials are used in a host of modern electrical and electronic devices. Their functioning depends on the presence of small amounts of impurities such as phosphorus in the basic crystal element silicon. The process of adding impurities is called "doping." For some semiconductors, impurities can be introduced in the amounts and locations needed by using neutron irradiation to create an isotope that decays into the desired material.

The process is relatively simple. A pure silicon monocrystal is placed in a research or experimental reactor of several megawatts power level. The sample is irradiated with a previously calibrated thermal neutron flux for a specified time. This converts one of the silicon isotopes into a stable phosphorus isotope by the reactions

$$^{30}_{14}\mathrm{Si} + ^{1}_{0}\mathrm{n} \rightarrow ^{31}_{14}\mathrm{Si} + g$$

$$^{31}_{14}\mathrm{Si} \rightarrow ^{31}_{15}\mathrm{P} + ^{0}_{-1}\mathrm{e},$$

where the abundance of Si-30 is 3.1% and the half-life of Si-31 is 2.62 hours. After irradiation, the silicon resistivity is too high because of radiation damage caused by the fast neutron component of the flux. Heat treatment is required before fabrication, to anneal out the defects.

The principal application of neutron transmutation doping (NTD) has been to the manufacture of power thyristors, which are high-voltage, high-current semiconductor rectifiers (see References), so named because they replaced the thyratron, a vacuum tube. The virtue of NTD in comparison with other methods is that it provides a uniform resistivity over the large area of the device. Annual yields of the product material are more than 50 tons, with a considerable income to the reactor facilities involved in the work. NTD is expected to become even more important in the future for household and automotive devices. The doping method is also applicable to other substances besides silicon; e.g., germanium and gallium arsenide.

18.9 Neutrons in Fundamental Physics

Intense neutron beams produced in a research reactor serve as powerful

tools for investigation in physics. Three properties of the neutron are important in this work: (a) the lack of electrical charge, which allows a neutron to penetrate atomic matter readily until it collides with a nucleus; (b) a magnetic moment, resulting in special interaction with magnetic materials; and (c) its wave character, causing beams to exhibit diffraction and interference effects.

Measurements of neutron cross section of nuclei for scattering, capture, and fission are necessary for reactor analysis, design, and operation. An area of study that goes beyond those needs is called inelastic neutron scattering. It is based on the fact that the energy of thermal neutrons, 0.0253 eV, is comparable to the energy of lattice vibrations in a solid or liquid. Observations of changes in the energy of bombarding neutrons provide information on the interatomic forces in materials, including the effects of impurities in a crystal, of interest in semiconductor research. Also, inelastic scattering yields understanding of microscopic magnetic phenomena and the properties of molecular gases.

We recall that the magnetic moment of a bar magnet is the product of its length s and the pole strength p. For charges moving in a circle of radius r, the magnetic moment is the product of the area pr^2 and the current i. Circulating and spinning electrons in atoms and molecules also give rise to magnetic moments. Even though the neutron is uncharged, it has an intrinsic magnetic moment. Thus the neutron interacts differently with materials according to their magnetic properties. If the materials are paramagnetic, with randomly oriented atomic moments, no special effect occurs. Ferromagnetic materials such as iron and manganese have unpaired electrons, and moments are all aligned in one direction. Antiferromagnetic materials have aligned moments in each of two directions. Observations of scattered neutrons lead to understanding of the microscopic structure of such materials.

The wave length of a particle of mass m and speed u according to the theory of wave mechanics is

$$l = h/mu$$

where h is Planck's constant, 6.64×10^{-34} J-s. For neutrons of mass 1.67×10^{-27} kg, at the thermal energy, 0.0253 eV, speed 2200 m/s, the wavelength is readily calculated to be $l = 1.8 \times 10^{-10}$ m. This is fairly close to d, the spacing of atoms in a lattice; for example, in silicon d is 3.135×10^{-10} m. The wave property is involved in the process of neutron diffraction, in analogy to X-ray and optical diffraction, but the properties of the materials that are seen by the rays differ considerably. Whereas X-rays interact with atomic electrons and thus diffraction depends strongly on atomic number Z, neutrons interact with nuclei according to their scattering lengths, which are

unique to the isotope, and are rather independent of Z. Scattering lengths, labeled a, resemble radii of nuclei but have both magnitude and sign. For nearby isotopes, a values and the corresponding cross sections $s = pr^2$ differ greatly. For example the approximate s values of three nickel isotopes differ greatly: Ni-58, 26; Ni-59, 1, Ni-60, 10. In neutron diffraction one applies the Bragg formula $l = 2d \sin q$, where d is the lattice spacing and q is the scattering angle. A host of isotopes, elements, and compounds have been investigated by neutron diffraction, as discussed by Bacon (see References).

A still more modern and sophisticated application of neutrons is interferometry in which neutron waves from a nuclear reactor source are split and then recombined. We can describe the essential equipment needed. A perfect silicon crystal is machined very accurately in the form of the letter E, making sure the planes are parallel. A neutron beam entering the splitter passes through a mirror plate and analyzer. Reflection, refraction, and interference takes place, giving rise to a periodic variation of observed intensity. Insertion of a test sample causes changes in the pattern. The method has been used to measure accurately the scattering lengths of many materials. Images of objects are obtained in phase topography, so named because the introduction of the sample causes a change in phase in the neutron waves in amount dependent on thickness, allowing observation of surface features. Interference fringes have been observed for neutrons passing through slightly different paths in the earth's magnetic field. This suggests the possibility of studying the relationship of gravity, relativity, and cosmology.

18.10 Neutrons in Biological Studies

One of the purposes of research in molecular biology is to describe living organisms by physical and chemical laws. Thus, finding sizes, shapes and locations of components of biological structures is the first step in understanding. Neutron scattering provides a useful tool for this purpose. The radiation does not destroy the specimen; cross sections of materials of interest are of the same order for all nuclei so that heavier elements are not favored as in the case of X-rays; long wavelength neutrons needed to study the large biological entities are readily obtained from a reactor. Of special importance is the fact that scattering lengths for hydrogen (3.8×10^{-15} m) and deuterium (6.5×10^{-15} m), are quite different, so that the neutron scattering patterns from the two isotopes can be readily distinguished.

An example is the investigation of the ribosome (see References). It is a particle about 25 nanometers in diameter that is part of a cell and helps manufacture proteins. The *E. coli* ribosome is composed of two subunits,

one with 34 protein molecules and two RNA molecules, the other with 21 proteins and one RNA. The proteins are quite large, with molecular weight as high as 65,000. Study with X-rays or an electron microscope is difficult because of the size of the ribosome. For the neutron experiment, two of the 21 proteins are "stained" with deuterium; i.e., they are prepared by growing bacteria in D_2O rather than H_2O.

A beam of neutrons from a research reactor at Brookhaven National Laboratory is scattered from a graphite crystal which selects neutrons of a narrow energy range at wave length 2.37×10^{-10} m. The specimen to be studied is placed in the beam in front of a helium-3 detector, which counts the number of neutrons as a function of scattering angle. The neutron wave, when scattered by a protein molecule, exhibits interference patterns similar to those of ordinary light. A distinct difference in pattern would be expected depending on whether the two molecules are touching or separated, as shown in Fig. 18.3. For the ribosome, the distance between centers of molecules was deduced to be 35×10^{-10} m. Tentative "maps" of the ribosome subunit have been developed, as well.

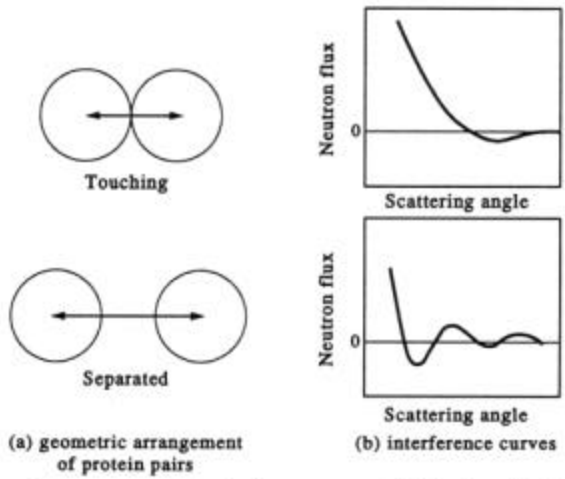


FIG. 18.3 Interference patterns for the ribosome, a particle in the cell. Estimates of size and spacing are a start toward understanding biological structures.

18.11 Research with Synchrotron X-rays

Knowledge of the structure of molecules is made possible by the use of synchrotron X-rays, because of their high intensity and sharp focus. Studies are faster and less damaging than those with conventional X-rays (see References). Materials in crystalline form are bombarded with photons and the diffraction patterns are produced on a sensitive screen. The patterns are analyzed by computer using the Fourier transform to determine electron densities and thus atom locations. Suitable manipulations yield 3D data.

Knowing molecular structure provides information on how chemicals work and helps find better drugs and treatment for disease. A classic example of a synchrotron X-ray study result was the determination of the structure of the rhinovirus HRV14, the cause of the common cold. The crystals were very sensitive to radiation and would cease to diffract before data were obtained by ordinary X-rays. Many other macromolecular proteins, enzymes, hormones, and viruses have been investigated. It is possible to observe chemical processes as they occur, e.g., photodissociation of hydrocarbons and of ozone. Information for improvement of industrial processes and products is also made available.

18.12 Summary

Many examples of the use of radiation for beneficial purposes can be cited. Diseases such as cancer can be treated by gamma rays. Food spoilage is reduced greatly by irradiation. Medical supplies are rendered sterile within plastic containers. Sewage sludge can be disinfected by irradiation. New and improved crops are produced by radiation mutations. The sterile insect technique has controlled insect pests in many areas of the world. Radiation serves as a catalyst in the production of certain chemicals. Properties of fibers and wood are enhanced by radiation treatment. Desirable impurities can be induced in semiconductor materials by neutron bombardment. The scattering by neutrons provides information on magnetic materials, and interference of neutron beams is used to examine surfaces. Scattered neutrons yield estimations of location and size of minute biological structures. Synchrotron X-rays are required for detailed study of biological molecules.

18.13 Exercises

18.1. Thyroid cancer is treated successfully by the use of iodine-131, half-life 8.04 days, energy release about 0.5 MeV. The biological half-life of I-131 for the thyroid is 4 days. Estimate the number of millicuries of the isotope that should be administered to obtain a dose of 25,000 rads to the thyroid gland, of weight 20 grams.

18.2. The disease polycythemia vera (PV) is characterized by an excess of red blood cells. Treatment by chemotherapy and radiation is often successful. In the latter, the patient is injected with a solution of sodium phosphate containing phosphorus-32, half-life 14.28 days, average beta energy 0.69 MeV. Estimate the dose in rads resulting from the administration of an initial 10 mCi of P-32, of which 10% goes to the bone marrow of weight 3 kg. Recall 1 rad $=10^{-5}$ J/g and 1 mCi $=3.7 \times 10^{7}$ dis/sec. Suggestion: Neglect biological elimination of the isotope.

18.3. A company supplying cobalt-60 to build and replenish radiation sources for food processing uses a reactor with thermal flux $10^{14}/cm^2$-s. In order to meet the demand of a megacurie a month, how many kilograms of cobalt-59 must be inserted in the reactor? Note that the density of Co-59 is 8.9 g/cm^3 and the neutron cross section is 37 barns.

18.4. A cobalt source is to be used for irradiation of potatoes to inhibit sprouting. What strength in curies is needed to process 250,000 kg of potatoes per day, providing a dose of

10,000 rad? Note that the two gammas from Co-60 total around 2.5 MeV energy. What is the amount of isotopic power? Discuss the practicality of absorbing all of the gamma energy in the potatoes.

18.5. Transmutation of silicon to phosphorus is to be achieved in a research reactor. The capture cross section of silicon-30, abundance 3.1% is 0.108 barns. How large must the thermal flux be to produce an impurity content of 10 parts per billion in a day's irradiation?

Computer Exercises

18A. The classic "predator-prey" balance equations simulate interacting populations such as foxes and rabbits. Run the LOTUS 1-2-3 progress PREDPREY to see trends with time.

18.B. An adaptation of the predator–prey equations can be used to analyze the control of the screwworm fly by the sterile male technique. Study the trend in population under different assumptions and initial conditions using the program ERADIC (eradicate/irradiate). In particular, find the time required to reduce the population to less than one female fly.

18.14 References for Chapter 18

Interstitial Collaborative Working Group: Lowell L. Anderson, et al., *Interstitial Brachytherapy* : *Physical, Biological, and Clinical Considerations*, 1990, Raven Press, New York.

IAEA Bulletin, Vol. 33, No. 1, 1991. The issue features nuclear medicine.

Rolf F. Barth, Albert H. Soloway, and Ralph G. Fairchild, "Boron Neutron Capture Therapy for Cancer," *Scientific American*, October 1990, page 100. Discusses past experiments and new possibilities. Reference reading provided.

Boron Neutron Capture Therapy
http://trinity.tamu.edu/~diepquan/bnct.htm
Health Physics instrumentation class report by Diep Q. Quan.

BNCT Briefing Book
http://id.inel.gov/cart/briefbook/index.html
By Idaho National Engineering & Environmental Laboratory.

Mark B. Garnick and William R. Fair, "Combatting Prostate Cancer," *Scientific American*, December 1998, p. 74 ff.

Prostate cancer treatment
http://www.theragenics.com
A commercial supplier of radioactive seeds

John Henkel, "Irradiation: A Safe Measure for Safer Food," *FDA Consumer*, May-June 1998, Vol. 32, No. 3, pp 12-17.

P.J. Skerrett, "Food Irradiation: Will It Keep the Doctor Away?" *Technology Review*, November/December 1997, MIT, Cambridge.
(also available in Past Issues on the web site http://www.techreview.com)

Iowa State Food Safety Project
http://www.extension.iastate.edu/foodsafety/rad/irradhome.html
Information and links.

Food Irradiation Information from Food Safety and Inspection Service
http://www.fsis.usda.gov/oa/topics/irrmenu.htm
Select Irradiation of Meat Food Products for access to USDA Final Rule in Federal Register, December 23, 1999.

Facts about Food Irradiation
http://www.iaea.or.at/worldatom/inforesource/other/food/index.html
Links to a number of Fact Sheets from the International Atomic Energy Agency.

Radiation Information Network: Food Irradiation
http://www.physics.isu.edu/radinf/food.htm
Extensive discussion, references, and links by Idaho State University..

V. M. Wilkinson and G. W. Gould, *Food Irradiation: A Reference Guide*, Butterworth-Heinemann, Oxford, 1996. Topics, definitions, and discussion with references to all relevant terms.

E. A. Murano (Ed.), *Food Irradiation: A Sourcebook*, Iowa State University Press, Ames, IA, 1995. Processing, microbiology, food quality, consumer acceptance, and economics.

Argentina irradiates urban sludge
http://www.iaea.org/worldatom/inforesource/bulletin/bull391/argentina.html
IAEA publication *INSIDE Technical Cooperation* March 1997.

A. M. V. Van der Vloedt and B. Butt, "The New World Screwworm Eradication Programme in North Africa," *IAEA Bulletin* Vol. 32, No. 4, 1990, p. 35.

D. A. Lindquist and M. Abusowa, "Eradicating the New World Screwworm from the Libyan Arab Jamahiriya," *IAEA Bulletin* Vol. 34, No. 4, 1992, p. 9. Describes the success of the international program. With 12,000 cases in 1990, the number dropped to zero by May, 1991.

History of Screwworm Eradication
http://www.nal.usda.gov/speccoll/screwworm/history.htm
Discovery and application of Sterile Male Technique. From National Agricultural Library.

Eradication of tsetse fly in Zanzibar
http://www.fao.org/NEWS/1998/980505-e.htm
http://www.iaea.org/worldatom/Press/P_release/1998/prn0798.shmtl
News items from sponsoring agencies.

Simulation exercise on SIT
http://ipmworld.umn.edu/chapters/SirSimul.htm
Program "Curaçao" by Phil A. Arneson.

G. E. Bacon, *Neutron Diffraction*, 3rd Ed., Clarendon Press, Oxford, 1975. A classical reference on the subject.

G. Foldiak, Editor, *Industrial Applications of Radioisotopes*, Elsevier, Amsterdam, 1986.

William D. Ehmann and Diane E. Vance, *Radiochemistry and Nuclear Methods of Analysis*, John Wiley & Sons, New York, 1991. Covers many of the topics of this chapter.

Robert J. Woods and Alexei K. Pikaev, *Applied Radiation Chemistry: Radiation Processing*, John Wiley & Sons, New York, 1994. Includes synthesis, polymerization, sterilization, and food irradiation.

Herman Winick, "Synchrotron Radiation," *Scientific American*, November 1987, p. 257 ff.

Massimo Altarelli, Fred Schlacter, and Jane Cross, "Ultrabright X-ray Machines," *Scientific American*, December 1998, p. 66 ff.

Kevin L. D'Amico, Louis J. Terminello, and David K. Shuh, *Synchrotron Radiation Techniques in Industrial, Chemical, and Materials Science*, Plenum Press, New York, 1996. Emphasis on structural biology and environmental science.

J. R. Helliwell and P. M. Rentzepis, (Eds.), *Time-resolved Diffraction*, Oxford University Press, 1997. Research on time-dependent structural changes by use of X-rays (including synchrotron radiation), electrons, and neutrons.

19

Reactor Safety

IT IS well known that the accumulated fission products in a reactor that has been operating for some time constitute a potential source of radiation hazard. Assurance is needed that the integrity of the fuel is maintained throughout the operating cycle, with negligible release of radioactive materials. This implies limitations on power level and temperature, and adequacy of cooling under all conditions. Fortunately, inherent safety is provided by physical features of the fission chain reaction. In addition, the choice of materials, their arrangement, and restrictions on modes of operation give a second level of protection. Devices and structures that minimize the chance of accident and the extent of radiation release in the event of accident are a third line of defense. Finally, nuclear plant location at a distance from centers of high population density results in further protection.

We shall now describe the dependence of numbers of neutrons and reactor power on the multiplication factor, which is in turn affected by temperature and control rod absorbers. Then we shall examine the precautions taken to prevent release of radioactive materials to the surroundings and discuss the philosophy of safety.

Thanks are due to Earl M. Page for suggestions on reactor safety and Robert M. Koehler on reactor design and operation.

19.1 Neutron Population Growth

The multiplication of neutrons in a reactor can be described by the effective multiplication factor k, as discussed in Chapter 11. The introduction of one neutron produces k neutrons; they in turn produce k^2, and so on. Such a behavior tends to be analogous to the increase in principal with compound interest or the exponential growth of human population. The fact that k can be less than, equal to, or greater than 1 results in significant differences, however.

The total number of neutrons is the sum of the geometric series $1 + k + k^2 + \ldots$ For $k < 1$ this is finite, equal to $1/(1 - k)$. For $k > 1$ the sum is infinite, i.e., neutrons multiply indefinitely. We thus see that knowledge of the effective multiplication factor of any arrangement of fuel and other material is needed to assure safety. Accidental criticality is prevented in a

number of situations: (a) chemical processing of enriched uranium or plutonium, (b) storage of fuel in arrays of containers or of fuel assemblies, (c) initial loading of fuel assemblies at time of startup of a reactor. A classic measurement involves the stepwise addition of small amounts of fuel with a neutron source present. The thermal neutron flux without fuel f_0 and with fuel f is measured at each stage. Ideally, for a subcritical system with a non-fission source of neutrons in place, in a steady-state condition, the multiplication factor k appears in the relation

$$f/f_0 = 1/(1-k).$$

As k gets closer to 1, the critical condition, the flux increases greatly. On the other hand, the reciprocal ratio

$$f_0/f = 1-k$$

goes to zero as k goes to 1. Plotting the measured flux ratio as it depends on the mass of uranium or the number of fuel assemblies allows increasingly accurate predictions of the point at which criticality occurs, as shown in Fig. 19.1. Fuel additions are always intended to be less than the amount expected to bring the system to criticality.

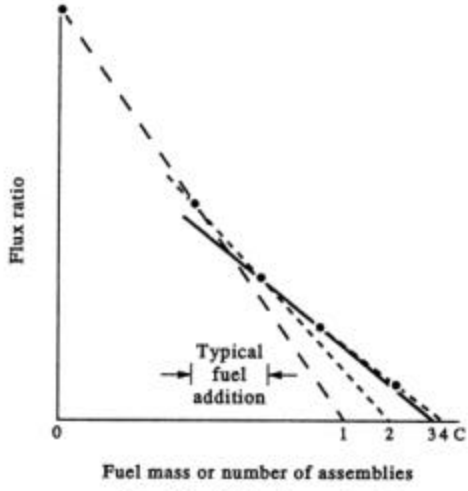


FIG. 19.1 Critical experiment.

Let us now examine the time-dependent response of a reactor to changes in multiplication. For each neutron, the gain in number during a cycle of time length ℓ is $dk = k - 1$. Thus for n neutrons in an infinitesimal time dt the gain is $dn = dk\ n\ dt/\ell$. This can be treated as a differential equation. For constant dk, the solution is

$$n = n_0 \exp(t/T),$$

where T is the period, the time for the population to increase by a factor $e = 2.718...$, given by $T = \ell/dk$. When applied to people, the formula states that

the population grows more rapidly the more frequently reproduction occurs and the more abundant the progeny.

A typical cycle time ℓ for neutrons in a thermal reactor is very short, around 10^{-5} s, so that a dk as small as 0.02 would give a very short period of 0.0005 s. The growth according to the formula would be exceedingly rapid, and if sustained would consume all of the atoms of fuel in a fraction of a second.

A peculiar and fortunate fact of nature provides an inherent reactor control for values of dk in the range 0 to around 0.0065. Recall that around 2.5 neutrons are released from fission. Of these, some 0.65% appear later as the result of radioactive decay of certain fission products, and are thus called delayed neutrons. Quite a few different radionuclides contribute these, but usually six are identified by their different fractions and half-lives (See Ex. 19.12). The average half-life of the isotopes from which they come, taking account of their yields, is around 8.8 s. This corresponds to a mean life $\tau = t_H/0.693 = 12.7$ s, as the average length of time required for a radioactive isotope to decay. Although there are very few delayed neutrons, their presence extends the cycle time greatly and slows the rate of growth of the neutron population. To understand this effect, let β be the fraction of all neutrons that are delayed, a value 0.0065 for U-235; $1 - \beta$ is the fraction of those emitted instantly as "prompt neutrons." They take only a very short time ℓ to appear, while the delayed neutrons take a time $\ell + \tau$. The average delay is thus

$$\bar{\ell} = (1-\beta)\ell + \beta(\ell + \tau) = \ell + \beta\tau .$$

Now since $\beta = 0.0065$ and $\tau = 12.7$ s, the product is 0.083 s, greatly exceeding the multiplication cycle time, which is only 10^{-5} s. The delay time can thus be regarded as the effective generation time, $\bar{\ell} \cong \beta\tau$. This approximation holds for values of dk much less than β. For example, let $dk = 0.001$, and use $\bar{\ell} = 0.083$ s in the exponential formula. In 1 second $n/n_0 = e^{0.012} = 1.01$, a very slight increase.

On the other hand, if dk is greater than β we still find very rapid responses, even with delayed neutrons. If all neutrons were prompt, one neutron would give a gain of dk, but since the delayed neutrons actually appear much later they cannot contribute to the immediate response. The apparent dk is then $dk - \beta$, and the cycle time is ℓ. We can summarize by listing the period T for the two regions.

$$dk \ll \beta, \qquad T \cong \frac{\beta\tau}{dk}$$

$$dk \gg \beta, \qquad T \cong \frac{\ell}{dk - \beta},$$

Even though b is a small number, it is conventional to consider dk small only if it is less than 0.0065 but large if it is greater. Figure 19.2 shows the growth in reactor power for several different values of reactivity r, defined as dk/k. These curves were generated using the full set of delayed neutron emitters. Since k is close to 1, $r \cong dk$. We conclude that the rate of growth of the neutron population or reactor power is very much smaller than expected, so long as dk is kept well below the value b, but rapid growth will take place if dk is larger than b.

We have used the value of b for U-235 for illustration, but should note that its effective value depends on reactor size and type of fuel; e.g., b for Pu-239 is only 0.0021. Also, the value of the neutron cycle time depends on the energy of the predominant neutrons. The ℓ for a fast reactor is much shorter than that for a thermal reactor.

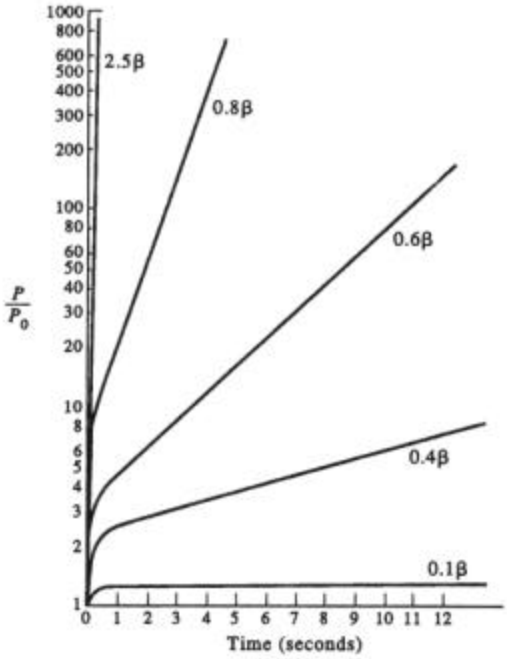


FIG. 19.2 Effect of delayed neutrons.

In the many hundreds of critical experiments and manipulations of nuclear fuel in processing plants, there have been serious criticality accidents, involving radiation exposure and several deaths. In the early days of the nuclear project, fewer precautions were taken (see References for summary information.). Even as late as 1999 an accident in Japan resulted from the addition of an excess of enriched uranium to a process vessel.

In Computer Exercises 19.A and 19.B we demonstrate the growth with time of the neutron population as it depends on reactivity. In 19.A, a

spreadsheet is used, while in 19.B the program is written in BASIC.

19.2 Assurance of Safety

The inherent nuclear control provided by delayed neutrons is aided by proper design of the reactor to favor certain negative feedback effects. These are reductions in the neutron multiplication factor resulting from increases in reactor power. With additional heat input the temperature increases, and the negative reactivity tends to shut the reactor down. Design choices include the size and spacing of fuel rods and the soluble boron content of the cooling water. One of the temperature effects is simple thermal expansion. The moderator heats up, it expands, the number density of atoms is reduced, and neutron mean free paths and leakage increase, while thermal absorption goes down. In early homogeneous aqueous reactors this was a dominant effect to provide shutdown safety. In heterogeneous reactors it tends to have the opposite effect in that reductions in boron concentration accompany reduction in water density. Thus there must be some other effect to override moderator expansion effects. The process of Doppler broadening of resonances provides the needed feedback. An increase in the temperature of the fuel causes greater motion of the uranium atoms, which effectively broadens the neutron resonance cross section curves for uranium shown in Fig. 4.6. For fuel containing a high fraction of uranium-238 the multiplication decreases as the temperature increases. The Doppler effect is "prompt" in that it responds to the fuel temperature whereas the moderator effect is "delayed" as heat is transferred from fuel to coolant. The use of the term "Doppler" comes from the analogy with frequency changes in sound or light when there is relative motion of

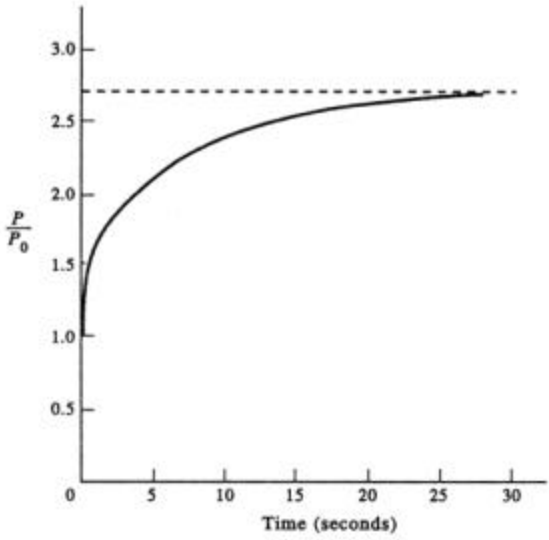


FIG. 19.3 Effect of temperature on power.

the source and observer.

The amounts of these effects can be expressed by formulas such as

$$\rho = \alpha \, \Delta T$$

in which the reactivity ρ is proportional to the temperature change ΔT, with a temperature coefficient α that is a negative number. For example, if the value of α is -10^{-5}/°C, a temperature rise of 20°C would give a reactivity of -0.0002. Another relationship is

$$\rho = a \, \Delta P/P$$

with a negative power coefficient a and fractional change in power $\Delta P/P$. For example in a PWR if $a = -0.012$, a 2% change in power would give a reactivity of -0.00024.

Temperature effects cause significant differences in the response of a reactor to disturbances. The effects were ignored in Fig. 19.2, and the population grew exponentially, but if effects are included, as in Fig. 19.3, the power flattens out and becomes constant.

Even though a reactor is relatively insensitive to increases in multiplication in the region $dk < b$, and temperature rises provide stability, additional protection is provided in reactor design and operating practices. Part of the control of a reactor of the PWR type is provided by the boron solution (see Section 11.5). This "chemical shim" balances the excess fuel loading and is adjusted gradually as fuel is consumed during reactor life. In addition, reactors are provided with several groups of movable rods of neutron-absorbing material, as shown in Fig. 19.4. The rods serve three main purposes: (a) to permit temporary increases in multiplication that brings the reactor up to the desired power level or to make adjustments in power; (b) to cause changes in the flux and power shape in the core, usually striving for uniformity; and (c) to shut down the reactor manually or automatically in the event of unusual behavior. To ensure effectiveness of the shutdown role, several groups of safety rods are kept withdrawn from the reactor at all times during operation. In the PWR they are supported by electromagnets that release the rods on interruption of current, while in the BWR they are driven in from the bottom of the vessel by hydraulic means.

The reactivity worth of control and safety rods as a function of depth of insertion into the core can be measured by a comparison technique. Suppose a control rod in a critical reactor is lifted slightly by a distance dz and a measurement is made of the resulting period T of the rise in neutron population. Using the approximate formula from Section 19.1,

$$T \cong b \, t \, /dk,$$

we deduce the relation of dk to dz. The reactor is brought back to critical by an adjustment of the soluble boron concentration. Then the operation is

repeated with an additional shift in rod position. The experiment serves to find both the reactivity worth of the rod as a function of position and by summation the total worth of the rod. Figure 19.5 shows the calibration curves of a control rod in an idealized case of a core without end reflectors. It is noted that the effect of a rod movement in a reactor depends strongly on the location of the tip. The basis for the S-shaped curves of Fig. 19.5 is found in reactor theory, which tells us that the reactivity effect of an added absorber sample to a reactor is approximately dependent on the square of the thermal flux that is disturbed. Thus if a rod is fully inserted or fully removed, such that the tip moves in a region of low flux, the change in multiplication is practically zero. At the center of the reactor, movement makes a large effect. The slope of the curve of reactivity vs. rod position when the tip is near the center of the core is twice the average slope in this simple case.

Estimates of total reactivity worth can also be made by the rod-drop technique. A control rod is allowed to fall from a position outside the core to a full-in position. The very rapid change of neutron flux from an initial value f_0 to a final value f_1 is shown in Fig. 19.6. Then the reactivity worth is calculated from the formula

$$r/b = (f_0/f_1) - 1.$$

The result is somewhat dependent on the location of the detector.

An instrumentation system is provided to detect an excessive neutron flux and thus power level, to provide signals calling for a "trip" of the

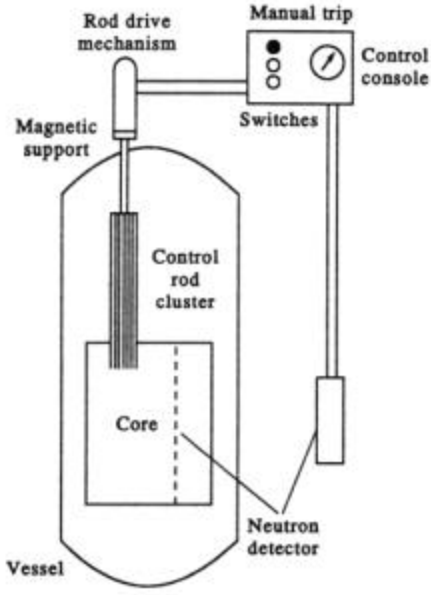


FIG. 19.4 Reactor control.

reactor. As sketched in Fig. 19.4, independent detectors are located both inside the core and outside the reactor vessel. Data from core detectors are processed by a computer to determine whether or not power distributions are acceptable.

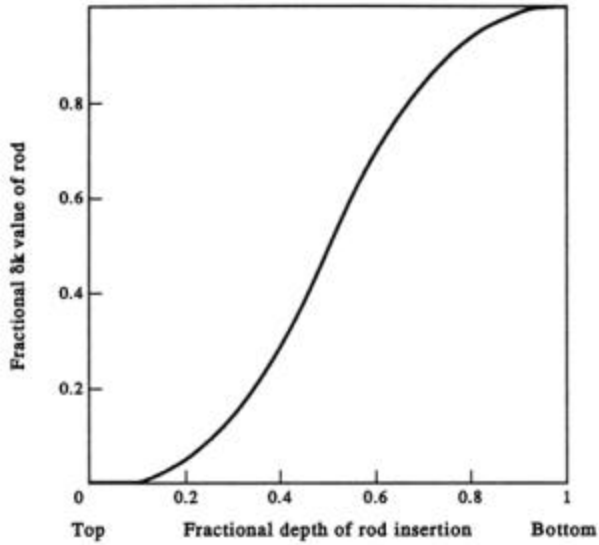


FIG. 19.5 Control rod worth as it depends on depth of insertion in an unreflected reactor core.

Since almost all of the radioactivity generated by a reactor appears in the fuel elements, great precautions are taken to assure the integrity of the fuel. Care is taken in fuel fabrication plants to produce fuel pellets that are identical chemically, of the same size and shape, and of common U-235 concentration. If one or more pellets of unusually high fissile material content were used in a reactor, excessive local power production and temperature would result. The metal tubes that contain the fuel pellets are made sufficiently thick to stop the fission fragments, to provide the necessary mechanical strength to support the column of pellets, and to withstand erosion by water flow or corrosion by water at high temperatures. Also, the tube must sustain a variable pressure difference caused by moderator-coolant outside and fission product gases inside. The cladding material usually selected for low neutron absorption and for resistance to chemical action, melting, and radiation damage in thermal reactors is zircaloy, an alloy that is about 98% zirconium with small amounts of tin, iron, nickel, and chromium. The tube is formed by an extrusion process that eliminates seams, and special fabrication and inspection techniques are employed to assure that there are no defects such as deposits, scratches, holes, or cracks.

Each reactor has a set of specified limits on operating parameters to assure protection against events that could cause hazard. Typical of these is

the upper limit on total reactor power, which determines temperatures throughout the core. Another is the ratio of peak power to average power which is related to hot spots and fuel integrity. Protection is provided by limiting the allowed control rod position, reactor imbalance (the difference between power in the bottom half of the core and the top half) and reactor tilt (departure from symmetry of power across the core), maximum reactor coolant temperature, minimum coolant flow, and maximum and minimum primary system pressure. Any deviation causes the safety rods to be inserted to trip the reactor. Maintenance of chemical purity of the coolant to minimize corrosion, limitation on allowed leakage rate from the primary cooling system, and continual observations on the level of radioactivity in the coolant serve as further precautions against release of radioactive materials.

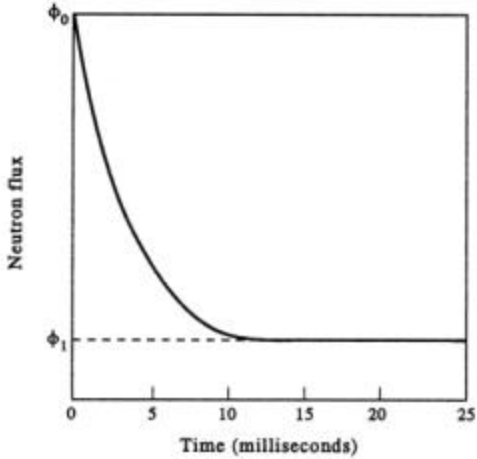


FIG. 19.6 Neutron flux variation with time in the rod-drop method of measuring reactivity.

Protection of fuel against failure that would release fission products into the coolant is thus an important constraint in the operation of a reactor. Correct choices must be made of the enrichment of U-235, the operating power level, the length of time between refuelings, and the arrangement of new and partially-burned fuel, all with an eye on cost.

The term "burnup" is widely used. Take a typical cubic centimeter of fuel and let all fission be due to U-235. The macroscopic fission cross section is S_f, the fission rate in a neutron flux f is $f = fS_f$, and the power density is $p = fw$, where w is the energy per fission. The energy produced in a time t is $W = pt$. Now the density of uranium is $d = N_U m_U$, where N_U and m_U are the number density and mass of a uranium atom, respectively. The burnup in watt-seconds per gram is then $B = W/d$. A numerical factor allows easy conversion to MWd/tonne. As shown in Exercise 19.13, B can be shown to depend on the enrichment in U-235, expressed as the ratio

N_{235}/N_U.

In Section 11.5 we examined the trends in fuel and control boron for a reactor visualized as a single region. Modern power reactor cores consist of several regions. At the start of an operating cycle, it will contain fresh and partially burned fuel; at the end, partially and fully burned fuel.

For a reactor core with n zones, let k_i be the multiplication constant of fuel in zone i and assume nearly equal power over the core. Then the average k is

$$k = \sum_{i=1}^{i=n} k_i \ .$$

It has been found that k_i varies with burnup according to

$$k_i = k_0 - aB$$

where B is the burnup in megawatt-days per metric ton (MWd/tonne), k_0 is the initial multiplication constant, and a is a constant.

The amount of control absorber required to keep the reactor critical is a measure of the average k of the core. Figure 19.7 shows its variation with

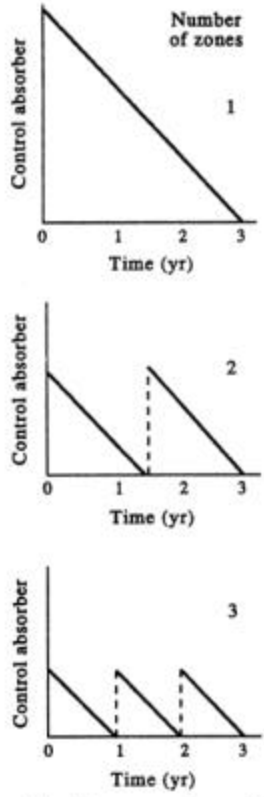


FIG. 19.7 Reactor operation with different numbers of fuel zones. The initial control absorber varies inversely with the number of regions.

time for different numbers of zones. As noted, the larger is n, the smaller is the initial control absorber.

A little algebra shows us (see Exercise 19.14) that the discharge burnup of fuel depends on the number of zones. Letting $B(1)$ be that for one zone, the burnup for n zones is

$$B(n) = (2n/(n + 1))\, B(1).$$

Thus $B(2) = (4/3)B(1)$, $B(3) = (3/2)B(1)$, etc. For very large n, corresponding to continuous refueling as in the Canadian reactors, the burnup turns out to be twice $B(1)$.

In the foregoing paragraphs we have alluded to a few of the physical features and procedures employed in the interests of safety. These have evolved from experience over a number of years, and much of the design and operating experience has been translated into widely used standards, which are descriptions of acceptable practice. Professional technical societies, industrial organizations, and the federal government cooperate in the development of these useful documents.

In addition, requirements related to safety have a legal status, since all safety aspects of nuclear systems are rigorously regulated by federal law, administered by the United States Nuclear Regulatory Commission (NRC). Before a prospective owner of a nuclear plant can receive a permit to start construction, he must submit a comprehensive preliminary safety analysis report (PSAR) and an environmental impact statement. Upon approval of these, a final safety analysis report (FSAR), technical specifications, and operating procedures must be developed in parallel with the manufacture and construction. An exhaustive testing program of components and systems is carried out at the plant. The documents and test results form the basis for a operating license.

Throughout the analysis, design, fabrication, construction, testing and operation of a nuclear facility, adequate *quality control* (QC) is required. This consists of a careful documented inspection of all steps in the sequence. In addition, a *quality assurance* (QA) program that verifies that quality control is being exercised properly is imposed. Licensing by the NRC is possible only if the QA program has satisfactorily performed its function. During the life of the plant, periodic inspections of the operation are made by the NRC to ascertain whether or not the owner is in compliance with safety regulations, including commitments made in Technical Specifications and the FSAR.

19.3 Emergency Core Cooling and Containment

The design features and operating procedures for a reactor are such that under normal conditions a negligible amount of radioactivity will get into

the coolant and find its way out of the primary loop. Knowing that abnormal conditions can exist, the worst possible event, called a design basis accident, is postulated. Backup protection equipment, called engineered safety features, is provided to render the effect of an accident negligible. A loss of coolant accident (LOCA) is the condition typically assumed, in which the main coolant piping somehow breaks and thus the pumps cannot circulate coolant through the core. Although in such a situation the reactor power would be reduced immediately by use of safety rods, there is a continuing supply of heat from the decaying fission products that would tend to increase temperatures above the melting point of the fuel and cladding. In a severe situation, the fuel tubes would be damaged, and a considerable amount of fission products released. In order to prevent melting, an emergency core cooling system (ECCS) is provided in water-moderated reactors, consisting of auxiliary pumps that inject and circulate cooling water to keep temperatures down. Detailed analysis of heat generation and transfer is required in an application to the NRC for a license to operate a nuclear power plant (see References). The operation of a typical ECCS can be understood by study of some schematic diagrams.

The basic PWR reactor system (Fig. 19.8) includes the reactor vessel, the primary coolant pump, and the steam generator, all located within the containment building. The system actually may have more than one steam generator and pump–these are not shown for ease in visualization. We show in Fig. 19.9 the auxiliary equipment that constitutes the engineered safety (ES) system. First is the *high-pressure injection system*, which goes into operation if the vessel pressure, expressed in pounds per square inch (psi), drops from a normal value of around 2250 psi to about 1500 psi as the result of a small leak. Water is taken from the borated water storage tank and introduced to the reactor through the inlet cooling line. Next is the *core flooding tank*, which delivers borated water to the reactor through separate nozzles in the event a large pipe break occurs. Such a rupture would cause a reduction in vessel pressure and an increase in building pressure. When the vessel pressure becomes around 600 psi the water enters the core through nitrogen pressure in the tank. Then if the primary loop pressure falls to around 500 psi, the *low-pressure injection* pumps start to transfer water from the borated water storage tank to the reactor. When this tank is nearly empty, the pumps take spilled water from the building sump as a reservoir and continue the flow, through coolers that remove the decay heat from fission products. Another feature, the building spray system, also goes into operation if the building pressure increases above about 4 psi. It takes water from the borated water storage tank or the sump and discharges it from a set of nozzles located above the reactor, in order to provide a means for

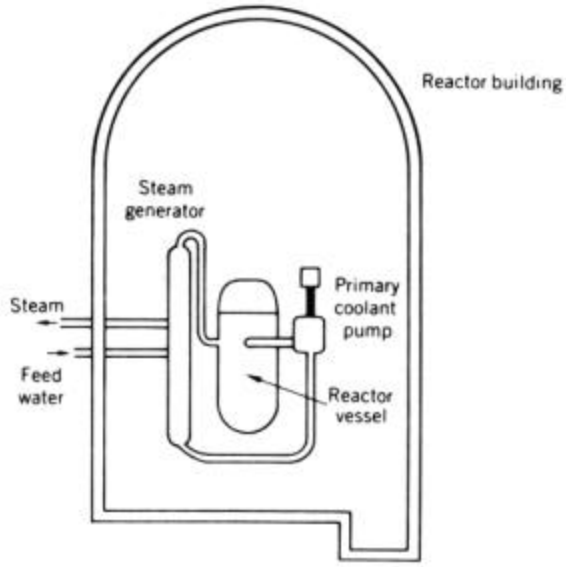


FIG. 19.8 Reactor containment.

condensing steam. At the same time, the emergency cooling units of the reactor building are operated to reduce the temperature and pressure of any released vapor, and reactor building isolation valves are closed on unnecessary piping to prevent the spread of radioactive materials outside the building.

We can estimate the magnitude of the problem of removing fission product heat. For a reactor fueled with U-235, operated for a long time at power P_0 and then shut down, the power associated with the decay of accumulated fission products is $P_f(t)$, given by an empirical formula such as

$$P_f(t) = P_0 A t^{-a}.$$

For times greater than 10 seconds after reactor shutdown the decay is represented approximately by using $A = 0.066$ and $a = 0.2$. We find that at 10 s the fission power is 4.2% of the reactor power. By the end of a day, it has dropped to 0.68%, which still corresponds to a sizable power, viz., 20 MW for a 3000 MWt reactor. The ECCS must be capable of limiting the surface temperature of the zircaloy cladding to specified values; e.g., 2200°F, of preventing significant chemical reaction, and of maintaining cooling over the long term after the postulated accident.

The role of the steel-reinforced concrete reactor building is to provide containment of fission products that might be released from the reactor. It is designed to withstand internal pressures and to have a very small leak rate. The reactor building is located within a zone called an exclusion area, of radius of the order of half a kilometer, and the nuclear plant site is several kilometers from any population center.

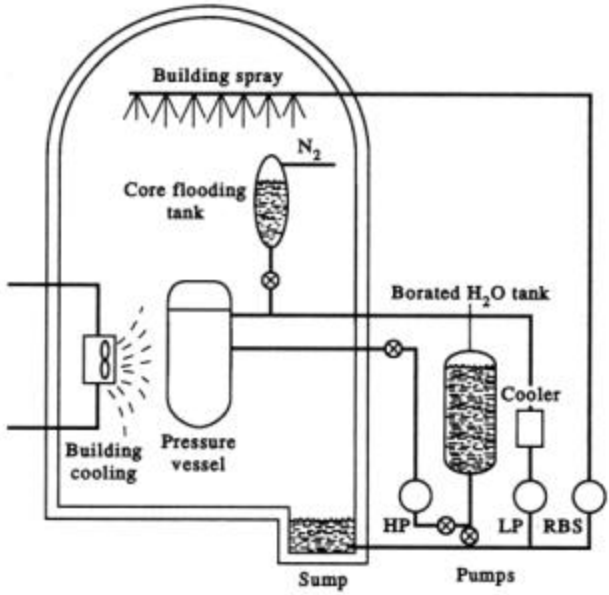


FIG. 19.9 Emergency core cooling system.

A series of experiments called Loss of Flow Tests (LOFT) was done at Idaho Falls to check the adequacy of mathematical models and computer codes related to LOCA/ECCS. A double-ended coolant pipe break was introduced and the ability to inject water against flow reversal and water vapor determined. Tests showed that peak temperatures reached were lower than predicted, indicating conservatism in the calculation methods.

19.4 Probabilistic Risk Assessment

The results of an extensive investigation of reactor safety were published in 1975. The document is variously called "Reactor Safety Study," or "WASH-1400," or "Rasmussen Report," after its principal author. The study (see References) involved 60 scientists and cost several million dollars. The technique used was probabilistic risk analysis (PRA), a formal method of analyzing reactor systems. The objective is to find the chance of an undesired event such as core damage, breach of containment, or release of radioactivity, and to determine potential causes. The first step is to investigate all of the possible faults in the equipment or processes. Flow diagrams of fluid systems and circuit diagrams of electrical systems serve as reference. *Event trees* are logic diagrams relating an initiating event to either successful mitigation or failure. Figure 19.10 shows a simple event tree. Probabilities of success and failure at each branch are applied. The principal logic diagrams are the *fault trees*, which trace causes and effects mathematically, using Boolean algebra, a form of set theory. Figure

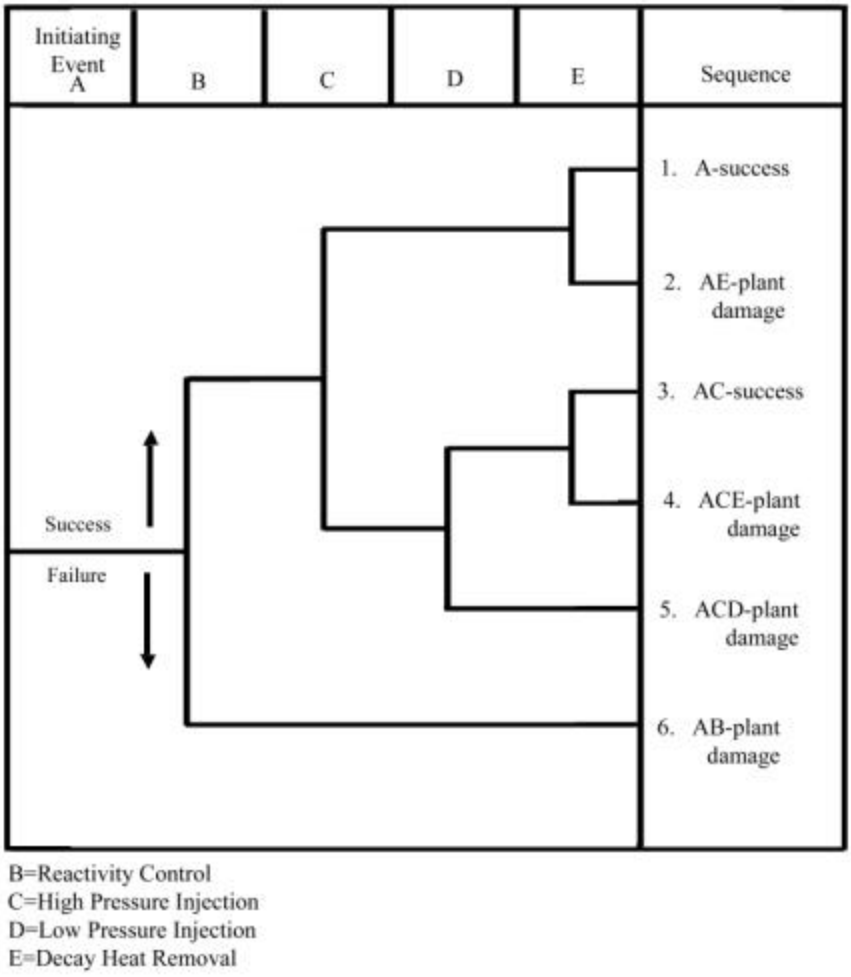


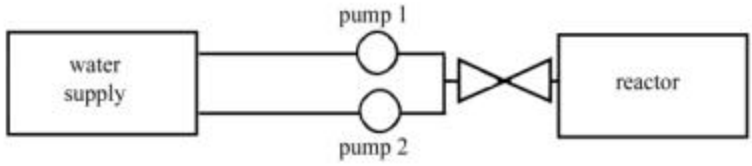
FIG. 19.10 Simple event tree (After NUREG/CR-4350 Vol.1).

19.11(a) shows a simple high pressure injection system to which we can apply the concept for illustration. The failure of both pumps and/or the valve prevents cooling water to reach the reactor. In Figure 19.11(b) the fault tree diagram shows two types of "gate," the AND ($\cap$) which requires two or more events to result in failure, and the OR ($\cup$) which requires only one event. We have attached symbols A, B, C, F, and T to the various events for use in the mathematical manipulation. Note that F occurs if both A and B occur, expressed in Boolean algebra as

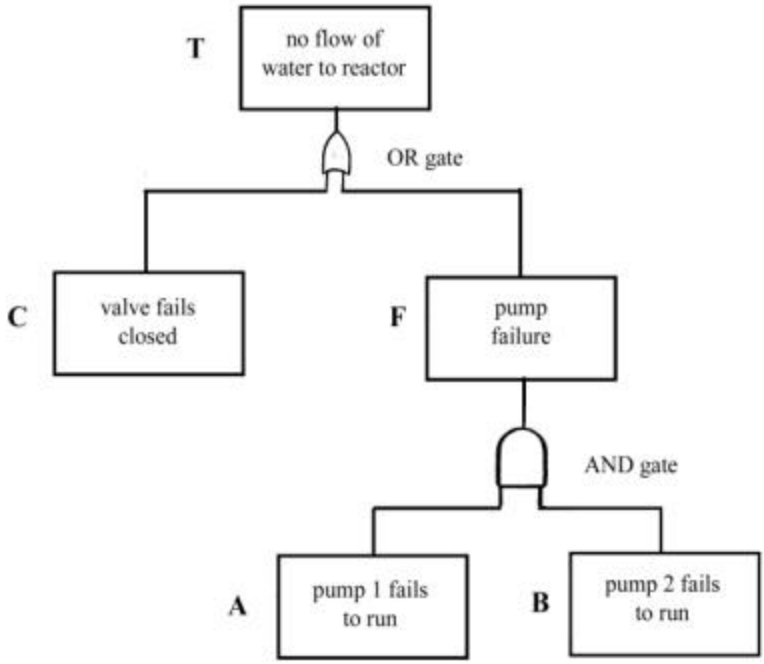
$$F = A \cap B,$$

an intersection. Also, T occurs if either C or F occurs, expressed as

$$T = C \cup F,$$



(a) physical arrangement of pumping system



(b) fault tree

FIG. 19.11 Simple example of PRA diagrams (after NUREG-0492)

a union. Theory (e.g., Lewis in References) tells us what the probability of T is in terms of C and F, viz.,

$$P(T) = P(C) + P(F) - P(C \cap F).$$

Insert the formula for F and note that since A, B, and C are independent events the probabilities $P(A \cap B)$ and $P(C \cap A \cap B)$ are simply products of the separate probabilities. Thus,

$$P(T) = P(C) + P(A)\,P(B) - P(A)\,P(B)\,P(C).$$

The virtue of Boolean algebra is seen by comparison of this formula with the statement in words that the probability of failure of the high pressure injection system is the sum of the probabilities of individual failures of the valve and the pumps less the probability of failure of both

valves and pumps, which was included already. To illustrate numerically, let event probabilities P(A) and P(B) be 10^{-3} and P(C) be 10^{-4}. Inserting numbers,

$$P(T) = 10^{-4} + 10^{-6} + 10^{-10}$$
$$\cong 1.01 \times 10^{-4},$$

which shows that the top event is dominated by the possibility of valve failure. The product of three probabilities can be neglected assuming rare events. The numerical result illustrates two ideas–that fault trees can reveal potential vulnerabilities and that redundancy in safety equipment is beneficial. The figure calculated can be included in the simple event tree of Figure 19.10.

Several good books on fault trees are listed in References. Among important topics discussed in those references are: Venn diagrams, used to visualize relationships of intersections and unions; conditional probability, related to sequences of events; the Bayes theorem, a technique for updating failure probability data; and common cause failures, those where several components can fail from a single cause.

The ultimate objective of PRA is to calculate risks to people, calculated using a principle most simply stated as

$$\text{risk} = \text{frequency} \times \text{consequences}.$$

For reactors, *frequency* means the number of times per year of operation of a reactor that the incident is expected to occur, and *consequences* means the number of fatalities, either immediate or latent. The technique of PRA is used to determine which changes in equipment or operation are most important to assure safety, and also give guidance on emergency plans.

If an incident occurring at a nuclear plant has the potential of releasing radioactivity to the atmosphere, a chain of reactions to alert or warn the public is set in motion. The Nuclear Regulatory Commission and the Federal Emergency Management Agency (FEMA) cooperate in providing requirements and in monitoring tests of readiness. Each nuclear station and the state in which it is located are required to have emergency plans in place, and to hold drills periodically, resembling action to be taken in a real accident situation. In such exercises, state and local officials are notified and an emergency team made up of many organizations makes a coordinated response. Included are radiation protection staff, police and fire departments, highway patrol, public health officers, and medical response personnel. Command posts are set up; weather observations are correlated with radiation conditions to evaluate the possible radiation exposure of the public. Advisories are sent out by radio, sirens are sounded, and the public is advised to take shelter in homes or other buildings. In extreme cases people would be urged to evacuate the affected area.

In case of actual accident involving reactors or transportation of fuel or waste, members of the public who suffer a loss can be compensated. The Price-Anderson Act was passed by Congress in 1957 to provide rules about nuclear insurance that were favorable to the development of the nuclear industry. A limit was set on liability for a reactor accident of $160 million from private insurance companies plus $5 million from each operating reactor. Thus with 100 reactors operating, the total is $660 million. Congressional review is possible for larger claims. Some of the features of Price-Anderson make it a type of "no-fault" insurance that simplifies settlement of claims. Two important points are noted: (a) it is not a subsidy by the government, since nuclear utilities pay the premiums to private insurers; and (b) it makes up for the lack of individual coverage in homeowner's policies.

19.5 The Three Mile Island Accident and Lessons Learned

On March 28, 1979, an accident occurred at a reactor called Three Mile Island (TMI) near Harrisburg, Pennsylvania. A small amount of radioactivity was released, and a number of people were evacuated or left the area for a while. The event was reported fully by news media and caused alarm throughout the region and beyond. We briefly describe what happened at TMI and the resultant improvement in reactor safety.

In Chapters 11 and 12 we have described the features of a typical pressurized water reactor system. We shall refer especially to Fig. 12.7 in reviewing the TMI chronology. The reactor was operating steadily at nearly full power when at 4 a.m. there was a malfunction in the steam generator's feedwater system. (Recall that the feedwater pump returns the condensed steam from the turbine). Because of this failure, the turbine generator was automatically tripped and control rods were driven into the reactor to reduce its power. To this point, nothing unusual had happened. Three backup feedwater pumps should have provided the necessary water. However, they could not because, as it was later learned, a valve to the steam generator had been left closed by mistake. Not until some 8 minutes was this discovered and the valve opened. As a result, the steam generators dried out. Thus the primary water coolant temperature and pressure increased to about 2355 psi, causing a relief valve on the pressurizer to open. The coolant then could escape to a vessel called the quench tank designed to condense and cool any releases from the reactor system. The pressurizer relief valve stuck open, a fact not realized by the operators for 2 hours. Therefore a considerable amount of coolant was released, eventually filling the quench tank and causing a rupture disk on the tank to blow out. Coolant water containing

some radioactivity spilled into the containment building, finding its way to the sump. In the meantime, the reactor pressure continued to fall. At 1600 psi, the emergency core cooling system (ECCS) actuated, as it was supposed to. The high-pressure pumps injected makeup water into the reactor vessel. The pressurizer appeared to the operators to be full of water, a condition that would prevent its functioning. They shut off the ECCS and later stopped the main reactor coolant pumps. This severe lack of water caused the core to heat up and become uncovered. Although the main fission power had been cut off, there remained the large amount of residual heat from the decaying fission products. The coolant flow in the core was inadequate to cool the fuel rods and much damage was experienced. Considerable radioactivity, especially of noble gases such as xenon and krypton, along with iodine, was transferred out of the reactor. The sump pumps automatically sent the radioactive water from the containment into tanks in an auxiliary building next door. The tanks overflowed, permitting radioactive material to escape through filters into the atmosphere. While trying to get water back into the containment building, additional releases were made. The reactor cooling system was finally turned on and the core temperature began to fall. There was fear that metal-water reactions had produced a bubble of potentially explosive hydrogen gas. Efforts were directed for several days toward eliminating this. It is not certain that such a bubble actually existed. Soon after the release of radioactive gases, measurements of atmospheric contamination were initiated by detectors in an airplane, a truck, and at fixed locations in the vicinity. The best estimates are that the highest possible dose to anyone was less than 100 mrems. This was based on assumed continuous exposure outdoors at the site boundary for 11 days. The average exposure to people within 50 miles was estimated to be only 11 mrems, noted to be less than that due to a medical X-ray. As a result of a warning by the governor of Pennsylvania, many people, especially pregnant women, left the area for several days. Estimates published by the Department of Health, Education and Welfare indicate that the exposure over the lifetimes of the two million people in the region there would be statistically only one additional cancer death (out of 325,000 due to other causes).

