Uses of infrared thermography in the Low-Cost Solar Array Program

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Abstract

The Jet Propulsion Laboratory has used infrared thermography extensively in the Low-Cost Solar Array (LSA) photovoltaics program. A two-dimensional scanning infrared radiometer has been used to make field inspections of large free-standing photovoltaic arrays and smaller demonstration sites consisting of integrally mounted rooftop systems. These field inspections have proven especially valuable in the research and early development phases of the program, since certain types of module design flaws and environmental degradation manifest themselves in unique thermal patterns. The infrared camera was also used extensively in a series of laboratory tests on photovoltaic cells to obtain peak cell temperatures and thermal patterns during off-design operating conditions. The infrared field inspections and the laboratory experiments are discussed, and sample results are presented.

Introduction

In its role as lead center for the National Photovoltaics program, the Jet Propulsion Laboratory (JPL) is responsible for coordinating nationwide research and development in many areas of solar cell, module, and total generating-system design and construction. The ultimate goal of the program is to develop the technology for commercial production of solar cells and modules capable of generating energy, with a life cycle that makes it cost-competitive with large-scale fossil-fuel electric generation facilities. The cost of terrestrial photovoltaics has already been decreased by an order of magnitude, compared with the earliest spaceborne systems.

Advances in silicon manufacturing technology and module-reliability information constantly spur new module designs by the several major domestic manufacturers. Several generations of module designs have already been installed in many governmental and privately financed photovoltaic demonstration projects. The scope of these projects ranges from about 20 peak watts (W_p) of installed capacity to provide power for remote roadside signs and ocean buoys, through 2- to 3-kW_p arrays mounted on the roofs of experimental energysaving homes, to large 100 kW_p arrays used to reduce the need for purchased electrical power for airports, schools, and other large buildings. The Jet Propulsion Laboratory has conducted extensive examinations and inspections of many of the photovoltaic array demonstration projects, primarily to gather reliability data. Inspection methods include visual examinations, several types of electrical performance checks, and thermal inspections with an Inframetrics Model 525 infrared scanning radiometer, sensitive in the 8- to 12-μm wavelength band. The latter inspections have proven to be especially valuable, since several failure and potential failure modes are manifested by localized solar-cell heating. The use of thermography to detect cell and module flaws in specialized spaceborne photovoltaic arrays has previously been reported on by Prudhomme, et al.[1]

Key electrical characteristics of solar cells and interconnected strings of cells are presented in the next section, and several failure modes and their causes are identified. The following section will present some results of thermal inspections of several photovoltaic field sites, and will classify infrared scan results as particular failure modes. The next section will discuss the use of the infrared radiometer in a series of laboratory hot-spot heating tests originally designed as photovoltaic-module thermal-performance acceptance criteria.

Electrical characteristics of solar cells and modules

Photovoltaic, or solar, cells are devices that convert some fraction of the energy of incident light directly to electricity. While several properly manufactured materials exhibit this characteristic, most of today's commercially available terrestrial photovoltaic modules use single-crystal silicon cells, due to favorable economics. Other silicon production methods are being explored, however, and may yield significant cost reductions.

Most silicon solar cells are fabricated from single crystals of p-type silicon grown in diameters of 2 to 5 inches. The long cylindrical crystals are cut into wafers typically 0.015 in. thick, and an n-type impurity is diffused into a thin layer on one side, in effect forming a diode junction. After application of an antireflection coating, metallic contacts are attached to both surfaces. Cells are typically interconnected electrically through these contacts to form a single module with desired current and voltage characteristics. Present trends are to encapsulate the cells within a pottant layer, which is then sandwiched between a thin substrate and a protective cover, usually made of glass.

Illuminated solar cells exhibit current-voltage characteristics typified by Curve A in Figure 1. A variable resistive load applied across the terminals of this illuminated cell can force the cell to operate between open circuit (infinite load, zero current), and short circuit (zero load, zero terminal voltage) conditions. At any intermediate value of load, the power produced is the product of cell voltage and current. The power produced by the cell is thus zero in both the open and short-circuit conditions, and reaches a maximum generally near the knee of the curve. In Figure 1, the peak powers represented by the shaded area under the curve, will be generated by the illuminated cell at voltage V_a and current I_a.

Cell illumination has little effect on the shape of the current-voltage characteristic, but directly affects the output current and, hence, output power. For most practical purposes, varying the cell illumination simply translates the curve along a very steep line that is determined by cell series resistance. Curves B and C in Figure 1 represent a half-illuminated cell and a fully shadowed cell, respectively.

