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THEME PRESENTATION

QUANTIFYING RELIABILITY/DURABILITY OF FLAT-PLATE PHOTOVOLTAIC MODULES

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ROSS: What I would like to do in the next 30 minutes is first provide an overview of photovoltaic performance parameters and materials of construction for the few of you in the audience who are outside of the photovoltaics program. Many of you are within the program, so you will find this, obviously, a repeat. Next, I would like to describe some of the work we have done to identify the levels of allowable degradation for various failure mechanisms, based on the economic goals of the program. I will start with what we want to achieve, from the point of view of overall product reliability, and then look at the allowable levels of degradation in various specific mechanism categories. That will provide a framework for defining what we mean by quantifying degradation and what we need in the way of assessment tools.

A Generalized Reliability-Lifetime Target

To repeat the overall photovoltaic program goal, as Ed described it, the program has been striving for a module price of 70¢ a watt, a 10% efficiency, and a 20-year lifetime. The cost and efficiency combine to yield an area cost of about $70 per square meter. From a lifetime point of view, the economists assume no degradation during the 20-year life, and zero performance after 20 years. All of us know that products don't work ideally for 20 years and drop off. To provide a useful engineering lifetime requirement I have generalized the 20-year ideal life into what I call the generalized reliability durability target. That is: life-cycle economic performance shall be equivalent to no degradation for 20 years. The equivalency allows for some gradual degradation over time, but also provides for extended operation beyond 20 years, to yield a total integrated performance that is equivalent to 20 years with no degradation. The target is thus based on life-cycle modeling of the aggregate energy obtained from the array and the aggregate O&M expenses. I will be addressing this in detail in a moment, but first let me define some of the photovoltaic definitions and nomenclature.

Photovoltaic Nomenclature

I am going to be speaking specifically of solar cells made from single-crystal silicon or semicrystalline silicon, which is a matrix of small single-crystals. The crystalline silicon is manufactured into wafers that are typically 10 to 15 thousandths of an inch thick and 3 to 5 inches in diameter. Most solar cells are made of p-type doped silicon, with an n-type doped layer on top, to give the p-n diode junction. To collect the power, a metallization is applied to the top surface--an open gridwork to allow the light to reach the silicon cell. The bottom is typically a continuous metallization. The cells are combined electrically into modules where they are surrounded by a pottant material and supported by a substrate on the bottom, a superstrate on the top, or both. Either the top or bottom of the module may be a thin-film material, and I will

describe those in a little bit. The modules are subsequently aggregated into panels and arrays. The arrays themselves are connected to inverters to convert the dc power to ac. We are going to be limiting our attention to the cell and module level, which is where most of the life-limiting failure mechanisms are.

Module Construction Materials

Next, I would like to briefly summarize the typical materials used in present-day modules. As I commented earlier, the cells are primarily silicon, particularly the ones in the field, although new thin-film cells are also being developed. Dr. Dalal will be speaking of thin-film cells in the talk following mine.

The workhorse of metallization systems for quite a period of time was developed during the space program in the late sixties, and is composed of a silver-titanium-palladium sandwich. The palladium is actually in the center. In addition to the Ag-Ti-Pd system, we have silk-screened silver metallizations, and various nickel-plating systems. These metallization systems create most of the corrosion problems associated with the cells.

Interconnects, used to connect the cells, are made primarily of copper; some aluminum. Copper, clad with other materials, is also being used to obtain improved fatigue resistance.

The superstrates on the top of the module are typically glass or Tedlar; both of these have excellent antisoiling characteristics and weatherability.

The pottant materials are EVA, silicone rubber, polyvinyl butyral, or EMA.

The substrates on the bottom, in the case where glass is used on the top, are typically a Mylar or Tedlar laminant. In the case where thin films like Tedlar are used on the top, the substrate is a structural material like aluminum, steel, or glass. Some of the earlier modules were made with fiberglass substrates, either polyester or epoxy glasses.

Typical present-day photovoltaic modules are nominally about four feet long and ranging in width from about a foot up to two feet.

Typical Failure Mechanisms

Next, let me summarize the failure mechanisms that are associated, or have been associated in the past, with these various parts of the module.

