PV Reliability Development Lessons from JPL's Flat Plate Solar Array Project

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***Abstract*—Key reliability and engineering lessons learned from the 20-year history of the Jet Propulsion Laboratory's Flat-Plate Solar Array Project and thin film module reliability research activities are presented and analyzed. Particular emphasis is placed on lessons applicable to evolving new module technologies and the organizations involved with these technologies. The user-specific demand for reliability is a strong function of the application, its location, and its expected duration. Lessons relative to effective means of specifying reliability are described, and commonly used test requirements are assessed from the standpoint of which are the most troublesome to pass, and which correlate best with field experience. Module design lessons are also summarized, including the significance of the most frequently encountered failure mechanisms and the role of encapsulant and cell reliability in determining module reliability. Lessons pertaining to research, design, and test approaches include the historical role and usefulness of qualification tests and field tests.**

***Index Terms*—Photovoltaic, reliability, lessons learned, JPL FSA project.**

I. Introduction

During the 10 years of JPL's Flat Plate Solar Array (FSA) Project (from 1975 to 1985) the reliability of crystalline-silicon modules was brought to a high level with lifetimes approaching 20 years, and excellent industry credibility and user satisfaction (1). At the end of the FSA project, JPL engineering and reliability personnel spent another seven years working with the Solar Energy Research Institute (now NREL) developing reliability technology for thin-film modules. These new thin-film technologies involved new cell materials with more monolithic structures, but were basically responsive to the same reliability drivers and development methods.

At this point, ~20 years later, it is useful to review the lessons learned from JPL's crystalline-Si and thin-film reliability development efforts and apply the technology base, where applicable, to enhance the reliability of today's modules.

To this end, this paper summarizes the key reliability development lessons learned from the JPL module reliability development history with particular emphasis on lessons of use to new technologies and companies. For convenience, the lessons are divided into four topical areas: Reliability Management Lessons, Reliability Requirement Lessons, Reliability Design Lessons, and Reliability Testing Lessons.

II. FSA Reliability Management Lessons

Critical to successfully managing PV module reliability is understanding the value of increased or decreased module reliability at the PV systems level. Reliability directly influences the economic viability of photovoltaics as an energy source by not only controlling the total number and size of revenue payments received from future sales of electricity, but it also influences O&M costs, and the cost of money required to build the PV system. After considerations of present-value discounting and escalation of the worth of electricity in future years, a 30-year PV plant, for example, can be worth 25 to 30 percent more than a 20-year-life plant (2). Based on this economic sensitivity to plant life and the billion dollar cost of a utility-scale PV power plant today, there is a strong incentive to strive for a long life for such systems....and a large incentive to allocate substantial funds for improving reliability.

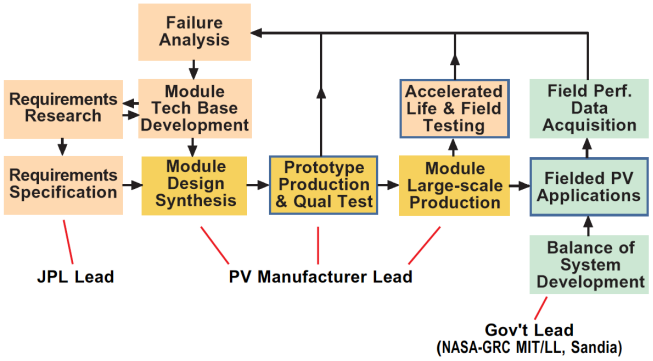

Fig. 1. Flow chart of US DOE PV Program module development activities undertaken in the years 1975 to 1985.

A. Establishing an Overall Reliability Management Approach

During the 1975-1985 time frame, the FSA Project was a key cog in what, in my opinion, was a very well implemented overall U.S. Department of Energy (DOE) National PV Program (1). Figure 1 highlights the key module engineering elements of the broad government/industry partnership. These involved all aspects of the problem from requirements definition for future PV applications, to design synthesis of candidate designs using current technologies, to thoroughly evaluating the designs in both laboratory and field applications, to identifying problem areas and root causes, and to developing new improved technologies to resolve identified design weaknesses.

B. Establishment of Mechanism-Specific Reliability Goals

A key step in managing the reliability development process and achieving high reliability was establishing mechanism-specific reliability goals. This forced several disciplines on the design process: first, it required that all failure mechanisms be determined, and that the economic importance at the system level be determined for each failure or degradation occurrence.

TABLE I - LIFE-CYCLE ENERGY COST IMPACT AND ALLOWABLE DEGRADATION LEVELS FOR CRYSTALLINE-SILICON MODULE FAILURE MECHANISMS

Type of Degradation	Failure Mechanism	Units of Degradation	Level for 10% Energy ▲Cost Increase*		Allocation for 30-year Life Module	Economic Penalty
			k=0	k=10		
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	$\%/yr^2$	0.05	0.25	0.001	Energy
Power Degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.18	0.1	O&M
	Module open circuits	%/yr	0.33	1.18	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.18	0.1	O&M
	Bypass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	$\%/yr^2$	0.022	0.122	0.01	O&M
	Module delamination	$\%/yr^2$	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	years of life	27	20	35	End of life

* k=Discount rate

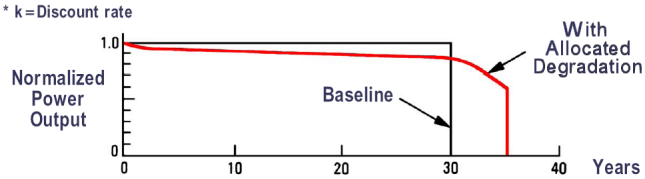

Fig. 2. Allocated degradation versus time for 30-year life photovoltaic system.

