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QUARTZ CRYSTAL OSCILLATORS

by Marv Willrodt

The accuracy of most Hewlett-Packard counters and many other instruments is determined to a great extent by the accuracy of the mechanical vibrating frequency of a thin crystalline quartz plate used in the time base reference oscillator.

Since the quartz plate is vibrating mechanically, its frequency will be influenced among other things by physical size, which can change as the quartz plate expands or contracts with temperature changes.

Several things are done to reduce the magnitude of this frequency change on high quality quartz oscillators:

1. Controlling carefully the angle at which the crystal is cut from the raw quartz.
2. Adding temperature compensating elements in the crystal circuit.
3. Mounting the crystal assembly in an oven to maintain constant temperature.

Other factors such as poor mounting, contamination, etc., also degrade performance of poorly made crystals.

Non-oven crystals have the advantage over oven crystals in that they do not require warm-up after power has been removed from the counter for some time and are thus desirable for many of the portable applications for which counters are used. They have the disadvantage, of course, that frequency change

To make a quality quartz oscillator, a source of pure quartz must be located.

with ambient temperature change is much greater than for good oven crystals.

Temperature effect can be reduced by combining temperature compensating elements--temperature sensitive capacitors for instance--with the crystal. Such units are known as temperature compensated crystal oscillators or TCXO's for short. A good TCXO can be 10 or 100 times better than a room temperature crystal; however, the nature of temperature-frequency characteristics of crystals varies enough so each one must be carefully measured and then individually compensated with its own specific network. This process is time consuming and consequently expensive. Bear in mind that improved output stability is achieved by keeping the oscillator output frequency within predetermined acceptable limits by compensating the circuit, not by changing the quartz plate itself.

TYPES OF OVENS

A crystal oven, as the name implies, heats the crystal and maintains it at a constant temperature usually around 65°C regardless of the ambient temperature outside the oven. Ovens are of two general types, on-off and proportional.

The on-off oven uses a snap action thermostat as a temperature sensing element. The cost is low but performance is only moderate since the thermostat by nature has a temperature differential between the "on" condition and the "off" condition, thus the crystal temperature is constantly being cycled by some small amount which shows up as output frequency cycling. Wear and sticking of the thermostat points can cause a gradual shift of oven temperature or even erratic operation. Also arcing of the points can introduce electrical noise into the oscillator output. All of these things are undesirable since they cause frequency error.

Proportional ovens are throttling devices in that the rate of heat input is constantly adjusted to match the rate of heat loss to the oven surroundings. A thermistor in a bridge circuit senses temperature and controls an amplifier

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which supplies heat at the required rate--the farther the oven is off temperature, the faster heat is supplied.

Operation might be compared to keeping the speed of an automobile constant by changing the throttle setting to provide continuous, stepless adjustment. By contrast a thermostatically controlled oven might be compared to trying to maintain a constant speed by turning the ignition switch of an automobile on and off. This would supply energy at a maximum rate or not at all.

The most stable quartz oscillators use a double oven--that is, one proportional oven mounted within a second proportional oven. Since the inner oven now never sees a change of more than about 1°C regardless of room temperature, its control circuit can be made much more precise to maintain inner oven temperature to within 0.01 degree or so. While a good proportional oven crystal offers a very small frequency change with room temperature change, it does require that the instrument be connected to power at all times to keep the oven hot. If power is ever removed, overnight--or even for a short time, the crystal goes through a warm-up cycle before it again stabilizes. This can take from a fraction of an hour to several days depending on the stability specifications and can be a disadvantage, particularly for a portable instrument.

The quartz is then carefully cut to proper size.

To see what the frequency stability means to the users of an HP counter, let us look at some typical HP oscillators specifications.

The three most important specifications define oscillator performance with respect to: **time**, ambient **temperature**, and **line voltage** variations.

