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FINAL REPORT

DEVELOPMENT OF AN ACCELERATED TEST DESIGN FOR PREDICTING THE SERVICE LIFE OF THE SOLAR ARRAY AT MEAD, NEBRASKA

to

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

for the

ENCAPSULATION TASK OF THE
LOW-COST SOLAR ARRAY PROJECT

The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Progam to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

June 7, 1979

G. B. Gaines, R. E. Thomas, G. T. Noel,
T. S. Shilliday, V. E. Wood, and D. C. Carmichael

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BATTELLE — COLUMBUS

ABSTRACT

This report describes an accelerated test which is designed to predict the life of the 25-kW photovoltaic array installed near Mead, Nebraska. Emphasis is placed on the power-output degradation at the module level and on long-term degradation modes, as appropriate for life prediction of mature devices for which infant failures are few.

A quantitative model for accelerating testing using multiple environmental stresses is used to develop the test design. The model accounts for the effects of thermal stress by a relation of the Arrhenius form. This relation is then corrected for the effects of nonthermal environmental stresses, such as relative humidity, atmospheric pollutants, and ultraviolet radiation. The correction factors for the nonthermal stresses include temperature-dependent exponents to account for the effects of interactions between thermal and nonthermal stresses on the rate of degradation of power output. A priori quantitative estimates of the model parameters are then used to compute expected degradation rates under various test conditions associated with a complete factorial experimental design. The conditions at the center point of the accelerated test design are selected to cause a loss of 50 percent of the initial power output for the modules over a period of approximately 8 months. The times to failure for other test conditions are then computed and the conditions are adjusted to yield expected failure times between approximately 1 month and 2 years. The resulting model is then used to obtain extrapolated estimates of the expected life of the modules currently operating at Mead, Nebraska.

The test conditions, measurements, and data analyses for the accelerated tests are presented for determining the predicted life of the modules in service at Mead. Constant-temperature, cyclic-temperature, and UV types of tests are specified, incorporating selected levels of relative humidity and chemical contamination and an imposed forward-bias current and static electric field. It is recommended that as a first step in test implementation, the model be selectively validated using identified portions of the accelerated test design.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the technical contributions and direction provided to this project by Hugh Maxwell and Cliff Coulbert of JPL. We also wish to acknowledge that numerous other personnel of JPL and Battelle contributed to the development of this accelerated test design methodology and the resulting test plan. The cooperation and assistance in this study of Steve Forman and other members of the staff of MIT-Lincoln Laboratory are sincerely appreciated.

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INTRODUCTION

Under present evaluations of allowable costs for materials and processing of photovoltaic arrays, economic viability requires that the service life of the arrays be approximately 20 years or longer. Qualification and performance tests indicate that presently available arrays - and the modules making them up - provide acceptable performance at the time of installation. A major question remaining, therefore, is: "How long will such arrays continue to provide acceptable power in normal environments found in the United States?". Laboratory or field determinations of service life under normal environmental conditions (normal levels of environmental "stresses") require an unacceptable length of time for valid predictions. Tests which accelerate module aging, without changing the mode of aging occurring under normal environmental stresses, are essential to compress the test period.

As part of the Low-Cost Solar Array Project, managed by the Jet Propulsion Laboratory for the Department of Energy, Battelle's Columbus Laboratories undertook the task of designing an accelerated test, the goal of which is to predict the life of the 25-kW array located at Mead, Nebraska. This was a three-part task. The first part involved the development of an appropriate test design methodology which took into account the number of tests to be performed, the expected aging modes, and the distribution of test samples among the various test conditions, among other considerations. This methodology is described in Report ERDA/JPL 954328-77/1, "Methodology for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays". This report is designated as [RS4] in the following discussions.

The second part consisted of a review and limited experimental assessment of measurement techniques which can be useful in determining degradation of the many elements and interfaces of the module either by destructive or nondestructive methods. In the current discussions, the two reports describing these results are referred to as [RS5]. They are entitled, "Measurement Techniques and Instruments Suitable for Life-Prediction Testing of Photovoltaic Arrays", Report Nos. DOE/JPL-954328-78/1 and DOE/JPL-954328-79/12.

The third part consists of the test design itself. This current report is concerned with this subject, and constitutes the last report of Contract DOE/JPL 954328.

Several features and assigned directions of the approach to life predictions impact the test design study in important ways. Among these features and directions are the following:

(1) The primary emphasis is on long-term degradation phenomena at the module level. This emphasis is tantamount to assuming a mature module design; that is, the infant mortality rate is assumed to be small. Moreover, "catastrophic" failures owing to such events as large hail are not considered.

