RELIABILITY AND PERFORMANCE EXPERIENCE WITH FLAT-PLATE PHOTOVOLTAIC MODULES*

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Summary

As part of the United States National Photovoltaics Program, the Jet Propulsion Laboratory's Flat-Plate Solar Array (FSA) Project has maintained a comprehensive engineering sciences activity addressed to understanding the reliability attributes of terrestrial flat-plate photovoltaic arrays and to deriving analysis and design tools useful for achieving the high levels of reliability necessary for future large-scale application. This paper builds upon the field-performance experience gained from several years of photovoltaic system-application experiments and the research results stemming from the development of reliability design and analysis techniques. The result is an overview of the array reliability problem in total, and available means of achieving high reliability at minimum cost.

1. INTRODUCTION

The reliability of photovoltaic solar arrays is probably second in importance only to cost in the list of factors influencing the market acceptance of this new technology. Because of their modular nature, photovoltaic arrays possess a higher than normal sensitivity to common-mode failures, but at the same time offer a wealth of redundancy options to increase reliability. Achieving the high reliability demanded by future large-scale application requires that these reliability design attributes be understood well and used effectively.

As a tool for managing module and array reliability development, the FSA Project has adopted a target for life-cycle-reliability costs equivalent to 20 years with no significant array-power degradation. Because small levels of degradation or replacement are economically justified, a typical array meeting the target life will last somewhat longer than 20 years to recapture the life-cycle costs associated with the gradual degradation expected (see Fig. 1).

A convenient means for quantifying the life-cycle costs associated with reliability attributes is based on computing the break-even photovoltaic energy cost over the expected life of the application (1,2):

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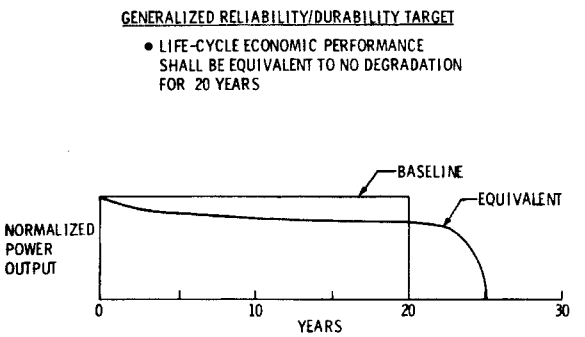


Figure 1. Reliability/Durability Target Relationship.

Table I. Economic Impact of Degradation Types.

TYPE OF DEGRADATION	UNITS	LEVEL CAUSING 10%* COST INCREASE k = 0	k = 10
FIXED CELL FAILURE RATE**	FRACTION PER YEAR	0.0006	0.0008
FIXED MODULE FAILURE RATE	FRACTION PER YEAR	0.007	0.016
LINEAR DROP IN POWER	FRACTION PER YEAR	0.010	0.014
FIXED DROP IN POWER	FRACTION	0.10	0.10
DROP IN MODULE WEAROUT LIFE	YEARS	2.0	4.75

*10% INCREASE IN LIFECYCLE ENERGY COST, k = DISCOUNT RATE
**SOURCE CIRCUIT = 8 PARALLEL x 200 SERIES BLOCKS WITH DIODES

$$R = \frac{C_0 + \sum_{i=1}^{L} C_i M_i (1 + k)^{-i}}{\sum_{i=1}^{L} E_i (1 + k)^{-i}} \qquad (1)$$

where:
- R = Cost (worth) of energy (startup-year \$/kWh)
- E_i = Energy generated in year i (kWh)
- C_0 = Initial plant cost (startup-year \$)
- C_i = Cost per module replacement action (startup-year \$/module)
- M_i = Number of modules replaced in year i
- k = Present-value discount rate
- L = Plant lifetime (years)

Notice that the above expression explicitly includes the effects of array degradation versus time (E_i), module initial cost (C_0), and the cost of module replacement ($C_i M_i$).

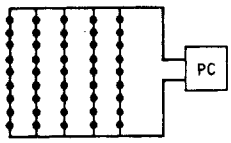
In assessing the implications of the 20-year-equivalent-life target it is instructive to examine the life-cycle-cost impact of typical failure modes which are likely to exist in future low-cost modules and systems. Assuming a module cost of \$0.70 per watt, Table I indicates the level of degradation, for each of five typical modes of array degradation, that will result in a 10% life-cycle system cost increase. Because these five failure modes may occur concurrently, the total cost impact must include the sum of these effects.