AGING RATE:

Aging rate specifies maximum frequency change with time. Any oscillator can be much better than specified but will never be worse than the indicated rate unless it is malfunctioning. You may have noticed that HP has two kinds of specifications--some oscillators are specified as having a daily aging rate, such as $<3 \times 10^{-9}$/day, while others are specified as having a monthly aging rate, such as $<3 \times 10^{-7}$/month. (3×10^{-7} can also be written as

$$\frac{3}{10{,}000{,}000},$$

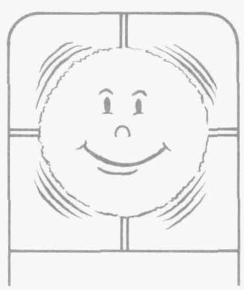
as 3 parts in 10^7, as 0.0000003 or a 0.00003%). It would seem that you could multiply 3×10^{-9} parts per day by 30 days to get 90×10^{-9} or approximately 1×10^{-7} as a monthly aging rate. This is correct and perfectly valid. HP oscillators with a daily aging rate specification use proportional oven and are sufficiently buffered from the en-

MODEL	CRYSTAL FREQUENCY	STABILITY: AGING RATE	STABILITY: TEMPERATURE	STABILITY: SHORT TERM	STABILITY: LINE VOLTAGE
5246L	1 MHz	2×10^{-7} per month	$\pm 2 \times 10^{-6}$ (+10° + +50°C) $\pm 2 \times 10^{-5}$ (0°C to 65°C)		$\pm 1 \times 10^{-7}$ for 10% change
5248L	1 MHz	3×10^{-9} per 24 hours	$\pm 2 \times 10^{-10}$ per °C from -20° to +55°C	2×10^{-10} rms	$\pm 5 \times 10^{-10}$ for 10% change
5248M	5 MHz	5×10^{-10} per 24 hours	$\pm 5 \times 10^{-11}$ per °C (0° to 50°C) $\pm 2.5 \times 10^{-9}$ (0° to 50°C)	5×10^{-11} rms	$\pm 1 \times 10^{-10}$ for 10% change
5300A	10 MHz	3×10^{-7} per month	$\pm 5 \times 10^{-6}$ (0° to 50°C)		$\pm 1 \times 10^{-7}$ for 10% change
5326/ 5327	10 MHz	3×10^{-7} per month	$\pm 2.5 \times 10^{-6}$ (0° to 50°C)		$\pm 1 \times 10^{-7}$ for 10% change
5326/ 5327 Opt.011	10 MHz	5×10^{-10} per day	$\pm 3 \times 10^{-9}$ (0° to 50°C)	1×10^{-11} rms	$\pm 5 \times 10^{-9}$ for 10% change

vironment so aging rate can be determined in one day.

Grinding, lapping and polishing operations are completed next.

The above calculation cannot necessarily be reversed for a crystal specified in terms of aging rate per month. The 5300A counter, for instance, has a specified aging rate of $<3 \times 10^{-7}$ parts per month. Dividing this specification by 30 days gives a daily aging rate of $<1 \times 10^{-8}$. By way of comparison this is only about three times worse than the aging rate of a 5245L crystal. In this case, aging cannot be measured in one day; to see why, one has only to look at the



The finished crystal is mounted and electrical and mechanical checks are made to verify proper oscillation.

temperature specifications of this same oscillator--namely $\pm 5 \times 10^{-6}$ for 0° to 50°C. If the temperature-frequency curve were linear (which is usually not the case) the change would be $\pm 1 \times 10^{-7}$ per °C temperature change. Thus, an ambient temperature change of one °C shows up as a change 10 times greater than one day's aging of the crystal. What one is really measuring in one day is room temperature change--not crystal aging. To determine crystal aging rate, one has to check the oscillator once a day when room temperature is at a constant value, plot these points for a month or so, then draw a line through the points. The slope of the line is the aging rate of the crystal.

If aging of these room temperature crystals were specified on a daily basis, you may find some personnel trying to measure the aging rate in one day and then calling you if it does not meet the specifications. In reality, he may be measuring ambient temperature, so it is up to you to help him out by pointing out some of the factors which influence crystal performance.

Oven crystals typically have a curve as in Figure 1 and will be about 1 part in 10^5 high when the crystal is at room temperature, as when first turned on from a cold start or if the oven fails to operate.