The effects of dirt accumulation and cleaning are not considered in the test design since the experience to date at Mead indicates that this is not a likely long-term failure mode that will limit the lifetime of the array. These effects are important, however, and merit extensive investigation; studies of the array at Mead and other sites are being conducted by MIT Lincoln Laboratory and the Jet Propulsion Laboratory.

(2) The dependent variable of primary interest is power output. Thus, environmental stresses, and their interactions, are assessed as to their effects on the reduction of the ratio of power output at time, t, and initial power output at the time of module installation in the field (t = 0).

As discussed further in the body of the report, the selection of the dependent variable - power output - implies that much is known about the relationships between those degradation modes observed in the field so far - such as cover/cell delamination and bleaching of the antireflecting cell coating - and power output. This is not yet the case. Therefore, the test design is based on engineering judgments as to these relationships so as to effect a timely estimate of the array service life. At the same time, the functional relationships between power output and environmental and operational stresses had to be kept simple enough to reduce the number of tests - and the parameters to be estimated - to a tractable level for an affordable, cost-effective test.

(3) The experimental test design deals with the <u>actual modules</u> installed in the Mead Array, that is, Block II modules fabricated by two manufacturers: Solarex and Sensor Technology. Additionally, Mead, Nebraska is taken to represent the actual "normal-stress" environment.

(4) Ideally, the test design would consist of one set of tests which take into account all stresses and their interactions. Experimental reality precludes this approach. For example, no known ultraviolet radiation source is capable of furnishing sufficient flux in the 0.3 to 0.4 μm wavelength range to expose simultaneously and uniformly several modules of conventional sizes. Therefore, to achieve a practical test plan, the total test design developed in this program consists of <u>three sets of tests</u>. In this report, these are labeled constant-temperature tests, cyclic-temperature tests, and UV tests.

OBJECTIVE

As a significant first step in applying accelerated tests to solar arrays for life prediction purposes, this study was conducted to develop a test design for predicting the service life of a specific solar array in a specific geographic site, viz. the 25-kW, flat-plate photovoltaic array installed near Mead, Nebraska. The test is designed to be carried out in 2 years, or less, and to have predictive validity for a service life as long as 20 years. In support of this objective, selected measurements were performed to aid in establishing potential failure modes and/or functional relationships between power output, other degradative effects, and environmental stresses.

IDENTITY AND PROPERTIES OF THE MATERIALS OF MODULE CONSTRUCTION

The principal materials used in the construction of the two types of modules making up the Mead array have been identified and are shown in Table 1. The identifications were made through information supplied by JPL and by the manufacturers and through analyses carried out at Battelle.

The two types of modules are quite similar with respect to anticipated degradation modes. Potentially important differences are noted in other areas,in cell metallization, for example.

TABLE 1. IDENTIFICATION OF MODULE MATERIALS

	Manufacturer	
	Solarex	Sensor Technology
Top cover	Silicone	Silicone (RTV 615)
AR coating[(a)]	Ta_2O_5	SiO_x
Metallization	Ti/Pd/Ag	Ni/Pb-Sn
Interconnects	Cu/Pb-Sn	Cu/Pb-Sn
Substrate	Polyester/glass fiber	Plastic screen/aluminum
Frame	Aluminum	Aluminum

(a) Antireflective coating

Table 2 lists some relevant material properties which it has been possible to identify. Additional information of this type would be desirable. Its acquisition may warrant special experimental work. Many of these material properties, their importance in module design and operation, and their reaction to the stresses to which modules are exposed will influence directly the nature and rate of module degradation.