The TMI accident is believed to be the result of a combination of design deficiency, equipment failure, and operator error. In the design area it should not have been possible for radioactive water to be pumped out of the containment without anyone's knowledge. Also, instrumentation to allow operators full knowledge of the system thermal-hydraulic status should have been available. The main equipment failure was the stuck pressurizer valve. In this incident the equipment as a whole performed quite well, but

there are examples of failure of valves, pumps, and switches that could be eliminated by better quality control during fabrication and by better inspection and maintenance. Operator errors were numerous, including the closing of the valve in the feedwater line, misreading the condition of the pressurizer, and shutting off both the emergency core cooling pumps and the reactor cooling pumps.

Opponents of nuclear power view TMI as proof of their contention that reactors are unsafe; supporters of nuclear power point out that no one was injured, that the emergency equipment functioned, that the reactor core stood up better than expected.

A recovery program for TMI was initiated. The interior of the reactor pressure vessel was examined by using miniature TV cameras attached to the ends of long cables inserted from the top. The damage was greater than originally thought. The upper 5 feet of the core was missing, having slumped into the portion below, and solidified molten fuel was found in the lower part of the vessel. Special handling tools were devised to extract the damaged fuel. Care was taken by measurements and analysis to assure that the debris would not go critical during recovery. The fuel was transferred to a series of always-safe canisters for storage and shipment.

Shortly after the TMI-2 accident the Nuclear Regulatory Commission requested that utilities take a large number of corrective actions in the interest of improved safety at nuclear power plants. Among the items in the Action Plan (see References) were (a) increase in the number of qualified operating personnel; (b) upgrading of training and operator licensing practices; (c) reviews of control room design to take account of human factors; (d) new detectors and instruments that would permit operators to know the status of the reactor at all times; (e) hydrogen detecting equipment; (f) improvement in monitoring of accident conditions, including inadequate core cooling; (g) improved intercommunication between the NRC and the plants; and (h) better emergency preparedness plans.

In anticipation of NRC action, the nuclear industry conducted a study called Industry Degraded Core Rulemaking (IDCOR), the purpose of which was to provide well documented data bases for decisions in severe accidents. In the study existing PRA data were collected and brought up to date. Realistic rather than conservative calculations of sequences were made. Seven specific LWRs were selected for treatment on the basis of differences–PWRs vs. BWRs, large dry containment vs. ice condenser, etc. The study developed physical understandings, mathematical models, and computer calculations for all important processes. Among the conclusions reached was that, in an accident it would take a long time for containment failure to occur, giving operators opportunity to react. Fission product

releases to the environment were predicted to be much lower than those of the Safety Study, WASH 1400 (Section 19.4). No early fatalities from a severe accident were predicted. On the basis of such results, IDCOR concluded that major design of operational changes in reactors were not warranted. In spite of the severity of the TMI-2 core damage, the amount of radioactivity released in the accident was significantly lower than would be predicted by the use of the methods of the Safety Study. This discrepancy prompted new studies of the "source terms," i.e., the amounts of radioactivity that might escape into the atmosphere as the result of an accident and the subsequent leaking of the containment. A typical source term would be that for 8-day iodine-131.

A second study was sponsored by the Nuclear Regulatory Commission, NUREG-0956. It concentrated on a set of improved computer codes developed by Battelle Memorial Institute, BMI-2104. These codes treated the complicated process of core melting, hydrogen production, core-concrete interaction, fission product release, and containment performance under high pressure. Refinements of the modeling techniques included the effect of pressure suppression equipment and the presence of other buildings in the system. The codes were verified and their uncertainties examined. Again PRA methods were applied to a representative set of reactors. Independent reviews of the program were carried out by experts. The NRC concluded that the work was a definite improvement over the Safety Study, but that the risks depended a great deal on the specific design of the containment building.

Other studies were conducted by the American Nuclear Society and by the American Physical Society. The general conclusion was that source terms could be reduced because of retention of chemicals in the coolant and on surfaces. Shortly before the TMI-2 accident, the movie "China Syndrome" was released. It focused on a hypothetical accident in which the whole core is assumed to melt its way through the reactor vessel and go on in the earth toward China. No such scenario is valid but public fears were aroused.

Figure 19.12 illustrates the improvement in going from WASH-1400 to BMI-2104 for one example reactor, the Surry Nuclear Station of Virginia Electric Power Company. The interpretation of the lower curve is as follows: the chance for as many as *one* early fatality is seen to be 3.1×10^{-6} per reactor year†. If one selects a larger number of fatalities, for example

† Many do not understand the terminology used by reactor safety analysts, e.g., "a 10^{-6} chance per year of harm." Norman Rasmussen, after which the Report (Section 19.4) was named, remarks, "For most people, a rare event is one that occurs once in a lifetime, like Halley's comet, frequency 10^{-2}. Once in 100 lifetimes is 10^{-4}, that's getting hard to believe."

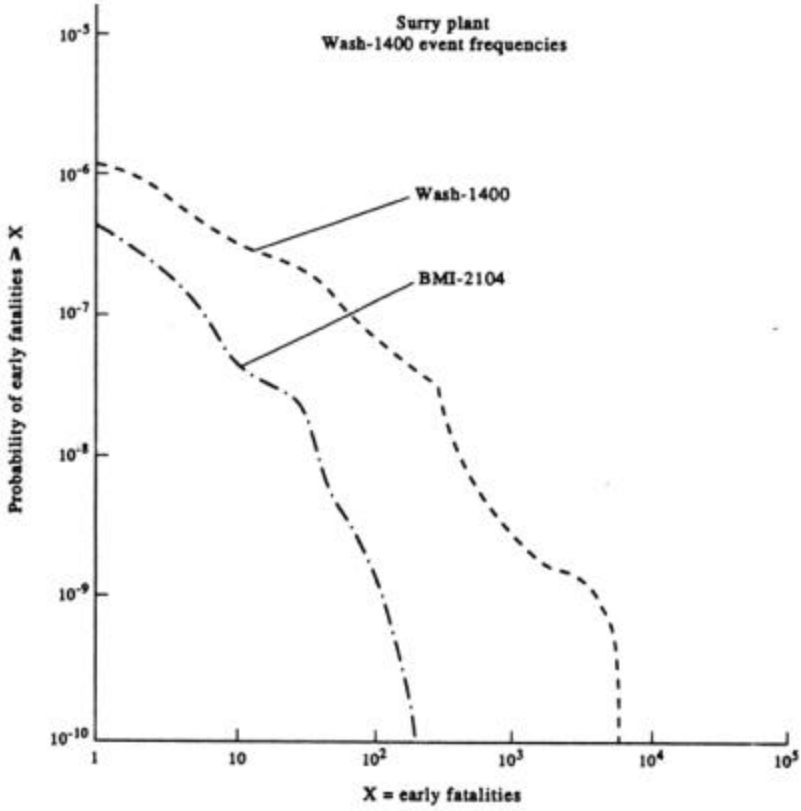


FIG. 19.12 Distribution function for the Surry, Virginia plant. The probabilities for various numbers of early fatalities are shown. Adapted from NUREG-0956.

200, the chance drops by a factor of about 5000. However, the chance of latent cancer fatalities is quoted to be larger, 3.4×10^{-3} per reactor year. This still corresponds to a prediction of less than one death per year for the more than 100 U.S. reactors.

When the findings on source term are used in establishing emergency plans, evacuation of people from a large area surrounding a damaged plant would be an inappropriate action. In 1985, NRC initiated a program called Individual Plant Examination (IPE) to seek out vulnerabilities and report them. PRA was the only way to accomplish that. No significant problems were uncovered.

19.6 The Chernobyl Accident

On April 26, 1986, a very serious reactor accident occurred at the Chernobyl† reactor near Kiev in the U.S.S.R. Ukraine. An explosion took place that blew a hole in the roof of the building housing the reactor, the

† Ukraine prefers the spelling "Chornobyl" but we will use the more familiar form.

graphite moderator caught fire, and a large amount of radioactive material from the damaged nuclear fuel was released into the atmosphere. The amount of radiation exposure to workers and the public is not precisely known, but the doses exceeded those from fallout from earlier weapons tests. A number of workers were killed, nearby towns were contaminated, and it is estimated that the collective dose to the public increased the cancer risk. A large number of people were evacuated from the town of Pripyat. Agriculture was disrupted in the Soviet Union and a ban on food imports was imposed by several European countries.

The Chernobyl-4 reactor is of a type labeled RBMK, of which there were 18 in the U.S.S.R. Its core is cylindrical, of height 7 m and diameter 12 m, consisting of blocks of graphite to serve as moderator and structure. The blocks are pierced with vertical holes, through which 8.8 cm diameter pressure tubes pass. Clusters of 18 slightly enriched (2% U-235) uranium oxide fuel rods are placed inside the tubes, and circulating ordinary water is brought to boiling to supply steam to the generator. The 1661 fuel channels form a square array with 25 cm spacing. Separate channels are provided for 222 control and shutdown rods. A refueling machine above the core allows individual fuel assemblies to be changed during reactor operation. A vapor suppression water pool is located beneath the reactor, but is not connected to the core itself. Figure 19.13 shows the reactor and its building.

The sequence of events leading to the accident was revealed in August 1986 by the U.S.S.R. in a meeting in Vienna called by the International Atomic Energy Agency. An experiment involving the supply of electricity to the reactor equipment in emergency situations was being performed. As in all reactors, if power from the electrical grid is interrupted, standby diesel generators are available. To bridge the gap until the diesels start, however, an auxiliary supply is desirable. This test related to the use of electricity produced during the coastdown of turbogenerators. Emergency power was to be provided to coolant pumps, and feedwater pumps of the steam generator.

It appears that the experiment had been planned by a separate organization that was supplying some new electrical devices. Possibly because of lack of familiarity with the reactor plant, too little attention was given to safety measures, even though the emergency core cooling system was to be deactivated. The operators were under some pressure to complete the test because the next maintenance period was over a year away. In addition, the local dispatcher requested a delay of 8 hours, which may have heightened impatience and induced reckless action by the operators.

The first step in the test was to reduce the power from 3200 MWt to the range 700-1000 MWt. In attempting to do so the operators allowed the

power to drop to 30 MWt. At this level there was too low a neutron flux to burn out the xenon-135 being produced. The buildup of absorber made it very difficult to bring the power level back up. In violation of all rules the operators pulled out most of the control rods, but still could not get the power higher than 200 MWt. At this power the reactor system tends to be unstable.

At this point the coolant pumps were run at a flow rate higher than required for the power level, and the coolant was brought near the boiling point. Various safety systems were disabled to prevent circuit trips and thus to enable the experiment to continue. Later, when coolant flow was reduced, steam voids were created. The fatal flaw in the design of the RBMK reactor played its role at this point.

The graphite reactor had an inherent positive void coefficient, in contrast with the negative coefficient of light water reactors. Only by an elaborate system of detectors, circuits, and control rods was the reactor power managed in normal operation. The reactivity produced by the steam voids caused the power to flash up to around 30,000 MWt, i.e., ten times the operating level. The power could not be reduced quickly because too many rods were too far out to have any effect. The excess energy pulverized the fuel and caused the steam pressure to build up rapidly. The pressure increased and ruptured the coolant tubes and the resultant explosion blew a

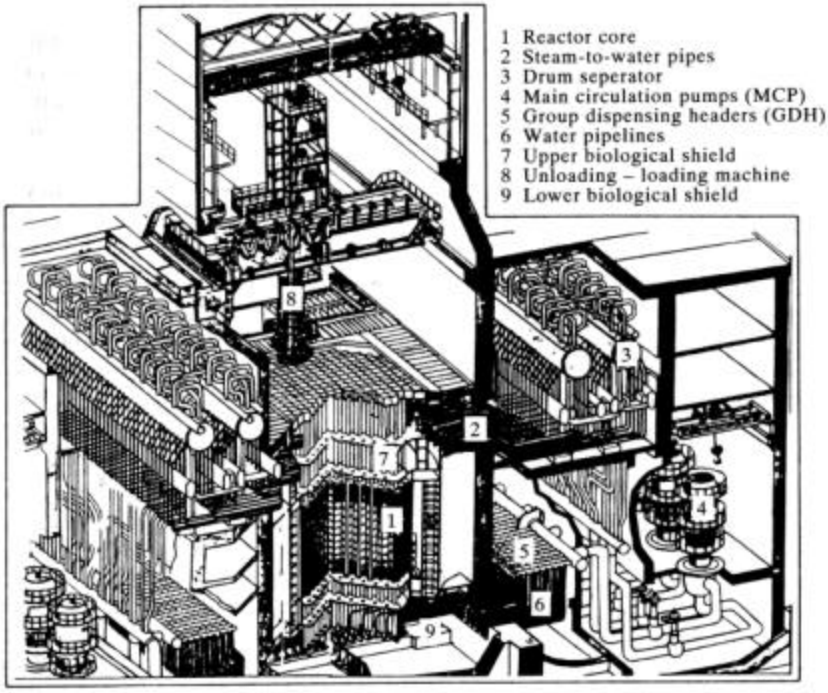


FIG. 19.13 The Chernobyl reactor and building prior to the 1986 accident.

hole in the roof. The normal nitrogen-helium blanket of the core was lost, and air and water contacted the hot graphite moderator. Chemical reaction involving steam, zirconium, and graphite produced large amounts of hydrogen and carbon monoxide, which reacted explosively with air above the core. Although there were thick concrete side walls, the roof was ordinary industrial construction. The building was designed to provide confinement, but not containment for several atmospheres pressure as in typical light water reactors of the U.S. and other countries.

The hot graphite, normally at 750°C, caught fire and continued to burn for several days. Burning material was deposited outside, starting some 30 fires. The intense heat melted and vaporized core material, resulting in the release of a large amount of fission products to the atmosphere. A radioactive cloud drifted toward the Scandinavian countries and Eastern bloc countries. The contamination was first observed in Sweden, but air activity increased throughout the world.

To try to put out the graphite fire, many tons of lead and rock were dropped on the core by helicopter. Boron carbide was also dropped to prevent recriticality. A tunnel was dug beneath the reactor and filled up with concrete to prevent contamination of groundwater.

Out of the radioactive content of the core, there was an estimated release of 3% of transuranic elements, 13% of cesium-137, 20% of iodine-131, and all of the noble gases. A total of around 80 megacuries of activity was released. Estimates of the exposure to people at various locations have been made. A total of 203 operating personnel, firefighters and emergency workers were hospitalized with radiation sickness, of whom 31 died. Their exposures ranged from 100 rems to as high as 1500 rems. Thousands of people were evacuated, many of whom were permanently re-located, with great cost and undoubtedly much distress. A total of 135,000 people were evacuated from a 30 km zone, including 45,000 from the town of Pripyat. Most of those in the evacuation zone received less than 25 rems. Using the total estimated dose of 1.6 million person-rems, an increase of up to 2% in cancer deaths over the next 70 years would be predicted. The exposure outside the U.S.S.R. was considerably less, being only several times natural background radiation.

A structure called a sarcophagus was erected around the damaged reactor, in an effort to prevent future releases of radioactivity. There is evidence of deterioration, with the possibility of inleakage of rainwater.

Several implications of the accident were noted shortly after the accident:

(a) The U.S.S.R. should revise its reactor safety philosophy and practice, with greater attention to human factors as well as improved safety systems.

Some equivalent of public scrutiny regarding safety, as in the free world, will be required. (b) International cooperation on the subject of reactor accidents needs to be enhanced. Included are information exchange and research projects on accidents and their biological consequences. (c) Although light water reactors have a negative power coefficient, cannot burn, and have strong containment buildings, the nuclear industry of the West would do well to re-examine its reactors and operating practices in light of Chernobyl. The important lessons from Chernobyl are that reactor accidents can have major consequences, and that the hazard is not limited to the country in which the accident occurs.

One consequence of the accident was the formation of a set of joint research projects between the U.S. and the Russian Federation. These emphasized data bases, computer codes, and the development of a plan for Russian nuclear safety research. Details are found in the web site of the International Nuclear Safety Center (see References).

In October 1989, the U.S.S.R. requested the International Atomic Energy Agency (IAEA) to evaluate the steps taken to protect the public following the Chernobyl accident. The IAEA created the International Chernobyl Project, involving more than 200 specialists from many organizations, to make a series of inspection visits. The Project found that the Soviet estimates of contamination were generally correct, that the method of estimating population dose was sound, albeit conservative. The Project found that there were many health problems related to the severe stress and anxiety due to uncertainties about the situation and the future. Strong recommendations were made by the group to continue research on Chernobyl and to seek greater international cooperation on nuclear safety.

Reviews of the aftermath of Chernobyl were made at the tenth anniversary of the accident (see References).

It was confirmed that the psychological effects were widespread and significant. An increased incidence in thyroid cancer among children was reported, with the favorable news that treatment was generally successful and that there were very few deaths.

19.7 Philosophy of Safety

The subject of safety is a subtle combination of technical and psychological factors. Regardless of the precautions that are provided in the design, construction, and operation of any device or process, the question can be raised “Is it safe?”. The answer cannot be a categorical “yes” or “no,” but must be expressed in more ambiguous terms related to the chance of malfunction or accident, the nature of protective systems, and the consequences of failure. This leads to more philosophical questions such as

"How safe is safe?" and "How safe do we want to be?"

In an attempt to answer such questions, the NRC adopted in 1986 what are called *safety goals*. These are intended to free neighbors of nuclear plants from worry. Regulations are "...to provide reasonable assurance..." that a severe core accident will not occur at a U.S. nuclear plant." Design and operation are to be such that risks of death from a nuclear accident are no greater than a thousandth of known and accepted risks. The comparison is to be made with other common accidents for those people living within a mile of the plant and with cancer from all causes for those living within 10 miles.

Every human endeavor is accompanied by a certain risk of loss or damage or hazard to individuals. In the act of driving an automobile on the highways, or in turning on an electrical appliance in the home, or even in the process of taking a bath, one is subject to a certain danger. Everybody agrees that the consumer deserves protection against hazard outside his personal control, but it is not at all clear as to what lengths it is necessary to go. In the absurd limit, for instance, a complete ban on all mechanical conveyances would assure that no one would be killed in accidents involving cars, trains, airplanes, boats, or spacecraft. Few would accept the restrictions thus implied. It is easy to say that reasonable protection should be provided, but the word "reasonable" has different meanings among people. The concept that the benefit must outweigh the risk is appealing, except that it is very difficult to assess the risk of an innovation for which no experience or statistical data are available, or for which the number of accidents is so low that many years would be required for adequate statistics to be accumulated. Nor can the benefit be clearly defined. A classic example is the use of a pesticide that assures protection of the food supply for many, with finite danger to certain sensitive individuals. To the person affected adversely, the risk completely overshadows the benefit. The addition of safety measures is inevitably accompanied by increased cost of the device or product, and the ability or willingness to pay for the increased protection varies widely among people.

It is thus clear that the subject of safety falls within the scope of the social-economic-political structure and processes and is intimately related to the fundamental conflict of individual freedoms and public protection by control measures. It is presumptuous to demand that every action possible should be taken to provide safety, just as it is negligent to contend that because of evident utility, no effort to improve safety is required. Between these extreme views, there remains an opportunity to arrive at satisfactory solutions, applying technical skill accompanied by responsibility to assess consequences. It is most important to provide understandable information,

on which the public and its representatives can base judgments and make wise decisions as to the proper level of investment of effort and funds.

19.8 Summary

Prevention of release of radioactive fission products and fuel isotopes is the ultimate purpose of safety features. Inherent reactor safety is provided by delayed neutrons and temperature effects. Control rods permit rapid shutdown, and reactor components are designed and constructed to minimize the chance of failure. Emergency core cooling equipment is installed to reduce the hazard in the event of an accident. Licensing is administered by the Nuclear Regulatory Commission, which expects plants to use probabilistic safety analysis (PRA).

An accident at Three Mile Island Unit 2 in 1979 resulted in considerable damage to the reactor core but little radioactive material was released. The event stimulated the nuclear industry to make many changes that enhance reactor safety.

A serious accident occurred in 1986 at Chernobyl, U.S.S.R. As a result of an unauthorized experiment there was an explosion and fire, accompanied by the release of a great deal of radioactivity. Nearby cities were evacuated, a number of people were killed, and many received significant dosage. Information on this event and its public consequence will be collected for years to come. Reactor safety will remain a topic of continued discussion and action will be subject to public opinion.

19.9 Exercises

19.1. (a) If the total number of neutrons from fission by thermal neutrons absorbed in U-235 is 2.42, how many are delayed and how many are prompt? (b) A reactor is said to be "prompt critical" if it has a positive reactivity of β or more. Explain the meaning of the phrase. (c) What is the period for a reactor with neutron cycle time 5×10^{-6} s if the reactivity is 0.013? (d) What is the period if instead the reactivity is 0.0013?

19.2. A reactor is operating at a power level of 250 MWe. Control rods are removed to give a reactivity of 0.0005. Noting that this is much less than β, calculate the time required to go to a power of 300 MWe, neglecting any temperature feedback.

19.3. Measurements of the fast neutron cycle time ℓ were made on EBR-I, the first reactor to produce electricity. Calculate its value in two different ways: (a) Using the ratio ℓ/β, called the Rossi-α, of 1.7×10^{-3}/s and β of 0.0068; (b) Using a rough formula $\ell = 1/(u\,\Sigma_a)$ with 1 MeV neutrons, for which $\sigma_c = 0.1$ barn and $\sigma_f = 1.2$ barn. Note $N_U = 0.048$, $u = 2200$ m/s for $E = 0.0253$ eV.

19.4. During a critical experiment in which fuel is initially loaded into a reactor, a fuel element of reactivity worth 0.0036 is suddenly dropped into a core that is already critical. If the temperature coefficient is -9×10^{-5} /°C, how high will the temperature of the system go above room temperature before the positive reactivity is canceled out?

19.5. How long will it take for a fully withdrawn control rod in a reactor of height 4 m to drop

into a reactor core neglecting all friction and buoyancy effects? (Recall $s = \frac{1}{2} gt^2$ with $g = 9.8$ m/s^2.)

19.6. Calculate the ratio of fission product power to reactor power for four times after shutdown–1 day, 1 week, 1 month, and 1 year, using the approximation $A = 0.066$, $a = 0.2$.

19.7. A reactivity of –0.0025 due to Doppler effect results when the thermal power goes from 2500 MW to 2800 MW. Estimate the contribution of this effect on the power coefficient for the reactor.

19.8. Assuming a probability of reactor core meltdown of 3×10^{-4} per reactor year, calculate the chance of one meltdown for 100 reactors in a period of 20 years.

19.9. Counting rates for several fuel addition steps in a critical experiment are listed below.

Number of fuel assemblies	Counting rate (counts/min)
0	200
50	350
100	800
125	1,600
140	6,600
150	20,000

At the end of each fuel addition, what is the estimated critical number of assemblies? Was the addition always less than the amount expected to make the array critical?

19.10. When a control rod is raised 4 cm from its position with tip at the center of a critical reactor, the power rises on a period of 200 seconds. using a value $b = 0.008$ and $t = 13$ seconds, estimate the $d k$ produced by the rod shift and the slope of the calibration curve $\Delta k/\Delta z$. Estimate the rod worth if the core height is 300 cm.

19.11. Measurements are made of the periods of power rise in a research reactor of height 24 inches for shifts in control rod position. From the periods, values are obtained for the slope of the reactivity $\Delta r_i/\Delta z_i$, with units percent per inch, as listed below:

i	z_i	$\Delta r_i/\Delta z_i$	i	z_i	$\Delta r_i/\Delta z_i$
1	0		10	12.5	
		0.02			1.03
2	3		11	13	
		0.16			1.08
3	5.5		12	14	
		0.38			1.02
4	7.5		13	15	
		0.68			0.95
5	9		14	16.5	
		0.83			0.77
6	10		15	18.5	
		0.89			0.40
7	11		16	21	
		0.96			0.11
8	11.5		17	24	
		0.98			
9	12				
		1.02			

Plot the slope against average position $\bar{z}_i = (z_{i+1} + z_i)/2$. Pass a smooth curve through the points, then find the area under the curve as a function of z. Estimate the rod worth when the tip is 16 inches up from the bottom.

19.12. Commonly-used fractions and half-lives of the nuclides that are delayed neutron emitters

for thermal neutron fission in uranium-235 are as follows:

Group i	Fraction b_i	Half-life $t_H)_i$
1	0.000247	54.51
2	0.001385	21.84
3	0.001222	6.00
4	0.002645	2.23
5	0.000832	0.496
6	0.000169	0.179

Verify that the total fraction is 0.0065 and that the average half-life is approximately 8.8 s.

19.13. (a) Show that a megawatt per tonne is the same as a watt per gram. (b) Show that the burnup in MWd/tonne is given by the formula

$$B = cEf\, s_{f235} wt/m_U$$

where the enrichment is

$$E = N_{235}/N_U$$

and

$$c = 1.157 \times 10^{-5}\ .$$

(c) Calculate B for a flux of 2×10^{13}/cm^2-s for three years with enrichment 0.03. Note $m_U = 395 \times 10^{-24}$ grams, $s_{f235} = 586 \times 10^{-24}$ cm^2, and $w = 3.04 \times 10^{-11}$ W-s/fission.

19.14. To remain critical at the end of a cycle of operation, a power reactor must have an average multiplication factor k_F. For a one-zone core, this is related to the burnup B by

$$k_F = k_0 - aB$$

where a is a constant, so that the discharge burnup is

$$B(1) = (k_0 - k_F)/a.$$

For a two-zone core, we have

$$k_F = (k_0 - aB)/2 + (k_0 - 2aB)/2 = k_0 - (3/2)aB.$$

The discharge burnup is $2B$ or

$$B(2) = (4/3)B(1).$$

Continue the analysis to find $B(3)$ and $B(4)$. Check the results against the formulas quoted in the text.

Computer Exercises

19.A. A simplified version of the analysis of neutron population growth is called the one-delayed-group model. The six emitters listed in Ex. 19.12 are replaced by a single emitter with mean life t = 12.7 s, effective neutron lifetime $\bar{\ell}$ = 0.083 s, decay constant l = 0.0785 s^{-1}, total fraction b = 0.0065. Differential equations for the neutron population n and the delayed emitter concentration c are written:

$$dn/dt = n(r - b)/\bar{\ell} - lc$$

$$dc/dt = nb/\bar{\ell} + lc$$

To solve, finite difference methods are used in the Lotus 1-2-3 program OGRE (One Group Reactor Kinetics) (a) Load the program OGRE into Lotus 1-2-3 and inspect the input and output data. (b) Try various reactivity values such as 0.0001, 0.0005, and 0.001, using a time step of 0.01 s. (c) Plot the time responses of n using graphing techniques of Lotus 1-2-3. (d) Change the time step for r = 0.001 from 0.01 s to 0.1 s. Explain the results and discuss actions required. (e) Restore the spreadsheet file to its original condition.

19.B. The BASIC program KINETICS solves the time-dependent equations for neutrons and

delayed emitters, yielding the neutron population as a function of time. Six emitters are used, and feedback is neglected. (a) Run the program using the menus, observing symbols, equations, and input data. (b) Try various input reactivity values-positive, negative and zero; small and large with respect to b = 0.0065.

19.C. The effect of temperature feedback on the time response of a reactor can be estimated by use of the Lotus 1-2-3 program RTF (Reactor Transient with Feedback). RTF solves simple differential equations that express the rates of change with time of power and temperature. There is a negative temperature coefficient of reactivity and power is extracted according to a temperature difference. (a) Load the program RTF into Lotus 1-2-3 and scan the tables to see how the power varies with time for the sample problem. (b) Use the plotting capability of Lotus 1-2-3 to draw a graph of power P vs. time t. (c) Examine the effect of changing the reactor fuel from uranium to plutonium. Pu has an effective neutron lifetime of only 0.04 s in comparison with the value for U of 0.083 s. Let all other factors be the same as in (a) above. (d) Restore the spreadsheet file to its original condition.

19.D. A typical PWR core contains around 200 fuel assemblies, arranged to optimize production and safety. The computer program COREFUEL shows top views of cores with different fuel patterns, including that of Three Mile Island Unit 2 prior to its accident. Run this BASIC program using the menus.

19.E. The power excursion without cooling in the Three Mile Island Unit 2 reactor (TMI-2) turned fuel assemblies into a mass of broken and melted material. Load and run the BASIC program RUBBLE, which sketches the cavity formed by the slumping of damaged fuel.

19.F. Features of the Chernobyl reactor prior to its accident are sketched in three BASIC computer programs: CIRCLE6, which shows the array of 19 fuel rods within an aluminum tube, forming their assembly; SQRCIR6, which shows the array of holes in the graphite core for insertion of fuel or rods; and CORODS, which illustrates the arrangement of control rods that led to the accident. Load and run the programs.

19.10 References for Chapter 19

Ronald Allen Knief, *Nuclear Criticality Safety: Theory and Practice*, American Nuclear Society, La Grange Park, IL, 1985. Methods of protection against inadvertent criticality, with an appendix on the Three Mile Island recovery program.

Brian L. Koponen, Ed., Nuclear Criticality Safety Experiments, Calculations, and Analyses–1958 to 1998: Compilation of Papers from the *Transactions of the American Nuclear Society*, Golden Valley Publications, Livermore, CA, 1999.

Criticality Accidents
http://www.enviroweb.org/issues/nuketesting/accident/critical.htm
Atomic Energy Commission, 1943-1970

William R. Stratton, A Review of Criticality Accidents, LA-3611, Los Alamos Scientific Laboratory, 1967. Early information on events and their causes.

Nuclear Safety, Technical Information Center, U.S. Department of Energy, Oak Ridge, TN. Quarterly magazine.

The Virtual Nuclear Tourist
http://www.cannon.net/~gonyeau/nuclear/index.htm
All about nuclear power. By Joseph Gonyeau.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

E. E. Lewis, *Nuclear Power Reactor Safety*, John Wiley & Sons, New York, 1977.

F. R. Farmer, Editor, *Nuclear Reactor Safety*, Academic Press, New York, 1977.

History of Nuclear Power Plant Safety
http://users.owt.com/smsrpm/nksafe
Select decade time line, 1940-2000.

ECCS Evaluation Models
www.nrc.gov/NRC/CFR/PART050/index.html
Select Appendix K for regulation on emergency core cooling system.

Dennis D. Wackerly, William Mendenhall III, and Richard L. Scheaffer, *Mathematical Statistics with Applications*, 5th edition, Wadsworth Publishing Co., Belmont, CA, 1996.
A popular textbook on basic statistics.

Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power, WASH-1400 (NUREG-75/014), U.S. Nuclear Regulatory Commission, 1975. Often called the Rasmussen Report after the director of the project, Norman Rasmussen. The first extensive use of probabilistic risk assessment in the nuclear field.

PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants, NUREG/CR-2300, Vols. 1 and 2, Nuclear Regulatory Commission, January 1983. A comprehensive 936-page report prepared by the American Nuclear Society and the Institute of Electrical and Electronic Engineers. Issued after the Three Mile Island accident, it serves as a primary source of training and practice.

Norman J. McCormick, *Reliability and Risk Analysis: Method and Nuclear Power Applications*, Academic Press, New York, 1981.

N. H. Roberts, W. E. Vesely, D. F. Haasl, and F. F. Goldberg, *Fault Tree Handbook*, NUREG-0492, Nuclear Regulatory Commission, Washington, DC, 1981.
A frequently-cited tutorial containing fundamentals and many sample analyses.

Ralph R. Fullwood and Robert E. Hall, *Probabilistic Risk Assessment in the Nuclear Power Industry: Fundamentals and Applications*, Pergamon Press, Oxford, 1988.

Ernest J. Henley and Hiromitsu Kumamoto, *Probabilistic Risk Assessment*, IEEE Press, New York, 1992.

E. E. Lewis, *Introduction to Reliability Engineering*, John Wiley & Sons, New York, 1996.

Society for Risk Analysis
http://www.sra.org
Contains an extensive glossary of chemical and nuclear terms.

Understanding Risk Analysis: A Short Guide for Health, Safety, and Environmental Policy Making, American Chemical Society and Resources For the Future, 1998.
http://www.rff.org/misc_docs/risk_book.htm.
The 39 pages can be downloaded as a pdf file. A good qualitative discussion of risk including history, perceptions, methodology, and limitations.

John Kemeny et al., *The Need for Change: The Legacy of TMI*, Pergamon Press, Elmsford, NY, 1979. Subtitle: Report of the President's Commission on the Accident at Three Mile Island.

M. Rogovin and G. T. Frampton, Jr., Three Mile Island: A Report to the Commissioners and the Public, NUREG/CR-1250, Nuclear Regulatory Commission, 1980.

Three Mile Island 2 Accident
http://www.nrc.gov/OPA/reports/tmi.htm
Account of the accident with diagram, references, and glossary, by NRC.

TMI-2 Recovery and Decontamination Collection
http://www.libraries.psu.edu/crsweb/tmi/tmi.htm
Pennsylvania State University Library

M. Sandra Wood and Suzanne M. Schultz, *Three Mile Island: A Selectively Annotated Bibliography*, Greenwood Press, New York, 1988.

IDCOR Nuclear Power Plant Response to Serious Accidents, Technology for Energy Corp., Knoxville, TN, November 1984.

Report on the Accident at the Chernobyl Nuclear Station, NUREG-1250, U.S. Nuclear Regulatory Commission, January 1987. A compilation of information obtained by DOE, EPRI, EPA, FEMA, INPO, and NRC.

David R. Marples, *Chernobyl and Nuclear Power in the USSR*, St. Martin's Press, New York, 1986. A comprehensive examination of the nuclear power industry in the USSR, the Chernobyl accident, and the significance of the event in the USSR and elsewhere, by a Canadian specialist in Ukraine studies.

IAEA Bulletin, Vol. 34, No. 2, 1992. The issue features international aspects of nuclear safety.

Chernobyl Status
http://www.nrc.gov/OPA/gmo/tip/tip09.htm
Summary of the accident and subsequent events, by NRC.

Chernobyl Ten Years On: Radiological and Health Issues
http://www.nea.fr/html/rp/chernobyl/chernobyl.html
Assessment in 1995 by OECD Nuclear Energy Agency.

International Conference: One Decade After Chernobyl
http://www.iaea.or.at/worldatom/thisweek/preview/chernobyl/conclsn9.html
Highlights, conclusions, and recommendations of 1996 conference.

Darryl Randerson (Ed.), *Atmospheric Science and Power Production*, Department of Energy, 1984. Third version of book on estimation of concentrations of radioactivity from accidental releases.

Joint Coordinating Committee for Civilian Nuclear Reactor Safety
http://www.eh.doe.gov/ihp/jccc/JCCCNRS.html
Cooperation between the U.S. and members of the Former Soviet Union.

International Nuclear Safety Center (INSC)
http://www.insc.anl.gov
Joint research between U.S. and Russian Federation. Worldwide reactor data, bibliographies, and nuclear materials properties.

Richard Wolfson, *Nuclear Choices: A Citizen's Guide to Nuclear Technology*, MIT Press, Cambridge, MA, 1993. Nuclear power and nuclear weapons, with comments on the accidents at TMI and Chernobyl.

Dominic Golding, Jeanne X. Kasperson, and Roger E. Kasperson, Eds., *Preparing for Nuclear Power Plant Accidents*, Westview Press, Boulder, CO, 1995. Critical of existing emergency plans, use of PRA, source term analysis, and warning systems. Sponsored by Three Mile Island Public Health Fund.

20

Nuclear Propulsion

NUCLEAR PROCESSES are logical choices for compact energy sources in vehicles that must travel long distances without refueling. The most successful application is to the propulsion of naval vessels, especially submarines and aircraft carriers. Thermoelectric generators using the isotope plutonium-238 provide reliable electric power for interplanetary spacecraft. Research and development has been done on reactors for aircraft and rockets, and reactors may be used in future missions.

20.1 Reactors for Naval Propulsion†

The discovery of fission stimulated interest on the part of the U.S. Navy in the possibility of using nuclear power for submarine propulsion. The development of the present fleet of nuclear ships was due largely to Admiral H. G. Rickover, a legendary figure because of his reputation for determination, insistence on quality, and personalized management methods. The team that he brought to Oak Ridge in 1946 to learn nuclear technology supervised the building of the land-based prototype at Idaho Falls and the first nuclear submarine, *Nautilus*. As noted by historians for the project (see References), the name had been used for submarines before, including Jules Verne's fictional ship.

The principal virtue of a nuclear-powered submarine is its ability to travel long distances at high speed without refueling. It can remain submerged because the reactor power plant does not require oxygen. Research on the Submarine Thermal Reactor was conducted by Argonne National Laboratory, and the development was carried out at the Bettis Laboratory of Westinghouse Electric Corporation.

The power plant for the *Nautilus* was a water-moderated, highly enriched uranium core, with zirconium-clad plates. The submarine's first sea trials were made in 1955. Some of its feats were a 1400-mile trip with average speed 20 knots, the first underwater crossing of the Arctic ice cap, and traveling a distance of over 62,000 miles on its first core loading. Subsequently the *Triton* reproduced Magellan's trip around the world, but

† Thanks are due Commander (Ret.) Marshall R. Murray, USN, for some of the information in this section.

completely submerged. The Nautilus was decommissioned in 1980 and is now in a museum at Groton, CT.

Over the years of the Cold War, the U.S. nuclear fleet was built up, with more than 100 nuclear-powered submarines and a number of aircraft carriers. The first of the latter was the *Enterprise*, deployed in 1961. It has eight reactors, 85 aircraft, and 5830 men. Figure 20.1 shows the carrier with Einstein's familiar formula spelled out on the deck by members of the crew. Since then, seven additional carriers have been built, some of which saw service in the Gulf War and follow-up activities.

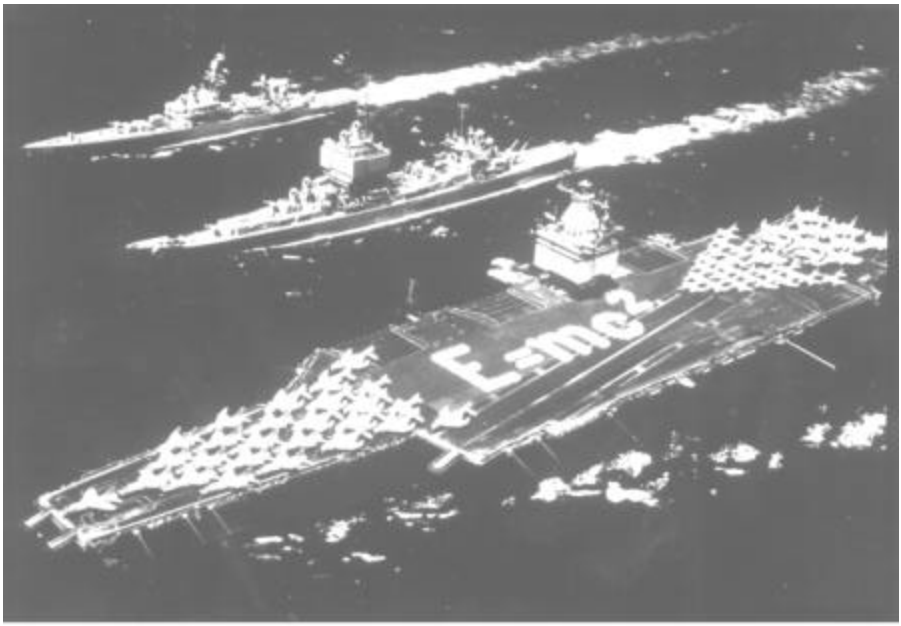


FIG. 20.1 The nuclear-powered aircraft carrier USS *Enterprise*. Sailors in formation on the flight deck spell out Einstein's formula. The accompanying ships are the USS *Long Beach* and the USS *Bainbridge* (Courtesy U.S. Navy)

Attack submarines are designed to seek and destroy enemy submarines and surface ships. One of the latest is *Seawolf*, powered with one reactor and armed with *Tomahawk* cruise missiles. Ballistic missile submarines are designed as deterrent to international conflict. An example is the *Ohio*, which carries 24 long range *Trident* strategic missiles. These weapons can be ejected by compressed air while the vessel is under water, with the rocket motors started when the missile clears the surface. The number of U.S. nuclear-powered naval vessels is gradually being reduced by obsolescence and decision, and by international agreement, as part of the START program (see Section 26.3).

Commercial nuclear power has benefited in two ways from the Navy's

nuclear program. First, industry received a demonstration of the effectiveness of the pressurized water reactor. Second, utilities and vendors have obtained the talents of a large number of highly skilled professionals who are retired officers and enlisted men.

The U.S. built only one commercial nuclear vessel, the merchant ship N.S. *Savannah*. Its reactor was designed by Babcock & Wilcox Co. Carrying both cargo and passengers, it was successfully operated for several years in the 1960s, making a goodwill voyage to many countries (see References). After being on display at a naval museum in South Carolina, the N.S. *Savannah* was moved in 1994 to Virginia.

Several icebreakers powered by nuclear reactors were built by the U.S.S.R. and continue to be used in the far north for expedition cruises (see References).

Japan launched an experimental nuclear-powered merchant ship *Mutsu* in 1962. It successfully passed several rigorous sea trials, performing well in rough seas caused by a typhoon. Decommissioned in 1995 and placed in a museum, its experience served as the basis for the design of two other vessels (see References).

20.2 Space Reactors

Many years before the advent of the space program, an attempt was made to develop an aircraft reactor. A project with acronym NEPA (Nuclear Energy for the Propulsion of Aircraft) was started at Oak Ridge in 1946 by the U.S. Air Force. The basis for the program was that nuclear weapon delivery would require supersonic long-range (12,000 miles) bombers not needing refueling. An important technical question that still exists is how to shield the crew without incurring excessive weight. As described by Hewlett and Duncan (see References), the program suffered from much uncertainty, changes of management, and frequent re-direction. It was transferred from Oak Ridge to Cincinnati under General Electric as the ANP (Aircraft Nuclear Propulsion) program. The effort was terminated for several reasons: (a) the need for a much larger airplane than expected, (b) improvements in performance of chemically fueled jet engines, and (c) the selection of intercontinental ballistic missiles to carry nuclear weapons. Some useful technical information had been gained, but the project never came close to its objective.

The space program was given new impetus in 1961 with President Kennedy's goal of a manned lunar landing. Other missions visualized were manned exploration of the planets and ultimately colonization of space. For such long voyages requiring high power, the light weight of nuclear fuel made reactors a logical choice for both electrical power and propulsion.

One concept that was studied extensively was ion propulsion, with a reactor supplying the energy needed to accelerate the ions that give thrust. A second approach involved a gaseous core reactor, in which a mixture of uranium and a gas would be heated by the fission reaction and be expelled as propellant. Another more exotic idea was to explode a number of small nuclear weapons next to a plate mounted on the space vehicle, with the reaction to the explosion giving a repetitive thrust.

Fission reactors with thermoelectric conversion systems were developed in the period 1955-1970 by the Atomic Energy Commission. Its contractor, Atomics International, conducted the SNAP (Systems for Auxiliary Nuclear Power) program. The most successful of these was SNAP-10A, which was the first and only U.S. reactor to be flown in space. Two systems were built–one tested on earth, the other put in orbit. Their fuel was an alloy of enriched uranium and zirconium hydride to operate at high temperatures (810K). The coolant was liquid sodium-potassium (NaK) for efficient heat transfer. The NaK was circulated through the reactor and a thermoelectric converter system that produced 580 watts of electrical power. The total weight of one system was 435 Kg. The space version was launched in 1965 by an Agena rocket and started up by remote control. It operated smoothly in orbit for 43 days until it was accidentally shut down by an electric failure in the spacecraft. The ground version operated satisfactorily for 10,000 hours. Further details are provided by Bennett (see References). Another successful reactor SNAP-8 used mercury as coolant, with conversion to 50 kW of electric power in a Rankine cycle. Further details of these reactors appear in the book by Angelo and Buden (see References).

The nuclear system that received the most attention in the space program was the solid core nuclear rocket. Liquid hydrogen would be heated to a high temperature as gas on passing through holes in a reactor with graphite moderator and highly enriched uranium fuel. In the proposed vehicle the hydrogen would be exhausted as propellant through a nozzle. The Rover project at Los Alamos was initiated with a manned mission to Mars in mind. Flight time would be minimized by using hydrogen as propellant because its specific impulse would be about twice that of typical chemical fuels. A series of reactors named Kiwi, NRX, Pewee, Phoebus, and XE′ were built and tested at the Nuclear Rocket Development Station located in Nevada. The systems used uranium carbide fuel, graphite moderator, and once-through hydrogen coolant, entering as a liquid and leaving as a gas. The best performance obtained in the NERVA (Nuclear Engine for Rocket Vehicle Application) program was a power of 4000 MW for 12 minutes. The program was a technical success, but was terminated in 1973 because of a change in NASA plans. Following the lunar landing in the Apollo

program, a decision was made not to have a manned Mars flight. It was judged that radioisotope generators and solar power would be adequate for all future space needs.

Various R&D programs on space reactors to provide electric power were initiated subsequently, e.g., the SP-100, which was to be a reactor in the 100 kW-1 MW range. Most of the projects were eventually canceled.

20.3 Space Isotopic Power

Chemical fuels serve to launch and return space vehicles such as the shuttle. For long missions such as interplanetary exploration, where it is necessary to supply electric power to control and communication equipment for years, nuclear power is needed. The radioisotope thermoelectric generator (RTG) has been developed and used successfully for 18 missions. It uses a long-lived radionuclide to supply heat that is converted into electricity. The power source has many desirable features: (a) lightness and compactness, to fit within the spacecraft readily; (b) long service life; (c) continuous power production; (d) resistance to environmental effects such as the cold of space, radiation, and meteorites; and (e) independence from the sun, permitting visits to distant planets.

The isotope used to power the RTGs is plutonium-238, half-life 87.74 y, which emits alpha particles of 5.5 MeV. The isotope is produced by reactor neutron irradiation of the almost-stable isotope neptunium-237, half-life 2.14×10^6 y. The latter is a decay product of uranium-237, a 6.75-day beta emitter that arises from neutron capture in uranium-236 or by (n,2n) and (*g*,n) reactions with uranium-238. The high-energy alpha particles and the relatively short half-life of Pu-238 give the isotope the high specific activity of 17 Ci/g and the favorable power to weight ratio quoted to be 0.57 W/g.

Typical of the RTGs is the one sent to the moon in the Apollo-12 mission. It powered a group of scientific instruments called ALSEP (Apollo

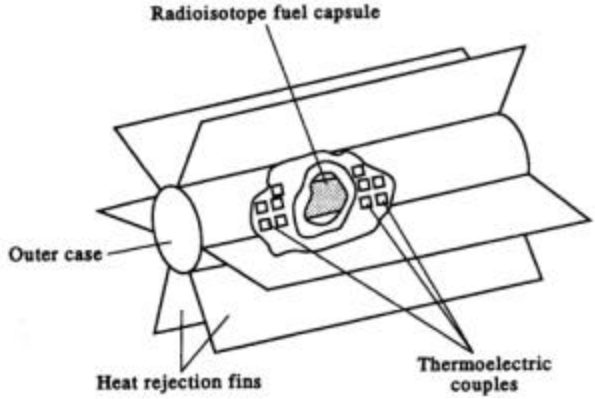


FIG. 20.2 Isotopic electrical power generator. (SNAP-27 used in Apollo-12 mission.)

Lunar Surface Experimental Package), which measured magnetic fields, dust, the solar wind, ions, and earthquake activity. The generator is shown schematically in Fig. 20.2. Lead-telluride thermoelectric couples are placed between the PuO_2 and the beryllium case. Data on the generator are shown in Table 20.1.

TABLE 20.1
Radioisotope thermoelectric generator SNAP-27

System weight 20 kg	Thermal power 1480 W
Pu-238 weight 2.6 kg	Electrical power 74 W
Activity 44,500 Ci	Electrical voltage 16 V
Capsule temperature 732°C	Operating range - 173°C to 121°C

This generator, called SNAP-27, was also used in several other Apollo missions, and data were returned to earth for the period 1969-1977. For the 1975 Viking mission, the somewhat smaller SNAP-19 powered the Mars landers, which sent back pictures of the surface of that planet.

An advanced model, called multi-hundred watt (MHW), provided all electrical power for the two Voyager spacecraft (Fig. 20.3), designed and operated by the Jet Propulsion Laboratory of NASA. They were launched in the summer of 1977, and reached Jupiter in 1979 and Saturn in late 1980 and early 1981, sending back pictures of Saturn's moons and rings. Voyager 1 was then sent out of the solar system to deep space. Taking advantage of a rare alignment of three planets, Voyager 2 was redirected to visit Uranus in January 1986. The reliability of the power source after 9 years in space was crucial to the mission. Because of limited light at the 1.8 billion miles from the sun, long exposure times of photographs and thus great stability of the spacecraft were needed. By sending radio signals to Voyager 2 the onboard computers were reprogrammed to allow very small corrective thrusts (see References). Several new moons of Uranus were discovered, including some whose gravity stabilizes the planet's rings. Voyager 2 arrived at Neptune in 1989, then went on to outer space. The MHW generator used silicon-germanium as thermoelectric material rather than lead-telluride; each generator was heavier and more powerful than SNAP- 27. Similar power supplies are used for the Lincoln Experimental Satellites (LES 8/9), which can communicate with each other and with ships and aircraft.

A still larger supply, called General Purpose Heat Source (GPHS) is being used in the Galileo spacecraft sent out in October 1990 toward Jupiter. On its way it photographed the asteroids Gaspra and Ida, viewed the impacts of the Shoemaker-Levy 9 comet on the surface of Jupiter, and made flybys of moons Io and Europa. A battery-powered instrumented probe was sent down through Jupiter's atmosphere. Photographs and further information have been provided by NASA (see References). Concerns were

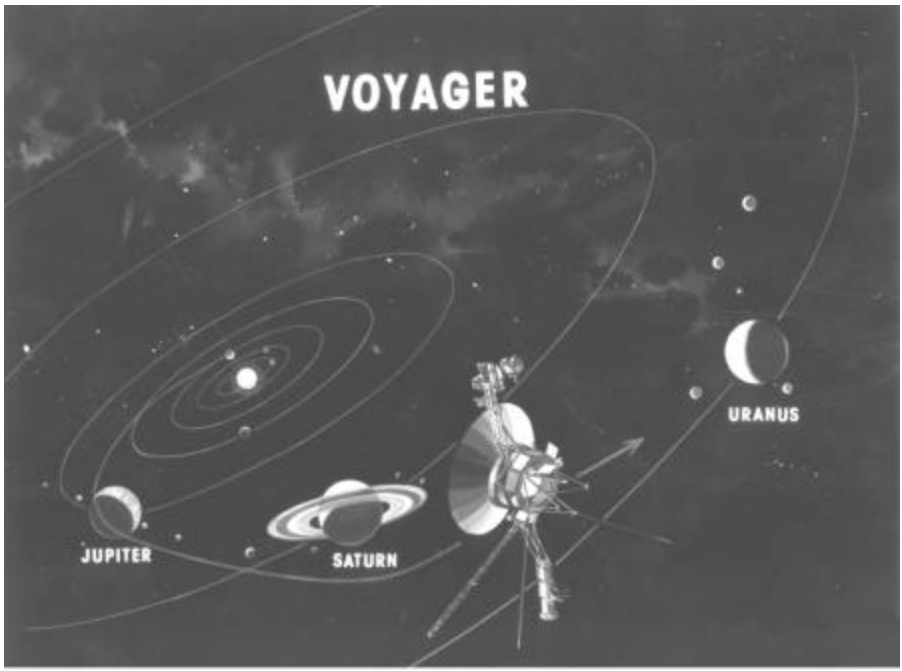


FIG. 20.3 Voyager 2 spacecraft as it passed Saturn in 1981. (Courtesy National Aeronautics and Space Administration).

raised about possible abortion of the Galileo mission, with contamination of the atmosphere by plutonium. A lawsuit to prevent its launching was unsuccessful. Difficulties have been encountered with the deployment of its antenna, and the mission may not come up to expectations. Studies of this distant planet will complement those made of nearby Venus by the solar-powered Magellan.

The spacecraft Ulysses, launched in November 1990, is also powered by a GPHS. It is a cooperative mission between the U.S. and Europe, to study the solar wind–a stream of particles from the Sun–and the star's magnetic field. Ulysses will rendezvous with Jupiter to use the planet's gravity to take the spacecraft out of the ecliptic (the plane in which the planets move).

The Cassini spacecraft, launched in 1997 toward Saturn and its moon Titan, contains three RTGs to power instruments and computers, each with about 10.9 kg of PuO_2. The total power was initially 888W (see References).

To help maintain proper temperatures for sensitive electronic components, small (2.7 g, 1 W) Pu-238 sources called Radioactive Heating Units (RHUs) are provided. These were used in the missions to distant planets and also in the Sojourner minirover that explored the surface of Mars (see References).

Power supplies planned for missions of the more distant future will be in

the multi-kilowatt range, have high efficiency, and make use of a dynamic principle. In the dynamic radioisotope power system (DIPS), the isotopic source heats the organic fluid Dowtherm A, the working fluid for a Rankine thermodynamic cycle, with the vapor driving a turbine connected to an electric generator. In a ground test the DIPS operated continuously for 2000 hours without failure. Details of all of these RTGs are given in the book by Angelo and Buden (see References).

Long range missions for the 21st century planned by NASA include the recovery of resources at a lunar base and from an asteroid, a space station orbiting the earth, and eventually a manned Mars mission. Such activities will require nuclear power supplies in the multi-megawatt range.

Other isotopes that can be used for remote unattended heat sources are the fission products strontium-90 in the form of SrF_2 and cesium-137 as CsCl. When the use of oil-fired power unit is not possible because of problems in fuel delivery or operability, an isotopic source is very practical, in spite of the high cost. If the two isotopes were extracted by fuel reprocessing in order to reduce the heat and radiation in radioactive waste, many applications would surely materialize.

Success with power sources for space applications prompted a program to develop a nuclear-powered artificial heart. The basic components of the system were (a) a 32 W Pu-238 heat source; (b) a Stirling close- cycle piston engine as thermal converter, using argon as working fluid; (c) a mechanical blood pump; and (d) artificial plastic ventricles. Power up to 3 W is available to circulate blood. The program has been suspended, one would hope only temporarily, since heart disease is the No. 1 killer throughout the world. A nuclear-powered artificial heart that was small, compact, and truly portable might dispel some of the opposition to the use of bulky mechanical artificial hearts, which immobilize the patient and have turned out to be less successful in saving lives than heart transplants.

20.4 Future Nuclear Space Applications

The extent to which nuclear processes are used in space depends on the degree of commitment to a space program. Over the years. U.S. enthusiasm for space programs has varied greatly. The Russian Sputnik of 1957 prompted a flurry of activity; President Kennedy's proposal to put a man on the Moon gave the space effort new impetus. Public support has waned as launches became more routine and new national social problems gained prominence. The Challenger tragedy of 1986 resulted in a loss of confidence in NASA and was a setback to plans for new missions.

In 1989, President Bush announced a new program called Space Exploration Initiative (SEI), involving return to the Moon and establishing a

base there, then to make a manned trip to the planet Mars. A report by the Synthesis Group (see References) discussed justification and strategies. One nuclear aspect of the project was the possibility of mining helium-3 from the surface of the Moon for use in fusion reactors, as discussed in Section 14.5. The proposed SEI program was not accepted by Congress, and more modest NASA activities involving unmanned spacecraft such as Mars Pathfinder took its place. The exploration of the surface of Mars by the remotely-controlled Sojourner minirover was viewed on television by millions of people.

A manned mission to Mars in the year 2014 remains on NASA's long-term agenda, as expressed in its strategic enterprise Human Exploration and Development of Space (HEDS). Continuing studies of feasibility are made by the Exploration Office. The Reference Mission involves the use of two 80 metric ton chemical rockets to put equipment and personnel into low Earth orbit. For the trips from there to the orbit of Mars, called the Trans-Mars Injection (TMI), a nuclear rocket of the NERVA type (see Section 20.2) is required. This will permit a quick transit of around 160 days, allowing some 550 days for exploration, until the planets are in the correct position for return, which takes another 160 days. When the vehicle reaches full speed after about 35 minutes of burn, the engine can be shut down, and the spacecraft will coast the rest of the way. One trip would carry cargo including a rover for exploration, a nuclear reactor of the SP-100 type for making chemicals on the Mars surface, and a lightweight inflatable habitat. A piloted mission would be made two years later. For the descent and ascent between Mars orbit and surface, chemical rockets would be needed. Studies of geology and microbiology would be carried out, investigating further the possibility of life forms. The fuel produced on Mars–methane (CH_4) and liquid oxygen–would come from the thin CO_2 atmosphere and the supply of H_2 brought from Earth. Advanced "bimodal" reactors being studied would provide both propulsion and electric power, and be used to transport both to and from Mars. NASA has provided a web site on travel to Mars and enthusiasts have formed the Mars Society to promote the idea (see References).

Computer Exercise 20.B describes two simple BASIC programs that simulate planetary motion.

The nuclear thermal rocket sketched in Fig. 20.4 is a relatively simple device. Hydrogen propellant is stored in a tank as a liquid. The reason that space travel by nuclear rocket is advantageous can be seen from the mechanics of propulsion. The basic rocket equation relating spacecraft velocity u, fuel exhaust velocity u_f, and the masses of the full and empty rocket m_0 and m, is

$$u = u_f \log_e (m_0 / m)$$

or the inverse relation

$$m / m_0 = \exp\left(-u / u_f\right),$$

with the mass of vehicle plus payload being m_0 - m. The burning products of a chemical system are relatively heavy molecules, whereas a nuclear reactor can heat light hydrogen gas. Thus for a given temperature, u_f is much larger for nuclear and m is closer to m_0, i.e., less fuel is needed.

To escape from the earth or from an orbit around the earth requires work to be done on the spacecraft against the force of gravity. The escape velocity u_e for vertical flight is

$$u_e = \sqrt{2 g_0 r_E}$$

where g_0 is the acceleration of gravity at the earth's surface, 32.174 ft/s^2 or 9.80665 m/s^2, and r_E is the radius of the earth, about 3959 miles or 6371 km. Inserting numbers we find the escape velocity to be around 36,700 ft/s, 25,000 mi/h, or 11.2 km/s.

Calculations of trajectory can be made with the program ORBIT1, described in Computer Exercise 20.A.

