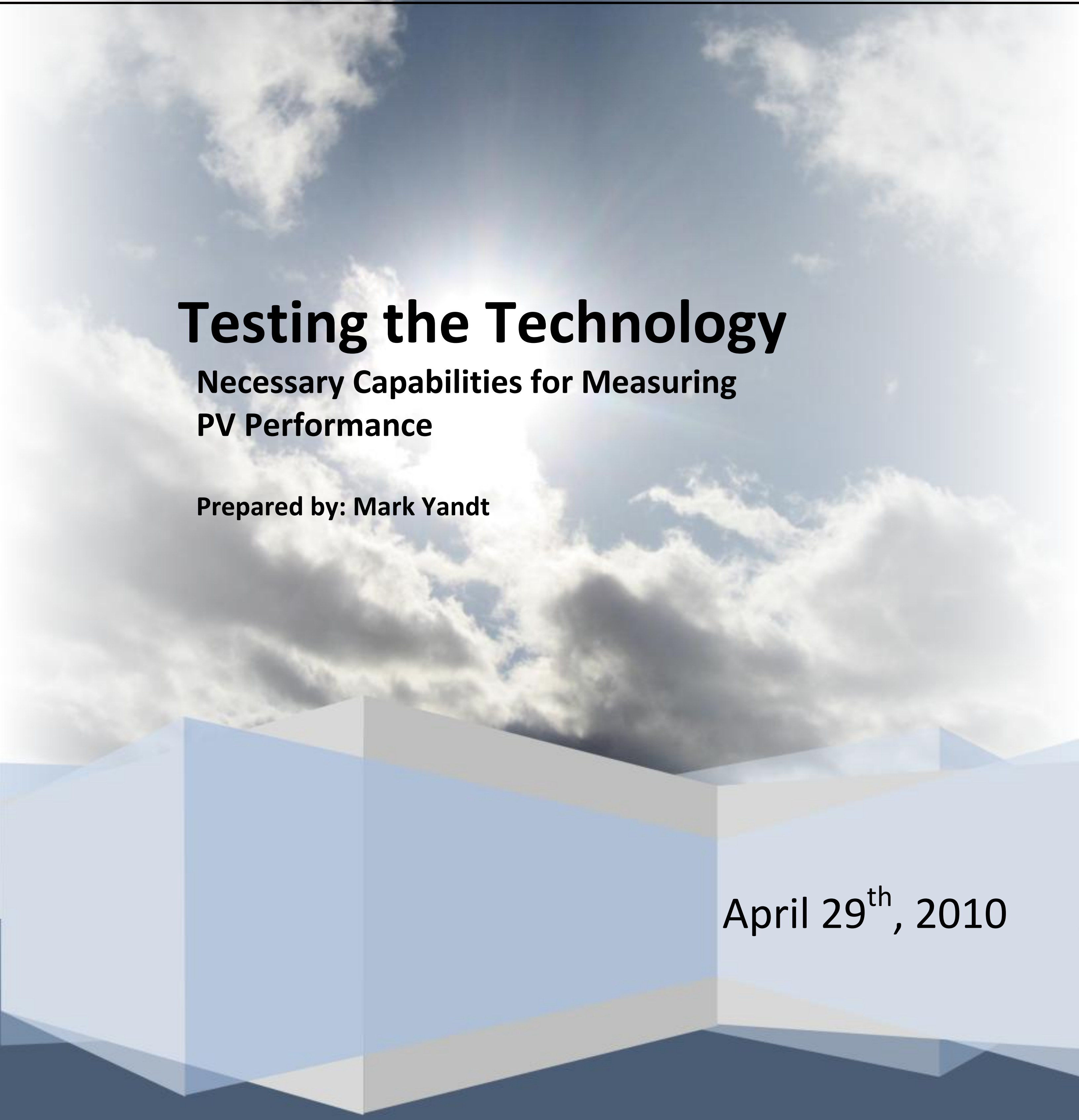
SUNLab
Solar Cells and Nanostructured Devices Laboratory



Testing the Technology

Necessary Capabilities for Measuring PV Performance

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Abstract

The ability to accurately characterize a Photovoltaic (PV) product is critical at every level of system development. The characterization of systems and devices allows research teams and product development groups to not only map the progress of their own technology but also compare it to that of their competitors. Access to state of the art testing equipment thus allows these teams to make effective design decisions and to form sound business strategies. This report will identify and review important testing capabilities as well as the equipment and facilities necessary for PV characterization throughout the development process during:

- Cell Design and Optimization
- Module/Panel Performance, Reliability & Qualification Testing
- Overall System Performance and Monitoring

Most testing during cell design and optimization as well as that done during reliability testing is considered *indoor* testing. There exist a few groups around the world that specialize in PV testing which have nearly all of the capabilities mentioned in this report among others in house, but this is not common. Usually, these equipment and resources are shared between a number of test suites each of which specialize in a particular type of testing. Test suites for *outdoor* testing intended to characterize overall system performance are similar in that the equipment required is chosen depending on the technology and the system under investigation; any given facility may not require all of the instruments that will be discussed presently.

Table of Contents

Testing the Technology

Necessary Capabilities for Measuring PV Performance

1 Testing During Cell Design and Optimization

As new solar cells are designed and fabricated they are tested. Improvements are made and new designs are fabricated based on the successes and shortcomings of the previous generation. The ability to accurately characterize devices is just one part of the cycle, but it is critical. Test facilities at this stage should allow for reproducible measurements to be made quickly and accurately. The better the information that can be collected from devices and analyzed, the better design decisions will be, and the more efficient the development cycle will become.

1.1 Laboratory Testing

In the laboratory during the initial development stages it is necessary to be able to measure the current (I) – voltage (V) characteristics of solar cells and subcells. In this regard the goal when setting up a characterization station is most often flexibility. It is desirable to be able to measure the I-V characteristics of all different shapes and sizes of cells at a range of controlled temperatures with and without illumination in order to extract the cells efficiency, series and shunt resistances, fill factor, and temperature coefficients. These properties will be discussed later in this report.

There are a number of ways that such a testing station can be set up but the basic components are the following:

- Solar Simulator (lamp which mimics the sun’s spectrum)
- Test Platform, which may include:
    - Plated stage used for low resistance contact to the backside contacts of chips
    - Temperature control with a Thermal Electric Cooler (TEC) under test stage
    - Heat sink and sufficient ventilation used to dissipate heat that is electrically pumped away from the test stage.
    - Vacuum pump connected to hole in stage to hold chips securely on test stage
- Micro-manipulators allowing three degrees of freedom used to finely adjust the positions of probes to make contact with bare cells and other delicate devices.
- Microscope for viewing fine cell features (such as the top contacts) as well as probes in order to accurately position them to make electrical contact with a device
- Power supply, power meter
    - 4-wire measurement capability to remove contact resistance
- Data acquisition system
    - Electronic control of bias voltage, measurement resolution and current limits during an I-V sweep
    - Electronic control of solar simulator power or intensity
    - Electronic control of device (or at least stage) temperature

- Electronic collection, labeling, and storage of data.