TABLE 2. PROPERTIES OF MODULE MATERIALS IN THE MEAD ARRAY

	Transmittance, Reflectance, Absorptance	Phase Transition Temperatures, C	Vapor Permeation	Linear (/C) Expansion Coefficient	Mechanical Strength	Modulus N/m^2	Hardness (Abrasion Resistance)	Thermal Conductivity, cal/cm sec C	Volume Electrical Resistivity, Ω-cm	Dielectric Strength	Emissivities	Bond Strength
RTV 615 Silicone	T = 90 percent n = 1.406	-60 +204	3×10^{-6} $\frac{cc - cm}{sec\ cm^2 - cm\ Hg}$	270×10^{-6}	Tensile 5.6 kg/cm^2 Tear 4.5 kg/cm		45 Shore A Dur	4×10^{-4}	1×10^{15}	500 V/mil		
Ta_2O_5	n = 2.15 (0.4 – 14 μm)	1470 (decomposes)		0.55×10^{-6}			NR	NA	NA			
SIO_x	n = 1.5 – 2.0 (0.4 – 1.1 μm)	1610-1710		7.0×10^{-6} (SiO_2)			NR	0.003 (SiO_2)	$10^9 - 10^{14}$			
Ti (PVD)	NR	1675 (melt)		8.8×10^{-6}	NR	1.27 x 10''	NR	0.05	90×10^{-6}	NR	NR	
Pd (PVD)	NR	1549 (melt)		11.6×10^{-6}	NR	1.2 x 10''	NR	0.18	11×10^{-6}	NR	NR	
Ag (PVD)		961 (melt)		19.5×10^{-6}			NR	1.0	1×10^{-6}	NR	0.01	
Cu (bulk)		1083 (melt)	NR	17.5×10^{-6}		1.2 x 10''	NR	0.91	2×10^{-6}	NR	0.15 (0.6)	
Pb-Sn (40-60)		183		23.5×10^{-6}			NR	0.13	15×10^{-6}	NR		
Ni (electro-less)	NR	1455 (melt)		12×10^{-6}	NR	1.65 x 10''	NR	0.14	8×10^{-6}	NR	0.04	
Polyester/ glass fiber	T = 0 percent	94 (?)	0.15 percent/day (absorption)	20×10^{-6}	0.083×10^9 N/m^2	6.9-8.3 $\times 10^9$		2.86×10^{-4}	$10^2 - 10^{14}$	150–400 V/mil		Good to rough surface, poor to polished metal
Plastic screen			NR		NR		NR					
Aluminum (sheet)	T = 0 percent	660 (melt)	Low	23.6×10^{-6}	0.28×10^9 N/m^2	9.6×10^{10}		0.50	4×10^{-6}		0.02-0.08	
Silicon	T = 0 percent n = 3.5 (1.35 μm) Ref = 30 percent (2 – 30 μm)	1415 (melt)	NR	3.2×10^{-6}	2-3 $\times 10^8$ N/m^2	1.12×10^{11}	NR	0.20		30 (V/μm)	0.7	

NR = Not relevant.

COLLECTION AND ASSESSMENT OF AVAILABLE MODULE AND MATERIAL PERFORMANCE DATA

In developing a detailed test plan for predicting service life of commercial modules, it is important to use information available on the performance of modules and materials of the types of interest as a function of time and exposure to relevant stresses, both at normal stress levels and at abnormal levels if they have been used. This information provides insight into the modes of degradation most likely to play a significant role in the ultimate failure of a module and, thus, valuable inputs to test design considerations. Although information from the Mead, Nebraska site is most relevant to this study, experience with the Mead array encompasses only approximately 2 years. Therefore, other sources of information have been used. Information has been obtained through site visits to Mead and NASA-LeRC; discussions with appropriate staff at MIT-Lincoln Laboratory, JPL, Rockwell Science Center, and Clemson University; study of contractor reports and literature, and review of JPL problem failure reports.

The following sections relating to the various module "components" contain remarks and observations based on the performance and degradation data presently available.

Performance and Degradation of Elements in the Optical Path to Cell

Dirt

The effects and types of dirt on the cover surface vary enormously with the site. Comparatively, dirt from the Mead site is more easily cleaned from the modules than that from industrial sites. Among the various sites examined, power decreases range from about 5 to 40 percent per year. Dirt collection is greatest for silicone covers; glass and FEP Teflon show the least effects. As noted previously, dirt collection is not considered to be one of the critical degradation modes for this array and is not included in the test design for this application. It is, however, an important effect and merits continued study.

Change in η, and α for Surface Layer

Little evidence was found of any affected surface layer of the cover material (below the dirt). That is, changes in the refractive index, η, and the absorptivity, α, have not shown up yet as substantive degradative modes.

Increase in α of Bulk Cover

Small changes have occurred thus far; some yellowing of silicones might be present.

Delamination of Cover from Cell

Delamination is a recurrent problem at all sites, although it is less of a problem at the cover-to-cell (silicone-to-cell) interface than at other interfaces. Long-term effects of delamination are unknown.

Performance and Degradation of the Cells

"Bleaching" of Antireflective (AR) Coating

Considerable qualitative evidence suggests that the reflectivity of the AR coating changes with module exposure time. SiO_x coatings (Sensor Technology modules) show larger effects than Ta_2O_5 coatings (Solarex modules).

Increase in Series Resistance (R_S)

The effects of increased series resistance, R_S, have not been separately identified in the field data. Laboratory data suggest that this effect can be serious (especially with silver silk-screened metallization, not used in the Mead modules).

Decrease in Shunt Resistance (R_{SH})

Likewise, the effects of shunt resistance have not been separately identified using field data. Individual cell measurements on one module which had been at Mead for 6 months showed that 2 out of 44 cells were shorted. When the shorts occurred is unknown. They might have existed at the time of module fabrication.