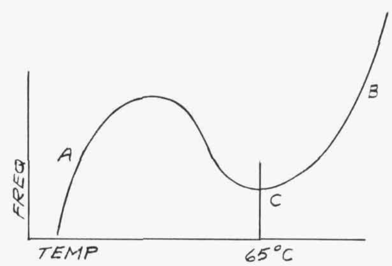


Figure 1

Point "C" will be at a different temperature for each crystal so for this reason you can't get a replacement crystal without the oven for a 5245L or 5245M oscillator. Each oven is set to operate at the crystal turn-oven temperature and the special equipment required makes this impractical to do in the field.

Room temperature crystals are cut from the raw quartz at a different angle than an oven crystal. The effect is to pull the points A and B apart in temperature as at D and F. This puts the turn-over temperature E at a nominal value somewhere between 25 and 35°C as in Figure 2.

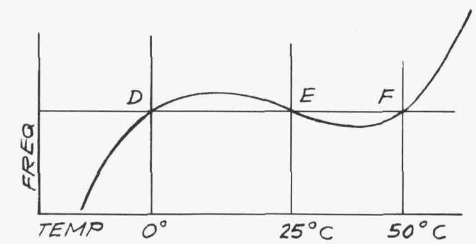


Figure 2

A room temperature crystal specified for $\pm 5 \times 10^{-6}$ frequency change for 0° to 50°C temperature change might follow any of the curves shown in Figure 3. Curve A is ideal; B is a possibility; C is linear. Yet all three meet the specifications. Notice that below 0°C or above 50°C most curves have a steep slope, so stability may degrade by another order of magnitude in the next 10 degrees (-10°C or +60°C in this case).

TCXO's have compensating elements which pull point 1 down and point 2 up to give a smaller total excursion in frequency, however, the slope between the points is not changed significantly. The aging rate of a crystal oscillator cannot

(continued on page 6)