Solar cell cracking is probably the most severe and most prevalent failure mechanism in the field. It is also probably the largest contributor to power loss. The cells are very brittle, like a sheet of glass, and can be easily cracked by bending or differential expansion stresses. If the cells are not properly interconnected with redundant interconnects, cracks can open-circuit the array and cause substantial amounts of power loss. Thermal cycling, humidity cycling, and hail impact stress are the primary culprits.

Interconnect breakage is another historical failure mechanism, starting with spacecraft arrays, and has been prevalent in some terrestrial arrays. It too is caused by differential expansion of materials due to thermal and humidity cycling. Open circuiting of the cell strings is, of course, the major problem.

Another important failure mechanism is cell metallization delamination, which causes series resistance increase due to increased contact resistance between the metallization and the silicon wafer. Temperature/humidity/electrical-bias corrosion-type mechanisms are key in this area. Again, power loss due to increased series resistance is typically the way it is manifested.

We next have a whole series of encapsulant-related mechanisms such as delamination, cracking and yellowing that I have grouped into a common category. All of the normal weathering environments are involved here: temperature and humidity cycling, ultraviolet, hail, wind and atmospheric oxidants -- all combining in chemical reactions with the encapsulants. This is one of the more difficult areas of degradation to quantify. Except in the case of yellowing, where you have a transmission loss, the prominent affect is simply a reduction in the environmental protection afforded to the solar cells and the circuitry. The net result of encapsulant degradation is largely an acceleration of the other mechanisms, such as metallization corrosion.

Electrical insulation breakdown from long-term dc stresses is one of the more interesting degradation mechanisms we are looking at.

Optical soiling is a very important mechanism because it has a direct power loss associated with it.

Another mechanism is hot-spot heating. Solar cells have the property that if you reverse bias them, with the voltage in the opposite direction of the normal voltage, you can create localized heating. One of the environments the encapsulant system must withstand is elevated temperatures associated with localized hot-spot heating within the cell, up to 160°C if not properly controlled.

Reliability Design Approaches

In the next portion of my presentation, I would like to briefly summarize means of addressing these degradation problems. Basically, there are three approaches. One is to try to control the piece part failures themselves, by understanding the fundamental mechanisms and identifying materials or design approaches that solve them. A second approach is to incorporate redundancy to allow a certain number of failures, but still maintain electrical continuity and power from the array. As a third approach, we can implement maintenance and replacement strategies that are available to us.

How do we trade off these various solution approaches? As an example, I would like to consider solar-cell cracking, which happens to be probably the most prevalent failure mechanism in the field. We have good historical data from two large applications, with almost 100,000 solar cells each, that were involved with very extensive audits. We found that

about 1% of the cells were breaking in the field every year due to various mechanisms: hail, differential expansion, flaws that were there that simply opened up because of the differential expansion. But not all of the broken ones failed. The metallization bridges the cracks quite often, and maintains continuity. It turns out that the number of cells that failed with an open-circuit failure, or a large loss of power, is only on the order of about 1 per 1000. This was at a very heavily damaged site, so we consider this number of failures to be an upper bound. A typical failure level is expected to be on the order of 0.0001 per year. This very low failure rate places some fairly severe constraints on us in terms of trying to measure it accurately.

Quantifying the Effect of Cell Failures

To get a feeling for the significance of the cell failure level, consider an array that is wired with all of the cells in the source circuits in pure series. A 15-volt system, which is typical for a 12-volt battery-charging system, will have 36 cells in series. If we fail one cell per 10,000 per year, at the end of 5 years our power plant will be down about 1.8%. Not too bad. If we increase the voltage to 150 volts, a little low for residential applications, but in that ball park, we find the increase of the seriesing of cells has hurt us. With the same level of cell failures the power is down 16% after 5 years. At a central power-station voltage level, around 1500 volts, we find that one cell failure per 10,000 per year cell failure is disastrous. We have lost 85% of our power in five years. Clearly, we either have to achieve breakage levels far below one per 10,000 per year, or we have to incorporate redundancy strategies, or both.

The question then becomes, how do you compute the power loss of a complex redundant system with a failure rate of only one per 10,000? It is very difficult, because you have such sporadic failures, and such a nonlinear electrical circuit. However, we have developed a methodology, a whole family of graphs, that allows us to compute the expected power loss of a plant as a function of the series paralleling and cell failure rate. We can thus understand the power losses associated with different series-parallel networks.