Table II carries the analysis a step further and suggests a possible "strawman" allocation of the allowable degradation among the five failure-mode categories to achieve a total performance consistent with the 20-year target. The distribution among the categories reflects this author's best judgment. The remainder of the paper addresses each category in light of the historical experience to date,

Table II. Strawman Degradation Allocations.

TYPE OF DEGRADATION	INCLUDED MECHANISMS	UNITS	DEGRADATION ALLOCATION
FIXED CELL FAILURE RATE	CELL CRACKING, INTERCONNECT FATIGUE	FRACTION PER YEAR	0.0001
FIXED MODULE FAILURE RATE	STRUCT. FAILURE, INSUL. BREAK	FRACTION PER YEAR	0.005
LINEAR DROP IN POWER	YELLOWING, AR COATING, CELL DEGRADATION	FRACTION PER YEAR	0.01
FIXED DROP IN POWER	SOILING	FRACTION	0.05
MODULE WEAROUT LIFE	OBSOLESCENCE, CORROSION	YEARS	25

(CELL FAILURE RATE (R) = 0.0001 PER YEAR)



ARRAY VOLTAGE	SERIES CELLS (S)	POWER LOSS AT 5 YEARS
15	36	1.8%
150	360	16.5%
1500	3600	83.5%

POWER LOSS = 1 - $[1 - (\text{YEARS} \times R)]^S$

Figure 2. Array degradation versus numbers of series cells.

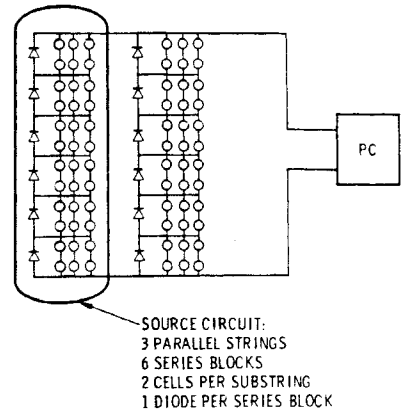


Figure 3. Series/Parallel Nomenclture.

and summarizes projected means of achieving the allocations listed in Table II.

2. CELL FAILURES

At the root of the high sensitivity to cell failures indicated in Table I is the need to interconnect electrically thousands of nearly identical solar cells in series and parallel to achieve the voltage and current levels of the intended application. For example, a 150-volt residential array will require 300 to 400 series cells, and a 1500-volt central-station application will require 3000 to 4000. This large number of series elements makes an array extremely sensitive to infrequent cell failures even when a high level of circuit redundancy is used.

Fig. 2 graphically illustrates this sensitivity by noting the effect of one cell failure per 10000 per year on various system configurations. To control this exaggerated sensitivity at high-voltage levels, extensive use of circuit redundancy techniques such as series/paralleling and bypass diodes is recommended (2,3).

Fault-Tolerant Circuit Design

Before the degradation allocation associated with solar-cell failures can be addressed further, the influencing effects of the available circuit redundancy solutions must be considered. The first step toward circuit redundancy is generally associated with dividing the large matrix of cells that makes up the array into a number of parallel solar-cell networks referred to as "branch circuits" or "source circuits". The circuits provide convenient points for monitoring array performance and provide an ability to isolate small areas of the total array for maintenance and repair.

As shown in Fig. 3, each source circuit may contain a single string of series solar cells or a number of parallel strings interconnected periodically by cross ties. The cross ties divide each source circuit into a number of series blocks. One or more series blocks may also be bridged by a bypass diode which is designed to carry the source-circuit current in the event that local failures constrict the current flow to the point of voltage reversal and power dissipation.

A key problem in assessing the impact of cell failures has been in quantifying the influence of specific series/parallel and bypass diode

arrangements on array degradation. This problem has been solved in recent years by the development of an extensive parametric analysis based on the statistical distribution of failed substrings due to random cell open-circuit failures (4,5). Reference 5 contains a large number of parametric plots, an example of which is shown in Fig. 4, which allows rapid computation of the effects of cell failures and circuit redundancy on array power loss.

