with concentrators is the measurement of E_{tot}. The simplest approach is to determine the one-sun I_{SC} and assume that this value is linear with light level. Another approach is to use calibrated neutral-density filters [2, 128, 129]. Neutral-density filters can be calibrated to better than 1% at a given wavelength using lasers, but typically they have a ±5% variation in transmissivity with wavelength over a 400- to 1100-nm range, limiting their usefulness to single-junction devices that are insensitive to spectral errors, such as Si and GaAs. The linearity can also be inferred by a series of measurements with aperture or changing flash-lamp voltage [111]. Other approaches to determining the linearity involve exposing the cell to low-level periodic sunlight and concentrated sunlight [130, 131]. Ideally, a calibrated linear reference cell should be used, but spatial nonuniformity of the concentrated beam can lead to a larger error than that if linearity had been assumed. Again, ideally, the spectral responsivity should be measured as a function of bias light level to address the issue that, for nonlinear devices, the spectral error M will change with total irradiance. Groups have developed spectral response systems capable of measuring the responsivity as a function of bias light level to about 200 suns [132, 133].

Concentrator modules cannot normally be measured in solar simulators because the optics are not a point source; the bulb(s) or integration optics will be imaged on the cell, resulting in a much larger spatial variation in intensity than that the module would encounter under natural sunlight. For this reason, concentrator modules are typically evaluated outdoors under natural sunlight over some period of time. There are no standards for concentrator cell, module or system measurements, although the PVUSA method in equation (16.2) has been used to evaluate concentrator systems [32, 43]. Concentrator modules and arrays evaluated at Sandia National Laboratories have consisted of the performance (P_{max}, or $I-V$ characteristics) as a function of direct-beam irradiance and heat sink temperature [129].

16.3.8 Solar Simulators

Solar simulators are used to simulate natural sunlight for repeatable and accurate indoor testing of the $I-V$ characteristics of PV cells or modules. The ideal solar simulator should have less than ±1% variation in the light level during the $I-V$ measurement period, less than a ±1% spatial variation in irradiance in and several cm above the test plane, and introduce less than a 1% spectral mismatch error between the test and reference cell. These constraints are essential to ensure an uncertainty in the efficiency of less than ±2%. Solar simulators are classified according to the spatial nonuniformity of the total irradiance, temporal instability of irradiance, total irradiance within a given field of view, and spectral match to the reference spectrum [134, 135]. Groups that evaluate multijunction cells and modules have found that single-source simulators can introduce large errors in I_{SC}, and P_{max}. Multisource solar simulators suitable for evaluating reference cells have been discussed in Section 16.3.6 [108–118, 136].

The temporal variation in light level during the $I-V$ measurement can be corrected if the intensity and device current are measured at the same time for each $I-V$ data point. Most commercial and custom $I-V$ systems for continuous light sources do not correct this temporal variation in the light level, although most groups have procedures in place to correct long-term drift in the simulator total irradiance over a period of hours or longer. The spatial uniformity varying with time for arc lamps cannot be readily