Figure 1: Shows one example of a testing station with many of the items listed above. It is set up to measure the electrical characteristics either bare cells or chips-on-carriers under illumination. Neutral density filters are in place to reduce the intensity of the lamp light incident on the solar cell. Micro manipulators and probes are visible and have been used to make electrical contact to the contacts on the top surface of the solar cell.

Included in the testing station but not visible in the photo are a computer controlled temperature controller, a computer controlled power supply/meter and a data acquisition system used to view and store current-voltage data as well as to make simple repetitive calculations for comparison and calibration purposes.

The solar simulator that is continuously illuminating the setup in this picture is an Oriel 92191 which is capable of uniformly illuminating a solar cell at up to 150 suns intensity and is powered by a 1600 W xenon lamp [1]. The maximum uniform beam area is approximately 5 cm by 5 cm at low concentration. A series of optional filters are used to control the output spectrum and can be chosen to yield a beam that simulates the following Air Mass (AM) spectra: AM0, AM1, AM1.5G, AM1.5D, and AM2 [1].

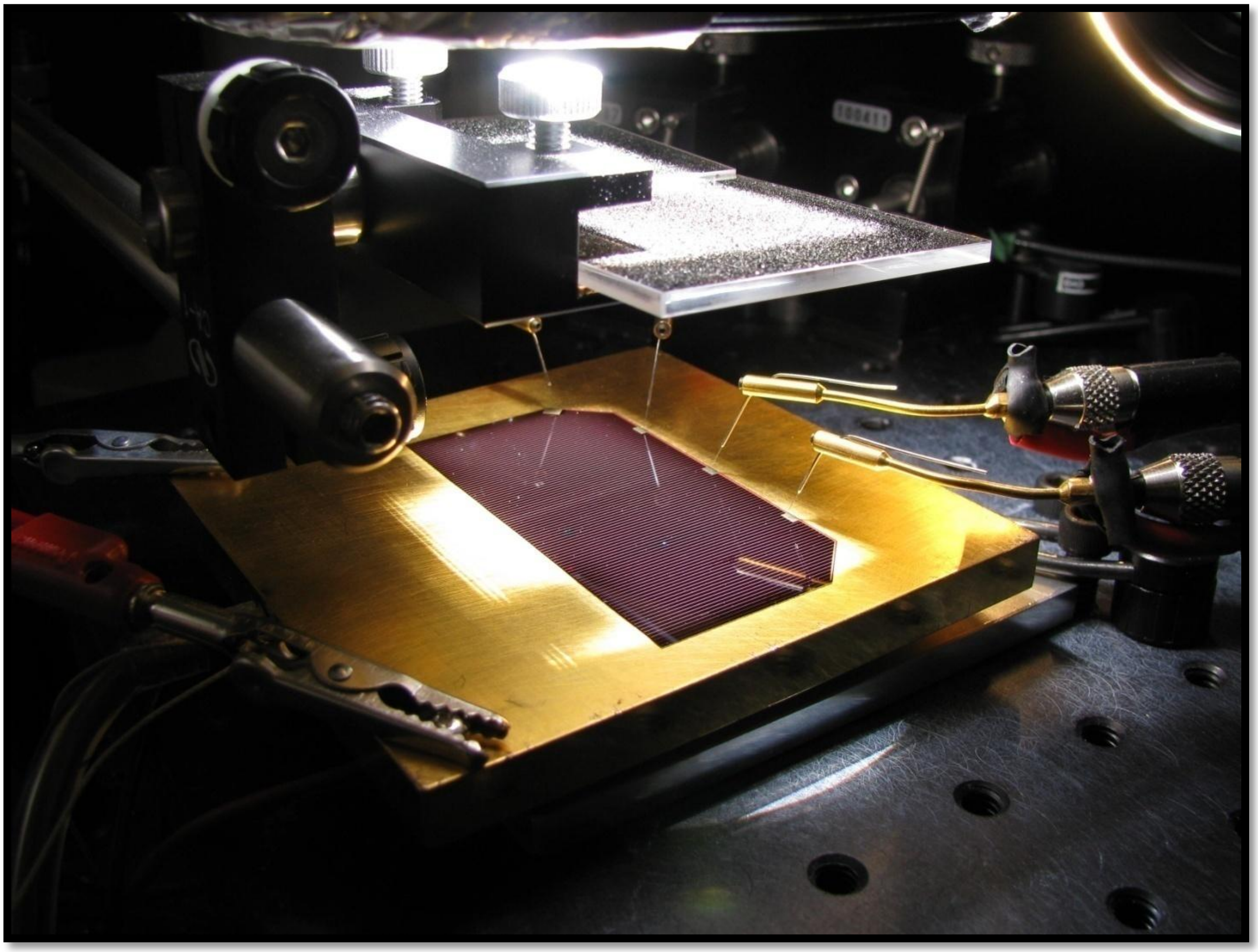

Figure 1: Oriel solar simulator test station SUNLab, School of Information Technology and Engineering, University of Ottawa, 2010. In this picture a solar cell is illuminated under an attenuated beam. The solar cell is positioned, and secured with a vacuum pump, on a gold plated stage which often serves as the connection to the back contact of the cell. Four micro manipulators are used to touch probes down onto the top contact pads on the surface of the cell [2].

1.2 Solar Simulators

Among the most expensive pieces of equipment necessary in an indoor test suite will be one or more solar simulators. These systems are used to simulate sunlight which is then used to illuminate a solar cell so that electrical characteristics of the cells can be measured in a controlled environment within the confines of the laboratory.

The most important specifications when choosing a solar simulator are the following:

- Spectral control
- Spatial and spectral uniformity
- Temporal stability
- Beam divergence
- Intensity control

It is practically impossible to achieve a simulator that controls each of these specifications perfectly so the selection of a simulator should be made with the purpose of the particular test suite in mind.

There are two basic types of solar simulators based on which many variations have been developed to suite particular needs. The first type are flash systems which work based on the same principle as a camera flash in which a high voltage is built up by storing charge in a capacitor which is then discharged across a xenon flash tube. The second type are known as continuous illumination or continuous power solar simulators in which a slightly different bulb design (short-arc xenon lamp) allows the lamp to remain on continuously. As the names suggest the main difference between the two simulator types is simply the duration of illumination or equivalently, the amount of average power that they output in a given period of time that is in turn incident on the device under inspection.

It is helpful to take a look at the lamp technology at the heart of the systems in order to better understand the differences between them.

1.2.1 Short-Arc Xenon Lamps (for continuous illumination)

Xenon short-arc lamps are by far the most common bulbs in modern continuous power simulators despite their relatively low efficiency because of xenon's relatively flat emission spectrum over the visible wavelengths and the high total output power that they are able to achieve [3]. Air Mass (AM) filters are used, sometimes more than one in series, to further modify the spectrum such that it closely resembles that of the sun.

