# SOLAR 2010: SOLAR CELL PRODUCTION REQUIRES EFFECTIVE METROLOGY– RECENT IR THERMOGRAPHY DEVELOPMENTS CAN HELP

Chris Bainter
FLIR Systems, Inc., Thermography Div.
1107 Fair Oaks Ave., #884
South Pasadena, CA 91030
Chris.Bainter@flir.com

## ABSTRACT

Two recent developments in IR thermography improve on the benefits this technology supplies in the development and production of solar panels. One development is a lock-in technique that increases sensitivity in defect detection. The second is more cost-effective spectrally filtered IR cameras that allow inspections through glass that is part of a solar panel assembly. These IR thermography improvements are described in this paper.

## 1. INTRODUCTION – CHARACTERIZING DEFECTS AND PERFORMANCE

PV cells suffer from a variety of defects that limit conversion efficiency. The frequency and severity of these problems depends on the technology used in PV cell construction. Much of the industry's R&D efforts are aimed at reducing assembly and production defects. For example, too many defects in the semi-conducting material structure go undetected before PV cells are put into solar panel assemblies. Similarly, defects can occur in the final assembly of solar panels that also decrease conversion efficiency. However, inspections need to be ongoing throughout the solar panel life cycle (Fig. 1.) Therefore, characterizing a solar panel's performance requires cost-effective test and measurement methods to reveal both material and panel assembly problems.

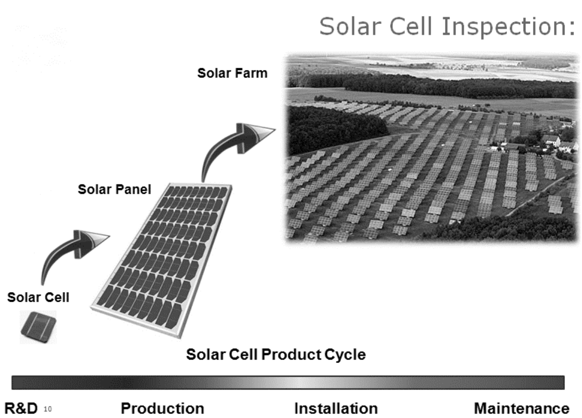


**Fig. 1.** Test and inspection is required at every stage of a solar panel's life.

A wide variety of test and measurement methods are used depending on the specific stage of solar panel R&D or production. One method in use for the past several years is infrared (IR) thermography. Interest in this technology continues to grow because it is a relatively fast and easy way to spot defects, while requiring moderately priced equipment. With an IR video camera and appropriate stimulation of the solar cell, various kinds of defects become visible (Fig. 2). [i]

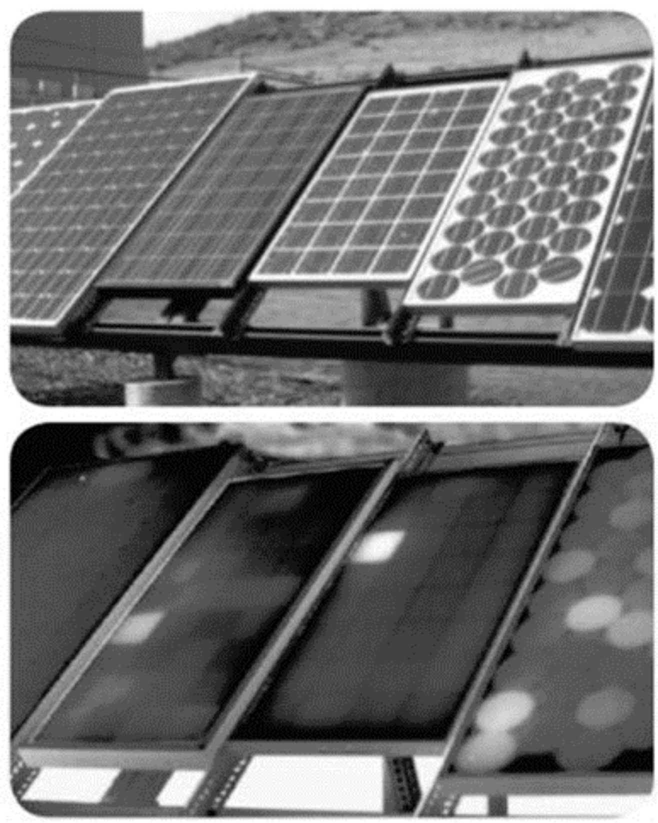

**Fig. 2.** Digital photo (upper) and IR thermogram (lower) of operating solar panels. Gross defects are indicated by cells that appear light gray or white in the lower view).