For some mechanisms, such as encapsulant soiling, the economic impact is directly proportional to the degradation level and is easily calculated. For others, such as open-circuit or short-circuit failures of individual solar cells, elaborate statistical-economic analyses that include the effects of circuit redundancy, maintenance practices, and life-cycle costing were required (2). Without such analyses, failure levels could not be interpreted with meaning, and cost effective goals could not be established. Thus, the overall FSA reliability process included the generation of the required system's level reliability assessment tools, as well as the extensive tools required for failure mechanism characterization, quantification, and resolution.

As an example, Fig. 2 illustrates a typical power versus time plot for a 30-year life PV system, while Table I lists 13 principal failure mechanisms for flat-plate crystalline-Si photovoltaic modules, together with their economic significance. Similar data were also generated for thin-film modules (2).

The units of degradation listed in the third column of the table provide a convenient means of quantifying the failure levels of the individual mechanisms according to their approximate time dependence. For example, units of %/yr in the context of component or module failures reflect a constant percentage of components failing each year. For components that fail with increasing rapidity, ($\%/y^2$) is the unit used. For those mechanisms classified under power degradation, the %/yr units refer to the percentage of power reduction each year.

Using the units described above, columns 4 and 5 indicate the level of degradation for each mechanism that will result in a 10% increase in the cost of delivered energy from a large PV system. Because the mechanisms will generally occur concurrently, the total cost impact is the sum of the 13 cost contributions. To help manage the reliability development effort, column 6 lists a strawman allocation of allowable degradation among the 13 mechanisms. In this case, the reliability allocations are consistent with a 20% increase in the cost of energy over that from a perfect, failure-free system with a 30-year life. This 20% shortfall is made up by having the eventual wearout and array replacement occur after 35 years.

Although different degradation allocations could have been chosen in Table I, the important point is that these allocations allow the significance of observed failures to be measured, and goals to be developed to guide mechanism-specific research and resolution activities.

Of particular importance is the small size of these allocations relative to there ability to be easily measured: e.g. 1 per 20,000 per year cell failures, 0.2% per year module power degradation, and 1 per 1000 per year module failures. This level of degradation can only be measured using the field experience from a large utility-scale system or from the aggregated results from a large number of smaller-scale systems.

TABLE II - KEY ENVIRONMENTS CONTROLLING THE RELIABILITY OF CRYSTALLINE-SILICON MODULES

- System Operating Voltage
  - Large number of series cells magnifies cell-failure effects
  - High voltage exacerbates corrosion and safety issues
- Operating Temperature and Temperature Cycles
  - Accelerates nearly all failure mechanisms
  - x2 life reduction for each 10°C increase in Temperature
- Ambient Humidity Level
  - x2 life reduction for each 10% increase in Relative Humidity
- Ultraviolet Exposure Level
  - Encapsulant degradation (highly nonlinear with UV level)
- Ambient Soiling Level
  - Much worse in urban environments
- Maximum Hail Size
  - Site specific, a problem with early applications in central US
- Presence of Salt Fog
  - Very specific to marine locations
- Maximum Wind & Snow Loads
  - Site specific, generally not a significant issue

III. FSA RELIABILITY REQUIREMENT LESSONS

Although Table I, defines allowable goals for acceptable levels of individual failures, the most fundamental requirement that the module reliability design must address is the level of applied stresses in the intended applications. Table II lists the key environments identified as the reliability drivers for crystalline-silicon modules during the FSA tenure (ordered from most significant to least).

System voltage heads the list because it impacts a large number of reliability parameters including voltage isolation and grounding requirements, electrochemical corrosion, hot-spot heating, bypass diodes, and the number of series cells in an array source circuit. Since the number of series cells affects the array's tolerance to open-circuit cell failures, system voltage indirectly influences the tolerance of the array to cracked cells and interconnect open circuits (2,3).

Operating temperature also shares the top of the list by having an accelerating influence on nearly every failure mechanism including voltage isolation, corrosion, hot-spot heating, photothermal degradation of encapsulants, delamination, interconnect fatigue, and cell cracking. All but the last two

mechanisms typically have an Arrhenius dependency on temperature (log reaction rate inversely proportioned to reciprocal absolute temperature) with a reaction rate doubling for approximately every 10°C increase in temperature (4,5). This implies that an application that operates 10°C hotter than another will last only half as long. Interconnect fatigue and cell cracking are sensitive to differential expansion stresses caused by the number of temperature cycles (2,3) and the high and low temperature extremes.

Humidity, like temperature, has a strong accelerating influence on many degradation mechanisms including corrosion and electrical leakage currents (6). For such mechanisms the degradation reaction rate often doubles for approximately every 10% increase in relative humidity (4). Thus, an application with a 10% higher humidity level may only last half as long. Humidity can also lead to large differential expansion stresses that aggravate delamination and interconnect fatigue.

The remaining environments of soiling, salt-fog, wind and hail tend to be fairly site specific and have been found to have important, but more limited influences on module reliability (2,3).