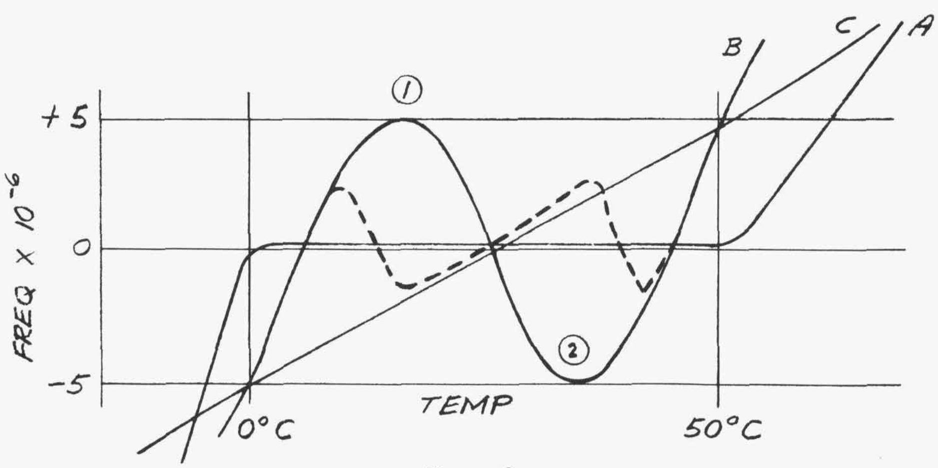


Figure 3

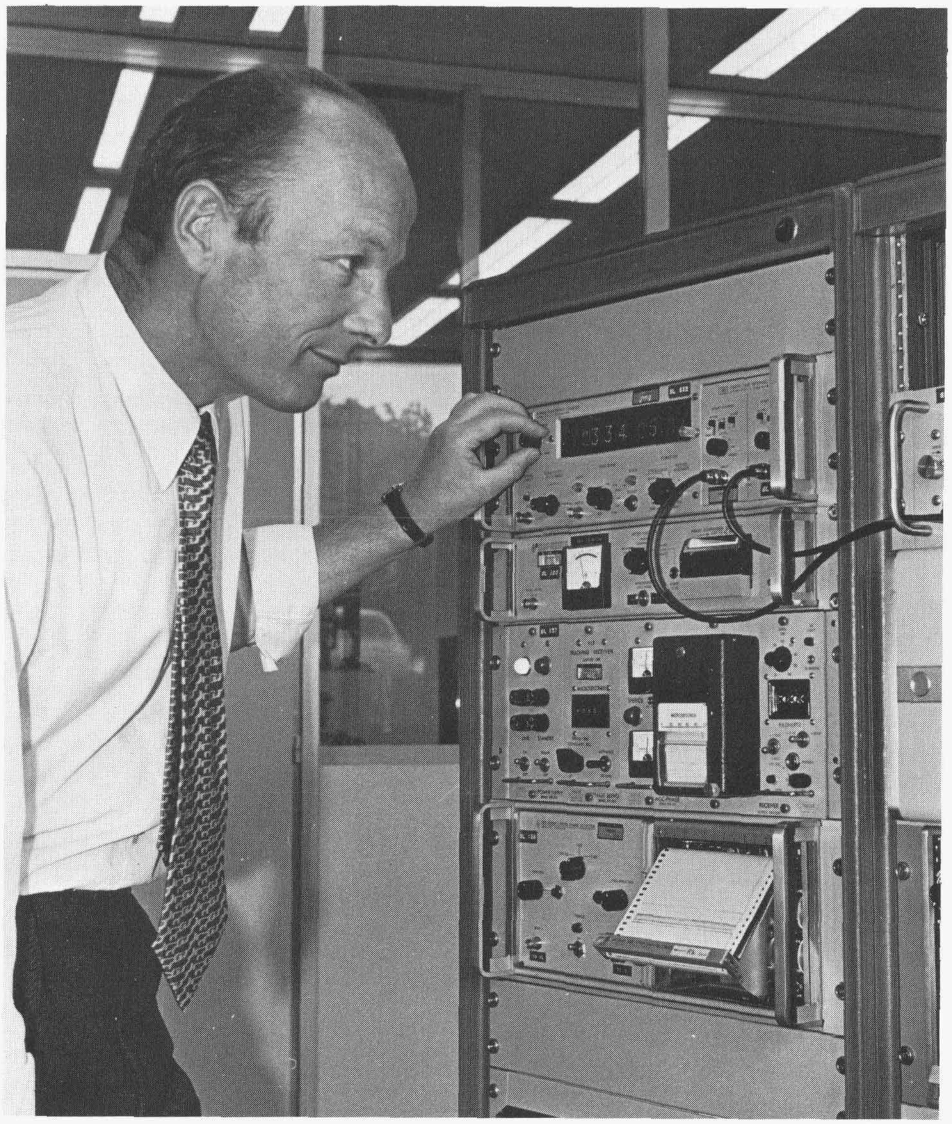
PERIODIC CALIBRATION AND STANDARDS LABS

When using oscilloscopes, voltmeters, frequency counters and other electronic instrumentation, it is often beneficial to analyze the limitations on accuracy inherent in the piece of the test gear. Being familiar with measurement errors means fewer erroneous measurements and better results. To do this we thought it would be beneficial to take a brief look at the operation of a calibration laboratory. Because of the interest occasionally expressed in learning about HP facilities outside the United States, in this issue we will view the operation of the Calibration and Standards Laboratory at Hewlett-Packard S.A. in Geneva, Switzerland.