Cell Cracking

Cell breakage has been of major importance. Its effects depend, of course, on where the cell breaks, for example, whether or not the metallization lines are broken. The majority of cracks do not break the metallization. More recent cell developments have included redundant connections, thus reducing the effects of the breakage problem.

High cell Temperature

Many instances have occurred where individual cell temperatures have been significantly higher than the average. Nonuniformity in the IV characteristics among the cells making up a module can account for this in part and might be a potentially serious problem.

Performance and Degradation of the Interconnects

Corrosion

Evidence exists that corrosion has occurred within many modules. Whether these effects stem from residual corrosive species in the module and/or from direct corrosion owing to the presence of species introduced during normal exposure is as yet unknown.

Breakage

Interconnect separation has occurred in the field. Poor solder joints and inadequate stress relief are likely sources of this problem.

Performance and Degradation of the Substrate/Frame

No major problems having to do with power output degradation have been associated with degradation of the frame or substrates. The potential for such problems exists, however, because the substrate frame can contribute to mechanical stresses in the cells and interconnects and possibly to voltage breakdown. (It should be noted that the design of the substrate for one of the module types contains grooves that have seriously affected the performance of the module, particularly cell cracking. This design was changed in later production models. As noted here, however, the substrate and frame components have not degraded in service.)

Assessment of Performance Data

In 2 years of operation, less than 1 percent of the modules have failed at the Mead site. Failures have been primarily of the "infant mortality" type or due to catastrophic hail breakage. They are of less value analytically to this life-prediction program than those failures which occur for reasons other than manufacturing deficiencies and related shortcomings.

Taking magnitude of power output as the criterion, relatively few module failures have been observed in a 2 to 2-1/2-year period. By far the greatest single cause of output-power reduction over this period has been the surface accumulation of dirt, causing a reduction of radiation incidence upon the solar cells, although most of the loss at Mead is recoverable upon washing. The surface accumulation of dirt is clearly a significant degrader of module performance and its treatment as an aging mechanism may require special consideration for different sites.

Nevertheless, there is ample visible evidence of module changes such as cell cracking, interconnect corrosion, AR coating bleaching, delamination, and the presence of moisture in modules. The probability is very high that as exposure continues and these changes progress, some of them will reduce power output.

From among these observed or anticipated module changes, those assessed in this investigation to be the most probable contributors to performance degradation are, in approximate order of decreasing importance:

a. Increase in cell series resistance, R_S
b. Delamination of cover
c. Interconnect breakage
d. Cell cracking
e. Increase in bulk absorbtivity of the materials in the optical path to the cell
f. Interconnect corrosion.

IDENTIFICATION OF ENVIRONMENTAL STRESSES AND THEIR EXPECTED RELATIONSHIP TO MODULE CHANGES

Interactive Stresses

The potentially interactive stresses which are judged to contribute to degradation of the power output of the photovoltaic modules of interest to this test design are insolation, especially its UV components; temperature; temperature cycling; moisture; mechanical forces; and chemical contamination. Mechanical forces may give rise to several forms of stress. Among them are bending or flexure, shear in the plane of the module, and expansion forces in a direction normal to the module plane. From the standpoint of widely dispersed atmospheric contaminants such as SO_2, NO_x, and O_3, rural Nebraska is rather "clean". However, being located amidst intense agricultural activity, the array may be exposed to significant levels of ammonia, nitrates, chlorides, and perhaps other contaminants arising from fertilizers, feed lots, herbicides, and pesticides.

Tables 3, 4, and 5 display judgmental information on possible anticipated effects of various stresses on discernible module changes. The stresses are those to which modules installed at the Mead site may be expected to be exposed. The discernible module changes, with one or two exceptions, are changes observed in the field-exposed modules. These changes have not specifically been identified as causes of degradation in module power output since in most cases the specific cause-and effect relationship has not been established. Nevertheless, the occurrence of such changes in the relatively short term forces one to anticipate the occurrence of associated long-term problems with module performance.

Stong interactions among certain stresses are expected to make important contributions to some of the module changes listed in Tables 3, 4, and 5. Among those interactions which may be particularly critical are moisture-chemical contamination, temperature-moisture, and temperature-mechanical.

