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CRYSTALLINE-SILICON RELIABILITY LESSONS FOR  
THIN-FILM MODULES

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Introduction

During the past 10 years the reliability of crystalline-silicon modules has been brought to a high level with lifetimes approaching 20 years, and excellent industry credibility and user satisfaction. With the emergence of thin-film power modules it is important to review the lessons learned from the crystalline-Si product development history and apply the technology base, where applicable, to enhance the development of thin-film modules.

The transition from crystalline modules to thin-film modules is comparable to the transition from discrete transistors to integrated circuits. New cell materials and monolithic structures will require new device processing techniques, but the package function and design will evolve to a lesser extent. Although there will be new encapsulants optimized to take advantage of the mechanical flexibility and low-temperature processing features of thin-films, the reliability and life-degradation stresses and mechanisms will remain mostly unchanged. Key reliability technologies in common between crystalline and thin-film modules include hot-spot heating, galvanic and electrochemical corrosion, hail-impact stresses, glass breakage, mechanical fatigue, photothermal degradation of encapsulants, operating temperature, moisture sorption, circuit design strategies, product safety issues, and the process required to achieve a reliable product from a laboratory prototype.

Crystalline-Si Research Objective and Approach

Before examining the lessons learned from the crystalline-Si module development effort it is instructive to review briefly its objective and approach.

Increased array life and reliability directly influence the economic viability of photovoltaics as an energy source by controlling the total number and size of revenue payments received from future sales of electricity. After considerations of present value discounting and escalation of the worth of electricity in future years, a 30-year PV plant, for example, is worth 25 to 30 percent more than a 20-year-life plant. Based on this economic sensitivity to plant life, a 30-year life was chosen as the target of the crystalline-Si module development effort (Fig. 1) (1).

To achieve this high level of reliability a systematic reliability program (Fig. 2) was undertaken in 1975 by the Jet Propulsion Laboratory Flat-Plate Solar Array Project to develop the technology base required (2). Figure 3 lists the principal failure mechanisms for crystalline-Si modules and notes the economic importance of each and the target allocation level for each which is consistent with achieving a 30-year life (3). The next three figures illustrate the history of occurrence of crystalline-Si field reliability problems and the research developments over the past 10 years which have led to the present high reliability of crystalline-Si modules.

## Lessons Learned

The remainder of the figures systematically summarize the key reliability lessons learned from the 10-year crystalline-Si module development effort. For convenience the lessons are subdivided into five topic areas:

- o Module Reliability Lessons
- o Reliability Research Lessons
- o Module Qualification Experience
- o Qualification Test Experience
- o Field Test Experience

## Conclusions

An important lesson from the crystalline program (and the nuclear program) is that honest conscientious working of reliability and safety issues can significantly affect the economic viability and public acceptance of the product. Resolving the issues is not cheap, and cannot be accomplished overnight. For example, it still takes approximately 2 years from initial product design to successful passing of product qualification specifications for a crystalline-Si module.

As with your family car, initial cost and efficiency are directly measurable; lifetime and reliability are the greatest areas of user risk and play a key role in purchase decisions.

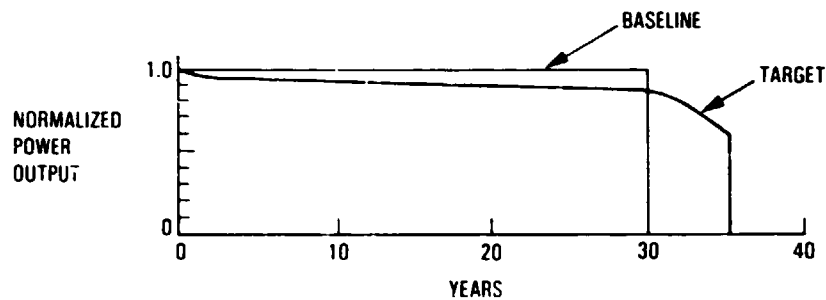
## References

1. Five Year Research Plan, 1984-1988, National Photovoltaics Program, Office of Solar Electric Technologies, U.S. Department of Energy, May 1983.
2. Ross, R.G. Jr., "Reliability Research Toward 30-year-life Photovoltaic Modules", Proceedings of the 1st International Photovoltaic Science and Engineering Conference, Kobe, Japan, November 15-18, 1984, pp. 337-340.
3. Ross, R.G. Jr. "Technology Developments Toward 30-year-life of Photovoltaic Modules" Proceedings of the 17th IEEE Photovoltaic Specialists Conference, Orlando, FL, May 1-4, 1985, pp. 464-472.