A. Quantifying Application Stress Requirements

Once the important application-dependent and site-dependent stresses are identified, a key difficulty is reducing them to specific stress-time requirements against which the module can be designed and verified. Some environments, such as system voltage level, are easily identified; others such as hail stone size, temperature and humidity extremes, and maximum wind velocity, require reference to historical weather data and considerations of statistical likelihood over the life of the intended application.

In general, two types of stress-time requirements were found useful: (1) a statement of the actual site-application requirement (such as 30 years of the operating temperatures of a Boston roof-mounted array), and (2) an accelerated qualification test against which the module can be tested.

The site-application requirement is needed for detailed life-prediction simulation analyses, and during the FSA Project, was computed based on SOLMET hourly weather histories for sites in the United States (7). For example, time-varying module temperature and humidity level can be computed from the hourly weather data using heat transfer and water-sorption models that include the application thermal boundary conditions for an array at a site of interest. This results in a numerical data base description of the application's stress-time environment.

Although the analytical stress-time data base is very useful in life-prediction computer simulations, it fails to provide a requirement that a fabricated module can be quickly and inexpensively tested to; this need is met by a qualification or life test. Ideally the qualification or lifetest stress-time level is selected to correlate to a given application stress-time environment; certainly this is the desired goal.

Probably the best way to reduce a large hourly data base of environmental parameters to a more easily interpreted test environment is to generate a model for the dependence of the aging mechanism of interest on the hourly environmental parameters.

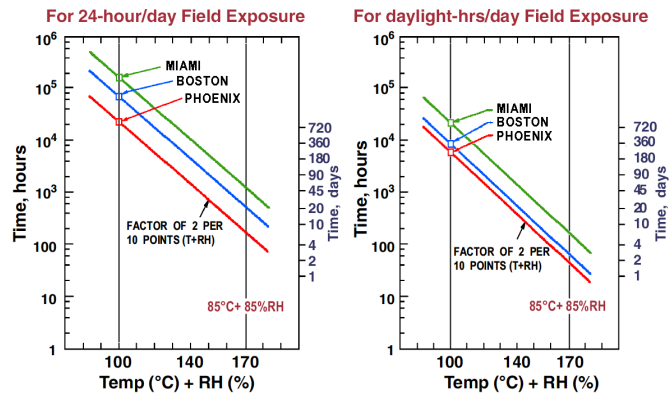

Fig. 3. T+RH plot describing general Arrhenius relationship between module life expectancy and temperature/humidity conditions.

Figure 3 illustrates such an approach for generic temperature humidity aging where the hourly temperature-humidity data for three sites has been aggregated using the model of a degradation rate doubling for each 10 points increase in T+RH level. Each of the curves (Phoenix, Boston and Miami) displays the exposure time to the environment on the lower scale that is equivalent to a 20-year operation of a ground-mounted array at that site. Although the curves in this plot are drawn for a rate doubling for each 10 points increase in T+RH, curves of a different slope could easily be drawn for mechanisms with a different rate dependency.

Note that the right-side plot only aggregates T+RH data for daylight hours; this may be more relevant for a mechanism that requires the presence of an array voltage to be active. Details of the theory behind the T+RH relationship and the more broad use of the plot have been described previously (4, 8).

A key advantage of a plot such as Fig. 3 is that equivalent constant-environment test conditions are displayed directly on the lower scale. Thus, a 40°C/90% RH aging test corresponds to 140 on the lower scale, and an 85°C/85% RH test corresponds to 170. Thus, for the assumed reaction rate (2x per 10 points T+RH), equivalent test times for these three sites can be read directly off the right-hand time scale. By running tests at parametric stress levels and plotting the corresponding time to failure, one can also use the plot to determine the effective reaction rate for a particular mechanism of interest.

B. FSA Qualification Test Experience

During the 10 years of the FSA Project, a number of module qualification tests were developed and refined to the final Block V sequence detailed in Table III (9, 10, 11, 12). These test levels were carefully selected and revised with time so as to fail early module designs with a known history of field problems and to pass modules with good field performance. A review of the experience with these tests provides important lessons for designers of future PV modules:

Temperature Cycling and Humidity Cycling. Consistent with their importance as key accelerators of degradation mecha-

TABLE III - JPL MODULE QUALIFICATION TEST EVOLUTION

QUAL TEST	I	II	III	IV	V	NOTES
THERMAL CYCLING						
Range (°C)	-40 to +90	-40 to +90	→	→	→	
Number cycles	100	50	→	→	200	
HUMIDITY CYCLING						
Relative Humidity	90	→	→	→	85	
Temp. Range (°C)	+70*	-23 to +40	→	→	-40 to +85	*No cycling, 70°C
Number cycles	-	5	→	→	10	Constant for 168 h
MECHANICAL CYCLING*						*Excluding shingle modules
Pressure (kPa)	-	±2.4	→	→	→	
Number Cycles	-	100	→	10,000	→	
WIND RESISTANCE (kPa)	-	-	-	1.7*	→	*Shingles only
TWISTED MOUNT (mm/m)	-	20	→	→	→	
HAIL IMPACT						
Diameter (mm)	-	-	-	20	25.4	
Terminal Velocity (m/s)	-	-	-	20.1	23.2	
Num. Impacts	-	-	-	9	10	
HOT-SPOT HEATING (h)	-	-	-	-	100	
ELECTRICAL ISOLATION (volts)	-	1500	→	2000*	3000*	*1500 for resid. modules

nisms, the Block V temperature and humidity tests served as the workhorse requirements in the JPL qual test sequence to uncover failures caused by differential expansion and corrosion such as delamination of encapsulants, loss of cell metallization, and open circuiting of cell interconnects. The tests had good correlation to field failures and were generally the most difficult to pass. Typical failure mechanisms included encapsulant delamination, interconnect fatigue, cracked cells, cell metallization corrosion, and warping of plastic parts. The 85°C and 90°C upper temperature limits of these tests accurately reflect upper-bound field operating temperatures, and the -40°C reflects realistic ambient lows.