TABLE 3. POSSIBLE CONTRIBUTIONS OF STRESS TO DEGRADATION OF OPTICAL PATH TO CELL*

Discernible Module Change	Environmental Stresses						
	Insolation						
	Broad Band	UV	Temperature	Temperature Cycling	Moisture	Mechanical	Air or Precipitation-Borne Chemical Contamination
Increases in absorbtivity, α, of cover layers or their surfaces**	Probably small	Possibly significant in long term. May be controlled by impurities	No direct effect	No direct effect	Change in surface topography due to hail could affect reflectivity, scattering, or dirt retention	No effect	Effect of typical atmospheric contaminants probably minor. Possible effects from NH_3 and pesticide emissions
Delamination of cover from cell***	No significant effect	Photochemical reactions may degrade bonding	Indirect–see mechanical	Indirect–see mechanical	May degrade bonding	May be large through differential thermal expansion and expansion of entrapped vapor wind forces	Possible contributor to bond degradation

*Surface-collected dirt as a contributor to module opacity will be considered separately.

**It was concluded that the consequences of any reasonably expected changes in refractive index would be too small to merit consideration.

***Module integrity may be violated by the occurrence of delamination between cells, over interconnects, or at edges. The role of stresses in this form of change is generally the same as cited above. However, whereas the above case deals primarily with bonds between silicone and oxides (SiO_x or Ta_2O_5) the other case deals primarily with bonds between silicones and polyesters or between silicones and metals (interconnects). Therefrom arise some differences in detail.

TABLE 4. POSSIBLE CONTRIBUTIONS OF STRESS TO DEGRADATION OF SILICON CELLS

Discernible Module Change	Stresses: Insolation — Broad Band	Insolation — UV	Temperature	Temperature Cycling	Moisture	Mechanical	Air or Precipitation-Borne Chemical Contamination
Bleaching of AR coating	No significant effect expected	No significant effect expected	No direct effect expected	No direct effect expected	Possible significant effect from internal moisture. Greater for SiO_x than for Ta_2O_5	No significant effect expected	Facts unknown. Some effects possible
Increase in resistance of cell metallization*	Expected to be small but photomechanical processes may occur	Expected to be small but photomechanical processes may occur	Possible indirect effects through differential thermal expansion (mechanical) and corrosion (chemical)	Fatigue/ hardening effects possibly significant	Probably corrosive medium in liquid and gaseous form. Ni/Pb-Sn more vulnerable than Ti-Pd-Ag	No evidence of mechanical stress-induced problems. Merits observation	For Ag, acid-producing agents, i.e., SO_2, NO_x, Cl, important. For Pb-Sn, acids and some base-producing agents, i.e., NH_3, K, Na, important
Decrease in shunt resistance	No evidence of a contribution	No evidence of a contribution	No evident direct effect	No evident direct effect	Potential contributor as a conducting medium	Important only to extent that shunting results from cell cracking	Could contribute in presence of moisture
Cell cracking	No direct effect. Possible thermal contribution	No effect	Differential thermal expansion may contribute. Judged to be a module design problem **	No significant effect expected	Possible contribution through vaporization or freezing of entrapped moisture	Of uncertain significance	No contribution expected
High cell temperature	A consideration but no unique contribution foreseen	A consideration but no unique contribution foreseen	No direct contribution to degradation	No direct effect	No expected effect	Relevant only indirectly through cell cracking metallization debonding and delamination	No expected effect

*A primary contributor to increased cell series resistance, R_s. **Back bias of cells in module can lead to large local temperature variations.

TABLE 5. POSSIBLE CONTRIBUTIONS OF STRESS TO DEGRADATION OF CELL INTERCONNECTS

Discernible Module Change	Stresses: Insolation – Broad Band	Stresses: Insolation – UV	Stresses: Temperature	Stresses: Temperature Cycling	Stresses: Moisture	Stresses: Mechanical	Stresses: Air or Precipitation-Borne Chemical Contamination
Corrosion	No expected effect except thermal	No expected effect	Expected to be important, often through an Arrhenius-type relationship	Potentially important. High temperatures might create a dry system from an otherwise moist one.	Very important	Little expected effect	Could be very important particularly with moisture present
Breakage	No expected effect except thermal	No expected effect	Possible effect through differential thermal expansion. Self heating may occur at sites of resistance increase due to corrosion	Same as for temperature. Fatigue effects may occur	No expected effect	A possible contributor through thermal effects or from external forces (i.e., wind)	Corrosion could increase susceptibility to breakage

Potentially Noninteractive Stresses

When stresses can be declared noninteractive, even though their effects individually may be significant, they can be dealt with outside the modified factorial (multiple stress) experiment thereby reducing the complexity and cost of that experiment. In fact, justified separate treatment is one means whereby the complete factorial experiment can be modified. A few stresses have been tentatively identified as ones which can be treated separately. They are accumulated surface dirt, hail, cell back-bias, and thermal shock. They are discussed briefly in the following sections, but it is to be noted that they are not treated in the test design.