In a short-arc lamp, such as the one shown in Figure 2, xenon gas is bound in a glass envelope made of fused quarts which is strong enough to contain the pressurized xenon at high temperatures (glass temperature reaches ~600-700°C) during operation while maintaining clarity throughout the emission spectrum [3]. The pure tungsten anode is larger than the cathode and a blunt end is machined in order to dissipate the intense heat (anode temperature reaches ~2000°C)

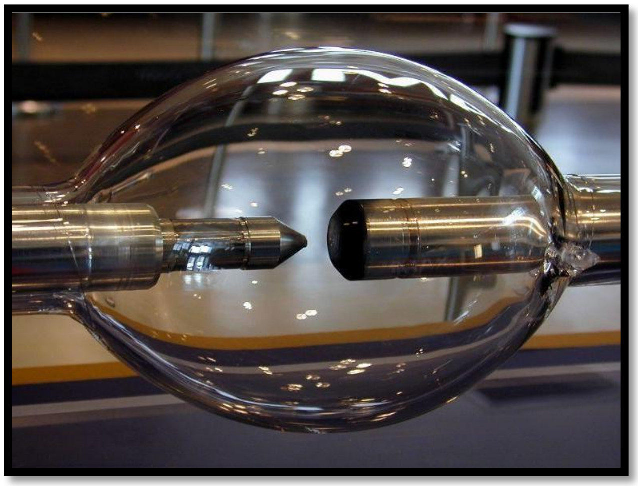

Figure 2: Xenon short-arc lamp similar to those used in modern solar simulators [4].

that is focused on it due to bombardment of electrons. The cathode is made of thorium doped tungsten which decreases the work function and thus increases the electron emission characteristics while also making it easier to machine [3].

Another advantage of this lamp design is the fact that light is produced in a very small conic volume near the cathode which for the purpose of gathering the light acts as a point source [3]. Thus the lamp light can be focused into a parallel beam with the application of a parabolic mirror or focused to achieve higher intensity by placing the cathode at the focal point of a properly designed elliptical mirror. The later is of particular use when trying to design a high concentration, continuous power, solar simulator.

Thanks to the refinement of xenon lamp technology over many years driven by multiple industrial applications including film and theater projection in particular, xenon short-arc lamps are now particularly well suited for solar simulation applications.

1.2.2 Flash Tubes (for flash illumination)

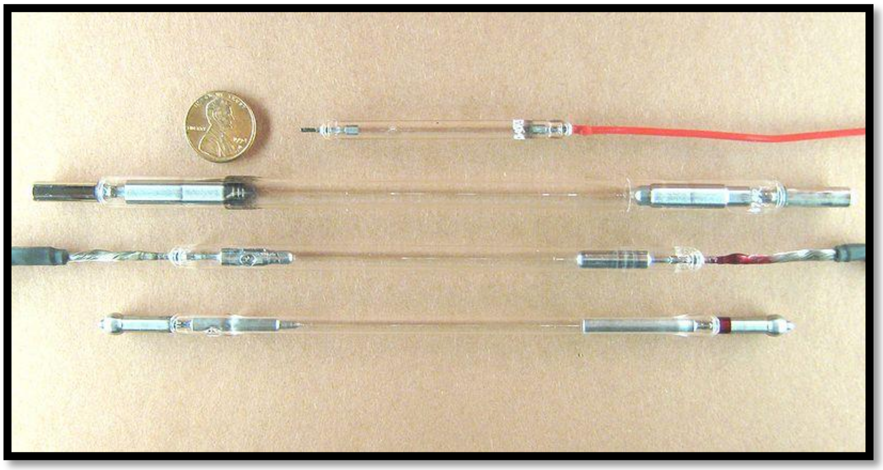

Figure 3: Flash lamps similar to those used in modern solar simulators. The top three are xenon lamps and the bottom one is krypton identifiable by the shape of the anode and the cathode [6].

Xenon flash tubes such as those shown in Figure 3 operate on the same principle as their short-arc counterparts except that the arc is much longer extending the length of the xenon tube which can be many centimeters in length. Skilled glass blowers are able to form the glass envelope into virtually any shape necessary to meet the needs of the specific application [5]. In order to initiate an arc between electrodes which are much farther apart than in the short-arc case described earlier, a special ignition process must be used. First, the anode and cathode are connected to a capacitor and a relatively high voltage is built up between them. This voltage must be high enough to respond to ignition but not high enough to initiate the arc on its own. A high voltage trigger pulse is then applied near or directly to the glass envelope which acts to ionize the gas in the tube so that the voltage at the electrodes will exceed the breakdown voltage of the gas and cause an arc. The current pulse through the ionized gas heats the xenon sufficiently to cause light emission as ionized atoms return to their neutral state. The electrons fall from higher energy levels and emit photons in the process [5].

For the purpose of solar simulation, xenon gas (as opposed to krypton) is generally the gas of choice due to its relatively high efficiency (~50%) as well as the quality of its illumination spectrum. Internal pressures may range from 0.01 to 4 atmospheres, the trend being that higher pressures yield higher efficiencies [5].

It should be noted that the xenon spectrum does suffer from inherent undesirable spectral lines throughout the spectrum beginning in the ultraviolet and continuing into the near infrared. These lines dominate at low current densities but become much less significant especially in the visible spectrum as the current density through the lamp increases [7]. Spectral lines are also less significant at higher positive gas pressures though the pressure has far less effect than the current density [7]. Some standards for solar simulators, including requirements on the spectrum, are given in the following section *Illumination Standards.*

1.2.3 Continuous Power Systems

At low concentration (~1 sun) continuous power simulators are extremely useful diagnostic tools which can be used to illuminate a solar cell in the safety of the laboratory in order to measure the cells I-V characteristics. Complete I-V curves can be collected quickly and accurately by sweeping through bias voltages and measuring the output current from the cell during illumination. These systems simulate not only the type of light that will be incident on a solar cell outdoors but also the thermal load that the cell will experience in a real panel or module.

There is great potential for the thermal load on a solar cell to have an effect on device performance under concentration because a significant average power must be dissipated from the cell in order to keep the operating temperature under control. Also, continuous testing, especially at high concentration, is understandably a much more rigorous method of identifying physical weaknesses in solar cell construction and packaging than any type of flash testing. High concentration continuous power simulators will expose voids in solder under the cell, poor wire bonds, and shunts among other issues because they result in hot spots and eventually cell failure.

There are drawbacks to continuous power illumination as well. These systems are generally more expensive, especially those that are capable of high concentration. They require elaborate cooling systems to remove the excess heat from the cell. They generally illuminate very small areas and the intensity can be difficult to scale accurately without changing the spectrum and other beam characteristics.

1.2.4 Flash Systems

Flash simulators are quite versatile. They are relatively inexpensive compared to continuous power solar simulators, and are capable of large throughput in an assembly line application. They can generally achieve a wide range of intensities for solar cell characterization under concentration. If a solar cell can be held at various temperatures a flash simulator can thus be used to determine temperature coefficients at different intensities. Unfortunately due to the nature of the system there is not time during one light pulse to collect an entire I-V curve with many current voltage points. Since only one data point is usually collected per flash, either the sample must be flash illuminated many times or a few important points on the curve are collected and then the rest of the curve is interpolated.

One of the challenges associated with flash systems is determining when the spectrum of the flash is optimal within the microsecond to millisecond light pulse [5]. Determining the appropriate window is critical because the spectrum will shift over the duration of the flash. Thankfully, modern high speed spectrometers are capable of measuring extremely fast spectrums and are generally used during setup and calibration of flash systems to determine at what point during the light pulse a current- voltage measurement should be taken [8].