Hot-Spot Testing. The need for hot-spot testing is principally associated with high-voltage applications, which can generate substantial reverse voltages across a temporarily shadowed or cracked cell, and thereby result in damaging hot-spot heating levels. Such heating levels can destroy the module encapsulant system, leading to arcing and electrical safety issues. The complexity of the hot-spot heating phenomenon requires that a number of cell and module parameters be properly accounted for during testing. This resulted in a carefully defined hot-spot test procedure (10). This hot-spot test was generally easy to meet if generic bypass diode recommendations were followed (14).

Mechanical Loading, Twist and Hail Tests. These Block V qual tests were developed to define minimum mechanical-loading requirements for modules intended for generic applications. The tests account for wind, snow and ice loads, module mounting to non-planar support structures, and impact by hail stones of 2-cm diameter and less. They are effective design requirements and generally straightforward to meet with 3-mm (1/8-inch) tempered-glass module designs. Annealed glass may pass these tests, but often exhibits excessive numbers of field failures caused by high thermal stresses in the glass resulting from nonuniform solar heating of the module surface. Applications with a significant incidence of large (>2-cm diameter) hail stones may choose to design for a greater resistance to hail impact. The use of 5-mm (3/16-inch) tempered glass is generally the maximum needed, and is adequate for 5-cm diameter hail stones (1).

Voltage Standoff (Hipot) Testing. This requirement was developed for modules intended for use in applications with system voltages above 50 V. Passing the test requires great care in the design of the module's electrical insulation system and proved troublesome to meet. Typical problems include excessive leakage current through partially conductive gaskets and edge seals, and inadequately insulated electrical leads. It posed special problems for thin-film modules made with tin-oxide coated glass because the edge of the glass is often electrically connected to the cells through the conductive oxide.

C. Post-FSA Reliability Research Thrusts

Although the FSA reliability activities made tremendous progress in understanding and resolving module reliability issues, there were a few remaining reliability areas that were not fully researched and reduced to engineering practice. These included electrochemical corrosion and wet insulation resistance, photothermal aging, overheating of bypass diodes, and soiling.

Wet Insulation Resistance and Electrochemical Corrosion. In addition to voltage breakdown issues addressed by the Block V Hipot test, an important additional degradation mechanism is accelerated current leakage between cells and between cells and the module frame resulting from high humidity and wet operating conditions. Although no qual test existed during the FSA project for electrical isolation under wet conditions, extensive research was carried out at JPL in the post-FSA timeframe that led to extensive improvements in our understanding of the relevant processes (15-20).

Key findings included the importance of conductance along encapsulant free surfaces interfaces (15, 16), the strong role of an encapsulant material's ionic cleanliness (17, 18, 19), and the enormous acceleration (orders of magnitude) associated with humidity level and wet surfaces (15-19). Temperature, as expected, was also determined to be a strong accelerator.

Based on the research results, draft test methods for wet insulation resistance were drafted and published (17, 20), and design guidelines were developed for limiting electrochemical corrosion in both single-crystal and thin-film modules (16-20).

Photothermal Aging. This requirement addresses the resistance of module encapsulants to ultraviolet photothermal aging. During the FSA and post-FSA years, a large body of research was focused at understanding photothermal aging and deriving accelerated test techniques suitable for characterizing UV/thermal degradation effects and screening new material developments (21,22). A key result from this research was the development of PV encapsulant materials, like Ethylene Vinyl Acetate (EVA), with greatly enhanced UV/thermal stability, and a much better understanding of the long-term degradation mechanisms associated with PV encapsulants and their interfacial bonds.

As shown in Fig. 4, a particularly important finding was the very nonlinear dependency of the yellowing of EVA on UV irradiance level. In contrast, as shown in Fig. 5, increased temperature was found to be a highly predictable accelerator,

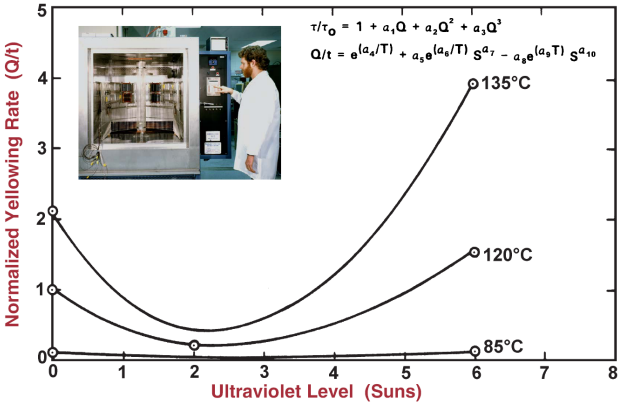

Fig. 4. Measured dependency of EVA yellowing on aging temperature and UV flux level (5, 24).

following a classic Arrhenius dependency (5). This led to the recognition that a useful accelerated test could involve extended exposure at 1-sun UV, together with a carefully controlled elevated temperature such as 85 to 100°C (23).