A typical module of 40 cells may be configured with all 40 cells in series, or may contain from one to four parallel strings of cells; one that consists of four parallel strings of 10 cells in series is illustrated in Figure 2. In series connection of solar cells, the composite current-voltage characteristic may be constructed by adding the voltages of individual cell curves along lines of constant current. Hence a single string of 10 illuminated cells in series, each cell having an I-V curve as shown in Figure 1, Curve A, would exhibit a composite I-V curve as shown in Figure 3, Curve A. In parallel connection, the composite current-voltage characteristic is determined by adding the currents along lines of constant voltage. Thus, the entire module with four parallel strings of 10 illuminated cells in series is represented by Curve B on Figure 3.

Two principal schemes are used to determine the proper current and voltage operating conditions for all modules in an array. One is simply to select a value of array operating voltage and hold it fixed (or within a narrow range) to charge batteries or run certain equipment. A second is to monitor the array I-V curve continuously, and to set the load resistance to optimize power production. Small changes in individual cell, module, and even large subarray current-voltage characteristics may not significantly affect the choice of array operating parameters.

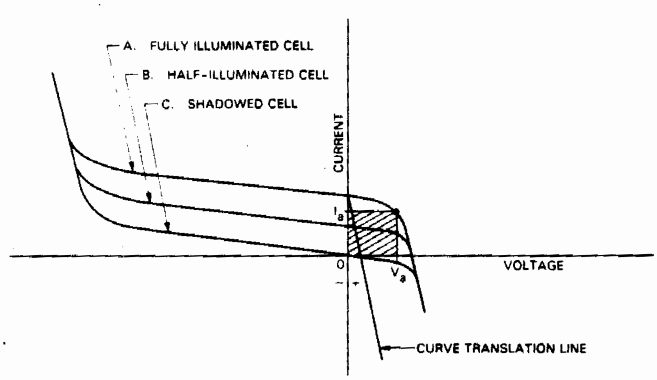

Figure 1. Characteristic solar cell current-voltage relationship.

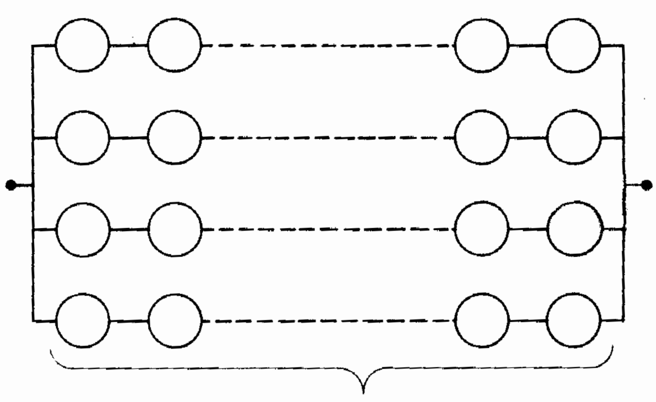

Figure 2. Representative photovoltaic module electrical connections.

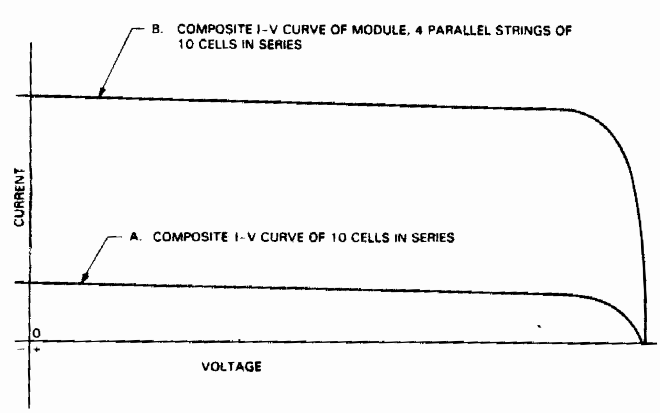

Figure 3. Composite string and module I-V curve.

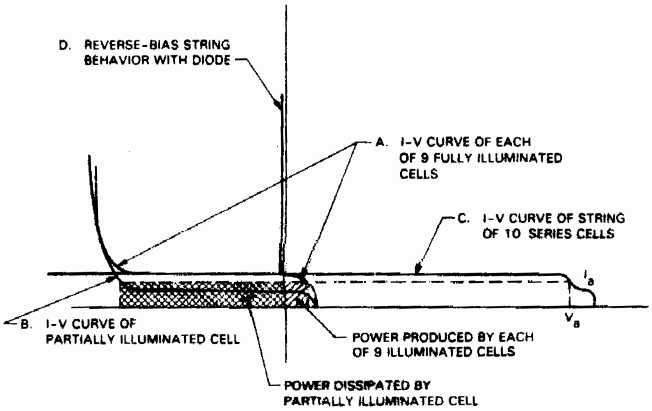

Figure 4. Reverse-biased phenomena.