1.2.5 Illumination Standards

Class 1 flash simulators must achieve a spectrum that matches that of the reference spectral irradiance to within ± 25% [9]. Spatial uniformity of large simulators capable of illuminating test planes of 30 cm x 30 cm or larger must be less than ±3%, while the temporal stability must not vary more than 2% from the average value during the measurement [9].

Far more standard specifications exist but detailed explanation of which are beyond the scope of this report. Standards for solar testing systems continue to evolve through a consensus process and hence should be verified when shopping for a solar simulator. The main publishers of such standards are the same as those listed in Section 2.1 *Origin of Qualification Standards* and the particular references are given here for convenience.

- ***IEC 60904-9, Photovoltaic devices - Part 9: Solar simulator performance requirements***
- ***ASTM E927, Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing.***

1.3 Quantum Efficiency

Quantum Efficiency (QE) measurements are important because they give designers critical information about the quality of the material in an absorptive device. The term QE can be defined in two sub categories, namely Internal Quantum Efficiency (IQE) and External Quantum Efficiency (EQE). EQE describes the ratio of electron-hole pairs produced in the cell to photons that are incident on the surface of the cell. IQE describes the ratio of electron-hole pairs produced in the cell to photons that enter the cell, the difference being that the photons reflected at the cell surface are not accounted for. QE measurements are used to identify the energy bandgaps of the absorptive materials in a device which determines which sections of the solar spectrum will be absorbed by a particular absorptive layer. QE measurements also indicate if there are problems in the manufacturing or growth processes which are leading to poor quality devices and poor material characteristics. The sensitivity or quantum efficiency of a material is used along with the materials absorption coefficient in the design of a solar cell and hence confirming that the integrated solar cell does in fact have the sensitivity that was expected helps to confirm that current generation, recombination, and diffusion mechanisms are working as expected [10].

Quantum efficiency measurements, such as those shown in Figure 4, are particularly important for multi-junction devices because of the necessity for current matching between subcells that are converting photons to electrical current in series with one another. In this case the energy bandgaps of the materials in each subcell are carefully chosen to optimize conversion efficiency for a particular illumination spectrum. The relative positions of the energy bandgaps (as well as current generation, recombination, and diffusion mechanisms as mentioned above) in these subcells can be verified in a completed device by carefully designing a QE measurement [10].

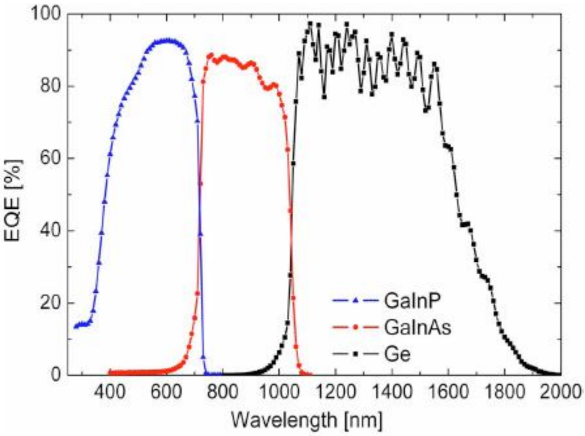

Figure 4: External Quantum Efficiency (EQE) measurement of a state of the art, high efficiency, metamorphic, triple junction solar cell [11].

A quantum efficiency measurement station requires the following components:

- Monochromator (or spectrometer) used to select narrow spectral lines throughout the solar spectrum scanning from the ultraviolet through the near infrared which are aimed at

the solar cell to determine its response.
  - Broadband light source from which the spectrometer may select narrow wavelength bands
- Power supply, power meter
  - 4-wire measurement capability to remove contact resistance
  - Solar cell must be forward biased in multi-junction cell in order to measure the short circuit response from the subcell under investigation
- Bias light sources (used to ensure that subcell under inspection is current limiting the rest of the device for multi-junction cells)
  - Light sources should be high enough intensity to ensure biased subcell is not current limiting and ideally the whole active surface area should be illuminated
- Various free space optics to guide light from monochromator to device
- Test Platform
  - Plated stage used for low resistance contact to the backside contacts of chips
  - Temperature controlled with a Thermal Electric Cooler (TEC) under test stage
  - Heat sink and sufficient ventilation used to dissipate heat that is electrically pumped away from the test stage.
  - Vacuum pump connected to hole in stage to hold chips securely on test stage
- Data acquisition system
  - Chopper wheel, Lock-in amplifier used to chop and hence isolate the scanning signal from the monochromator.
  - Electronic control of bias voltage, measurement resolution and current limits during an I-V sweep
  - Electronic control of device (or at least stage) temperature
  - Electronic collection, labeling, and storage of data.

2 Module/Panel Performance, Reliability & Qualification Testing

2.1 Origin of Qualification Standards

The first silicon based flat panel solar modules were available on the market in the early 1970's spurred by the looming energy crisis. Unfortunately these panels were terribly unreliable due to the fact that manufacturers were producing the panels for the first time and appropriate qualification testing did not exist [12].

By the late 1970's and into the early 1980's the need for a systematic approach to fault identification and reliability testing was recognized. Funded by the US Department of Energy, the Low-Cost Solar Array program was instituted [13]. As part of the program the Jet Propulsion Laboratory (JPL) looked at the current technologies and identified the most common failure mechanisms. The following 13 failure mechanisms were identified [13]:

- open-circuited cell regions,
- shorted cells,
- open-circuited interconnects,
- gradual cell power degradation,
- optical degradation of the module package,
- front-surface soiling,
- glass breakage,
- open circuits in the module wiring,
- hot-spot failures of cells in a module,
- shorted bypass diodes,
- shorts to the frame or ground,
- delamination of the module encapsulant,
- life-limiting wear out

Once these issues had been identified every failure mechanism was systematically studied in order to better understand its potential causes and to develop design solutions. Allowable failure rates were proposed and test protocols were developed that failed modules known to be faulty and passed ones known to survive in the field. Out of this research were born the first qualification tests known as the Block V qualification sequence. The tests included the following [13]:

- Temperature cycling
- Humidity-freeze cycling
- Cyclic pressure loading
- Ice ball impact
- Electrical isolation (hi-pot)
- Hot-spot endurance
- Twisted-mounting surface test

The implementation of these qualification tests resulted in 5 year failure rates dropping from nearly 50% to less than 0.015% overnight [12]. The program was considered a huge success and has been the basis from which all qualification standards have been adapted since.

The Commission of European Communities (CEC) was the next group to publish a qualification standard. The CEC 502 sequence was quite different from Block V omitting some tests and adding the following ones [13]:

- UV irradiation
- High-temperature storage
- High-temperature and high-humidity storage
- Mechanical loading

Back in the USA, Underwriters Laboratories (UL) issued the UL 1703 safety standard which included most of the Block V tests as well as numerous additional safety related tests. This standard however required only that modules did not become hazardous as a result of test sequences and outlined no requirements for a systems post-test performance [13].