The Challenger accident in 1986 resulted in increased attention to safety. It also raised the question as to the desirability of using robots for missions instead of human beings. The benefit is protection of people from harm; the disadvantage is loss of capability to cope with unusual situations. Among the hazards experienced by astronauts are high levels of cosmic radiation outside the earth's atmosphere, possible impacts of small meteorites on the spacecraft, debilitating effects of long weightlessness, and in the case of a nuclear-powered vehicle, radiation from the reactor. To avoid the possibility of contamination of the atmosphere with fission products in the event a mission is aborted, it is planned to start the reactor only when it is safely in orbit. For power supplies using radioisotopes, encapsulation of the

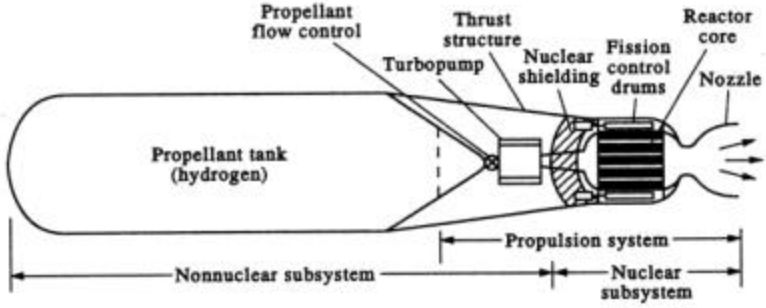


FIG. 20.4 Nuclear-thermal rocket system. Hydrogen stored in liquid form is heated in the solid core and expelled as propellant. (Courtesy Gary Bennett).

Pu-238 with iridium and enclosing the system with graphite fiber reduces the possibility of release of radioactivity. For space missions, risk analyses analogous to those for power reactors are carried out.

Some time in the distant future, electric propulsion may be used. Charged particles are discharged backwards to give a forward thrust. Its virtue is the low mass of propellant that is needed, to permit a larger payload or a shorter travel time. There are several possible technologies: (a) electrothermal, including arcjets and resistojets (in which a propellant is heated electrically), (b) electrostatic, using an ion accelerator, or (c) electromagnetic, such as a coaxial magnetic plasma device. The distinction between electric propulsion and thermal propulsion is in the ratio of thrust and flow rate of propellant, which is the specific impulse, I_{sp}. For example, the shuttle launcher has a high thrust but also a high flow rate, and its I_{sp} is about 450 s. Electric propulsion has a low thrust but a very low flow rate, giving an I_{sp} of some 4000 s.

Research on the Hall Thruster, an ion engine, is in progress at Princeton Plasma Physics Laboratory. Electrons are injected to neutralize space charge and permit heavy ion flow to provide thrust (see References).

Looking into the very distant future, some scientists contemplate the "terraforming" of Mars by the introduction of chemicals that change the atmosphere, and ultimately permit the normal existence of lifeforms. Finally, the vision is always present of manned interstellar travel, paving the way for colonization of planets outside our solar system. The discovery of a number of stars with planets has given encouragement to that idea.

What the future of nuclear applications in space will be depends on the accomplishments and aspirations of mankind in space. The urge to investigate and understand is a strong and natural aspect of the human psyche, and some say it is desirable or necessary to plan for interplanetary colonization. Supporters of space exploration cite its many spinoff benefits. Others remind us that there are many serious problems on earth that need attention and money. How to balance these views remains an issue to be resolved by the political process.

20.5 Summary

Nuclear reactors serve as the power source for the propulsion of submarines and aircraft carriers. Tests of reactors for aircraft and for rockets have been made and reactors are being considered for future space missions. Thermoelectric generators using plutonium-238 provided electric power for lunar exploration in the Apollo program and for interplanetary travel of the spacecrafts Voyager, Galileo, Ulysses, and Cassini.

20.6 Exercises

20.1. (a) Verify that plutonium-238, half-life 87.7 years, α -particle energy 5.5 MeV, yields an activity of 17 Ci/g and a specific power of 0.57 W/g. (b) How much plutonium would be needed for a 200 microwatt heart pacemaker?

20.2. Noting that the force of gravity varies inversely with r^2 and that centrifugal acceleration balances gravitational attraction for an object in orbit, (a) Show that the velocity of a satellite at height h above the earth is

$$u_S = r_E \sqrt{g_0 / (r_E + h)}$$

where g_0 is the acceleration of gravity at the surface of the earth, of radius r_E. (b) Calculate the velocity of a shuttle in orbit at 100 miles above the earth. (c) Derive a formula and calculate h in miles and kilometers for a geosynchronous (24 h) communications satellite.

20.3. If the exhaust velocity of rocket propellant is 11,000 ft/s (3.3528 km/s), what percent of the initial mass must be fuel for vertical escape from the earth?

Computer Exercises

20.A. The initial velocity of a rocket ship determines whether it falls back to earth, goes into orbit about the earth, or escapes into outer space. The BASIC program ORBIT1 calculates the position of a spacecraft and its distance from the center of the earth for various input values of the starting point and velocity.

(a) Try 100 miles and 290 miles per minute.

(b) Explore various starting points and velocities. Comment on the results.

20.B. (a) To view the motions of Earth and Mars about the Sun, run the BASIC program PLANETS.

(b) To see numerical features of the relative motion of the planets over the years, run the BASIC program PLANETS1. Verify that the phase differences are 0° and 180° when the planets are in conjunction and in opposition, respectively. Find out how many years it takes to return to the initial phase difference of 44.3°.

20.C. A trip to Mars would probably be made in a spacecraft assembled in orbit around the earth at altitude say 100 miles (160.9 km). Find its initial speed using the formula for u_s in Ex. 20.2. What is its period, as the time for one revolution? Using computer program ALBERT from Chapter 1, find the fractional increase of mass of the ship (and the astronauts) at that speed. Recall that the radius of the earth is 6378 km.

20.7 References for Chapter 20

Richard G. Hewlett and Francis Duncan, *Nuclear Navy 1946-1962*, University of Chicago Press, Chicago, IL, 1974.

Commander William R. Anderson, U.S.N., and Clay Blair, Jr., *Nautilus-90-North*, World Publishing Co., Cleveland, OH, 1959. An account by the chief officer of the nuclear submarine *Nautilus* of the trip to the North Pole.

Herbert J. Gimpel, *The United States Nuclear Navy*, Franklin Watts, Inc., New York, 1965. History of the Polaris submarine, with many photographs.

Nautilus Museum
http://www.ussnautilus.org
History, tour, and links.

U.S. Navy Online Home Page
http://www.navy.mil
Select Ships or Fact File for information on submarines and aircraft carriers.

John W. Simpson, *Nuclear Power from Underseas to Outer Space*, American Nuclear Society, La Grange Park, IL, 1994. History of the development of the nuclear submarine *Nautilus*, the first commercial nuclear power plant at Shippingport, and the nuclear thermal rocket engine, NERVA.

Theodore Rockwell, *The Rickover Effect: How One Man Made a Difference*, Naval Institute Press, Annapolis, 1992. Describes the key role Admiral Rickover had in the U.S. Navy's nuclear submarine program and the first nuclear power plant.

Adams Atomic Insights
http://ans.neep.wisc.edu/~ans/point_source/AEI/AEI_home.html
Select Topical Index and articles on nuclear ships (including N.S. Savannah), and nuclear batteries.

Voyage to the North Pole on a Nuclear Icebreaker
http://www.stanfordalumni.org/jg/mig/travel_vacation/travel_study/np/northpole.html
Select *Sovetski Soyuz.*

Japanese Nuclear Ship R&D
http://www.jaeri.go.jp/english/index.cgi
Select Research Activities, Jaeri Annual Report 1998, Section 8.3.

Gary L. Bennett, "Historical Overview of the US Use of Space Nuclear Power," *Space Power* Vol. 8, No. 3, 1989, p. 259.

Nuclear Power in Space
http://www.nuc.umr.edu/Brochures/SpacePower.html
http://www.ne.doe.gov; select Public Information/Documents and download pdf report.

John W. Lawrence, "Nuclear Power Sources in Space: A Historical Review," *Nuclear News*, November 1991, p. 85.

Mohamed S. El-Genk, Editor, *A Critical Review of Space Nuclear Power and Propulsion, 1984-1993*, AIP Press, New York, 1994. Includes papers on radioisotope generators and nuclear thermal propulsion.

Joseph A. Angelo, Jr. and David Buden, *Space Nuclear Power*, Orbit Book Co., Malabar, FL, 1985.
A definitive textbook.

Richard P. Laeser, William I. McLaughlin, and Donna M. Wolff, "Engineering Voyager 2's Encounter with Uranus," *Scientific American*, November 1986, p. 36. Discusses the power problem due to decay of Pu-238 in RTGs.

Ellis D. Miner, "Voyager 2's Encounter with the Gas Giants," *Physics Today*, July 1990, p. 40.

Radioisotope Power Systems
http://www.ne.doe.gov/space/space-history.html
History and description of RTG.

The Galileo Home Page
http://www.jpl.nasa.gov/galileo
Photos and information about the spacecraft.

Radioisotope Thermoelectric Generators (RTG)
http://www.jpl.nasa.gov/galileo/messenger/oldmess/RTGs.html
Description of power units in the spacecraft Galileo.

Cassini
http://www2.jpl.nasa.gov/files/misc/cassini_press_kit.txt
Voluminous details on the spacecraft and voyage.

Rover Sojourner to Mars
http://nkma.ksc.nasa.gov/mars/rover/descrip.html
Data on construction and deployment.

America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative, Arlington, VA, 1991. An illustrated description of the proposed goals and plans for the space trips to the Moon and Mars. Thanks to David Bartine and William Sides for the copy.

Human Exploration of Mars
The Reference Mission of the Mars Exploration Study Team
http://www.spaceref.com/mars/human.html
The Whole Mars Catalog. Download reports.

The Mars Society
http://www.marssociety.org
Activities, news, publications, and conventions.

Nuclear Thermal Propulsion (Federation of American Scientists)
http://www.fas.org/nuke/space/index.html
Select History; Strategic Defense Initiative; Space Exploration Initiative; TIMBERWIND (particle bed reactor).

Hall Thruster research (Princeton Plasma Physics Laboratory)
http://www.pppl.gov
Select Publications/PPPL Hotline/August 27, 1999. Download pdf file.

21

Radiation Protection

PROTECTION OF biological entities from hazard of radiation exposure is a fundamental requirement in the application of nuclear energy. Safety is provided by the use of one or more general methods that involve control of the source of radiation or its ability to affect living organisms. We shall identify these methods and describe the role of calculations in the field of radiation protection. Thanks are due Dr. James E Watson, Jr. for his excellent suggestions on this chapter.

21.1 Protective Measures

Radiation and radioactive materials are the link between a device or process as a source, and the living being to be protected from hazard. We can try to eliminate the source, or remove the individual, or insert some barrier between the two. Several means are thus available to help assure safety.

The first is to avoid the generation of radiation or isotopes that emit radiation. For example, the production of undesirable emitters from reactor operation can be minimized by the control of impurities in materials of construction and in the cooling agent. The second is to be sure that any radioactive substances are kept within containers or multiple barriers to prevent dispersal. Isotope sources and waste products are frequently sealed within one or more independent layers of metal or other impermeable substance, while nuclear reactors and chemical processing equipment are housed within leak-tight buildings. The third is to provide layers of shielding material between the source of radiation and the individual and to select favorable characteristics of geological media in which radioactive wastes are buried. The fourth is to restrict access to the region where the radiation level is hazardous, and take advantage of the reduction of intensity with distance. The fifth is to dilute a radioactive substance with very large volumes of air or water on release, to lower the concentration of harmful material. The sixth is to limit the time that a person remains within a radiation zone, to reduce the dose received. We thus see that radioactive materials may be treated in several different ways: *retention*, *isolation*, and *dispersal*; while exposure to radiation can be avoided by methods involving *distance*, *shielding*, and *time*.

The analysis of radiation hazard and protection and the establishment of safe practices is part of the function of the science of radiological protection or health physics. Every user of radiation must follow accepted procedures, while health physicists provide specialized technical advice and monitor the user's methods. In the planning of research involving radiation or in the design and operation of a process, calculations must be made that relate the radiation source to the biological entity, using exposure limits provided by regulatory bodies. Included in the evaluation are necessary protective measures for known sources, or limits that must be imposed on the radiation source, the rate of release of radioactive substances, or the concentration of radioisotopes in air, water, and other materials.

The detailed calculations of radiological protection are very involved for several reasons. There is a great variety of situations to consider, including reactor operations and uses of isotopes. Many scientific and engineering disciplines are needed–physics, chemistry, biology, geology, meteorology, and several engineering fields. Increased utilization of computers favors the development of more sophisticated calculation methods, while providing increasing convenience. The collection of new experimental data on the interaction of radiation and matter and the relationship of dose and effect results in evolving recommendations and regulations. Finally, the enhanced awareness of radiation and concern for safety on the part of the public have prompted increased conservatism, which entails refinement in methods and a requirement for fuller justification of methods and results.

In the operation of nuclear power plants and uses of radioisotopes adherence to government regulations is mandatory, in order to maintain a license. The principal document of the U.S. Nuclear Regulatory Commission (NRC) is *Code of Federal Regulations:10 Energy* (see References). Part 20 "Standards for Protection Against Radiation," has an abbreviated designation 10CFR20.

The establishment of regulations is a slow process, starting with the study of research information by advisory bodies such as ICRP and NCRP, recommendations for dose limits and protection policies, review by the regulatory body with input from the public, institutions, and industry, with final issuance of mandatory requirements, along with guidance documents. As a consequence, the limits and methodology for different situations may be inconsistent, but fundamentally safe. A case in point is the older use of a "critical organ" and maximum permissible concentrations of radionuclides, and the newer use of "committed effective dose equivalent" referring to the summation of all effects on the body. The old and the new are contrasted in the Nuclear Regulatory Commission's discussion of regulation 10CFR20 in the *Federal Register* of January 9, 1986. We shall present examples of both

methods for two reasons: (a) to help the reader to make use of all pertinent literature of radiological protection, and (b) to illustrate the trend toward greater precision and realism in radiation protection.

We now discuss the relationship of dose to flux, the effect of distance and shielding materials, internal exposure, environmental assessment, and dose limits for workers and the public.

21.2 Calculation of Dose

We now consider some simple idealized situations to help the reader understand concepts without becoming involved in intricate calculations. The estimation of radiation dose or dose rate is central to radiation protection. The dose is an energy absorbed per unit weight, as discussed in Section 16.2. It depends on the type, energy, and intensity of the radiation, as well as on the physical features of the target. Let us imagine a situation in which the radiation field consists of a stream of gamma rays of a single energy. The beam of photons might be coming from a piece of radioactive equipment in a nuclear plant. The stream passes through a substance such as tissue with negligible attenuation. We use the principles of Chapter 4 to calculate the energy deposition. Flux and current are the same for this beam, i.e., j and f are both equal to nu. With a flux f cm^{-2}-s^{-1}, and cross section S cm^{-1}, the reaction rate is fS cm^{-3}-s^{-1}. If the gamma ray energy is E joules, then the energy deposition rate per unit volume is fSE J cm^{-3}-s^{-1}. If the target density is r g-cm^{-3}, the dose in joules per gram with exposure for a time t seconds is

$$H = fSEt/r..$$

This relationship can be used to calculate a dose for given conditions or to find limits on flux or on time.

For example, let us find the gamma ray flux that yields an external dose of 0.1 rem in 1 y, with continuous exposure. This is the dose limit to members of the public according to 10CFR20 (Section 16.2). Suppose that the gamma rays have an energy of 1 MeV, and that the cross section for energy absorption with soft tissue of density 1.0 g/cm^3 is 0.0308 cm^{-1}. With a quality factor of 1 for this radiation, the numerical values of the dose and the dose equivalent are the same, so

$$H = (0.1 \text{ rad})\ (1 \times 10^{-5} \text{ J/g-rad}) = 1 \times 10^{-6} \text{ J/g}.$$

Also E = 1 MeV = 1.60×10^{-13} J. Solving for the flux,

$$f = \frac{Hr}{SEt} = \frac{(1.0 \times 10^{-6}\,\text{J/g})(1\,\text{g/cm}^3)}{(0.0308\,\text{cm}^{-1})(1.60 \times 10^{-13}\,\text{J})(3.16 \times 10^{7}\,\text{s})}$$

or

$$f = 6.42 \text{ cm}^{-2} \text{ s}^{-1}.$$

This value of the gamma ray flux may be scaled up or down if another dose limit is specified. The fluxes of various particles corresponding to 0.1 rem/y are shown in Table 21.1.

TABLE 21.1
Radiation Fluxes (0.1 rem/y)

Radiation type	Flux (cm^{-2}-s^{-1})
X- or gamma rays	6.4
Beta particles	0.10
Thermal neutrons	3.1
Fast neutrons	0.085
Alpha particles	10^{-5}

Another situation is the exposure of a person to air containing a radioactive contaminant, for example the noble gas krypton-85, half-life 10.73 y, an emitter of beta particles of average energy 0.251 MeV. Let us derive and apply a formula for the case of continuous exposure during working hours. We wish to relate dose H in rems to activity A in μCi, with an exposure time of t seconds. A rough estimate comes from a simple assumption–that the person is immersed in a large radioactive cloud, and that the energy absorption in air, E_a, is the same as in the human body, and the same as that released by decay of the radionuclide, E_r. Write expressions for each of these,

$$E_a = H(\text{rems})(1 \text{ rad/rem})(10^{-5} \text{ J/g-rad}) (1.293 \times 10^{-3} \text{ g/cm}^3)$$

$$E_r = A(\mu\text{Ci}) (3.7 \times 10^4 \text{ dis/sec-}\mu\text{Ci}) (E \text{ MeV})(1.60 \times 10^{-13} \text{ J/MeV}) (t \text{ s}).$$

Equate these and solve for the dose, but reducing the figure by a factor of 2 if the person is on the ground, and the cloud occupies only half of space. The result is

$$H = 0.229 \, AEt.$$

Assume continuous exposure for 40 h/week, 50 weeks/y, 3600 s/h, so that $t = 7.2 \times 10^6$ s. Insert E =0.251 MeV and H = 5 rems, the annual dose limit for plant workers. Solve for the activity

$$A = 5/((0.229)(0.251)(7.2 \times 10^6)$$

$$= 1.2 \times 10^{-5} \text{ μCi.}$$

This agrees fairly well with the figure of 1×10^{-5} listed in the 1993 edition of the old NRC 10CFR20. We shall see in Section 21.7 that the latest method yields a larger dose limit.

21.3 Effects of Distance and Shielding

For protection, advantage can be taken of the fact that radiation intensities decrease with distance from the source, varying as the *inverse square of the distance*. Let us illustrate by an idealized case of a small

source, regarded as a mathematical point, emitting S particles per second, the source "strength." As in Fig. 21.1, let the rate of flow through each unit of area of a sphere of radius R about the point be labeled f (cm^{-2} - s^{-1}). The flow through the whole sphere surface of area $4\pi R^2$ is then $f\ 4\pi R^2$, and if there is no intervening material, it can be equated to the source strength S. Then

$$f = \frac{S}{4\pi R^2}\ .$$

This relation expresses the inverse square spreading effect. If we have a surface covered with radioactive material or an object that emits radiation throughout its volume, the flux at a point of measurement can be found by addition of elementary contributions.

Let us consider the neutron radiation at a large distance from an unreflected and unshielded reactor operating at a power level of 1 MW. Since 1 W gives 3.3×10^{10} fissions per second (Section 6.4) and the number of neutrons per fission is 2.42 (Section 6.3), the reactor produces 8.0×10^{16} neutrons per second. Suppose that 20% of these escape the core as fast neutrons, so that S is 1.6×10^{16} s^{-1}. Apply the inverse square relation, neglecting attenuation in air, an assumption that would only be correct if the reactor were in a spacecraft. Let us find the closest distance of approach to the reactor surface to keep the dose below 100 mrems/y, as in Table 21.1. The limiting fast flux is 0.085 cm^{-2}-s^{-1}. Solving the inverse-square formula, we obtain

$$R = \sqrt{S / (4\pi f)} = \sqrt{(1.6 \times 10^{16}) / (4\pi 0.085)}$$
$$= 1.22 \times 10^{8} \text{ cm}.$$

This is a surprisingly large distance, about 760 miles. If the same reactor were on the earth, neutron attenuation in air would reduce this figure greatly, but the necessity for shielding by solid or liquid materials is clearly revealed by this calculation.

As another example, let us find how much radiation is received at a distance of 1 mile from a nuclear power plant, if the dose rate at the plant boundary, 1/4-mile radius, is 5 mrems/y. Neglecting attenuation in air, the inverse-square reduction factor is 1/16 giving 0.31 mrems/y. Attenuation would reduce the dose to a negligible value.

The evaluation of necessary protective shielding from radiation makes use of the basic concepts and facts of radiation interaction with matter described in Chapters 4 and 5. Let us consider the particles with which we must deal. Since charged particles–electrons, alpha particles, protons, etc.–have a very short range in matter, attention needs to be given only to the penetrating radiation–gamma rays (or X-rays) and neutrons. The

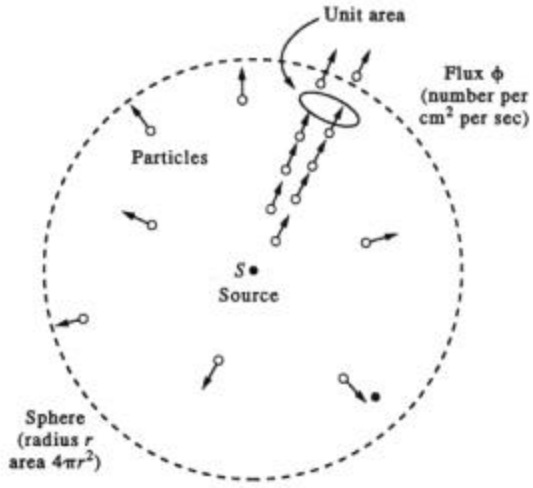


FIG. 21.1 Inverse square spreading of radiation.

attenuation factor with distance of penetration for photons and neutrons may be expressed in exponential form $\exp(-Sr)$ where r is the distance from source to observer and S is an appropriate macroscopic cross section. In shielding analysis, this is called the linear attenuation coefficient, m, with units cm^{-1}. Now S or m depends on the number of target atoms, and through the microscopic cross section s also depends on the type of radiation, its energy, and the chemical and nuclear properties of the target.

For fast neutron shielding, a light element is preferred because of the large neutron energy loss per collision. Thus hydrogenous materials such as water, concrete, or earth are effective shields. The objective is to slow neutrons within a small distance from their origin and to allow them to be absorbed at thermal energy. Thermal neutrons are readily captured by many materials, but boron is preferred because accompanying gamma rays are very weak.

Let us compute the effect of a water shield on the fast neutrons from the example reactor used earlier. The macroscopic cross section appearing in the exponential formula $\exp(-Sr)$ is now called a "removal cross section," since many fast neutrons are removed from the high-energy region by one collision with hydrogen, and eventually are absorbed as thermal neutrons. Its value for fission neutrons in water is around 0.10 cm^{-1}. A shield of thickness 2.5 m = 250 cm would provide an attenuation factor of $\exp(-25) = 10^{-10.9} = 1.39 \times 10^{-11}$. The inverse-square reduction with distance is

$$\frac{1}{4\pi R^2} = \frac{1}{4\pi(250)^2} = 1.27 \times 10^{-6}.$$

The combined reduction factor is 1.77×10^{-17}; and with a source of 1.6×10^{16} neutrons/s, the flux is down to 0.28 neutrons/cm^2-s, which is somewhat

higher than the safe level of 0.085 as in Table 21.1. The addition of a few centimeters of water shield would provide adequate protection, for steady reactor operation at least. Computer Exercise 21.B describes a program NEUTSHLD that finds fast flux from a fission source as a point or a plane.

For gamma ray shielding, in which the main interaction takes place with atomic electrons, a substance of high atomic number is desired. Compton scattering varies as Z, pair production as Z^2, and the photoelectric effect as Z^5. Elements such as iron and lead are particularly useful for gamma shielding. The amount of attenuation depends on the material of the shield, its thickness, and the photon energy. The literature gives values of the mass attenuation coefficient μ/ρ, which is the ratio of the linear attenuation coefficient μ (macroscopic cross section Σ) and the material density ρ, thus it has units cm^2/g. Typical values for a few elements at different energies are shown in Table 21.2. For 1 MeV gammas in iron, for example, density 7.86 g/cm^3, we calculate $\Sigma = (0.0596)(7.86)=0.468$ cm^{-1}. In contrast, for water H_20, molecular weight 2(1.008) + 16.00 = 18.016, the average value of μ using numbers from Table 21.2 with weight fractions is

$$(0.112)\ (0.126) + (0.888)\ (0.0636) = 0.0706\ cm^{-1}.$$

This is also the value of Σ since $\rho = 1$. Thus to achieve the same reduction in gamma flux in iron as in water, the thickness need be only 15% as much.

TABLE 21.2
Mass Attenuation Coefficients (cm^2/g)
Reference: NUREG/CR-5740, 1991.

Energy (MeV)	H	O	Al	Fe	Pb	U
0.01	0.385	5.76	2.58	169.6	125.7	173.7
0.1	0.294	0.151	0.161	0.342	5.35	1.72
1	0.126	0.0636	0.0613	0.0596	0.0684	0.0757
2	0.0876	0.0445	0.0432	0.0425	0.0454	0.0479
10	0.0324	0.0208	0.0231	0.0299	0.0496	0.0519

As an example of gamma shielding calculations, let us find the flux of gamma rays that have made no collision in arriving from a point source. This *uncollided flux* is a product of a source strength S, an exponential attenuation factor $\exp(-\Sigma r)$, and an inverse square spreading factor $1/(4\pi r^2)$, i.e.,

$$\phi_u = S \exp(-\Sigma r)/ (4\pi r^2).$$

For example, find the uncollided flux at 10 cm from a 1 millicurie source ($S = 3.7 \times 10^7$/s). We readily calculate Σ for lead, $\mu/\rho = 0.0684$ cm^2/g, density 11.3 g/cm^3, to be 0.773 cm^{-1}, and $\Sigma r = 7.73$. Inserting numbers,

$$\phi_u = (3.7 \times 10^7)\ (4.39 \times 10^{-4})/(4\pi\ 100) = 12.9\ cm^{-2}\ s^{-1}.$$

This is not the complete flux that strikes a receptor at the point because those scattered by the Compton effect can return to the stream and contribute, as sketched in Fig. 21.2. To account for this "buildup" of radiation a multiplying *buildup factor B* depending on Sr is introduced. Fig. 21.3 shows B for 1 MeV gammas in the most common shielding materials–lead, iron, and water. The total flux is then

$$f = B f_u,$$

which shows that the buildup factor is the ratio of the actual flux to the uncollided flux. It remains to find B from the graph or tables, as 3.04, so that the flux is

$$f = (3.04)\ (12.9) = 39.2\ \text{cm}^{-2}\text{-s}^{-1}.$$

This calculation was rather straightforward, but it is more difficult if the flux is known and one wants to find the distance. Note that r appears in three places in the flux formula, so trial-and-error methods are needed. This tedious process is greatly assisted by use of the computer program EXPOSO, see Computer Exercise 21.A. To bring the exposure down to 5 mrems/y, the value of r is around 15 cm.

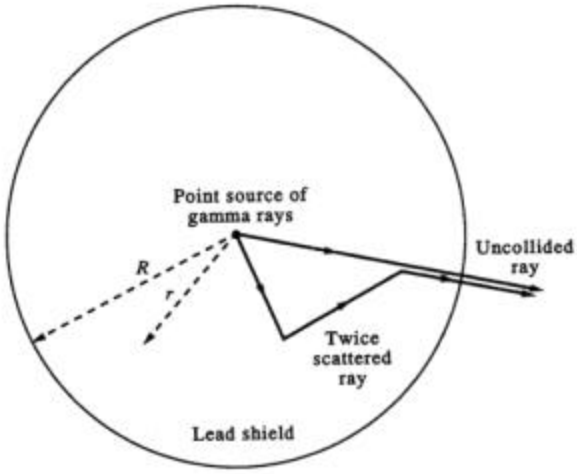


FIG. 21.2 Buildup effect.

Although calculations are performed in the design of equipment or experiments involving radiation, protection is ultimately assured by the measurement of radiation. Portable detectors used as "survey meters" are available commercially. They employ the various detector principles described in Chapter 10, with the Geiger-Müller counter having the greatest general utility. Special detectors are installed to monitor general radiation levels or the amount of radioactivity in effluents.

The possibility of accidental exposure to radiation always exists in a laboratory or plant, in spite of all precautions. In order to have information

immediately, personnel wear dosimeters, which are pen-size self-reading ionization chambers that detect and measure dose. For a more permanent record, film badges are worn. These consist of several photographic films of different sensitivity, with shields to select radiation types. They are developed periodically, and if significant exposure is noted, individuals are relieved of future work in areas with potential radiation hazards for a suitable length of time.

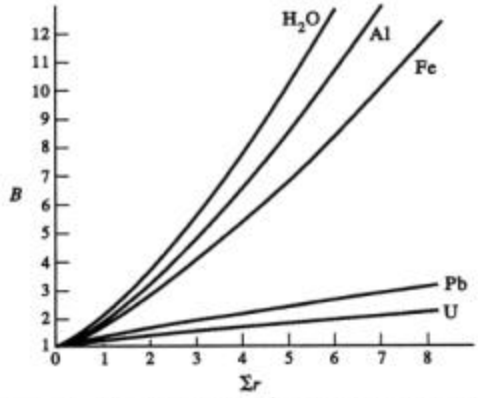


FIG. 21.3 Buildup factors, 1 MeV gammas. *B* for concrete and aluminum are about the same.

Operation, maintenance, and repair of nuclear equipment involves some possible exposure to radiation. Even though it is assumed that any radiation is undesirable, it is necessary on practical grounds to allow a certain amount of exposure. It would be prohibitively expensive to reduce the level to zero. A basis for what action to take is the philosophy expressed in the phrase, "as low as is reasonably achievable," with the acronym ALARA. Planning, design, and operation are done with the ALARA principle in mind. For example, a repair job on contaminated equipment is planned after making careful surveys of radiation levels. The repair is to be carried out by a small crew of well-trained people who will do the work quickly and with minimum contact with the radiation sources. Temporary shielding, special clothing, and respirators are used as needed to minimize doses. Factors considered are: (a) the maximum exposure both to individuals and to the group of workers as a whole, (b) other non-radiological risks, (c) the state of technology, and (d) the economic importance of the operation being performed. If the expected total dosage to the group is more than a fraction of the allowed quarterly dose, a formal ALARA evaluation is made, accounting for both the dollar costs and the dose costs. For a complete discussion by the NRC of the regulatory implications of ALARA, see References.

21.4 Internal Exposure

We now turn to the exposure of internal parts of an organism as a result of having taken in radioactive substances. Special attention will be given to the human body, but similar methods will apply to other animals and even to plants. Radioactive materials can enter the body by drinking, breathing, or eating, and to a certain extent can be absorbed through pores or wounds. The resulting dosage depends on many factors: (a) the amount that enters, which in turn depends on the rate of intake and elapsed time; (b) the chemical nature of the substance, which affects affinity with molecules of particular types of body tissue and which determines the rate of elimination (the term biological half-life is used in this connection, being the time for half of an initial amount to be removed); (c) the particle size, which relates to progress of the material through the body; (d) the radioactive half-life, the energy, and kind of radiation, which determine the activity and energy deposition rate, and the length of time the radiation exposure persists; (e) the radiosensitivity of the tissue, with the gastrointestinal tract, reproductive organs, and bone marrow as the most important.

In the older regulatory framework, limiting concentrations of radionuclides in air or water are calculated using the concept of "critical organ," the one receiving the greatest effective dose from a certain ingested radionuclide. The organ selected thus dominates the hazard to the body, and effects on other organs are neglected. We apply the method to calculate the maximum permissible concentration (MPC) in units $\mu Ci/cm^3$ of iodine-131 in water consumed by plant workers. I-131 has a half-life of 8.0 days and releases 0.23 MeV of beta-gamma energy per decay. The thyroid gland, of mass 20 g, will be taken as the critical organ because of the affinity of the thyroid for iodine. According to ICRP 2 (see References), the allowed annual dose is 30 rads. We first find the activity A that will yield that dose. The method of Section 21.2 is applied again. The energy absorbed is

$$(30 \text{ rads})(10^{-5} \text{ J/g-rad})(20 \text{ g}) = 0.0060 \text{ J}.$$

The energy released is

$$(A\ \mu\text{Ci})(0.23 \text{ MeV/dis})(3.7 \times 10^4 \text{ dis/sec-}\mu\text{Ci}) \times (1.60 \times 10^{-13} \text{ J/MeV})(3.16 \times 10^7 \text{ s}).$$

Equate and solve for $A = 0.139\ \mu$Ci.

Now we find the rates of supply and elimination of I-131 to the organ, assumed to be in balance in steady state. Using the formula of Section 16.1, with biological half-life of 138 days, the effective half-life t_E is 7.56 days and the decay constant l_E is 0.0917 d^{-1}. Thus the elimination rate is proportional to $l_E A = (0.0917)(0.139) = 0.0127$. The consumption rate of water for the standard man is 2200 cm^3 per day, but it is assumed that

workers drink 1.5 times the average during their 8 hour-day, and they work only 50 weeks at 40 h/wk. The rate of intake of contaminated water is thus 755 cm^3/day, and if 30% of the iodine goes to the thyroid, the supply rate of I-131 is (755)(0.3)(MPC). Equate rates and solve for MPC = 5.65×10^{-5} $\mu Ci/cm^3$, which rounds off to 6×10^{-5} $\mu Ci/cm^3$, the figure appearing in the older (1993) version of 10CFR20.

When there is more than one radioisotope present, the allowed concentrations must be limited. The criterion used is

$$\Sigma_i \frac{C_i}{(\mathrm{MPC})_i} \leq 1$$

where i is an index of the isotope. This equation says the sum of quotients of actual concentrations and maximum permissible concentrations must be no greater than 1.

21.5 The Radon Problem

The hazard of breathing air in a poorly ventilated uranium mine has long been recognized. The death rate of miners has historically been higher than that for the general population. The suspected source is the radiation from radioactive isotopes in the decay chain of uranium-238, which by emission of a series of α particles eventually becomes lead-206. The data are clouded by the fact that uranium miners tend to be heavy smokers.

Well down the chain is radium-226, half-life 1599 years. It decays into radon-222, half-life 3.82 days. Although radon-222 is an alpha emitter, its shorter-lived daughters provide most of the dosage. Radon as a noble gas along with its suspended particulate decay products is breathed in with air. Some radioactive particles deposit on the lung surfaces. Decay of the radon and its daughters releases ionizing radiation.

The problem of radon near piles of residue from uranium mining, the mill tailings, has been known, and rules adopted about earth covers to inhibit radon release and about use of the tailings for fill or construction. More recently it has been discovered that a large number of U.S. homes have higher than normal concentrations of radon. Such excessive levels are due to the particular type of rock on which houses are built. Many homes have a concentration of 20 picocuries per liter, in contrast with the average of about 1.5 pCi/l and in excess of the EPA limit of 4 pCi/l. In recent years, EPA has given the subject a great deal of attention.

Application of dose-effect relationships yields estimates of a large number of cancer deaths due to the radon effect, as high as 20,000 per year in the U.S. Such numbers depend on the validity of the linear relationship of dose and effect discussed in Section 16.3. If there were a threshold, the

hazard would be very much smaller.

It was originally believed that the radon concentrations in buildings were high because of conservation measures that reduced ventilation. Investigations revealed that the radon comes out of the ground and is brought into the home by drafts, similar to chimney action. Temperature differences between the air in the house and in the ground beneath cause pressure differences that cause the flow. One might think that covering the earth under a house with plastic would solve the problem, but even slight leaks let the radon through. In areas known to have significant radon levels, it is considered wise for home owners to obtain radon test kits, which are rather inexpensive. If levels well above 4 pCi/l are found, action is recommended. The best solution is to ventilate a crawl space or to provide a basement with a small blower that raises the pressure and prevents radon from entering.

The dimensions of the problem are yet not fully appreciated nationally; continued study is required to determine the proper course of action at the national level.

21.6 Environmental Radiological Assessment†

The Nuclear Regulatory Commission requires that the ALARA principle, discussed in Section 21.3, be applied to the releases of radioactive materials from a nuclear power plant. A deliberate effort is to be made to stay below the specified limits. These refer to any person in the unrestricted area outside the plant. According to 10CFR50, Appendix I, the annual dose resulting from a liquid effluent must be less than 3 millirems to the individual's total body or 10 millirems to any organ. The dose from air release must be less than 10 millirems from gamma rays and 20 millirems from beta particles. To comply with ALARA, it is necessary for the plant to correlate a release of contaminated water or air to the maximum effect on the most sensitive person. An acceptable method to calculate releases and doses is found in NRC's Regulatory Guide 1.109, October 1977 (see References). This "Reg. Guide" discusses the factors to be considered, gives useful formulas, and provides basic data. Older health physics methods are used, but since the dose limit sought is very small, the results are conservative. Among the important factors are:

1. The amounts of each radioisotope in the effluent, with special attention to cesium-137, carbon-14, tritium, iodine, and noble gases.
2. The mode of transfer of material. The medium by which radioactivity is received may be drinking water, aquatic food, shoreline deposits, or

† Appreciation is extended to Mary Birch of Duke Power Company for helpful discussions.

irrigated food. For the latter, pathways include meat and milk. If the medium is air, human beings may be immersed in a contaminated cloud or breathe the air, or material may be deposited on vegetables.

3. The distance between the source of radioactivity and person affected, and how much dilution by spreading takes place.
4. The time of transport, in order to account for decay during flow through air or by streams, or in the case of foodstuffs, during harvesting, processing, and shipment.
5. The age group at risk: infant (0-1 y), child (1-11 y), teenager (11-17 y), and adult (17 and older). Sensitivities to radiation vary considerably with age.
6. The dose factor, which relates dose in millirems to the activity in picocuries. These numbers are tabulated according to isotope, age group, inhalation or ingestion, and organ (bone, liver, total body, thyroid, kidney, lung, and GI tract).

As an example, let us make an approximate calculation of the dose resulting from a release of radioactive water from a nuclear power station into a nearby river. A volume of 1000 gallons contaminated mainly with cesium-137, half-life 30.2 years, is to be released over a period of 24 hours; i.e., at 0.694 gallons per minute. The water discharges into a stream with flow rate 2×10^4 gpm. If the initial cesium-137 concentration is 10^5 pCi/l, the dilution factor of $0.694/(2 \times 10^4) = 3.47 \times 10^{-5}$ reduces the concentration to 3.47 pCi/l. The potential radiation hazard to the population downstream is by two types of ingestion: drinking the water or eating fish that live in the water. The age groups at risk are infants (I), children (C), teenagers (T), and adults (A). Consumption data are as shown in Table 21.3.

TABLE 21.3
Consumption by Age Group (Table E-5, Reg. Guide 1.109)

	I	C	T	A
Water (liters/y)	330	510	510	730
Fish (kg/y)	0	6.9	16	21

The row in the table that refers to fish must be multiplied by a bioaccumulation factor of 2,000 (its units are pCi/liter per pCi/kg). Consider the dose to an adult. To the consumption rate of water of 730 liters/y must be added the effect of eating fish, (2,000) (21) = 42,000, giving a total of 4.27×10^4 liter/y. Now apply a dose conversion in mrems per pCi for cesium-137 as in Table 21.4. Each number should be multiplied by 10^{-5}. For example, the adult total body dose conversion factor is 7.14×10^{-5}.

The product of the factors is

$$(3.47 \text{ pCi/l})(4.27 \times 10^4 \text{ liters/y})\ (7.14 \times 10^{-5} \text{ mrems/pCi})$$

or 10.6 mrems. Since this is well above the limit of 3 mrems, a reduction in

TABLE 21.4
Ingestion Dose Conversion Factors in units of 10^{-5}
(Table E-12, Reg. Guide 1.109)

Group	Bone	Liver	Total body	Kidney	Lungs	GI tract
I	52.2	61.1	4.33	16.4	6.64	0.191
C	32.7	31.3	4.62	10.2	3.67	0.196
T	11.2	14.9	5.19	5.07	1.97	0.212
A	7.97	10.9	7.14	3.70	1.23	0.211

rate of release will be required. Exercise 21.9 illustrates a fuller treatment of such dose calculations.

The general environmental effect of supporting parts of the nuclear fuel cycle must be described in an application for a construction permit for a power reactor. Data acceptable to the Nuclear Regulatory Commission for that purpose appear in the *Code of Federal Regulations* Part 51.51, as "Table of Uranium Fuel Cycle Environmental Data."

21.7 Newer Radiation Standards

A major revision of regulations on radiation exposure was proposed by the Nuclear Regulatory Commission in 1986, published as a Final Rule in 1991, and required for use from January 1, 1994. The newer version of the rule 10CFR20†, intended to provide greater protection for both workers and the public, was based on recommendations of the International Committee on Radiological Protection (ICRP).

The improved regulations are more realistic in terms of hazards, and bring to bear accumulated knowledge about radiation risk. The complicated task of deducing doses is accomplished by computer methods. Whereas the traditional limits on dosage are based on the critical organ, the new 10CFR20 considers the dosage to the whole body from whatever sources of radiation are affecting organs and tissues. Radiations from external and internal sources are summed to obtain the total dose. Also, long-term effects of radionuclides fixed in the body are added to any short-term irradiation effects. The basis for the limits selected are the risk of cancer in the case of most organs and tissues, and the risk of hereditary diseases in offspring in the case of the gonads.

A new concept called "committed effective dose equivalent" is introduced. Recall from Section 16.2 that dose equivalent is the product of absorbed dose and the quality factor. The word "committed" implies taking account of future exposure following ingestion of radioactive material. The time span is taken to be a typical working life of 50 years, e.g., between

† Federal Register, Vol. 56, No. 98, Tuesday, May 21, 1991, p. 23360 ff. The Introduction contains useful reading on the history of dose regulations in the U.S.

ages 20 and 70. Suppose that a certain radionuclide is deposited in an organ of the human body. Over time thereafter the nuclide decays and is eliminated, but provides a dose to that organ. The total dose, labeled H_{50}, is called a committed dose equivalent. It is assumed that the dose is experienced within the year the nuclide is deposited, which will be more nearly true the shorter the effective life in the body.

To calculate H_{50}, suppose that N_0 atoms are deposited in a gram of an organ or tissue. The number left after a time t is

$$N = N_0\,(1/2)^{t/te},$$

where t_e is the effective half-life, as discussed in Section 16.1. The number that have been lost is $N_L = N_0 - N$ and the fraction of these that decay is t_e/t_H, as shown in Ex. 16.6. Thus the number that decay is

$$N_D = N_L(t_e/t_H).$$

As each nucleus decays, it delivers energy E, and thus the committed dose equivalent is

$$H_{50} = N_D E.$$

Let us apply these relations to some radionuclides. The half-life of tritium of 12.3 y is a fairly large fraction of 50 y but the biological half-life is only t_b = 10 days, so t_e is also about 10 days. The fraction that decays within the organ is $10/(4.5 \times 10^3)$ and the fraction lost is almost exactly 1. In contrast, for plutonium-239, $t_H = 2.4 \times 10^4$ y, t_b = 100 y for bone, and t_e = 99.6 y. The fraction left after 50 y is $(1/2)^{50/100} = 0.707$, while the fraction lost is 0.293. Of these, decay accounts for only $99.6/(2.4 \times 10^4) = 0.0042$.

Finally, the word "effective" takes account of the relative risk associated with different organs and tissues, by forming a weighted sum, using weighting factors w_T as listed in Table 21.5. If $(H_{50})_T$ represents the committed dose to organ or tissue T, the effective dose is a sum over T,

$$(H)_{50})_E = S_T\, w_T\, (H_{50})_T.$$

If only one organ were important, as in the case of iodine-131 in the thyroid, the effective dose to the whole body would only be 3% of what it would be if the same dose were delivered throughout the body.

From the factors in Table 21.5, and from the knowledge of chemical properties, half-life, radiations, and organ and tissue data, the NRC has deduced the limits on concentration of specific radionuclides. Dose restrictions are for an annual limit of intake (ALI) by inhalation or ingestion of 5 rems per year (or a 50-year dose of 50 rems) for a plant worker. The derived air concentration (DAC) would give one ALI in a working year through breathing contaminated air. Extensive tables of ALI and DAC for hundreds of radioisotopes are provided in the new 10CFR20. They allow the calculation of exposure to mixtures of isotopes.

TABLE 21.5
Organ and Tissue Radiation Weighting Factors
(reference new 10CFR20)

Organ or tissue	Weighting factor
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder†	0.30

† 0.06 each for five organs.

The two quantities are related by

$$\text{DAC } (\mu\text{Ci/ml}) = \text{ALI } (\mu\text{Ci})/(2.4 \times 10^9)$$

where the numerical factor is a product of four things: 50 wk/y; 40 h/wk; 60 min/h; and 2×10^4 ml (air breathed per minute).

A distinction is made between two types of dose: The first is "stochastic," which is the same as "probabilistic," defined as dosages related to the chance of cancer or hereditary effect, with the number of health effects proportional to the dose. The worker dose limit for stochastic effects is 5 rems/y. The second is "non-stochastic" or "deterministic," which are doses to tissues for which there is a threshold dose for an effect, so that a definite limit can be set on an annual dose, e.g., 50 rems. The skin and the eye lens are examples.

We can revisit the situation of a cloud of radioactive krypton-85 as in Section 21.2. Detailed calculation on all organs lead to the conclusion that only the skin will be significantly affected and thus the non-stochastic limit applies. The ALI and DAC values are correspondingly higher, the latter being 1×10^{-4} μCi/cm^3, ten times the value in the old 10CFR20. For other radionuclides and modes of exposure, the new calculated concentrations can be smaller, the same, or larger than the old.

An example adapted from NRC material will be helpful in understanding the new rule. Suppose that a worker in a nuclear plant receive 1 rem of external radiation and also is exposed over 10 working days to concentrations in air of iodine-131 of 9×10^{-9} μCi/ml and of cesium-137 of 6×10^{-8} μCi/ml (these correspond to the older MPCs). What is the fraction (or multiple) of the annual effective dose equivalent limit? We sum the fractions that each exposure is of the annual limit of 5 rems. The external exposure contributes 1/5 = 0.2. The ALI figures, taking account of the ICRP weighting factors for the various organs for the two isotopes, are 50 μCi for I-131 and 200 μCi for Cs-137. We need to find the actual activities taken in. Using the standard breathing rate of 1.2 m^3/h, in

80 h the air intake is 96 m^3. The activities received are thus 0.86 μCi for I and 5.8 μCi for Cs. The corresponding fractions are 0.86/50 = 0.017 and 5.8/200 = 0.029, giving a total of external and internal fractions of

$$0.2 + 0.017 + 0.029 = 0.246$$

or around 1/4 of the limit. In this particular case, the expected hazard is lower than by the older method.

Other features of the new rule are separate limits on exposures (a) of body extremities–hands, forearms, feet, lower legs; (b) of the lens of the eye; and (c) of an embryo and fetus. The risk to the whole body per rem of dosage is 1 in 6000. For the limit of 5 rems the annual risk is 8×10^{-4}, which is about 8 times acceptable rates in "safe" industries. The figure is to be compared with the lifetime risk of cancer from all causes of about 1 in 6.

Dose limits for individual members of the public (0.1 rem/y) are quite a bit lower than those working with radionuclides (5 rems/y). In calculating concentrations of radionuclides in air released to an unrestricted area, differences in time of exposure, breathing rate, and average age are accounted for by dividing worker DAC values by 300 for inhalation or 219 for submersion. Examples (in μCi/ml) are Cs-137, $(6 \times 10^{-8})/300 = 2 \times 10^{-10}$ and gaseous Xe-133, $(1 \times 10^{-4})/219 = 5 \times 10^{-7}$.

21.8 Summary

Radiation protection of living organisms requires control of sources, barriers between source and living being, or removal of the target entity. Calculations required to evaluate external hazard include: the dose as it depends on flux and energy, material, and time; the inverse square geometric spreading effect; and the exponential attenuation in shielding materials. Internal hazard depends on many physical and biological factors. Maximum permissible concentrations of radioisotopes in air and water can be deduced from the properties of the emitter and the dose limits. Application of the principle of ALARA is designed to reduce exposure to levels that are as low as reasonably achievable. There are many biological pathways that transport radioactive materials. New dose limit rules are based on the total effects of radiation–external and internal–on all parts of the body.

21.9 Exercises

21.1. What is the rate of exposure in mrems/y corresponding to a continuous gamma ray flux of 100 cm^{-2}- s^{-1}? What dose equivalent would be received by a person who worked 40 hours per week throughout the year in such a flux?

21.2. A Co-60 source is to be selected to test radiation detectors for operability. Assuming that the source can be kept at least 1 m from the body, what is the largest strength acceptable (in μCi) to assure an exposure rate of less than 500 mrems/y? (Note that two gammas of

energy 1.17 and 1.33 MeV are emitted.)

21.3. By comparison with the Kr-85 analysis, estimate the MPC in air for tritium, average beta particle energy 0.006 MeV.

21.4. The nuclear reactions resulting from thermal neutron absorption in boron and cadmium are

$$^{10}_{5}\mathrm{B}+^{1}_{0}\mathrm{n}\rightarrow^{7}_{3}\mathrm{Li}+^{4}_{2}\mathrm{He}\,,$$

$$^{113}_{48}\mathrm{Cd}+^{1}_{0}\mathrm{n}\rightarrow^{114}_{48}\mathrm{Cd}+g\left(5\,\mathrm{MeV}\right).$$

Which material would you select for a radiation shield? Explain.

21.5. Find the uncollided gamma ray flux at the surface of a spherical lead shield of radius 12 cm surrounding a very small source of 200 mCi of 1 MeV gammas.

21.6. Concentration limits of some radionuclides in water released to the public, according to 10CFR20 in the old and new versions are listed:

Radionuclide	Concentration limits (μCi/ml)	
	old	new
tritium	3×10^{-3}	1E-3
cobalt-60	3×10^{-5}	3E-6
strontium	3×10^{-7}	5E-7
iodine-131	3×10^{-7}	1E-6
cesium-137	2×10^{-5}	1E-6

Calculate the ratio new/old for each radionuclide.

21.7. Water discharged from a nuclear plant contains in solution traces of strontium-90, cerium-144, and cesium-137. Assuming that the concentrations of each isotope are proportional to their fission yields, find the allowed activities per ml of each. Note the following data:

Isotope	Half-life	Yield	Limit (μCi/ml)†
^{90}Sr	29.1 y	0.0575	5E-7
^{144}Ce	284.6 d	0.0545	8E-6
^{137}Cs	30.2 y	0.0611	1E-6

† According to 10CFR20 (1993 version).

21.8. A 50-year exposure time is assumed in deriving the dose factors listed in Section 21.6. These take account of the radioisotope's physical half-life t_p and also its biological half-life t_b, which is the time it takes the chemical to be eliminated from the body. The effective half-life t_e can be calculated from the formula

$$1/t_e = 1/t_p + 1/t_b.$$

Find t_e for these three cases cited by Eichholz (see References):

Radionuclide	t_p	t_b
Iodine-131	8.04 days	138 days
Cobalt-60	5.27 years	99.5 days
Cesium-137	30.2 years	70 days

If t_p and t_b are greatly different from each other, what can be said about the size of t_e?

21.9. Find the highest organ dose for each of the four age groups for the release of water contaminated with cesium-137 discussed in Section 21.6. Which group had the highest risk? Is the proposed release within regulation 10CFR20 Appendix B?

21.10. The activities of U-238, Ra-226, and Rn-222 in a closed system are approximately equal, in accord with the principle of secular equilibrium. Assuming that the natural uranium content of soil is 10 ppm, calculate the specific activities of the isotopes in microcuries per gram of soil (Table 3.1 gives half-lives needed to calculate).

Computer Exercises

21.A. BASIC program EXPOSO looks up gamma ray attenuation coefficients and buildup factors on data tables and finds the radiation exposure at a distance from a point source.

(a) Run the program and explore its menus.

(b) Verify that the flux at 10 cm from a point millicurie 1 MeV gamma ray source in lead is 39.2/cm^2-s.

(c) Use the program to find the lead distance from a millicurie 1 MeV source that yields 5 mrems/y, to within one millimeter.

(d) Check the figures for a reactor in space (Section 21.3) using the shield option 7 (none).

21.B. A small research reactor core is located near the bottom of a deep pool of water. The water serves as moderator, coolant, and shield. (a) With a power of 10 MW and a fission neutron leakage fraction of 0.3, estimate, using the point source version of the computer program NEUTSHLD, the uncollided flux of fast neutrons at a distance of 20 ft from the core, treated as a point source. (b) Samples to be irradiated are placed near the core, the dimensions of which are 30 cm $\times$ 30 cm $\times$ 60 cm high. Assuming that the neutron source strength per unit area is uniform, calculate, using the plane version of NEUTSHLD, the fast neutron flux at 10 cm from the center of a large face of the core.

21.C. A study is made of leukemia incidence over a 100 km^2 area in the vicinity of a nuclear power plant. Some apparent clustering of cases is observed that might be attributed to proximity or wind direction. Run computer program CLUSTER to see how small samples of completely random statistical data normally are clustered. Then edit line 410 of the program from 100 to 1000 and then to 10,000 to see the population becoming more uniform.

21.D. To improve the uniformity of irradiation of large objects in a water pool, a set of five "point" cobalt-60 sources (average gamma ray energy 1.25 MeV) are arranged in a plane at coordinates in centimeters (0,0), (20,20), (20,-20), (-20, -20), and (-20, 20). Explore the variation of total gamma flux over a parallel plane 10 cm away, using computer program EXPOSO to calculate contributions of each source. Compare with results in a case where all five sources are concentrated near the point (0,0).

21.10 References for Chapter 21

Radiation Information Network
http://www.physics.isu.edu/radinf/index1.html
Numerous links to sources. By Bruce Busby, Idaho State University.

Bernard Schleien, Lester A. Slayback, Jr., and Brian Kent Birky, Editors, *Handbook of Health Physics and Radiological Health*, 3rd Ed., Williams & Wilkins, Baltimore, 1998. A greatly expanded version of a classical document of 1970.

Herman Cember and Herbert Cember, *Introduction to Health Physics*, 3rd Ed., McGraw-Hill, New York, 1996. A thorough and easily understood textbook.

Herman Cember and Thomas E. Johnson, *The Health Physics Solutions Manual*, PS&E Publications, 1999. Recommended by the second author.

Joseph John Bevelacqua, *Basic Health Physics: Problems and Solutions*, John Wiley & Sons, New York, 1999. Helpful in preparing for CHP exam.

Joseph John Bevelacqua, *Contemporary Health Physics: Problems and Solutions*, John Wiley & Sons, New York, 1995.

Steven B. Dowd and Elwin R. Tilson, Eds., *Practical Radiation Protection and Applied Radiobiology*, W. B. Saunders, Philadelphia, 1999. All about radiation, its effects, and protection, from a nuclear medicine viewpoint. An appendix of web sites maintained also at http://www.radscice.com/dowd.html.

J. Kenneth Shultis and Richard E. Faw, *Radiation Shielding*, Prentice-Hall, Upper Saddle River, NJ, 1996. Includes transport theory and Monte Carlo methods.

James Wood, *Computational Methods in Reactor Shielding*, Pergamon Press, Oxford, 1982.

Theodore Rockwell III, *Reactor Shielding Design Manual*, McGraw-Hill, New York, 1956. A classic book on shielding calculations that remains a valuable reference.

Geoffrey G. Eichholz, *Environmental Aspects of Nuclear Power*, Lewis Publishers, Chelsea, MI, 1985.

Richard E. Faw and J. Kenneth Shultis, *Radiological Assessment: Sources and Doses*, American Nuclear Society, La Grange Park, IL, 1999. Fundamentals and extensive data. A reprint with a few changes of a 1991 book published by Prentice-Hall.

John E. Till and H. Robert Meyer, Editors, *Radiological Assessment, A Textbook on Environmental Dose Analysis*, Nuclear Regulatory Commission, NUREG/CR-3332, 1983.

Kenneth L. Miller and William A. Weidner, Editors, *CRC Handbook of Management of Radiation Protection Programs*, CRC Press, Boca Raton, FL, 1986. An assortment of material not found conveniently elsewhere, including radiation lawsuit history, the responsibilities of health physics professionals, information about state radiological protection agencies, and emergency planning. More than half of the book is a copy of regulations of the Department of Transportation.

Radon Exposure of the U.S. Population - Status of the Problem, NCRP Commentary No. 6, National Council of Radiation Protection and Measurements, Bethesda, MD 1991. Notes that data on the effect of radon on the general population are not available, and must be inferred from experience with miners, whose smoking habits confuse the issue. No major initiative is indicated, but a continuing survey is recommended.

International Basic Safety Standards for Protection Against Ionizing Radiation, Safety Series No. 115, International Atomic Energy Agency, Vienna, 1996. Extensive tables of limits.

Code of Federal Regulations, Energy 10, Office of the Federal Register, National Archives and Records Administration, U.S. Government Printing Office, Washington, DC (annual issuance).

Part 20−Standards for Protection against Radiation
http://www.nrc.gov/NRC/CFR/PART020/index.html
Links to each subsection.

NRC Regulatory Guides
http://www.nrc.gov/NRC/RG/index.html
Select Power Reactors from General Index
1.109 Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10CFR Part 50 Appendix I, October 1977 (pdf 2785 KB).

1.111 Methods for Estimation of Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors, July 1977 (pdf 1291 KB).
Select Occupational Health
8.8 Information Relevant to Ensuring that Occupational Radiation Exposures at Nuclear Power Stations Will Be As Low As Reasonably Achievable, June 1978 (pdf 1192 KB).

Committee on the Biological Effects of Ionizing Radiations, National Research Council, *Health Risks of Radon and Other Internally Deposited Alpha-Emitters, BEIR IV*, National Academy Press, Washington DC, 1988. Emphasizes lung cancer and the relationship of smoking and radon.

Committee on Health Effects of Exposure to Radon (BEIR VI), National Research Council, *Health Effects of Exposure to Radon: Time for Reassessment? National Academy Press*, Washington DC, 1994. Conclusion: new information needs to be considered and improved models developed.

Radon Update
http://www.physics.isu.edu/radinf/radon.htm#top
Based on an article by Dr. A. B. Brill in *Journal of Nuclear Medicine*, February 1994, provided by Physics Department, Idaho State University.

Radiation, Science, and Health
http://cnts.wpi.edu/RSH/index.html
Organization criticizes conservatism of standards advisory bodies and government regulators.

NIST Physics Laboratory
http://physics.nist.gov
Select Physical Reference Data, X-ray and Gamma-Ray Data. Figures differ slightly from those in NUREG/CR-5740.

ICRP Publication 2, Recommendations of the International Commission on Radiological Protection, *Health Physics 3*, Pergamon Press, Oxford, 1960.

International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna, 1996. Policies, practices, and extensive dose limit tables.