Depending on circumstances, this stimulation could be sunlight under normal operating conditions, as shown in the thermographic view of Fig. 2 (taken with a relatively low-cost IR camera with an uncooled microbolometer detector). Alternatively, electrical stimulation or artificial light could be used during the early stages of development or production. In any case, thermal data collected with IR cameras can be manipulated and analyzed with computer software to characterize what is going on electronically in a PV cell's material structure.

Most often, IR inspection methodologies have been used for crystalline silicon (C-Si) types of PV cells before they become part of a solar panel with a glass cover installed. This is because IR camera sensors have a limited ability to detect thermal radiation through glass. Since most thin film cells use depositions on glass as an integral part of their construction, IR inspections on them have been difficult. However, as will be shown, spectral filtering can help make IR thermography a viable inspection technique, even when glass is part of a solar panel assembly.

## 2. TYPICAL TYPES OF DEFECTS

A PV cell can be modeled as an ideal diode in parallel with a photocurrent source. Typical defects are modeled as parasitic resistances, such as *shunt resistance* ($R_{SH}$) and *series resistance* ($R_S$) (Fig. 3).

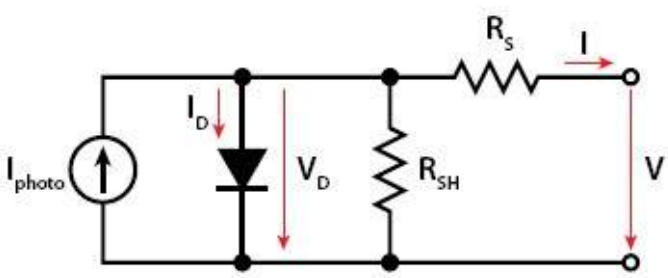


**Fig. 3.** Circuit model of a PV cell.

In a typical silicon PV cell, conversion efficiency is limited by free carrier recombination, due to bulk material defects. For instance, in multicrystalline silicon (mc-Si) wafers there are significant concentrations of crystallographic non-uniformities, such as dislocations, grain boundaries, and impurities. In thin metallic film PV cells, lateral non-uniformities in current flow affect efficiency. Thus a few bad cells can affect the performance of a larger solar panel that is constructed by connecting individual PV cells.

Often, high $R_{SH}$ (shunt resistance) is identified as a particularly troublesome defect, which can result from:

- Improper handling during processing
- Diamond saw scribing at cell boundaries
- Over-firing during cell metallization
- Poor edge isolation processes
- Random shunts inherent in most production processes

Dominant sources of $R_S$ (series resistance) are contact resistance, bus bar resistance, screen-printed "fingers", and lateral conductions in the emitter. The relative importance of each source depends on bias level and current flow.

## 3. MEASUREMENT METHODOLOGIES

In the early stages of PV cell production, the parameters most commonly used to characterize defects are resistivity (to screen wafer material), plus a variety of electronic measurements on wafers prior to solar panel assembly. The latter include I-V and C-V measurements to characterize charge carrier characteristics/current density, free charge recombination lifetime, bulk material lifetime, effective lifetime, etc.

Test techniques vary greatly in terms of complexity, equipment cost, and the time required for a typical set of measurements. For instance, electrical C-V, I-V, and resistivity profiling in early production stages require wafer probing and thickness measurements. The latter require additional optical or capacitive gauging techniques. Some of these may also require time-consuming sample preparation.

Conventional IR thermography has been used for several years, because it is a quick way to detect gross defects and thereby avoid further processing of bad PV cells. In most C-Si cells without a glass cover, it allows fast detection of the major shunts by the application of a reverse bias voltage, or by just observing the temperature of the cell under typical operation. However, with a glass cover, the spectral sensitivity of an IR camera's detector is drastically reduced. Even an indium gallium arsenide (InGaAs) detector with sensitivity in the spectral range of 0.9-1.7µm, where many glasses have low IR absorption, will have difficulty seeing defects unless their temperature is much higher than normal operating temperatures.

In more general terms, the sensitivity of an IR camera used in conventional thermography is limited by its inherent detector sensitivity, or noise equivalent temperature difference (NETD). The NETD for cooled cameras with InGaAs detectors is ~20mK, and ~80mK for cameras with an uncooled microbolometer detector. Fig. 4 is an image of a PV cell with shunt resistance defects using an IR camera with a microbolometer detector having a spatial resolution of 320 x 240 pixels.