Reverse-Biased Cells

In practice, no two cells from the same processing lot exhibit the same I-V curves under identical illumination conditions. Consider a single string of 10 cells in series, as in Figure 2. For simplicity, assume that nine of the cells exhibit I-V curves shown as Curve A of Figure 4, and one cell has an I-V curve shown as Curve B. The rules of series connection given above indicate that the overall string I-V characteristic is represented by Curve C in Figure 4. Properly chosen overall array operating conditions may cause the cell-string voltage to operate at V_a. Each of the 10 cells in series must then pass the same current, I_a, so that each of nine cells will be producing power, represented by the lightly shaded region in Figure 4. The cell exhibiting I-V Curve B must also pass current I_a, and so is forced to run in negative voltage, or reverse-bias. This cell will thus dissipate the amount of power represented by the crosshatched area in Figure 4. Since the amount of power dissipated by the reverse-biased cell only depends on the shape of its I-V curve and the required operating voltage, it is quite possible for the single cell to dissipate not only the power that is produced by the other nine in series, but also some power generated by other modules in series with it. This power must be dissipated as heat to the environment, causing the reverse-biased cell's temperature to rise. Cells sufficiently reverse-biased may reach temperatures high enough to cause permanent damage to the module through solder melting, module blistering, and cell cracking due to thermal stress. In the example of Figure 2, a cracked cell could open-circuit one of the four parallel strings, resulting in string power loss. Moreover, the remaining three strings would have to carry increased current, due to other modules being in series. This added current may force some of the cells in the remaining three strings into reverse bias. Some small degree of reverse bias in individual cells may occur as the result of natural slight nonuniformities in cell I-V curves even under properly chosen operating conditions. Therefore, slight variations in cell temperatures (<3°C) by a few cells in an operating photovoltaic array are expected in practice, and are not necessarily signs of major problems or power loss. The presence of many cells operating at highly elevated temperatures is a sign of severe reverse biasing, and may indicate improper design, resulting in extensive power dissipation and loss, and possible module damage. It may also be evidence of partially or fully shadowed cells, which also exhibit shifted I-V curves. Additional data on the electrical characteristics of photovoltaic cells may be found in the literature.[2]

Module protection. Several schemes have been devised to restrict the level of reverse bias a cell may attain. First, good design practice dictates use of cells closely matched in I-V characteristics, and normal operating voltage high enough to preclude reverse biasing. Second, cell and module series-paralleling strategies have been devised to limit the degree of reverse bias and power loss due to failed cells. Finally, bypass diodes are being installed in the latest generations of photovoltaic modules. These diodes limit the reverse bias and power loss by passing current around a group of cells whose net voltage is slightly negative. The combined series string-diode electrical behavior is shown in Figure 4.

Thermographic field inspection of photovoltaic arrays

One of the first uses of the JPL scanning infrared radiometer was in field inspection of a 60 kW_p array of photovoltaic modules at Mount Laguna, California, in 1979. Significant power loss and visible cell failures had been observed since shortly after array installation. Figure 5 is a photograph of typical modules installed at the Mount Laguna site. Figure 6 is a thermograph showing several modules as mounted with the array operating normally. In this format, brighter regions are generally hotter. Figure 7 is a close-up thermograph of a single module in the array. The large number of hot cells is clear evidence of a problem due to serious mismatching of individual cell I-V curves, and operation at a system voltage that causes many cells to operate in reverse bias. This was later verified by extensive electrical measurements.