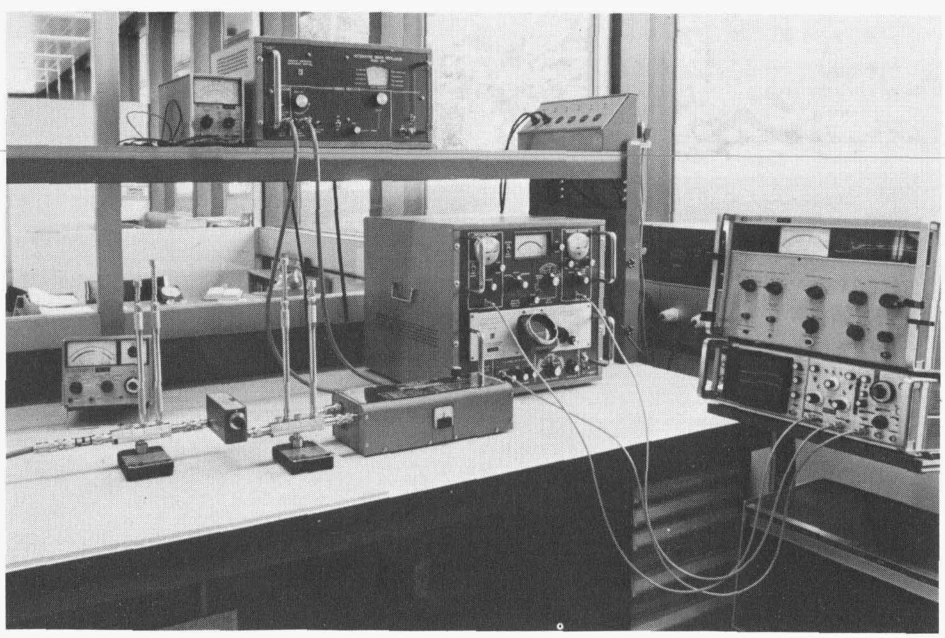
A calibration lab has a number of references used for calibration; these include DC and RF voltage, frequency and time, impedance, power, attenuation, and others.

A well equipped standards lab has references certified by a national standards laboratory, such as the National Bureau of Standards in the U.S. or one of the various European National Standards Laboratories.

These devices allow the best possible measurement accuracy because their absolute accuracy is only limited by their quality and the capability of the national standards laboratory where they had been certified. These references are periodically re-certified at a rate depending upon its use and nature.



Felix Lazarus checks the stability of an oscillator. (top right)



Attenuation is verified on the attenuation measuring system. The device under test is the step attenuator supported between the two double stub tuners.

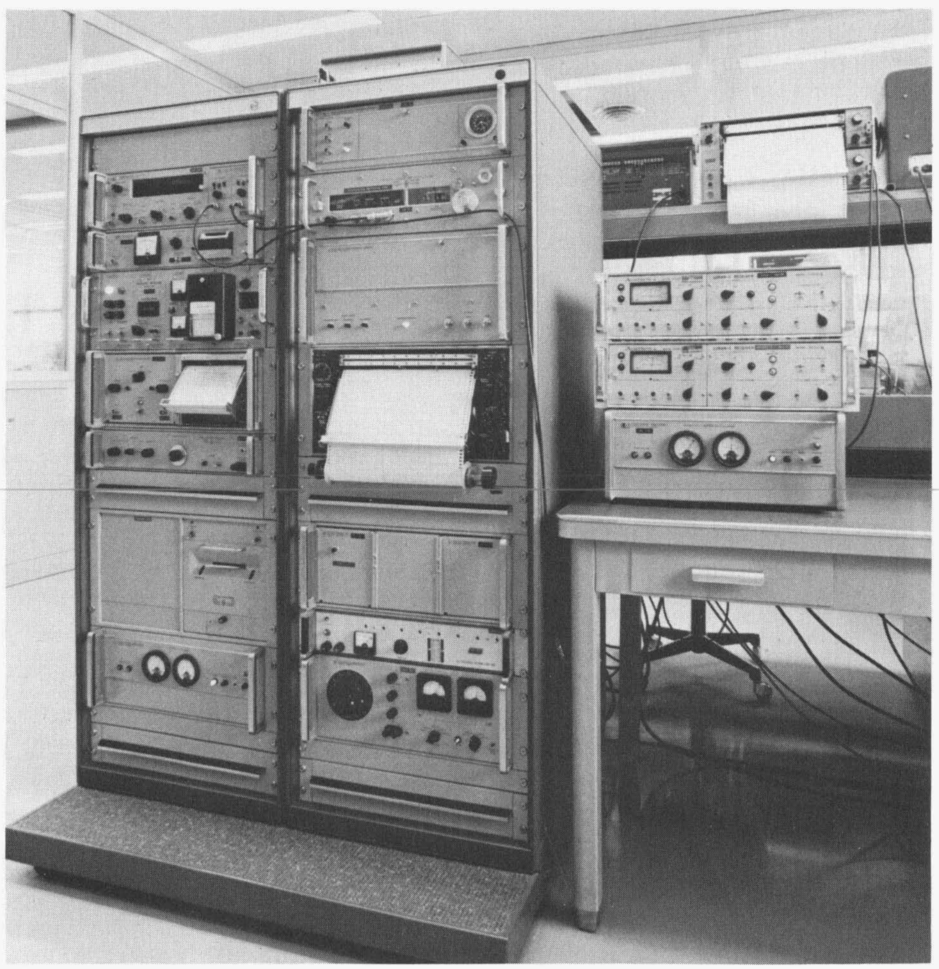
First line standards not only require a considerable initial investment, but also incur extremely high maintenance costs because of the periodic re-certification. Highly qualified and trained personnel are required for proper use, in addition to the severely controlled environmental conditions needed to maintain stability. Such expenditures often cannot be justified by a small or medium sized company.