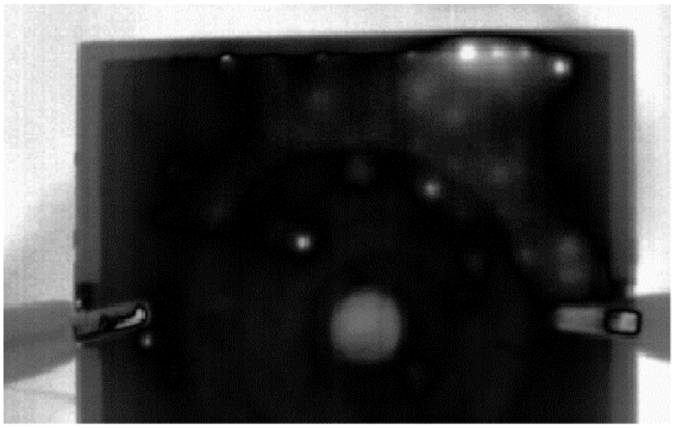

Image courtesy of MoviTHERM

**Fig. 4.** IR image of 60x60mm PV cell without a glass cover showing shunt defects (lighter areas) under steady state reverse bias conditions.

In Fig. 4 the triangular shapes on the left and right of the cell are alligator clips used to apply bias voltage; the circular area is a reflection of the camera lens. The white spots and lighter gray regions in the upper right portion of the image indicate increased thermal activity due to shunts. Only severely shunted areas become visible as bright and localized spots. The darker gray regions are a result of weaker shunt defects. Locating the origins of these weaker shunts is extremely difficult due to the thermal diffusion (spreading of thermal energy over time) as well as the weak thermal radiation of the defect itself.

## 4. ELECTROLUMINESCENCE (EL) AND PHOTOLUMINESCENCE (PL) TECHNIQUES

One way to overcome these sensitivity and resolution problems is to use a stimulated luminescence technique. EL and PL techniques can be used to generate solar cell images with better spatial resolution that reveals localized shunts, series resistance, and areas of charge carrier recombination. EL applies a forward voltage and current to cause localized irradiance due to carrier recombination (Fig. 5). PL uses light irradiation for the same purpose.

In the test setup of Fig. 5, current flow through the PV cell causes it to emit light in the near infrared (NIR) region of the spectrum. This technique is able to examine the uniformity of the solar cell with respect to its ability to convert photons into electrons. Since EL and PL techniques only work in the NIR region, both types of system require a camera with a cooled NIR detector. Cameras with uncooled microbolometer detectors are long wave IR instruments, and therefore not suitable, albeit less expensive.

Care must be taken during EL testing to avoid applying a destructive amount of current to a PV cell. In cases where a cell may be more vulnerable to damage from EL test currents, lock-in thermography is an alternative, with even better sensitivity and spatial resolution.

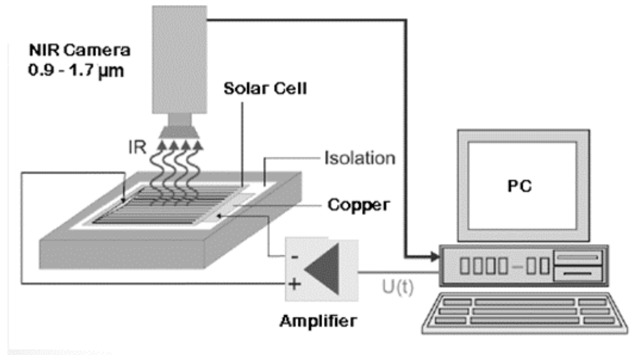


Image courtesy of MoviTHERM

**Fig. 5.** Measurement setup for solar cell emission analysis using MoviTHERM's IR-NDT system, "SolarCheck". The PV cell is being electrically stimulated using an EL technique.

## 5. LOCK-IN THERMOGRAPHY

To detect a wider variety of defects, researchers have for the past 10 years or so used the technique of lock-in thermography (LIT). By stimulating a PV cell with pulsed light, heat, or electrical signals, a lock-in amplifier tuned to the excitation frequency of the stimulus allows the system to detect subtle thermal responses beyond the noise floor limitations of the camera. This technique is capable of detecting temperature differences with microKelvin resolution, far exceeding the 20mK resolution of modern InGaAs cameras.

Historically, these test systems were custom in-house developments, since commercial-off-the-shelf systems were not available. More recently, commercial systems have come onto the market, such as those supplied by MoviTHERM (www.movitherm.com). These systems integrate a FLIR IR camera with software modules from a German company, Automation Technology (www.automationtechnolody.de) for a complete, commercially available LIT test solution (Fig. 6).