As an example of deriving life expectancy estimates from measured degradation rates and hourly weather data, Table IV utilizes the measured yellowing reaction rates shown in Figs. 4 and 5 to integrate the effects of measured hourly UV and temperature levels derived from SOLMET weather data (24). The estimated degradation after 20 years is computed as 20 times the dot-product of the two matrices, and leads to an estimate of 3.5% for a ground-mounted array and 7.9% for a (hotter running) roof-mounted array.

A second complicating factor in testing UV stability is the coupled mechanism of the gradual loss of UV screens and antioxidants introduced into encapsulant materials to protect against photothermal degradation. Thus, the working life of these suppression additives was also found to be a key factor in the life of a PV encapsulant system (21).

TABLE IV - 20-YEAR UV AGING PARAMETERS FOR PHOENIX

Cell temperature, °C	Relative Yellowing Rate at each Temperature-UV Level											
	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	65	61	58	55	52	49	46	44	41	39	37	35
65	33	31	29	28	26	25	24	23	21	20	19	18
55	16	15	14	13	13	12	12	11	11	10	10	9
45	7	7	7	6	6	6	6	5	5	5	5	4
35	3	3	3	3	3	3	2	2	2	2	2	2
25	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9
15	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1

Cell temperature, °C	Annual Hours spent at each Temperature-UV Level											
	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	0	0	0	0	0	0	0	0	0	11	4	0
65	0	0	0	0	0	1	17	24	107	294	167	6
55	0	0	0	32	18	56	130	81	201	142	177	17
45	22	74	32	110	62	84	144	73	172	154	55	1
35	134	131	63	124	97	93	113	49	53	17	0	0
25	190	129	92	86	53	21	22	0	0	0	0	0
15	129	94	36	35	8	0	0	0	0	0	0	0
5	55	20	3	0	0	0	0	0	0	0	0	0

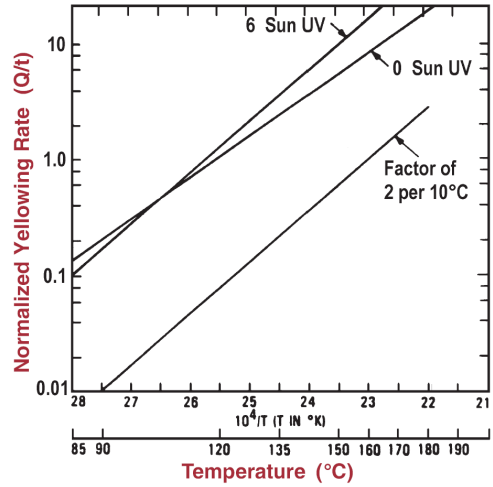

Fig. 5. The measured dependency of EVA yellowing rate on aging temperature is basically Arrhenius with a reaction rate doubling for approximately every 10°C increase in temperature (5, 24).

At the end of JPL's involvement in PV, the complexity of UV degradation mechanisms and the lack of commercially available test facilities precluded the definition of a readily available accelerated qualification test for full-size PV modules. To provide long-term photothermal stability, module designs of the time relied on the use of materials and processes carefully developed to be UV stable in specialized laboratory characterization and life tests.

Bypass Diode Overheating. Insufficient heat sinking and excessive current levels were determined to be the primary causes of bypass diode failures. To meet this need, bypass diode design recommendations and a qual test procedure were developed to help achieve acceptable bypass diode thermal design and implementation (13). The requirement limits the diode junction temperature under hot field conditions (100 mW/cm^2, 40°C ambient) to 50°C below the diode manufacture's stated maximum allowable junction temperature.

Soiling. Front surface soiling by airborne contaminants can lead to significant degradation of module performance in cases where the illuminated surface is a polymer material. As with photothermal oxidation, no short-term qual tests proved reliable for predicting long-term soling levels, but material selection guidelines and soil-resistant coatings were developed based on long-term field tests (1,2,25). Glass was proven to be an excellent low-soiling surface.

IV. RELIABILITY DESIGN LESSONS

In 1985, after ten years of fielding PV modules in large demonstration systems, an excellent database of design weaknesses had been systematically uncovered as noted in Fig. 6.

As each problem area was identified, technical resolutions were developed including design guidelines, improved materials and fabrication processes, and analysis and test methodologies. These we refer to as the reliability technology base that was developed during the FSA tenure. Key technology base

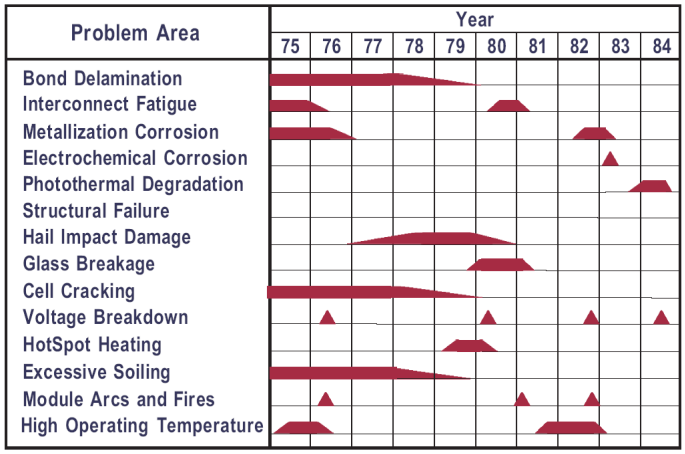

Fig. 6. Flow chart of principal reliability problems as they arose during the FSA's 1975-1985 tenure.

contribution areas are noted in Table III and are heavily documented in nearly 400 reports that are organized by technical topic in top-level summaries (1, 2, 16, 21-23, 26).