The next question that arises is: Is it worth adding the extra interconnections from an economic point of view, or do you simply make a replacement when a failure occurs? To achieve an answer to this question we have performed economic analyses trading off the life-cycle costs of implementing redundancy as opposed to replacement strategies. There are two scenarios that we have looked at, one where we have no replacement whatsoever, and one where we replace every time a cell fails, assuming we can find the failed-cell module and are able to replace it at a nominal cost. The optimal strategy from a life-cycle-cost point of view is no maintenance whatsoever, basically live with the failures, and have sufficient redundancy--something on the order of 200 series blocks per source circuit. The paralleling isn't particularly sensitive, although single strings, or eight or more parallel strings, is best.

Establishing Allowable Degradation Levels

With this brief understanding of the failure mechanisms and available solution strategies, let me next address the problem of establishing allowable degradation levels. A useful figure of merit for the significance of each mechanism is the level that will lead to a 10% cost increase in the total energy from the plant, assuming optimal series-parallel redundancy. Our results show that if we have about 6 per 10,000 cell failures each year in the field, it will increase the cost of energy about 10%; the module failure rate is around 7 per thousand per year for a 10% cost increase. This is for a zero discount rate, which turns out to be fairly appropriate for assessment. If you were to work with an economic discount rate of 10%, these numbers are changed somewhat, but not terribly different.

Next, I have generated a strawman degradation allocation for the levels of degradation that can be allowed for each mechanism category and still achieve 20-year life. I have arbitrarily chosen 1 per 10,000 per year for the cell failure rate. That is probably fairly easily achievable and represents only a small percentage of the total allowable degradation. For module failure rate, which is very difficult to quantify from field data because the designs are changing so rapidly, I have assigned 5 per 1000 per year. A 1% per year linear drop in power is allowed for things like yellowing, or increased series resistance of the metallization from corrosion. A 5% fixed drop in power is allowed to handle soiling.

To make up for the energy loss associated with these mechanisms we need to extend the actual product life another 5 years, out to about 25 years.

In summary I hope I have given you a feeling for the kind of degradation levels and failure rates we can stand in various mechanism categories. The subject of the Research Forum is the available means for quantifying the extent to which products meet these degradation levels, without having to wait for 25 years to find out.

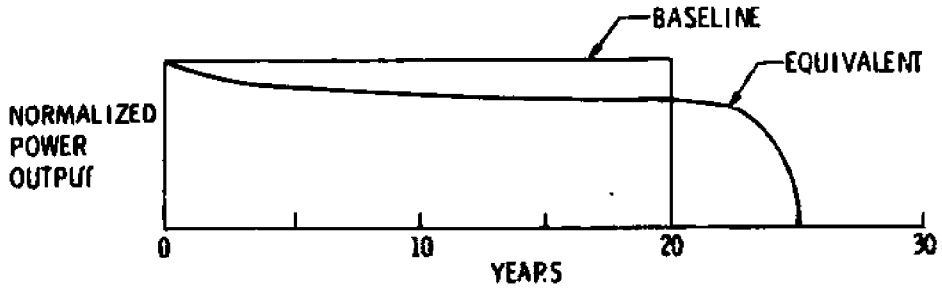
Array Reliability-Durability Targets

BASELINE PROJECT GOALS:

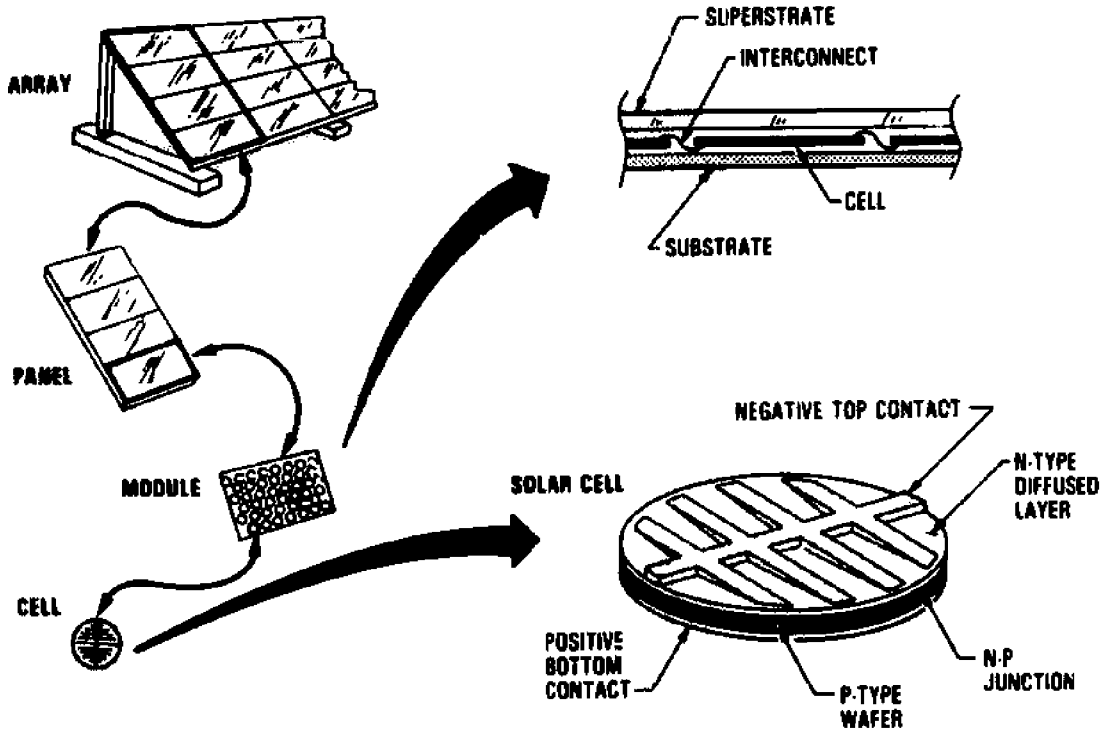
PRICE: 70¢/WATT (1980$)
EFFICIENCY: ≥ 10 PERCENT
LIFETIME: NO DEGRADATION FOR 20 YEARS

GENERALIZED RELIABILITY/DURABILITY TARGET

- LIFE-CYCLE ECONOMIC PERFORMANCE SHALL BE EQUIVALENT TO NO DEGRADATION FOR 20 YEARS



Array Nomenclature



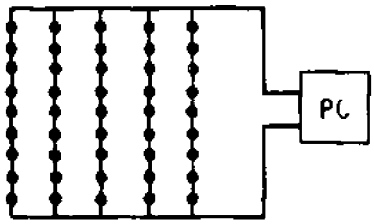
Typical Materials of Construction (Cells and Modules)

COMPONENT	TYPICAL MATERIALS
CELLS	SILICON, CdS, α-Si
CELL METALLIZATION	Ag-Ti-Pd, SILK SCREEN SILVER Ni-PLATING/SOLDER
CELL INTERCONNECTS	COPPER, ALUMINUM, CLAD METALS
SUPERSTRATE	GLASS, TEDLAR
POTTANT	EVA, SILICONE RUBBER, PVB, EMA
SUBSTRATE	MYLAR, TEDLAR, FOIL LAMINANTS FIBERGLASS (POLYESTER, EPOXY) ALUMINUM, STEEL GLASS

Key Failure Modes and Mechanisms

FAILURE MECHANISM	KEY ENVIRONMENTAL STRESSES	EFFECT
SOLAR-CELL CRACKING	THERMAL CYCLING, HUMIDITY CYCLING, HAIL	CELL STRING, OPEN CIRCUITING, LOSS OF CURRENT
CELL INTERCONNECT BREAKAGE (FATIGUE)	THERMAL CYCLING, HUMIDITY CYCLING	CELL STRING, OPEN CIRCUITING
CELL METALLIZATION DELAMINATION	TEMPERATURE/HUMIDITY ELECTRICAL BIAS	INCREASED SERIES RESISTANCE, LOSS OF POWER
ENCAPSULANT DELAMINATION, CRACKING, AND YELLOWING	TEMPERATURE/HUMIDITY CYCLING, ULTRAVIOLET, HAIL, WIND, ATMOSPHERIC OXIDANTS	LOSS OF POWER, ACCELERATION OF OTHER FAILURE MECHANISMS
ELECTRICAL INSULATION BREAKDOWN	VOLTAGE STRESS HUMIDITY, TEMPERATURE	MODULE FAILURE
OPTICAL SOILING	DEW, ATMOSPHERIC CONTAMINANTS	LOSS OF POWER