First line traceable references are used periodically to calibrate second line traceable references, which generally can be of less stringent quality and therefore lower cost than first line traceable references. Their handling is also easier and does not require special techniques or care. They therefore often constitute the best compromise of accuracy vs. price for normal equipment maintenance laboratories that are generally not demanding the extreme accuracy requirements of first line traceable references.

Second line traceable references are used to calibrate other standards, with again a decrease in accuracy and cost.

Periodic calibration is needed to continue to obtain all the performance designed into your instrument. Refer to the Operating and Service manual for the recommended optimal calibration periods.

Here Jiri Rektorik is making preliminary settings on a differential voltmeter. (top right)



This test set-up is used to calibrate time and frequency standards. Note the strip chart recorders that obtain a time plot of drift.

(continued from page 3)

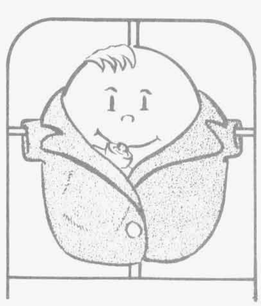
be changed once the quartz crystal has been manufactured and the oscillator circuit designed, so it is important that these jobs be done well initially.

TEMPERATURE EFFECTS:

Temperature effects specify oscillator performance with ambient temperature change. A crystal inside a well-designed oven goes through a very small temperature change (less than 1 degree) and is thus stable with ambient changes. Two points are worth remembering with respect to temperature effects. First, the change of frequency with temperature is usually not a linear function; furthermore, each crystal even though the same kind, may have a very different frequency-temperature curve. Individual oscillator frequency-temperature curves must be made to determine a particular unit's actual performance. Second, the effects of temperature change can be reduced by providing a more constant ambient (controlling room temperature) when better performance is required.

LINE VOLTAGE CHANGE:

Crystal oscillator frequency is also influenced by line voltage changes (often times because the power dissipation increases and therefore the temperature inside the instrument rises). Good circuit design, proper buffering, and good mechanical design can reduce these effects. If the operator needs better performance, he can use a line regulator to reduce oscillator frequency changes with line voltage changes.



When great stability is needed, the quartz crystal is placed with a heating element in an insulating jacket.

SHORT-TERM STABILITY:

Short-term stability of many oscillators is also defined. This is a frequency change with time but is specified for intervals of 10 seconds or less rather than for a day or month, as is done with aging rate. Short-term stability is the statistical variation of frequency about some average value due to noise introduced by the crystal oscillator circuit. For a well-designed oscillator circuit, this should be a random variation--that is, it should not be coherent with 60 or 120 Hz or any other frequency generated in the counter. Since this is a random function, the shorter the averaging time the worse the short-term stability. For counter applications, short-term stability is usually specified for a 1-second averaging time. For measuring intervals less than 1 second, the ±1 count error is always of far more consequence than the short-term stability. Counters seldom use gates longer than 1 or 10 seconds so a short-term specification in terms of minutes or hours is meaningless.