Under normal operating conditions, typical encapsulated solar cells operate 20°C to 25°C above ambient air temperature. Some of the badly reverse-biased cells were found by in situ thermographic measurements to be 110°C to 115°C above ambient; this is the temperature range at which permanent module damage may result from solder melting and cell cracking due to thermal stress. These phenomena were verified by repeated close visual examinations. Many hairline cracks were found in cells throughout the large array. Figure 8 is a thermogram

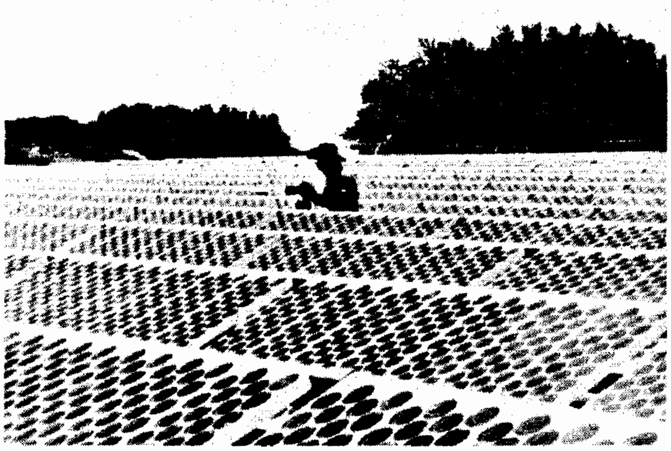

Figure 5. Photograph of photovoltaic modules at the Mount Laguna site.

Figure 6. Thermograph of photovoltaic modules at the Mount Laguna site.

Figure 7. Thermograph of single module with several reverse-biased cells.

Figure 8. Thermograph of single cracked cell.

of a cell in which a large portion has cracked off and is electrically isolated from the circuit. This reduction in active cell area has the same effect as shadowing the inactive area, which, by the discussions of the previous section, will cause a shifting of the cell I-V curve and subsequent operation in reverse bias.

Repeated inspection trips to Mount Laguna revealed that patterns of reverse-biased cells constantly change. This is believed to be caused by cracks in cells that do not totally isolate cell areas electrically at all times. It is suspected that the degree of electrical isolation depends strongly on environmental factors and the instantaneous electrical characteristics of the other cells in the module. This is important, as in many cases entire cells with hairline cracks appeared hot. However, under closer thermographic inspection, definite thermal gradients were noted. Figure 9 is a thermogram of a back-biased cell in which a linear isothermal region has been artificially highlighted. Close visual examination of this cell later indicated the presence of a hairline crack parallel to this isothermal region. Thus, rapid thermographic inspection techniques are more practical than close visual cell-by-cell examinations in very large arrays.

A 3-kW_p array of solar cells was installed on the roof of a residence in Tempe, Arizona, by John Long, a home developer. The modules were of a new design, not made by the manufacturer of the modules at Mt. Laguna. Figure 10 illustrates how the infrared scanner was secured to a remotely operated pan/tilt-head that was placed atop a tall ladder adjacent to the rooftop photovoltaic array. This arrangement permitted a convenient and thorough thermographic inspection from the ground.

Figure 11 illustrates reverse-biased cells within the array. One serious problem that was discovered was partial shadowing, at some times of the day, of some of the modules by an air exhaust duct protruding from the roof. Also found were localized regions of increased solar illumination due to specular reflection from the polished metal of that air exhaust duct. This type of insolation mismatch may also drive some cells into reverse bias. But the infrared camera was able to point out a far more serious problem in this case. An attempt was made to open-circuit all major subarray elements with in-place electrical switches. Thermographic inspection of the array showed two major subarray sections that still exhibited a large number of reverse-biased cells, a situation that cannot exist if the subarrays are truly open-circuited. Close visual inspection of modules indicated that sharp electrical conductors within the modules had contacted and shorted to neighboring modules, negating ground-switching equipment. The potentially serious design flaw was easily corrected by a combination of minor design changes and module-mounting procedures. The corrected modules have been reinspected, and their subsequent use in other array sites has proven them to be highly reliable and of good design.

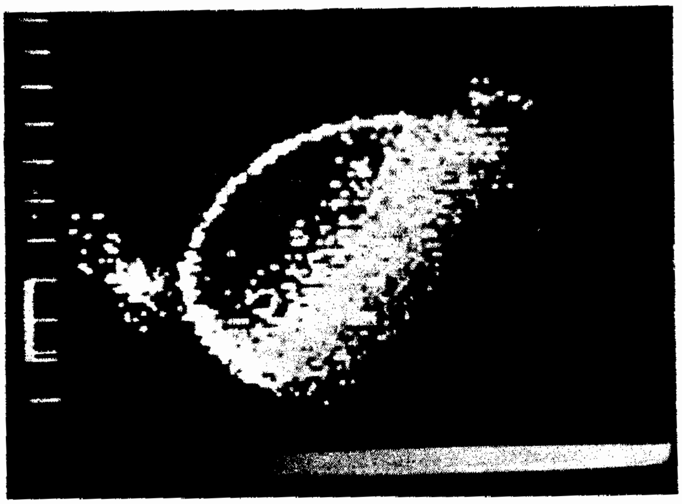

Figure. 9. Thermograph of cracked cell, with crack region artificially highlighted.