22

Radioactive Waste Disposal

MATERIALS THAT contain radioactive atoms and that are deemed to be of no value are classed as radioactive wastes. They may be natural substances, such as uranium ore residues with isotopes of radium and radon, or products of neutron capture, with isotopes such as those of cobalt and plutonium, or fission products, with a great variety of radionuclides. Wastes may be generated as by-products of national defense efforts, of the operation of commercial electric power plants and their supporting fuel cycle, or of research and medical application at various institutions. The radioactive components of the waste may emit alpha particles, beta particles, gamma rays, and in some cases neutrons, with half-lives of concern from the standpoint of storage and disposal ranging from several days to thousands of years.

Since it is very difficult to render the radioactive atoms inert, we face the fact that the use of nuclear processes must be accompanied by continuing safe management of materials that are potentially hazardous to workers and the public. The means by which this essential task is accomplished is the subject of this chapter.

22.1 The Nuclear Fuel Cycle

Radioactive wastes are produced throughout the nuclear fuel cycle sketched in Fig. 22.1. This diagram is a flow chart of the processes that start with mining and end with disposal of wastes. Two alternative modes are shown–once-through and recycle.

Uranium ore contains very little of the element uranium, around 0.1 percent by weight. The ore is treated at processing plants known as mills, where mechanical and chemical treatment gives "yellowcake," which is mainly U_3O_8, and large residues called mill tailings. These still have the daughter products of the uranium decay chain, especially radium-226 (1599 years), radon-222 (3.82 days), and some polonium isotopes. Tailings are disposed of in large piles near the mills, with an earth cover to reduce the rate of release of the noble radon gas and thus prevent excessive air contamination. Strictly speaking the tailings are waste, but they are treated separately.

Conversion of U_3O_8 into uranium hexafluoride, UF_6, for use in isotope

enrichment plants produces relatively small amounts of slightly radioactive material. The separation process, which brings the uranium-235 concentration from 0.7 wt% to 3-4%, also has little waste. It does generate large amounts of depleted uranium ("tails") at around 0.3% U-235. Depleted uranium is stored and could be used as fertile material for future breeder reactors. The fuel fabrication operation, involving the conversion of UF_6 to UO_2 and the manufacture of fuel assemblies, yields considerable waste in spite of recycling practices. Since U-235 has a shorter half-life than U-238, the slightly enriched fuel is more radioactive than natural uranium.

FIG. 22.1 Nuclear fuel cycles. The once-through shown on the left is used in the U.S.; the recycle shown on the right is used in other countries.

The operation of reactors gives rise to liquids and solids that contain radioactive materials from two sources. One is activation of metals by neutrons to produce isotopes of iron, cobalt, and nickel. The other is fission products that escape from the fuel tubes or are produced from uranium residue on their surfaces.

Spent fuel, resulting from neutron irradiation in the reactor, contains the highly radioactive fission products and various plutonium isotopes, along with the sizeable residue of uranium that is near natural concentration. As shown on the left side of Fig. 22.1, the fuel will be stored, packaged, and disposed of by burial according to current U.S. practice.

In some other countries the spent fuel is being reprocessed. As sketched in the right side of Fig. 22.1, uranium is returned to the isotope separation facility for re-enrichment and the plutonium is added to the slightly enriched fuel to produce "mixed-oxide" fuel. Only the fission products are subject to disposal.

22.2 Waste Classification

For purposes of management and regulation, classification schemes for radioactive wastes have evolved. The first contrasts defense and non-defense wastes. The original wastes were from the Hanford reactors, used in World War II to produce weapons material. The wastes were stored in moist form in large underground tanks. Over subsequent years part of these defense wastes have been processed for two reasons: (a) to fix the wastes in stable form; and (b) to separate out the two intermediate half-life isotopes, strontium-90 (29.1 y) and cesium-137 (30.2 y), leaving a relatively inert residue. Additional defense wastes were generated by reactor operation over the years for the stockpile of plutonium and tritium for nuclear weapons, and the spent fuel from submarine reactors was reprocessed.

Non-defense wastes include those produced in the commercial nuclear fuel cycle as described above, by industry, and by institutions. Industrial wastes come from manufacturers using isotopes and from pharmaceutical companies. Institutions include universities, hospitals, and research laboratories.

Another way to classify wastes is according to the type of material and the level of radioactivity. The first class is high-level waste (HLW), from reactor operations. These are the fission products that have been separated from other materials in spent fuel by reprocessing. They are characterized by their very high radioactivity; hence the name.

A second category is spent fuel, which really should not be called a waste, because of its residual fissile isotopes. However, in common usage, since spent fuel in the U.S. is to be disposed of in a high-level waste repository, it is often thought of as HLW.

A third category is transuranic wastes, abbreviated TRU, which are wastes that contain plutonium and heavier artificial isotopes. Any material that has an activity due to transuranic materials of as much as 100 nanocuries per gram is classed as TRU. The main source is nuclear

weapons fabrication plants.

Mill tailings, as the residue from processing uranium ore, are a separate category, as noted earlier.

Another important category is low-level waste (LLW), which officially is defined as material that does not fall into any other class. LLW has a small amount of radioactivity in a large volume of inert material, and generally is subject to placement in a near-surface disposal site. The name "low-level waste" is misleading in that some LLW can have a curie content comparable to that of some old high-level waste.

Two other categories are naturally occurring radioactive materials (NORM) such as byproducts of phosphate mining, and accelerator-produced materials (NARM). Both have slight radioactivity.

Still other categories are used for certain purposes, e.g., remedial action wastes, coming from the cleanup of formerly-used facilities of the Department of Energy; mixed wastes, which are those containing both hazardous chemicals and radioactive substances; and "below-regulatory-concern" (BRC) wastes, having trivial amounts of activity.

Some perspective of the nuclear waste problem can be gained from Table 22.1, extracted from Department of Energy data. The table shows that the volume of spent fuel is relatively small compared with that of low-level wastes and especially mill tailings.

TABLE 22.1
Radioactive Waste Inventories
Adapted from DOE/RW-0006 (see References)

Category	Volume (m^3)
Spent fuel	
commercial	13,808
DOE	1,091
High level waste	
commercial	2,000
DOE	345,350
Transuranic waste	
DOE	238,040
Low-level waste	
commercial	1,751,000
DOE	320,760
Uranium mill tailings	118,700,000
Environmental waste	28,000,000
Mixed waste	147,250

22.3 Spent Fuel Storage

The management of spent fuel at a reactor involves a great deal of care in mechanical handling to avoid physical damage to the assemblies and to minimize exposure of personnel to radiation. At the end of a typical

operating period of 1 year for a PWR, the head of the reactor vessel is removed and set aside. The whole space above the vessel is filled with borated water to allow fuel assemblies to be removed while immersed. The radiation levels at the surface of an unshielded assembly are millions of rems per hour. Using movable hoists, the individual assemblies weighing about 600 kg (1320 lb) are extracted from the core and transferred to a water-filled storage pool in an adjacent building. Computer Exercise 22.A shows the arrangement of fuel assemblies in racks of a water storage pool. About a third of the core is removed; fuel remaining in the core is rearranged to achieve the desired power distribution in the next cycle; and fresh fuel assemblies are inserted in the vacant spaces. The water in the 40-ft-deep storage pool serves as shielding and cooling medium to remove the fission product residual heat. We may apply the decay heat formula from Section 19.3 to estimate the energy release and source strength of the fuel. At a time after shutdown of 3 months (7.9×10^6 s) the decay power from all the fuel of a 3000 MWt reactor is

$$P = 3000\ (0.066)\ (7.9 \times 10^6)^{-0.2} = 8.26 \text{ MW}.$$

If we assume that the typical particles released have an energy of 1 MeV, this corresponds to 1.4 billion curies (5.2×10^{19} Bq). To insure integrity of the fuel, the purity of the water in the pool is controlled by filters and demineralizers, and the temperature of the water is maintained by use of coolers.

The storage facilities consist of vertical stainless steel racks that support and separate fuel assemblies to prevent criticality, since the multiplication factor k of one assembly is rather close to 1. When most reactors were designed, it was expected that fuel would be held for radioactive "cooling" for only a few months, after which time the assemblies would be shipped to a reprocessing plant. Capacity was provided for only about two full cores, with the possibility of having to unload all fuel from the reactor for repairs. The abandonment of reprocessing by the U.S. required utilities to store all spent fuel on site, awaiting acceptance of fuel for disposal by the federal government in accord with the Nuclear Waste Policy Act of 1982 (NWPA). Re-racking of the storage pool was the first action taken. Spacing between assemblies was reduced and neutron-absorbing materials were added to inhibit neutron multiplication. For some reactors this was not an adequate solution of the problem of fuel accumulation, and thus alternative storage methods were investigated. There were several choices. The first was to ship spent fuel to a pool of a newer plant in the utility's system. The second was for the plant to add more water basins or for a commercial organization to build basins at another central location. The third was to use storage at government facilities, a limited amount of which was promised in NWPA.

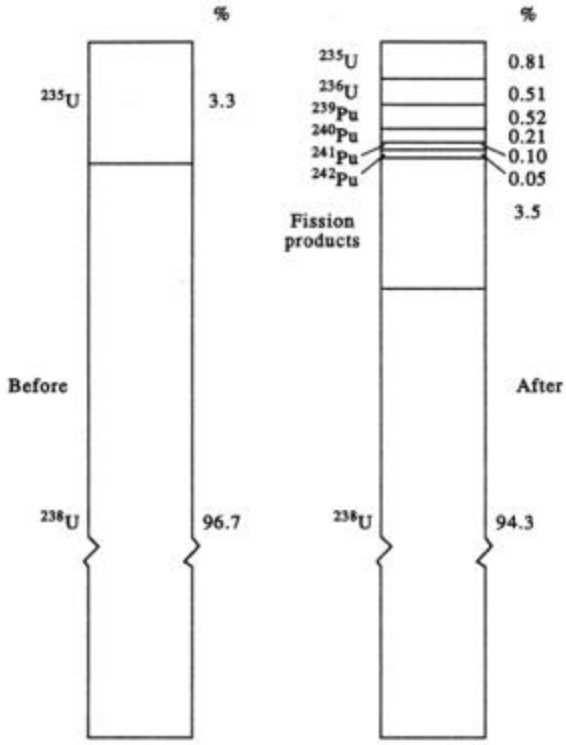


FIG. 22.2 Composition of nuclear fuel before and after irradiation with neutrons in a reactor. (From Raymond L. Murray, *Understanding Radioactive Waste*, 1994, courtesy of Battelle Press, Columbus, OH.)

The fourth was rod consolidation, in which the bundle of fuel rods is collapsed and put in a container, again to go in a pool. A volume reduction of about two can be achieved. A fifth was to store a number of dry assemblies in large casks, sealed to prevent access by water. A variant is the storage of intact assemblies in dry form in a large vault. Dry storage is the favored alternative. An ideal solution would be to use the same container for storage, shipment, and disposal. A combination of methods may instead be adopted as DOE accepts spent fuel.

The amount of material in spent fuel to be disposed of annually can be shown to be surprisingly small. Dimensions in meters of a typical PWR fuel assembly are $0.214 \times 0.214 \times 4.06$, giving a volume of 0.186 m^3. If 60 assemblies are discharged from a typical reactor the annual volume of spent fuel is 11.2 m^3 or 394 cubic feet. For 100 U.S. reactors this would be 39,400 ft^3, which would fill a standard football field (300 ft $\times$ 160 ft) to a depth of less than 10 inches, assuming that the fuel assemblies could be packed closely.

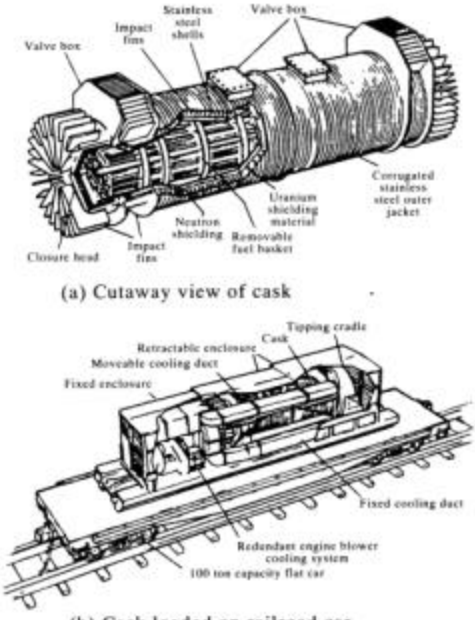
The amount of fission products can be estimated by letting their weight be equal to the weight of fuel fissioned, which is 1.1 g per MWd of thermal

energy. For a reactor operating at 3000 MW this implies 3.3 kg/d or about 1200 kg/y. If the specific gravity is taken to be 10, i.e., 10^4 kg/m^3, the annual volume is 0.12 m^3, corresponding to a cube 50 cm on a side. This figure is the origin of the claim that the wastes from a year's operation of a reactor would fit under an office desk. Even with reprocessing the actual volume would be considerably larger than this.

The detailed composition of a spent fuel assembly is determined by the number of megawatt-days per tonne of exposure it has received. A burnup of 33 MWd/tonne corresponds to a 3-year operation in an average thermal neutron flux of 3×10^{13}/cm^2-s. Figure 22.2 shows the composition of fuel before and after. The fissile material content has only been changed from 3.3% to 1.43%, and the U-238 content is reduced only slightly.

22.4 Transportation

Regulations on radioactive material transportation are provided by the federal Department of Transportation and the Nuclear Regulatory Commission. Container construction, records, and radiation limits are among the specifications. Three principles used are: (a) packaging is to provide protection; (b) the greater the hazard, the stronger the package must be; and (c) design analysis and performance tests assure safety. A classification scheme for containers has been developed to span levels of radioactivity from exempt amounts to that of spent nuclear fuel. For low-level waste coming from processing reactor water, the cask consists of an outer steel cylinder, a lead lining, and an inner sealed container. For spent fuel, protection is required against (a) direct radiation exposure of workers and the public, (b) release of radioactive fluids, (c) excessive heating of internals, and (d) criticality. The shipping cask shown in Fig. 22.3(a) consists of a steel tank of length 5 m (16.5 ft) and diameter 1.5 m (5 ft). When fully loaded with 7 PWR assemblies the cask weighs up to 64,000 kg (70 tons). The casks contain boron tubes to prevent criticality, heavy metal to shield against gamma rays, and water as needed to keep the fuel cool and to provide additional shielding. A portable air-cooling system is attached when the cask is loaded on a railroad car as in Fig. 22.3(b). The cask is designed to withstand normal conditions related to temperature, wetting, vibration, and shocks. In addition, the cask is designed to meet four performance specifications that simulate real conditions in road accidents. The cask must withstand a 30 ft (~10 m) free fall onto an unyielding surface, a 40 in. (~1 m) fall to strike a 6 in. (~15 cm) diameter pin, a 30-min exposure to a fire at temperature 1475°F (~800°C), and complete immersion in water for a period of 8 h. Some extreme tests have been conducted to supplement the design specifications. In one test a trailer rig



(a) Cutaway view of cask

(b) Cask loaded on railroad car

FIG. 22.3 Spent fuel shipping cask. (Courtesy of General Electric Company).

carrying a cask was made to collide with a solid concrete wall at speed 84 mph. Only the cooling fins were damaged; the cask would not have leaked if radioactivity had been present.

Public concern has been expressed about the possibility of accident, severe damage, and a lack of response capability. The agencies responsible for regulation do not assume that accidents can be prevented, but expect all containers to withstand an incident. In addition, efforts have been made to make sure that police and fire departments are familiar with the practice of shipping radioactive materials and with resources available in the form of state radiological offices and emergency response programs, with backup by national laboratories.

22.5 Reprocessing

The physical and chemical treatment of spent nuclear fuel to separate the components–uranium, fission products, and plutonium–is given the name reprocessing. The fuel from the Hanford and Savannah River Plant weapons production reactors and the naval reactors has been reprocessed in the defense program at the federal government national laboratories. Commercial experience with reprocessing in the U.S. has been limited. In the period 1966-1972 Nuclear Fuel Services (NFS) operated a facility at West Valley, NY. Another was built by Allied General Nuclear Service (AGNS) at Barnwell, SC, but it never operated on radioactive material, as a matter of national policy. In order to understand that political decision it is

necessary to review the technical aspects of reprocessing.

Upon receipt of a shipping cask of the type shown in Fig. 22.3, the spent fuel is unloaded and stored for further decay in a water pool. The assemblies are then fed into a mechanical shear that cuts them into pieces about 3 cm long to expose the fuel pellets. The pieces fall into baskets that are immersed in nitric acid to dissolve the uranium dioxide and leave zircaloy "hulls." The aqueous solution from this chop-leach operation then proceeds to a solvent extraction (Purex) process. Visualize an analogous experiment. Add oil to a vessel containing salt water. Shake to mix. When the mixture settles and the liquids separate, some salt has gone with the oil; i.e., it has been extracted from the water. In the Purex process the solvent is the organic compound tributyl phosphate (TBP) diluted with kerosene. Countercurrent flow of the aqueous and organic materials is maintained in a packed column as sketched in Fig. 22.4. Mechanical vibration assists contact.

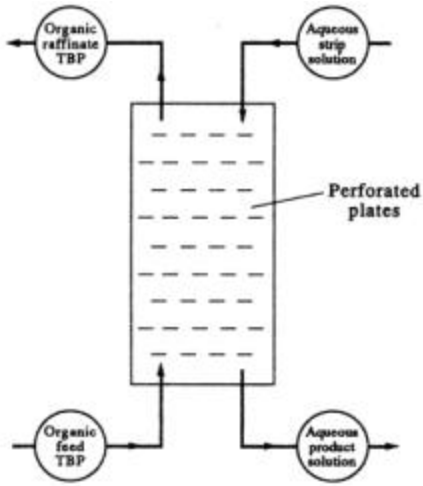


FIG. 22.4 Solvent extraction by the Purex method.

A flow diagram of the separation of components of spent fuel is shown in Fig. 22.5. The amount of neptunium-239, half-life 2.355 days, is dependent on how fresh the spent fuel is. After a month of holding, the isotope will be practically gone. The three nitrate solution streams contain uranium, plutonium, and an array of fission product chemical elements. The uranium has a U-235 content slightly higher than natural uranium. It can either be set aside or re-enriched in an isotope separation process. The plutonium is converted into an oxide that is suitable for combining with uranium oxide to form a mixed oxide (MOX) that can form part or all of the fuel of a reactor. Precautions are taken in the fuel fabrication plant to protect workers from exposure to plutonium.

In the reprocessing operations, special attention is given to certain

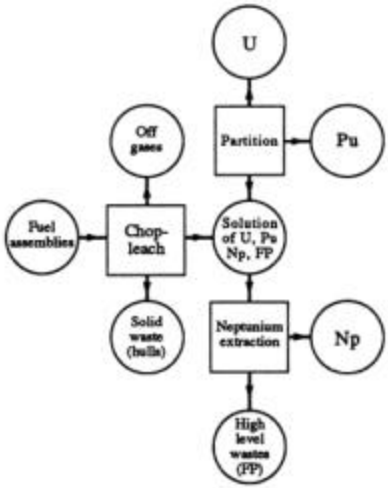


FIG. 22.5 Simplified flow chart of nuclear fuel reprocessing.

radioactive gases. Among them are 8.04-day iodine-131, 10.73-y krypton-85, and 12.32-y tritium, which is the product of the occasional fission into three particles. The iodine concentration is greatly reduced by reasonable holding periods. The long-lived krypton poses a problem because it is a noble gas that resist chemical combination for storage. It may be disposed of in two ways: (a) release to the atmosphere from tall stacks with subsequent dilution, or (b) absorption on porous media such as charcoal maintained at very low temperatures. The hazard of tritium is relatively small, but water containing it behaves as ordinary water.

Reprocessing has merit in several ways other than making uranium and plutonium available for recycling:

(a) The isolation of some of the long-lived transuranic materials (other than plutonium) would permit them to be irradiated with neutrons, achieving additional energy and transmuting them into useful species or innocuous forms for purposes of waste disposal.

(b) There are numerous valuable fission products such as krypton-85, strontium-90, and cesium-137, that have industrial applications or that may be used as sources for food irradiation.

(c) The removal of radionuclides with intermediate half-lives allows canisters of wastes to be placed closer together in the ground because the heat load is lower.

(d) There are several rare elements of economic and strategic national value that can be reclaimed from fission products. Availability from reprocessing could avoid interruption of supply from abroad for political reasons. Examples are rhodium, palladium, and ruthenium.

(e) The volume of wastes to be disposed of would be lower because the

uranium has been extracted.

(f) Even if it were not recycled, the recovered uranium could be saved for future use in breeder reactor blankets.

Several countries abroad–France, the U.K., Germany, Japan, and the former U.S.S.R.–have working reprocessing facilities, and benefit from some of the above virtues.

An important aspect of reprocessing is that the plutonium made available for recycling can be visualized as a nuclear weapons material. Concern about international proliferation of nuclear weapons prompted President Carter in 1977 to issue a ban on reprocessing. It was believed that if the U.S. refrained from reprocessing, it would set an example to other countries. The action had no effect, since the U.S. had made no real sacrifice, having abundant uranium and coal reserves, and countries lacking resources saw full utilization of uranium in their best interests. It was recognized that plutonium from nuclear reactor operation was unsuitable for weapons because of the high content of Pu-240, which emits neutrons in spontaneous fission. Finally, it is possible to achieve weapons capability through the completely different route of isotope separation yielding highly enriched uranium. The ban prevented the AGNS plant from operating. President Reagan lifted the ban in 1981, but industry was wary of attempting to adopt reprocessing because of uncertainty in government policy and lack of evidence that there was a significant immediate economic benefit. There is no indication that commercial reprocessing will be resumed in the U.S.

22.6 High-Level Waste Disposal

The treatment given wastes containing large amounts of fission products depends on the cycle chosen. If the fuel is reprocessed, as described in the previous section, the first step is to immobilize the radioactive residue. One popular method is to mix the moist waste chemicals with pulverized glass similar to Pyrex, heat the mixture in a furnace to molten form, and pour the liquid into metal containers called canisters. The solidified waste form can be stored conveniently, shipped, and disposed of. The glass-waste is expected to resist leaching by water for hundreds of years.

If the fuel is not reprocessed, there are several choices. One is to place intact fuel assemblies in a canister. Another is to consolidate the rods, i.e., bundle them closely together in a container. A molten metal such as lead could be used as a filler if needed. What would be done subsequently with waste canisters has been the subject of a great deal of investigation concerning feasibility, economics, and social-environmental effects. Some of the concepts that have been proposed and studied are:

1. Send nuclear waste packages into space by shuttle and spacecraft. The weight of protection against vaporization in accidental re-entry to the Earth's atmosphere would make costs prohibitive.
2. Place canisters on the Antarctic ice cap, either held in place or allowed to melt their way down to the base rock. Costs and environmental uncertainty rule out this method.
3. Deposit canisters in mile-deep holes in the Earth. The method is impractical with available drilling technology.
4. Drop canisters from a ship, to penetrate the layer of sediment at the bottom of the ocean. Although considered as a backstop, there are evident environmental concerns.
5. Sink vertical shafts a few thousand feet deep, and excavate horizontal corridors radiating out. In the floors of these tunnels, drill holes in which to place the canisters, as sketched in Fig. 22.6, or place waste packages on the floor of the corridor itself. The latter is the currently preferred technology in the U.S. high-level waste disposal program.

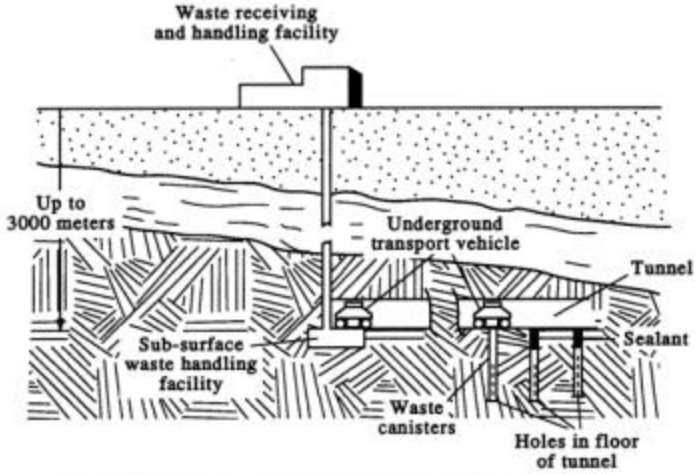


FIG. 22.6 Nuclear waste isolation by geologic emplacement.

The design of a repository for high-level radioactive waste or spent fuel uses a multibarrier approach. The first level of protection is the waste form, which may be glass-waste or an artificial substance; or uranium oxide fuel, which itself inhibits diffusion of fission products and is resistant to chemical attack. The second level is the container, which can be chosen to be compatible with the surrounding materials. Choices of metal for the canister include steel, stainless steel, copper, and nickel alloys. The third level is a layer of clay or other packing that tends to prevent access of water to the canister. The fourth is a backfill of concrete or rock. The fifth and final level is the geological medium. It is chosen for its stability under heat as generated by the decaying fission products. The medium will have a pore

structure and chemical properties that produce a small water flow rate and a strong filtering action.

The system must remain secure for thousands of years. It must be designed to prevent contamination of water supplies that would give significant doses of radiation to members of the public. The radionuclides found in fission products can be divided into several classes:

1. Nuclides of short half-life, up to about a month. Examples are xenon-133 (5.24 d) and iodine-131 (8.04 d). These would pose a problem in case of accident, and give rise to heat and radiation that affect handling of fuel, but are not important to waste disposal. The storage time for fuel is long enough that they decay to negligible levels.
2. Materials of intermediate half-life, up to 50 years, which determine the heating in the disposal medium. Examples are: cerium-144 (284.6 d), ruthenium-106 (1.020 y), cesium-134 (2.065 y), promethium-147 (2.62 y), krypton-85 (10.73 y), tritium (12.32 y), plutonium-241 (14.4 y), strontium-90 (29.1 y), and cesium-137 (30.2 y).
3. Isotopes that are still present after many thousands of years, and which ultimately determine the performance of the waste repository. Important examples are radium-226 (1599 y), carbon-14 (5715 y), selenium-79 (1.1×10^6 y), technetium-99 (2.13×10^5 y), neptunium-237 (2.14×10^6 y), cesium-135 (2.3×10^6 y), and iodine-129 (1.7×10^7 y). Radiological hazard is contributed by some of the daughter products of these isotopes; for example lead-210 (22.6 y) comes from radium-226, which in turn came from almost-stable uranium-238.

There are several candidate types of geologic media, found in various parts of the U.S. One is rock salt, identified many years ago as a suitable medium because its very existence implies stability against water intrusion. It has the ability to self-seal through heat and pressure. Another is the dense volcanic rock basalt. Third is tuff, a compressed and fused volcanic dust. Extensive deposits of these three rocks as candidates for repositories are found in the states of Texas, Washington, and Nevada, respectively. Still another is crystalline rock, an example of which is granite as found in the eastern U.S.

A simplified model of the effect of a repository is as follows. It is known that there is a small but continued flow of water past the emplaced waste. The container will be leached away in a few hundred years and the waste form released slowly over perhaps a thousand years. The chemicals migrate much more slowly than the water flows, making the effective time of transfer tens of thousands of years. All of the short and intermediate half-life substances will have decayed by this time. The concentration of the long half-life radionuclides is greatly reduced by the filtering action of the geologic medium. For additional details on the process of performance

assessment, see References.

A pair of Computer Exercises provide an introduction to the mathematical modeling of the behavior of radioactive waste in a repository or disposal facility. A simple moving pulse with decay is studied in 22.B, and the spreading of a pulse by dispersion is shown in 22.C.

A plan and a timetable for establishment of a HLW repository in the U.S. was set by Congress. The Nuclear Waste Policy Act of 1982 (NWPA) called for a search of the country for possible sites, the selection of a small number for further investigation, and characterization of one or more sites, taking account of geology, hydrology, chemistry, meteorology, earthquake potential, and accessibility.

In 1987, Congress decreed that site studies in Texas and Washington State should cease and mandated that Nevada would be the host state. The location would be Yucca Mountain, near the Nevada Test Site for nuclear weapons. The project was delayed for several years by legal challenges from the State of Nevada, but characterization was begun in 1991, with cognizance by DOE's Office of Civilian Radioactive Waste Management. To test suitability of the site an Exploratory Studies Facility was dug, consisting of a corridor 10 m in diameter and five miles long. Among features investigated were the effect of heating to 300° C and the flow of water down through the rock. As reported in the Viability Assessment document (see References), the Yucca Mountain site is favorable because of the desert climate (only about seven inches of water per year), the unsaturated zone with deep water table (2000 ft), the stability of the geologic formation, and a very low population density nearby. A Reference Design Document (RDD) was issued in January 1999. Some of the features cited are:

100 mi (160 km) northeast of Las Vegas, NV
70,000 tonnes of spent fuel and other wastes in 10,200 packages
underground horizontal tunnels (drifts)
diameter of drifts 18 ft (5.5 m); spacing 92 ft (28 m)
emplacement level about 1000 ft (305 m) below the surface
waste packages hold 21 PWR or 44 BWR fuel assemblies

Multiple barriers include the fuel pins and cladding, a 2 cm thick container of C-22, a nickel alloy† that is highly resistant to corrosion, and an outer shell 10 cm thick of carbon steel. Spent fuel will come by rail to the repository, be transferred to the disposal containers, and carried by transporter to the emplacement location. The waste package will sit in the concrete-lined drift on a support assembly attached to a pier, allowing for uniform heat loss. The packages can be retrieved if necessary; eventually a

† hastelloy, percentages 57 Ni, 21 Cr, 13 Mo, 4 Fe, 2 Co.

backfill would be added to the drift. A ceramic coating of the package and a "drip shield" may be used. Water is not expected to reach the waste for 10,000 years.

The projected date for the start of burial is around 2010. According to NWPA, DOE was required to accept spent fuel by 1998, but has not complied, to the concern of the nuclear industry. Safety standards developed by the Environmental Protection Agency (40CFR191) are to be used in licensing and regulation by the Nuclear Regulatory Commission (10CFR60). Protection must be provided for people beyond 10 kilometers from the site for a period up to 1000 years from the time of closure of the facility. The groundwater travel time from the disturbed zone to the accessible environment must be at least 1000 years. Limits are placed on the total release of radioactive materials over a period of 10,000 years after closure of the disposal facility. These specifications are designed to ensure that the extra whole-body dose to any member of the public is less than 25 mrems per year, and that there should be no more than one additional premature cancer death every 10 years, in contrast with the approximately 4 million cancer deaths from other causes in a similar period.

The law called for a study of a monitored retrieval storage (MRS) system, to serve as a staging center prior to disposal in a repository. Efforts to find a host were unsuccessful. Use of the Nevada Weapons Testing Grounds as a storage area for spent fuel has been promoted as a stop-gap.

Financing for the waste disposal program being carried out by the federal government is provided by a Nuclear Waste Fund. The consumers of electricity generated by nuclear reactors pay a fee of 1/10 cent per kilowatt hour, collected by the power companies. This adds only about 2% to the cost of nuclear electric power.

Progress in establishing the repository at Yucca Mountain has been slow and the completion date has been repeatedly extended. The difficulties and uncertainties of the project have prompted consideration of alternatives. One is to irradiate certain radioisotopes in the spent fuel in what is called a "burner." The objective is to destroy problem isotopes such as cesium-137 and strontium-90 that contribute to heating in the early period and neptunium-237, technetium-99, and iodine-129 that dominate the hazard at long times. These constitute only about a percent of the waste stream. If they are removed, the remaining waste needs to be secure for only about 100 years rather than the 10,000 years for spent fuel. An R&D program entitled Accelerator Transmutation of Wastes (ATW) is being conducted at Los Alamos National Laboratory. The concept involves the pyrochemical separation of constituents of spent fuel using the IFR technology (see Section 13.3). The key fission products, actinides, and possibly plutonium

TABLE 22.2
Activation Products in Reactor Coolant

Isotope	Half-life (years)	Radiation emitted	Parent isotope
C-14	5715	β	N-14*
Fe-55	2.73	x	Fe-54
Co-60	5.27	β, γ	Co-59
Ni-59	7.6×10^4	x	Ni-58
Ni-63	100	β	Ni-62
Nb-94	2.4×10^4	β, γ	Nb-93
Tc-99	2.13×10^5	β	Mo-98, Mo-99†

* (n,p) reaction.
† Beta decay.

are to be irradiated with neutrons in a subcritical system. An accelerator of some 100 MW proton beam power causes spallation (see Section 8.6) in a molten lead target. A surrounding liquid contains the isotopes to be burned, and heat is removed by liquid lead. Electricity is produced, with some used to power the accelerator and the rest delivered to a grid. It is estimated that some 15 of such burners would be needed to handle the U.S. spent fuel for the future. For further details, see References.

22.7 Low-Level Waste Generation, Treatment, and Disposal

The nuclear fuel cycle, including nuclear power stations and fuel fabrication plants, produces about two-thirds of the annual volume of low-level waste (LLW). The rest comes from companies that use or supply isotopes, and from institutions such as hospitals and research centers.

In this section we look at the method by which low-level radioactive materials are produced, the physical and chemical processes that yield wastes, the amounts to be handled, the treatments that are given, and the methods of disposal.

In the primary circuit of the nuclear reactor the flowing high-temperature coolant erodes and corrodes internal metal surfaces. The resultant suspended or dissolved materials are bombarded by neutrons in the core. Similarly, core metal structures absorb neutrons and some of the surface is washed away. Activation products as listed in Table 22.2 are created, usually through an (n,γ) reaction. Computer Exercise 22.D displays a series of radionuclides involved in the activation process and decay with release of radiation. In addition, small amounts of fission products and transuranic elements appear in the water as the result of small leaks in cladding and the irradiation of uranium deposits left on fuel rods during fabrication. The isotopes involved are similar to those of concern for HLW.

Leaks of radioactive water from the primary coolant are inevitable, and

result in contamination of work areas. Also, radioactive equipment must be removed for repair. For such reasons, workers are required to wear elaborate protective clothing and use a variety of materials to prevent spread of contamination. Much of it cannot be cleaned and re-used. Contaminated dry trash includes paper, rags, plastics, rubber, wood, glass, and metal. These may be combustible or non-combustible, compactible or non-compactible. Avoidance of contamination of inert materials by radioactive materials is an important technique in waste reduction. The modern trend in nuclear plants is to try to reduce the volume of waste by whatever method is appropriate. Over the period 1980-1998, by a combination of methods, the nuclear industry reduced the LLW volume by a factor of more than 15. Costs of disposal have not decreased proportionately, however, since capital costs tend to be independent of waste volume.

One popular technique is incineration, in which the escaping gases are filtered, and the ash contains most of the radioactivity in a greatly reduced volume. Another method is compaction, using a large press to give a reduced volume and also to make the waste more stable against further disturbance after disposal. "Supercompactors" that reduce the volume greatly are popular. A third approach is grinding or shredding, then mixing the waste with a binder such as concrete or asphalt to form a stable solid.

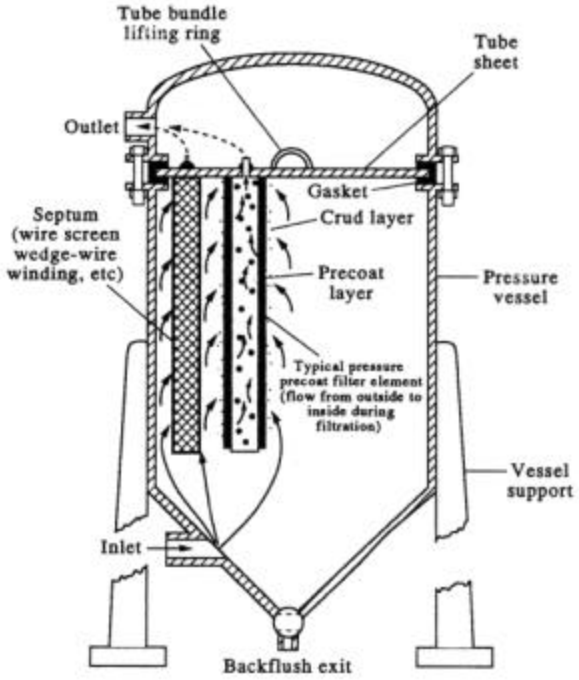


FIG. 22.7 Disposal-cartridge filter unit used to purify water and collect LLW (Courtesy ORNL).

Purification of the water in the plant, required for re-use or safe release to the environment, gives rise to a variety of wet wastes. They are in the form of solutions, emulsions, slurries, and sludges of both inorganic and organic materials. Two important physical processes that are used are filtration and evaporation. Filters are porous media that take out particles suspended in a liquid. The solid residue collects in the filter which may be a disposable cartridge or may be re-usable if backwashed. Figure 22.7 shows the schematic arrangement of a filter in a nuclear plant. The evaporator is simply a vessel with a heated surface over which liquid flows. The vapor is drawn off leaving a sludge in the bottom. Figure 22.8 shows a typical arrangement.

The principal chemical treatment of wet LLW is ion-exchange. A solution containing ions of waste products contacts a solid such as zeolite (aluminosilicate) or synthetic organic polymer. In the mixed-bed system, the liquid flows down through mixed anion and cation resins. As discussed by Benedict, Pigford, and Levi (see References), ions collected at the top move down until the whole resin bed is saturated, and some ions appear in the effluent, a situation called "breakthrough." Decontamination factors may be as large as 10^5. The resin may be re-used by application of an elution process, in which a solution of Na_2SO_4 is passed through the bed to extract the ions from the resin. The resulting waste solution will be smaller than before, but will probably be larger than the exchanger. Whether to

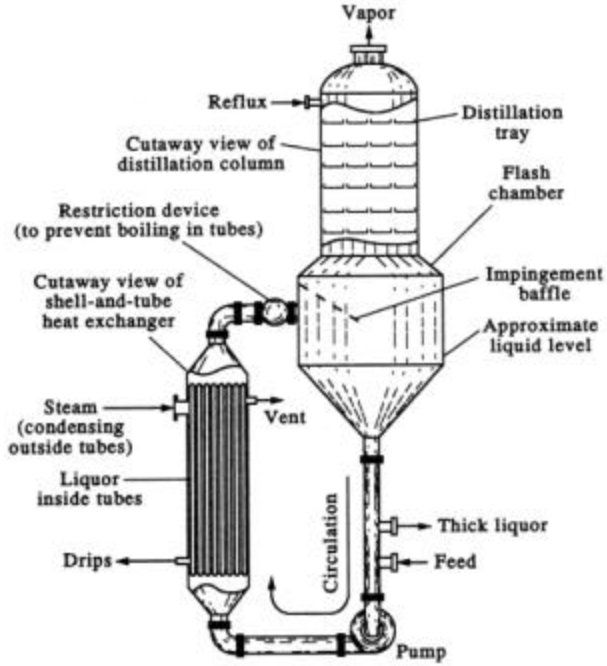


FIG. 22.8 Natural-circulation evaporator used to concentrate LLW (Courtesy ORNL).

discard or elute depends on the cost of the ion-exchanger material.

The variety of types of LLW from institutions and industry is indicated by Table 22.3. The institutions include hospitals, medical schools, universities, and research centers. As discussed in Chapter 17, labeled pharmaceuticals and biochemicals are used in medicine for diagnosis and therapy, and in biological research to study the physiology of humans, other animals, and plants. Radioactive materials are used in schools for studies in physics, chemistry, biology, and engineering, and are produced by research reactors and particle accelerators. The industries make various products: (a) radiography sources; (b) irradiation sources; (c) radioisotope thermal generators; (d) radioactive gages; (e) self-illuminating dials, clocks, and signs; (f) static eliminators; (g) smoke detectors; and (h) lightning rods. Radionuclides that often appear in low-level waste from manufacturing include carbon-14, tritium, radium-226, americium-241, polonium-210, californium-252, and cobalt-60. Low-level waste disposal from the decommissioning of nuclear power reactors is of considerable future importance and is discussed separately in Section 22.8.

TABLE 22.3
Institutional and Industrial Low-Level Waste Streams
(adapted from the Environmental Impact Statement for NRC 10CFR61)

Fuel fabrication plant	Industrial
Trash	Trash
Process wastes	Source and special nuclear materials†
Institutions	Special
Liquid scintillation vials	Isotope production facilities
Liquid wastes	Tritium manufacturing
Biowastes	Accelerator targets
	Sealed sources, e.g., radium

† SNM = Pu, U-233, etc.

Although defined by exclusion, as noted in Section 22.2, low-level radioactive waste generally has low enough activity to be given near-surface disposal. There are a few examples of very small contaminations that can be disregarded for disposal purposes, and also some highly radioactive materials that cannot be given shallow-land burial.

The method of disposal of low-level radioactive wastes for many years was similar to a landfill practice. Wastes were transported to the disposal site in various containers such as cardboard or wooden boxes and 55-gallon drums, and were placed in trenches and covered with earth, without much attention to long-term stability.

A total of six commercial and 14 government sites around the U.S. operated for a number of years until leaks were discovered, and three sites at West Valley, NY, Sheffield, IL, and Maxey Flats, KY, were closed. One

problem was subsidence, in which deterioration of the package and contents by entrance of water would cause local holes in the surface of the disposal site. These would fill with water and aggravate the situation. Another difficulty was the "bathtub effect," in which water would enter a trench and not be able to escape rapidly, causing the contents to float and be exposed.

Three remaining sites at Richland, WA, Beatty, NV, and Barnwell, SC, handled all of the low-level wastes of the country. These sites were more successful in part because trenches had been designed to allow ample drainage. Managers of the sites, however, became concerned with the waste generators' practices and attempted to reduce the amount of waste accepted. This situation prompted Congress to pass in 1980 the Low-Level Radioactive Waste Policy Act (LLRWPA), followed by the Low-Level Radioactive Waste Policy Amendments Act of 1985. These laws placed responsibility on states for wastes generated within their boundaries, but recommended regional disposal. Accordingly, a number of interstate compacts were formed, with several states remaining independent. Figure 22.9 shows the division of the U.S. into states and compacts. The alignment of states has tended to change over the years.

At the same time, the Nuclear Regulatory Commission developed a new rule governing low-level waste management. Title 10 of the Code of Federal Regulations Part 61 (10CFR61) calls for packaging of wastes by the generator according to isotope type and specific activity (Ci/m^3). Waste classes A, B, and C are defined in 10CFR61, and increasing levels of security prescribed. Greater-than-Class-C wastes are unsuitable for near-surface disposal, and are managed by DOE as equivalent to high-level waste.

Computer Exercise 22.E describes an elementary "expert system" that determines the proper class of a given waste based on half-life and specific activity.

The required degree of waste stability increases with the radioactive content. Limits are placed on the amount of liquid present with the waste and the use of stronger and more resistant containers is recommended, in the interests of protecting the public during the operating period and after closure of the facility.

Regulation 10CFR61 calls for a careful choice of the characteristics of the geology, hydrology, and meteorology of the site in order to reduce the potential radiation hazard to workers, the public, and the environment. Special efforts are to be made to prevent water from contacting the waste. Performance specifications include a limit of 25 mrems per year whole-body dose of radiation to any member of the public. Monitoring is to be carried out over an institutional surveillance period of 100 years after

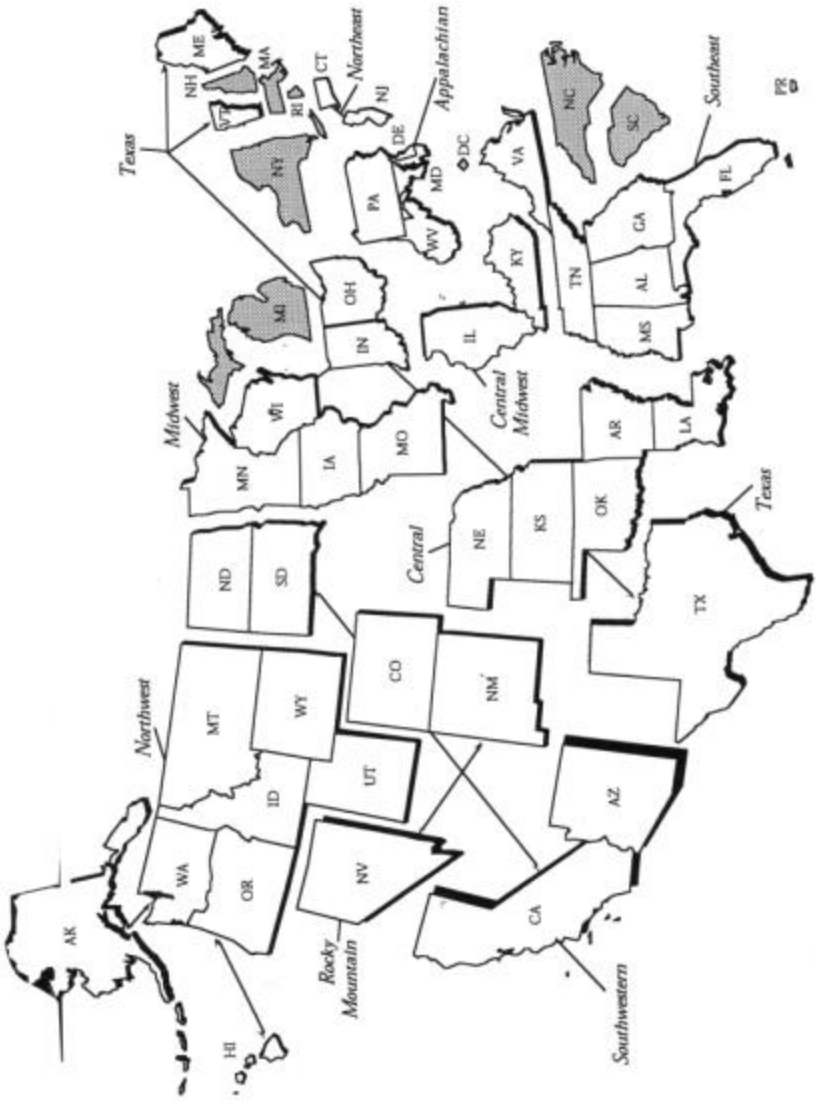


FIG. 22.9 U.S. interstate compacts for disposal of low-level radioactive wastes. States shaded are unaffiliated (Courtesy of Afton Associates and LLW Forum).

closure. Measures are to be taken to protect the inadvertent intruder for an additional 500 years. This is a person who might build a house or dig a well on the land. One method is to bury the more highly radioactive material deep in the trench; another is to put a layer of concrete over the wastes.

The use of an alternative technology designed to improve confinement stems from one or more public viewpoints. First is the belief that the limiting dose should be nearer zero or even should be actually zero. Second is the concern that some unexpected event might change the system from

the one analyzed. Third is the idea that the knowledge of underground flow is inadequate and not capable of being modeled to the accuracy needed. Fourth is the expectation that there may be human error in the analysis, design, construction, and operation of the facility. It is difficult to refute such opinions, and in some states and interstate compact regions, legislation on additional protection has been passed in order to make a waste disposal facility acceptable to the public. Some of the concepts being considered as substitutes for shallow land burial are listed.

Belowground vault disposal involves a barrier to migration in the form of a wall such as concrete. It has a drainage channel, a clay top layer and a concrete roof to keep water out, a porous backfill, and a drainage pad for the concrete structure. *Aboveground vault disposal* makes use of slopes on the roof and surrounding earth to assist runoff. The roof substitutes for an earthen cover. *Shaft disposal* uses concrete for a cap and walls, and is a variant on the belowground vault that conceivably could be easier to build. *Modular concrete canister disposal* involves a double container, the outer one of concrete, with disposal in a shallow-land site. *Mined-cavity disposal* consists of a vertical shaft going deep in the ground, with radiating corridors at the bottom, similar to the planned disposal system for spent fuel and high-level wastes from reprocessing. It is only applicable to the most active low-level wastes. *Intermediate depth disposal* is similar to shallow-land disposal except for the greater trench depth and thickness of cover. *Earth-mounded concrete bunker disposal,* used in France, combines several favorable features. Wastes of higher activity are encased in concrete below grade and those of lower activity are placed in a mound with concrete and clay cap, covered with rock or vegetation to prevent erosion by rainfall.

Each of the interstate compacts embarked on investigations in accord with LLRWPA and 10CFR61. These involved site selection processes, geological assessments, and designs of facilities. The nature of the facilities proposed depended on the location, with shallow land burial deemed adequate for the California desert at Ward Valley, but additional barriers and containers planned for North Carolina in the humid Southeast. However, as the result of concerted opposition taking the form of protests, lawsuits, political action and inaction, and occasional violence, progress was very slow in establishing low-level waste disposal capability. Thus in spite of excellent planning and vigorous efforts, and the expenditure of millions of dollars in preparation, political and regulatory factors prevented most of the programs in the United States from coming to fruition. The only sites receiving low-level wastes as of the year 2000 were the Northwestern at Hanford and Barnwell in South Carolina, with certain materials accepted by Envirocare in Utah. A comprehensive review of the situation appears in a

report by the General Accounting Office (see References).

An alternative to ground disposal called Assured Isolation (or Storage) was proposed in 1995 (see References). It involves an above-ground facility that relies on engineered barriers rather than geological characteristics. With modular packaging and side-loading, the waste can be readily inspected and preventive maintenance performed. Flexibility is provided to continue operation, or seal the facility, or remove the waste to another location. A decommissioning fund would be provided with long-term monitoring and retrieval capability. It would be licensed under NRCs radiation protection 10CFR20 (See Section 21.7) rather than 10CFR61. Costs were estimated and a licensing strategy outlined in some DOE-sponsored reports (See References).

An elementary analysis by use of a spreadsheet of the behavior of a selected set of radionuclides in low-level radioactive waste is described in Computer Exercise 22.F. The effects of storage, decay, and retardation are displayed.

22.8 Environmental Restoration of Defense Sites

The legacy of World War II and the Cold War includes large amounts of radioactive waste and contamination of many defense sites. Priority was given to weapons production rather than environmental protection, leaving a cleanup task that will take several decades to carry out and cost many billions of dollars.

One of the most pressing problems to solve is the degraded condition of underground tanks at Hanford, used to store the waste residue from reprocessing to extract plutonium. The single-wall tanks have leaked and there is concern for the contamination of the nearby Columbia River. Some of the wastes have been processed to extract the valuable Cs-137 and Sr-90, and the contents of some tanks have been successfully stabilized to prevent hydrogen explosion. Ideally, all of the waste would be transferred to double-layered tanks or immobilized in glass. Similar tanks are located at the Savannah River Plant in South Carolina, where plutonium and tritium were produced.

Transuranic wastes (TRU) consist of materials and equipment contaminated by small amounts of plutonium. They have been stored or temporarily buried over the years, especially at Hanford, Idaho Falls, Los Alamos, Oak Ridge, and Savannah River. These waste are scheduled to be buried in the Waste Isolation Pilot Plant (WIPP), a repository near Carlsbad, NM, that opened in 1999. The geological medium is salt, which has several advantages–its presence demonstrates the absence of water and it is plastic, self-sealing under pressure. The TRU is packaged in 55 gallon

drums and shipped to WIPP in a cylindrical cask called TRUPAC II, which contains seven drums in each of two layers. The waste is buried around 2160 ft (658 m) below the surface. Construction of WIPP was under the supervision of DOE, with advice by the National Research Council, and regulation by the Environmental Protection Agency. Performance assessment was done by Sandia. For details of the roles of the various organizations, see References.

The monumental challenge of environmental restoration of sites used in the U.S. defense program is being addressed by the Department of Energy. It has been recognized that it is not feasible to completely decontaminate the sites. Instead, cleanup to an extent practical is followed by "stewardship," involving isolation, monitoring, and maintenance of certain locations for a very long period. To achieve the goal of protection of the public and the environment, the DOE Environmental Management program has initiated research on new efficient technologies to handle radioactive materials. As described in DOE's guiding document "Pathways to Closure," (see References) the concept of program integration is invoked. Key features are comprehensive data, cost-saving ideas, and sharing of information.

22.9 Nuclear Power Plant Decommissioning

"Decommissioning," a naval term meaning to remove from service, e.g., a ship, is applied to actions taken at the end of the useful life of a nuclear power plant (30-40 years). The process begins at shutdown of the reactor and ends with disposal of radioactive components in a way that protects the public. LLW disposal from dismantled reactors will be a major problem in decades to come.

The first action is to remove and dispose of the spent nuclear fuel. Several choices of what to do with the remainder of the plant are available. The options as identified formally by the NRC are (a) SAFSTOR or mothballing, in which some decontamination is effected, the plant is closed up, and then monitored and guarded for a very long period, perhaps indefinitely; (b) ENTOMB or entombment, in which concrete and steel protective barriers are placed around the most radioactive equipment, sealing it to prevent release of radioactivity, again with some surveillance; (c) DECON or immediate dismantlement, in which decontamination is followed by destruction, with all material sent to a LLW disposal site; (d) delayed dismantlement, the same as the previous case, but with a time lapse of a number of years to reduce personnel exposure. The distinction among these various options is blurred if it is assumed that the facility must eventually be disassembled. It becomes more a question of "when." Aside

from the aesthetic impact of an essentially abandoned facility, there is a potential environment problem related to the finite life of structural materials.

Operation of the reactor over a long period of time will have resulted in neutron activation, particularly of the reactor vessel and its stainless steel internal parts. Contamination of other equipment in the system will include the same isotopes that are of concern in low-level waste disposal. Various techniques are used to decontaminate—washing with chemicals, brushing, sand blasting, and ultrasonic vibration. To cut components down to manageable size, acetylene torches and plasma arcs are used. Since such operations involve radiation exposure to workers, a great deal of pre-planning, special protective devices, and extra manpower are required. A very large volume of waste is generated. Some of it may be too active to put into a low-level waste disposal site, but will not qualify for disposal in a high-level waste repository. Cobalt-60 dominates for the first 50 years, after which the isotopes of concern are 76,000-year nickel-59 and 24,000-year niobium-94.

Cost estimates for reactors in the 1000 MWe category vary, in part because past decommissioning experience has been with small research or test reactors, and in part because design and operating history play a role. It appears that costs will be around $150 million for a PWR and 50% higher for a BWR. Additional data have been obtained in the decommissioning of the Shippingport reactor in Pennsylvania. Also, a standardized cost-estimation procedure has been developed. The NRC requires that all reactors have a fund established for decommissioning. In any case, the consumers of electrical power will ultimately pay the costs.

An option that has not yet been fully explored is "intact" decommissioning, in which the highly radioactive region of the system would be sealed off, making surveillance unnecessary. The virtues claimed are low cost and low exposure. Ultimately, renewal of the license after replacing all of the worn-out components may be the best solution.

A number of reactors will need to be decommissioned in the period 2000-2020. Factors that will determine action include the degree of success in reactor life extension and the general attitude of the public about the disposal of nuclear stations as low-level radioactive waste.

22.10 Summary

Radioactive wastes arise from a great variety of sources, including the nuclear fuel cycle, and from beneficial uses of isotopes and radiation by institutions.

Spent fuel contains uranium, plutonium, and highly radioactive fission

products. In the U.S. spent fuel is accumulating, awaiting the development of a high-level waste repository. A multi-barrier system involving packaging and geologic media will provide protection of the public over the centuries the waste must be isolated. The favored method of disposal is in a mined cavity deep underground. In other countries, reprocessing the fuel assemblies permits recycling of materials and disposal of smaller volumes of solidified waste. Transportation of wastes is by casks and containers designed to withstand severe accidents.

Low-level wastes come from research and medical procedures and from a variety of activation and fission sources at a reactor site. They generally can be given near-surface burial. Isotopes of special interest are cobalt-60 and cesium-137. Transuranic wastes are being disposed of in the Waste Isolation Pilot Plant. Establishment of regional disposal sites by interstate compacts has generally been unsuccessful in the U.S. Decontamination of defense sites will be long and costly. Decommissioning of reactors in the future will contribute a great deal of low-level radioactive waste.

22.11 Exercises

22.1. Compare the specific activities (dis/sec-g) of natural uranium and slightly enriched fuel, including the effect of uranium-234. Note the natural uranium density of 18.9 g/cm^3 and the half-lives and atom abundances in percent for the three isotopes:

Isotope	Half-life (y)	Natural	Enriched
U-235	7.04×10^8	0.720	3.0
U-238	4.46×10^9	99.2745	96.964
U.234	2.45×10^5	0.0055	0.036

What fraction of the activity is due to uranium-234 in each case?

22.2. Using the data below (a) calculate the power capacity of all U.S. PWRs, BWRs, and the LWR total, and (b) estimate the total annual amount of solid radioactive waste produced by U.S. power reactors.

	PWR			BWR	
No.	Average Power (MWe)	Waste (m3/GWe-y)	No.	Average Power (MWe)	Waste (m3/GWe-y)
69	949.33	23.2	35	929.31	91.5

22.3. A batch of radioactive waste from a processing plant contains the following isotopes:

Isotope	Half-life	Fission yield, %
I-131	8.04 d	2.9
Ce-141	32.50 d	6
Ce-144	284.6 d	6.1
Cs-137	30.2 y	5.9
I-129	1.7×10^7 y	1

Letting the initial activity at $t = 0$ be proportional to l and the fission yield, plot on semilog paper the activity of each for times ranging from 0 to 100 yr. Form the total and identify which isotope dominates at various times.

22.4. Traces of plutonium remain in certain waste solutions. If the initial concentration of Pu-239 in water were 100 parts per million (μg/g), find how much of the water would have to be evaporated to make the solution critical, neglecting neutron leakage as if the container

were very large. Note: for H, $s_a = 0.332$; for Pu, $s_f = 752$, $s_a = 1022$, $n = 2.88$.

22.5. If the maximum permissible concentration of Kr-85 in air is 1.5×10^{-9} μCi/cm^3, and the yearly reactor production rate is 5×10^5 Ci, what is a safe diluent air volume flow rate (in cm^3/s and ft^3/min) at the exit of the stack? Discuss the implications of these numbers in terms of protection of the public.

22.6. Calculate the decay heat from a single fuel assembly of the total of 180 in a 3000-MWt reactor at one day after shutdown of the reactor. How much longer is required for the heat generator rate to go down an additional factor of 2?

22.7. Data on fission products (in %) to accompany numbers in Figure 22.2 are as follows: U-238, 0.16; U-235, 1.98, Pu-239, 1.21; and Pu-241, 0.15.

(a) Calculate the percentages of total power due to each fissionable isotope.

(b) Assuming that one-third of the 180 fuel assemblies in the reactor are removed each year and that each contains 470 kg of U, find what weight of fission products the 60 assemblies contains.

(c) What weight of fission products would be produced annually in the whole reactor if operated at its full rating of 3000 MWt, knowing that 1.1 grams of fuel fissions per MWd?

(d) Deduce a capacity factor (actual energy divided by rated energy) from the results of (b) and (c) above.

22.8. Assume that high-level wastes should be secured for a time sufficient for decay to reduce the concentrations by a factor of 10^{10}. How many half-lives does this require? How long is this in years for strontium-90? For cesium-137? For plutonium-239?

22.9. A 55-gallon drum contains an isotope with 1 MeV gamma ray, distributed uniformly with activity 100 μCi/cm^3. For purposes of radiation protection planning, estimate the radiation flux at the surface, treating the container as a sphere of equal volume of water, and neglecting buildup. Note that the flux at the surface of a sphere of radius R, source strength S dis/sec-cm^3, attentuation coefficient S, is

$$f = (S/(2S))(1-c/(2x))$$

where $x = S\,R$ and $c = 1 - \exp(-x)$.