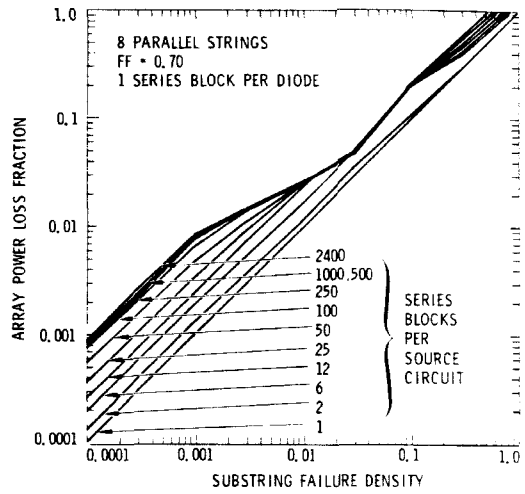


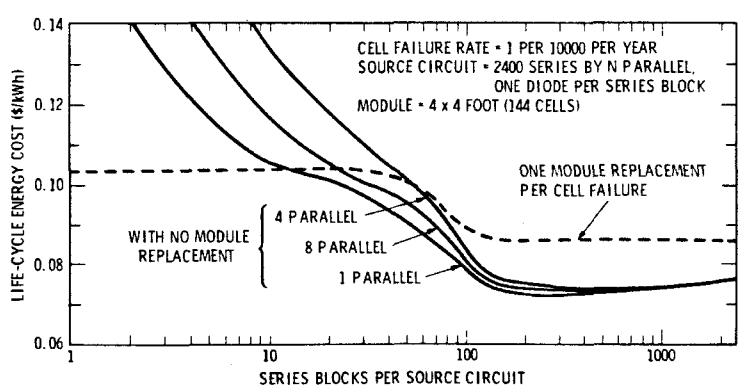
Figure 4. Example Plot for Power Loss Determination.

Using these techniques, together with typical array and balance-of-system costs and efficiencies per (2), and a cell failure rate of 0.0001 per year, we can calculate the break-even life-cycle energy costs for various redundancy and replacement options using Equation 1. Fig. 5 displays the calculated life-cycle energy costs for two replacement strategies as a function of the number of series blocks in branch circuits composed of 8-parallel x 2448 series cells. In the first strategy no module replacement is allowed and it can be seen that the life-cycle costs increase sharply with low numbers of series blocks. This reflects the rapid array degradation exhibited in Fig. 2 for series-string circuits without bypass diodes. For the second strategy (dashed curve) in Fig. 5, modules are replaced each time a solar cell fails during the 20-year life of the plant. This results in no power degradation, but does cause a substantial module replacement-cost contribution. This cost also varies with the number of series blocks due to improvements in module yield that occur when module series/paralleling achieves 8 parallel x 2 or more series blocks. This degree of module series/paralleling is only reached in this example when 272 or more series blocks are used per branch circuit.

At this point it is important to note that the economic impact of cell failures presented in Table I assumes the high level of redundancy associated with the minimum life-cycle costs in Fig. 5. The critical question is therefore shifted to the feasibility of achieving the low cell-failure rates indicated as being necessary.

For purposes of assessing this feasibility a cell failure is

Figure 5. Life-cycle Energy Cost versus Series/Paralleling and Maintenance Strategy.



considered as more than 25% degradation in short-circuit-current compared with the average cell. This is generally sufficient to cause reverse biasing of the local bypass diode and therefore loss of power from the series block containing the failed cell.

Typical causes of cell failure include cell cracking, local shadowing and open-circuit cell interconnects.

Cell Cracking

Of the cell failures seen in the field, cell cracking is by far the most prevalent and is occurring at a rate of about 1% per year. The saving finding is that only 0.1 to 0.01 of these cracked cells have resulted in electrically-failed cells. The remainder remain electrically operative, quite often because the cell metallization bridges the break and holds the cell together.

Quantification of the cell failure rates has required extensive and expensive auditing of the actual field performance of several large multikilowatt photovoltaic application experiments. The three primary causes of cell cracking appear to be differential expansion between the cell and its support, impact loading by hailstones, and reduced strength due to cell damage occurring during cell processing and module assembly. Qualitative design techniques exist that address the first two causes (6,7), and cell proof-testing techniques can be utilized to screen out the one-out-of-a-thousand weak or damaged cell (8). Another cost-effective cell-failure solution is the use of multiple electrical attachment to each solar cell.

Cell Interconnects

Cell interconnects are both an important tool for reliability improvement and a source of failures. Given that a cell has cracked or otherwise degraded in a local area, the extent of module or array degradation can be substantially lessened by electrically attaching to the cell at more than one location. One means of assessing the degree of improvement possible is to consider analytically a large number of randomly oriented potential cracks and then to determine the fraction that would lead to open-circuiting or significant cell degradation ($\geq$10% area loss). Many of the latest module designs are taking advantage of multiple interconnect attachment points and are expected to have substantially lowered failure rates. With present cell failure rates at about 0.0001 per year, it is expected that the improved redundancy will lead to values approaching 0.00001 per year.