In lieu of repeating previous reviews of these individual technologies, we examine just one of the more intriguing and recurring issues in module design: the relative role of the module encapsulant system in achieving module reliability.

After many years of testing both bare cells and modules, it became increasingly clear that the encapsulant is the most problem-prone part of the module, and it generally does not enhance the reliability of the solar cells over their performance unencapsulated. For example, in tests at Clemson University, bare crystalline-Si cells routinely demonstrated better reliability than the same cells when encapsulated in any of a variety of typical photovoltaic encapsulant systems (27, 28). The principal demonstrated function of the encapsulant is to structurally support the cells and isolate them electrically for safety reasons. Secondary functions include providing an easily cleaned external surface and reducing the cell operating temperature by increasing the surface emissivity.

Unfortunately, while attempting to provide these functions, the module encapsulant often aggravates or creates a number of failure mechanisms. These include cracking, yellowing, delamination, accelerated corrosion, and differential expansion stresses. In addition, the encapsulant may fail to perform its intended function, resulting in voltage breakdown, excessive leakage currents, increased soiling or increased operating temperatures. The conclusion is that cells must be chosen with good inherent reliability, and the encapsulant must be carefully selected to perform its functions while not degrading the reliability and efficiency of the unencapsulated cells.

Aside from failures associated with the encapsulant, the part of a crystalline-Si module second most likely to have a failure is the electrical circuit. This includes solar cell electrical interconnects and solder joints, bus wires, and electrical terminal components. Typical failures include mechanical fatigue of conductors, broken solder joints, corrosion of electrical terminals, photothermal degradation of connectors and cabling, and thermal warping of junction boxes.

TABLE III - KEY TECHNOLOGY BASE CONTRIBUTION AREAS

- **New lamination adhesives**, primers, and stabilizers (PVB, EVA, EMA) for lower cost and improved weathering
- **Circuit redundancy configurations** for controlling cell cracking and broken interconnects
- **Interconnect design and test methods**
- **Cell attachment techniques** to minimize losses due to cell cracking
- **Glass strength** calculation methods
- **Bypass diode design** and hotspot test methods
- **Hail resistance data** and test methods
- **Cell fracture strength** and test methods
- **Voltage breakdown data** and test methods
- **Electrochem corrosion** Data and test methods
- **UV-thermal durability data** and test methods

The most reliable element of a crystalline-Si module is often the cells themselves. Although cell reliability problems were infrequent in the 1980s crystalline-Si modules, historical failure mechanisms included cell cracking, metallization delamination (increased series resistance), and degradation of the anti-reflective coating. This demonstrated high reliability with 1980s crystalline-Si cells may or may not be achievable with modern advanced-technology or thin-film cells.

Thus, establishing the inherent reliability of unencapsulated cell structures is an important first step in the process of achieving high-reliability long-life PV modules.

V. RELIABILITY TESTING LESSONS

Because the physics of most failure mechanisms is poorly understood, achieving high reliability requires a strong reliance on empirical characterization and testing. This can take the form of laboratory accelerated tests, outdoor test racks, or complete system application experiments. Each has its lessons.

A. Laboratory Testing

At the root of achieving long-life modules is ensuring that all the important problems are identified early so that they can be systematically addressed. The qualification tests described earlier (Table I) have been found to be the most cost-effective way to identify obvious reliability problems, and should be applied as early in the design process as possible using prototype hardware manufactured with candidate materials and processes. Even with careful attention to the lessons of the past, *new module designs almost never passed the qual tests on the first try.*

In addition to the qual tests, it is important to conduct long-term life tests at parametric stress levels to achieve a quantitative understanding of the parameter dependencies involved with complex failure mechanisms. Photothermal aging and corrosion of cells and modules are obvious examples. Because of the expense and many months required, this type of testing must generally proceed systematically as part of an integrated research effort, as opposed to being a part of a short-term product development cycle. A key advantage of this type of testing is that it provides data to support life predictions.

B. Outdoor Test Racks

A second testing approach requiring extended test durations is outdoor testing on field test racks. Unfortunately, the correlation between this type of testing and observed failures in field applications has historically been poor. Key problems stem from the limited number of samples on test, and the absence of many user-interface stresses such as applied voltages. This type of testing is mostly useful for backing up the qual tests, to catch a not-tested-for mechanism that might become visible after a modest period of field aging. The tests can be enhanced substantially by incorporating as many user-interface stresses as possible and increasing the number of samples on test to a maximum. Important user-interface stresses include module operating point (open circuit, maximum power point, and short circuit), array voltage biasing of the cell string above and below the module-frame ground potential, partial shadows, and increased operating temperatures.