22.10. Some older data are available on annual radioactive waste volumes and activities per MWe of pressurized water reactor power for different waste streams (NUREG-0782, Vol. 3, p. D-23). Costs of processing, transport, and burial of wastes of "as-generated" waste have been estimated (NUREG/CR-4555, pp. 17-19). From the tabulated data below, calculate specific activities (Ci/m^3) and costs per year for each stream, and the total annual cost for 1 GWe. What is the average cost per cubic foot of waste handled? What fraction is the waste cost of the value of electricity produced at 5 cents/kWh?

Stream	Volume (m^3)	Activity (Ci)	Cost ($/ft^3)
Resins	0.081	0.40	125.70
Concentrated liquids	0.124	0.11	125.90
Filters	0.013	0.126	225.90
Compactible	0.215	0.005	15.40
Noncompactible	0.111	0.058	297.00

Computer Exercises

22.A. For a computer display of a stylized water pool for the storage of spent fuel at a nuclear plant, load and run the BASIC program FUELPOOL.

22.B. If buried radioactive waste is dissolved at a constant rate by water infiltration, it will be released as a square pulse. As the pulse migrates in an aquifer with some effective speed, the number of nuclei decrease because of decay. BASIC program WASTPULS displays the motion in time. Load and run the program, trying a variety of combinations of distances,

speeds, and half-lives.

22.C. The transport of a waste radionuclide by groundwater involves the flow with retardation due to holdup in pores. A process called dispersion causes an initial square pulse to be rounded as it moves along. BASIC computer program WTT gives numerical values of the contaminant concentration observed at a point in space for various times. Run the program with the default values, then change individual parameters such as dispersivity to observe effects.

22.D. The sequence of products resulting from neutron capture in a non-radioactive nucleus is displayed in the BASIC program ACTIVE. Included is the activation product and the residual nucleus after decay. Load and run the program to observe the sequence. Suggest a set of specific nuclear species for which the diagram is appropriate, giving cross sections and half-lives wherever possible.

22.E. The Nuclear Regulatory Commission specifies in the *Code of Federal Regulations* 10 *Energy Part* 61 *Section* .55 (10CFR61.55) a classification scheme for low-level radioactive waste. The radionuclides present and their concentrations determine whether a shipment is Class A, B, or C. Computer program LLWES (low-level waste expert system) in BASIC provides an easy way to classify a given waste. The program also illustrates an expert system, which yields answers by a specialist to questions by a worker. Load and run the program, then use the menus to learn about the NRC's rule and to test the expert's knowledge. Select some isotope or combination of isotopes and assign specific activity values to find out the classification. Note the effect of increasing or decreasing the concentration significantly.

22.12 References for Chapter 22

Robert G. Cochran and Nicholas Tsoulfanidis, *The Nuclear Fuel Cycle: Analysis and Management*, 2nd Ed., American Nuclear Society, La Grange Park, IL, 1999.

The Nuclear Waste Primer, by The League of Women Voters Education Fund, Lyons & Burford, New York, 1993. Brief and elementary information.

Raymond L. Murray, "Radioactive Waste Storage and Disposal," *Proceedings of the IEEE*, Vol. 74, No. 4, April 1986, p. 552. A survey article that covers all aspects.

Raymond L. Murray, *Understanding Radioactive Waste*, 4th Ed., Battelle Press, Columbus, OH, 1994. An elementary survey intended to answer typical questions by the student or the public.

A. M. Platt, J. V. Robinson and O. F. Hill, *The Nuclear Fact Book*, Harwood Academic Publishers, New York, 1985. A large amount of useful data on wastes is included.

Donald C. Stewart, *Data for Radioactive Waste Management and Nuclear Applications*, John Wiley & Sons, New York, 1985.

Proceedings of the Symposium on Waste Management, Tucson, AZ. An annual event with a collection of papers on all aspects of radioactive waste around the world. Editor, Roy G. Post.

A. Alan Moghissi, Herschel W. Godbee, and Sue A. Hobart, Editors, *Radioactive Waste Technology*, The American Society of Mechanical Engineers, New York, 1986. Sponsored by ASME and the American Nuclear Society, its 705 pages are packed with useful descriptive material and data on generation, treatment, transportation, regulation, and disposal.

Nuclear Waste Policy Act of 1982
http://www.rw.doe.gov/progdocs/nwpa/nwpa.htm
Text of law on HLW and spent fuel. Includes update to 1987.

Waste Isolation Systems Panel (Thomas S. Pigford et al.,) *A Study of the Isolation System for Geological Disposal of Radioactive Wastes*, National Academy Press, Washington, DC, 1984.

Robert E. Berlin and Catherine C. Stanton, *Radioactive Waste Management*, John Wiley & Sons, New York, 1989. Many tables, charts, and diagrams on all types of nuclear wastes.

Introduction to Radiological Performance Assessment
http://www.inel.gov/national/reports.html
Select pdf file. By G. Moss of National Low-Level Waste Management Program.

Reference Design Description for a Geologic Repository, Rev. 02
http://www.ymp.gov/toc/rdd.htm
Details on the site, handling operations, and barrier characteristics.

Viability Assessment for a Repository at Yucca Mountain, Nevada
http://www.ymp.gov/va.htm
Summary of findings as of December 1998 on site characteristics, design, performance, and costs. Need Adobe Acrobat Reader.

William Bebbington, "The Reprocessing of Nuclear Fuels," *Scientific American*, December 1976, p. 30

Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi, *Nuclear Chemical Engineering*, 2nd Ed., McGraw-Hill, New York, 1981

Nuclear Wastes: Technologies for Separation and Transmutation, National Academy Press, Washington, DC, 1996. Study by a National Research Council committee on the feasibility of reducing long-lived isotopes by reprocessing followed by neutron irradiation.

A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology: A Report to Congress
http://www.pnl.gov/atw/reporttocongress/index2.html
Download pdf document DOE/RW-0519.

U.S. Nuclear Regulatory Commission, Final Environmental Impact Statement on 10 CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste," NUREG-0945, Vols. 1-3, November 1982.

LLW Forum
http://www.afton.com
Select Clients/Low-Level Radioactive Waste Forum/LLW Forum Publications/LLW Notes.

J. Howard Kittel, Editor, *Near-Surface Land Disposal*, Vol. 1 of *Radioactive Waste Management Handbook*, Harwood, Chur, Switzerland, 1989.

Status of Low-Level Radioactive Waste Disposal
http://www.access.gpo.gov
Select General Accounting Office/GAO Reports/Report Number "RCED-99-238"

William F. Newberry, Thomas A. Kerr, and David H. Leroy, "Assured Storage Facilities: A New Perspective on LLW Management," *Radwaste Magazine*, September 1995, p. 13. A candid and thoughtful article on the need for a new paradigm. A follow-up article appears in the September 1996 issue of the magazine.

B. Chau, A. A. Sutherland, and R. D. Baird, "Life Cycle Costs for Disposal and Assured Isolation of Low-Level Radioactive Waste in Connecticut," DOE/LLW-246, 1998.

Donald J. Silverman and Michael A. Bauser with Robert D. Baird, "Licensing an Assured Isolation Facility for Low-Level Radioactive Waste," Vols. 1, 2, DOE/LLW-250a, 250b, 1998.

Integrated Data Base Report- 1996: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics, DOE/RW-0006, Rev. 13, December 1997. Printed versions of the annual report have been replaced by a web site report in pdf format (See DOE/EM). No update of the document is likely.

Thomas E. Carleson, Nathan A. Chipman, and Chien M. Wai, Eds., *Separation Techniques in Nuclear Waste Management*, CRC Press, Boca Raton, FL, 1995. Describes many processes in various areas of the world.

Robert Noyes, *Nuclear Waste Cleanup Technology and Opportunities*, Noyes Publications, Park Ridge, NJ, 1995. Survey of the national problem and available technologies, based on government reports.

Roy E. Gephart and Regina E. Lundgren, *Hanford Tank Cleanup: A Guide to Understanding the Technical Issues*, Battelle Press, Columbus, OH, 1998.

Katherine N. Probst and Michael H. McGovern, *Long-Term Stewardship and the Nuclear Weapons Complex: The Challenge Ahead*, Resources for the Future, Washington, DC, 1998. Candidly reviews the problem of contamination at weapons sites and identifies needs for site environmental monitoring, maintenance, controls, and information management.

National Transuranic Waste Program
http://www.wipp.carlsbad.nm.us
Information about the Waste Isolation Pilot Plant, including fact sheets on plutonium and TRUPACT II.

The Waste Isolation Pilot Plant, National Academy Press, Washington, DC 1996. A review by a committee of the National Research Council.

Performance Assessment of WIPP
http://www.nwer.sandia.gov/wlp/wipp/wipp.htm
Select Performance Assessment.

EPA's WIPP Program
http://www.epa.gov/radiation/wipp
Answers to many questions.

DOE Office of Environmental Management
http://www.em.doe.gov
Select Publications/List of Publications. Download pdf files "Accelerated Cleanup: Pathways to Closure," "From Cleanup to Stewardship," and "Integrated Data Base Report."
http://www.em.doe.gov/progint/info.html
Select pdf documents "Achieving Waste and Material Management and Site Cleanup More Efficiently," and "EM Integration Handbook."

Environmental Internet Resource

http://www.dscr.dla.mil/htis/env-htis.htm
Large number of links.

Methodology and Technology of Decommissioning Nuclear Facilities, IAEA Technical Reports Series No. 267, Vienna, 1986.

Decommissioning, Decontamination, and Reutilization of Commercial and Government Facilities, Proceedings of an ANS Topical Meeting September 7-12, 1997, American Nuclear Society, La Grange Park, IL, 1997.

Standard Review Plan for License Termination
http://techconf.llnl.gov/cgi-bin/library?source=*&library=rad_cri_srp&file=*
Access to complete set of NRC's documents on decommissioning.

Bernard L. Cohen, *Before It's Too Late*: *A Scientist's Case for Nuclear Energy*. Plenum Press, New York, 1983. Includes data and discussion of radiation, risk, and radioactive waste. A powerful statement by a strong advocate of nuclear power.

Marvin Resnikoff, *The Next Nuclear Gamble: Transportation and Storage of Nuclear Waste*. Council on Economic Priorities, New York, 1983. Written by an opponent and critic of nuclear power.

Frederick Frankena and Joann Koelln Frankena, *Radioactive Waste as a Social and Political Issue: A Bibliography*, AMS Press, New York, 1991. Inclusive of pro- and anti-nuclear references on several technical aspects.

Riley E. Dunlap, Michael E. Kraft, and Eugene A. Rosa, Eds., *Public Reactions to Nuclear Waste: Citizens' Views of Repository Siting*, Duke University Press, Durham, NC, 1993. Principally papers from a 1989 symposium. Public perception of great risk and lack of trust are revealed.

23

Laws, Regulations, and Organizations†

AFTER WORLD WAR II Congress addressed the problem of exploiting the new source of energy for peaceful purposes. This led to the Atomic Energy Act of 1946, which was expanded in 1954. The Atomic Energy Commission had functions of promotion and regulation for 28 years. Compliance with licensing rules plays an important role in the operation of any nuclear facility. A number of other organizations have evolved to provide technical information, develop standards, protect against diversion of nuclear materials, improve nuclear power operations, and perform private research and development.

23.1 The Atomic Energy Acts

The first law in the U.S. dealing with control of nuclear energy was the Atomic Energy Act of 1946. Issues of the times were involvement of the military, security of information, and freedom of scientists to do research (see References).

In the declaration of policy, the Act says, "... the development and utilization of atomic energy shall, so far as practicable, be directed toward improving the public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace." The stated purposes of the Act were to carry out that policy through both private and federal research and development, to control information and fissionable material, and to provide regular reports to Congress. Special mention was given to the distribution of "byproduct material," which includes the radioactive substances used for medical therapy and for research. The act created the United States Atomic Energy Commission, consisting of five commissioners and a general manager. The AEC was given broad powers to preserve national security while advancing the nuclear field. A Joint Committee on Atomic Energy (JCAE) provided oversight for the new AEC. It included nine members each from the Senate and the House. Advice to the AEC was provided by the civilian General Advisory Committee and the Military Liaison Committee.

† Thanks are due Angelina Howard of the Nuclear Energy Institute for helpful information.

The Atomic Energy Act of 1954 revised and liberalized the previous legislation and expanded the AEC's role in disseminating unclassified information while retaining control of restricted weapons data. The groundwork was laid for a national program of reactor research and development with cooperation between the AEC and industry, including some degree of private ownership. The act authorized sharing of atomic technology with other countries, spelled out licensing procedures for using nuclear materials, and clarified the status of patents and inventions.

The powerful AEC carried out its missions of supplying material for defense, promoting beneficial applications, and regulating uses in the interests of public health and safety. It managed some 50 sites around the U.S. Seven of the sites were labeled "national laboratories," each with many R&D projects under way. The AEC owned the facilities, but contractors operated them. For example, Union Carbide Corp. had charge of Oak Ridge National Laboratory. During the Cold War of the late 1940s and early 1950s new plutonium and enriched uranium plants were built, weapons tests were conducted in the South Pacific, and a major uranium exploration effort was begun. Under AEC sponsorship a successful power reactor research and development program was carried out. Both the U.S. and the U.S.S.R. developed the hydrogen bomb, and the nuclear arms race escalated.

Critics pointed out that the promotional and regulatory functions of the AEC were in conflict, in spite of an attempt to separate them administratively. Eventually, in 1974, the activities of the AEC were divided between two new agencies, the Energy Research and Development Administration and the Nuclear Regulatory Commission.

23.2 The Environmental Protection Agency

The National Environmental Policy Act of 1969 (NEPA) included a Council on Environmental Quality in the executive branch, and required environmental impact statements on all federal projects. The Environmental Protection Agency was then proposed and accepted. A prominent part of EPA is the administration of the Superfund to clean up old waste sites. EPA has responsibility for standards on hazardous, solid, and radioactive wastes. EPA also sets standards for radiation protection that are used by the Nuclear Regulatory Commission in its licensing and regulation.

The principal activities of the EPA are highlighted by titles of programs in its budget summary (see References): clean and safe water, global warming, clean air, human health, toxic waste sites, childrens' health, pollutants, sound science, redevelopment, Indian tribes, and public information. EPA seeks to minimize radiation from natural sources as well

as man-made sources by using guides and standards, by helping solve new radiation problems, and by responding to emergencies. It also assists in forming radiological emergency programs. One program has to do with assessment and mitigation of radon exposure. Of relevance to the electrical power industry is the EPA research program on the causes and effects of acid rain.

The Code of Federal Regulations Title 40 Part 61 covers standards for radionuclide emissions with a 10 mrem/y limit. In 10CFR61 for Department of Energy facilities and Nuclear Regulatory Commission licensed facilities limits are those causing an annual dose equivalent of 25 mrems to the whole body or 75 mrems to the thyroid or 25 mrems to any other organ of any member of the public. In 40CFR191 on management of spent fuel and HLW, limits are specified on the curies of radioactivity that can be released per thousand metric tons of heavy metal (uranium, plutonium, etc.) during the 10,000 years following disposal. The lowest figure, 10 Ci, is for Th-230 or Th-232; most isotopes are limited to 100 Ci; the highest figure, 10,000 Ci, is for Tc-99.

23.3 The Nuclear Regulatory Commission

The federal government through the Nuclear Regulatory Commission (NRC) has the authority to license and regulate nuclear facilities of all types, from a multi-reactor power stations down to isotope research in an individual laboratory. The Office of Nuclear Reactor Regulation of the NRC requires applicants for a reactor license to submit a voluminous and detailed Safety Analysis Report and an Environmental Report. These documents provide the basis for issuance of a construction permit, and later when the plant is completed, an operating license. The process involves several steps: review of the application by the NRC staff; an independent safety evaluation by the Advisory Committee on Reactor Safeguards (ACRS); the holding of public hearings in the vicinity of the proposed plant by an Atomic Safety and Licensing Board (ASLB); and the testing of qualifications of the people who will operate the plant. In addition to completing a written examination, operators are tested on the plant's simulator and on their knowledge of the location and operation of equipment. The NRC and the Federal Emergency Management Agency (FEMA) collaborate in setting criteria for emergency response programs that are developed by the utilities, state government, and local government. The five NRC commissioners make the final decision on low-power operation and full-power operation.

Once a plant is licensed, the Office of Inspection and Enforcement has oversight. The nuclear operations are subject to continual scrutiny by the

resident inspector and periodic inspection by teams from the regional NRC office. Training of operating personnel goes on continuously, with one shift in training while other shifts run the plant. Periodic exercises of the emergency plan for the 10-mile radius zone about the plant are conducted. Nuclear stations are required to report unusual events to the NRC promptly. The NRC maintains a nuclear engineer on duty at all times to receive calls and take action as needed. The staff routinely reviews all incidents. For a number of years NRC administered a program called Systematic Assessment of Licensee Performance (SALP). A new substitute is the Reactor Oversight Process (see References), which involves monitoring performance in three areas–reactor safety, radiation safety, and safeguards (against security threats). The process gives attention to human performance, safety culture, and corrective actions. Plants provide reports to the NRC on a set of performance indicators. Companies are subject to fines for lack of compliance with regulations, and if necessary NRC can shut a plant down. The principal reference is the *Code of Federal Regulations Title 10, Energy*. Key sections of that annually updated book are: Part 20 Standards for Protection Against Radiation; Part 50 Domestic Licensing of Production and Utilization Facilities; Part 60 Disposal of High Level Radioactive Wastes in Geological Repositories; Part 61 Licensing Requirements for Land Disposal of Radioactive Waste; Part 71 Packaging and Transportation of Radioactive Material; and Part 100 Reactor Site Criteria. Part 50 has a number of appendices covering criteria for general design, quality assurance, emergency plans, emergency core cooling system, and fire protection. For web access to the complete document, see References.

Other NRC references are the Regulatory Guides ("Reg. Guides"), each consisting of many pages of instructions. Titles appear on NRC's web site (see References), with ability to download key Guides.

NRC's policies and practices are undergoing a transition. Traditionally, evaluation of compliance has been based on deterministic design information, that involving engineering data and analysis. It has also been prescriptive in nature, in which specific instructions to nuclear facilities are provided, e.g., Appendix A of 10CFR50 which covers general design criteria. In 1995, NRC expressed its intent to add risk-informed regulation. Probabilistic risk assessment (PRA, see Section 19.4) was to be used to decide the most important areas for attention in terms of safety. NRC also endorsed the idea of performance-based regulation, in which goals of performance are provided, but the utilities are able to decide how to achieve the goals. The combination of approaches is designated as Risk-Informed Performance-Based regulation. Definitions and discussion of the various

approaches to regulation appear in a white paper on the Internet (see References).

An example of regulation that has required much effort to implement is the Maintenance Rule, a brief statement by NRC in 1996 of expectations on monitoring the performance of structures, systems, and components (SSC) with respect to maintenance. PRA was not mandated, but needed to define the scope of safety significance. The nuclear industry responded with detailed guidance documents (see References)

The NRC can delegate some of its authority to individual states by negotiation. An Agreement State can develop its own regulations for users of radiation and radioactive material; i.e., facilities other than those of the nuclear fuel cycle. However, the regulations must be compatible with, and no less strict than, those of the NRC.

In addition to its licensing and regulatory activities, the NRC carries out an extensive research program related to radiation protection, nuclear safety, and radioactive waste disposal. Part of the research is "in-house" and part is through contractors to the NRC.

The Office of Nuclear Material Safety and Safeguards has responsibility for interaction with, and reporting to, the International Atomic Energy Agency on fissionable material for safeguards purposes.

23.4 The Department of Energy

The federal government has legal responsibility for assuring adequate energy supply through the Department of Energy (DOE). This cabinet-level department was formed in 1977 from several other groups, and is headed by the Secretary of Energy.

The agency supports basic research in science and engineering and engages in energy technology development. It also manages national defense programs such as nuclear weapons design, development, and testing. DOE operates several multiprogram laboratories† and many smaller facilities around the U.S. The Office of Civilian Radioactive Waste Management has responsibility for carrying out the Nuclear Waste Policy Act of 1982, which involves management of the Waste Fund, repository site selection, and the design of a storage facility. It also maintains a low-level radioactive waste disposal program. The broader scope of DOE activities can be seen from some of the sections in an *Annual Performance Report* (to Congress): International Climate Change Initiatives, The Next Generation

† Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Engineering and Environmental Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest Laboratory, and Sandia National Laboratories.

of Nuclear Power Plants, Isotopes for Health Care, High Performance Computing, Leading Worldwide Control of Weapons Materials, Innovative Environmental Technologies, Disposal of Spent Nuclear Fuel, and Toward a Streamlined Management Structure. The document highlights the need for a balanced and diversified mix of energy sources, including conservation, coal, and nuclear power.

A report that describes U.S. energy policy is *Comprehensive National Energy Strategy* (see References). Goals of this plan are listed as: (I) Improve the efficiency of the energy system; (II) Ensure against energy disruption; (III) Promote energy production and use in ways that respect health and environmental values; (IV) Expand future energy choices; and (V) Cooperate internationally on global issues.

23.5 International Atomic Energy Agency

President Eisenhower, in a speech in 1953 to the General Assembly of the United Nations, proposed the Atoms-for-Peace program, which involved sharing U.S. nuclear technology with other countries. Included was formal training in universities and national laboratories for foreign scientists and engineers. International conferences were held in 1955, 1958, 1964, and 1971 at Geneva, with all countries of the world invited to participate.

In the same speech, President Eisenhower proposed an international atomic organization. In response, the United Nations established the International Atomic Energy Agency (IAEA), through a statute ratified by the necessary number of countries in 1957. Over 130 nations support and participate in its programs, which are administered from its headquarters in Vienna. The objective of the IAEA is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." Its main functions are:

(a) To help its members develop nuclear applications to agriculture, medicine, science, and industry. Mechanisms are conferences, expert advisor visits, publications, fellowships, and the supply of nuclear materials and equipment. Special emphasis is placed on isotopes and radiation. Local research on the country's problems is encouraged. Nuclear programs sponsored by IAEA often help strengthen basic science in developing countries, even if they are not yet ready for nuclear power.

(b) To administer a system of international safeguards to prevent diversion of nuclear materials to military purposes. This involves the review by the IAEA of reports by individual countries on their fissionable material inventories and on-the-spot inspections of facilities. Included are reactors, fuel fabrication plants, and reprocessing facilities. Such monitoring is done

for countries that signed the Non-Proliferation Treaty of 1968, and do not have nuclear weapons. The form of the monitoring is set by agreement. If a serious violation is found, the offending nation could lose its benefits from the IAEA.

IAEA is one of the largest science publishers in the world, since it sponsors a number of symposia on nuclear subjects each year and publishes the proceedings of each. The outlet in the U.S. is Bernan UNIPUB. IAEA also promotes international rules, for example in the area of transportation safety.

23.6 Institute of Nuclear Power Operations

Many organizations contribute to the safety and effectiveness of nuclear power generation, not the least of which are the operating companies themselves. One organization, however, provides a broad stimulus to excellence that warrants special attention. The Institute of Nuclear Power Operations (INPO), is the industry's self-regulation organization. Its objective is to promote the highest level of safety and reliability in the operation of nuclear electric generating plants.

Based in Atlanta, GA, INPO has about 350 employees, a number of whom are on loan from industry. It was founded by the electric utilities operating nuclear plants in 1979 shortly after the Three Mile Island accident. Corporate leaders saw the need for the utilities to be actively responsible for safety rather than merely complying with NRC regulations. The Kemeny Commission, in its report on the accident, recognized the need for forming INPO. All utilities that have nuclear plants are members of INPO as a private non-profit organization. Its programs embrace nuclear systems vendors and utilities outside the U.S. In its work to promote excellence in safety and reliability of operation of nuclear electric generating plants it has four cornerstone programs. It evaluates the operational performance of utilities, analyzes plant events and distributes lessons-learned information, evaluates training and provides accreditation, and assists member companies. More than 100 reactors operated by over 40 utilities are influenced by INPO's activities. INPO has no role as an advocate of nuclear power but recognizes that excellent performance is vital to public confidence.

Evaluations are performed regularly by teams of INPO staff members and personnel from other utilities. They visit a facility for two weeks–reviewing, observing, and discussing activities. Day-to-day operations and maintenance programs are examined, along with management practices. Candid interactions lead to an evaluation report that identifies both strengths and areas needing improvement. Such evaluations

are shared only with the utility for its use in improving performance. This ability to communicate freely is regarded as very important.

Data on operational events are obtained by the INPO program called Significant Event Evaluation and Information Network (SEE-IN), established in 1980. It is designed to share experiences. INPO receives reports from the utilities and other sources, studies them for possible precursors of severe problems, and sends out information on a computer-based communication system NUCLEAR NETWORK. INPO also prepares formal documents including Significant Event Reports (SERs) which describe the most important occurrences, and Significant Operating Experience Reports (SOERs) which are comprehensive reviews of key topics. The latter documents provide recommendations for solutions in areas such as radiological protection, training, and maintenance practices.

An enormous amount of information on nuclear power plant equipment has been collected and put into INPO's data base Equipment Performance Information Exchange (EPIX). Events and incidents involving equipment failure are reported and analyzed for root causes and ways to prevent future problems. A continuous flow of information to and from INPO keeps the industry up to date on equipment performance. Of especial value is the ability of a utility to quickly obtain information on the solution of an equipment problem by access to EPIX.

In the area of training of personnel, INPO administers the National Academy for Nuclear Training. The Academy's objective is to assure ample knowledge and skill on the part of nuclear personnel and to promote professionalism among nuclear workers. INPO issues guidelines on training in classes and on simulators. It reviews the training programs set up by utilities for supervisors, shift technical advisors, operators, maintenance personnel, and technicians. It also manages the accreditation done by the independent National Nuclear Accrediting Board. The Academy provides workshops, meetings, training courses, and reports, all aimed at the improvement of performance by workers, supervisors, and management.

Assistance programs that continually evolve to meet the changing needs of the nuclear industry help member utilities improve nuclear operations. Through assistance visits, working meetings, workshops, technical documents, and loan of personnel, INPO fosters comparison and exchange of successful methods among members. INPO carefully watches a set of performance indicators, which are quantified trends that measure success in achieving excellence. Examples are plant availability to produce electricity, industrial safety, safety system performance, fuel reliability, unplanned automatic scrams, radiation exposure, and volume of radioactive waste. With input from its Board of Directors and Advisory Council, INPO assists

in setting target goals for the industry, with distinctions between PWRs and BWRs as appropriate. Fig. 23.1 shows trends over the years of two of the key performance indicators, unplanned scrams and radiation exposure, as a composite for the two types of reactor.

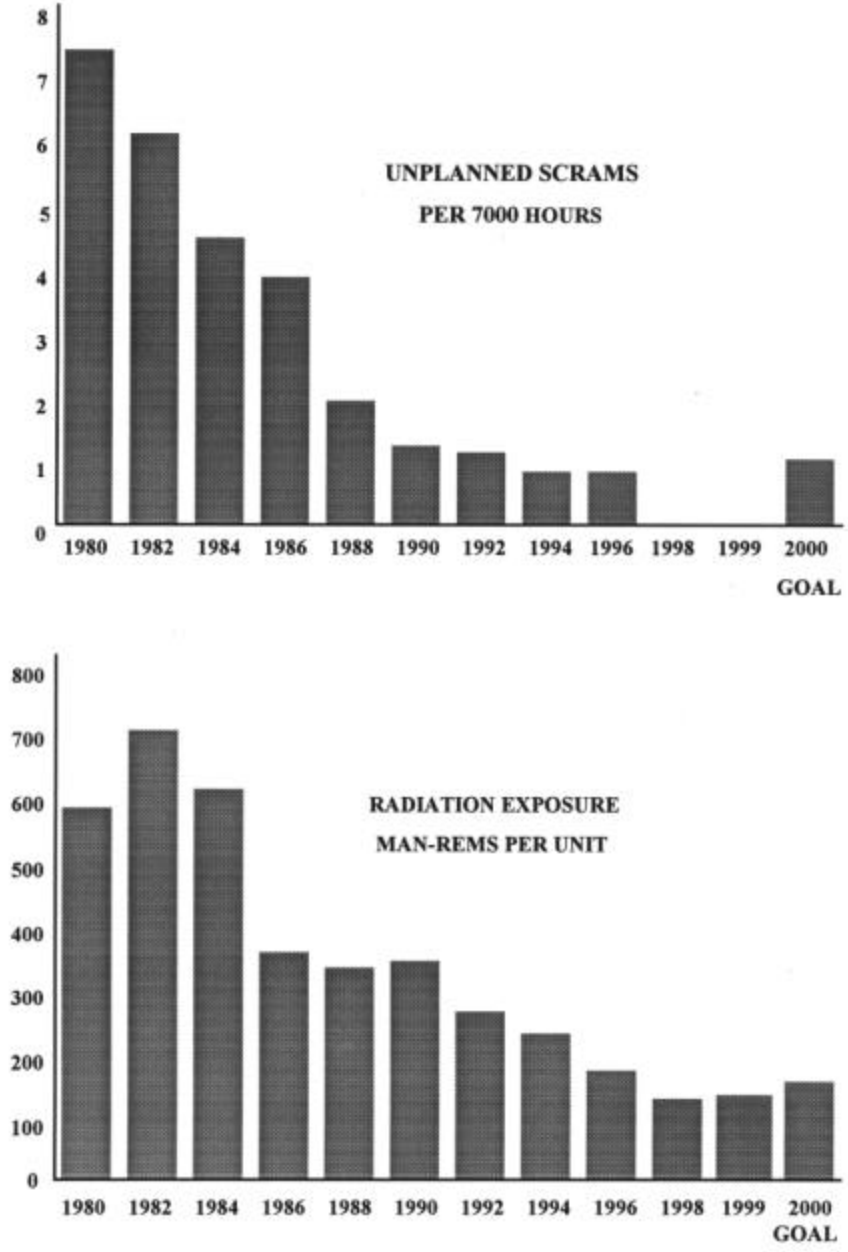


FIG. 23.1 Trends in two nuclear utility key performance indicators. (Adapted from INPO data).

The organization welcomes utilities from other countries as participants who receive benefits of information exchange but are not subject to evaluations or accreditations. Other countries often assign liaison engineers to the INPO staff. International cooperation on nuclear power is stimulated by an allied organization called the World Association of Nuclear Operators (WANO), with centers in Atlanta, Paris, Moscow, and Tokyo, and a coordinating center in London (see References). It establishes the performance indicators and facilitates communication, comparison, and emulation among organizations in many countries. INPO is the U.S. representative to WANO and makes its information capabilities available worldwide. The WANO-Atlanta Center is co-located with INPO. Whenever possible, WANO helps maintain stable nuclear power operations in countries that have economic and social problems.

INPO's activities are recognized as independent and supplementary to those of the NRC. The industry supports and oversees INPO but gives it authority to enforce its recommendations, thus providing self-regulation by peer review. It is widely accepted that the activities of the Institute of Nuclear Power Operations have significantly contributed to the improvement in the level of safety in the U.S. and abroad.

Thanks are due Philip McCullough for helpful information on INPO.

23.7 Other Organizations

The following brief descriptions of organizations that supply information and assistance to the nuclear industry do not do justice to their importance in electrical power generation.

The Electric Power Research Institute (EPRI) is a private non-profit organization in Palo Alto, CA. It was founded in 1973 to carry out the major research program needed to meet the expected electric power demand. Its stated mission is "to discover, develop, and deliver advances in science and technology for the benefit of member utilities, their customers, and society." It supports studies by its contractors in the general energy field, in coal combustion, nuclear power, and electrical systems. Its product is in the form of research and development reports, distributed widely for use by the industry. EPRI has sponsored the development of computer codes to be used by utilities in managing their fuel cycle and reactor safety analysis programs. EPRI has major initiatives in reactor safety as related both to operations and maintenance, in reliability methodology aimed at reducing operating and maintenance costs while assuring safety, planning for operating license renewal, and contributions to the industry's plan to install advanced light water reactors. Its Nuclear Safety Department staff makes in-depth analyses of potential accidents and recommends ways to

avoid them. The process involves the study of event reports, setting priorities, and proposing remedies. A few of the topics covered are: probabilistic risk assessment, pressurized thermal shock of reactor vessels, steam generator tube rupture, fuel failure, control of hydrogen, seismic protection, and station blackout, the effect of the fission product source term on emergency planning, decay heat removal capability, diesel generator reliability, and reduction in reactor trips. EPRI's mission relates to all electricity generation, but it works in close cooperation with INPO on nuclear power generation.

The Edison Electric Institute (EEI), named for inventor Thomas Edison, was formed in 1933 to represent investor-owned electric utilities. It consists of over 300 companies, affiliates, and associates, and its staff draws on thousands of experts in the industry to serve on the organization's many committees. Examples are the Policy Committee on Energy Resources and the Nuclear Power Executive Advisory Committee. EEI deals with broad issues of interest to the electric industry, such as management, economics, legislation, regulation, and environmental matters. Subjects of concern to EEI are the future of the nuclear option and maintenance of reliable transmission capability in a changing regulatory environment. Links to its organizations and related sites are found in References.

The Nuclear Energy Institute is the Washington-based policy organization of the nuclear energy industry. NEI has more than 260 corporate members in 15 countries. They include companies that operate nuclear power plants, design and engineering firms, fuel suppliers, companies involved in nuclear medicine and nuclear industrial applications, universities, and labor unions. NEI, with member participation, develops policy on key legislative and regulatory issues affecting the industry. It then serves as a unified industry voice before Congress, Executive Branch agencies, and federal regulators. NEI also provides a forum to resolve technical and business issues for the industry through a number of committees and task forces. Finally, NEI provides accurate and timely information through speeches, print publications, and its web site (See References). The wide range of information on nuclear energy and technologies is provided for the general public, students and teachers, journalists, financial analysts, and congressional staff members. Featured topics include reliability and efficiency, environmental preservation, transportation safety, education and careers, as well as the basics of nuclear plant operations, nuclear policy issues, and facts and statistics. The organization is committed to maintaining the nuclear option as an environmentally friendly, emission-free source for the U.S. and the world, and to promoting the values of safety, reliability, and efficiency. More than

4000 industry professionals participate in NEI activities and programs. NEI maintains close relations with other industry organizations, such as INPO, WANO, EEI, ANS, NRECA, and APPA.

The American Nuclear Society is the principal professional organization of those working in the nuclear field in industry, government, and universities. Founded in 1954, it has around 13,000 members. Its stated objective is "to advance science and engineering related to the atomic nucleus." This is achieved by providing objective technical evaluation of nuclear issues, coordinating development of nuclear standards, and educating the public, particularly students and teachers, about nuclear matters. ANS emphasizes the importance to its members of professionalism and responsibility. It publishes journals including *Nuclear Science and Engineering*, *Nuclear Technology*, *Radwaste Magazine*, and *Nuclear News*. ANS also coordinates the publication of technical books and conference reports, including *Transactions of the American Nuclear Society*. Its divisions represent major subject areas such as Reactor Physics, Nuclear Criticality Safety, and Isotopes and Radiation. Its committees serve functions such as public information, planning, and standards. Local sections and student chapters throughout the country hold regular technical meetings in behalf of members and the nuclear field.

The Institute of Electrical and Electronics Engineers (IEEE) has two major nuclear groups–the Nuclear Power Engineering Committee and the Power Generation Committee. These have subcommittees on topics such as Operations, Surveillance, and Testing; Energy Development; Nuclear Power; Quality Assurance; and Human Factors and Control Facilities. The monthly publication *Proceedings of the IEEE* often contains survey articles on nuclear topics.

Several other journals provide technical information on nuclear energy. Examples are *Annals of Nuclear Energy*, *Waste Management*, and *Nuclear Engineering International*, a British publication that covers world nuclear activities.

Nuclear utility groups on various subjects are informal working associations of experts with common technical or administrative problems. Of the more than thirty topics, examples are PWR steam generators, nuclear waste management, seismic qualification, degraded core rule-making, and plant life extension. Nuclear owners groups are composed of people from companies owning equipment supplied by one of the four vendors–Westinghouse, General Electric, Babcock and Wilcox, and ABB Combustion Engineering–and having a common technical problem.

The American Public Power Association (APPA) represents and provides services to 1750 community-owned electrical utilities. The

National Rural Electric Cooperative Association (NRECA) supports rural electrification and development. It embraces a variety of other cooperative organizations.

Related organizations are: the National Association of Regulatory Utility Commissioners (NARUC), whose principal function is to improve the quality and effectiveness of public utility regulation in the U.S.; and the Nuclear Non-Operating Owners Group (NNOG), which as its name implies is an association of organizations that own nuclear facilities operated by others. It is principally a forum for exchange of information and ideas.

Standards are descriptions of acceptable engineering practice. Professional technical societies, industrial organizations, and the federal government cooperate in the development of these useful documents. They represent general agreement, arrived at by careful study, writing, review, and discussion by qualified practitioners. Many hundreds of scientists and engineers participate in standards development.

The American National Standards Institute (ANSI) provides an umbrella under which standards are written and published for use by reactor designers, manufacturers, constructors, utilities, and regulators (see References). Some of the societies that are active in standards development are the American Nuclear Society (ANS), the Health Physics Society (HPS), the American Association of Mechanical Engineers (ASME), the Institute of Electrical and Electronics Engineers (IEEE), and the American Society for Testing and Materials (ASTM).

The first nuclear engineering education program in the U.S. was initiated in 1950 at then North Carolina State College. Subsequently, some eighty programs were established, a number with research and training reactors. Graduates assumed positions of leadership in the development of nuclear applications. In the course of time, however, some departments were merged with others or terminated, and many of the reactors were shut down (see References). There still remains a small source of qualified manpower in the U.S. Many companies and government agencies provide assistance to students of nuclear science and engineering. An example involving NEI and INPO is found in References.

23.8 Energy Policy Act

Efforts were underway for several years in the U.S. to develop a comprehensive energy program that would integrate the activities of the Department of Energy, the Nuclear Regulatory Commission, the Environmental Protection Agency, and other federal agencies, with contributions by the private sector. These initiatives culminated in the passage by Congress of the legislation entitled Energy Policy Act of 1992

(Public Law 102-486). It provided energy efficiency goals and standards, promoted alternative fuels, prescribed new R & D on electric vehicles, restructured the production of electricity, addressed radioactive waste disposal, established a uranium enrichment corporation, and simplified nuclear plant licensing. In essence, the law affirms the nation's commitment to preserve and extend the nuclear option as part of a broad energy mix. From the more than 350 pages of the Act, we can highlight the features that are related primarily to nuclear energy, with the understanding that some of the requirements of the law would inevitably be modified by subsequent congressional action.

Energy efficiency. This topic is addressed first and at considerable length. Standards, guidelines, and incentives are provided for conservation efforts in buildings, residences, appliances, and transportation. Utilities are encouraged to invest in energy conservation in power generation and supply, and state regulators urged to further such actions.

Electric cars. The expansion of usage of electric vehicles, those operating on motors with current supplied by batteries, is mandated by a 10-year commercial demonstration program. DOE is to work with manufacturers and the electric utility industry to develop practical inexpensive vehicles and the infrastructure that supports servicing and battery recharging. If fully implemented, a national program in electrification of transportation could make a major impact on fossil fuel demands and on atmospheric pollution.

Electrical generation. The early legislation that gave utilities an essential monopoly in their service area, the Public Utility Holding Company Act of 1935, is reformed to permit other organizations to generate electric power, under cognizance of the Federal Energy Regulatory Commission (FERC). For a brief description of FERC, see References. We will reserve discussion on the issue of diversity in generation as a part of energy economics in the next chapter.

High-level radioactive waste. The Act focuses on the use of the Yucca Mountain site for disposal of spent fuel. The Administrator of EPA is to provide safety standards for protection of the public, including the maximum annual effective dose equivalent, using recommendations of the National Academy of Sciences. NRC rules are to be consistent with those of EPA, including the recognition of the existence of engineered barriers and post-closure oversight. DOE is to assure Congress that waste disposal plans are adequate to cover new nuclear power plants. A small amount of money is allocated to low-level waste reduction. By omission of action by Congress, the states and compacts will continue to be guided by the Low-Level Radioactive Waste Policy Act and its Amendment.

U.S. Enrichment Corporation. This national organization is created "to operate as a business enterprise on a profitable and efficient basis." It can lease DOE enrichment facilities and market and sell enrichment services to anyone. It is to assess the future of AVLIS (See Section 9.4) and to put it on a commercial basis if appropriate. A national strategic uranium reserve is to be created. A decontamination and decommissioning fund with assessment to utilities is established, with a limit on total annual charge to $150 million, prorated according to use.

Fusion energy. A broadly based program is expected, with U.S. participation in the engineering design phase of the International Thermonuclear Experimental Reactor (ITER). Needs for strengthening cooperation with other countries are to be examined. In addition to magnetic confinement studies, R&D is authorized on both laser and heavy ion inertial confinement fusion.

Advanced nuclear reactors. Technologies to be pursued include medium-sized passive safety reactors, but can involve others as well, on a cost-sharing basis. Noteworthy is the attention given to the alternatives to light water reactors–high-temperature-gas-cooled reactors and liquid metal reactors. The reactors are to be cost effective, easy to design and license, safe, and proliferation-resistant. A date of 1996 is set for design and certification of the advanced LWRs by the NRC, with preliminary design of the other types.

Nuclear plant licensing. NRC is authorized to issue a combined construction and operating license, and to identify needed tests and analyses. A hearing would be held just before the plant goes into operation.

Authority over BRC wastes. States are to have authority over the regulation of wastes designated as below regulatory concern (BRC) by the NRC, with the latter's policies invalidated.

Plutonium shipments. A study is to be conducted by the President of the safety of shipments of plutonium by ships.

23.9 Summary

Congress passed the Atomic Energy Act of 1946, amended in 1954, to further peaceful purposes as well as to maintain defense. The Atomic Energy Commission was formed to administer the programs. Later, the AEC was split. Currently the Department of Energy is responsible for development of nuclear energy and the Nuclear Regulatory Commission enforces rules on radiation set by the Environmental Protection Agency. The International Atomic Energy Agency helps developing countries and monitors nuclear inventories. Among other influential organizations are the Institute for Nuclear Power Operations, the Electric Power Research

Institute, and the Nuclear Energy Institute. The American National Standards Institute and the American Nuclear Society are active in developing standards for processes and procedures in the nuclear industry. Education and training in nuclear technology are provided by a number of universities. The Energy Policy Act of 1992 provides comprehensive national goals and requirements on energy efficiency and generation.

23.10 References for Chapter 23

U.S. Federal Government Agencies Directory
http://www.lib.lsu.edu/gov/fedgov.html
A comprehensive set of links maintained by Louisiana State University Libraries.

History of Energy 1800-1994
http://www.eia.doe.gov/cneaf/electricity/chg_str/append_b.html
Chronology of events in U.S. and Canada.

Environmental Protection Agency
http://www.epa.gov
Select About EPA/EPA's Budget or Policy Statements and Strategy Documents/Strategic Plan

George T. Mazuzan and J. Samuel Walker, *Controlling the Atom: The Beginnings of Nuclear Regulation 1946-1962*, California University Press, Berkeley and Los Angeles, 1984.
Written by historians of the Nuclear Regulatory Commission, the book provides a detailed regulatory history of the Atomic Energy Commission.

A Short History of Nuclear Regulation, 1946-1992
http://www.nrc.gov/SECY/smj/shorthis.htm
The first chapter is drawn from the book by Mazuzan and Walker.

Code of Federal Regulations, Energy, Title 10, Parts 0-199, U.S. Government Printing Office, Washington, DC (annual revision). All rules of the Nuclear Regulatory Commission appear in this book, published by the Office of the Federal Register, National Archives and Records Service, General Services Administration. Available to be downloaded by sections in pdf at the NRC web site.

Nuclear Regulatory Commission
http://www.nrc.gov
Select About NRC/Mission and Organization; or select Reference Library/ Regulatory Guides/Power Reactors (e.g., 1.174 and 1.175 on PRA guidance).

NRC Site Contents
http://www.nrc.gov/NRC/CONTENTS/nrc.html
Search feature and links to all parts of the web site.

NRC's Reactor Oversight Process
http://www.nrc.gov/NRR/OVERSIGHT/index.html
Links to four relevant documents.

Risk-Informed Performance-Based Regulation
http://www.nrc.gov/NRC/COMMISSION/POLICY/whiteppr.html
Informative discussion of regulatory transition.

Nuclear Industry documents
"Industry Guidelines for Monitoring the Effectiveness of Maintenance of Nuclear Power Plants,"
NUMARC 93-01; "Industry Guidelines for Monitoring the Condition of Structures at Nuclear Power Plants," NEI-96-03. Can be downloaded as pdf files at NRC web site.

U.S. Department of Energy
http://www.doe.gov
Select At a Glance/Our Mission. Includes links to programs at all of the National Laboratories.

DOE Information Bridge
http://www.osti.gov/bridge/home.html
A large collection of online reports. Select Help for information on use of the site. Example: use Easy Search to access pdf document Annual Report to Congress, 1998.

Comprehensive National Energy Strategy: National Energy Policy Plan: The National Energy Plan, DOE/S-0124. (A report to the Congress required by Title VIII of the Department of Energy Organization Act, Public Law 95-91).
http://www.hr.doe.gov/nesp/cnes.htm
Also available from Superintendent of Documents, Washington, DC, 20402.

International Atomic Energy Agency
http://www.iaea.org/worldatom
Choose one of the Programmes: Nuclear Applications; Nuclear Energy; Nuclear Safety; Technical Cooperation; and Safeguards.

Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order*, Resources for the Future, Washington, DC, 1987. History of origin of IAEA, structure and activities, and relationship to safeguards.

World Association of Nuclear Operators
http://www.insc.anl.gov/neisb/neisb4/NEISB_1.4.html
Extract from NEI Source Book.
http://kdd2.fepc.or.jp/koho/9901_s2e.htm
Japanese perspective of WANO.

Electric Power Research Institute
http://www.epri.com
Select EPRI Facts/Introducing EPRI; or Select Nuclear Power/About Nuclear Power. Access to reports for members only.

Edison Electric Institute
http://www.eei.org
Select EEI Information/About EEI; or Select Find It/Related Sites for links to members and other organizations.

Nuclear Energy Institute
http://www.nei.org
Select About NEI/NEI Mission and Profile. Topics: regulation, weapons material usage, spent fuel and low-level waste disposal, electricity deregulation, and advanced nuclear power plants.

American Nuclear Society
http://www.ans.org
The organization and nuclear information. Select About or Publications.

Institute of Electrical and Electronics Engineers
http://www.ieee.org
Select Organizations/Societies/Nuclear and Plasma Sciences Society/Publications/
Transactions on Nuclear Science. Also Select "about npss fields of interest."

American National Standards Institute
http://www.ansi.org
Select About ANSI. Information on purchasing standards.

U.S. Nuclear Engineering Education: Status and Prospects, National Academy Press, Washington, DC, 1990. A study by a committee of the National Research Council.

Educational Assistance Program
http://www.nei.org
Select Search/INPO for information on National Academy for Nuclear Training.

Teachers and Nuclear Energy, OECD Nuclear Energy Agency, Paris, 1994. An international seminar for secondary school teachers.

Nuclear Engineering Education Sourcebook
http://www.ne.ncsu.edu/Source/sourcebook.html
Includes links to lists of faculty in all institutions. Kuruvilla Verghese and John G. Gilligan, Editors

Dan R. Williams and Larry Good, *Guide to the Energy Policy Act of 1992*, PennWell Books, Tulsa, OK, 1994.

Introduction to FERC
http://www.ferc.fed.us/intro/intro2.htm
Federal Energy Regulatory Commission's home page.

Jacek Jedruch, *Nuclear Engineering Data Bases, Standards, and Numerical Analysis*, Van Nostrand Reinhold, New York, 1985. A useful collection of information that would be difficult to find elsewhere.

References for the full text of laws related to nuclear power and radioactive waste as originally written appearing in *United States Statutes at Large*, U.S. Government Printing Office:
"Atomic Energy Act of 1946," Public Law 585, Chapter 524, Vol. 60, Part 1, 79th Congress, 2nd Session, pp. 755-775, August l, 1946.
"Atomic Energy Act of 1954," Public Law 703, Chapter 1073, Vol. 68, Part 1, 83rd Congress, 2nd Session, pp. 919-961, August 30, 1954.
"Price-Anderson Act" (atomic energy damages), Public Law 85-256, Vol. 71, 85th Congress, 1st Session, pp. 576-579, September 2, 1957.
"National Environmental Policy Act of 1969", Public Law 91-190, Vol. 83, 91st Congress, 1st Session, pp. 852-856, January 1, 1970.
"Energy Reorganization Act of 1974," Public Law 93-438, Vol. 88, 93rd Congress, 2nd Session, pp. 1233-1253, October 11, 1974.
"Department of Energy Organization Act of 1977," Public Law 95-91, Vol. 91, 95th Congress, pp. 565-613, August 4, 1977.

"Low-Level Radioactive Waste Policy Act" (of 1980), Public Law 99-240, 96th Congress, 2nd Session, pp. 3347-3349, December 22, 1980.
"Nuclear Waste Policy Act of 1982," Public Law 97-425, Vol. 96, 97th Congress, 2nd Session, pp. 2201-2263, January 7, 1983.
"Low-Level Radioactive Waste Amendments Act of 1985," Public Law 99-240, Vol. 99, 99th Congress, 1st Session, pp. 1842-1924, January 15, 1986.

24

Energy Economics

THE DEFINITION of economics appearing in a popular textbook† is as follows:

> Economics is the study of how societies use scarce resources to produce valuable commodities and distribute them among different people.

The definition is relevant in that we seek answers to questions such as these:

(a) What are the comparative costs of electricity from nuclear plants and from coal or oil plants?
(b) What is the expected use for nuclear power in the future?
(c) What choices of nuclear power research and development must be made?

In the present chapter we shall consider the first of these questions, examining the origin of costs of electricity and reviewing past events and trends. In a later chapter we study the long-range role of nuclear power.

As background for the discussion of electric power and nuclear's role, it is instructive to examine the energy flow diagram of Figure 24.1. Several points to note are: (a) nuclear accounts for over 7 percent of the total supply; (b) oil imports are over 60 percent of the total oil supply; (c) the total of all renewables, including hydro, solar, wind, biofuels, and geothermal, is comparable to nuclear; (d) energy for transportation is over 26 percent of the total consumption. The chart strongly suggests that conservation of natural gas and oil should have high priority. The amounts of electricity generated by the various energy sources can be seen in Table 24.1.

24.1 Components of Electrical Power Cost

The consumer's interest lies in the unit cost of electricity delivered to the home. The author's light bill, in a region of the country that uses nuclear for over one-third of electricity generation, gives a figure of close to 8 cents/kWh. This cost includes three typical components–generation (55%), transmission (32%), and administration (13%). This says that the generation

† Paul A. Samuelson and William D. Nordhaus, *Economics*, 16th edition, New York, Irwin/McGraw-Hill, Inc., 1998.

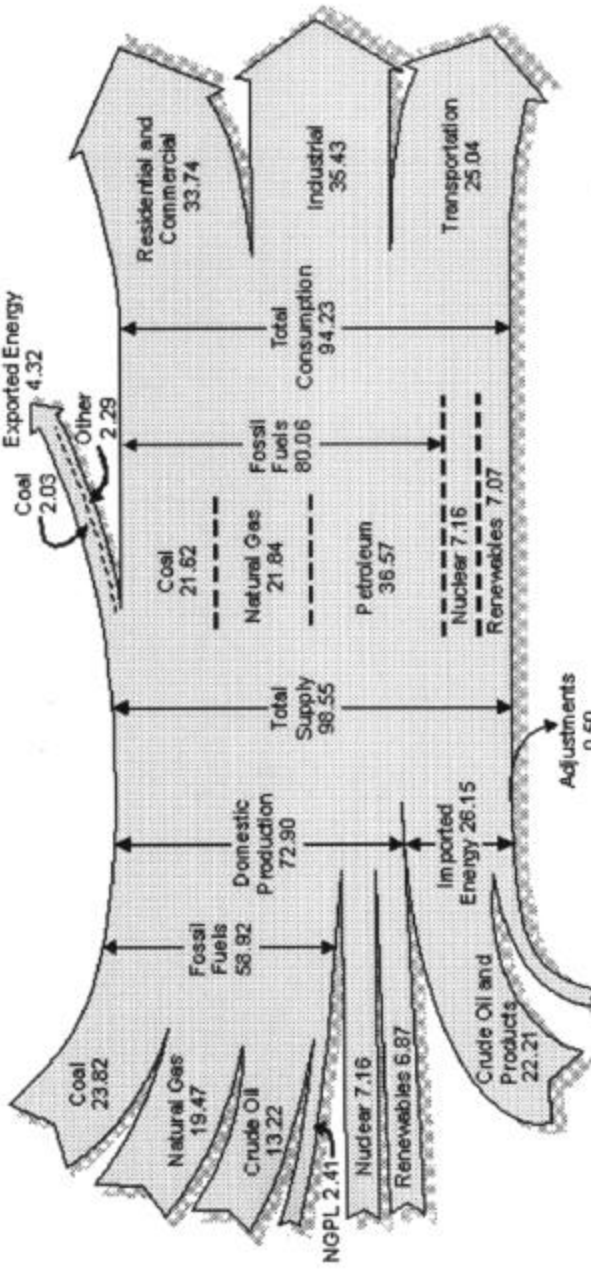


FIG. 24.1 U.S. energy sources and uses. Units are quads (quadrillion Btu). Source: Annual Energy Review 1998, DOE/EIA-0384(98).

or "bus bar" cost of electricity for this particular area would be around 4 cents/kWh or 40 mills/kWh.

The comparison between costs of nuclear and its main competitor, coal, varies in several ways. On the average, the two have about that same cost,

TABLE 24.1
Electric Energy Amounts and Percentages from Various Sources (from DOE/EIA web site)

Source	Amount ($\times 10^9$ kWh)	Percent
Coal	1872	51.7
Nuclear	674	18.6
Hydro	324	9.0
Gas	545	15.1
Oil	129	3.6
Other†	76	2.1
Total	3620	100.0

†Geothermal, solar, wind, biomass, etc.

but there are large variations among countries, with the ratio coal/nuclear between 0.8 and 1.7. Electrical generation costs are dominated by fuel costs for coal and by capital costs for nuclear. Thus differences on a global or national or regional basis depend on the distance from coal fields and on the discount rate. For example, nuclear electricity is relatively inexpensive in Japan and many European countries because of the cost of importing coal. Another factor is the regulatory environment of the country and the degree of emphasis on clean air or nuclear safety. Operating and maintenance (O&M) costs for nuclear plants are generally high because of the great complexity of the equipment and the stringent safety requirements of the regulators. However, O&M costs can vary widely among utilities with comparable facilities because of differing degrees of management effectiveness. Capital costs of both fossil and nuclear plants were high during the decade of high interest rates and high inflation, but the increase in cost was greater for nuclear plants because they are basically more expensive and the time to construct was excessive. Table 24.2 gives the trend of plant costs for half the U.S. reactors over four time periods in which commercial operation began.

The capital costs of nuclear plants vary greatly, but the average is somewhat over 2 billion dollars. This figure represents the money required to construct the plant, including interest. Nuclear power has long been regarded as "capital-intensive" because equipment costs are high while fuel

TABLE 24.2
Construction Costs for Nuclear Units (source: Energy Information Administration, U.S. Department of Energy, DOE/EIA-0439(84)).

Period†	Number of units	Average cost ($/k We)
1971-1974	13	313
1975-1976	12	460
1977-1980	13	576
1982-1984	13	1229

† During which units entered commercial operation.

costs are low. Typically, the main parts of the nuclear plant itself and percentages of the cost are: reactor and steam system (50%), turbine generator (30%), and balance of plant (20%). Additional costs include land, site development, plant licensing and regulation, operator training, interest and taxes during construction, and an allowance for contingencies.

Further perspective is needed on the capital cost component. Utilities are different from private companies in that they serve an assigned region without competition. In exchange, the price that they can charge for electricity is regulated by public commissions of state governments. When a utility decides to add a plant to its system it raises capital by the sale of bonds, with a certain interest rate, and by the sale of stock, with a dividend payment to the investor. These payments can be combined with income tax and depreciation to give a charge rate that may be as high as 20% The interest charge on the capital invested must be paid throughout the construction period. This is an important matter, since the average total time required to put a plant into operation in the U.S. is about 13 years, in contrast with a figure of less than 6 years in 1972. Figure 24.2 shows the trend in construction periods for the recent past. Several reasons have been advanced for the long time between receipt of a construction permit and commercial operation. In some cases plants were well along when new regulations were imposed, requiring extensive modifications. Others have been involved in extended licensing delays resulting from intervention by public interest groups. Others suffered badly from lack of competent management.

24.2 Forecasts and Reality

The demand for electrical power varies on a daily basis as a result of the activities of individuals, businesses, and factories. It also varies with the season of the year, showing peaks when either heating or air conditioning is used extensively. The utility must be prepared to meet the peak demand, avoiding the need for voltage reduction or rotating blackouts. The existing megawatts capacity must include a margin or reserve, prudently a figure such as 20%. Finally, the state of the national economy and the rate of development of new manufacturing determines the longer-range trends in electrical demand. Utilities must continually be looking ahead and predicting when new plants are required to meet power demand or to replace older obsolete units.

Such forecasts have to be made well into the future because of the long time required to build a new power plant. But forecasts can readily turn out to be wrong because of unforeseen events or trends, including the interruption of energy supplies from abroad, shifts in the state of the

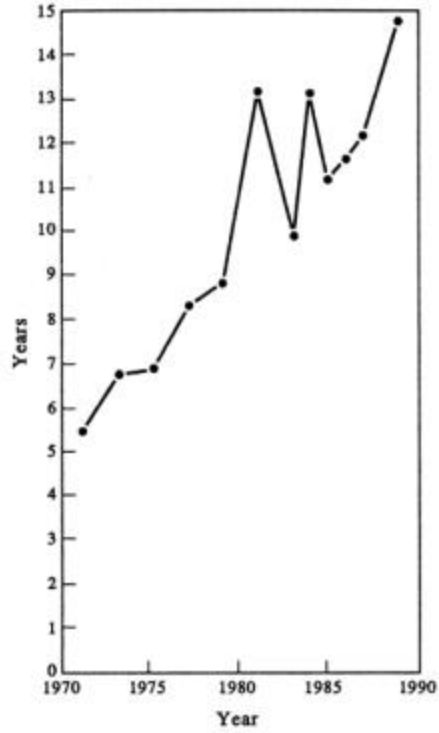


FIG. 24.2 Construction times for nuclear power plants. Adapted from DOE/EIA-0439(84).

economy, and major changes in the regulatory climate. If an estimate of power demand is too low and stations are not ready when needed, customers face the problem of shortages; but if the estimate is too high, and excessive capacity is built, customers and shareholders must bear the effects of added expense.