As amorphous silicon (a:Si) modules entered the market the Block V tests were reviewed and the Interim Qualification Tests (IQT) were developed. The following three tests were included in the IQT sequence {{25 Osterwald, Carl R 2003}}:

- surface cut susceptibility
- ground continuity
- wet insulation resistance test

Technical Committee 82 (TC-82) of the International Electrotechnical Commission (IEC) was first established in 1982 and eventually drafted an international qualification standard which came to be known as IEC 61215. IEC 61215 has since been one the most influential standards in the industry having an extremely positive effect on the reputation of PV modules in terms of reliability [13].

Prior to the worldwide adoption of IEC 61215 another standard was developed in the USA in an attempt to create a single document that was applicable to both crystalline and a:Si technologies. The problem was that amorphous silicon devices experienced an inherent initial light induced degradation which prevented accurate measurement of performance degradation due to the test sequences alone. The problem was solved by the IEEE 1262 standard which called for short thermal annealing steps to remove the light induced degradation in the a:Si modules before test sequences were performed. Eventually, TC-82 developed a separate document (IEC 61646) that applied specifically to a:Si modules[13].

Since this time qualification standards have continued to evolve and broaden. The most influential and current standards are maintained by the following organizations:

- ***International Electrotechnical Commission (IEC)***

- ***American Society for Testing and Materials (ASTM International)***

- ***International Organization for Standardization (ISO)***

2.2 Module Qualification Tests

The following sections describe the various tests and necessary equipment that are most commonly used during qualification testing. It should be noted that these tests were originally developed to improve the reliability of silicon flat panels as described in Section 2.1 which still dominate the commercial market. As third generation photovoltaic technologies emerge, these qualification tests are adapted to ensure that inherent material/system issues are not unfairly treated.

It should also be noted that the specific tests described are intended to exploit known reliability issues and also to confirm that PV systems will not become safety hazards during their operational life. While accelerated tests are very useful in this regard, qualification tests tend to be relatively short. True *reliability* tests often consist of more rigorous extensions of tests presented here often continuing until the failure of a panel for example. Reliability testing must also be conducted alongside real time field testing in order to ensure that the effect of accelerated test is realistic and not an artifact of the acceleration itself [13].

2.2.1 Wet Insulation (a.k.a. Wet Leakage or Wet High Pot.) & High Potential Tests

The Wet Insulation and High Potential tests are intended to ensure that the current carrying parts of the system are electrically insulated from the frame (or outside perimeter in the case of frameless panels) in order to eliminate the possibility of a ground fault. The Wet Leakage test also ensures that moisture does not enter the active part of a module which would put the module at risk of delamination or corrosion [10].

The High Potential test is performed on a dry panel. Given an applied voltage of 1000 V plus twice the maximum system voltage the current through the insulation is measured and must be < 50 μA. The resistance at an applied voltage of 500 V must be < 50 MΩ [10].

In the Wet Insulation test a module is submerged in a tank of water or other surfactant solution of known surface tension (</m^2), resistivity (<3500 Ω-cm) and temperature (~22˚C) and the insulation resistance is measured between the shorted module leads and the solution. The maximum allowed leakage current is 10 μA plus 5 μA times the surface area in m^2 [10].

These tests are safety tests and thus are performed before and after the other stress tests to make sure that the module remains well insulated even under harsh conditions.

In terms of equipment required to perform these tests it should be noted that power supplies must now deal with much higher voltages and currents than those previously discussed for laboratory measurements of individual cells. The current and voltage ranges required must be carefully considered when setting up a test suite.

2.2.2 Thermal Cycling Sequence

The Thermal Cycling Sequence is intended to accelerate the effect of stresses due to different thermal expansion coefficients within the module. This ensures that the interfaces between encapsulants, cells, interconnects, and bonding materials, etc. are not prone to breakage. Electrically biasing the panel during the test is also important in order to ensure that the real stresses on solder joints are simulated [10].

The Thermal Cycling Sequence consists of 200 cycles of 4 steps as shown in Figure 5. In step 1 the panel temperature is lowered to -40°C where it remains for 10 minutes. The panel temperature is then gradually increased until it reaches 85°C where it is again held for 10 minutes. Then the temperature is gradually decreased and the process is repeated [10][13].

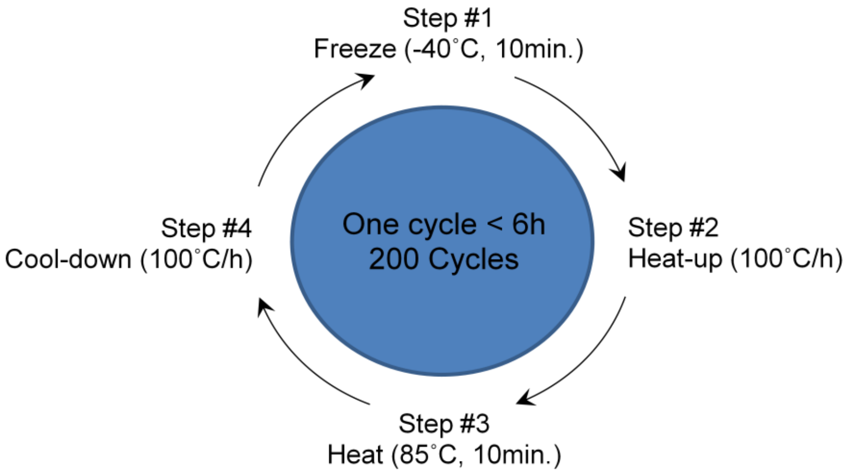

Figure 5: Thermal Cycling Sequence

The test is followed by electrical measurements to determine if there has been an effect on performance and the Wet Insulation and/or High Potential tests are performed to ensure the panel is still well electrically insulated.

2.2.3 Damp Heat Sequence

The Damp Heat Sequence (shown in Figure 6) is intended to stress the encapsulation potentially causing delamination. The Ice Ball impact test and the Mechanical Load test simulate extreme weather conditions that may also cause damage to encapsulation [10][13].

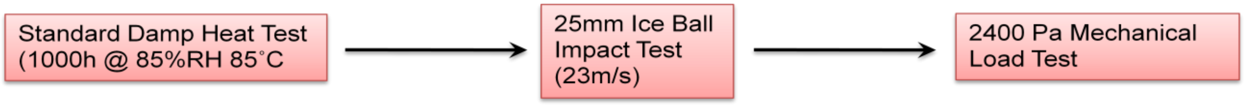

Figure 6: Damp Heat Sequence

The sequence is followed by electrical measurements to determine if there has been an effect on performance and the Wet Insulation and/or High Potential tests are performed to ensure the panel is still well electrically insulated.

2.2.4 Hot Spot Test

The purpose of the Hot Spot Test is to simulate an event that causes a particular local operating temperature that is ~5-40˚C higher than that of surrounding cells. The test consists of five 1-hour exposures at 1000 W/m^2 in the worst possible hot spot configuration [10].

2.2.5 UV Exposure, Thermal Cycling & Humidity Freeze Sequence

This test sequence is also intended to stress the encapsulation potentially leading to delamination. This is not a thermal shock test because of the slow temperature change. Figure 7 shows the test sequence in detail [10][13].