Forcing an elevated, but reasonable operating temperature such as 85°C or 100°C can be an effective way to accelerate certain field aging mechanisms in a predictable way. Simultaneous testing at two separate accelerated temperature levels can allow determination of the degradation-rate temperature dependence and therefore provides improved extrapolation of degradation data to nominal field conditions.

C. Application Experiments

Because of the shortcomings of laboratory and test-rack aging, many problems are not acknowledged as such until they are encountered in a large operating system. The large number of modules involved in such systems is extremely useful in quantifying the significance of the problem, and the user-interface stresses are real. One failure out of 10 in a qualification test, or in a field test rack, is often discounted as a curiosity; 10% failures in a large system is a 'problem.'

Because of the often-present desire to field a large high-visibility application as soon as possible, there is great pressure to shortcut the laboratory-testing and design-qualification process, and to go directly to the field. This almost always results in tarnished reputations, slipped schedules, minimal learning, cost overruns, and early application retirement. The high cost of failure in the field, together with the need for field testing argues for careful laboratory characterization and life testing, followed by thoughtful selection of a low-risk first field application. This system should be instrumented to obtain quantitative data on failures, and be designed with failure containment features and failure contingency plans.

D. Failure Analysis

Aside from the testing method used to identify a reliability problem, a thorough and careful failure analysis is a critical next step. It is not sufficient to know that a module open-circuited; one must determine where and why in order to effect a corrective action. Did an interconnect fail due to a faulty design, or did someone forget to solder a lead to a solar cell? The correct response is critically dependent on understanding the true root cause of the problem.

VI. Summary Remarks

Achieving 30-year-life flat-plate PV modules requires a systematic approach to the identification of failure mechanisms, to the establishment of allowable failure levels, to the development of reliability design and test methods, and to the definition of cost-effective solutions. Based on this methodology, the reliability of flat-plate crystalline-Si PV modules was steadily improved from 5-year-life modules of the early 1970s to 10- to 20-year-life modules of the mid 1980s. It is expected that current-day modules have much in common with their 1980s crystalline precursors and will be able to make substantial use of the reliability design and test methods developed during JPL's PV tenure. At the same time, however, new module materials and processes will require a diligent reliability program involving evaluation, testing, and the development of new solution techniques unique to the attributes and peculiarities of today's technologies.

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References

[1] Ross, R.G., Jr., and Smokler, M.I., *The Flat-Plate Solar Array Project Final Report, Volume VI, Engineering Sciences and Reliability*, JPL Publication 86-31, JPL Document 5101-289, DOE/JPL-1012-125, JPL, Pasadena, California, October 1986.

[2] Ross, R.G., Jr., "Reliability of Photovoltaic Modules," Vol. 706: Photovoltaics for Commercial Solar Power Applications, SPIE Fiber/LASA'86 Symposium, Cambridge, MA, Sept. 14-20, 1986.

[3] Ross, R.G. Jr., "Technology Developments Toward 30-year-life of Photovoltaic Modules," *Proceedings of the 17th IEEE PV Specialists Conference*, Orlando, FL, May 1-4, 1984, pp. 464-472.

[4] Otth, D.H., and Ross, R.G., Jr., "Assessing Photovoltaic Module Degradation and Lifetime from Long-Term Environmental Tests," *Proceedings of the 29th IES Annual Meeting*, Los Angeles, CA, April 19-21, 1983, pp. 121-126.

[5] Gonzalez, C.C., Liang, R., and Ross, R.G., Jr., "Predicting Field Performance of Photovoltaic Modules from Accelerated Thermal and Ultraviolet Aging Data," *Proceedings of the International Solar Energy Society*, Montreal, Canada, June 22-29, 1985.

[6]. Mon, G.R., Wen, L.C., Meyer, J., Ross, R.G., Jr., and Nelson, A., "Electrochemical and Galvanic Corrosion Effects in Thin-film Photovoltaic Modules, *Proc. of the 20th IEEE PV Specialists Conf., Las Vegas, NV, Sept. 26-30, 1988*, pp. 108-113.

[7] *SOLMET Volume 1 &2, Hourly Solar Radiation-Surface Meteorological Observations*, TD-9724, National Oceanic and Atmospheric Administration, Asheville, NC, Dec. 1977 and Feb. 1979.

[8] Cuddihy, E.F., The Aging Correlation (RH+T): Relative Humidity (%) + Temperature (Deg C), JPL Publication 86-7, JPL Document 5101-283, DOE/JPL-1012-121, Jet Propulsion Laboratory, Pasadena, California, January 15, 1986.

[9] *Block V Solar Cell Module Design and Test Specification for Intermediate Load Applications*, JPL Internal Document No. 5101-161, Jet Propulsion Laboratory, Pasadena, CA, February 20, 1981.

[10] Hoffman, A.R., Griffith, J.S., and Ross, R.G. Jr., "Qualification Testing of Flat Plate Photovoltaic Modules", *IEEE Transactions on Reliability*, Vol. R3l, No. 3, August, 1982, pp. 252-257.

[11] Smokler, M.I. and Runkle, L.D., "Experience in Design and Test of Terrestrial Solar Cell Modules," Proceedings of AS/ISES 1982 Annual Meeting, Houston, Texas, June 1-5, 1982, pp. 1591 – 1600.