The history of nuclear growth and eventual stagnation over the last several decades serves well to illustrate this situation. There was a post-World War II economic boom in which the demand for electric power was about 7% per year. New coal-fired plants provided most of the growth. In 1957 the first commercial power reactor was started at Shippingport, Pennsylvania, and new designs of larger units were developed by two concerns. Some of these were attractive to utilities because they were turnkey plants, priced very favorably. A large number of orders were placed in the 1960s to the main vendors–Westinghouse, General Electric, Babcock & Wilcox, and Combustion Engineering. These orders were placed based on sustained electric power demand growth well to the end of the century, and an expected construction time of about six years.

Predictions were optimistic in that period. For example, in 1962 and

later in 1967, the Atomic Energy Commission predicted† the following installed nuclear capacities:

Year	*GWe*
1970	10
1980	95
2000	734

The reasons for the optimism were expectation that the U.S. economy would continue to expand, that electricity would substitute for many fuels, and that nuclear would fill a large fraction of the demand, reaching 56% by the year 2000. The level of 95 GWe was actually reached late in the 1980s, but the figure only reached 100 GWe after an additional decade.

What is the reason for the great discrepancy between forecast and reality? The first is that it took longer and longer to build nuclear plants, adding large interest costs to the basic capital cost. When this was compounded by high inflation rates, the total costs increased dramatically, as we saw in Table 24.2. Second, the Middle East oil boycott of 1973 caused an increase in the cost of energy in general, accentuated a national recession, and prompted conservation practices by the public. The growth rate of electrical demand fell to 1% per year. As a consequence, many orders for reactors were canceled. However, by this time, a large number of reactors were in various stages of completion–reactors that would not be needed for many years, if ever. Some that were about 80% completed were finished, but work on others of 50% or less was stopped completely. The hard fact was that it was cheaper to abandon a facility on which half a billion dollars had been invested rather than to complete it.

In the 1980s the demand for electricity began to increase again, but by that time, other factors had developed that discouraged utility management from resuming a building program. In earlier years, the utilities in a state were regulated monopolies that could readily pass on costs to the consumers and could show continued decreases in the cost of electricity. When the recession occurred, costs increased, and customers adopted conservation measures, reducing income from the sale of electricity.

In this period, the role of the Public Utilities Commissions (PUCs) became more important. These state regulatory organizations are committed to protect the consumers' interest. They became alarmed at the rising costs of nuclear plants and were reluctant to allow utilities to pass costs on to consumers, thus reducing the margin of profit to the company and its stockholders. The practice of prudence review is applied to the construction of facilities, after construction is complete. Questions are asked, "Would a

† Civilian Nuclear Power–A Report to the President-1962 (and 1967 Supplement), U.S. Atomic Energy Commission.

reasonable person have incurred those costs, or canceled the project?" A related "used and useful" test asks, "Were those facilities actually needed?" or "Should a cheaper power source have been built?" Expenditure by utilities have been disallowed for many reasons. Some costs were unreasonable, such as cost overruns that could have been avoided with better project management. Others were in the category of errors in judgment but only in hindsight. An example is a decision to build a generating plant that turned out to be larger than necessary. In many cases, expenditures by the utility were disallowed even though they were outside the control of the management. Examples were delay in regulatory action, regulatory requirements for major post-TIM-2 changes in equipment, high interest rates, and inflation. The timing of prudence review is such that a disallowance must be absorbed by investors or the utility must enter into an expensive lawsuit. As a consequence of unhappy experience, utility executives became increasingly wary of any new large-scale long-term commitment. The prospect of fiscal disaster outweighed that of criticism for failing to anticipate and meet electricity needs.

24.3 Challenges and Opportunities†

Depending on one's point of view, the nuclear industry in the U.S. is (a) highly productive, (b) experiencing problems, or (c) dead. There are elements of truth in each of these characterizations. On a very positive note, more than 100 reactors were in operation as of the turn of the century, contributing around 22% of the total U.S. electricity, with no harm to the public, and at a cost that was well below that of oil-fired units and many coal-burning plants. Realistically, however, it is a fact that the cost of nuclear plants had increased dramatically and that in many areas nuclear is more expensive than coal. Utilities find little sympathy for their requests for rate increases to meet costs of operation. No new orders for reactors have been placed since 1978; and few new reactors will be started until regulatory stability, financial optimism, and public support are achieved.

It is not possible to identify any single cause for the situation. We can indicate many of the factors that had an effect, however, without attempting to quantify their contribution. Post-World War II optimism about nuclear energy was based on the successful development of military applications, and the belief that translation into peaceful uses was relatively easy and straightforward. After studying and testing several reactor concepts the U.S. chose the light water reactor. Hindsight indicates that safety might have been assured with far less complexity and resultant cost by adoption of heavy water reactors or gas-cooled reactors.

† Thanks are due Caren Byrd of Morgan Stanley for some thoughts on this chapter.

Nuclear power was barely getting started when the environmental movement began and consumers' interests became more vocal and influential. Opposition to nuclear power appears to have been composed of many elements. Early activists expressed themselves as opposed to the power of the entity called the military-industrial complex. Since nuclear energy is involved in both weapons and commercial power, it became a ready target for attack. Those philosophically inclined toward decentralized authority, the return to a simpler life style, and the use of renewable energy were enlisted into the antinuclear cause. Those fearful of radiation hazard and those concerned about the growth of nuclear weapons were willing recruits also. Well-organized opposition forces set about to obstruct or delay reactor construction through intervention wherever possible in the licensing process. The Nuclear Regulatory Commission had a liberal attitude toward intervenors in the interests of fairness. The net effect in many cases was to delay construction and thus increase the cost. The high costs then served as an additional argument against nuclear power. The general public has tended to be swayed by statements of the organized opposition, and to become doubtful or concerned. Traditional distrust of government was accentuated in the 1970s by the pains of the war in Viet Nam. The aftermath of the Watergate affair was a loss in confidence in national leadership. The public was further sensitized by the revelation that industrial chemicals were affecting plant and animal life and that wastes had been mismanaged, as at Love Canal. Because of accompanying radiation, wastes from nuclear power were regarded as more dangerous than ordinary industrial wastes. Concerns were aggravated by the apparent inability of government and industry to deal effectively with nuclear wastes. Changes in policy and plans between national administrations based on differences in approach were ascribed to ignorance.

Delays in reactor construction resulted from other factors. In the interests of improved protection of the public, the Nuclear Regulatory Commission increased the number and detail of its rules and guidelines, often requiring that changes in equipment be made or additional equipment be installed. Examples of mistakes in design, installation, and testing, cost overruns, shoddy workmanship, and inept management received a great deal of media attention, further eroding confidence among investors and the general public.

Inflation in the 1970s drove costs of construction up dramatically. The effect on nuclear plants was especially severe because of their complexity and the requirement of quality assurance at every stage from material selection to final testing.

The Three Mile Island accident of 1979 (Section 19.5) dealt a severe

blow to the nuclear power industry in the U.S. Although releases of radioactivity were minimal and no one was hurt, the image of nuclear power was seriously tarnished. Media attention was disproportionate to the significance of the event, and greatly increased the fears of local residents. The apparent confusion that existed immediately after the incident and the revelation of errors in design, construction, and operation caused national concern over the safety of all reactors.

The Chernobyl accident of 1986 (Section 19.6) commanded international attention. The effect on public opinion may have been greater in Europe than in America, in part because of the geographic proximity to the event. It is generally appreciated in the U.S. that the Chernobyl reactor was operated by the U.S.S.R. without adequate precautions, was basically more unstable than LWRs, and lacked a full containment. Nonetheless, the spectre of Chernobyl will remain over the U.S. nuclear industry for some time to come.

As in all endeavors, success or failure depends both on the capability of the leaders and on surrounding circumstances and events. The environment surrounding modern nuclear utilities is complex and demanding. Competition among utilities and between utilities and other independent generators has increased, because consumers are anxious to obtain the lowest cost electricity. To attract and keep customers, the margin of profit must be reduced or production costs must be minimized, or both. Among the steps taken by utilities are removal of excess layers of management and reductions in staffing. Recognizing that operations and maintenance (O&M) costs are a major part of the cost of producing electricity, utilities are increasing attention to efficiency in the maintenance and repair process. They are concentrating on reduction in the time required for refueling outages, and eliminating unscheduled reactor trips, to enhance capacity factors. Such actions have to be taken with care that safety is not jeopardized. It is clear that every additional monitoring device or safety equipment or special procedure intended to enhance safety adds to the product cost. As performance improves, it becomes harder to find areas of further improvement. But it is difficult for a regulator, either from government or industry, to refrain from recommending new safety initiatives. In the limit, the industry could be put out of business by escalating costs. From another point of view, the addition of excessive complexity to a facility can be counterproductive to safety. This suggests that greater attention be given to establishing priorities, and to reducing costs in other areas besides those that are safety-sensitive. A more important goal still is the achievement of a uniform level of excellence in every nuclear unit in the country.

A recent trend toward consolidation of management has been noted. Companies such as Entergy are buying nuclear plants for market value, which is much lower than initial cost. As a result, electric power from nuclear can be generated at costs competitive with that from natural gas.

The foregoing discussion refers primarily to ways the nuclear industry can survive in operating existing facilities. Much thought and study has gone into the question of how to expand the opportunity to contribute to long-term national energy needs. Some of the proposed actions can be noted: (a) use of highly structured and effective methods of managing construction, (b) improvement of the regulatory process, (c) maintenance and operation measures that stretch the life of reactors well beyond the normal 40 years, (d) design of smaller, simpler, and safer reactors that fit local power needs better, (e) expanded educational and public information programs, (f) expansion of the use of automatic controls, computer-based management systems, and expert systems to aid operation, and (g) the design and development of advanced reactors that fully utilize operating experience and assure an increased safety margin.

In the following paragraphs we shall discuss reasons behind some of these opportunities to improve the stature and promise of nuclear power.

24.4 Technical and Institutional Improvements

A great deal of effort has been devoted to finding ways to enhance prospects for the nuclear industry. Solutions should build on success and progress to date. A brief review of some of the more popular ideas follows.

Computer assistance

Safety and productivity in operating nuclear plants will be enhanced by expanded use of computers. Word processing capability is standard, and plant computers provide status information displays based on measurements by a host of instruments. Computerized records on equipment maintenance are employed by most utilities. The computer is also a valuable adjunct to conducting activities during regular scheduled outages for testing and repair. It makes it possible to reduce the time for a complete outage to less than one month.

The computer is used in the application of artificial intelligence (AI). The term originally referred to the imitation of human thinking, but now embraces a great variety of knowledge manipulation concepts. The many facets of AI are displayed on a web site and a glossary is available (see References). A summary follows.

(a) *Data base management* involves the ability to extract information effectively.

(b) An *expert system* captures a large body of human knowledge and makes it available for decisions and problem solving. An explanation of reasoning can be provided.
(c) *Simulation* uses computer programs to model a real system, as in the simulator for a nuclear power plant control room. A variety of hands-on experiences are provided for learning and practice by operators.
(d) *Fuzzy logic* treats the continuous range of statements between "false" and "true." It is mainly used in expert systems. For further explanations and links, see References.
(e) *Robotics* is the science and application of computers, circuits, and machines to simulate the movement of human beings. Robots can perform tasks in confining or hazardous environments, such as high radiation fields.
(f) *Neural networks* are computer programs that seek to model processing in the neurons of the brain, with the possibility of modifications that resemble learning.
(g) *Virtual reality* provides a simulated visual and tactile environment that permits training of workers in preparation for complex operations.
(h) *Natural languages,* i.e., conversing with the computer in English.

Extensive research on expert systems has been carried out by the Electrical Power Research Institute (see References). The ideal expert system can absorb data about an operation problem, draw upon previously stored information bases, and process the data in real time or off-line. It can apply the stored analytic ability and the experience of many specialists, to provide understandable recommendations on preventive or corrective action. Usually, such expertise is expressed in terms of a set of several hundred rules based on facts and intuition. The expert system can also give an explanation of the logic used to arrive at the answer, and be able to grow, i.e., become more knowledgeable and competent.

Studies to date indicate that the most favorable uses of expert systems will be in ordering of control rod movement at reactor startup, fuel rearrangement at time of refueling, accident diagnosis, and assessment of plant deterioration over its life. The capability of an operator to manage an emergency is clearly expanded greatly by the availability of an expert system. One concern, of course, is that the availability of the powerful computer assistance might discourage operators from using their own mental capacity and reasoning ability. The aid might actually turn out to be a crutch.

A natural extension of the expert system in the future would include computer calculations of expected responses of the system, as a step beyond the training simulators currently used. The ultimate is automatic control of

the whole power plant. It is generally felt that some human presence will always be needed, no matter what the level of sophistication of the computer system.

Digital Control of Nuclear Plants

The instrumentation and control (I&C) system of a power reactor provides two main functions: (a) supplies continuous information about the status of the reactor, including neutron flux, power level, power distribution in the core, temperatures, pressures, water levels, and control rod positions; and (b) provides commands to trip the reactor if preset limits are exceeded. Much of the output is displayed in the control room in the form of meter readings. Other signals caused by deviations or failures of equipment actuate warning lights or alarms.

Traditionally, the I&C systems of nuclear power plants have been of the *analog* type, involving a sensor, a feedback circuit, and a display device. Analog devices tend to drift and to degrade, becoming unreliable with time. In the interests of improved reliability and safety, the nuclear industry is gradually converting to *digital* I&C, which involves computer software and microprocessor-based hardware. The Nuclear Regulatory Commission recommends and supports the transition with several Reg. Guides (see References). The changeover from analog to digital is of major consequence from the standpoints of economics, training, and testing. Even if only safety-related systems are changed, large costs for equipment and installation are incurred. Since the technology is different, new learning by operators, maintenance personnel, and supervisors if required. Finally, a method is needed to verify the functional reliability of the revised system under a large variety of conditions, to avoid costly power outages when the system goes into operation. One technique is to use a simulator that can quickly reproduce many challenges (see References). In a National Research Council report (see References) these issues and others are addressed, with conclusions and recommendations to NRC.

Reactor Life Extension

The nominal life of a nuclear plant has long been considered to be 40 years. The life of a plant is the period between startup and the time it becomes necessary to shut it down permanently. Two principal developments would prompt the termination of operation of a nuclear facility. The first would be a condition of marginal safety because of potential failure of vital equipment. The second would be excessive outage for maintenance and repairs, rendering the system uneconomical.

In the light of the high capital costs of replacement plants, efforts are

being made to stretch the life of plants to more than 40 years. Problem areas that can be attacked are: (a) difficulty in finding spare parts, making it necessary to substitute components or complete systems; (b) corrosion in PWR steam generators due to copper in the system, which requires plugging in excessive number of tubes and eventually replacing the generators; (c) deterioration of electrical systems due to cable aging, especially in a hot moist environment; (d) buildup of radioactive deposits that make maintenance difficult because of radiation levels; (e) intergranular corrosion of primary piping in BWRs; and (f) radiation damage of PWR reactor vessel welds from fast neutron bombardment. This effect makes the vessel vulnerable to pressurized thermal shock (PTS), a phenomenon in which temperature changes in embrittled material result in vessel rupture. Since such an event must be avoided at all costs, this effect clearly limits continued operation. PTS can be postponed by using low-leakage fuel at the surface of the core. This can be low enrichment fuel or partially burned fuel both of which have reduced neutron production rates. The BWR does not have such a problem because of the larger water layer between fuel and vessel wall.

A great deal can be done to alleviate some potential problems by rigorous inspection and preventive maintenance programs, making use of computerized data bases to detect trends and to provide reminders for action. Very careful control of the chemical composition of the primary and secondary coolant water will reduce corrosion and deposit buildup.

License Renewal

The lifetime figure for a nuclear power plant of 40 years was set by Congress on the basis of the time for amortization. License renewal for 20 years can be sought by a utility at the 20 year mark, but at least 10 years before expiration. Two NRC rules apply: Environmental Regulation 10CFR51 and the License Renewal Rule 10CFR54 (See References for web access to the two regulations). Special attention in the licensing must be given to the potential effects of aging of components and systems, with information on ways to mitigate the effects. The objective is to determine if the plant can operate safely in the extended period. The license renewal process is outlined in an NRC web site (see References).

The applicant for a renewal license must submit an environmental report that analyzes the plant's impact during the continued operation. Use can be made of a Generic Environmental Impact Statement (GEIS, see References) prepared by NRC, with adaptation to fit the specific plant. A distinction is to be made in the application between requirements on "active" and "passive" components.

The first U.S. plants to seek license renewal were Calvert Cliffs, operated in Maryland by Baltimore Gas & Electric, and Oconee, operated in South Carolina by Duke Power. Subsequently, a number of plants initiated plans for license renewal.

24.5 Effect of Deregulation and Restructuring

The electrical generation industry faces problems related to access to its transmission lines. There is a growing number of non-utility producers of electricity using wind, water, and cogeneration. Industrial consumers seeking the lowest cost electricity would like to buy power from such independent generators and use the existing utility-owned network. Users in the northern U.S. would like to import more power from Canada. The process of transferring large blocks of power around the grid is called "wheeling." Utilities are concerned about the effect of increased wheeling on system stability and reliability, on costs of new transmission lines, and on safety. The problem is not solely that of the utilities, because residential and commercial users may experience higher costs if the utilities lose large customers.

Various new approaches to energy management on the part of utilities have been required by public utility commissions. The broadest category is Integrated Resource Planning (IRP), which takes account of all aspects of energy, including environmental effects and social needs. Within it is Demand Side Management (DSM) which seeks to reduce usage rather than meeting customers' requirements. DSM emphasizes encouragement of conservation and avoidance of new large facilities by use of alternative energy sources. Related is Least Cost Planning (LCP) which requires the examination of all costs, including existing plants. This comes into play when a major equipment replacement such as steam generator is needed. Shutting down the plant might be more economical. In all of these methods, the PUC played a more active role in decisionmaking than previously.

The Energy Policy Act of 1992 (Section 23.8) will continue to have a significant effect on the electric utility industry. Some of its pertinent provisions are noted. For example, the Public Utility Holding Company Act of 1935 (PUHCA), which governed power production by utilities, was modified to allow greater competition among power producers, including a new category called "exempt wholesale generators" (EWGs), which are unregulated power producers. The objective was to let market forces play a greater role. Independent power producers (IPPs), those outside the utility structure, were encouraged to develop. The Federal Energy Regulatory Commission (FERC) was given greater power, especially to order transmission access, when it can be shown that it is in the public's interest,

i.e., reliability is maintained and costs to users is reduced. The process of integrated resource planning (IRP) is required at the state level. The new law thus accelerates the process of utility industry restructuring that had been evolving since the energy crisis of the 1970s.

Nuclear power's position was enhanced by the Energy Act through streamlining of the reactor licensing process, the use of certification of standardized reactor designs, and the establishment of a government corporation for uranium enrichment. However, the effect of other features of the Act is uncertain. Mandatory efficiency standards were set for electrical equipment, and the development of an electric automobile given greater support. Meeting efficiency goals clearly would tend to reduce the need for new electric power, while massive electrification of ground transportation would increase demand. From the regulatory standpoint, it will be easier to license new reactors, thus encouraging investors. On the other hand, new competition will increase the economic pressure on the utilities. They must cut costs but are required by NRC and INPO to maintain safety. The recurring question "How safe is safe enough?" needs to be addressed to the satisfaction of the industry, the regulator, and the public.

The Energy Act of 1992 requires that each state of the U.S. to develop a plan for transition of electric generation by regulated monopoly to a free market. A variety of techniques to assure equity among the various stakeholders have been developed. One of the key issues in the debates is how to handle "stranded costs." These costs to utilities result from the change itself and consist of several categories: (a) locked-in power purchase contracts with independent generators required by the Public Utilities Regulatory Policies Act (PURPA); (b) regulatory assets, which are programs for energy efficiency, low-income assistance, and deferred fuel costs, approved by regulatory bodies; (c) capital investment debt, incurred in the construction of nuclear power plants, normally to be paid off over many years by income from consumers (d) decommissioning funds required over and above those already accumulated. The question is, "Who should bear the burden of the stranded costs?" Users of electricity and their advocacy groups believe that the consumer should not have to pay for what is considered mismanagement on the part of utility executives, and provide a bailout of the industry. They argue that investors in utility stocks and bonds must take their chances on loss just as with any other investment. Utilities on the other hand point out that there was a contract involving approved expenditures in exchange for reliable electricity and that decisions to build nuclear plants were fully supported by regulators. Those holding stocks or bonds obviously do not want the value of their investment to

decline. The ideal solution of this problem is to devise a formula that gives each party a fair part of the burden, such that the transition can be effected smoothly and efficiently, with realization of the goal of reduced costs to consumers with assured reliability.

The subject of deregulation is very complex because of the many issues and variety of groups affected, as well as differing situations among the states, which are addressing the opportunities and problems. Several discussions of the subject from different vantage points are found in References.

24.6 Advanced Reactors

Light water reactors of the PWR and BWR type have performed very well over several decades. However, in the U.S. without any action being taken, a number of reactors would come to the end of their license period and be shut down. Many believe that it is in the best interests of society to continue the nuclear option as a part of an energy mix. To do so, nuclear power must be acceptable to the public, the utilities, the regulatory agencies, and the financial community. This implies the need for confidence in reactor safety and economy.

The U.S. nuclear power industry includes electric utilities using reactors, equipment manufacturers and vendors, and service organizations. That industry is convinced that electricity from nuclear power will continue to be necessary to sustain economic growth. Leaders note that nuclear power does not contribute to pollution and potential global warming, and helps provides energy security through the reduction of reliance on uncertain supplies of foreign oil. The industry believes that energy conservation and the use of renewable sources of energy are highly desirable but not sufficient for long-term needs, especially in light of a growing population and the demand for environmental protection.

Accordingly, a Strategic Plan for Building New Nuclear Power Plants (see References) was published with a final version dated 1998. The document serves to highlight the industry's commitment to encouraging new plant orders. The Plan identifies a number of "building blocks" for accomplishing goals. Among these are continued plant safety and reliability, stable licensing including NRC design certification, well-defined utility requirements, successful first-of-a-kind engineering, progress in disposal of high-level and low-level wastes, adequate fuel supply, enhanced government support, and improved public acceptance.

Crucial to the success of the mission are changes in the method of licensing of siting, construction, and operation by the Nuclear Regulatory Commission. The conduct of a single hearing for the license based on

standardization of designs will reduce the time required and eliminate much uncertainty. Experience gained in the more than 30 years of commercial reactor operation is to be applied to the design, operation, and maintenance of the new advanced reactors. Self-improvement initiatives through INPO will be continued.

The first major step in carrying out the Plan was the development of an Advanced Light Water Reactor Utility Requirements Document (see References). It provides policy statements about key features such as simplification of systems, margins of safety, attention to human factors, design for constructibility and maintainability, and favorable economics.

Two different concepts were specified:

(a) A large output (1300 Mwe) "evolutionary" design that benefits from current designs, and (b) A mid-size output (600 MWe) "passive" design that depends more on natural processes for safety instead of mechanical-electrical devices.

Numerical specifications include completion in five years, low worker radiation exposure (less than 100 mrems/y), refueling on a 24-month basis, and an ambitious 87 percent average availability over a 60-year design life.

A thorough analysis was made of the means by which standardization can be achieved in design, maintenance, and operation, along with the benefits that accrue:

(a) A reduction in construction time and costs comes from the use of common practices.

(b) Use of identical equipment in several plants favors both economy and safety.

(c) Standardized management, training, and operating procedures will lead to greater efficiency and productivity.

Three advanced reactor designs intended to meet the U.S. nuclear industry objectives were developed. A description of the principal candidates is given below.

The ABB Combustion Engineering System 80+ (see References) is an evolutionary 1300 MWe reactor that satisfies the Requirements Document. Its containment is spherical rather than the typical cylindrical, giving more working space. Its control system features the latest in electronics, including fiber optics, computers, and visual displays. Safety is enhanced by many features, including a gas-turbine for emergency a-c power. A combination of simplicity and economy of scale makes the cost of electricity competitive. Versions of the design have been built in Korea.

General Electric Co. has an Advanced Boiling Water Reactor design of 1300 MWe (see References). The ABWR circulates coolant by internal pumps. Passive safety features include containment cooling using natural

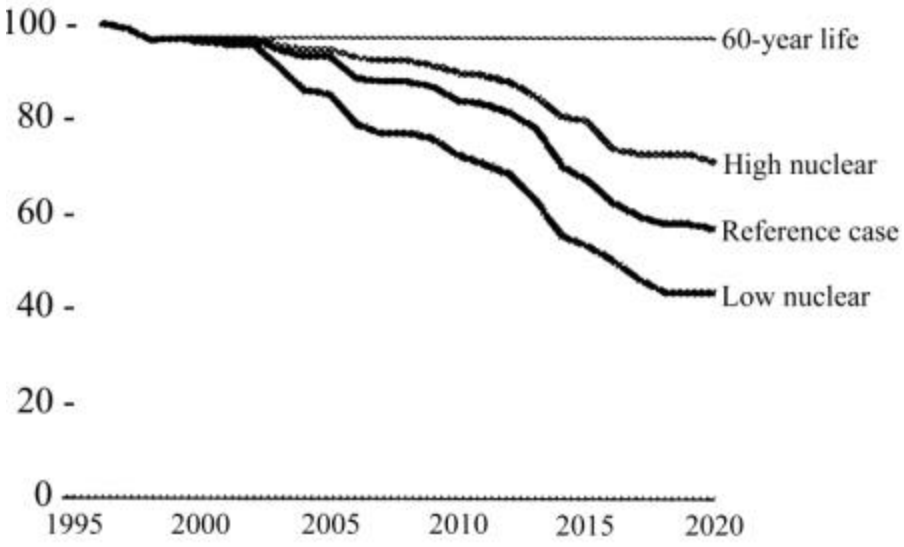


FIG. 24.3 Predicted U.S. nuclear capacity 1996-2020 (GW).
Source: Annual Energy Outlook 2000, DOE/EIA-0383(2000).

convection. Analysis of the plant by PRA indicates negligible hazard to the public. The reactor design conforms to the Requirements Document and was reviewed by the NRC. Two ABWRs are being built in Japan and others are planned.

Westinghouse has designed an advanced reactor with acronym AP600, with a lower power level of 600 MWe (see References). The principal design goals were simplicity and enhanced safety. Numbers of pipes, valves, pumps, and cables have been greatly reduced in this design. The AP600 has a number of passive processes for safety, using gravity, convection, condensation, and evaporation. Examples are a large water storage reservoir for emergency cooling and another one for containment wall cooling.

Early reactor development in the period 1950-1965 was spearheaded by the federal government, through the Atomic Energy Commission. In the new advanced reactor program, the Department of Energy is helping the endeavor, but there is now an imposing array of organizations cooperating to bring about the new generation of reactors. In addition to overall guidance by the Nuclear Energy Institute, support is provided by the Edison Electric Institute (EEI), the Electric Power Research Institute (EPRI), and the Institute of Nuclear Power Operations (INPO).

The future of nuclear power in the U.S. in the 21st century is dependent on the number of reactors that (a) are shut down for economic reasons, (b) achieve license renewal, and (c) are built in the advanced reactor program. Forecasts by the Department of Energy of electrical generation are shown in

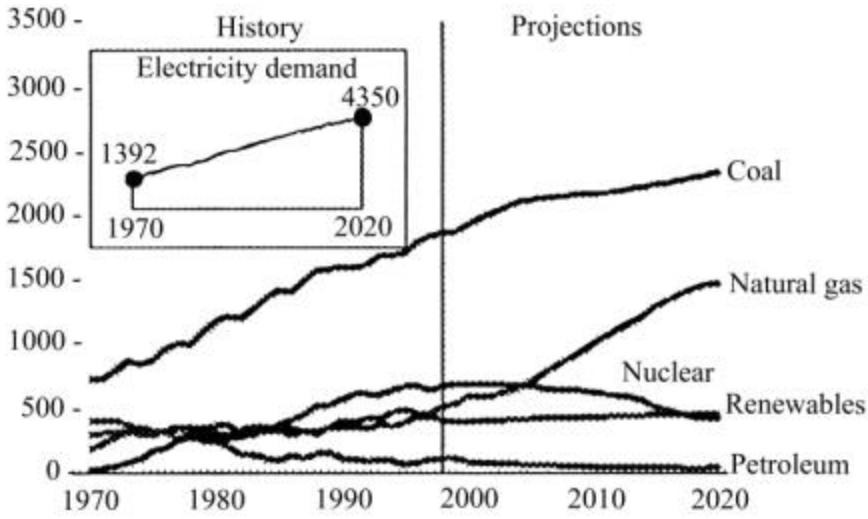


FIG. 24.4 Electricity generation by fuel, 1970-2020 (billion kWh).
Source: Annual Energy Outlook 2000, DOE/EIA-0383(2000).

Figures 24.3 and 24.4. The graphs do not include the possibility that new reactors will be built. If there are no new orders, the implications are clear. With continuing deaths but no births, a species soon becomes extinct.

24.7 Summary

Half the cost of electric power is for generation. Electricity from plants using coal or nuclear fuel is comparable in cost, with a trade off between capital costs and fuel costs. Costs of construction of nuclear plants and the time to complete them in the U.S. were exorbitant for several reasons. There have been no orders for new nuclear plants since 1978. The nuclear industry has several opportunities for improvements including license extension, but is faced with the challenges of electricity restructuring. Several advanced reactor concepts are being promoted to preserve the nuclear option.

24.8 Exercises

24.1. Many different energy units are found in the literature. Some of the useful equivalences are:

1 eV = 1.602 x 10^{-24} J
1 cal = 4.185 J
1 Btu = 1055 J
1 bbl (oil) = 5.8 10^{6} Btu
1 quad = 10^{15} Btu
1 Q = 10^{18} Btu
1 exajoule (EJ) = 10^{18} J.

(a) Find out how many barrels of oil per day it takes to yield 1 GW of heat power.

(b) Show that the quad and the exajoule are almost the same.

(c) How many quads and Q correspond to the world annual energy consumption of around 300 EJ?

(d) How many disintegrations of nuclei yielding 1 MeV would be needed to produce 1 EJ?

24.2. Find the yearly savings of oil using uranium in a nuclear reactor, with rated power 1000 MWe, efficiency 0.33, and capacity factor 0.8. Note that the burning of one barrel of oil per day corresponds to 71 kW of heat power (see Exercise 24.1). At 25 dollars a barrel, how much is the annual dollar savings of oil?

24.9 References for Chapter 24

Energy Crises of the 1970s
http://www.american history.si.edu/csr/powering/hirsh3/frmain.htm
By Smithsonian National Museum of American History.

Peter Stoler, *Decline and Fail: An Ailing Nuclear Power Industry*, Dodd, Mead, & Co., New York, 1985. History of nuclear power, with emphasis on plants not completed and the reasons for the difficulties. Suggests ways to revive the nuclear option.

Alvin M. Weinberg, *Continuing the Nuclear Dialogue*, American Nuclear Society, La Grange Park, IL, 1985. Essays spanning the period 1946-1985, selected and with introductory comments by Russell M. Ball.

Karl O. Ott and Bernard I. Spinrad, *Nuclear Energy: A Sensible Alternative*, Plenum Press, New York, 1985. Titles of sections: Energy and Society, Economics of Nuclear Power, Recycling and Proliferation, Risk Assessment, and Special Nuclear Issues Past and Present.

Nuclear Power: Technical and Institutional Options for the Future, National Academy Press, Washington, DC, 1992. A study by a committee of the National Research Council of ways to preserve the nuclear fission option. An analysis of nuclear power's status, obstacles, and alternatives.

Philip C. Jackson, Jr., *Introduction to Artificial Intelligence*, 2nd Ed., Dover Publications, New York, 1985. A popular update of a classic work.

John A. Bernard and Takashi Washio, *Expert Systems Applications Within the Nuclear Industry*, American Nuclear Society, La Grange Park, IL, 1989.

Matt Ginsberg, *Essentials of Artificial Intelligence*, Morgan Kaufmann Publishers, San Mateo, CA, 1993.

SHAI's AI Glossary
http://www.shai.com/ai_general/glossary.htm
Provided by Stottler Henke Associates, Inc. Site includes links on AI.

Expert Systems Development at EPRI
http://www.epri.com
Search on Expert System for BWR or on KBATC (for Knowledge-Based Technology Applications Center)

Fuzzy Logic and Intelligent Technologies for Nuclear Science and Industry (Proceedings), World Scientific Publishing Co., Singapore, 1998. Titles of papers for the 3rd conference, held in Europe, are at http://wspc.com.sg/books/compsci/3845.html.

Richard C. Dorf and Robert H. Bishop, *Modern Control Systems*, Addison-Wesley, Menlo Park, CA, 1998. Feedback control theory with practical examples. A chapter titled Digital Control Systems. Two nuclear problems.

EPRI/Utility Program Demonstrating Advanced Nuclear Control System
http://www.epri.com
Search on Advanced Nuclear Control System for discussion of B&W reactor conversion to digital I&C.

Reg. Guides on Digital Computer Software
http://www.nrc.gov/NRC/RG/index.html
Select Power Reactors to access Regulatory Guides 1.168-1.173.

Digital Instrumentation and Control Systems in Nuclear Power Plants
http://www.nap.edu/readingroom/books/digital
Report by a National Research Council committee, published by National Academy Press, Washington, DC, 1997

License Renewal
http://www.nrc.gov/NRC/REACTOR/LR/index.html
Overview, Process, Regulations, Guidance, and Applications. Nuclear Regulatory Commission.

NUREG-1437 Generic Environmental Impact Statement for License Renewal of Nuclear Plants
http://www.nrc.gov/NRC/NUREGS/indexnum.html
Available to utilities to reference in license renewal application.

NRC Standard Design Certifications
http://www.nrc.gov
Select Reference Library/Title 10 CFR/Part 52 for regulation (Subpart B and Appendices M-O).

ALWR Utility Requirements Document
http://www.epri.com
Search on title for abstract of 1996 report from EPRI.

Michael W. Golay and Neil E. Todreas, "Advanced Light-Water Reactors," *Scientific American*, April 1990, page 82.

Advanced Reactors
http://www.uic.com.au/nip16.htm
A briefing paper from Australia. Table of reactor data, features, and status.

Advanced Reactors
http://www.cannon.net/~gonyeau/nuclear/advanced.htm
Links to the principal designs. By Joseph Gonyeau.
(Future URL is http://nucleartourist.com from Nuclear Energy Institute)

Advanced-Design Nuclear Power Plants
http://www.nei.org/library/facts.html
Summary of status. From Nuclear Energy Institute.

Advanced Boiling Water Reactor (ABWR)
http://www.toshiba.co.jp/product/abwr/index.htm
Diagrams and description by Toshiba.

ABB Combustion Engineering System 80+
http://www.nuc.berkeley.edu/designs/sys80/sys80.html
University of California Nuclear Engineering student report.

AP600
http://www.ap600.westinghouse.com
Attractive and informative web site.

U.S. Nuclear for the 21st Century
http://www.nei.org
Select Search/ALWR for presentations by Louis B. Long and Joe F. Colvin.

Timothy J. Brennan, Editor, *A Shock to the System: Restructuring America's Electricity*, Resources for the Future, Washington, DC, 1996.

Electricity Market Reform: An IEA Handbook, OECD/IEA, Paris, 1999. History, transition issues, and recommendations.

Electric Restructuring and Utilities Deregulation: A Facility Manager's Guide, APPA: Association of Higher Education, Alexandria, VA, 1998. Information and advice for educational institutions. Addresses "green power."

Shimon Awerbuch, Leonard S. Hyman, and Andrew Vesey, *Unlocking the Benefits of Restructuring: A Blueprint for Transmission*, Public Utilities Reports, Arlington, VA, 1999.

Restructuring and the Electric Industry
http://ncsl.org/programs/esnr/RESTRU.HTM
Links to Glossary and Checklist for Legislators. From the National Conference of State Legislatures.

The Restructuring of the Electric Power Industry
http://www.eia.doe.gov/cneaf/electricity/page/restructure.html
Select the title of the booklet. From the Energy Information Administration of DOE.

Restructuring the Electric Power Industry
http://www.nei.org
Select Library, Fact Sheets. From Nuclear Energy Institute

Congressional Research Service Reports (supplied by Committee for the National Institute for the Environment):
Electric Utility Restructuring Briefing Book
http://www.cnie.org/nle/eng-42
Links to a number of aspects of the subject.

Electric Utility Restructuring: Overview of Basic Policy Questions, by Larry B. Parker
http://www.cnie.org/nle/eng-37.html

Electricity: The Road Toward Restructuring, by Amy Abel and Larry Parker
http://www.cnie.org/nle/eng-7.html

Annual Energy Outlook with Projections to 2020
http://www.eia.doe.gov/oiaf/aeo
Report DOE/EIA-0383(2000) on all forms of energy.

25

International Nuclear Power

ALTHOUGH THE United States spearheaded research and development of nuclear power, its use in other parts of the world has expanded greatly. There are two reasons: (a) many countries do not have natural energy sources of coal and oil, and (b) some countries such as France and Japan have state-owned or strongly state-supported nuclear power systems. On the other hand, the distribution of use of nuclear power throughout the world is quite uneven. We shall now look at the global power situation and examine trends for large geographic or socioeconomic units–Western Europe, the Far East, the former U.S.S.R., and developing countries.

We will not be able to give a full and detailed account of the complex and changing energy situation abroad because of the many countries and organizations involved. Rather, we will concentrate on the status and trends of nuclear power plants. It turns out that the best information on international nuclear power is found on the World Wide Web. For data on the countries themselves consult the CIA World Factbook and World Information. For many of the nuclear facilities see The Virtual Nuclear Tourist. The features of many nuclear plants can be found from the International Nuclear Safety Center. For a complete list of nuclear organizations around the world, use the IAEA's INIS. The DOE Energy Information Administration provides a great deal of data on politics, economics, energy, and nuclear power.

In the decade of the 1990s, three major economic movements tended to dominate the nuclear electric industry of the world. These were privatization, globalization, and deregulation. In privatization, facilities are sold by a government to private industry in order to raise cash and potentially achieve better performance. Globalization involves the purchase of companies across national borders, for example Entergy of New Orleans buying London Electricity and then selling it to Electricité de France. Consolidation into multinational companies also is popular. Deregulation (also see Section 24.5) opens up new options for sources of supply of electrical energy to customers. The above three processes tend to make the nuclear power situation abroad more fluid and complex. In Europe, it is the European Union that is the driving force behind deregulation, rather than by states as in the U.S. Reviews and analyses are found in References.

At the social/political level, the strength of opposition to all aspects of nuclear energy has a decided influence on actions of politicians. The resultant conflict between government and industry in some countries results in stagnation or the demise of nuclear power.

25.1 Reactor Distribution

A review of the status of nuclear power in countries around the world is provided in Table 25.1, which shows the number of reactors and the megawatts of power for those in operation and under construction, for all nations that are committed to nuclear power. The damaged TMI-2 and Chernobyl reactors have been omitted from the table, but it includes some whose future is uncertain. The table should be treated as a snapshot of a status subject to change.

Several observations can be made about the table. The U.S. has about one-fourth of the reactors of the world. France, with its population around a fifth of that of the U.S., has by far the largest per capita usage of nuclear power. When construction is complete, France will produce nearly half as much nuclear electricity as the U.S. Japan has a growing nuclear power system, third in the world after the U.S. and France. Korea continues to add power plants. Except for a small program in South Africa, the continent of Africa is not represented; except for Brazil and Argentina, countries in Latin America have no power reactors. The developing nations of those regions may adopt nuclear power in the future. The People's Republic of China, in spite of its vast population, is just getting started on a power program.

Another perspective of the world's nuclear activities is provided by Figure 25.1, giving the percentage of the various countries' electricity that is supplied by nuclear power. The distributions of Table 25.1 and Figure 25.1 tend to reflect the status of technological development, with variations dependent on available natural resources and public acceptance. Finally, we note that two-thirds of the more than 100 countries of the globe do not have any plans for reactors.

25.2 Western Europe

A transition has occurred in power generation in Western Europe. More electricity there comes from nuclear than from any other power source.

The leading user of nuclear power in Europe is France. Its nuclear situation is dominated by the fact that the country does not have gas, oil, or coal, but does have some uranium. Power is supplied by one company, Electricité de France (EdF), which is making a profit and reducing its debt, in spite of a very large growth in facilities. All support for the French power

TABLE 25.1
World Nuclear Power as of December 31, 1999.
(Source: *Nuclear News*, American Nuclear Society, March 2000)

	Units Operating		Total	
Country	No.	MWe	No.	MWe
Argentina	2	935	3	1,627
Armenia	1	376	1	376
Belgium	7	5,680	7	5,680
Brazil	1	626	3	3,116
Bulgaria	6	3,538	6	3,538
Canada	22	15,149	22	15,149
China	3	2,079	11	8,549
Cuba	0	0	2	834
Czech Republic	4	1,648	6	3,610
Finland	4	2,656	4	2,656
France	55	57,393	59	63,203
Germany	20	22,326	20	22,326
Hungary	4	1,731	4	1,731
India	10	1,740	18	5,320
Iran	0	0	1	950
Japan	52	43,255	57	48,081
Lithuania	2	2,370	2	2,370
Mexico	2	1,308	2	1,308
Netherlands	1	452	1	452
North Korea	0	0	2	2,000
Pakistan	1	125	2	425
Romania	1	705	5	3,185
Russia	26	19,849	31	24,174
Slovakia	5	2,052	8	3,312
Slovenia	1	620	1	620
South Africa	2	1,842	2	1,842
South Korea	16	12,970	20	16,770
Spain	9	7,345	9	7,345
Sweden	12	10,075	12	10,075
Switzerland	5	3,170	5	3,170
Taiwan	6	4,884	8	7,484
Ukraine	15	13,045	20	17,795
United Kingdom	35	12,468	35	12,468
United States	104	98,030	107	101,633
Non-U.S.	330	252,412	389	301,541
Total	434	350,442	496	403,174

system is provided by two companies: Framatome for reactor design and construction, and Cogema for fuel supply and waste management. The Ecole Polytechnique provides the education of all of the operators and managers, and thus the common training is transferable between units.

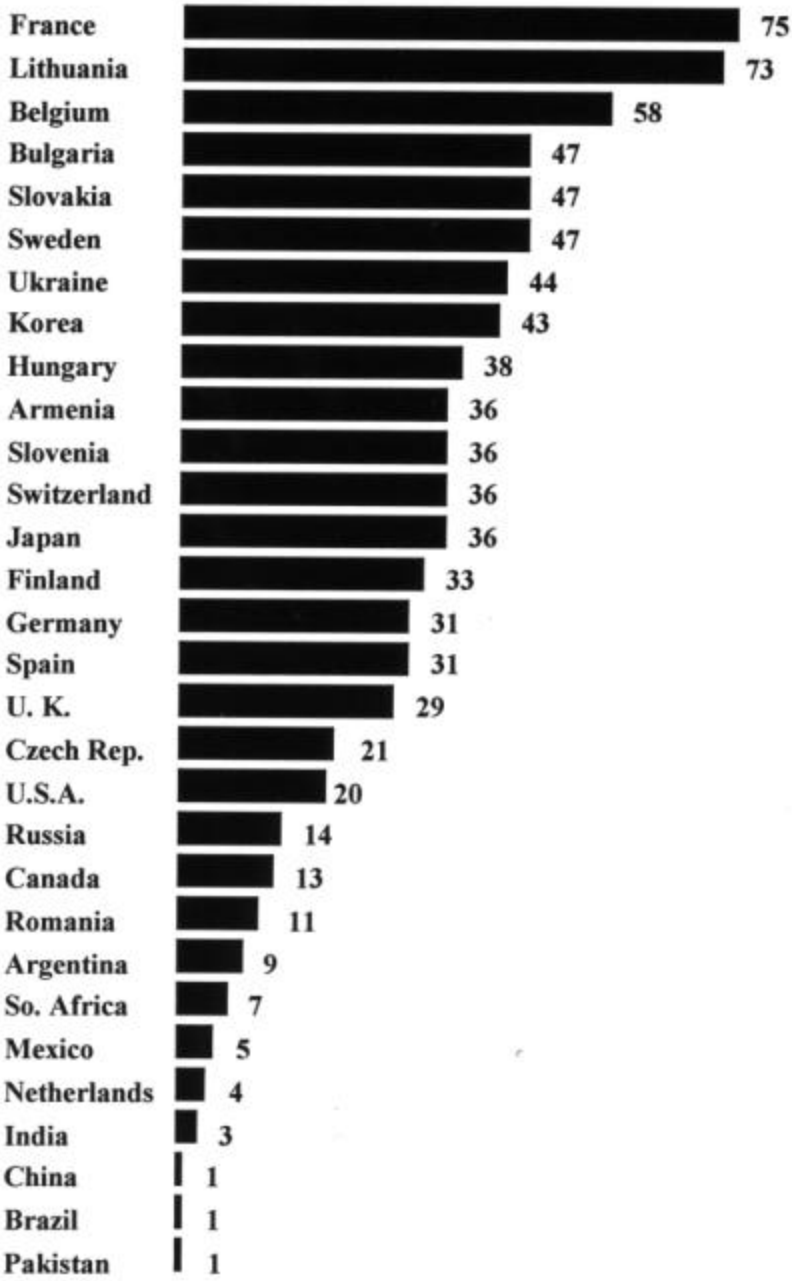


FIG. 25.1 Nuclear share of electricity generation, 1999. Numbers are percentages. (Source: IAEA)

Safety in reactor operation is thus enhanced. Because reactors are standardized and the system is state-owned, France is able to avoid the licensing and construction problems of the U.S. It only requires six years to build a nuclear power station. Over the years, there was little opposition to

nuclear power in France, in part because the state had provided attractive amenities to local communities while emphasizing the necessity of the power source for the nation's economy. EdF sells low-cost electricity to other countries, including the United Kingdom, using a cable under the English Channel. Lacking fossil fuel resources, France has focused on energy security through the production and use of nuclear power. Almost 80% of its electricity comes from its 58 reactors. The growth in nuclear has leveled, however, and public support has weakened. Political factors will determine whether France builds new reactors to replace older ones or phases nuclear out.

The fast breeder reactor Superphenix had operated successfully until sodium leaks caused it to be shut down, and attempts to revive the program failed. The lower power Phenix serves as a research vehicle.

With the unification of Germany in 1990, the nuclear power program of the former East Germany was suspended in the interests of safety. Operation of the remaining plants was very successful, with high capacity factors. Some electricity was available for export. A strong political opposition to nuclear power exists in some parts of Germany. Among the concerns are the purported danger of transportation of fuel cycle materials and the nuclear waste disposal problem. Through the influence of the Green Party, which prefers renewable energy, there are government plans to shut down prematurely the rest of the 19 nuclear power plants. It is not clear what will substitute for the current 30% nuclear.

In Belgium, the utility Electrabel provides generation and transmission as well as several other public services. A large fraction (57%) of the country's electricity is provided by nuclear plants. Cooperation with France continues.

Sweden had a strong nuclear R&D program, leading to 12 reactors that produced about half of the country's electricity. Following the TMI accident, a public referendum called for continuing operation of the plants. However, a decision was made not to expand nuclear power and pressure caused one reactor to be closed. Power needs were to be made up by importation. In light of concerns about CO_2 emissions and the adverse effects of additional hydroelectric power, the rest of the reactors may be allowed to continue operating. The complex situation is discussed in References.

Finland has two Soviet PWRs and two Swedish PWRs, all of which operate at very high capacity factors. The country has developed an effective underground nuclear waste storage system. Prospects for additional reactors are unlikely because of weak public support.

Switzerland enjoys very high reactor capacity factors, with an average of

around 85%. The Beznau plant is designed for district heating, providing 70 MWt heat power to 5000 households in six towns within a 13 km radius. Increased demand has been met by increasing the power rating of existing reactors and through import of more electricity from France. Some Swiss favor nuclear plants because they reduce coal imports and are free of pollution. However, antinuclear activists are seeking a referendum requesting decommissioning the five plants after 30 years of operation and extending the moratorium on new plants.

Spain is seeking to improve its economic condition through growth in electricity usage. It has made good progress, in spite of turmoil in the Basque region, where terrorist action forced suspension of construction on two reactors. The country has excellent facilities for production of nuclear equipment. A moratorium on new nuclear plants was set in 1983. Economic growth will rely on imported natural gas.

Portugal is expected to continue to rely on natural gas and does not intend to develop nuclear facilities.

The United Kingdom has a long history of using gas-cooled nuclear reactors for commercial electricity. For years, the cooperation of a state agency and a commercial organization worked well. In 1990, the nuclear industry was privatized, with British Energy buying facilities. The Sizewell B PWR was put into operation in 1996. It features a highly modern computer management system. A few of the older Magnox reactors are being phased out after several decades of operation. Britain maintains reprocessing facilities, serving Japan.

Italy adopted nuclear power at an early date, but after a public vote in 1987 mothballed or closed all of its reactors. The country relies on oil-fired plants and imported electricity. No nuclear generation is likely in the future.

The Netherlands produces only a small part of its electricity from reactors, and new reactors are unlikely.

Austria had completed one power reactor but never operated it because of a national referendum. The frustrated reactor operators decided to dismantle and sell the plant components.

The Western European nuclear power situation in general resembles that of the United States in that few new reactors are coming on line and there are no firm plans for an expansion of the energy source. A continued emphasis on service is expected.

25.3 Eastern Europe and the CIS

In the late 1980s the former Soviet Union was embarked on a nuclear power expansion program aimed at increasing electricity about 10% per year, with a long-range goal of around 100,000 MWe. It was expected that

the use of centralized factories making standardized designs and the use of specialist teams would permit construction times of less than 5 years.

With the advent of the Chernobyl accident and related adverse public reaction, and the economic stresses associated with the political changes in Eastern Europe, the planned program is unlikely to be met. The breakup of the Soviet Union in 1991 and the creation of the Commonwealth of Independent States (CIS) resulted in a new national distribution of reactors. There are reactors in Russia, Ukraine, and Lithuania. Several countries formerly allied with the Soviet Union were dependent on it for designs and technical assistance. Those that still have reactors are Armenia, Czech Republic, Slovakia, Hungary, Romania, and Bulgaria.

Russia has a number of the RBMK light-water-cooled graphite-moderated reactors still in operation. An equal amount of power comes from VVERs, and several newer reactors are coming on line. One fast breeder BN-600 reactor, Beloyarskiy, is in operation. Financial difficulties make it unlikely that Russia's hopes for expansion of nuclear power will be realized.

Ukraine has severe economic problems, including difficulty in buying fuel for its reactors. Fossil and nuclear plants each provide nearly half of its electricity. Most of the reactors are VVERs. Two of the Chernobyl RBMK reactors continue to operate in spite of urging from other countries to shut them down. Ukraine continues to anticipate a growth in nuclear power.

Lithuania's two reactors at Ignalina are of the RBMK type, like Chernobyl, and the European Union made closure of one of them as a condition for acceptance of Lithuania.

The reactor at Aktau in Kazakhstan was shut down after many years of operation. It was unique in that it was a fast breeder reactor and used its waste heat for desalination of water.

Armenia's one reactor was shut down because of concerns about earthquakes, but was started again because of an energy crisis. The European Union wants the plant closed for safety reasons.

The Czech Republic has a four-unit plant with modern VVERs, and two other reactors are under slow construction.

Poland started building a reactor in the 1980s but stopped after Chernobyl. Completion is uncertain.

Hungary has a four-unit Russian plant that provides a large fraction of the country's electric power. The country's policy includes developing nuclear energy resources.

Romania's one pressurized heavy water reactor built by Canada is operating, with four others only partially completed.

Bulgaria operates six Soviet-supplied PWRs, which have been criticized

for poor safety. Four are slated to be shut down, two are to be modernized, and a new one built.

Slovakia has several Russian VVER-440 reactors in operation, providing about half of the country's electricity, and other reactors are under construction. Safety is being upgraded with assistance by Siemens.

Slovenia, formerly part of Yugoslavia, has one PWR.

Concern has been expressed that the political and economic situation in Eastern Europe would result in more reactor accidents. It is generally conceded that reactors of Eastern Europe and the Commonwealth of Independent States are not as safe as West European or American reactors, and that in many cases maintenance and operating practices are not as rigorous. The countries have been urged to shut down some of the older reactors in the interests of safety, but have resisted on the grounds that the need for electric power is crucial. The U.S. and other nations are providing technical advice and financial assistance to the countries of the former U.S.S.R. Organizations in the U.S. include the Department of Energy, the Nuclear Regulatory Commission, the Nuclear Energy Institute. The countries of the European Union and the World Association of Nuclear Operators are also involved.

One justification for helping is the principle that "a reactor failure anywhere is a failure everywhere," reflecting extreme public sensitivity to reactor incidents. Another basis is enunciated by nuclear power commentator Simon Rippon†, "Help must be given to improve reactors in Eastern Europe and the CIS for one reason only: because the continued operation of the majority of these plants is vital to the economic survival of the countries concerned. The greater threat to the world at large is not of another Chernobyl, but the chaos that could ensue if the new Eastern economies fail."

25.4 The Far East

The principal user of nuclear power in the Far East is Japan. Government and industry have been committed to a successful nuclear program. Starting with a nuclear capacity of 33 GWe in 1991, Japan had hoped to reach 50 GWe by 2000 and 72.5 GWe by 2010. These goals are not likely to be reached, even though reactor construction times are low, slightly over 4 years. The operation of existing PWRs and BWRs has been highly efficient, a result of the Japanese work ethic, mutual company-employee trust, and attention to detail. Japan's national goal of becoming essentially energy-independent is to be met by use of facilities for enrichment, fabrication, reprocessing, and waste disposal. Reprocessing is

† In *Nuclear News*, August 1992.

justified on grounds of assuring a stable fuel supply rather than on economics. In recovering plutonium and burning it in LWRs or preferably fast breeders, Japan avoids large stockpiles of plutonium. Research is in progress on advanced PWRs, a breeder reactor, a high-temperature gas-cooled reactor (see References), and a tokamak fusion system. Several nuclear accidents in Japan have dampened enthusiasm for nuclear power expansion. A sodium leak occurred in the fast breeder MONJU and there was a fire and explosion in a reprocessing plant. In 1999 a criticality accident happened when operators put too much enriched uranium in a vessel. Fears of contamination of the vicinity were unfounded, but one worker died from radiation exposure. Nevertheless, in the long run, concerns in Japan about gaseous emissions from fossil plants may outweigh concerns involving radioactivity.

South Korea has achieved a very large growth in productivity over recent decades. Since it must import all of its oil and gas, it is expanding its nuclear power program. Four of the reactors are CANDUs, the rest PWRs from Westinghouse, ABB-CE, and Framatome. One reactor was designed and built with Korean technology. A dozen additional plants are planned before 2015.

North Korea has experienced very severe economic problems and relations with South Korea remain tense. Two light water reactors will be built for North Korea by a consortium of U.S., Japan, South Korea, and the European Union. This is in exchange for cessation of North Korea's graphite reactor program, which would be capable of producing weapons material.

Taiwan, being an island, has no electrical power connections to other countries and for its rapid transition from agriculture to industry it has been highly dependent on imported oil. More than half of Taiwan's electricity comes from nuclear plants. Three LWR plants are operating, and General Electric is supplying two Advanced Boiling Water Reactors, to be completed around 2005.

China's situation is different from that of many countries of the world. It has a tremendous need for electric power, its per capita consumption being about 3% that of the U.S. China's principal energy source is coal, creating serious environmental problems. A major hydroelectric dam giving 18.2 GWe is under construction. Expansion of nuclear power with the help of foreign firms is underway, but the added power will be minimal in terms of the large population and energy demand. The 300 MWe Qinshan-1 PWR is of indigenous design and construction. Two others were provided by Framatome of France. Russia is supplying a VVER-1000.

Plans for nuclear power plants in Indonesia and the Philippines have

been suspended.

25.5 Other Countries

Nuclear programs of selected countries of several continents are reviewed briefly.

India has one BWR and several pressurized heavy water reactors of around 200 MWe capacity, with others under construction. The government nuclear program (see References) plans for 20,000 MWe by 2020, including two Russian VVER-1000s. India's fast reactor experimental facility is fueled by Pu-U carbide with a thorium blanket, intended to test the use of the large indigenous reserves of thorium. A number of coal, gas, and hydro plants are planned.

Pakistan has a very low per capita electricity consumption, but has a growing demand. This will likely be met by hydroelectric power and coal. A small 300 MWe PWR supplied by China augments the older 125 MWe plant.

Turkey is seeking to expand its electric power, mainly by use of imported natural gas and by developing new hydro power. Several nuclear plants are planned as well.

An aggressive program of electrification in South Africa is designed to improve living conditions. It will be mainly based on coal. One nuclear station has two PWR reactors from Framatome.

The heavy-water moderated reactors of Canada operated very successfully for many years. The CANDU (Canada Deuterium Uranium) uses natural or very slightly enriched uranium in pressure tubes that permit refueling during operation. Very high capacity factors are thus possible. Canada has established a heavy water industry and uses uranium mined within the country. The government corporation Atomic Energy Canada Ltd. (AECL) provided heavy water reactors for Korea. Of Canada's 22 CANDU reactors, 8 have been shut down because of management and technical problems. Restart is problematic. There are no plans for expansion in Canada, since the sentiment is toward conservation and renewable energy sources.

Mexico has one nuclear plant at Laguna Verde on the Gulf of Mexico, with two General Electric BWRs.

Two Russian-built reactors of 408 MWe are planned for Cuba. The U.S. objects on safety grounds. A review of the whole situation is given by DOE/EIA (see References).

Brazil's nuclear electricity from a U.S. supplied reactor is only about one percent of the main source, hydroelectric. The country is recovering from its late 1990s financial crisis but the planned expansion to eight 1300

MWe reactors from West Germany's Kraftwerk Union has been seriously reduced because of Brazil's large foreign debt.

Argentina has ample oil, natural gas, and hydro potential. It has two reactors and another on the way, and thus leads South America in nuclear power. Over 10% of the country's electricity comes from nuclear.

The foregoing sections indicate that the rate at which nuclear power is being adopted varies greatly throughout the world, because each country has a unique situation. In some countries public opinion is a dominant factor; in others limited capital; in still others, especially developing countries, a lack of technological base. For several Latin American countries, large national debts are limiting. Despite problems, the amount of nuclear power abroad continues to grow slowly. Table 25.2 shows the number of reactors and their power for the sum of those in operation and under construction in two categories: U.S. and non-U.S. The total world power is almost the same at the end and beginning of the period. The decline in U.S. reactors from an initial share of 47% to a final share of 25% is closely matched by the rise in reactors abroad. The shift tends to parallel the decline in U.S. leadership in several areas of technology.