Reverse-bias cell-heating tests

Specific module design and mounting methods strongly affect both the nominal operating cell temperature (NOCT), which is defined under specific environmental conditions, and the elevated cell temperatures attained in reverse bias operation. Apart from reliability considerations, silicon solar cells operate less efficiently at higher temperatures. It is thus important to verify that individual cells operating under severe reverse-bias conditions do not become hot enough to cause cell or module mechanical failure by the mechanisms discussed above. It is also useful to compare modules of different design by different manufacturers

Figure 10. Roof-mounted photovoltaic array at John Long residence, showing infrared scanner placement.

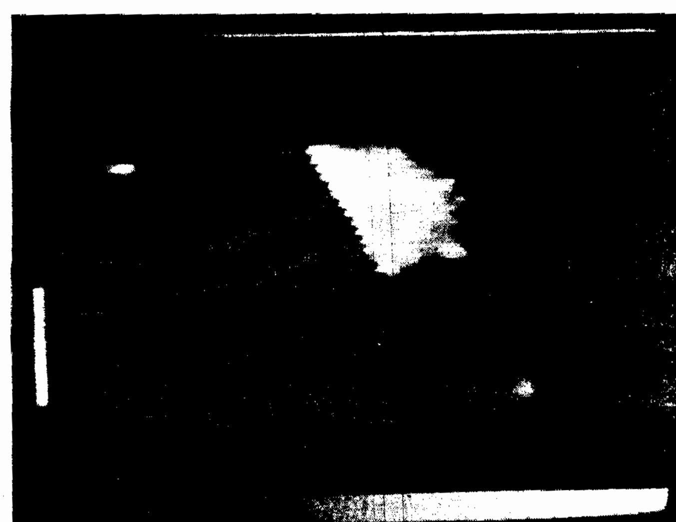

Figure 11. Thermograph of portion of PV array at John Long Residence; reverse-biased cells in shadow.

to learn about module construction properties that contribute to good thermal design (i.e., cool-running modules).

J. C. Arnett and C. C. Gonzalez at the Jet Propulsion Laboratory have specified a test procedure[3] designed to verify the ability of modules to withstand severe reverse-bias conditions with minimal damage. All new photovoltaic modules must meet this specification. Briefly, the laboratory test procedure requires I-V curves to be measured for all cells in the module. Three cells whose I-V curves exhibit well-defined properties are then selected for reverse-bias testing. The free-standing module temperature is raised by radiant heat lamps to the NOCT to simulate field conditions. Each of the three selected cells is then subjected to a total of 100 hours of a combination of worst-case cell illumination and reverse-bias conditions. The test is performed in a cyclic manner; one hour with heat and light on, followed by sufficient off-time to cool the cell down to the NOCT. The module must survive the test while displaying minimal mechanical and electrical damage.

A series of reverse-bias cell-heating tests were performed at JPL according to the designated test specification. Modules of several manufacturers and design types were examined to compare thermal performances. In these tests, cell temperatures were monitored by thermocouples placed in the center of the cell by drilling through the module substrate layer. Classical thermal modeling suggests that maximum cell temperature should occur at the center, but localized cell reverse-bias voltage-breakdown mechanisms, which are greatly dependent on random microflaws and temperature, may cause highly asymmetric cell heating. The JPL infrared radiometer was also used in these tests. The scanner was set up to view the front surface of each module being tested, and thermal gradients observed on the cell and module were recorded. Figures 12 and 13 are sample thermographs of two different reverse-biased cells under test. In these presentations several different isothermal regions are artificially highlighted in white. The contour map appearance is obtained by making multiple photographic exposures at each of several known isothermal levels determined by the position of the cursor on the graticule at the left edge of the picture. All isothermal regions were referenced to a controlled black-body temperature source (not shown); after correction for surface emissivity and background temperature, they may be identified within an estimated 4°C over a total range of 160°C. Note that thermal patterns obtained in this way are strictly valid only at the module superstrate (cover) of the front surface, since it is opaque to infrared radiation in the 8- to 12-μm wavelength band. Despite thin covers, temperature drops of several degrees may be expected between the cell and the superstrate front surface. Lateral heat transport through the superstrate is small, due to relatively low thermal conductance; hence, gradient patterns observed with the infrared radiometer are considered to be reasonably accurate.