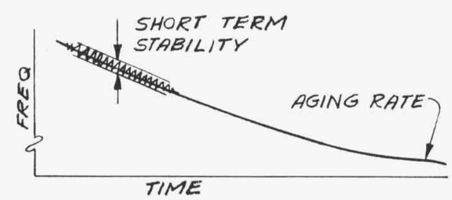
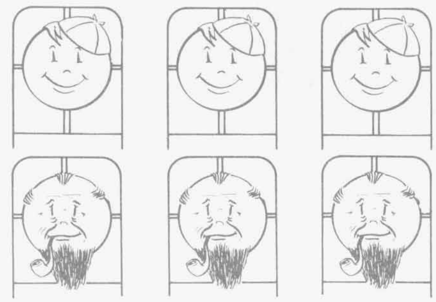


Figure 4

Short term variation can be measured using the 5360A computing counter as indicated in program library CCA 7, CCA 27 or as discussed in Application Note AN 52. Extreme care is needed in making this measurement to get a true indication of oscillator short-term performance rather than the measurement of a ground loop, mechanical vibration, stray RF pickup or some other undesired phenomena.

Very good oscillators may have other specifications which characterize frequency changes with oscillator load, physical orientation with respect to the pull of gravity, vibration, shock, and other environmental and application factors.



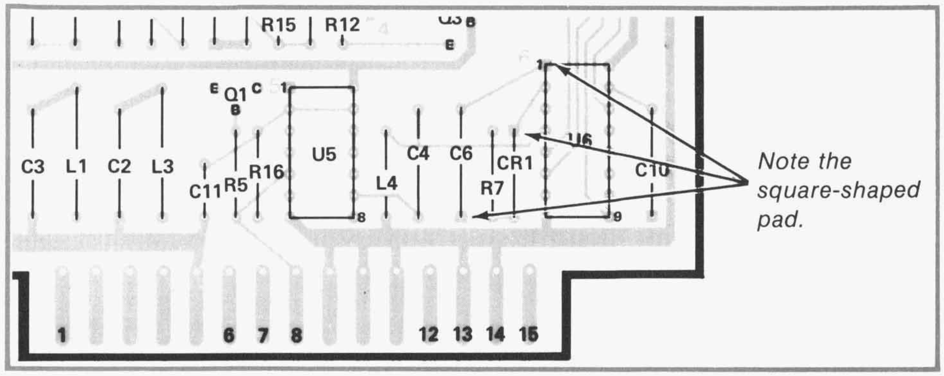
All crystals then go through an aging process to check performance over a long period.

All oscillators are checked to meet the minimum performance specifications indicated in the data sheet. If an oscillator does not meet the specifications, it is an indication of a trouble that has developed since the oscillator was originally built and tested and should therefore be corrected. Some oscillators may be much better than specified--even as much as 10 times better--particularly when operated under moderate environmental conditions. However, a user will not know how much his oscillator exceeds specifications unless he makes a detailed check. He may find, for instance, that his 5245L oscillator has an aging rate of -1.2×10^{-9} parts per day instead of the specified 3×10^{-9} parts per day. Aging may go either up or down but any one oscillator will always age in one direction only, i.e., it will not switch from aging down to aging up. If he maintains records showing traceability of his calibration to NBS and takes into account all errors in his calibration procedure, his measured aging rate of -1.2×10^{-9} per day is a perfectly valid number to use for all calibration he makes.

The next issue will contain a discussion of the various methods of calibrating an oscillator.

Marv Willrodt, currently an applications engineer with the Santa Clara Division of Hewlett-Packard, began his career with HP in 1951 as a design engineer. He was involved with the 524 counters, AC-4 decoder, 218A digital delay generator and 5214L preset counter. Marv is a photography buff and a stereophonic sound enthusiast.

NEW PC BOARD MARKING SYMBOL



HP printed circuit boards have featured triangles etched on the board as an aid to manufacturing and service people. This triangle was used to indicate 1) the "pin 1" end of IC's, 2) the positive end of electrolytic capacitors and 3) the cathode end of diodes.

Having the board marked in this manner proved helpful during repair, because the triangle made it easier to get oriented. It also reduced the chance of installing an IC, electrolytic or diode backward when replacing it.