Accumulated Surface Dirt

In most, if not all, field tests, dirt accumulated in module surfaces has been the primary cause of decrease of module power output. Its degrading qualities are probably associated primarily with absorption of incident radiation. However, scattering and, to a lesser degree, reflection, may also be factors. Moreover, it is possible that environmental constituents could induce surface reactions between the silicone and available particulate contamination, thereby leading to impaired transmission. In the Mead experience, most of the decrease in power output due to dirt accumulation is restored upon cleaning of the array.

The reasonable chance that surface dirt is largely noninteractive as a stress justifies separate treatment for it. However, to the extent that this stress makes a dominant contribution to output power degradation, it may mask the presence or contribution of other operative degradation modes or may even shield the module from certain stresses contributing to other modes of degradation. Thus, it is conceivable that it could exhibit interactive qualities of a somewhat positive nature.

Clearly more needs to be known about surface dirt as a stress. It is vital to characterize dirt accumulation on module surfaces at the Mead site qualitatively as well as quantitatively as a function of time and local conditions; to assess the effects of periodic cleaning and the ability of modules for self-cleaning with exposure to rain, wind, and other relevant environmental factors; and to evaluate the contribution of this stress to module power output degradation. Without this information, no valid judgment can be made regarding the possible utility of this stress as an accelerating factor for test purposes or regarding its possible interactive qualities. It is understood that dirt effects are being studied by JPL and MIT-Lincoln Laboratory. Again, these effects are not included in the test design.

Hail

The possible contributions of hail to module degradation are considered to be largely confined to cell cracking (which has occurred at Mead) and to the creation of surface damage on the module. The stress appears largely noninteractive; should significant degradation occur, however, it might exhibit interactions with other stresses. For example, it might impair the "cleanability" of the surface under natural or man-applied processes, and/or it might enhance the consequences of corrosion if cells are cracked.

Cell Back-Bias

It is the authors' understanding that the acceptance of the modules used in the Mead array was based on a minimum power output under "standard" conditions. Acceptance tests were not required on individual cells. Limited experimental evidence suggests that at least some accepted modules contain one or more cells that are essentially shorted. Moreover, the maximum power point among the cells of a module varies over a significant range. Therefore, modules are likely to have cells operating in a back-biased condition. An important question is: "Will modules with back-biased cells exhibit service-life characteristics different from modules without back-biased cells?". At this stage of experience, the question is unanswered. The differences would seem to lie, in part, in the IV (current-voltage) characteristics of the back-biased cell. Clearly, the IV characteristics of the total module will be affected. As a minimum, the existence of back-biased cells in a particular module should be known in following the power output over time in any testing. The test design presented subsequently, deals only with module degradation, not the total array. It does not take back-bias cells specifically into account, but clearly, effects from this condition need further study.

Thermal Shock

Several types of environmental exposures that occur in the field are difficult and costly to simulate in laboratory tests. Conditions leading to thermal shock are an example. Of particular interest are the conditions under which the module temperature is at its highest (full sun) and the surface is suddenly cooled (by rain, for example). These conditions are only partially covered by the thermal cycling experiments included in the test design.

APPROACH TO THE ACCELERATED TEST DESIGN

As noted previously, the objective of this work is to design a test which can be carried out in two years or less and which can furnish a prediction of a service life of 20 years or more. Several fundamental considerations regarding the task are important. First, it is to be noted that one important assumption is that accelerated test conditions can be found which compress the time period by a factor of ten and at the same time cause the modules to age for the same reasons as they would under normal environments. A second consideration of particular importance is the requirement that the test design be tractable both experimentally and economically. Accelerated test design for life prediction - although old in concept - is not in a sophisticated state, especially where several stresses are operative and the device to be tested is complex. From previous discussions, it is to be noted that potential degradation modes are numerous; furthermore, it is not certain which modes dominate in the aging process. These circumstances impose important constraints on the test design. Notably, many modes must be included, but, at the same time, the number of tests has to be limited so as to keep the cost/benefit ratio to an acceptable level. This important constraint manifests itself in the mathematical formulation of the relationships between the degradation rate and the environmental and operational stresses.

General Formulation of the Test Design

Power output of the module as a function of time is chosen as the dependent variable. As noted, very little field experience exists on which to base initial estimates of life; life is taken to be the time required to incur a 50 percent loss of initial power output. The major deterioration of power output to date has been attributed to dirt collection, an effect not treated in the test design which is restricted to long-term degradation. A limited experience exists with regard to effects of selected stresses on certain types of degradation. Nevertheless, power output is judged to be the most desirable dependent variable in spite of such limited field experience.