TABLE 25.2
Reactors Under Construction and Planned, for Ends of Years 1978-1999
(from issues of *Nuclear News*, American Nuclear Society)

	U.S.		Non-U.S.	
Year	No.	MWe	No.	MWe
1978	195	189,604	328	215,364
1979	189	182,015	341	223,753
1980	172	163,549	361	244,910
1981	166	157,654	363	244,422
1982	147	135,534	374	257,609
1983	139	128,507	389	275,003
1984	129	119,006	399	285,991
1985	129	118,962	407	293,919
1986	127	116,989	426	311,475
1987	126	116,939	438	320,231
1988	125	114,461	435	319,870
1989	119	109,012	427	311,450
1990	119	109,184	406	302,744
1991	119	109,307	392	296,919
1992	116	107,573	388	296,360
1993	116	107,906	390	298,352
1994	115	106,517	375	285,023
1995	113	104,453	382	290,304
1996	112	104,062	384	293,425
1997	108	101,582	387	298,021
1998	107	101,382	387	298,531
1999	107	101,633	389	301,541

25.6 Summary

The need for power and the lack of fuel resources in many countries has prompted the adoption of nuclear reactors for electric power. As of the end of 1999 there were 104 operating reactors in the U.S. and 330 abroad. The leading countries, in decreasing order of operating nuclear power, are the U.S., France, Japan, Germany, and Russia. The decline in U.S. reactors planned and under construction over the years is balanced by the rise in non-U.S. reactors.

25.7 References for Chapter 25

Privatization and the Globalization of Energy Markets
http://www.eia.doe.gov/emeu/pgem/contents.html
Discusses trends in many countries.

Electricity Reform Abroad and U.S. Investment
http://www.eia.doe.gov/emeu/pgem/electric
DOE report explaining processes and emphasizing privatization experience in Argentina, Australia, and the United Kingdom.

The World Factbook 1999
http://www.odci.gov/cia/publications/factbook
Information about all countries–geography, people, government, economy, communications, transportation, and transnational issues. By Central Intelligence Agency.

World Information
http://www.infoplease.com/a0107262
Facts and histories of countries.

International Nuclear Information System (INIS)
http://www.iaea.or.at/programmes/inis/ws/index.html
Links to all nuclear organizations by subject or by country. From International Atomic Energy Agency.

The Virtual Nuclear Tourist
http://www.cannon.net/~gonyeau/nuclear
Select Locations/World/Country-specific plant information and Photos.

European Nuclear Forums
http://www.foratom.org
Links to several forums, companies, government authorities, and research centers.

Nuclear Energy Agency
http://www.nea.fr
Nuclear arm of the Organisation for Economic Co-operation and Development (OECD), based in Paris, with 29 member countries, mainly in Europe, North America, and the Far East.

Energy Technology Data Exchange
http://www.etde.org
Select ETDEWEB for a large collection of documents. Membership is by registration. From International Energy Agency.

Nuclear Power Corporation of India, Ltd.
http://www.npcil.org/docs/plants.htm
Performance data for all plants.

Nuclear Energy in Sweden
http://www.uic.com.au/nip39.htm
A thoughtful paper from Australia's Uranium Information Centre.

International Nuclear Safety Center
http://www.insc.anl.gov or http://insp.pnl.gov:2080
Focus on Soviet-designed reactors: VVERs, RMBKs, and BNs. Restricted access for some data.
http://www.insc.anl.gov/maps/world.html
Click to find general locations (maps not clear).

NEI Source Book on Soviet-Designed Nuclear Power Plants, 5th Ed.
http://www.insc.anl.gov/neisb/neisb5
Download chapters or full document in pdf (1.4 MB, 362 pages). Program histories and situations; advantages and deficiencies of designs; actions being taken to upgrade.

International Energy Outlook
http://www.eia.doe.gov/oiaf/ieo99/nuclear.html
Nuclear Power section of report DOE/EIA-0484(99), covering all forms of energy.

The International Status of Nuclear Power
http://www.uic.com.au/nip07.htm
Briefing paper with a table of reactors (No. and MWe) with electricity generation and uranium required. From Australia.

Office of Nuclear Affairs of the French Embassy in Washington, DC
http://info-france-usa.org/nuclear/index.html
General information on nuclear power in France. Magnifique!

La Hague Reprocessing Plant
http://www.cogemalahague.fr
"We have nothing to hide from you (in French)"

Electricité de France (EDF)
http://www.edf.fr/html/fr/index.html
Operator of all nuclear plants in France.

Framatome
http://www.framatome.com/internet/framatome.nsf/internet/Sommaire_VINT
All about the world's leading nuclear manufacturer.

Cuba's Nuclear Reactors at Juragua
http://www.eia.doe.gov/cneaf/nuclear/cuba/main.html
A thorough overview and analysis.

High Temperature Engineering Test Reactor (Japan)
http://www.jaeri.go.jp/english/temp/temp.html
Description of reactor research program.

World Energy Database
http://www.eia.doe.gov/emeu/world/main1.html
Instructions for downloading data for report International Energy Annual.

Choosing the Nuclear Power Option: Factors To Be Considered, IAEA, Vienna, 1998.
Guidance on policy decisions for countries that may introduce nuclear power.

26

Nuclear Explosions

THE PRIMARY purpose of this book is to describe the peaceful and beneficial applications of nuclear energy. To attempt a discussion of the military uses is risky because of the emotional nature of the subject and the impossibility of doing justice to the complex problems involved. To neglect the subject, however, would be misleading, as if we wished to suggest that nuclear energy is entirely benign. Thus, we shall review some important facts and ideas about nuclear explosions and their uses, with three objectives:

(a) to distinguish between nuclear power and nuclear weapons;
(b) to identify the technical aspects and strategic issues involved in the military use of nuclear processes;
(c) to indicate the continued need for control of nuclear materials.

We shall describe nuclear explosions, nuclear weapons proliferation and safeguards, disarmament, and the options for disposal of weapons material.

26.1 Nuclear Power vs. Nuclear Weapons

In the minds of many people there is no distinction between reactors and bombs, resulting in an inordinate fear of nuclear power. They also believe that the development of commercial nuclear power in countries abroad will lead to their achievement of nuclear weapons capability. As a consequence of these opinions they favor dismantling the domestic nuclear industry and prohibiting U.S. commercial participation abroad.

Recalling some World War II history will help clarify the situation. The first nuclear reactor, built by Enrico Fermi's team in 1942, was intended to verify that a self-sustaining chain reaction was possible, and also to test a device that might generate plutonium for a powerful weapon. The experiment served as a basis for the construction of plutonium production reactors at Hanford, Washington. These supplied material for the first atom bomb test at Alamogordo, New Mexico, and later for the bomb dropped at Nagasaki. The reactors used generated heat but no electric power, and were designed to favor the production of plutonium-239. More recently, plutonium for weapons was produced by reactors at the Savannah River Plant in South Carolina.

Isotope separation production facilities at Oak Ridge during World War II yielded uranium enriched to about 90% U-235. The material was fabricated into the bomb used at Hiroshima. Subsequently, separation facilities have been used to give the 3-4% fuel for light water power reactors. Such fuel can be made critical when formed into rods and moderated properly with water, but it cannot be used for construction of a nuclear weapon. If the fuel is inadequately cooled while in a reactor, fission heat can cause cladding damage and, under worst conditions, fuel melting. The resultant chemical reaction with water bears no resemblance to a nuclear explosion. Therefore it can be stated positively that a reactor cannot explode like a nuclear bomb.

The spent fuel in a reactor contains a great deal of U-238, some U-235, Pu-239, Pu-240, and Pu-241, along with fission products. If this "reactor grade" plutonium is chemically separated and made into a weapon, the presence of neutrons from spontaneous fission of Pu-240 will cause premature detonation and an inefficient explosion. For this reason spent fuel is a poor source of bombs. A much more likely avenue to obtain "weapons-grade" plutonium is the dedicated research reactor, with low levels of neutron exposure to prevent Pu-240 buildup. Another favorable means is a specially designed separation method to obtain nearly-pure U-235. Neither of these approaches involves nuclear power reactors used for commercial electricity.

26.2 Nuclear Explosives

Security of information on the detailed construction of modern nuclear weapons has been maintained, and only a qualitative description is available to the public. We shall draw on unclassified sources (see References) for the following discussion of the earliest versions.

First, we note that two types of devices have been used: (a) the fission explosive ("atom bomb") using plutonium or highly enriched uranium and (b) the fusion or thermonuclear explosive ("hydrogen bomb"). The reactions described in earlier chapters are involved. Next, it is possible to create an explosive fission chain reaction by two different procedures–either by the "gun" technique or by "implosion." Figure 26.1 is a simplified sketch of the gun system, in which a plug of highly enriched uranium is fired into a hollowed-out cylinder of uranium, to produce a supercritical mass. A natural U "tamper" holds the combined materials together momentarily. This atom bomb was given the name Little Boy. Figure 26.2 is a sketch of the implosion method, in which high chemical explosives in the form of lenses compress a plutonium metal sphere to supercriticality. A uranium tamper is also used. This weapon was called Fat

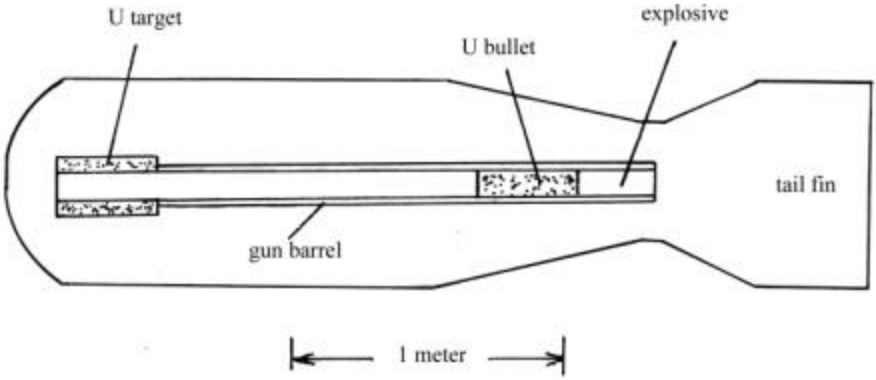


FIG. 26.1 Uranium fission nuclear weapon, gun type Little Boy.

Man. In either of these devices, an initial supply of neutrons is required. One possibility is the polonium-beryllium source, using the (a, n) reaction, analogous to Rutherford's experiment (Section 4.1). The excess reactivity of the supercritical masses causes a rapid increase in power and the accumulated energy blows the material apart, a process labeled "disassembly." In the case of implosion, when the fissile material is compressed there is an increase in ratio of surface to volume that results in larger neutron leakage, but a decrease in mean free path that reduces leakage. The latter effect dominates, giving a net positive increase of multiplication.

According to report ANL-5800 (see References) an unreflected spherical plutonium assembly has a critical mass of about 16 kg, while that of a highly-enriched (93.5%) uranium sphere is around 49 kg. By adding a one-inch layer of natural uranium as reflector, the critical masses drop to 10 kg and 31 kg, respectively. The critical mass of uranium with full reflector varies rapidly with the U-235 enrichment, as shown in Table 26.1. It is noted that the total mass of a device composed of less than 10 percent U-235 is impractically large for a weapon.

TABLE 26.1
Critical Masses of U-235 and U vs. Enrichment

% U-235	U-235 (kg)	U (kg)
100	15	15
50	25	50
20	50	250
10	130	1300

An appreciation of the effect on critical mass of an implosion that increases uranium density can be gained by the study of Computer Exercise 26.A.

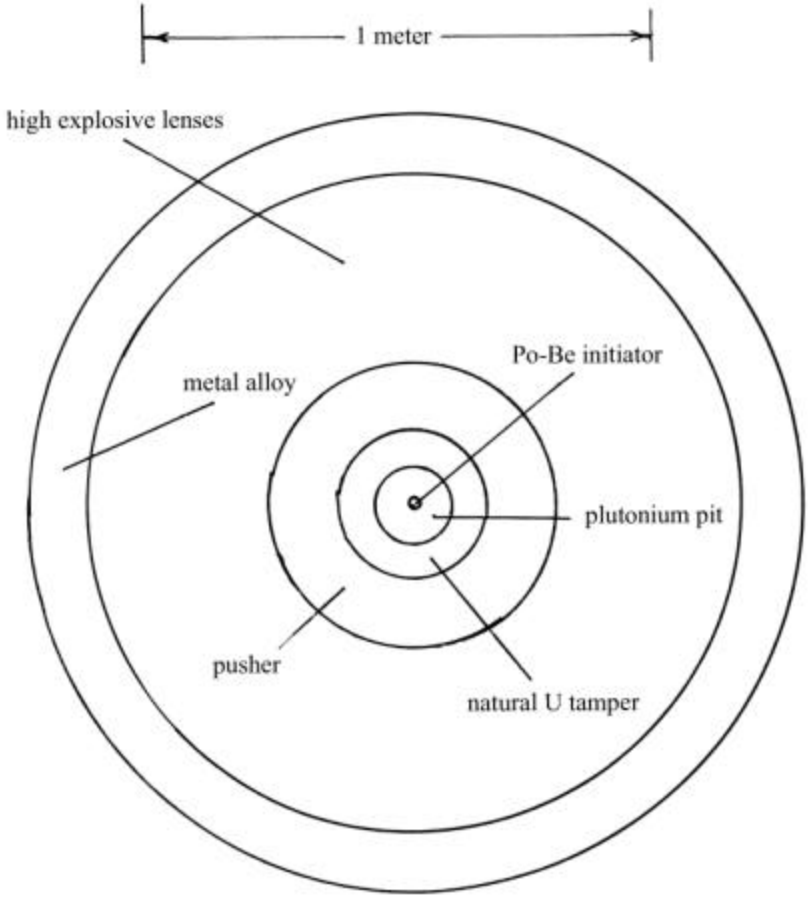


FIG. 26.2 Plutonium fission nuclear weapon, implosion type Fat Man.

Details of the compact and versatile modern thermonuclear weapons are not available, but we can describe the processes involved in the first hydrogen bomb explosion, the Ivy/Mike shot in the South Pacific in 1952. It included heavy hydrogen as fusion fuel, involving the two reactions also to be used in fusion reactors,

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \quad \text{or} \quad {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}\,. $$

The following description is an abbreviation of that found in the book *Dark Sun* (see References). As sketched in Figure 26.3, the unit called "Sausage" was a hollow steel cylinder 20 ft long and 6 ft 8 in. in diameter. The cavity was lined with lead. At one end of the cavity was a "primary" sphere of plutonium and enriched uranium that would be caused to fission by implosion. In the middle of the cavity was a cylindrical container of

liquid deuterium, much like a large thermos bottle. Along its axis was a stick of Pu called the "sparkplug", which served as a "secondary" fission source. The deuterium container was surrounded by a natural U "pusher." Finally, the inside of the casing was lined with polyethylene.

The sequence of events was as follows. An electrical discharge to detonators set off the high-explosive shell of the primary. A uranium tamper and shell vaporized and compressed the central plutonium ball while setting off a Po-Be source inside, releasing neutrons. X-rays from the resulting supercritical fireball heated the polyethylene to a plasma that re-radiated X-rays to heat the U pusher. Neutrons and energetic alpha particles were released in the heated deuterium and fission took place in the sparkplug. Some tritium was formed, which contributed to the fusion reaction. Additional energy and radiation came from fast neutron fission in the uranium-238 in the tamper. The resultant explosion created a crater 200 feet deep and a mile across.

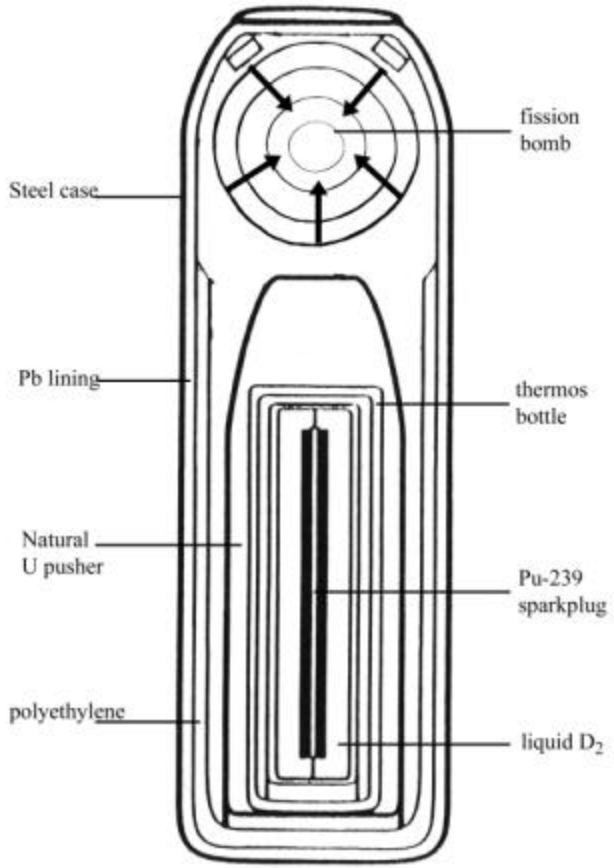


FIG. 26.3 Thermonuclear weapon (Adapted from Rhodes, see References).

In later weapon versions, the fusion component was composed of lithium deuteride. Neutrons from fission interact with the lithium-6 according to the equation

$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \rightarrow ^{3}_{1}\mathrm{H} + ^{4}_{2}\mathrm{He} + 4.8\,\mathrm{MeV}\,.$$

The tritium produced allows for the D-T reaction to occur. Other thermonuclear devices used tritium as the principal explosive material.

Nuclear explosives release their energy in several ways. First is the blast effect, in which a shock wave moves outward in air, water, or rock, depending on where the event occurs. Second is the thermal radiation from the heated surrounding material, at temperatures typically 6000°C. Finally, there is the nuclear radiation, consisting mainly of neutrons and γ rays. The percentages of the energy that go into these three modes are respectively 50, 35, and 15. There is a great deal of radioactive fallout contamination from fission products, in addition to the X- rays, γ rays, and neutrons.

The energy yield of a weapon is measured in equivalent tons of chemical explosive. By convention, 1 ton of TNT corresponds to 10^9 calories of energy. The first atom bomb had a strength of 20,000 tons. A smaller device of 3 kilotons was exploded underground in the Gnome test. A large cavity was created, as shown in Figure 26.4. The Ivy/Mike explosion gave 10.4 megatons. Tests of 50 megaton devices have been reported. The energy of explosion is released in a very short time, of the order of a microsecond.

The radiation effect of a nuclear explosion is extremely severe at distances up to a few kilometers. Table 26.2 shows the distances at which neutron dose of 500 rems is received for different yields.

TABLE 26.2
Distance-Yield Relation for Nuclear Explosion

Yield (tons)	Radius (meters)
1	120
2	450
10,000	1050
1,000,000	2000

Special designs of devices have been mentioned in the literature. Included are “radiological weapons” intended to disperse hazardous radioactive materials such as Co-60 and Cs-137. Another is the “neutron bomb,” a small thermonuclear warhead for missiles. Exploded at heights of about 2 km above the earth, it has little blast effect but provides lethal neutron doses.

By special arrangements of material in the fusion bomb, certain types of radiation can be accentuated and directed toward a chosen target. Examples of third-generation nuclear weapons could yield large quantities of lethal gamma rays or electromagnetic pulses (EMP) that disrupt solid state

FIG. 26.4 Underground cavity created by the *Gnome* fusion explosion, part of the Plowshare program. Note the person standing near the center. (Courtesy of Lawrence Livermore National Laboratory, U.S. Department of Energy).

electronic circuits. More detailed diagrams and descriptions of fission and fusion bombs are found in the book by Hansen (see References).

A consequence of a major exchange of nuclear missiles near the earth's surface would be an increase in the particles suspended in air. Part would be dust created by the blast; part would be smoke from fires in forests and other combustibles ignited by the heat. As a result, the amount of sunlight reaching the ground would be reduced, causing cooling of the atmosphere. The situation has been called "nuclear winter" by some investigators, who predict serious modification of the climate, with a reduction in agricultural production. Such an effect occurred in the early 1800s as the result of the

eruption of a volcano. The subject of atmospheric cooling has been studied a great deal, but there is disagreement among scientists as to the magnitude of the effect. The original theory was criticized for failure to take proper account of self-correcting processes, including increased precipitation that would tend to dispel dust and smoke.

26.3 The Prevention of Nuclear War

The nuclear arms race between the U.S. and the U.S.S.R. that began after World War II was stimulated by mutual suspicion and fear, and by technological advances in nuclear weapons. Each of the superpowers sought to match and to exceed the other's military capability.

As of 1945 the U.S. clearly had nuclear weapons superiority, but by 1949 the U.S.S.R. had developed its own atom bomb. After considerable controversy the U.S. undertook to develop the hydrogen bomb (Super bomb, or "Super") using thermonuclear fusion, and by 1952 had restored the advantage. By 1953 the Soviets had again caught up. In the ensuing years each country produced very large numbers of nuclear weapons. If deployed by both sides in an all-out war, with both military and civilian targets, hundreds of millions of people would die.

The policy adopted by the two powers to prevent such a tragedy was deterrence, which means that each country maintains sufficient strength to retaliate and ruin the country that might start a nuclear war. The resultant stalemate is given the term "mutual assured destruction" (MAD). This "balance of terror" could be maintained unless one country develops an excessive number of very accurate missiles, and chooses to make a first strike that disables all retaliatory capability.

The methods by which nuclear warheads can be delivered are: (a) carried by bombers, such as the U.S. B-52; (b) intercontinental ballistic missiles (ICBMs) launched from land bases; and (c) missiles launched from submarines such as the *Poseidon* and *Trident*, which are later versions of the first nuclear submarine, *Nautilus*.

The ICBM is propelled by rocket, but experiences free flight under the force of gravity in the upper atmosphere. The nuclear warhead is carried by a reentry vehicle. The ICBM may carry several warheads (MIRV, multiple independently targetable reentry vehicles), each with a different destination.

An alternative is the cruise missile, an unmanned jet aircraft. It can hug the ground, guided by observations along the way and by comparison with built-in maps, and maintaining altitude by computer control (see References)

There are two uses of nuclear weapons. One is tactical, whereby limited and specific military targets are bombed. The other is strategic, involving

large-scale bombing of both cities and industrial sites, with intent both to destroy and to demoralize. Most people fear that any tactical use would escalate into strategic use.

Thousands of nuclear warheads have been available to the superpowers for many years, with the number of megatons equivalent TNT per weapon ranging from 0.02 to 20. The area that could be destroyed by all these weapons is around 750,000 square kilometers, disrupting each country's functions such as manufacturing, transportation, food production, and health care. A civil defense program would reduce the hazard, but is viewed by some as tending to invite attack.

The international aspect of nuclear weapons first appeared in World War II when the Allies believed that Germany was well on its way to producing an atomic bomb. The use of two weapons by the United States to destroy the cities of Hiroshima and Nagasaki alerted the world to the consequences of nuclear warfare. Many years have been devoted to seeking bilateral or international agreements or treaties that seek to reduce the potential hazard to mankind. The increase in fallout from nuclear weapons testing prompted the Limited Test Ban Treaty of 1963. It forbade nuclear tests in the air, water, or space, and the United States and the Soviet Union thereafter conducted all testing underground. However, this treaty did not control the expansion in nuclear arms.

In 1968 an international treaty was developed at Geneva with the title Non-Proliferation of Nuclear Weapons (NPT). The treaty is somewhat controversial in that it distinguishes states (nations) that have nuclear weapons (NWS) and those that do not (NNWS). The main articles of the treaty require that each of the latter would agree (a) to refrain from acquiring nuclear weapons or from producing them, and (b) to accept safeguards set by the International Atomic Energy Agency, based in Vienna. The treaty involves an intimate relationship between technology and politics on a global scale and a degree of cooperation hitherto not realized. There are certain ambiguities in the treaty. No mention is made of military uses of nuclear processes as in submarine propulsion, nor of the use of nuclear explosives for engineering projects. Penalties to be imposed for noncompliance are not specified, and finally the authority of the IAEA is not clear. The treaty has been signed by five NWS (U.S., Russia, Great Britain, France, and China) and 180 NNWS. In 1995 the NPT was extended indefinitely. India was a signatory as NNWS but proceeded to develop and test a nuclear weapon.

The nuclear weapons states (NWS) can withhold information and facilities from the nonnuclear weapons states (NNWS) and thus slow or deter proliferation. To do so, however, implies a lack of trust of the

potential recipient. The NNWS can easily cite examples to show how unreliable the NWS are.

We have already discussed in Section 22.5 the attempt by President Carter to prevent proliferation. By banning reprocessing in the U.S. he had hoped to discourage its use abroad. It is continuing U.S. policy to prohibit the sale to foreign countries of sensitive equipment and materials, those believed to be adaptable for construction of nuclear weapons. If the policy is extended to the transfer of legitimate nuclear power technology, however, such policies can be counterproductive, for several reasons. International relations suffer, and the U.S. loses any influence it might have on nuclear programs. Perceived inequity may strengthen a country's determination to achieve weapons capability and to seek alternative alliances that further that goal.

Negotiations began in 1967 on Strategic Arms Limitation Talks (SALT) and an accord was signed in 1972. SALT I led to a ceiling on strategic nuclear weapons and thus tended to achieve equality in strength. However, it said nothing about continued improvements in missiles. It restricted the deployment of Antiballistic Missile (ABM) defense systems. Each nation was allowed to defend its capital and one other location.

The SALT II agreement between leaders of the two nations in 1979 dealt with detailed limits on types of launchers and missiles, including the MIRV type. It placed emphasis on preserving the ability of both sides to verify compliance. The treaty was never ratified by the U.S. Congress, and talks were not resumed.

In 1983, a program of detection and interception of nuclear missiles was initiated by President Ronald Reagan. This research and development effort was called Strategic Defense Initiative (SDI) but soon became known popularly as "Star Wars" because of its space implications. In this multibillion dollar project, various devices were proposed and studied, including earth satellite weapons platforms, X-ray laser beams, small tactical nuclear bombs, and "smart pebbles," small high speed objects that could destroy incoming missiles. The SDI program was controversial for technical reasons having to do with feasibility and political reasons related to the wisdom of mounting the program. Some believe, however, that it had a favorable influence on the achievement of an end to the Cold War.

Negotiations continued over the years, leading to the Intermediate-Range Nuclear Force Treaty (INF) of 1988, in which a number of missiles were destroyed in the U.S. and U.S.S.R., with inspection teams from the other country functioning smoothly. Two new sets of accords called Strategic Arms Reduction Talks (START) were developed in the Reagan-Bush era. The use of the word "reduction" instead of "limitation" is

significant. The number of warheads under these agreements is as follows:

Country	Original	After START I	After START II
U.S.	9,986	8,500	3,000-3,500
Ex-U.S.S.R.	10,232	6,500	3,000-3,500

With progress in arms reduction, the Star Wars program became less relevant and was greatly scaled down. The elimination of thousands of warheads was an important step in terms of world safety, but there still remain enough weapons for mutual destruction. The breakup of the Soviet Union left ICBMs in the independent states of Ukraine, Belarus, and Kazakhstan, but agreement was reached to transfer the weapons to Russia. Internal economic, political, and ethnic tensions make control difficult. Concern has been expressed also that weapons scientists and engineers of the former U.S.S.R. may be induced for economic reasons to emigrate to nations seeking nuclear capability, e.g., Libya, Iran, Iraq, and North Korea.

Another byproduct of the international political changes is the purchase by the U.S. from Russia of highly enriched uranium (HEU) from dismantled nuclear weapons, to be converted by blending into low-enriched uranium (LEU) for use in power reactors. Several virtues accrue: financial benefit to Russia, diversion of weapons grade material to peaceful purposes, and relief from the necessity by the U.S. to expand isotope separation capability. Computer Exercise 26.B considers the arithmetic of the process by which HEU is diluted into reactor grade uranium and investigates cost aspects of a U.S. purchase from Russia.

26.4 Nonproliferation and Safeguards

We now discuss proliferation of nuclear weapons and the search for means to prevent it. Reducing the spread of nuclear materials has recently become more important as the result of increases in political instability and acts of violence throughout the world.

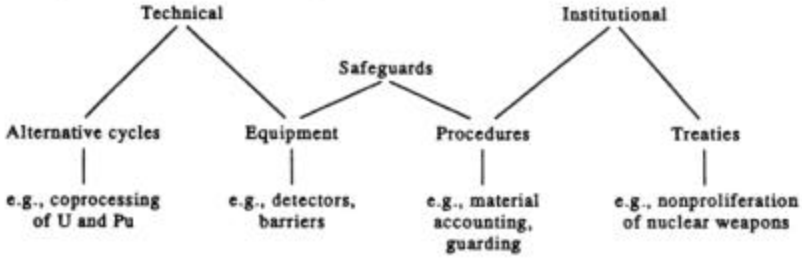
To prevent proliferation we can visualize a great variety of technical modifications of the way nuclear materials are handled, but it is certain that a country that is determined to have a weapon can do so. We also can visualize the establishment of many political institutions such as treaties, agreements, central facilities, and inspection systems, but each of these is subject to circumvention or abrogation. It must be concluded that nonproliferation measures can merely reduce the chance of incident.

We now turn to the matter of employment of nuclear materials by organizations with revolutionary or criminal intent. One can define a spectrum of such, starting with a large well-organized political unit that seeks to overthrow the existing system. To use a weapon for destruction might alienate people from their cause, but a threat to do so might bring about some of the changes they demand. Others include terrorists groups,

criminals, and psychopaths who may have little to lose and thus are more apt to use a weapon. Fortunately, such organizations tend to have fewer financial and technical resources.

Notwithstanding difficulties in preventing proliferation, it is widely held that strong efforts should be made to reduce the risk of nuclear explosions. We thus consider what means are available in Table 26.3, a schematic outline.

TABLE 26.3
Nonproliferation Measures



Protection against diversion of nuclear materials involves many analogs to protection against the crimes of embezzlement, robbery, and hijacking. Consider first the extraction of small amounts of fissile material such as enriched uranium or plutonium by a subverted employee in a nuclear facility. The maintenance of accurate records is a preventive measure. One identifies a material balance in selected process steps; e.g., a spent-fuel dissolver tank or a storage area. To an initial inventory the input is added and the output subtracted. The difference between this result and the final inventory is the material unaccounted for (MUF). Any significant value of MUF prompts an investigation. Ideally, the system of accountability would keep track of all materials at all times, but such detail is probably impossible. Inspection of the consistency of records and reports is coupled with independent measurements on materials present.

Restricting the number of persons who have access to the material and careful selection for good character and reliability is a common practice. Similarly, limiting the number of people who have access to records is desirable. It is easy to see how falsification of records can cover up a diversion of plutonium. A discrepancy of only 10 kg of plutonium would allow for material for one weapon to be diverted. Various personnel identification techniques are available such as picture badges, access passwords, signatures, fingerprints, and voiceprints.

Protection against intruders can be achieved by the usual devices such as ample lighting of areas, use of a guard force, burglar alarms, TV monitoring, and barriers to access. More exotic schemes to delay, immobilize, or repel attackers have been considered, including dispersal of

certain gases that reduce efficiency or of smoke to reduce visibility, and the use of disorienting lights or unbearable sound levels.

Illegal motion of nuclear materials can be revealed by the detection of characteristic radiation, in rough analogy to metal detection at airports. A gamma-ray emitter is easy to find, of course. The presence of fissile materials can be detected by observing delayed neutrons resulting from brief neutron irradiation.

In the transportation of strategic nuclear materials, armored cars or trucks are used, along with escorts or convoys. Automatic disabling of vehicles in the event of hijacking is a possibility.

26.5 IAEA Inspections

Shortly after the Nonproliferation Treaty of 1968 was signed, the International Atomic Energy Agency set up a worldwide safeguards system. It applied to all source materials (uranium and thorium) and special fissionable materials (plutonium and uranium-233). The primary purpose of IAEA inspections has been to detect the diversion of significant quantities of nuclear material from peaceful to military purposes. Over the years since 1970 a large number of nondestructive portable instruments have been developed to carry out the surveillance. Gamma ray and neutron detectors are used to determine the enrichment of uranium and the content of plutonium in spent fuel.

The role of IAEA was highlighted in the 1991 investigation of the nuclear weapons program of Iraq under Saddam Hussein, under the auspices of the United Nations Security Council. Large amounts of uranium had been imported from other countries without being reported. Orders were placed abroad for equipment that could have a dual purpose. As revealed by IAEA inspectors, such equipment was channeled into the construction of modern versions of electromagnetic uranium isotope separators (Section 9.1), to centrifuges, and to reactors and reprocessing equipment for plutonium weapons production. In support of the field investigations after the end of the Gulf War, laboratory studies at the IAEA's laboratories in Austria were conducted. Samples taken by inspectors were found to contain as high as 6% enrichment in U-235. A particle spectral measurement confirmed the presence of polonium-210, which is a component of an initiator for an implosion-type nuclear weapon. Much of Iraq's nuclear capability was destroyed in the Gulf War and afterward, in response to sanctions by the United Nations. However, some may still be intact and efforts to rebuild may be underway.

On a long-range basis, the IAEA is concerned about the possibility that a repository for spent fuel, intended to isolate the waste from the biosphere,

may in fact become a "plutonium mine" in some future era, when energy shortages become acute and fissile materials become a very valuable commodity.

Various other countries are known or suspected of having or have at one time had nuclear weapon programs. Prominent among the lists given by Jones and Mc Donough and by Morrison and Tsipsis (see References) are Israel, India, Pakistan, North Korea, Iran, Iraq, and Libya.

The Comprehensive Test Ban Treaty (CTBT) of 1996 seeks international agreement not to "carry out any nuclear weapon test explosion or any other nuclear explosion." This means underground tests as well as those in the air, on water, or in space, even those for peaceful purposes. Excluded are explosions by inertial fusion devices or the destruction of any terrorist weapon. The treaty also calls for a system of monitoring and inspection to verify compliance. Ratification is required by the 44 states that either helped draft the document or have power reactors or research reactors. Many countries have signed, but not all have ratified. The treaty seems to have public support in the U.S. but some claim that acceptance by the U.S. would hamstring defense, while some nations would violate the treaty. For details on CTBT, see References.

26.6 Production of Tritium

Over the many years of the Cold War, the Department of Energy and its predecessors had maintained a stockpile of weapons material, especially tritium and plutonium. The isotope H-3, tritium, as one of the ingredients of the hydrogen bomb, was produced in heavy water reactors at the Savannah River Plant in South Carolina. Because of safety concerns, the reactors were shut down. A program of refurbishing the old reactors was undertaken, and as supporting capacity to produce a continuing supply of 12.3 year tritium, a development program called "New Production Reactor" was started. Two types of reactors were designed–a heavy water reactor and a high temperature gas-cooled reactor. With the reduction in international tension, the U.S. determined that tritium supplies would be adequate for two decades and suspended design of the new reactors. At the time, it was thought possible to use the supply from dismantled weapons. Subsequently, however, it was decided that an alternative supply was needed to maintain the stockpile, since tritium has a half-life of 12.3 y, corresponding to a loss of 5.5 percent a year. Consequently, DOE sponsored two studies of production techniques using either a power reactor or a particle accelerator. One of these must be put in place by the year 2005.

The production in a conventional reactor by neutron bombardment involves burnable poison rods. These are auxiliary to the main control,

containing an isotope of large thermal neutron cross section such as boron-10, which burns out quickly and allows a larger initial fuel loading. It was proposed by DOE to replace the boron rods with an appropriate number containing lithium-6. These target rods would consist of concentric cylinders of zircaloy, lithium aluminide, and stainless steel. Absorption of a neutron in Li-6, with thermal cross section 940 barns, yields tritium and an alpha particle. Tests at the Tennessee Valley Authority reactors indicated that production of tritium would be adequate and that the reactor would operate safely.

Research is underway on a program called Accelerator Production of Tritium (APT) at Los Alamos. Protons bombard tungsten targets in which spallation (Section 8.7) gives a copious supply of neutrons. A surrounding blanket contains lead (for neutron multiplication), water (to moderate neutrons), He-3 (to absorb neutrons and form tritium), and aluminum (to enhance efficiency). The proposed design has a 100 mA beam of 1700-MeV protons and with 75 percent operation yields around 3 kg of tritium per year. For further information see References.

26.7 Management of Weapons Uranium and Plutonium

During the Cold War both the U.S. and the U.S.S.R accumulated large amounts of highly-enriched uranium and weapons-grade plutonium. A program of dismantlement is under way as part of the START treaties. An excess of these materials over that needed for continued nuclear deterrence will be disposed of in some way. It has been estimated that there is a total of 100 tonnes of Pu and 200 tonnes of U, roughly in equal amounts in the two countries. The enriched uranium can be readily diluted with natural uranium to produce a low-enrichment fuel, helping meet the demand of current and future power reactors. The plutonium is not as easy to handle because there are no Pu isotopes to serve as diluent. Thus the stockpiles of Pu are vulnerable to diversion to nations or groups who might use, or threaten to use, the material to gain their ends.

The plutonium of principal concern is in pure form in contrast with that present in spent fuel. The latter would require special equipment to extract the Pu and the product would be less suitable for a weapon because of the presence of Pu-240.

Plutonium is far from being “the most dangerous substance known to man,” as claimed by some, but it is highly radiotoxic and requires special precautions in all handling. Use of Pu increases the chance of radioactive contamination as was experienced at various DOE sites, especially at Rocky Flats, Colorado.

There are several possibilities for managing the plutonium. Some

believe that it should be stored in anticipation of a need for its energy values some time during the 21st century. One could visualize a storage facility like Fort Knox where gold and silver are secured. Storage over a long period would require protection against chemical attack and accidental criticality, as well as from theft.

A National Academy of Sciences (NAS) panel composed of prominent knowledgeable people identified three principal options: (a) vitrification of the Pu with a highly radioactive contaminant to deter diversion and processing. This would result in glass logs that could be treated as spent fuel and put in an underground repository. Future mining of the Pu would be very unattractive. (b) Blending the plutonium as the oxide with a suitable amount of uranium oxide to form mixed oxide (MOX) that could serve as fuel for power reactors. This would eliminate the plutonium and have the advantage of a beneficial use. The disadvantage is the cost of processing and fabrication, which is significantly higher than that for uranium because of the hazard of ingesting the radioactive material. This approach requires the development of a suitable fuel fabrication plant. Several countries, notably France, England, Belgium, and Japan, are in a position to prepare and use the MOX, whereas the U.S. has little experience or inclination to use it, having abandoned the option of reprocessing spent fuel. (c) To place the Pu in a deep drilled hole in the ground. Although this is feasible, there is no strong support for the idea. The NAS panel also examined the option of using an accelerator-driven subcritical system to burn the plutonium, but concluded that there were too many uncertainties, including the possible need for reprocessing. The NAS recommended carrying along options (a) and (b) in parallel, a strategy that was adopted by the Department of Energy.

For disposal of Pu by immobilization and burial, a criterion called the "spent fuel standard" is applied, i.e., the Pu should be as inaccessible for weapons use as that in spent fuel from commercial reactors.

It is expected that the burning option would consist of a once-through fuel cycle. To use up the 50 tonnes of excess Pu in a reasonable period would require relatively few commercial reactors. It is straightforward arithmetic to determine the combination of time and number of reactors to perform the task. See Exercise 26.3.

Whatever method of disposal is finally adopted, meticulous procedures and records must be maintained, and special rigorous precautions taken to prevent the material getting into unscrupulous hands. The NAS report urged that agreements be reached between the U.S. and Russia, and mechanisms established through the IAEA that would assure that each nation fulfilled its commitments. This would reduce mutual concerns that one party might

retrieve Pu and re-arm nuclear weapons.

When one realizes the enormous damage that nuclear explosions can create, it is clear that all possible steps must be taken to prevent them from occurring. In addition to continued efforts to reduce the stockpile of armaments, to secure workable treaties, and to utilize technology to provide protection, there is an urgent need to eliminate all the unfavorable conditions–social, economic, and cultural–that prompt conflict in the world.

26.8 Summary

Although spent fuel from power reactors contains plutonium, it is not the same as a nuclear weapon. The original atom bombs used U-235 and Pu, but the much more powerful modern weapons are based on the fusion of hydrogen isotopes. Intercontinental ballistic missiles from land and missiles from submarines make up the bulk of the arsenals of the U.S. and the former U.S.S.R. Continual efforts are made to prevent further proliferation of nuclear weapons. It is imperative that nuclear explosions be avoided.

26.9 Exercises

26.1. The critical mass of a uranium-235 metal assembly varies inversely with the density of the system. If the critical mass of a sphere at normal density 18.5 g/cm^3 is 50 kg, how much reduction in radius by compression is needed to make a 40 kg assembly go critical?

26.2. A proposal is advanced to explode fusion weapons deep underground, to pipe to the surface the heat from the cavity produced, and to generate and distribute electricity. If no energy were lost, how frequently would a 100 kiloton device have to be fired to obtain 3000 MW of thermal power? Alternatively, how many weapons per year would be consumed?

26.3. Find out how many commercial reactors would be needed to consume 50 tonnes of Pu in 30 years, assuming the following data: reactor power 1000 MWe, efficiency 0.33, capacity factor 0.75, 60 assemblies removed and new ones installed per year, three year irradiation to fuel burnup 30,000 MWd/tonne, fuel weight per assembly 1000 lb, one-third of new fuel containing MOX at 2.5 percent Pu. Note: there are two ways to solve the problem.

Computer Exercises

26.A. The implosion of a mass of fissionable material can be studied by use of the computer program FASTR, introduced in Chapter 13. It is a neutron multigroup method for calculating criticality in a pure U-235 metal assembly.

(a) Calculate the critical size and mass for several values of the uranium density, including higher densities than normal as would be achieved by implosion of a nuclear warhead. Suggested values of the parameter UN (line 2310) besides 0.048 are 0.036 and 0.060.

(b) From the results of (a) above, deduce a good value of x in a formula for critical mass as a function of metal density of the form

$$M = M_0(r/r_0)^x$$

where M_0 is the critical mass at ordinary density r_0.

26.B. Arrangements are made for the purchase by the U.S. of Russian uranium at enrichment 94 w/o to be blended with natural U to create 3 w/o fuel for power reactors. Using computer program ENRICH3 (Chapter 9), estimate a fair price to pay per kilogram of HEU if the

blending is done (a) in Russia, or (b) in the U.S. If importation amounts to 10 tonnes/y for 5 years followed by 30 tonnes/y for 15 years, which would take about half the stockpile, what is the total worth in each case? What additional information would be useful to arrive at a proper figure?

26.10 References for Chapter 26

Robert Serber, *The Los Alamos Primer*, University of California Press, Berkeley, 1992. A set of five lectures on the early (1943) state of knowledge on the possibility of an atom bomb, with extensive explanatory annotations. Included are history, nuclear physics, and chain reactions.

Reactor Physics Constants, ANL-5800, 2nd Ed., U.S. Atomic Energy Commission, Washington, DC, 1963. Data on critical masses in Section 7.2.1.

Richard Rhodes, *The Making of the Atomic Bomb*, New York, Simon & Schuster, 1986. Thorough, readable, and authoritative, this is regarded as the best book on the Manhattan Project.

Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb*, Simon & Schuster, New York, 1995. Highly readable political and technical aspects. Role of espionage. Diagrams of H-bomb explosion on p. 506.

Chuck Hansen, *U.S. Nuclear Weapons: The Secret History*, Aerofax, Arlington, TX, 1988. Very detailed descriptions with many photos of all weapons and tests. Diagram of H-bomb explosion on p. 22.

The High Energy Weapons Archive
http://www.fas.org/nuke/hew/index.html
In FAQ by Carey Sublette select 8.0 The First Nuclear Weapons. From Federation of American Scientists.

Nuclear Resources
http://www.fas.org/nuke/index.html
Nuclear forces around the world; arms control; pictures and charts of U.S. nuclear warheads. Many links. From the Federation of American Scientists.

Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook*, Vol. I ,*U.S. Nuclear Forces and Capability*, Ballinger Publishing Co., Cambridge, MA, 1984. Facts and figures on weapons and delivery systems.

Samuel Glasstone and Philip J. Dolan, Compilers and Editors, *The Effects of Nuclear Weapons*, 3rd edition, U.S. Department of Defense and U.S. Department of Energy, U.S. Government Printing Office, Washington, DC, 1977.

Susan Thaul and Heather O'Maonaigh, Editors, *Potential Radiation Exposure in Military Operations*, National Academy Press, Washington, DC, 1999. Information and recommendations.

The Effects on the Atmosphere of a Major Nuclear Exchange, Committee on the Atmospheric Effects of Nuclear Explosions, National Academy Press, Washington, DC, 1985.

Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options, National Academy Press, Washington, DC, 1995. Describes options for Pu use and disposal

with recommendation that two be carried along in parallel. A limited-edition Executive Summary was also published in 1994.

K. K. S. Pillay, "Plutonium: Requiem or Reprieve," *Radwaste Magazine*, American Nuclear Society, January 1996 (Vol. 4, No. 3, pp. 59-65).

Accelerator Production of Tritium Project
http://apt.lanl.gov
Select Basic Information on APT

Ballistic Missile Defense Technologies, Office of Technology Assessment, Congress of the United States, U.S. Government Printing Office, Washington, DC, 1985.

James E. Nolan and Albert D. Wheelon, "Third World Ballistic Missiles," *Scientific American*, August 1990, p. 34.

Kosta Tsipis, "Cruise Missiles," *Scientific American*, Vol. 236, No. 2, February 1977, p. 20.

Dietrich Schroeer, *Science, Technology, and the Nuclear Arms Race*, John Wiley & Sons, New York, 1984.

IAEA Bulletin Vol. 32, No. 1, 1990, Safeguards and nuclear energy; Vol. 34, No. 1, 1992, Safeguards and non- proliferation. Issues of the magazine of the International Atomic Energy Agency dealing with the history, present status, and future of the organization. The second issue contains reports on the 1991 IAEA inspections in Iraq.

Lawrence Scheinman, *The Nonproliferation Role of the International Atomic Energy Agency: A Critical Assessment*, Resources for the Future, Washington, DC, 1985. Explains, notes problems, and suggests initiatives.

Comprehensive Test Ban Treaty
http://www.fas.org/nuke/control/ctbt/index.html
Full text, perspective, analysis, and commentary. From Federation of American Scientists.

Rodney W. Jones and Mark G. McDonough, et al., *Tracking Nuclear Proliferation: A Guide in Maps and Charts, 1998*, Carnegie Endowment for International Peace, Washington, 1998.

Stephen Schwartz, Ed., *Atomic Audit: The Costs and Consequences of U.S. Nuclear Weapons Since 1940*, Brookings Institute Press, Washington, DC, 1998. Highly critical of secrecy, carelessness, and waste of money.

Philip Morrison and Kosta Tsipis, *Reason Enough To Hope: America and the World of the Twenty-first Century*, MIT Press, Cambridge, MA, 1998. Recommends reduction of military forces and emphasis on Common Security.

Lawrence Livermore National Laboratory
http://www.llnl.gov
Select Web Site Map/Science and Technology/Research Areas.

Nuclear Weapons Systems Sustainment Programs
http://www.defenselink.mil/pubs/dswa
U.S. National Security Strategy.

Chuck Hansen's The Swords of Armageddon
http://www.uscoldwar.com
Describes contents of a comprehensive CD-ROM on nuclear weapons.

MILNET: Nuclear Weapons
http://www.milnet.com/milnet/nuclear.htm
Essays on several topics.

27

The Future

> We should all be concerned about the future because we will have to spend the rest of our lives there (Charles F. Kettering).

THE ILLS of the nuclear industry in the United States might be cured in the near future by one or more of the technical or administrative medicines described in a previous chapter. The assumption was implicit that it was desirable and necessary to preserve and extend the nuclear option in the U.S.

There are several broader questions:

What should be the role of nuclear power in the United States in the more distant future in comparison with other energy sources?

What will be the use of nuclear energy sources on a global and long-term basis?

What will be the ultimate energy source for mankind, after fossil fuels are gone?

To answer such questions fully goes beyond the writer's capability and the intended scope of this book. We shall be content to outline the dimensions of the nuclear role and to make some observations and suggestions.

There are several ways to look at the future. The first is acceptance, as by a fatalist, who has no expectation either of understanding or of control. The second is prediction, based on belief and intuition. The third is idealization, as by a utopian, who imagines what would be desirable. The fourth is analysis, as by a scientist, of historical trends, the forces that are operative, and the probable effect of exercising each of the options available. Some combination of these views may be the answer, including the realization that the future always will bring surprises. Nevertheless, if the human species is to survive and prosper, we must believe we have some control of our destiny, and take positive action to achieve a better world.

The oil crisis of 1973 involving an artificial shortage alerted the world to the importance of energy. A number of studies were published. Some of these are still relevant; others are very much out of date. Only a few will be cited here in References. In subsequent years, prices of oil declined, the oil supply was adequate, and natural gas became abundant, so public concern

relaxed, and few updates of the studies were made. Other reasons for reservations about the literature of the 1970s and 1980s can be cited.

1. Principal emphasis has been on the situation in the U.S. or in developed countries, with less attention to developing countries.

2. Various investigators come to quite different conclusions even if they use the same data, depending on their degree of pessimism or optimism. At one extreme is the book *The Limits to Growth* and later works (called "doomsday" studies), and the upbeat energy reports of the Hudson Institute (see References)

3. Extrapolations of data can be very wrong, as evidenced by predictions on the growth of nuclear power made in the 1960s.

4. Sharp differences exist between writers' opinion on the future role of nuclear power. For example, Worldwatch Institute dismisses it at the outset, while the U.S. National Academies view it as a desirable option.

5. Analyses may be irrelevant if they do not take account of social and political realities in addition to technical and economic factors.

In the next section, we identify some of the factors that need to be considered in planning for the energy future.

27.1 Dimensions

Many aspects of the world energy problem of the future affect nuclear's role. We can view them as dimensions since each has more than one possibility.

The first is the time span of interest, including the past, present, immediate future (say the next 10 years), a period extending well into the next century, and the indefinite future (thousands or millions of years). Useful markers are the times oil and coal supplies become scarce.

The second is location. Countries throughout the world all have different resources and needs. Geographic regions within the U.S. also have different perspectives.

The third is the status of national economic and industrial development. Highly industrialized countries are in sharp contrast with underdeveloped countries, and there are gradations in between the extremes. Within any nation there are differences among the needs and aspirations for energy of the rich, of the middle class, and of the poor.

The fourth is the political structure of a country as it relates to energy. Examples are the free enterprise system of the U.S., the state-controlled electricity production of France, the centrally-planned economy of the People's Republic of China, and the transitional economy of the Commonwealth of Independent States.

The fifth is the current nuclear weapons capability, the potential for

acquiring it, the desire to do so, or the disavowal of interest.

The sixth is the classification of resource available or sought: exhaustible or renewable; and fossil, solar, or nuclear.

The seventh is the total cost to acquire resources and to construct and operate equipment to exploit them.

The eighth is the form of nuclear that will be of possible interest: converters, advanced converters, breeders, actinide burners, accelerators, and several types of fusion devices, along with the level of feasibility or practicality of each.

The ninth is the relationship between the effect of a given technology on social and ethical constraints such as public health and safety and the condition of the environment.

The tenth is the philosophical base of people as individuals or groups, with several contrasting attitudes: a view of man as central vs. man as a part of nature; preference for simple lifestyle vs. desire to participate in a "high-tech" world; pessimism vs. optimism about future possibilities; and acceptance vs. abhorrence of nuclear. In addition, cultural and religious factors, national pride, and traditional relationships between neighboring nations are important.

27.2 World Energy Use

The use of energy from the distant past to the present has changed dramatically. Primitive man burned wood to cook and keep warm. For most of the past several thousands of years of recorded history, the only other sources of energy were the muscles of men and animals, wind for sails and windmills, and water power. The Industrial Revolution of the 1800s brought in the use of coal for steam engines and locomotives. Electric power from hydroelectric and coal-burning plants is an innovation of the late 1800s. Oil and natural gas became major sources of energy only in the twentieth century. Nuclear energy has been available for only about 50 years.

In order to think about the future, as a minimum it is necessary to understand the present. Data on energy production and usage are available from the U.S. Department of Energy and on population from the U.S. Bureau of the Census. Table 27.1 gives world consumption by geographic region. Of special note is the disparity in per capita consumption. Since productivity, personal income, and standard of living tend to follow energy consumption, the implications of these numbers for the human condition in much of the world is evident. The data on ratio of consumption and production confirm our knowledge that the Middle East is a major energy supplier through petroleum and shows that Western Europe and the Far East are quite dependent on imported energy.

A breakdown of the electrical production according to primary energy source by region is given in Table 27.2. We see that there is essentially no nuclear power in Africa or South America. Of that in the Far East, most is in Japan and Korea.

TABLE 27.1
World Primary Energy, 1998

Region	Consumption (10^{15} Btu)	Per capita (GJ)	Consumption/Production
Africa	11.8	16	0.45
North America	112.6	296	1.13
Central & South America	19.7	51	0.79
Far East & Oceania	99.3	32	1.32
Western Europe	69.5	155	1.60
Eastern Europe & FSU	49.0	132	0.84
Middle East	15.9	105	0.29
World	377.7	67	0.99

Source: *International Energy Annual*, DOE/EIA (see References)

TABLE 27.2
World Annual Electricity Production by Type (1997, Billions of kWh)

Region	Thermal	Hydro	Nuclear	Other*	Total
Africa	304	63	13	-	380
North America	2692	729	716	86	4223
Central & So. America	160	512	10	14	696
Far East & Oceania	2531	500	436	40	3508
Western Europe	1267	502	250	50	2659
East Europe & FSU	1019	249	250	1	1520
Middle East	334	19	-	-	353
World	8307	2574	2266	192	13340

*geothermal, biomass, solar, and wind
Source: *International Energy Annual*, DOE/EIA (see References)

TABLE 27.3
World Population Data, 1998

	Millions of inhabitants	Fertility rate	Life expectancy
Africa	761	5.4	51
North America	301	2.0	76
Latin America	507	2.8	69
Asia	3363	2.7	65
Near East	166	4.4	69
Europe	798	1.5	72
Oceania	30	2.4	72
World	5927	2.9	63

Source: *World Population Profile: 1998*, U.S. Bureau of the Census.

Predictions have been made on world future energy consumption patterns. Figure 27.1 is taken from the report. It shows that between 2000 and 2020 the use of natural gas increases greatly while that of nuclear rises somewhat but then declines. The projection may not take enough account

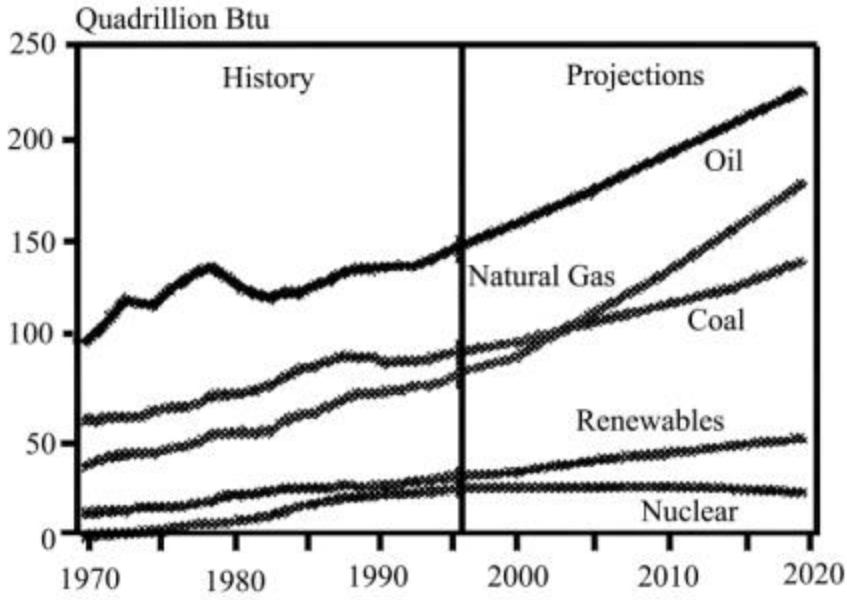


FIG. 27.1 World energy consumption, 1970-2020.
Source: *International Energy Outlook 1999*, DOE/EIA-0484(99).

of eventual acceptance of the virtue of nuclear power in avoiding gaseous emissions.

Data on world population are shown in Table 27.3. Note that Latin America includes the Caribbean. The fertility rate is defined as the number of children per woman. It is seen to be highest in underdeveloped regions. The trend of population in the future depends crucially on that parameter, as shown in Figure 27.2. The three growth projections involve fertility rates that vary with country and with time. The "high" case leads to a world population of 11 billion by the year 2050. The population in developed countries is expected to become flat.

27.3 Nuclear Energy and Sustainable Development

Throughout history there has been little concern for the environment or human welfare. European countries systematically extracted valuable resources from Mexico, South America, and Africa, destroying cultures on the way. In the expansion to the west in the U.S., vast forests were cleared to provide farmland. The passenger pigeon became extinct, and the bison nearly so. Slavery flourished in the U.S. until 1865. Only after European countries lost their colonies after world wars did African nations and India gain autonomy.

The environmental movement of the 1960s was stimulated by the book *Silent Spring* by Rachel Carson. That overuse of resources could be harmful was revealed by Garrett Hardin's essay "The Tragedy of the Commons." As

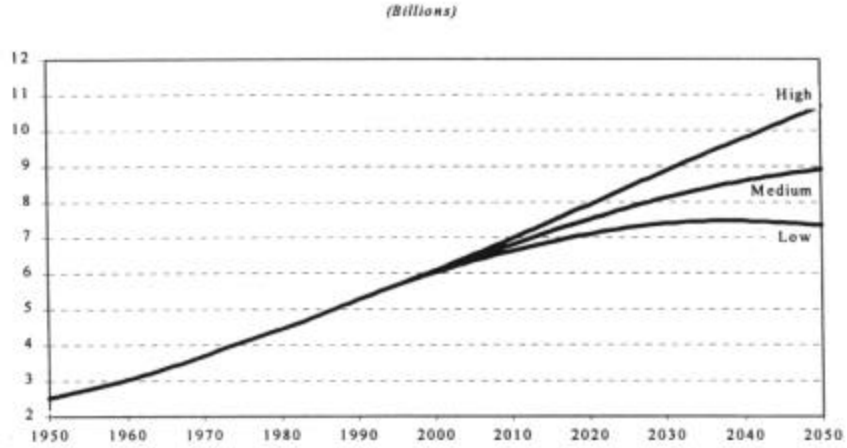


FIG. 27.2 Past and projected world population growth, 1950-2050, with three fertility scenarios. Source: *World Population Prospects: The 1998 Version*, United Nations, New York, 1999.

early as 1798 Malthus had predicted that exponential growth of population would exceed linear growth of food supply, leading to widespread famine. The idea was revived using sophisticated computer models by the Meadows, et al., in *The Limits to Growth* (see References), which predicted the collapse of civilization under various pressures associated with continued growth.

Finally, in the 1970s and 1980s the United Nations sponsored several international conferences on global problems and potential solutions. Out of these came the concept of "sustainable development." The phrase gained great popularity among many organizations that were concerned with the state of the world. The original definition of the term was "...meets the needs of the present without compromising the ability of future generations to meet their own needs." As noted by Reid (see References) the phrase can be interpreted to support business-as-usual or to require drastic cutbacks. However, it generally implies conserving physical and biological resources, improving energy efficiency, and avoiding pollution, while enhancing living conditions of people in developing countries. Ideally, all goals can be met. The subject is broad in that it involves the interaction of many governments, cultures, and economic situations. Several conferences have been held under United Nations auspices to highlight the issues, obtain agreements, and map out strategies. One prominent conference was the Earth Summit held in Rio de Janeiro in 1992, which included Agenda 21, a list of 2000 suggestions for action. A follow-up appraisal of results was made in 1997 (see References). Progress since is monitored by a "watch" organization (see References).