The above optimistic projection of course assumes that the interconnects themselves don't fail, and of course they do. Interconnect open circuiting due to mechanical fatigue is a historical photovoltaic array failure mode and has even recently taken its toll on some modern installations. Like cell breakage, it is primarily caused by thermal and humidity expansion differences between the cell and its supporting substrate or superstrate. Also like cell breakage, interconnect fatigue is not easily predicted by available analytical models until the level of failure reaches major proportions. Mon, Moore and Ross (9), for example, have empirically characterized the probability of failure of a variety of photovoltaic interconnects versus number-of-cycles and developed a fatigue curve that treats probability-of-failure as a parameter (Fig. 6). As can be seen from Fig. 6, even identically loaded interconnects can be expected to fail over a broad range of cycles, the weakest failing one hundred times sooner than the average.

As with cell cracking, the solution is to design for a manageable number of failures (maybe 10% during the array design life) and then to incorporate interconnect redundancy to control power losses associated with those that fail. For example, if three interconnects were used to connect each cell, 10% failed interconnects would lead to a cell failure density of one per thousand at the array design life.

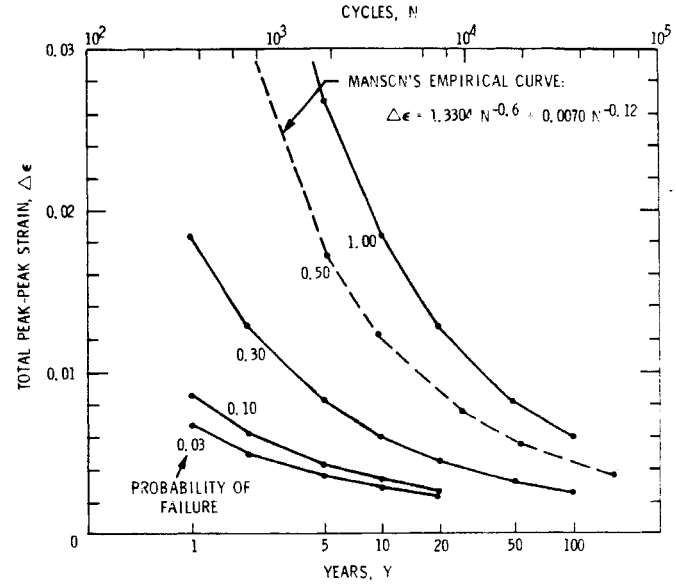


Figure 6. Fatigue curve for Copper Cell Interconnects with Probability of Failure as a Parameter

Future Cell-Failure Levels

With the conscientious application of available design and qualification techniques, this author predicts that cell failure levels well below 0.0001 per year will be achieved. The available techniques include:

(1) Cell proof-testing to cull out weak or damaged cells before incorporation into modules.
(2) Redundant cell interconnects with multiple cell attachment to provide fault tolerance to cracked cells and broken interconnects.
(3) Proper materials and process selection and testing to limit differential expansion and process-related stressing of the cells.
(4) Adequate hail-impact protection.
(5) Bypass diodes and cell paralleling to limit array losses due to cell failures.

3. MODULE FAILURES

In addition to failure modes that are best treated at the cell level, a number of failures are more appropriately considered at the module level. These include glass breakage, electrical insulation breakdown and various types of major encapsulant failure such as delamination. Like cell failures, these failures are also flaw-related and must be treated statistically when considering quantities of modules in a large array. Moore (10) and Mon (11) in work with the author have developed empirical/analytical tools to design for given statistical levels of glass breakage and electrical breakdown, respectively.

When designing for appropriate levels of module failures, it is important to note that a module failure is likely to cause an electrical hazard or major power loss and will therefore require immediate maintenance or replacement. As a result, module failure rates are traded off against life-cycle maintenance costs as opposed to redundancy and life-cycle energy loss, which are associated with cell failures.

Although the data base on module-level failures is very poorly defined at this time, this author judges that it might total 2% per year from the following contributing mechanisms:

(1) Glass superstrates broken by projectiles or thermal-expansion loads.
(2) Electrical shorts from cell circuitry to frame ground.
(3) Major encapsulant delamination due to weathering or hot-spot cell heating.
(4) Failed (shorted or reversed) bypass diodes.