More specifially, the dependent variable taken to be P(t)/P(0), where P(t) is the power output at time, t, under standard conditions of insolation and temperature, and P(0) is the initial power output (at t=0). The basic relationship employed is

$$\frac{P(t)}{P(0)} = [1-Kt]^{1/\beta} \quad . \tag{1}$$

K in this equation is the rate constant and is taken to be a function of the stress, S_i; β is an experimental parameter. Following the work of Simoni(*), β reflects the observations of many researchers that P(t)/P(0) is often not a linear function of time, as would be the case if β were equal to 1. Cases for β>1 are often observed; that is, for durations that are short relative to the service life, the rate of change of the property variable is less than it is toward later life. Of course, the equation can take care of the case if the opposite happens (β<1).

For reasons noted previously, the formulation of K as a function of stresses is critical to the test design. To keep the number of tests in reasonable bounds, the number of parameters to be estimated also has to be kept small. It is convenient to relate K to a product of nonthermal factors, each factor taking the value of unity when the stress associated is equal to zero. The basic form chosen is the following:

$$K = Ae^{-B/T}(1+f_1)^{a_1}(1+f_2)^{a_2}----(1+f_n)^{a_n} \quad . \tag{2}$$

where f_i represents the stress (relative humidity, for example) and a_i is an exponent which is a function of temperature; for example, $a_i = C_1 - C_2/T$, where C_1 and C_2 are constants. A and B are constants; T is the temperature. It is to be noted that this form for each factor cannot represent all that is known about the effects of each stress. For example, the corrosion rate of metals is not normally represented in this form. Usually it takes more than two parameters to represent the measured rate, and the parameters are different for each metal. Moreover, the parameters are a function of the type of corrosion exhibited

(*) Simoni, L.,"A New Approach to the Voltage-Endurance Test on Electrical Insulation",IEEE Transactions, EI-8, No. 3, 1973 (normal, crack corrosion, etc.). Nevertheless, the form used can take care of the fact that corrosion rate is a function of concentration of corrosive elements and depends (generally) exponentially on temperature. Thus, the choice of form is a compromise between keeping the number of tests small and adequately representing what is known about the form of the behavior. These same considerations can be applied to the behavior of all stresses considered, although as will be evident in the test design given subsequently, correction factors must be added to represent engineering judgments.

Center-Point Test Conditions

As described in the methodology of the report on the preceding study (RS4), designing the accelerated test requires that a priori estimates be made of the effects on power output of each stress. This is necessary for two main reasons. The first one is that the stress magnitudes should be chosen so that all the tests are completed in two years. The second is that estimates of the effects make possible an appropriate distribution of "failure" times, and optimum distributions of specimens among the test conditions can be realized to reduce the variance of the life prediction under normal stresses (see RS4).

But these a priori estimates of the parameters are just that - estimates. Barring the unexpected circumstances that all estimates are correct, the distribution of "failure" times will not be optimal; additionally, the longest failure time might be longer than two years (or might be shorter). Of course, such events do not negate the tests - only the test times will not be within the originally desired limits. If the failure time under a specified set of conditions (say the center-point conditions) is determined experimentally to be an unacceptable time, judgments can be made early to reset the test conditions among the tests to better distribute the failure times. The test conditions can be made more or less severe, as needed, according to the model formulated. This need not be done, of course; it is an option of the experimenter. Ideally, the center-point conditions are chosen to provide an intermediate time to failure on a logarithmic scale.

The concept of the center-point condition serves an additional purpose by making possible the assessment of each set of test conditions relative to the center-point conditions. A resulting severity hierarchical tree (see RS4) is set up, forcing the test designer to consider each stress in relationship to the magnitude of all other stresses. Running the center-point condition first is not a necessity; it is an option before committing effort to all other tests.

Partition of Tests Within the Total Test Design

In the field, modules are exposed to many stresses simultaneously. Simulation of this multistress exposure in an accelerated test ideally would include all stresses within a given set of test conditions. Such a simulation is not realistic experimentally. Because the test design is based on exposures of modules of the types used at Mead, suitable light sources to illuminate these modules within an environmental chamber are desirable. However, developing such sources would be a very costly undertaking. Because of such limitations, the total test design is broken down into three parts. Described subsequently, the three parts consist of a constant-temperature set of tests, a cyclic-temperature set, and a set based on ultraviolet radiation (UV). The first two parts employ full-sized modules; the last employs small (i.e., single-cell) samples. The first two are fully integrated designs in that constant-temperature parameters are first estimated, and these are used in the cyclic-temperature design. A full integration of the UV part of the total design is not practical at this point and has not been attempted. Table 6 lists the principal stresses in each part of the design.