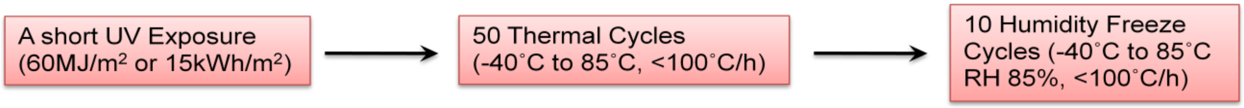

Figure 7: UV Exposure, Thermal Cycling & Humidity Freeze Sequence

It is also interesting at this point to take a look at the type of equipment or the type of facility that is needed to perform tests in which the environment must be carefully controlled. The Atlas 260 test chamber for accelerated-testing is shown in Figure 8. This test facility is capable of illuminating a 6' x 4' panel at 2.5 suns concentration with a full spectrum. Temperature & Humidity Cycling as well as light soaking is all controlled by the desired test program which outlines the sequence to be performed.

Figure 8: Atlas 260 test chamber at NREL, 2010 [14]**.**

2.2.6 Twist Test

As the name suggests the Twist test is a simulation of the deflection that a panel might experience when fastened to a nonplanar surface. One corner of the panel is deflected 1.2° from the plane of the other three corners to determine if the panel can withstand the force without damage.

The sequence is followed by electrical measurements to determine if there has been an effect on performance and the Wet Insulation and/or High Potential tests are performed to ensure the panel is still well electrically insulated [10].

3 Overall System Performance and Monitoring

Arguably the most interesting parameter when monitoring system performance is the overall power conversion efficiency (η). The calculation of this value seems straight forward if one is able to measure the electrical power produced by the system and the total insolation. The power conversion efficiency is then given by the ratio of the maximum electrical power (E_{max}) produced by the system to the total incident irradiance (G) times the module area (A) or $\eta = E_{max}/GA$. It is necessary however, for the purposes of achieving values that can be fairly compared against one another to standardize exactly how these quantities are measured. After all, it is important to keep in mind that the output of a PV module is a function of total irradiance, panel orientation, spectral irradiance, temperature, wind speed, soiling and even the definition of the module area [10][13].

Today, flat panel system performance is most often reported at Standard Reporting Conditions (SRC, AM1.5G, normalized to 1 kW/m^2, and a cell temperature of 25°C) for the purposes of comparing modules and estimating module price or worldwide PV market volume [15]. SRC are not the only standards however. The problem with a single standard is that different PV technologies harvest different parts of the spectrum differently. The performance of Concentrated Photovoltaic (CPV) technologies for example, which only harvest the direct portion of the spectrum, have been reported at Standard Operating Conditions (SOC, AM1.5D, normalized to 1 kW/m^2, cell temperature of 21°C) [15-17].

While reporting efficiencies that have been corrected to a standard is somewhat helpful for comparison of devices, it does not allow for a simple projection of the energy that a PV system will produce at an arbitrarily chosen location, especially in the case of triple junction cells and CPV technologies which are particularly sensitive to the spectrum of incident light. Another performance measure - known as the Energy Production Rate (EPR)- has been suggested for this purpose [15]. Determination of the EPR of a system requires the daily measurement of the energy produced by the PV system (E_{out}, kWh DC) and the integrated direct-beam solar radiation (DNI, kWh/m^2) and is given by $EPR=E_{out}/DNI$ in units of kWh/(kWh/m^2) or simply m^2. The EPR can thus be thought of as the energy production actually achieved for 1 sun or as the necessary aperture to produce the same electrical output if the system was 100% efficient.

The efficiency (η) of the system can be calculated by dividing the EPR by the total module area and the well known Performance Ratio (PR, the ratio of actual energy production to the power rating of the system) can be calculated by dividing the EPR by the power rating at SOC (P_{soc}). The advantage to reporting the EPR is that from this value the only information the reader requires to predict the total annual energy output at a new location is the annual DNI (measured with a pyrheliometer, See Section 3.3 for descriptions of instrumentation). With minor corrections for spectral variation (determined using a spectroradiometer) this method of prediction has been show to be accurate within ±10%.

3.1 Location

The first step to building an outdoor test suite capable of measuring the real performance of a photovoltaic system is to select a location. The selection process may be biased by considerations other than the ultimate output power of the system (which in general should be maximized) such as cost, convenience, accessibility or availability of property/facilities.

If the goal of the test suite is to determine the environmental suitability of a site because this data is either not available or not complete enough, then the location should be chosen based on the best data available and the type of PV system under investigation. The data collected at this site over a period of time may then be used to determine more accurately how a particular technology would perform in terms of maximum power output and hence return on investment in the location in question.

If the goal of the test suite is research-based and intended to determine the performance of a particular PV technology in a particular geographical area, then the choice of location is entirely based on the interest of the researcher. In this case any number of performance measures may be more interesting than maximizing the total output power.

If the goal of outdoor testing is to closely monitor the performance of an existing PV deployment then the location is already defined.

3.2 Mounting Structure

There are many novel means of mounting solar panels or modules, two of which are shown in Figure 9. Understandably, the mounting structure will have a huge impact on the performance of the system as well as the cost of the system. Mounting panels on a flat stationary frame such as a house will not receive nearly as many equivalent peak hours of sunlight as one mounted on a dual-axis tracking system.

These trends and others are quite intuitive but they must be understood when designing an outdoor testing facility because they will have a significant impact on the performance of the system and on the type of data that must be collected in order to fully characterize the system performance.