Because the triangle was placed near the component lead to be marked, confusion sometimes arose when several IC's, electrolytics, and diodes were arranged close together on a board. It was sometimes difficult to tell which component was being marked by the triangle.

A new method is now being implemented on some products that should eliminate the confusion.

Pin 1 of IC's, the + connection for electrolytics and the cathodes of diodes have a square shaped pad on the board. That is, the printed circuit trace ends in a small square, rather than the usual round pad.

Since the plated-thru hole for the component lead is drilled in the square, there can be no mistaking which lead is marked.

Another advantage is that both sides of the p.c. board are marked, simplifying parts identification when troubleshooting from the non-component side of the board. The visibility of the square on this side sometimes has a tendency to be reduced by solder, but it is still quite useful.

Four other identification markings exist on pc board that may be helpful. They are 1) an assembly part number, 2) a series number 3) a revision letter and 4) a production code. Being familiar with this system may help reduce repair time by allowing board substitutions or by indicating differences that may affect troubleshooting.

The assembly part number has ten digits (such as 05340-60027) and is the primary means to identify the board. Assemblies with the same part number are interchangeable, since the part number is changed when design changes are made that make the board incompatible with previous assemblies.

The series number (such as 1248A) is used to document minor electrical changes, such as the value of discrete parts or the parts number of an IC. The backdating section of the Operating and Service Manual or a current manual change sheet should indicate the differences between boards of different series numbers.

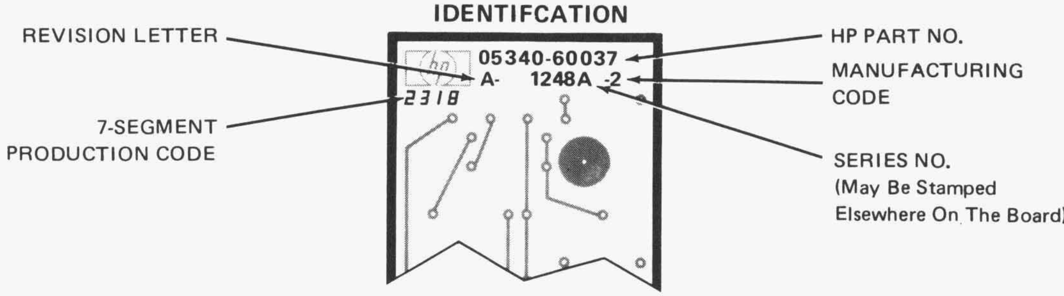
If the series number on the board being repaired differs from the board series number documented in the Operating and Service Manual, an electrical difference exists and it may be helpful and time-saving to determine the change before proceeding on the repair.

Revision letters (A, B, etc.) denote change in board layout. For example, if a capacitor type is changed (electrical value may stay the same) and requires different spacing for its leads, the printed circuit board layout is changed and the revision letter is incremented to the next letter. When a revision letter changes, the series number is also usually changed.

The production code is the four digit, seven segment number used for production purposes.

Thus time may be saved by being familiar with changes, especially of the series number changes. If there is a difference between the board series number in the manual, an electrical difference exists. Determining the difference before proceeding with the repair may be time well spent.

PRINTED CIRCUIT BOARD IDENTIFCATION



A SHORT QUIZ

Here's a variation of the resistor cube problem so you can prove to yourself that parallel resistor calculations are still easily solved.

In the figure on the right each resistor is 42 ohms, 1/4 watt.

1. What is the equivalent resistance from A to B?

15	42
21	98

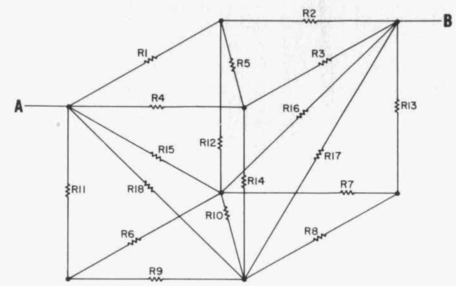
None of the above.

2. The maximum dc voltage that can be placed between A and B without exceeding the resistor ratings is:

2.29	6.48
4.58	9.67

None of the above.

(Solution will be in next issue.)



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