One might be pessimistic and question whether there is any hope of

achieving the desired improvements in light of failure over half a century. Or one might be optimistic that the concept can bring all parties together in a concerted effort and ultimate breakthrough.

A potential cure for a runaway population and continued misery is improved economic conditions. However, the gap between conditions in rich and poor countries persists, and no improvement is in sight. The problem has become more complex by the concerns about the environment related to the destruction of the rain forest in Central and South America. There are no easy solutions, but a few principles seem reasonable. Protection of the environment is vital, but it should not thwart the hopes of people in underdeveloped countries for a better life. It is obvious that simple sharing of the wealth would result in uniform mediocrity. The alternative is increased assistance by the developed countries, in the form of capital investment and technological transfer. This must be done recognizing the principle that the people of the country being helped should lead the program to improve.

There was a time in the past when international cooperation and assistance was considered to be highly desirable. The post-World War II Marshall Plan brought Germany and Japan back to a high level of productivity and prosperity. The Peace Corps effected improvements in many countries. The Atoms for Peace program of President Eisenhower in the 1950s provided nuclear information and assistance to dozens of countries, forming the basis of the international nuclear industry. The trend in recent years has been in the opposite direction, with emphasis on U.S. industrial competitiveness and U.S. leadership in world politics. It is quite possible that greater stability in the world would result from efforts to find more ways to cooperate–through partnerships of commercial organizations, bilateral national agreements, and arrangements developed under United Nations auspices.

One would expect that a philosophy that embraces human rights and supports justice would be implemented by major efforts to help less fortunate people around the world. But even if the motivation were only enlightened self-interest, helping bring up standards of living should open new markets for goods and services, and avoid the problem of competing products based on cheap labor.

Success in effecting improvements depends on the means by which help is provided. An issue to resolve is whether to help developing countries shape an overall economic and social plan that includes energy management or to advise how energy should be handled in the country's own plans.

Technology can be introduced in two ways: (a) supplying devices that are appropriate to the receiving country's urgent needs, and that are

compatible with existing skills to operate and maintain equipment; or (b) supplying equipment, training, and supervision of sophisticated technology that will bring the country quickly to industrial status. Arguments for and against each approach can easily be found. It is possible that both should be followed, to provide immediate relief and further the country's hopes for independence.

Advanced countries have applied restrictions to the transfer of nuclear technology to some developing nations, in an attempt to prevent the achievement of nuclear weapons capability. Third World countries resent such exclusion from the opportunity for nuclear power.

One major objective of sustainable development is the improvement of human health in developing countries. If nuclear medicine for diagnosis and treatment were expanded universally, it could make a great difference to the health of people such as those in Africa. For countries that cannot afford to import coal, oil, and natural gas, the introduction of nuclear power for widespread supply of electricity could facilitate pollution-free industrial and commercial development while enhancing human comfort. Nuclear plants can be built to utilize the waste heat for desalination of sea water, providing safe water for human consumption. For such to be implemented, a reactor type is needed that avoids the high capital cost of conventional light water reactors, requires little maintenance, and is passively safe.

27.4 Greenhouse Effect and Global Climate Change

The greenhouse effect is one of the processes by which the Earth is warmed. Sunlight of short wavelength can readily pass through water vapor and gases such as carbon dioxide in the atmosphere. Energy is absorbed by the Earth's surface, which emits long wavelength infrared radiation that is stopped by the vapor and gases. The effect accounts for an increase in natural temperature of about 30°C. Figure 27.3 shows the energy flows for the effect.

There is good evidence that the carbon dioxide content of the air has increased from a pre-industrial level of 200 ppm to a current value of around 350 ppm. Less certain is the amount of temperature change over that period because of natural fluctuations related to sun activity, volcanic dust, and shifting ocean currents.

Greenhouse gases are the collection of natural and manmade substances including water (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorochlorocarbons. Each of these have been increasing in concert with industrialization and increased biomass burning. Estimates have been made of a possible increase of 3°C to 8°C in global temperature by the middle of the 21st century if action is not taken. Consequences of

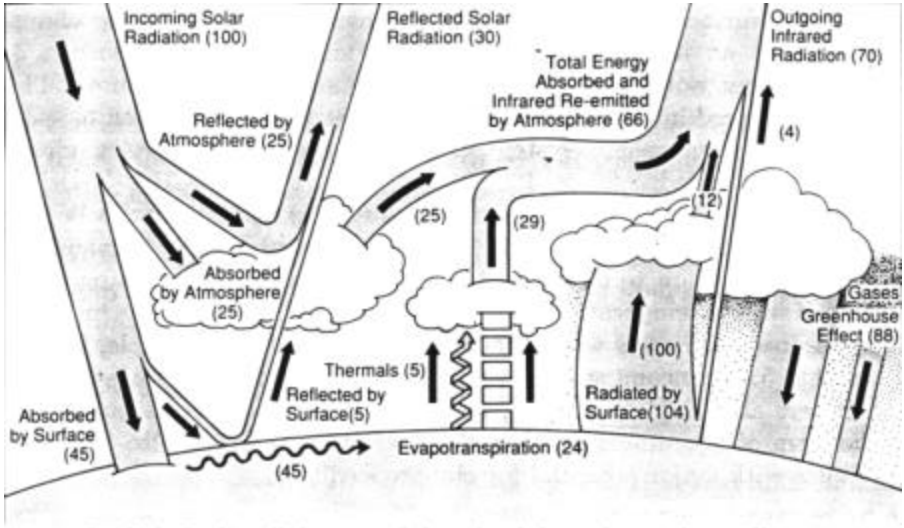


FIG. 27.3 Earth's radiation energy balance in relation to the greenhouse effect. Numbers are percentages of incoming sunlight (From Schneider, see References)

such global warming that have been proposed are: more severe weather including droughts, storms, and floods; higher incidence of tropical disease; and a melting of ice near the poles that would cause a rise in ocean level that would inundate coastal cities.

International concern led to the Kyoto Protocol of December 1997, which calls for a reduction in carbon emission by all countries, with different percentages for each. The U.S. would be expected to reduce seven percent from 1990 levels. Many nations have signed the treaty but few have ratified it.

The subject of global warming is controversial for several reasons. Some believe the potential consequences are so severe that it is urgent to take immediate action. Waiting for additional confirmation through research is considered to be too late. Others are concerned about the worldwide economic disruption that might be caused by drastic reduction of energy production to meet Kyoto goals. Opposition to action has been expressed in the U.S. about the low limits on emission by developing countries. The U.S. Congress has refused to ratify the Protocol on the grounds that it is unfair and if implemented could seriously affect the economy. From a scientific viewpoint, some believe that there is no real correlation between CO_2 increase and global temperature, that the modeling of trends is yet inadequate in that it does not take proper account of the role of clouds or the absorption of carbon in the ocean, and that the computer models have not been able to reproduce past history correctly.

Many suggestions have been advanced as to what to do if global

warming occurs: (a) use energy efficient equipment; (b) expand the use of electric vehicles; (c) convert from coal to natural gas; (d) levy carbon taxes; (e) initiate emission trading among countries; (f) stop deforestation and expand reforestation; (g) develop hydroelectric, solar, and wind power systems; (h) relicense nuclear power plants and construct the advanced designs, actions obviously supported by the nuclear industry.

Singer (see References) recommends a program of adaptation if necessary, noting that if there were global warming it could result in more evaporation of water from the oceans and ice accumulation in Greenland and Antarctica. He favors research on the sequestering of carbon by fertilization of the ocean to enhance the population of phytoplankton, a side effect of which would be an increased supply of food fish.

The nuclear industry calls attention to the fact that nuclear reactors provide electric power without any emission of carbon dioxide or other greenhouse gases. This gives a rationale for the continued operation of nuclear power plants, for extending life through relicensing, and for building new plants. Country data are presented by Australia on the weights of annual carbon release currently avoided by use of nuclear throughout the world (see References). The total is 2270 million tons.

A number of reports, books, and web pages provide ample reading material on the subject (see References).

27.5 Perspectives

Let us examine the role of nuclear energy in the global sense over centuries by developing a qualitative but logical scenario of the future. Any analysis of world energy requires several ingredients–an objective, certain assumptions, a model, necessary constraints, input data, performance criteria, and output information.

A primary assumption is that fossil fuels will ultimately become excessively expensive: oil within a few decades and coal within a century or so. Thus the objective of a meaningful analysis must be to effect a smooth transition from present dependence on fossil fuels to a stable condition that uses resources that are essentially inexhaustible or are renewable.

One constraint vital to the analysis is that a minimum first level of sufficient energy must be available to provide mankind's needs for food, shelter, clothing, protection, and health. This status corresponds to an agrarian life using locally available resources, little travel, and no luxuries. A desirable second level is an energy that will provide a quality of life that provides transportation, conveniences, comforts, leisure, entertainment, and opportunities for creative and cultural pursuits. This situation corresponds to an abundant life of Americans living in the suburbs and working in a

city, amply supplied with material goods and services. It is mandatory that the first level be assured and that the second level be sought for all people of the world. This goal implies existing differences between conditions in developed and developing nations should be eliminated to the best of our ability.

Conservation provides a means for effectively increasing the supply of energy. Experience has shown that great savings in fuel in developed countries have resulted from changes in lifestyle and improvements in technology. Examples that work are the use of lower room temperatures in winter, shifts to smaller automobiles with more efficient gasoline consumption, increased building insulation, energy-efficient home appliances and industrial motors, and electronically controlled manufacturing. Unfortunately the move to larger vehicles in the U.S. is in the wrong direction. There remains considerable potential for additional saving, which has many benefits–conservation of resources, reduced emission of pollutants, and enhanced industrial competitiveness. Finally, there is limited applicability of the concept to underdeveloped countries, where more energy use is needed, not less.

Protection of the environment and of the health and safety of the public will continue to serve as constraints on the deployment of energy technologies. The environmental movement has emphasized the damage being done to the ecology of the rain forest in the interests of development, the harm to the atmosphere, waters, and land from industrial wastes, and the loss of habitats of endangered or valuable species of wildlife. Air pollution due to emissions from vehicles and coal-fired power plants pose a problem in cities. Less well known is the release of radioactivity from coal plants, in amounts greater than those released from nuclear plants in normal operation. Although a core meltdown followed by failure of containment in a nuclear plant would result in many casualties, the probability of such a severe accident is extremely low. In contrast, there are frequent deaths resulting from coal mining or offshore oil drilling. There is an unknown amount of life-shortening associated with lung problems aggravated by emissions from burning coal and oil.

Eventually, people will appreciate the fact that no technology is entirely risk-free. Even the production of materials for solar energy collectors and their installation result in fatalities.

The use of electric power is growing faster than total energy because of its cleanliness and convenience. It is wasteful to use electrical power for low-grade heat that could be provided by other fuels. However, it is likely that the growth will be even more rapid in the future as computer-controlled robot manufacturing is adopted worldwide.

The needs for transportation in developed countries absorb a large fraction of the world's energy supply, largely in the form of liquid fuel. Petroleum serves as a starting point also for the production of useful materials such as plastics. In order to stretch the finite supply and give more time to develop alternatives, several conservation measures are required. Examples are more efficient vehicles and expansion of public transportation. Later, as oil becomes scarce, it will be necessary to obtain needed hydrocarbons by liquefying coal. This need suggests that coal should be conserved. Rather than expanding coal-fired electrical production, nuclear reactors could be built.

In the more distant future, as coal itself becomes scarce, fluid fuel would have to be produced from biomass, the production of which would inevitably compete with the production of food. An attractive alternative for transportation needs is the electric vehicle, powered by batteries charged by electrical power from a nuclear power plant, based either on fission or on fusion.

Nuclear energy itself may very well follow a sequential pattern of implementation. Converter reactors, with their heat energy coming from the burning of uranium-235, are inefficient users of uranium since enrichment is required and spent fuel is disposed of. Breeder reactors in contrast have the potential of utilizing most of the uranium, thus increasing the effective supply by a large factor. Sources of lower uranium content can be exploited, including very low-grade ores and the dissolved uranium in sea water, since almost all of the contained energy is recovered. In order to maintain an ample supply of uranium, storage of spent fuel accumulated from converter reactor operation should be considered instead of permanent disposal by burial as a waste. Conventional arguments that reprocessing is uneconomical are not as important when reprocessing is needed as a step in the planned deployment of breeder reactors. Costs for storage of spent fuel should be examined in terms of the value of uranium in a later era in which oil and coal are very expensive to secure. Eventually, fusion using deuterium and tritium as fuel may be practical, and fusion reactors would supplant fission reactors as the latter's useful lives end.

Because of the chemical value in the long term of natural gas, oil, and coal, burning them to heat homes and other buildings seems entirely wasteful. Electricity from nuclear sources is preferable. Resistance heating involves use of a high-quality energy for a low-grade process, and it would be preferable to employ heat pumps, which use electricity efficiently for heating purposes. As an alternative, it may be desirable to recover the waste heat from nuclear power plants for district heating. To make such a coupling feasible, excellent insulation would be required for the long pipes

from condenser to buildings, or the always-safe power plant would be built in close proximity to large housing developments.

Solar energy has considerable potential as a supplement to other heat and electricity sources for homes and commercial buildings, especially where sunlight is abundant. Direct energy solar boilers or arrays of photovoltaic cells are promising sources of auxiliary central-station power, to be used in parallel with nuclear systems that augment the supply at night. The large variations in output from solar devices can also be partially compensated for by thermal storage systems, flywheels, pumped water storage, and compressed gas.

The ultimate system for the world is visualized as a mixture of solar and nuclear systems, with distribution dependent on climate and latitude. Breeder reactors or fusion reactors would tend to be located near large centers of manufacturing, while the smaller solar units would tend to be distributed in outlying areas. Solar power would be very appropriate for pumping water or desalination of sea water to reclaim desert areas of the world. Other sources, such as hydroelectric, geothermal, and wind, would also be employed where those resources exist.

A conclusion that seems inevitable is that every source of energy imaginable should be used in its appropriate niche in the scheme of things. The availability of a variety of sources minimizes the disruption of life in the event of transportation strike or international incident. Indeed, availability of several sources that can be substituted for one another has the effect of reducing the possibility of conflict between nations. Included in the mix is extensive use of conservation measures. A corollary is that there should be a great deal of recycling of products. The reclamation of useful materials such as paper, metals, and glass would be paralleled by treating hazardous chemical wastes to generate burnable gas or application as fuel for the production of electricity.

Another conclusion from the above scenario is that a great deal of research and development remains to be done to effect a successful transition. Resources of energy and materials are never completely used up; they merely become harder to acquire, and eventually the cost becomes prohibitive. We shall discuss in our final section some possible research and development projects that could lead to the identification of new resources and discovery of better ways to use existing ones.

The effects of the status of the world of various assumptions and actions related to energy can be examined by application of program FUTURE in Computer Exercise 27.A.

27.6 Research and Development

The oil embargo of 1973, in which limits were placed on shipments from producing countries to consuming countries, had a sobering effect on the world. It prompted a flurry of activity aimed at expanding the use of alternative energy sources such as solar, wind, biomass, and oil shale, along with conservation. Easing of the energy crisis reduced the pressure to find substitutes, and as oil prices fell automobile travel increased. Use of energy in general is dominated by current economics. If prices are high, energy is used sparingly; if prices are low, it is used freely without concern for the future. Ultimately, however, when the resource becomes more and more scarce and expensive its use must be curtailed to such an extent that social benefits are reduced. If no new sources are found, or if no renewable sources are available, the quality of existence regresses and man is brought back to a primitive condition. The use of fossil fuels over the long term is dramatically portrayed by the graph of Fig. 27.4, presented by Hubbert around forty years ago but no less meaningful today.

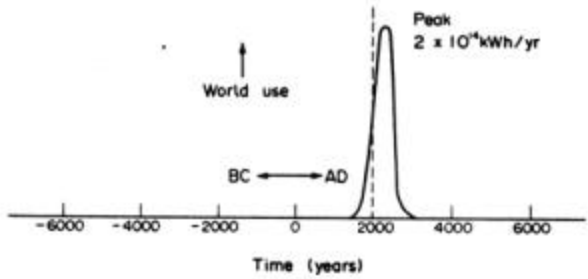


FIG. 27.4 The epoch of fossil fuels. (Adapted from *Energy Resources: A Report to The Committee on Natural Resources*, M. King Hubbert, National Academy of Sciences – National Research Council, Washington, D.C., 1962.)

Future civilizations will be astounded at the careless way the irreplaceable resources of oil, natural gas, and coal were wasted by burning, rather than used for the production of durable and recyclable goods.

International tensions are already high because of the uneven distribution of energy supplies. The condition of the world as supplies become very scarce is difficult to imagine. To achieve a long-term solution of the energy problem, money and effort must be devoted to energy research and development that will yield benefits decades and centuries into the future. Individual consumers cannot contribute except to conserve, which merely postpones the problem slightly. One cannot expect the producers of energy to initiate major R&D projects that do not have immediate profits. The important implication is that society cannot depend solely on the marketplace to protect its future. The logical way to accomplish the task is for individual governments to dedicate funds to

energy research with potential value to their countries, and to participate in an international energy program aimed at coordinating R&D on behalf of world survival. The international organization could select reliable and independent knowledgeable people to analyze the situation, and make the conclusions widely known to the public and its lawmakers. Firm decisions could be made to fund research and development over a period that extends through many national administrations. In order to fund such a program, it might be desirable to introduce taxes to be imposed on energy use and on all goods and services in proportion to their energy requirements, with the funds so derived earmarked for energy research.

The choice of R&D projects could be made only after a comprehensive study of energy resources, needs, and technology on a long-term global basis. Establishment of priorities would be an especially difficult task. Panels of analysts and advisors from many institutions, professions, and sectors of the economy, should be called on, to minimize the possibility of bias toward a particular approach. Examples of investigations that might be candidates for choice are listed below. Several of these are already in progress but need far greater funding; others are ideas that have not been pursued.

1. Study methods of improving science education and public understanding of technology, seeking to preserve into adult life the wonder and excitement of learning exhibited by small children, and inspiring students toward careers in science and engineering.
2. Attack the problem of maintaining knowledge and skills related to reactor research, development, design, and construction in an era without new reactor orders and an aging cadre of workers.
3. Continue a comprehensive investigation of processes related to serious accidents in nuclear plants, including studies of alternative designs that are both safe and economical.
4. Expand techniques for capturing, conserving, and transporting waste heat from electrical plants to heating of homes and commercial and industrial buildings and for process heat.
5. Increase efforts to improve efficiency and reduce costs in the use of solar energy for supplemental heating and generation of electricity by photovoltaics (see References).
6. Deploy and monitor inexpensive and easily-maintained containers for century-long dry storage of spent fuel assemblies, with expectation of eventual recovery for energy values.
7. Determine economic ways to separate all chemicals in spent fuel for recycling and use for beneficial purposes such as food irradiation, special heat sources, and targets for burning as radioactive wastes.

8. Develop reactors specifically for burning of actinide fuels and long-lived radioactive waste nuclides.
9. Design and test the use of accelerators for subcritical power sources and for burning radioactive materials.
10. Continue long-term testing of breeder reactors including those using the U, Pu cycle and a Th, U-233 cycle.
11. Carry along several parallel lines of fusion research and development, including mirror methods as well as magnetic and inertial confinement, with special attention to capital cost reduction.
12. Investigate the possible role of high-temperature superconductivity for magnets in fusion reactors.
13. Carry out a lunar exploratory mission to collect adequate amount of helium-3 to test in an advanced fusion process.
14. Expand the quest for light-weight, high-capacity batteries for the propulsion of automobiles and other vehicles, including tests of home charging and battery substitution centers.
15. Promote the development of low-cost urban transport systems involving magnetic rail suspension.
16. Develop inexpensive reactors to desalinate water using waste heat, in order to supply arid regions with water for drinking, irrigation, and manufacturing.
17. Explore the application of electricity from reactors for electrolysis of water to produce hydrogen gas for use in fuel cells (see References)
19. Develop intelligent robots for space missions and for operations in radiation fields.
20. Provide opportunity for research with no known practical benefit.

The cost of carrying out all of such programs would be very great indeed, and difficult to justify in terms of immediate tangible products. But the research and development must be carried out while the world is still prosperous, not when it is destitute because of resource exhaustion. The world must take the enlightened view of a prudent person who does not leave his future to chance, but invests carefully in order to survive in later years. In energy terms the world is already approaching its old age.

27.7 Summary

The energy future of the world is not clear, since both optimistic and pessimistic predictions have been made. The population growth of the world remains excessive, with growth rates in underdeveloped countries being highest. Nuclear power may play an important role in achieving sustainable development, avoiding global warming, and in easing international energy tensions. Converter reactors may give way to breeder

reactors and in turn to fusion reactors, giving full opportunity for the appropriate development of solar energy systems. Research and development are seen as key ingredients in the quest for energy adequate for the future.

27.8 Exercises

27.1. The volume of the oceans of the earth is 1.37×10^{18} m^3, according to *Academic American Encyclopedia*, Vol. 14, p. 326. If the deuterium content of the hydrogen in the water is 1 part in 6700, how many kilograms of deuterium are there? Using the heat available from deuterium, 5.72×10^{14} J/kg (see Exercise 14.4) and assuming a constant world annual energy consumption of around 300 EJ, how long would the deuterium last?

27.2. A plan is advanced to bring the standard of living of all countries of the world up to those of North America by the year 2050. A requisite would be a significant increase in the per capita supply of energy to other countries besides the U.S. and Canada. Assume that the Medium Growth Case of Figure 27.2 is applicable, resulting in a growth from 6 billion to 9 billion people. By what factor would world energy production have to increase? If the electricity fraction remained constant, how many additional 1000 MWe reactors operating at 75% capacity factor (or equivalent coal-fired power plants) would be needed to meet the demand?

Computer Exercise

27.A. Computer program FUTURE considers global regions and levels of development, mixes of source technology, energy efficiency, resource limitations, population, pollution, and other factors. Some of the methods and data of Goldemberg (see References) are used. Explore the menus, make choices or insert numbers, and observe responses.

27.9 References for Chapter 27

International Energy Annual
http://www.eia.doe.gov/emeu/iea
Comprehensive data from Energy Information Administration, U.S. Department of Energy, on production and consumption by type, country and region, and year.

International Energy Outlook 1999
http://www.eia.doe.gov/oiaf/ieo99/home.html
A report giving projections of energy markets through 2020, along with historical data from 1970.

World Energy Outlook, 1998 Edition, International Energy Agency, IEA/OECD, Paris, 1998. Uses a business-as-usual model looking 25 years ahead. Outlook by type of energy and by region. Token treatment of Kyoto commitments.

Palmer Cosslett Putnam, *Energy in the Future*, Van Nostrand, New York, 1953. A classic early study of plausible world demands for energy over the subsequent 50 to 100 years, sponsored by the U.S. Atomic Energy Commission. Includes a large amount of data and makes projections that were reasonable at the time. Written before the development of commercial nuclear power and before the environmental movement got under way, the book is quite out of date, but is worth reading for the thoughtful analysis.

Resources and Man, National Academy of Sciences–National Research Council, W. H. Freeman, San Francisco, 1969. Especially Chapter 8, "Energy Resources," by M. King Hubbert. A sobering study of the future that has been cited frequently.

Donnella H. Meadows, Dennis L. Meadows, Jorgen Randers, and William W. Behrens III, *The Limits to Growth: A Report for The Club of Rome's Project on the Predicament of Mankind*, Universe Books, New York, 1972. An attempt to predict the future, using the mathematical models and computer methods of Jay Forrester of MIT. Five major factors were studied–population, agricultural production, natural resources, industrial production, and pollution. The conclusions were that the world situation is very serious and demands immediate attention. The book had an important effect on opinion at the time of its publication, but questions have been raised since about its failure to include the effects of man's ingenuity and of scientific breakthroughs.

U.S. Energy Prospects: An Engineering Viewpoint, Task Force on Energy, National Academy of Engineering, Washington, DC, 1974. An early response to the 1973 oil embargo. Assessment of steps that would increase U.S. energy supplies and decrease consumption in a 10-year period. Practical engineering feasibility was emphasized. The expanded use of coal and nuclear for electricity would reduce the need for oil and gas. The general conclusion that a very large, expensive and well-coordinated effort was needed.

A Time To Choose: America's Energy Future, Energy Policy Project of the Ford Foundation, Ballinger, Cambridge, MA, 1974. A Zero Energy Growth scenario is favored. It involves conservation (especially in autos and buildings), expanded use of renewable energy sources, reduced growth rate in one or more of three sources: nuclear, offshore oil and gas, and Western coal and shale. The nuclear proliferation problem is highlighted.

Herman Kahn, William Brown, and Leon Martel, *The Next 200 Years: A Scenario for America and the World*, William Morrow, New York, 1976. Attention is called to a malaise characterized by pessimism, loss of confidence, and the assumption that the future is bleak. A contrasting view is that intelligence, good management, and luck will allow continued economic growth to meet the needs of a very large world population in a favorable post-industrial system. Imaginative solutions are presented for solutions of existing problems in the areas of population, economic growth, energy, raw materials, food, pollution, and thermonuclear war.

Energy in Transition 1985-2010, Final Report of the Committee on Nuclear and Alternative Energy Systems, National Research Council, National Academy of Sciences, Washington, 1979, W. H. Freeman & Co., San Francisco. Members of the group known as CONAES came from many disciplines and carried out a difficult task, with thrust, "Our observations focus on (1) the prime importance of energy conservation, (2) the critical near-term problem of fluid fuel supply, (3) the desirability of a balanced combination of coal and nuclear fission as the only large-scale intermediate-term options for electricity generation, (4) the need to keep the breeder option open, and (5) the importance of investing now in research and development to ensure the availability of a strong range of new energy options sustainable over the long term."

Sam Schurr, Joel Darmstadter, Harry Perry, William Ramsay, and Milton Russell, *Energy in America's Future: the Choices Before Us*, Resources for the Future, Johns Hopkins University Press, Baltimore, MA, 1979. Three broad goals of an energy strategy for the country are adequate energy supply for economic growth, conservation, and protection of human health and safety, and of the natural environment. Arrival at a consensus, careful planning, and considerable investment are required. Public acceptance of nuclear power is seen to be necessary.

Robert Stobaugh and Daniel Yergin, Editors, *Energy Future, Report of the Energy Project at the Harvard Business School*, Ballantine Books, New York, 1980. This edition is an update of the original (1979). The authors recognize the need to reduce imported oil, believe there is little chance to increase domestic production, find both coal and nuclear objectionable because of health and environmental side-effects, support conservation measures strongly, and urge development of solar energy.

Thomas Hoffmann and Brian Johnson, *The World Energy Triangle: A Strategy for Cooperation*, Ballinger, Cambridge, MA, 1981. A thoughtful investigation of the energy needs of the Third World and assessment of ways developed countries can help, to their own benefit. Sponsored by the International Institute for Environment and Development.

Alvin M. Weinberg, *Continuing the Nuclear Dialogue: Selected Essays*, American Nuclear Society, La Grange Park, IL, 1985 (selected and with introductory comments by Russell M. Ball). Dr. Weinberg is a pioneer in the nuclear field, a leading technical administrator, and one of the principal philosophers of nuclear energy. These selected brilliant and thoughtful writings span the period 1946-1985. They reflect trends and refute opposing views such as "soft energy paths."

Donald J. Wuebbles and Jae Edmonds, *Primer on Greenhouse Gases*, Lewis Publishers, Chelsea, MI, 1991. An update of a DOE report tabulating gases and their sources with data on effects.

Jose Goldemberg, *Energy, Environment and Development*, Earthscan Publications, London, 1996. Facts, figures, and analyses of energy planning, taking account initially of broad societal goals.

John L. Helm, Editor, *Energy: Production, Consumption, and Consequences*, National Academy Press, Washington, DC, 1990. A series of essays based on a symposium, "An Energy Agenda for the 1990s," sponsored by the National Academies of Science and Engineering. Topics include efficiency, electrification, environment, oil, natural gas, nuclear, and development.

Nuclear Power: Technical and Institutional Options for the Future, National Academy Press, Washington, DC, 1992. A study by a committee of the National Research Council of ways to preserve the nuclear fission option. An analysis of nuclear power's status, obstacles, and alternatives.

An Appropriate Role for Nuclear Power in Meeting Global Energy Needs
http://www.acus.org/publications
Select Policy Papers, download pdf document.

Richard Rhodes and Denis Beller, "The Need for Nuclear Power," *Foreign Affairs*, January/February 2000, p. 30. Assessment on a global basis.

Richard Rhodes, *Nuclear Renewal: Common Sense About Energy*, Penguin Books, New York, 1993. Assessment of risks; programs of France and Japan.

Alan E. Waltar, *America the Powerless: Facing Our Nuclear Energy Dilemma*, Cogito Books, Madison, WI, 1995. Poses issues and states realities.

Albert B. Reynolds, *Bluebells and Nuclear Energy*, Cogito Books, Madison, WI, 1996. Includes a discussion of new reactor designs.

Max W. Carbon, Nuclear Power: Villain or Victim? *Our Most Misunderstood Source of Electricity*, Pebble Beach Publishers, 1997.

Federal Energy Research and Development for the Challenge of the Twenty-First Century, (PCAST Report), November 1997. Urges the continuation and extension of life of nuclear plants to help minimize carbon emissions.

Comprehensive National Nuclear Energy Strategy, USDOE, April 1998. Cites the goal of health and environment by including nuclear in the energy mix of the U.S. and the world.

David Reid, *Sustainable Development: An Introductory Guide*, Earthscan Publishers, London, 1995. A thoughtful and informative book that describes the issues candidly.
David Pearce, *Economics and Environment: Essays on Ecological Economics and Sustainable Development*, Edward Elgar, Cheltenham, UK, 1998. A collection of papers by a distinguished author.

Earth Summit+5
http://www.un.org/esa/earthsummit
Special Session of the General Assembly to Review and Appraise the Implementation of Agenda 21.

Earth Summit Watch
http://earthsummitwatch.org
Monitors and encourages actions, pointing out what more is needed.

Lester R. Brown, Christopher Flavin, and Hilary French, *State of the World 2000*, W. W. Norton & Co. New York, 2000. A Worldwatch Institute Report on Progress Toward a Sustainable Society. Dismisses nuclear power as too expensive.

Daniel Yergin and Joseph Stanislaw, *The Commanding Heights: The Battle Between Government and the Marketplace That Is Remaking the Modern World*, Simon & Schuster, New York, 1998. An analysis of major global economic trends, especially privatization.

S. H. Schneider, "Introduction to Climate Modeling" in *Climate System Modeling*, K. E. Trenbeth, Ed., Cambridge University Press, New York, 1992.

Global Warming
http://www.uic.com.au/nip24.htm
A briefing paper from Australia.

Congressional Research Service
http://www.cnie.org (National Council for Science and the Environment)
Select CRS Briefing Book Global Climate Change for basic information, reports, the text of the Kyoto Protocol, and many Internet links.

Technology Implications for the U.S. of the Kyoto Protocol Carbon Emission Goals
http://www.asme.org/gric/98-25.html
An analysis by a task force of American Society of Mechanical Engineers

S. Fred Singer, *Hot Talk Cold Science*: *Global Warming's Unfinished Business*, The Independent Institute, Oakland, CA 1998.

Fuel Cell World
http://members.aol.com/fuelcells/4.htm
Basic facts about fuel cells.

About Photovoltaics
http://www.eren.doe.gov/pv/aboutpv.html
Explanation from U.S. Department of Energy.

Thorium Fuel for Light Water Reactors–Reducing Proliferation Potential of Nuclear Power Fuel Cycle
http://www.rtpc.com/tfuel.htm
Article in *Science & Global Security*, 1997 Vol. 6, p. 265 by Alex Galperin, Paul Reichert, and Alvin Radkowsky.

Research Support for the Power Industry
http://www.nap.edu/issues/15.1/morgan.htm
Article in *Issues in Science and Technology*, Fall 1998, by M. Granger Morgan and Susan F. Tierney.

Appendix

Conversion Factors

In order to convert from numbers given in the British or other system of units to numbers in SI units, multiply by the factors in the following table, adapted from *ASTM Standard for Metric Practice*, 2nd Ed., American Society for Testing and Materials, Philadelphia, PA, 1989. For example, multiply the energy of thermal neutrons of 0.0253 eV by 1.602×10^{-19} to obtain the energy as 4.053×10^{-21} J. Note that the conversion factors are rounded off to four significant figures.

Original system	SI	Factor
atmosphere	pascal (Pa)	1.013×10^{5}
barn	square meter (m^2)	1.000×10^{-28}
barrel (42 gal for petroleum)	cubic meter (m^3)	1.590×10^{-1}
British thermal unit, Btu	joule (J)	1.055×10^{3}
thermal conductivity (Btu/h-ft)	W/m-°C	1.73
calorie (cal)	joule (J)	4.185
centimeter of mercury	pascal (Pa)	1.333×10^{3}
centipose	pascal-second (Pa-s)	1.000×10^{-3}
curie (Ci)	disintegrations per second (dis/sec)	3.700×10^{10}
day (d)	second (s)	8.640×10^{4}
degree (angle)	radian	1.745×10^{-2}
degree Fahrenheit (° F)	degree Celsius (°C)	$°C = \frac{5}{9}(°F - 32)$
electron-volt (eV)	joule (J)	1.602×10^{-19}
foot (ft)	meter (m)	3.048×10^{-1}
square foot (ft^2)	square meter (m^2)	9.290×10^{-2}
cubic foot (ft^3)	cubic meter (m^3)	2.832×10^{-2}
cubic foot per minute (ft^3/min)	cubic meter per second (m^3/s)	4.719×10^{-4}
gallon (gal) U.S. liquid	cubic meter (m^3)	3.785×10^{-3}
gauss	tesla (T)	1.000×10^{-4}
horsepower (hp) (550 ft-lb/s)	watt (W)	7.457×10^{2}
inch (in.)	meter (m)	2.540×10^{-2}
square inch ($in.^2$)	square meter (m^2)	6.452×10^{-4}
cubic inch ($in.^2$)	cubic meter (m^3)	1.639×10^{-5}
kilowatt hour (kWh)	joule (J)	3.600×10^{6}
kilogram-force (kgf)	newton (N)	9.807

Original system	SI	Factor
liter (l)	cubic meter (m^3)	1.000×10^{-3}
micron (μ)	meter (m)	1.000×10^{-6}
mile (mi)	meter (m)	1.609×10^{3}
miles per hour (mi/h)	meters per second (m/s)	4.470×10^{-1}
square mile (mi^2)	square meter (m^2)	2.590×10^{6}
pound (lb)	kilogram (kg)	4.536×10^{-1}
pound force per square inch (psi)	pascal (Pa)	6.895×10^{3}
rad	gray (Gy)	1.000×10^{-2}
roentgen (r)	coulomb per kilogram (C/kg)	2.580×10^{-4}
ton (short, 2000 lb)	kilogram (kg)	9.072×10^{2}
watt-hour (W-h)	joule (J)	3.600×10^{3}
year (y)	second (s)	3.156×10^{7}

Atomic and Nuclear Data

(a) *Atomic Weights*(†) (based on mass of carbon-12 as exactly 12). For some elements that have no stable nuclide, the mass number of the isotope with longest half-life is listed.

Atomic Number	Name	Symbol	Atomic Weight	Atomic Number	Name	Symbol	Atomic Weight
1	Hydrogen	H	1.00794	36	Krypton	Kr	83.80
2	Helium	He	4.002602	37	Rubidium	Rb	85.4678
3	Lithium	Li	6.941	38	Strontium	Sr	87.62
4	Beryllium	Be	9.012182	39	Yttrium	Y	88.90585
5	Boron	B	10.811	40	Zirconium	Zr	91.224
6	Carbon	C	12.0107	41	Niobium	Nb	92.90638
7	Nitrogen	N	14.00674	42	Molybdenum	Mo	95.94
8	Oxygen	O	15.9994	43	Technetium	Tc	(98)
9	Fluorine	F	18.9984032	44	Ruthenium	Ru	101.07
10	Neon	Ne	20.1797	45	Rhodium	Rh	102.90550
11	Sodium	Na	22.989770	46	Palladium	Pd	106.42
12	Magnesium	Mg	24.3050	47	Silver	Ag	107.8682
13	Aluminum	Al	26.981538	48	Cadmium	Cd	112.411
14	Silicon	Si	28.0855	49	Indium	In	114.818
15	Phosphorus	P	30.973761	50	Tin	Sn	118.710
16	Sulfur	S	32.066	51	Antimony	Sb	121.760
17	Chlorine	Cl	35.4527	52	Tellurium	Te	127.60
18	Argon	Ar	39.948	53	Iodine	I	126.90447
19	Potassium	K	39.0983	54	Xenon	Xe	131.29
20	Calcium	Ca	40.078	55	Cesium	Cs	132.9055
21	Scandium	Sc	44.955910	56	Barium	Ba	137.327
22	Titanium	Ti	47.867	57	Lanthanum	La	138.9055
23	Vanadium	V	50.9415	58	Cerium	Ce	140.116
24	Chromium	Cr	51.9961	59	Praseodymium	Pr	140.90765
25	Manganese	Mn	54.938049	60	Neodymium	Nd	144.24
26	Iron	Fe	55.845	61	Promethium	Pm	(145)
27	Cobalt	Co	58.93320	62	Samarium	Sm	150.36
28	Nickel	Ni	58.6934	63	Europium	Eu	151.964
29	Copper	Cu	63.546	64	Gadolinium	Gd	157.25
30	Zinc	Zn	65.39	65	Terbium	Tb	158.92534
31	Gallium	Ga	69.723	66	Dysprosium	Dy	162.50
32	Germanium	Ge	72.61	67	Holmium	Ho	164.93032
33	Arsenic	As	74.92160	68	Erbium	Er	167.26
34	Selenium	Se	78.96	69	Thulium	Tm	168.93421
35	Bromine	Br	79.904	70	Ytterbium	Yb	173.04

Atomic Number	Name	Symbol	Atomic Weight	Atomic Number	Name	Symbol	Atomic Weight
71	Lutetium	Lu	174.967	95	Americium	Am	(243)
72	Hafnium	Hf	178.49	96	Curium	Cm	(247)
73	Tantalum	Ta	180.9479	97	Berkelium	Bk	(247)
74	Tungsten	W	183.84	98	Californium	Cf	(251)
75	Rhenium	Re	186.207	99	Einsteinium	Es	(252)
76	Osmium	Os	190.23	100	Fermium	Fm	(257)
77	Iridium	Ir	192.17	101	Mendelevium	Md	(258)
78	Platinum	Pt	195.078	102	Nobelium	No	(259)
79	Gold	Au	196.96655	103	Lawrencium	Lr	(262)
80	Mercury	Hg	200.59	104	Rutherfordium	Rf	(261)
81	Thallium	Tl	204.3833	105	Dubnium	Db	(262)
82	Lead	Pb	207.2	106	Seaborgium	Sg	(263)
83	Bismuth	Bi	208.98038	107	Bohrium	Bh	(264)
84	Polonium	Po	(209)	108	Hassium	Hs	(269)
85	Astatine	At	(210)	109	Meitnerium	Mt	(268)
86	Radon	Rn	(222)	110	Ununnilium	Uun	(269)
87	Francium	Fr	(223)	111	Unununium	Uuu	(272)
88	Radium	Ra	(226)	112	Ununbium	Uub	(277)
89	Actinium	Ac	(227)	113	Ununtrium	Uut	
90	Thorium	Th	232.0381	114	Ununquadium	Uuq	(285)
91	Protactinium	Pa	231.03588	115	Ununpentium	Uup	
92	Uranium	U	238.0289	116	Ununhexium	Uuh	(289)
93	Neptunium	Np	(237)	117	Ununseptium	Uus	
94	Plutonium	Pu	(244)	118	Ununoctium	Uno	(293)

(†) Adapted from "Atomic Weights of the Elements 1995," *Pure & Appl. Chem*., Vol. 68, No. 12, pp. 2339-2359, 1996. A biennial update by the Commission on Atomic Weights and Isotopic Abundances of the International Union of Pure and Applied Chemistry (IUPAC). Also see WebElements Periodic Table, http://www.webelements.com, by Mark Winter.

(b) Selected Atomic Masses (rounded to six decimals)

electron	0.000549	$^{7}_{3}$Li	7.016004	$^{17}_{8}$O	16.999132
proton	1.007276	$^{9}_{4}$Be	9.012182	$^{92}_{37}$Rb	91.919725
neutron	1.008665	$^{10}_{5}$B	10.012937	$^{140}_{55}$Cs	139.917277
$^{1}_{1}$H	1.007825	$^{11}_{5}$B	11.009305	$^{234}_{92}$U	234.040946
$^{2}_{1}$H	2.014102	$^{12}_{6}$C	12.000000	$^{235}_{92}$U	235.043923
$^{3}_{1}$H	3.016049	$^{14}_{6}$C	14.003242	$^{236}_{92}$U	236.045562
$^{3}_{2}$He	3.016029	$^{13}_{7}$N	13.005739	$^{238}_{92}$U	238.050783
$^{4}_{2}$He	4.002603	$^{14}_{7}$N	14.003074	$^{239}_{94}$Pu	239.052157
$^{6}_{3}$Li	6.015122	$^{16}_{8}$O	15.994915	$^{240}_{94}$Pu	240.053807

Reference: G. Audi and A. H. Wapstra, "The 1995 Update to the Atomic Mass Evaluation," *Nuclear Physics* A595, 409 (1995). Complete data on Internet at http://csnwww.in2p3.fr. Note that conversion factor used is 931.49386 MeV/amu rather than the CODATA figure below.

(c) Values of Fundamental Physical Constants

Speed of light, c	299792458 m/s
Elementary charge, e	$1.602176462 \times 10^{-19}$ C
Electron-volt, eV	$1.602176462 \times 10^{-19}$ J
Planck constant, h	$6.62606876 \times 10^{-34}$ J-s
Avogadro constant, N_A	$6.02214199 \times 10^{23}$/mol
Boltzmann constant, k	$1.3806503 \times 10^{-23}$ J/°K
Electron rest mass, m_e	$9.10938188 \times 10^{-31}$ kg or 0.510998902 MeV
Proton rest mass, m_p	$1.67262158 \times 10^{-27}$ kg
Neutron rest mass, m_n	$1.67492716 \times 10^{-27}$ kg
Atomic mass unit, u	$1.66053873 \times 10^{-27}$ kg or 931.494013 MeV
Magnetic constant, μ_0	$4\pi \times 10^{-7} = 12.566370... \times 10^{7}$
Electric constant, ε_0	$1/\mu_0 c^2 = 8.854187... \times 10^{-12}$

Reference: Peter J. Mohr and Barry N. Taylor, CODATA Recommended Values of the Fundamental Physical Constants: 1998, *Journal of Physical and Chemical Reference Data, 28* (1713) 1999. Replaces the 1986 version. Also on the web site of National Institute of Science and Technology http://physics.nist.gov/cuu. Download in pdf.

Answers to Exercises

1.1. 2400 J.
1.2. 20°F, 260°C, - 459°F, 1832°F.
1.3. 2.25×10^4 J.
1.4. 512 m/s.
1.5. 149 kW, 596 kWh
1.6. 2×10^{20}/s.
1.7. (a) (proof), (b) 2.2×10^{-9}g.
1.8 3.04×10^{-11} J.
1.9 3.38×10^{-28} kg.
1.10. 3.51×10^{-8} J.
1.11. $8.67 \times 10^{-4.}$
1.12. (proof).
1.13. (a) (proof), (b) 0.140, 0.417, 0.866.
1.14. (a) 6.16×10^4 Btu/lb, (b) $1.43 \times$ l0^5 J/g, (c) 3.0 eV.

2.1. 0.0828×10^{24}/cm^3.
2.2. 1.59×10^{-8} cm, 1.70×10^{-23} cm^3.
2.3 2200 m/s.
2.4 (proof).
2.5. 2.1 eV.
2.6. 3.26×10^{15}/s.
2.7. -1.5 eV, 4.77×10^{-8} cm, 12.0 eV, 2.9×10^{15}/s.
2.8. (sketch).
2.9. (proof).
2.10. 8.7×10^{-13} cm, 2.4×10^{-24} cm^2.
2.11. 1.35×10^{-13} .
2.12 28.3 MeV.
2.13. 1783 MeV.
2.14. $1.46 \times$ l0^{17} kg/m^3, 1.89×10^4 kg/m^3, 0.99×10^{13} kg/m^3.

3.1. 7.26×10^{-10} /s, 2.18×10^{10} Bq, 0.589 Ci.
3.2. 3.64×10^{10}/s vs. 3.7×10^{10}/s.
3.3. 1.65 μg.
3.4. 3.21×10^{14}/s, 8.68×10^3 Ci, 1.06×10^{14}/s, 2.86×10^3 Ci.
3.5. (diagram).
3.6. (graph).
3.7. 2.47×10^{20}, 1.74×10^{-17}/s, 4.30×10^3 dis/sec and Bq, 0.116 μCi.
3.8. (a) (graph), (b) 1.82 h, argon-41.
3.9. 1.61×10^3/y, radium.

4.1. (proof).
4.2. ${}^{14}_{6}\mathrm{C}$, ${}^{10}_{5}\mathrm{B}$.
4.3. 1.19 MeV.
4.4. 4.78 MeV.
4.5. 3.95×10^{-30} kg, 3.54×10^5 m/s, 1.3×10^{-3} MeV.
4.6. 2.05×10^7 m/s, 1.39×10^{-12} J or 8.65 MeV.
4.7. 1.20 MeV.
4.8. 1.46/cm, 0.68 cm.
4.9. 1.70×10^7 m/s, 4.1×10^4/cm^3.
4.10. 6×10^{13}/cm^2-s, 0.02/cm, $1.2 \times$ l0^{12}/cm^3-s.
4.11. 0.207, 0.074, 88, 0.4 cm.
4.12. (a) (proof), (b) 382 barns.
4.13. 0.274×10^{13}/cm^3-s, 0.149×10^{13}/cm^3-s.

4.14. 4.56×10^{-7}, 0.456.
4.15. 0.1852 b.vs. 0.19 b. from Table 4.1.
4.16. 0.504/cm, 0.099 cm, 4.9%.
4.17. 1.9%.
4.18. 0.0795 cm^{-1}, 0.328 cm^{-1}, 0.305 cm, 1.02 cm.

5.1. 0.0233, 42.8.
5.2. 1.45×10^{21}/s, 2.07×10^{-13} m.
5.3. (a) 0.245 meV, (b) (proof), (c) $E' = E_0/2$.
5.4 0.62 MeV.
5.5 ≅0.001 cm.
5.6 $0.033 \times 10^{24}/cm^3$, 0.46/cm, 1.51 cm.
5.7. 0.289 cm.
5.8. 0.39 cm, $l.92 \times 10^{-5}$ C/cm^3, 6.15×10^{-4} J/g.

6.1. 6.53 MeV.
6.2. $^{100}_{38}\mathrm{Sr}$.
6.3. (a) 66.4 MeV, 99.6 MeV, (b) 140, 93, (c) 0.96×10^6 m/s, 1.44×10^6 m/s.
6.4. 168.5 MeV.
6.5. 2.50.
6.6. 1.0%, 99%.
6.7. 0.00812 g/day.
6.8. 8.10×10^6, 5.89×10^6, 5.18×10^6.

7.1. 0.0265 amu, 24.7 MeV.
7.2. (proof).
7.3. 0.453 kg, 13,590 kg/day.
7.4. (a) 3.10×10^6 m/s, (b) $4.12 \times 10^{17}/cm^3$.
7.5. 9.3×10^5 K.
7.6. $2.72 \times l0^5$ eV.

8.1. 0.114 V.
8.2. 2.5×10^6/s.
8.3. 1.31×10^{-7} s.
8.4. (proof).
8.5. 0.183 Wb/m^2.
8.6. (a) 1.96 MeV, (b) 0.99906, (c) 0.999997249c = 299791633 m/s, (d) 1.33 tesla.
8.7 213 amu, 0.999989.
8.8. 750 mA, 373 MW.
8.9. (proof), 5.2×10^{-11}.
8.10. 20.958 μs, 9 picoseconds.
8.11. (a) $\Delta E(\mathrm{keV}) \cong [88.463/R(\mathrm{m})][E(\mathrm{GeV})]^4$, (b) 8.8×10^{-14}, (c) $p \cong ae^2/(6\pi\varepsilon_0 c^3)$.

9.1. (proof).
9.2. 1.0030.
9.3. 0.0304, 0.0314.
9.4. 95,900 kg, 76,600.
9.5. 0.85%.
9.6. 195 kg/day.
9.7. 490.
9.8. (proof).
9.9. (proof).
9.10. 0.422 kg/day, 0.578 kg/day.
9.11. 238.028915; 99.283621, 0.710971, 0.005408.
9.12. at 3 w/o $12.2M, at 5 w/o $23.8M, gain $6.0M.
9.13. (a) 640 ma, (b) 32 kW, (c) no.
9.14. (a) 2.5×10^6 m/s^2, 2.55×10^5, (b) 1.147.

10.1. $1.19 \times 10^{21}/cm^3$, 1/45.
10.2. 0.0165.
10.3. 6.0×10^5.
10.4. 0.30.
10.5. 10.
10.6. (a) n = 1: P(0) = 0.5, P(1) = 0.5; n = 2: P(0) = 0.25, P(1) = 0.50, P(2) = 0.25; n = 3: P(0) = 0.125, P(1) = 0.375, P(2) = 0.375, P(3) = 0.125.
10.7. n = 1 ($\bar{x}$ = 1/6): P(0) = 0.846, P(1) = 0.141; n = 2 ($\bar{x}$ = 1/3): P(0) = 0.716, P(1) = 0.239, P(2) = 0.040.
10.8. 740 cps, 4.44×10^4; 211; 4.3×10^{-8}.
10.9. (a) proof, (b) 0.2907, (c) 0.2623.
10.10. (derivation).

11.1. 2.21.
11.2. $2.04 \times 10^{10}/cm^2$-s.
11.3. 1.171, 1.033, 0.032.
11.4. 1.850, 1.178, 2.206.
11.5. 2.050; yes.
11.6. 8.64×10^6; 89,800 kg, 2700 kg; $40.4M.
11.7. (a) 28.8 m^3, 1.51 m, (b) 0.318.
11.8. (a) (proof), (b) 0.037.
11.9. 156 ft^3.
11.10. 1.45 min.
11.11. 0.0334
11.12. 3.58 cm, 0.0987 cm^{-2}, 0.441.
11.13. (plot).

11.14. (a) 1.84 w/o, (b) 2.26 w/o.

12.1. (proof).
12.2. (discussion).
12.3. 150 W/cm^2; 3 W/cm^2-°C.
12.4. 315°C.
12.5. 30°F.
12.6. 1830 MW, 1350 MW, 26%.
12.7. 664 kg/s, 2.6%.
12.8. 8.09×10^6 m^2, 366 J/m^2-h.
12.9. 20.5 million gal/day.
12.10. (proof).
12.11. (proof), 0.76.

13.1. 1.7, 0.7.
13.2. 0.9856.
13.3. (discussion).
13.4. 2.61, 0.2.
13.5. 6300 kg; 3880 days or 10.6 years.

14.1. 0.1 mm, 0.65 cm.
14.2. (proof).
14.3. (proof).
14.4. 5.72×10^{14} J/kg, 0.116; \$500/kg, 0.003 mills/kWh.
14.5. (c) 2.56×10^{-13} m, (d) 3.58×10^{-13} m, (e) 203 times, 177 times.

16.1. 6.25×10^{10}, 2.3×10^{-9}.
16.2. 200.
16.3. 1.67 mrads, 3.34 mrads, 6.7×10^{-4}.
16.4. 0.8%.
16.5. 400 mrems, 4 mSv.
16.6. 1/3.

17.1. Fe-59.
17.2. ${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{He}$,

${}^{3}_{1}\mathrm{H} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n}$

17.3. 0.63 mm.
17.4. 3.0 s.
17.5. 3.14×10^8 y.
17.6. 2378 years ago.
17.7. 5.9×10^{-5}.
17.8. $N_{Rb}/N_{Sr} = [\exp(-\lambda t) - 1]^{-1}$.
17.9. (discussion).
17.10. (discussion).
17.11. 11.97 days.
17.12. 2.65 y.
17.13. 4.66 µg, 0.00764 cm.
17.14. Ir-192, Co-60, Cs-137.
17.15. 0.0874; 0.1%.
17.16. 2.4×10^{-4}.

18.1. 5 mCi.
18.2. 241 rads.
18.3. 89.5 kg.
18.4. 19,500 Ci, 289 W.
18.5. 3.46×10^{13}/cm^2-s.

19.1. 0.0157, 2.40; 7.7×10^{-4} s; 63.8 s.
19.2. 30.2 s.
19.3. (a) and (b) 1.16×10^{-5} s.
19.4. 40°C.
19.5. 0.90 s.
19.6. 0.0068, 0.0046, 0.0034, 0.0021.
19.7. -0.0208.
19.8. 0.6 or 60%.
19.9. 117, 138, 150, 152, 153; yes.
19.10. 0.0195.
19.11. 9.2%.
19.12. (proof).
19.13. 29,700 MWd/tonne.
19.14. $B(3) = (3/2)B_1$, $B(4) = (8/5)B_1$.

20.1. 359 µg.
20.2. 7.81 km/s; 22,300 mi, 35,900 km.
20.3. 96%.

21.1. 1558 mrems/y, 371 mrems/y.
21.2. 54.5 µCi.
21.3. 5×10^{-4} µCi/cm^3.
21.4. Boron.
21.5. 382/cm^2-s.
21.6. 3, 10, 0.6, 0.3, 20.
21.7. (in µCi/ml): 3.14×10^{-7}, 2.98×10^{-7}, 3.34×10^{-7}.
21.8. 7.60 days, 94.6 days, 69.6 days.
21.9. (in mrem): I 0.002, C 0.044, T 0.046, A 0.044. Teenager (liver). Yes.
21.10. 3.36×10^{-6} µCi/g

22.1. 25,400 (49%); 95,900 (85%).
22.2. 27,500 m^3/y.
22.3. 0-10 days I-131; 10 days-114 days Ce-141; 114 days-4.25 y Ce-144; 4.25 y-100 y Cs-137.
22.4. 98.7%.
22.5. 1.05×10^{13} cm^3/s, 2.22×10^{10} ft^3/min.
22.6. 0.113 MW, 30.9 days.
22.7. (a) Percents: 4.6, 56.6, 34.6, 4.3, (b) 987 kg, (c) 1205 kg, (d) 82%
22.8. 33.219; 967 y, 1003 y, 801,000 y.

22.9. $2.15 \times 10^7/cm^2$-s.

22.10.

	Ci/m^3	$
resins	4.94	359.50
concentrated liquids	0.887	551.44
filters	9.69	103.64
compactible	0.023	116.89
noncompactible	0.526	1164.24
		2295.71

$119.51/ft^3$, 0.00525

24.1. 14,120; 284 quads, 0.284 Q; 6.24×10^{30}.

24.2. 12.5 million barrels, $312 million.

26.1. 0.57 cm.

26.2. Every 1.61 days, 227/y.

26.3. Approximately 8.

27.1. 43.6 billion years.

27.2. 6.63, 1142.

The Internet

The virtues of the Internet are well known. E-mail provides quick communication and the World Wide Web has a vast amount of information. Search engines are a valuable asset to learning and research. However, each one displays a different set of sites and it is necessary to use several engines. Those found most useful by this author are AltaVista, Yahoo!, Northern Light, Lycos, Google! and HotBot. Tutorials on search engines and subject directories are available, for example at
<http://home.sprintmail.com/~debflanagan/main.html>.

Web sites whose URLs are found by searches tend to appear, change, and disappear. If a site cannot be accessed, it may be because of a change in its URL. Try deleting words back toward the root directory.

It is recommended that an attempt be made to determine the author of an article and ascertain credentials. Information gathered by a high school or college student may or may not be accurate.

Because search engines generate enormous numbers of web sites, most of which are irrelevant, a great deal of time can be wasted in exploration. In this book, the author has attempted a start in the identification of sites that are appropriate and accurate. He proposes to establish a clearinghouse for good sites, sharing with users information on sites discovered by others. To participate in that community effort, merely send an e-mail message to the author at murray@eos.ncsu.edu, giving name, affiliation, and areas of interest. In reporting a good site, give its name, the URL, the sponsoring person or organization, and a description of its particular virtues.

Thanks are due Tara Calishain, Paul Gilster, and Alfia Wallace for ideas on the use of the Internet.

Computer Programs

The regular Exercises at the ends of chapters can be answered by use of a hand-held calculator. A Solution Manual is available to instructors from the publisher or the author.

The Computer Exercises make use of programs in BASIC or the spreadsheet Lotus 1-2-3. They operate with BASICA, GW-BASIC, or QBasic on a PC with 5 1/4 in. or 3.5 in. diskettes. Instructors may obtain the programs and instruction sheet without charge by writing the author, specifying the type of diskette needed. Any number of copies of the diskette may be made for student use. It is recommended that master backups be made and stored.

The author welcomes comments and suggestions about the programs, the regular Exercises, Computer Exercises, text, References, and web sites. Please contact as follows:

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Following is a list of filenames, the Computer Exercise number in which they are used, and a brief indication of function.

COMPUTER PROGRAMS

TITLE	CEX NO.	FUNCTION
ALBERT	1.A	RELATIVISTIC PROPERTIES OF PARTICLES
ELEMENTS	2.A	SYMBOLS, A, AND Z FOR ELEMENTS
BINDING	2.B	SEMI-EMPIRICAL MASS FORMULA FOR B AND M
DECAY1	3.A	RADIOACTIVE DECAY: ACTIVITY
DECAY	3.B	DECAY EQUATIONS, CALCULATIONS, GRAPH
GROWTH	3.C	CONSTANT GENERATION GROWTH OF NUCLIDE
RADIOGEN	3.D	PARENT-DAUGHTER RADIOACTIVITY RELATIONS
MOVENEUT	4.A	DISPLAYS MOVING PARTICLE
CURRENT	4.A	DISPLAYS STREAM OF PARTICLES
CAPTURE	4.A	DISPLAYS CAPTURE OF NEUTRON BY NUCLEUS
HEADON	4.A	DISPLAYS DIRECT ELASTIC COLLISION
RANDY	4.B	PRINTS OUT SET OF RANDOM NUMBERS
RANDY1	4.B	AVERAGE VALUE OF RANDOM NUMBERS
RANDY2	4.B	STATISTICS FOR RANDOM NUMBERS
ABSCAT	4.C	COMPARES ABSORPTION AND SCATTERING
SCATTER	4.D	DISPLAYS GENERAL ELASTIC COLLISION
ENERGY	4.E	VARIATION IN NUMBER OF COLLISIONS
ALBERT	4.F	RELATION OF NEUTRON V, T, AND E
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YIELD	6.B	FISSION YIELDS FOR LONG-LIVED NUCLIDES
SPECTRUM	6.C	FISSION NEUTRON ENERGY DISTRIBUTION
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