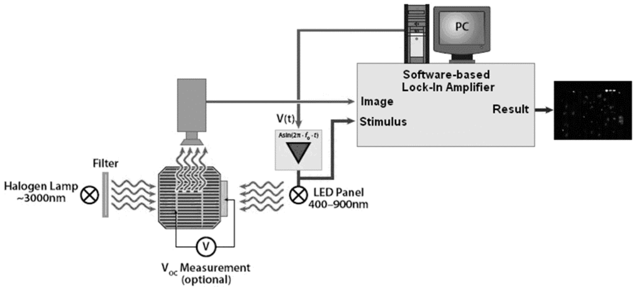


Image courtesy of MoviTHERM

**Fig. 6.** Non-contact LIT test configuration using modulated light as the PV cell stimulus. Optional open circuit voltage measurements do require electrical probing of the cell.

Fig. 7 is an image of shunt defects identified with this type of LIT system. The illuminated LIT technique allows mapping a cell's forward current density distribution, and can also reveal series resistance and sites where there is heightened carrier recombination.

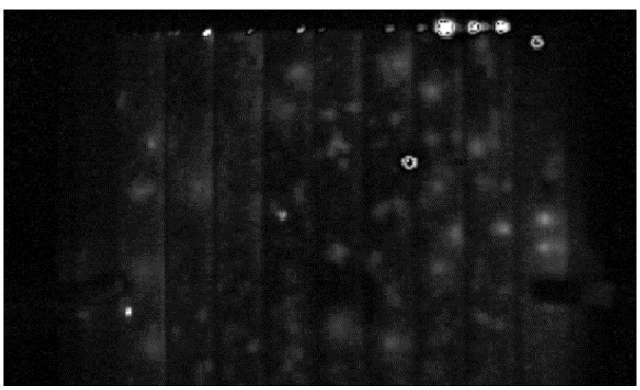

Image courtesy of MoviTHERM

**Fig. 7.** Image of the same solar cell in Fig. 4, now showing shunt defects more clearly (orange areas) when mapped with an LIT technique.

Compare Fig. 7 to Fig. 4. Note that the image resolution in Fig. 7 is better (i.e., not so diffused and blurry), with localized shunt defects more sharply defined by the white areas. With LIT, the reflection of the camera lens and outlines of the alligator clips no longer obscure large portions of the image, as they do in Fig. 4. LIT also requires significantly less energy input to the solar cell compared to conventional thermography. One reason is because measurement sensitivity is about 1000X better – around 0.02mK. These sharp LIT images provide additional information, such as non-uniform heating of the cell, as revealed by light gray areas.

LIT techniques are sensitive to the frequency of the stimulus signal. Generally, the frequency is kept low (i.e., several Hertz) to stay well below the noise floor of the system, but some experimentation may be required to find the optimum frequency. In some cases, a camera with a microbolometer detector might be usable for LIT measurements, and experimentation is going on in that area.

Another variation of the LIT technique is carrier density imaging (CDI), which provides quantitative information on charge carrier density. A discussion of CDI is beyond the scope of this paper, but briefly stated, it is based on free-carrier absorption of photo-generated excess carriers, and thus allows the imaging of charge carrier lifetime properties. With lock-in processing of the signal, much shorter lifetimes can be measured, and CDI can usually be carried out without special time-consuming wafer preparation. With appropriate software other PV cell properties can be derived, such as Fill Factor (FF) and Ideality Factor (   ).

## 6. SEEING IR RADIATION THROUGH GLASS

At the beginning of this paper the problem of detecting defects in PV cells covered by glass was mentioned. Recent investigations with filtered midwave IR cameras seem to offer some hope of overcoming this limitation.

The basic problem is the low amount of IR energy emitted from PV cell defects, which is then attenuated by glass in the region where IR camera detectors are spectrally sensitive. The amount of emitted energy (emittance) per unit of time and area is described by Plank's law. This is a rather complex mathematical formula, so it is usually described graphically for a perfect blackbody radiator (Fig. 8).