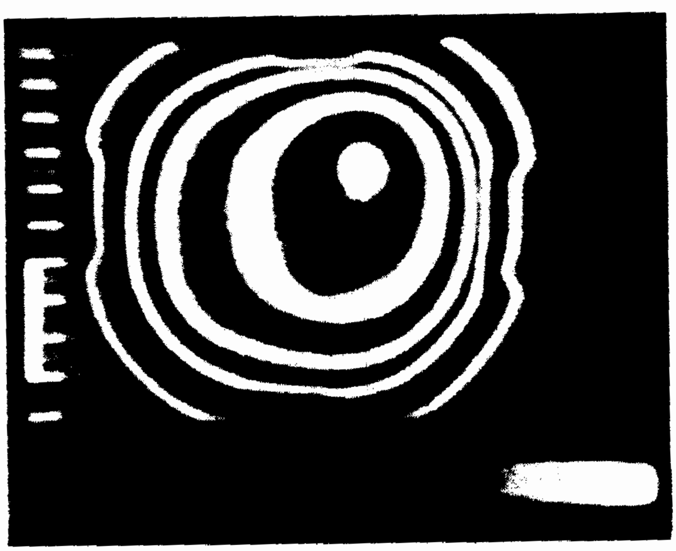

Figure 12. Multiple-exposure thermograph of reverse-biased cell.

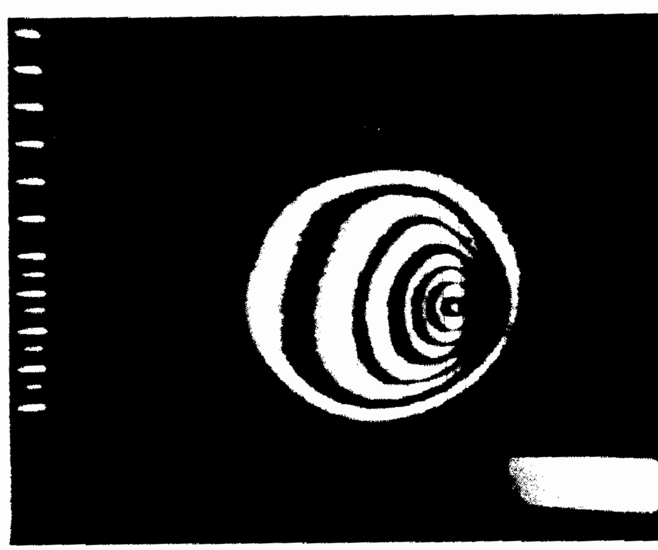

Figure 13. Multiple-exposure thermograph of reverse-biased cell.

The use of a scanning infrared radiometer is not required in the conduct of future cell reverse-bias cell-heating tests as specified.[3] It was useful in the initial tests performed on different manufacturers' modules at JPL in several ways: it aided in test specification development; data obtained from the infrared camera helped to verify thermocouple measurements in specific tests, and thermal gradient data provided insight into the thermal behavior of specific module designs and aided in the development of, and later to the test validation of, an analytical thermal model of reverse-biased cells.

Summary and conclusions

The two-dimensional scanning infrared radiometer has been used extensively by the LSA project at the Jet Propulsion Laboratory. Its principal use to date has been in the field inspection and troubleshooting of photovoltaic arrays at numerous types of demonstration projects. It has been extremely useful in the research and early development aspects of the program by detecting module design flaws and identifying poor module-mounting practices. It is believed, however, that when LSA project goals are attained and the use of photovoltaics becomes widespread, frequent and routine thermographic inspections of arrays will not be needed. Advanced modules and arrays should incorporate cells with closely matched I-V curves, should use good thermal design practices, and should use the proper degree of series-parallel interconnection strategies and internal diode protection to limit reverse bias, module damage, and power loss. Thermographic inspection may still be useful, however, after array installation to verify acceptable initial array-mounting and electrical-connection formats. It may also be desirable to reinspect arrays after severe environmental events that could damage cells, such as major hailstorms or windstorms.

Infrared thermography may be useful to the photovoltaics industry in additional ways. It would certainly be of use during the testing phases of new module designs. It may also be valuable in several manufacturing procedures, such as inspection of electrically interconnected strings of cells before encapsulation to verify acceptable matching of cell I-V curves; badly matched cells can be replaced easily at this stage. Thermal inspections and video recordings of completed modules just before shipping may be desirable from the quality assurance and legal warranty standpoint. The Jet Propulsion Laboratory will investigate several of these possibilities.

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