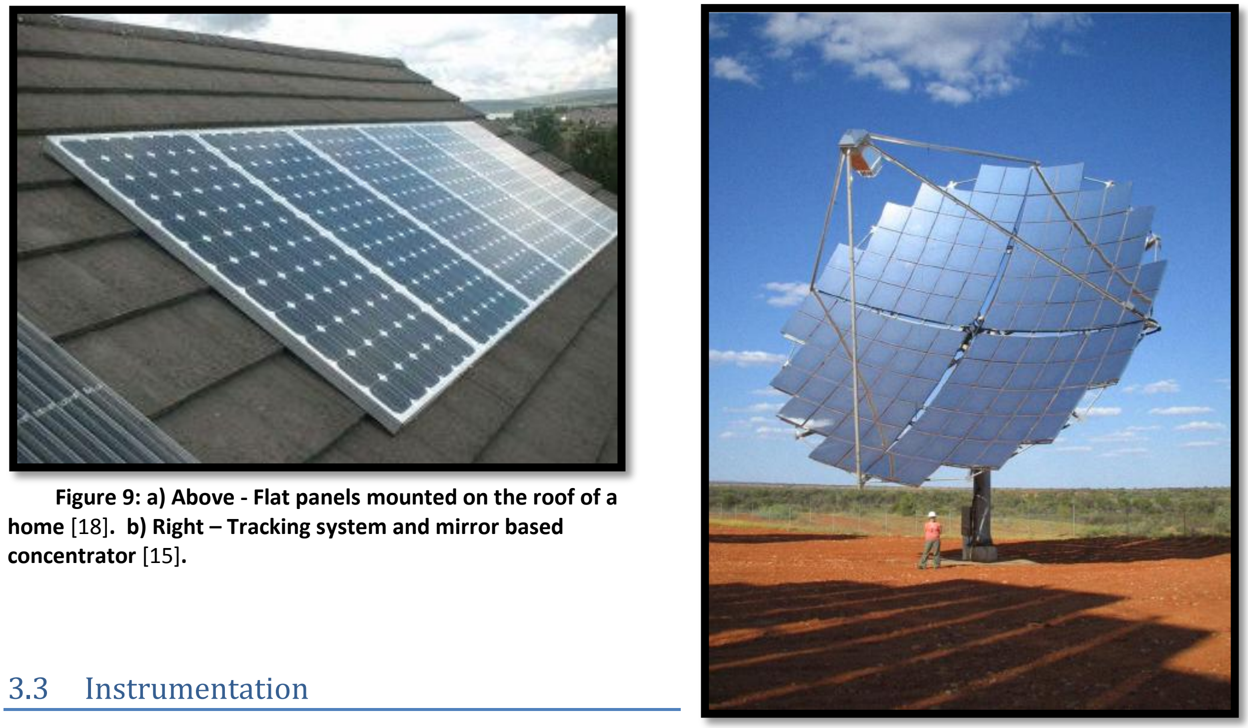

Figure 9: a) Above - Flat panels mounted on the roof of a home [18]. **b) Right – Tracking system and mirror based concentrator** [15].

3.3 Instrumentation

An outdoor test suite will require instrumentation to characterize the incident solar radiation (insolation) and equipment to measure the electrical power produced by the PV system. Insolation is broken down into three categories, which are shown in Table 1; each is measured individually using the indicated instrumentation. For reference, global and direct spectrums at an Air Mass (AM) of 1.5 are shown in Figure 10 where they are compared to the extraterrestrial spectrum (AM0).

Table 1: Insolation components and associated Instrumentation

Measurment	Instrument
Global	Pyranometer
Diffuse	Ball shaded pyranometer
Direct	Pyrheliometer

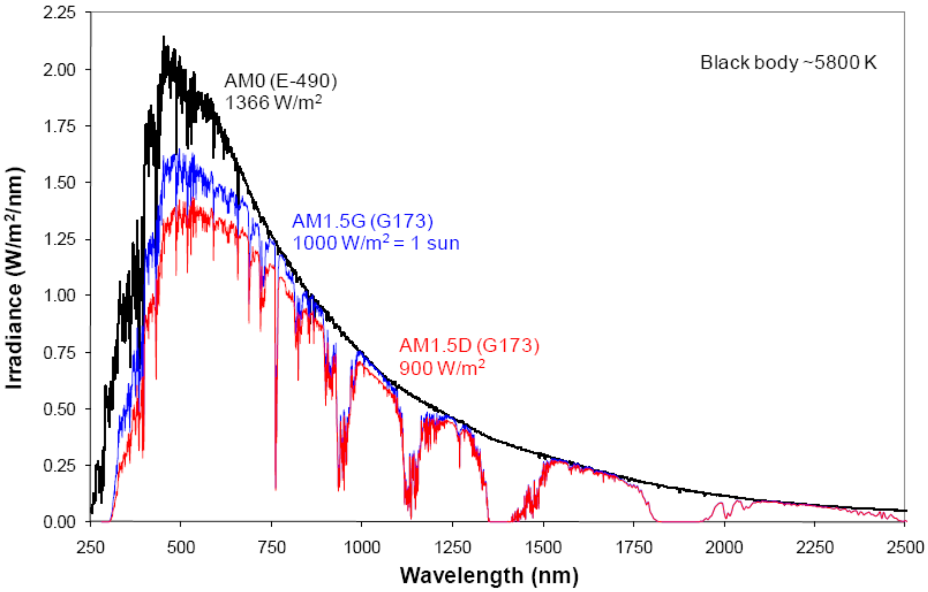

Figure 10: Spectral break down of incident solar radiation at an air mass of AM1.5 compared to the extraterrestrial (AM0) solar spectrum.

Figure 11: Kipp & Zonen pyranometer [19]..

A pyranometer (Figure 11) is a radiometric instrument intended to measure global irradiance (the sum of the direct and the diffuse light) over an entire hemisphere. The sensing element is a thermopile (a number of thermocouples (~50-100) connected in series) which acts to convert a temperature gradient into an electrical signal [20]. The thermopile is contained within a small disk with a black coating which, in the ideal case, has a flat absorption spectrum over the entire solar spectrum. The sensor is designed to have a linear response to incident radiation and to have a directional response that is described perfectly by the cosine of the angle between the sun's rays and the normal to the sensor [21]. The double glass dome has two purposes other than protecting the sensor from dust and rain. The first is to limit the absorption window by transmitting only wavelengths that are shorter than ~2800 nm while maintaining a 180° field of view. The result is a sensor that measures the solar irradiance between ~300 nm and ~2800 nm[20]. The second purpose of the glass dome is to protect the sensor surface from convective air currents which could affect the temperature at the surface of the sensor[20].

Absorbed radiation is converted to heat which flows through the thermopile and into the pyranometer housing. The gradient in the temperature produces a proportional voltage output from the thermopile which can be measured and recorded (this is the output from the pyranometer) and eventually converted to a total irradiance in W/m^2 [21][22].

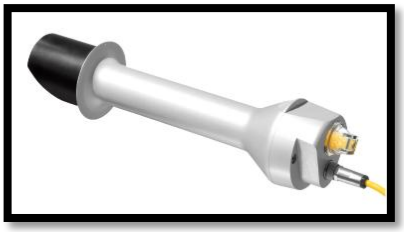

Figure 12: Kipp & Zonen pyrheliometer [22]..

A pyrheliometer (Figure 12) works in a manner very similar to a pyranometer in that incident radiation falls on a thermopile which converts the heat produced to an electrical signal. The difference is that in this case the instrument is designed to measure the incident power of the direct light only. This is known as Direct Normally Incident (DNI) light.

This is achieved by limiting the field of view to less than 5° and tracking the solar disk so that the sun is always within the 5° field of view. The front aperture generally has a glass window made of quarts which protects the instrument from dust and rain and limits the spectrum accepted by the device to between ~200 nm and ~4000 nm [23].

Figure 13 Kipp & Zonen pyranometers with shading balls and a pyrheliometer mounted on a duel axis solar tracker [24]..

To measure diffuse light a mechanical solution is normally adopted as shown in **Error! Reference source not found.**. The goal in this case is to block any light coming directly from the sun and to measure light that enters through an upward facing hemisphere by way of reflection or scattering. The most accurate solution makes use of a shading ball to shade a pyranometer sensor from the solar disk. This apparatus must track the motion of the sun to ensure that the shading ball remains in the correct position to shade the pyranometer.

Once the global, direct and diffuse light has been measured, only electrical output measurements are absolutely critical in order to calculate the efficiency (η) of the PV system. This is normally a matter of installing a power meter to measure DC output of the system, although the AC power measured at the output of an inverter is also interesting. This measurement allows for the determination of the net system output directly as well as the efficiency of the inverter.

