INFRARED NDT METHODS APPLIED TO
SOLAR CELL AND PANEL CHARACTERIZATION

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The purpose of this report is to briefly describe infrared nondestructive testing (infrared NDT) methods that have a good potential for providing valuable data concerning solar cell or panel characteristics without requiring contact with the photovoltaic device. In addition, preliminary tests with cells and panels were conducted and the infrared NDT results are presented and discussed.

I. INFRARED NONDESTRUCTIVE TESTING

Infrared nondestructive testing is an effective method for determining the location and type of imperfections in solar cells. The method is applicable to testing of bare cells, as well as potted arrays (panels) of cells. Simplistic infrared scanning alone cannot determine the causes of differences sensed in the scans in all cases. Data obtained during the present work indicated areas where simplistic methods are useful, as well as areas where advanced infrared methods would be required. Advanced methods eliminate the effect of extraneous parameters such as emissivity to extract important information about solar cell and panel condition. The information is presented to the operator in easy-to-interpret displays and tables organized via a computer which acts directly on the signal output from the scanner.

Figures 1-1 through 1-4 show several arrangements for infrared NDT of solar cells and arrays. Each arrangement has its own applications, advantages and precautions required for obtaining meaningful results. With the first two arrangements, advanced emissivity independent methods can be used. The second two use radiant heating and therefore cannot be made emissivity independent. However, effects such as cell heating due to back biasing should cause large enough temperature differences to override emissivity effects in these cases. In addition, solar panels having a heavy layer of potting compound can have a high and nearly uniform emissivity. Low emissivity aluminum serial number and identification tags, etc. fastened to the panels are easily identified.

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Figure 1-1 illustrates the electro-thermal method in which an electrical current is injected into the output leads of a solar panel or cell while it is scanned with an infrared scanner. Output of the scanner is presented as a television-like picture in which warmer areas are brighter and cooler areas are darker. Heat generated in each region of the cell is proportional to the resistance and the square of the current density at that location. This method has the advantage of being dependent upon actual electrical characteristics of the cells. The type of irregularity or defect detected in the cell depends upon whether forward or backward diode current through the cell is used during the electro-thermal test. Diode junction irregularities should best be revealed using back-bias heating since the heat generation would then be highly dependent upon voltage drop across the diode. Forward current heating, on the other hand, should best reveal non-uniformities due to variations in structure, attachments and dopant since variations in heating due to the diode junction itself should be minimized. Structural defects such as cracks that disrupt current flow in individual cells can cause part of a cell to be hotter than normal and part to be cooler than normal. Figure 1-2 illustrates infrared NDT of solar cells using a warm gas jet to provide heat input. This method would be most advantageous for detecting unbonds, delaminations and thickness differences. It has the advantage of being non-contacting (except for the heating gas).

Figure 1-3 depicts infrared NDT using a solar simulator to produce a power output which is coupled to a resistive load. In this case, the efficiency of the cells could be checked by measuring the current through the load, and the location of cells that overheat due to various types of defects could be simultaneously determined from the infrared scan results.

Figure 1-4 shows conceptually how an infrared unit for nondestructive tests on solar arrays in the field might be applied. Benefits from a portable field unit would be similar to those of the solar simulator unit described above.

In addition to assuring the quality of cells and panels before and after installation, infrared NDT methods can be advantageously applied to help in development of new solar cell designs. For example, the effectiveness of

front-surface collector grids in reducing sheet resistance effects can be determined by using the infrared system to determine the current density distribution.

Existing infrared electro-thermal NDT equipment was used to demonstrate the feasibility of applying this method to solar panels and individual cells. A 60-Hz half-wave forward exciting current was used in both applications. The panel NDT system is shown in Figure 1-5 and the system for NDT of individual cells is shown in Figure 1-6. The infrared scanner is seen in the foreground in Figure 1-5. On the left of the solar panel is a video unit on which the scanner's output is presented. To the right of the panel is a computer for analyzing data from the infrared scan and producing displays. The arrangement for infrared electro-thermal NDT of single solar cells was similar to that for panels as seen in Figure 1-6. However, it was necessary to use an IRTRAN-2 infrared lens to magnify the image and obtain the resolution needed for the single cell NDT unit. The lens is being adjusted by the technician in Figure 1-6. In addition, the cell was coated with an infrared opaque coating to avoid having to develop an emittance independent method⁽¹⁾ for the initial experiments.