It is projected that future modules should be able to achieve module-failure levels consistent with the 0.005 per year indicated in Table II.

4. GRADUAL DROP IN POWER

In addition to the statistical failure mechanisms discussed previously, a variety of observed mechanisms typically lead to gradual degradation or loss of power over the life of a photovoltaic array. These generally fall into two categories: optical losses and cell power degradation. Both of these degradation modes tend to be generic as opposed to being statistical, i.e., the majority of modules and cells of the same type degrade at the same rate with little statistical scatter. Most systems must be designed to accommodate this gradual power decrease, since the only correction techniques involve incremental addition of array area or total module replacement. Aside from external surface soiling, discussed in the next section, "Fixed Drop in Power," the observed optical degradation mechanisms include:

(1) Encapsulant transmission loss (uniform yellowing) due to UV and temperature-induced self-degradation.
(2) Encapsulant transmission loss (local yellowing) due to foreign matter diffusing into the encapsulant from such things as edge seals, mounting hardware, and electrical-terminal hardware.
(3) Deterioration of the anti-reflective coating on the solar-cell irradiated surface due to leaching or contamination from plating or corrosion products.

Substantial research has been done on these various degradation mechanisms over the past two years and a variety of highly stable materials and coatings have been identified (7, 12).

The second important category of gradual-degradation modes includes mechanisms related to solar-cell power degradation due to increased series resistance or junction shunting. Increased series resistance is often associated with a gradual deterioration of the adherence between the cell metallization and the cell bulk material due to corrosion-related processes. Junction shunting may be caused by the diffusion or migration of metallization elements into the cell junction or over the external surfaces of the cell.

As with the optical degradation mechanisms, research has identified a variety of highly stable cell metallization systems that promise degradation rates well below 1% per year (12).

For both degradation categories the most effective techniques for quantifying expected levels of degradation involve accelerated temperature/humidity testing (possibly with ultraviolet exposure) together with Arrhenius and other means of relating the data to long-term use conditions (12, 13). Application of these techniques to present commercial modules suggests that the 1% per year drop of power assumed in Table II should be readily achievable with future low-cost concepts.

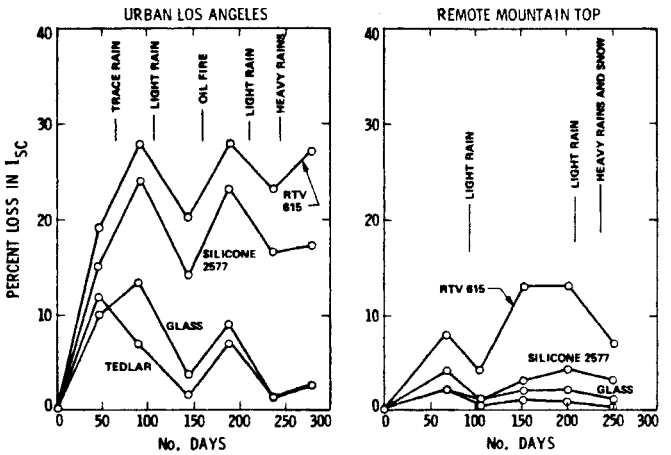


Figure 7. Array Performance Loss Due to Soiling.

5. FIXED DROP IN POWER

Although similar in effect to other optical-loss mechanisms, experimental data indicate that optical surface soiling due to dust and atmospheric contaminants reaches equilibrium levels in a few weeks and then fluctuates somewhat with natural cleaning mechanisms such as rain. The net result is most easily modeled as a fixed loss in array current and power over the life of the array.

Fig. 7 illustrates this soiling behavior for a variety of module surface materials in two site environments--one urban, the other remote. These and other data gathered by JPL over the past four years at a variety of sites in the United States indicate that average soiling levels below 5% should be easily achievable with glass or Tedlar-like optical-surface materials without washing (14). Very dusty remote sites and heavily polluted urban sites will, of course, exceed these levels, and may require periodic washing.

In response to these data Table II suggests a 5% allocation for fixed soiling-related losses.

6. MODULE WEAROUT LIFE

The last degradation category is the most difficult to quantify technically or to even define through known failure mechanisms. Nearly all of the known failure mechanisms have been studied and found to be gradual or statistical in nature and not associated with a wear-out end-of-life such as might be associated with automobile tires or light bulbs.

Mechanical fatigue of cell interconnects is a classic example of a wearout mechanism (Fig. 6). However, to achieve the desired low rate of random interconnect failures during the early life of the array, the wearout-life associated with 50% failures will typically be more than 100 years.