[12] Smokler, M.I., Otth, D.H., and Ross, R.G., Jr., "The Block Program Approach to Photovoltaic Module Development," *Proceedings of the 18th IEEE Photovoltaic Specialists Conference*, Las Vegas, Nevada, October 21-25, 1985, pp. 1150-1158.

[13] Otth, D.H., Sugimura, R.S., and Ross, R.G., Jr., "Development of Design Criteria and Qualification Tests for Bypass Diodes in Photovoltaic Applications," *Proceedings of the Institute of Environmental Sciences, 31st Annual Technical Meeting*, Las Vegas, NV, April 29-May 3, 1985, pp. 242-248.

[14] Gonzalez, C.C., R.G. Ross, Jr., et al., "Determination of Hot-Spot Susceptibility of Multi-String Photovoltaic Modules in a Central Station Application," *Proceedings of the 17th IEEE Photovoltaic Specialists Conference*, Orlando, FL, May 1-4, 1984, pp. 668-675.

[15] Mon, G.R., Wen, L., and Ross, R.G., Jr., "Encapsulant Free-Surfaces and Interfaces: Critical Parameters in Controlling Cell Corrosion," *Proceedings of the 19th IEEE PV Specialists Conference*, May 4-8, 1987, New Orleans, LA, pp. 1215-1221.

[16] Mon, G.R., Wen, L.C. and Ross, R.G., Jr., "Water-module Interaction Studies," *Proc. of the 20th IEEE PV Specialists Conf., Las Vegas, NV, September 26-30, 1988,* pp. 1098-1102.

[17] Mon, G.R., Wen, L.C., Sugimura, R.S., and Ross, R.G., Jr., "Reliability Studies of Photovoltaic Module Insulation Systems," *Proceedings of the 19th Electrical/Electronics Insulation Conference, Chicago, IL, September 25-28, 1989*, pp. 324-329.

[18] Mon, G.R., Whitla, G., Ross, R.G., Jr., and Neff, M., "The Role of Electrical Insulation in Electrochemical Degradation of Terrestrial Photovoltaic Modules," *IEEE Transactions on Electrical Insulation*, Vol. EI-20, No. 6, December 1985, pp. 989-996.

[19] Mon, G., and Ross, R.G., Jr., "Electrochemical Degradation of Amorphous-Silicon Photovoltaic Modules," *Proceedings of the 18th IEEE Photovoltaic Specialists Conference*, Las Vegas, NV, October 21-25, 1985, pp. 1142-1149.

[20] Sugimura, R.S., Mon, G.R., Wen, L.C. and Ross, R.G., Jr., "Electrical Isolation Design and Electrochemical Corrosion in Thin-film Photovoltaic Modules," *Proc. of the 20th IEEE PV Specialists Conf., Las Vegas, NV, September 26-30, 1988*, pp. 1103-1109.

[21] Cuddihy, E., Coulbert, C., Gupta, A., Liang, R., *The Flat-Plate Solar Array Project Final Report, Volume VII: Module Encapsulation*, JPL Publication 86-31, JPL Document 5101-289, DOE/JPL-1012-125, Jet Propulsion Laboratory, Pasadena, California, October 1986.

[22] Liang, R., Oda, K.L., Chung, S.Y., Smith, M.V., and Gupta, A., *Handbook of Photothermal Test Data on Encapsulant Materials*, JPL Publication 83-32, JPL Publication No. 5101-230, DOE/JPL-1012-86, Jet Propulsion Laboratory, Pasadena, CA, May 1, 1983.

[23] Mon, G.R., Gonzalez, C., Willis, P., Jetter, E., Sugimura, R.S., and Ross, R.G., Jr., "Long-Term Photothermal/Humidity Testing of Photovoltaic Module Polymer Insulations and Cover Films," *Proceedings of the 21st IEEE Photovoltaic Specialists Conference,* Kissimmee, FL, May 21-25, 1990, pp. 1043-1050.

[24] Gonzalez, C.C. and Ross, R.G., Jr., "Predicting Photothermal Field Performance," Proceedings of the 24th FSA Project Integration Meeting, JPL Publication 85-27, JPL Document 5101-259, DOE/JPL-1012-104, Jet Propulsion Laboratory, Pasadena, California, 1985, pp. 121-128.

[25] Cuddihy, E.F., and Willis, P.B., *Antisoiling Technology: Theories of Surface Soiling and Performance of Antisoiling Surface Coatings*, JPL Publication 84-72, JPL, Pasadena, CA, Nov. 15, 1984.

[26] Ross, R.G. Jr., JPL legacy web site with 480 FSA Engineering and Reliability documents: http://www2.jpl.nasa.gov/adv_tech/photovol/summary.htm

[27] Prince, J.L., Lathrop, J.W., Morgan, F.W., Royal, E.L., and Witter, G.W., "Accelerated Stress Testing of Terrestrial Solar Cells," Proceedings of the 17th IEEE Reliability Physics Symposium, San Francisco, California, April 24-26, 1979, pp. 77-86.

[28] Lathrop, J.W., *Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells*, 1st, 2nd, 3rd and 4th Annual reports, DOE/JPL-954929-79/4, -80/7, -81/8, and -83/10, Clemson University, Clemson, SC, May 1979, April 1980, January 1981, and October 1983.