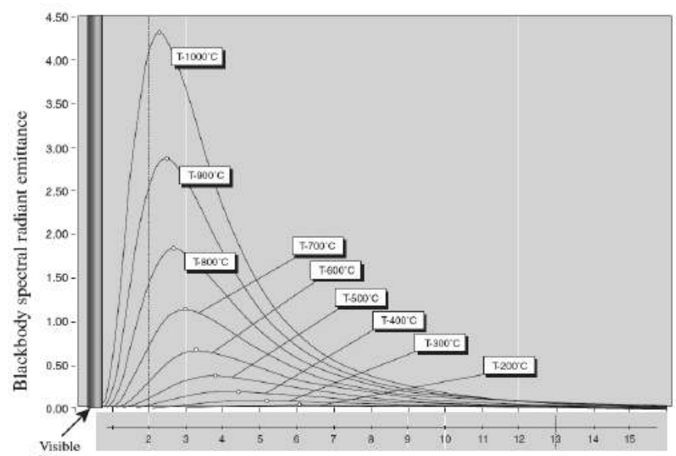


**Fig. 8.** Representation of Plank's law: blackbody emittance as a function of temperature (°C) and IR wavelength (µm).

As evident in Fig. 8, the peak emittance below 300°C is very low, and it has shifted toward a wavelength of about six microns. With the low transmittance of glass in that region, and typically small defect areas, the thermal detection of those defects becomes a significant challenge. However, if you can overcome the IR absorption problem of the glass, then an IR camera with a sensitive detector (~20mK) has a chance of seeing the defect, particularly if an LIT technique is used.

The glasses used for PV cells and solar panels are typically selected for high transmittance in the range of 0.4 to 1.1µm, where a cell's conversion efficiency is the highest. Various glass compositions are being developed that shift the iron absorption region of a typical commercial (soda-lime-silica) glass so it will be above 1.1 µm. Looking at the IR transmittance of a typical commercial glass, one can see that it remains relatively high up to about 3.5µm (Fig. 9). **Note:** transmittance also depends on glass thickness.

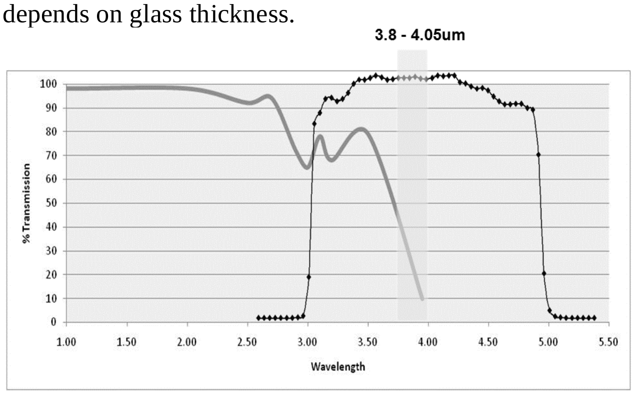


**Fig. 9.** IR transmittance of a commercial glass (dark gray line) and InSb detector spectral response (black line), with a notch filter's focused response (light gray bar).

FLIR Systems recently developed an IR camera with an indium antimonide (InSb) detector and spectral filter for an entirely different type of application. However, it appeared to be suitable for defect detection in PV cells and solar panels whose assemblies have glass panels. Inside the camera, the temperature of the detector and spectral filter are controlled with a small Stirling cycle cooler producing near-cryogenic temperatures. This gives the camera a peak spectral detection in the range of 3.80-4.05µm, which is still within a region of reasonably high transmittance of the commercial glass in Fig. 9.

Depending on the specific glass used in a solar cell assembly, other filters of this type might prove to be somewhat better. For example, FLIR also employs a 3.2-3.4 µm notch filter with an InSb sensor for the detection of gas emissions.

Fig. 10 illustrates the difference in defect detection when using an unfiltered InSb camera vs. one with the 3.80-4.05µm filter. This inspection was done on a normally operating solar panel system with a glass cover, which installs on roofs like regular singles and does not require additional roofing (i.e., not installed over existing shingles). Clearly, a standard InSb camera could not see any defects, while the filtered camera could. They show up as bright spots in the image. The scales at the right side of each image give the apparent temperature ranges of the solar panels in °C.