II. PRELIMINARY INFRARED ELECTRO-THERMAL NDT RESULTS

A. COMPLETE PANEL

Figure 2-1A and 2-1B show definitive front and rear views of a solar panel that was nondestructively tested in the as-received condition using the infrared electro-thermal method. A transparent rubbery encapsulant material about 1 or 2 mm thick covering the front of the solar cells in the panel was left intact throughout the nondestructive tests. Electro-thermally detected defects in the panel are described below together with brief interpretations. This silicon solar power panel had an intermittent condition that caused it to fluctuate erratically between two current-voltage characteristics. The

(1)D. R. Green, "Emissivity Independent Infrared Thermal Testing Method", Materials Evaluation, pp. 79-85, February 1965.

first condition (Figure 2-2A) was more nearly normal than the second (Figure 2-2B). Although the complete panel was never completely normal, the first condition is hereafter referred to as "normal" and the second as "abnormal".

Figure 2-2A shows the "normal" current-voltage (I-V) characteristic of the panel. Corresponding results of infrared scans on the front and rear of the panel during electro-thermal NDT while the panel was in the normal condition are shown in Figures 2-2B and 2-2C. Both front and rear infrared scans were made so the effects of delaminations under the rubbery front cover could be separated from true cell temperature differences. Such a delamination would cause a cooler than normal region on the front surface (due to decreased thermal conductance along the heat-flow path) and a warmer than normal region on the rear surface. Heat not flowing to the front surface through the delamination must exit through the rear surface (at equilibrium and ignoring lateral heat flow). True cell temperature increases resulting from abnormally increased power generation, on the other hand, would cause corresponding temperature increases on both the front and rear surfaces.

Figure 2-3A shows the abnormal I-V characteristic of the panel, and Figures 2-3B and 2-3C show the corresponding results of infrared electro-thermal NDT on the panel while it was in the abnormal condition.

Correlation of the infrared scan results with "normal" and abnormal characteristics can be seen by comparing Figures 2-2B and 2-3B. The intermittent condition is possibly associated with the right-most cell in the top row since it is the one in which the largest temperature change occurs when the panel's I-V characteristic changes. However, the intermittent could also be associated with the second cell from the right in the top row since it remains hotter than any other cell during the panel's abnormal low current condition. This high temperature may be the result of a variable resistive contact between the rear plane conductor and the cell. During the "normal" condition (high current) the contact resistance would be lower than it is in the abnormal condition.

A general temperature gradient from top to bottom of the entire panel can be seen in both the front and rear views. This is a normal condition that would be expected to result from vertical air convection currents. Two black rectangles can be seen in Figure 2-2C. These are caused by bright low emissivity tags on the rear of the panel as can be visually confirmed in Figure 2-1B.

Figure 2-4A shows that the interconnecting link between the right-most cells in the third and fourth rows from the top is partially unbonded where it attaches to the cell in the third row. This causes a small, dark rectangle to appear over the unbond in the lower right quadrant of the infrared scan on the cell located just below the center of Figure 2-4A. The dark rectangle shows up due to blockage of heat flow by the delamination under the metal interconnecting link. Figure 2-4B is a rear view infrared scan of the same region. The dark rectangle does not show in this view since the unbonded link is on the front side of the cell. An increase in temperature on the rear side under the unbonded lead would be expected. However, there is a large warmer area around the link. This area shows up on both the front and rear views, and is larger than might be expected to result from the blockage of heat flow through the unbond. Evidently there is another feature in addition to the unbond contributing to the warm region. A front conductor grid that was too thin would cause such an effect since there would be a voltage drop and a corresponding drop in current density distribution across the cell.

A possible cracked cell in which the front contact grid and/or the rear conductor plane in a cell is separated along the crack is shown in the infrared scans in Figures 2-5A and 2-5B. The low emissivity aluminum tag shows up in Figure 2-5B just as it did in Figure 2-2B.

Another possible cracked cell is shown in the infrared scans in Figures 2-6A and 2-6B. In this case it is probable that only the front conductor grid is broken along the crack since the dark area in the cell is not totally dark, but is only a slightly darker gray. This indicates that power generation in the darker cell area was not zero, but was only somewhat lower than normal.

Figures 2-7A and 2-7B show infrared scans on the front and rear of a cell that has extremely non-uniform characteristics. This cell is located second from the right in the top row, and can also be seen in the large area infrared scans shown in Figures 2-2 and 2-3. The non-uniform characteristics may be the result of resistive contact between the rear-plane conductor and the cell as described earlier. Figure 2-7A and 2-7B tend to confirm this opinion since the non-uniform area in the front and rear views do not correspond to the same area of the cell. This difference in heating location could result from a fractured contact joint with a shifting location of intermittent contact.