The Energy Production Rate (EPR) and the Performance Ratio (PR) of the PV system can also be calculated. The only remaining radiological information that would be helpful in some circumstances, but which is not extractable from measurements of global, direct and diffuse light, is the spectral content of the insolation. The spectral content is particularly important when analyzing the performance of high efficiency CPV systems.

Due to the requirement for current matching of each subcell of a high efficiency triple junction device relatively small shifts in the spectrum of incident light (due to changes in Air Mass (AM), Aerosol Optical Depth (AOD) or precipitable Water Optical Thickness) have a magnified effect on the net performance of the system [15]. It is especially important to make corrections for these influences when attempting to project the performance of future CPV power facilities at new locations [15].

The spectrum of the incident light is collected with a

Figure 14: The Kipp & Zonen PGS100 Sun Photometer and a pyrheliometer mounted below it both shown mounted on a solar tracker [25]..

spectroradiometer. This instrument consists of a high speed spectrometer and a coupling mechanism to get unaltered sunlight into the spectrometer. Coupling the light into the spectrometer will be done differently depending on whether the global or direct spectrum is of interest but normally some optics will be used to either focus light into the spectrometer directly or first into a permanent, calibrated fiber which then carries the light into the spectrometer. The Sun Photometer shown in Figure 14 is one example of an integrated spectroradiometer system.

4 Conclusions

An overview of the most common testing procedures and the equipment/facilities required to perform them has been presented for all levels of PV development. A test suite, whether indoor or outdoor, does not have to have all of the capabilities discussed herein, nor should a test suite be limited to the capabilities presented here. Rather one might begin with basic capabilities selected from those outlined and then expand based on the requirements of the specific application and as expertise is gained.

Reference to the applicable standards (which continue to evolve) was made in order to emphasize the importance of producing results that are easily understandable and that can be compared to results reported by the rest of the industry. The ability to make measurements with accuracy and precision and to report those results with clarity should be the goal of every test facility.

5 References

[1] Newport Corporation. (2010, **1600 W solar simulators** . *2010(04/03),* Available: http://www.newport.com/1600-W-Oriel-Solar-Simulators/374888/1033/catalog.aspx.

[2] SUNLab. (2010, .

[3] Hill Technical Sales Corp. **Short arc lamps** . *2010(04/01),* Available: http://www.hilltech.com/products/uv_components/Short_arc_lamps.html.

[4] Wikipedia. (2010, **Arc lamp** . *2010(3/2),* pp. 1. Available: http://en.wikipedia.org/wiki/Arc_lamp.

[5] PerkinElmer. (2010, **Flash lamps** . *2010(03/31),* Available: http://www.perkinelmer.com/Category/Category/ KeyName/TCH_ILL_CAT_Flash%20Lamps_029.

[6] Wikipedia. (2010, **Flash tube** . *2010(03/02),* pp. 1. Available: http://en.wikipedia.org/wiki/Flashtube.

[7] D. L. Klipstein. (1999, December 29, 99). **General xenon flash and strobe design guidlines** . *2010(03/31),* Available: http://members.misty.com/don/xeguide.html.

[8] Ultrafast Systems. (2010, **High speed spectrometers** . *2010(05/07),* Available: http://www.ultrafastsystems.com/high_speed_spectrometer.htm.

[9] Sciencetech Inc. **Flash solar simulator** . *2010(30/31),* Available: http://www.sciencetech-inc.com/catalog/1/solar_simulators/PSS06.

[10] K. Emery, "**Measurement and characterization of solar cells and modules** ," in *Handbook of Photovoltaic Science and Engineering*, Antonio Luque and Steven Hegedus, Ed. Southern Gate, Chichester, West Sussex PO19 8SQ, England: John Wiley & Sons Ltd, The Atrium, 2003, .

[11] W. Guter, J. Schöne, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett and F. Dimroth, "**Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight** ," *Appl. Phys. Lett.,* vol. 94, pp. 223504, 2009.

[12] Maish, Alexander B., et al, "**Photovoltaic system reliability**," in *Proceedings of the 26th IEEE Photovoltaic Specialists Conference ,* Anaheim CA, Sept 1997, .

[13] C. R. Osterwald, "**Standards, calibration and testing of PV modules and solar cells** ," in *Practical Handbook of Photovoltaics: Phundementals and Applications*, Tom Markvart and Luis Castaner, Ed. The Boulevard. Langford Lane, Kidlington, Oxford OX5 lGB, UK: Elsevier Advanced Technology, 2003, .

[14] NREL. (2010, Feb. 12 2010). **Indoor testing**. *2010(30/04),* pp. 1. Available: http://www.nrel.gov/pv/performance_reliability/indoor_testing.html.

[15] P. J. Verlinden and J. B. Lasich, "**Energy rating of Concentrator PV systems using multi-junction III–V solar cells** ," *Photovoltaic Specialists Conference, 2008. PVSC '08. 33rd IEEE,* pp. 1-6, 2008.

[16] P. J. Verlinden, A. Lewandowski, C. Bingham, G. S. Kinsey, R. A. Sherif and J. B. Lasich, "**Performance and Reliability of Multijunction III-V Modules for Concentrator Dish and Central Receiver Applications** ," *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on,* vol. 1; 1, pp. 592-597, 2006.

[17] P. J. Verlinden, A. Lewandowski, H. Kendall, S. Carter, K. Cheah, I. Varfolomeev, D. Watts, M. Volk, I. Thomas, P. Wakeman, A. Neumann, P. Gizinski, D. Modra, D. Turner and J. B. Lasich, "**Update on two-year performance of 120 kWp concentrator PV systems using multi-junction III–V solar cells and parabolic dish reflective optics** ," *Photovoltaic Specialists Conference, 2008. PVSC '08. 33rd IEEE,* pp. 1-6, 2008.

[18] Kellene Bishop. (2009, April 17, 2009). **Bring on the sun** . *2010(03/06),* pp. 1. Available: http://preparednesspro.wordpress.com/2009/04/17/bring-on-the-sun/.

[19] Kipp & Zonen. (2008, **Pyranometers** . *2010(03/04),* pp. 1. Available: http://www.kippzonen.com/?productgroup/331/Pyranometers.aspx.

[20] C. Woodford. (2009, **Pyranometers** . *2010(01/23),* Available: http://www.explainthatstuff.com/how-pyranometers-work.html.

[21] The Eppley Laboritory Inc. (2010, **Precision spectral pyranometer** . *2010(01/23),* Available: http://www.eppleylab.com/.

[22] Kipp & Zonen. (2010, **Pyranometers** . *2010(01/23),* Available: http://www.kippzonen.com/?productgroup/331/Pyranometers.aspx.

[23] Kipp & Zonen. (2008, **Pyrheliometers** . *2010(03/04),* pp. 1. Available: http://www.kippzonen.com/?productgroup/881/Pyrheliometers.aspx.

[24] Kipp & Zonen. (2008, **Sun trackers** . *2010(03/04),* pp. 1. Available: http://www.kippzonen.com/?productgroup/991/Sun+Trackers.aspx.

[25] Kipp & Zonen. (2008, **PGS 100** . *2010(03/04),* pp. 1. Available: http://www.kippzonen.com/?product/63122/PGS+100.aspx.