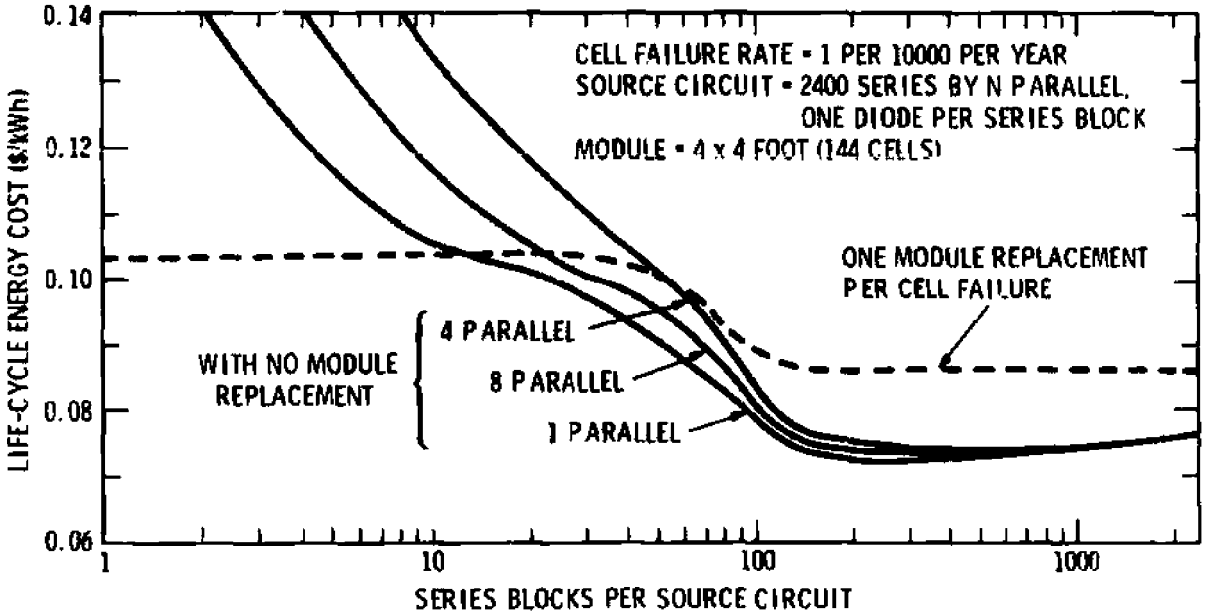
Effect of Cell Failures on Array Degradation
(No Circuit Redundancy)
(Cell Failure Rate R = 0.0001 per year)



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

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

Life-Cycle Energy Cost vs Series-Paralleling
(Optimum Maintenance)



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

Strawman Degradation Allocations
Equivalent to 20-Year Life

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

DISCUSSION

GUILLET: I just wanted to know how sensitive your economic analysis is to such things as interest rates.

ROSS: The discount rate was on the viewgraph and that basically reflects interest rate. You can see it is sensitive, but not terribly sensitive. This is comforting because it says that we don't have to worry about trying to outguess where the economy is going.

WAKSMAN: I had a question about treating the degradation rates as constant factors over time. Some of these parameters, such as soiling, I would imagine would go up to a certain level and then level out, whereas others such as yellowing could very well get more and more intense. They may not be constant-rate factors, and I wonder if you built these considerations into your models?

ROSS: That is exactly what I have done. The fixed drop in power, in fact, is due to module soiling, because our experimental measurements in the field today indicate that soiling rapidly reaches a equilibrium state and then stays at that level, fluctuating due to natural environmental cleaning processes. Other processes, like yellowing, yield a gradual increase. We have assumed a linear rate for yellowing, which is obviously a magnification, but the economic assumptions place most of the weight on the first few years of product life and diminish in importance as you get out beyond 15 years (if you have the higher discount rates). So the linear approximation is still a pretty good approximation for a lot of these mechanisms.