B. INDIVIDUAL CELL

Infrared electro-thermal NDT was also attempted on the type of individual silicon solar cell pictured in Figure 2-8. Figure 2-9 shows the results of a front view infrared scan, and Figure 2-10 shows a computerized isometric display of an infrared scan on the same area. (The bottom of the isometric display extends beyond the cell.) Much of the image character shown in Figures 2-9 and 2-10 results from emissivity differences. This was demonstrated by infrared scanning the front surface of the cell after applying an infrared-opaque coating. A computer isometric plot of the infrared scan after coating is shown in Figure 2-11. The coating caused a nearly flat image over the entire width of the cell. (The small wiggles in the lines are due to normal electronic noise.) Hence, the true temperature was uniform from side-to-side of the cell. There was a temperature gradient from top to bottom of the cell which is not visible in the isometric plots since it only makes a slight difference in the spacing between plot lines. Figure 2-12A shows a front-view infrared scan of a coated cell similar to the one used for Figures 2-9 through 2-11. The top-to-bottom temperature gradient can be clearly seen.

One of the front conductor grid fingers in the cell used for Figure 2-12A was cut with a micro grit blaster. Electro-thermal NDT results on the defective cell is shown in Figure 2-12B. No appreciable difference in results from electro-thermal NDT of the cell before and after cutting the grid finger could be seen. Considering that (1) no lateral temperature differences between grid fingers can be seen in Figures 2-11 and 2-12, (2) a large longitudinal temperature gradient along the grid fingers exists, and (3) cutting a grid finger

makes little or no difference in current distribution on the cell surface, it appears that the present grid fingers do not make much difference in current distribution in the cells at the high currents used for the tests. This does not necessarily mean that the grid fingers would not be effective under low current conditions of 1-sun solar power production. Correlation between the electro-thermal results and cell power losses is more likely when a concentrator is used to increase the solar intensity and hence, the power production in the cell.

INFRARED NDT METHODS

1-1 ELECTRO - THERMAL

INFRARED NDT METHODS

1-2 GAS - JET

INFRARED NDT METHODS

1-3 SOLAR SIMULATOR

INFRARED NDT METHODS

1-4 ILLUMINATION BY SUNLIGHT

Figure 1-5. Infrared electro-thermal NDT system for solar panels.

Figure 1-6. Infrared electro-thermal NDT system for individual solar cells.

(A) Front view of solar panel.

(B) Rear view of solar panel.

FIGURE 2-1

(A) I-V curve during "normal" resistance condition.

(B) Front view infrared scan of right side during "normal" resistance condition.

(C) Rear view infrared scan of same region as in B.

FIGURE 2-2

(A) I-V curve during abnormal resistance condition.

(B) Front view infrared scan of right side during abnormal resistance condition.

(C) Rear view infrared scan of same region as in B.

FIGURE 2-3

(A) Front view close-up infrared scan showing poor bond in interconnector of right-most cell in third row from top. I-V curve was same as in 2-2A.

(B) Rear view close-up infrared scan of same region as in A.

FIGURE 2-4

(A) Front view close-up infrared scan showing probable crack in third cell from the left in the bottom row. I-V curve was same as in 2-2A.

(B) Rear view close-up infrared scan of same region as in A.

FIGURE 2-5

(A) Front view close-up infrared scan showing possible crack in left-most cell in bottom row. I-V curve was same as in 2-2A.

(B) Rear view close-up infrared scan of same region as in A.

(A) Front view close-up infrared scan showing non-uniformity in second cell from right in top row. I-V curve was same as in Figure 2-3A.

(B) Rear view close-up infrared scan of same non-uniform cell as in A. Note that the non-uniformity in this view occurs at a different plane than in the front view.

FIGURE 2-8
Single silicon solar cell (front view).

FIGURE 2-9. Front view infrared scan of non-coated single silicon solar cell with 1.6 amp peak forward current. Conductor grid and other irregularities are visible due to emissivity differences.

BAPE METAL.

4 AMP FORWARD HEATING CURRENT.

FIGURE 2-10. Computer isometric display of infrared scan results on same area as in Figure 2-9.

BACK LEAD

FRONT LEAD

INFRARED SCAN FRONT VIEW SOLAR CELL
COATED WITH KRYLON FLAT BLACK.

4 AMP FORWARD HEATING CURRENT

FIGURE 2-11. Computer isometric display of infrared scan results on same area as in Figure 2-9 after coating.

(A) Without defect. Front view infrared scan of coated single silicon solar cell with 3 amp peak forward current.

(B) With defect. Same as A, but with contact grid finger cut in upper right quadrant.

FIGURE 2-12