Gradual depletion of UV absorbers, or gradual embrittlement of the module encapsulant system are additional mechanisms that could lead to accelerated degradation in later years due to optical or mechanical-stress mechanisms.

The most likely mechanisms leading to array end-of-life may be technical obsolescences, decreased reliability, or the useful life of the application itself.

In consideration of the lack of known wearout mechanisms, an end-of-life in excess of 25 years seems quite likely for mature module designs of the future.

7. SUMMARY AND CONCLUSIONS

As part of the United States National Photovoltaics Program, the Jet Propulsion Laboratory Flat-Plate Solar Array Project has carried out a comprehensive array engineering activity addressed to understanding the reliability attributes of terrestrial flat-plate photovoltaic arrays and to deriving analysis and design tools useful for array optimization and cost reduction. Known array failure and degradation mechanisms have been carefully studied and grouped, for the purpose of discussion, into five categories. A target reliability allocation has been developed for each degradation category based on the life-cycle-cost requirements of future large-scale applications and the technical realities of available photovoltaic materials and processes. Comparison of these future requirements with present performance and design alternatives suggests that lives in excess of 20 years are very possible for module designs of the near future.

8. REFERENCES

1. Ross, R.G., Jr., "Photovoltaic Design Optimization for Terrestrial Applications," Proceedings of the 13th IEEE Photovoltaics Specialists Conference, Washington, D.C., June 5-8, 1978, pp. 1067-1073.

2. Ross, R.G., Jr., "Flat Plate Photovoltaic Array Design Optimization," Proceedings of the 14th IEEE Photovoltaic Specialist Conference, San Diego, California, January 7-10, 1980, pp. 1126-1132.

3. Ross, R.G., Jr., "Photovoltaic Module and Array Reliability," Proceedings of the 15th IEEE Photovoltaic Specialists Conference, Orlando, Florida, May 12-15, 1981, pp. 1157-1163.

4. Gonzalez, C., and Weaver, R., "Circuit Design Considerations for Photovoltaic Modules and Systems," Proceedings of the 14th IEEE Photovoltaics Specialists Conference, San Diego, California, January 7-10, 1980, pp. 528-535.

5. Flat-Plate Photovoltaic Module and Array Circuit Design Optimization Workshop Proceedings, JPL Document No. 5101-170, Jet Propulsion Laboratory, Pasadena, California, May 19-20, 1980.

6. Moore, D., and Wilson, A., Photovoltaic Solar Panel Resistance to Simulated Hail, JPL Document No. 5101-62, Jet Propulsion Laboratory, Pasadena, California, October 15, 1978.

7. Carroll, W. et al, Photovoltaic Module Encapsulation Design and Materials Selection, JPL Document No. 5101-177, Jet Propulsion Laboratory, Pasadena, California, November 1, 1981.

8. Chen, C.P., Fracture Strength of Silicon Solar Cells, JPL Document No. 5101-137, Jet Propulsion Laboratory, Pasadena, California, October 15, 1979.

9. Mon, G.R., Moore, D.M., and Ross, R.G., Jr., Interconnect Fatigue Design for Terrestrial Photovoltaic Modules, JPL Document No. 5101-173, (DOE/JPL-1012-62), Jet Propulsion Laboratory, Pasadena, California, March 1, 1982.

10. Moore, D.M., Proposed Method for Determining the Thickness of Glass in Solar Collectors, JPL Document No. 5101-148, Jet Propulsion Laboratory, Pasadena, California, March 1, 1980.

11. Mon, G.R., "Defect Design of Insulation Systems for Photovoltaic Modules," Proceedings of the 15th IEEE Photovoltaics Specialists Conference, Orlando, Florida, May 11-15, 1981, pp. 964-971.

12. Lathrop, J.W., et al, Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells, 1st, 2nd, 3rd Annual reports, DOE/JPL-954929-79/4, 80/7 and 81/8, Clemson University, Clemson, South Carolina, May 1979, April 1980, January 1981.

13. Desombre, A., "Methodology for a Reliability Study on Photovoltaic Modules," Proceedings of Third E.C. Photovoltaic Solar Energy Conference, Cannes, France, 27-31 October, 1980, pp 741-745.

14. Hoffman, A.R., and Maag, C.R., Photovoltaic Module Soiling Studies, May 1978-October 1980, JPL Document No. 5101-131, Jet Propulsion Laboratory, Pasadena, California, November 1, 1980.