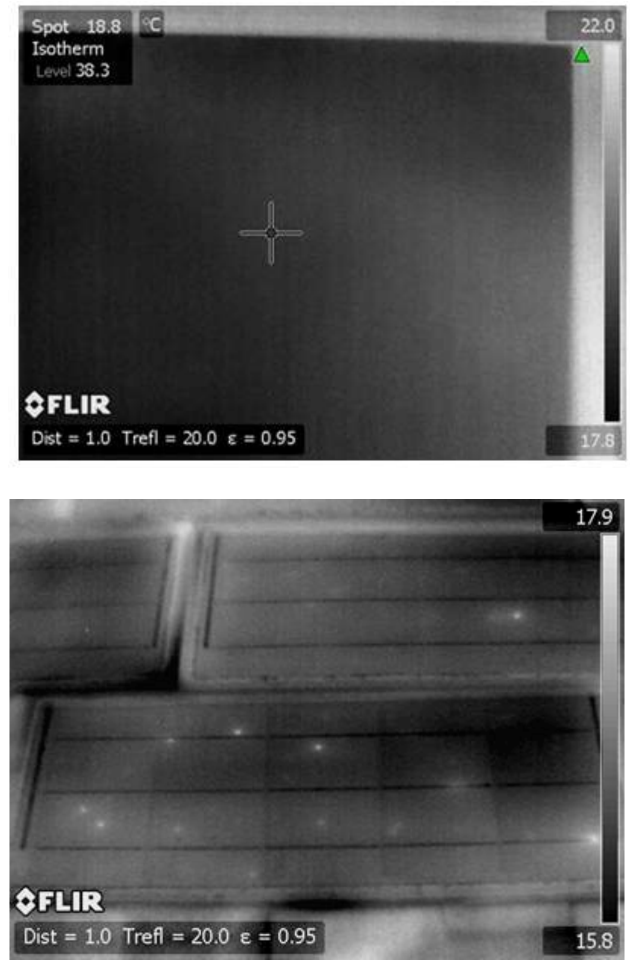


**Fig. 10.** Defect detection in a solar panel roof assembly with a protective glass cover. The upper image was captured by a standard IR camera with an InSb detector. The lower image was taken with the same type of camera, but equipped with a 3.80-4.05µm spectral filter.

More testing is required using different measurement techniques to find the optimum conditions for various types of PV cell and solar panel assemblies. However, the filtered detector approach seems very promising. (Those not familiar with thermography and the workings of IR cameras are referred to FLIR's "Infrared Handbook for R&D Professionals".) [1]

## 7. SUMMARY

A major advantage of IR thermography in solar cell defect detection, compared to many other test methods, is the short time required to complete a set of measurements without elaborate sample preparation. Gross defects can be seen by IR cameras equipped with uncooled microbolometer detectors. However, using more sensitive cameras with different types of cooled semiconductor detectors provides better results. With notch filters that limit a camera's spectral response to a narrow region of glass transmittance, defect detection is improved when viewing a defect through a glass panel.

LIT techniques enhance IR thermography capabilities by allowing detection below the noise floor of a typical camera, and thereby increase sensitivity by as much as 1000X. LIT also allows significant amounts of data to be acquired in seconds, compared to minutes or hours with other methodologies. This makes thermography and LIT methods good candidates for process related testing, as well as for use in R&D labs. With appropriate cameras (detectors), stimulation sources, and accessories, inspection systems can be created for most types of solar cell assemblies. These systems can spot shunt and series resistance defects, cracks, and other anomalies. With suitable software, they can also quantify charge carrier characteristics and calculate parameters such as Fill Factor and Ideality Factor.

## **8.** ACKNOWLEDGEMENTS

The thermographic measurement capabilities of the LIT systems mentioned in this paper are based on IR cameras supplied by FLIR Systems, Inc. Many of the parameter extractions are provided in Lock-In software "IrNDT" supplied by Automation Technology GmbH, Germany (www.autmationtechnology.de). Complete, integrated LIT systems, such as the "SolarCheck" system can be ordered from MoviTHERM, Irvine, CA, USA (www.movitherm.com). Engineers and scientists of these companies have contributed to, or performed peer reviews of parts of this paper.

### 8.1 About the Author

Chris Bainter is a senior scientific segment engineer for FLIR Systems in the southwestern US. In this role he provides application assistance on FLIR IR cameras, develops technical guides for their thermography products, and presents related training seminars. He earned a Bachelor of Science degree in Computer Engineering from Kansas State University. He can be reached at Chris.Bainter@FLIR.com.

## 8. REFERENCES

1. "Infrared Handbook for R&D Professionals", FLIR Systems, Inc., North Billerica, MA, available on the Web for download at: http://go.flir.com/LPM/LandingPage.aspx?404%3bhttp%3a%2f%2fgo.flir.com%3a80%2frdhbns.

---

Endnote:

[i] Many of the thermographic images appearing in this article were created using a color scale to represent temperatures. They were converted to a gray scale for ASES article reproduction purposes. Contact the author for samples of color thermograms collected from PV cells and solar panels.