## Figure 1. Crystalline-Silicon Reliability Objective

To achieve the technology base for 30-year array life

- Acceptable power degradation rates
- Acceptable component failure rates
- Acceptable maintenance costs



## Figure 2. Reliability Research Elements

- Establishment of mechanism-specific reliability goals
  - Identification of key degradation mechanisms
  - Determination of system energy-cost impacts
  - Allocation of system-level reliability
- Quantification of mechanism parameter dependencies
  - Governing materials parameters
  - Governing environmental-stress parameters
  - Qualitative understanding of mechanism physics
- Development of degradation prediction methods
  - Quantitative accelerated tests
  - Life-prediction models
- Identification of cost-effective solutions
  - Component design features
  - Circuit redundancy and reliability features
- Testing and failure analysis of trial solutions

Figure 3. Life-Cycle Cost Impacts and Allowable Degradation Levels

Type of Degradation	Failure Mechanism	Units of Degrad.	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 <sup>2</sup>	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 <sup>2</sup>	0.022	0.122	0.01	O&M
	Module delamination	%/yr <sup>2</sup>	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

Figure 4. Module Reliability Lessons

- Most module reliability problems are related to the encapsulant system
  - Soiling
  - Cracking
  - Yellowing
  - Delaminating
  - Accelerated corrosion
  - Voltage breakdown
  - Laminating (processing) stresses
  - Differential expansion stresses
- Primary function of encapsulant is structural support and electrical isolation for safety reasons. The secret is to perform these functions while not degrading the intrinsic reliability of the cells themselves
- Second most frequent module reliability problems are related to circuit integrity
  - Fatigue due to differential expansion stresses
  - Poor solder joints
- Crystalline-Si cell reliability problems are most often related to cell cracking, metallization adherence/series resistance and durability of anti-reflective coatings

### Figure 5. Reliability Research Lessons

- **Failure mechanisms fall into two broad classes: generic and statistical. Generic problems must be solved by design or process changes; statistical failures are effectively solved through redundancy and quality control**
- **The physics of most failure mechanisms is poorly understood. This requires a high reliance on empirical characterization and testing**
- **Increased temperature is an excellent universal accelerator of chemical degradation mechanisms. Typical acceleration is Arrhenius with a factor of 2 increase per 10°C**

### Figure 6. Module Qualification Experience

- **Qualification testing is a cost-effective way to identify obvious reliability problems; should be used during development as well as for design verification**
- **New designs almost never pass the Qual tests on the first try**  
**Corollary: Great political pressure to field unqualified hardware generally results in disaster**
  - **Slipped schedules, cost overruns**
  - **Early application retirement**
  - **Minimal learning**
  - **Decreased credibility**
- **Qual tests must be periodically updated to reflect field experience with previously tested modules**
- **Long-term life testing at parametric stress levels is required for quantitative correlation to extended field performance**

## Figure 7. Qualification Test Experience

- **Temperature cycling and humidity tests are workhorse tests with good correlation to field failures; they are generally the most difficult to pass**
- **Hot-spot testing is controversial, but correlates well to field experience. Its complexity requires a high skill and knowledge level**
- **Mechanical loading, twist, and hail tests are effective design requirements and generally straightforward to meet**
- **Voltage standoff (hipot) requirements require great care in design and are troublesome to meet**
- **Photothermal testing (UV) is extremely complex with poor correlation with field results (no Qual test exists)**
- **Soiling evaluation is best done in field tests, but is highly site-dependent (no Qual test exists)**

## Figure 8. Field Test Experience

- **Most problems are not accepted as problems until encountered in large operating systems**
  - **Large statistical sample size aids quantification**
  - **Operational user-interface stresses are present**
- **Corollary: Good module not proven good until tested in large operating system**
- **Corollary: Operational interaction of module with user system is important source of module stress**
- **Test-stand aging only useful for very generic problems; sample sizes too limited for statistical failures; many user interface stresses not present in test-stand tests**
- **Reliance on field-failure data places requirements on system experiments:**
  - **To obtain quantitative data on failures**
  - **To have failure containment features**
  - **To have failure contingency plans**

## Figure 9. Conclusions

- **Crystalline-Si and thin-film modules are expected to have much in common with respect to reliability problems, methods and solutions**
- **New materials and processes in thin-film modules will require a diligent reliability program**
  - **Establishment of mechanism-specific reliability goals**
  - **Quantification of mechanism parameter dependencies**
  - **Prediction of expected long-term degradation**
  - **Identification of cost-effective solutions**
  - **Testing and failure analysis of trial solutions**

## DISCUSSION

**YERKES:** Can you guess where problems might be different from those with the modules we have been doing for 10 years, in the new thin-film modules? Some insight on your part, from early examination.

**ROSS:** Most of our testing indicates that thin-film modules and crystalline modules are quite similar; things like hot-spot heating modes are almost identical. The cell-breakage problem is a big difference. Crystalline-silicon cell cracking was one of the more formidable problems, long-term, in differential expansion stresses and processing yields, and thin-film modules will have a different type of processing-yield problem, I'm sure. Crystalline cells allow series-paralleling to solve the cell-shorting mismatch type of problems. I'm not sure if that is going to be a problem with thin-film modules; it depends on how uniformly the deposition can occur. It may be a different problem with stainless-steel-backed modules; they may go through the same kind of cell shorting that crystalline modules do. Corrosion-type issues are clearly going to be different, although the data we have in our electrochemical corrosion studies indicate there is not much difference between the resistances of thin-film modules and those of crystalline modules. When you have a micrometer or so of material and lose a half micrometer you have lost a cell. On a crystalline cell you can lose a lot of the metallization system; there are bulk amounts of material that you can corrode away and still leave an active solar cell. The crystalline cells are less fragile in terms of mechanical damage. With thin-film cells, if you penetrate the back side with something, you could poke a hole right through the cell. At the same time, the thin-film cells are very resistant. If you lose a part of the cell they typically don't shunt and the lateral series resistance is such that a small area of damage doesn't seem to spread across the total cell in terms of total electrical effect. There are differences.