Stress Limits on the Test Conditions

A critical requirement on any accelerated test for service life prediction is that the laboratory test conditions age the modules for the same reason as field conditions do. This requirement dictates the limit of the "accelerating factor" that can be achieved. The major limitation imposed on the test design is a temperature maximum of 100 C. None of the module materials is threatened seriously by a change in failure mode at this temperature, although there is an indication that silicones might

TABLE 6. VARIABLES OF EACH PART OF THE TEST DESIGN

Test Part	Variables
Constant-Temperature[a]	Temperature, relative humidity, [SO_2]
Cyclic-Temperature[a]	Temperature, temperature excursion, relative humidity, [SO_2]
UV	UV(0.3 - 0.4 μm), temperature, relative humidity

(a) A constant forward-bias current on the modules is included in these tests, along with the application of a static electric field between the output terminal and module frame.

age by a different mode in the presence of steam(*). In the authors' judgment, deterioration of bulk properties of materials will not be the effect which determines these modules' service life. Rather deterioration of the interfaces - and subsequent resulting degradation - will likely lead to the earliest failures. Accordingly, the a priori judgment of the activation energies in the Arrhenius and Eyring factors were chosen to reflect this judgment, although the experimentally determined values will constitute the final evaluation.

Another limitation of note in the stress conditions of the test design concerns illumination. As with UV radiation, it is not experimentally practical to expose the modules to radiation across the AM2 spectrum while they are exposed to the other stress conditions. Yet, a current passing through the modules under exposure is judged to be potentially significant, especially under corrosive conditions. To simulate this current, the test design calls for a forward-bias current from an external power source equal to a 1-sun current under AM2 illumination. This condition biases the cell as under sun illumination, but the current will flow in the opposite direction.

The final limitation concerns the use of a corrosive species in the atmosphere. Former discussions in this report dealt with the environmental pollutants at the array site. Detailed information is not available about the identity and concentration of pollutants. Rather than complicate unnecessarily the experimental difficulties, it was judged to be prudent to use one pollutant, SO_2, in the experimental environment which acts as a surrogate pollutant for all corrosive species. The concentration is held as constant as feasible throughout a given test, whether under constant temperature or temperature cycling.

(*) Noll, Walter, Chemistry and Technology of Silicones, Academic Press, New York (1968)

ACCELERATED TEST DESIGN FOR MEAD, NEBRASKA

The test design consists of three separate sets of tests; constant-temperature tests, cyclic-temperature tests, and ultraviolet radiation (UV) tests. The constant- and cyclic-temperature tests are integrated designs; the constant-temperature tests are run to estimate the "static" parameters; the cyclic-temperature tests are run at the same temperatures as those used in the constant-temperature tests, but periodically temperature excursions are introduced and varied in magnitude in separate test conditions. Each set of these three sets of tests is next described.

Constant-Temperature Tests

Module Types to be Employed

The module types preferred for this test are those actually used in the Mead array, viz., Block-II modules fabricated by Solarex and Sensor Technology. Alternatively, miniature modules could be used, provided they contain at least three rows and three columns of cells, the materials and fabrication conditions are identical to the normal-sized modules, and all cells are connected in series.

Functional Relationship Between Rate Constant and Stresses

Temperature (constant under a given test condition), relative humidity, and a concentration of SO_2 are the chosen stresses for this test. Basically, an Eyring-type equation is used to represent the relationship between the rate constant, K, in reciprocal months, and the stresses:

$$K = Ae^{-B/T}(1+R)^{C-D/T}(1+S/S_0)^{E-F/T} \quad ; \qquad (3)$$

A is a parameter with dimensions of reciprocal months, R is the relative humidity, and S is the concentration of SO_2 in parts per million (ppm). S_0 is a constant, viz., 1 ppm; B, D, and F are constants with dimensions of temperature. C and E are dimensionless constants. This formulation was chosen to describe the effect of these stresses and at the same time keep the number of tests to an acceptable minimum. The Eyring-type equation has been modified so that each of the factors $(1+R)^{C-D/T}$ and $(1+S/S_0)^{E-F/T}$ are equal to 1 when R and S are zero, respectively.

To set the test conditions, a priori estimates of the parameters were made. These estimates are given in Table 7. Estimates of C and D are based on the expected results that relative humidity has rather small effects at values $\leq .40$ and larger effects at higher values. Estimates of E and F reflect the expected results that at temperatures somewhat above room temperature the contribution of $[SO_2]$ to K varies approximately linearly with concentration and exponentially with temperature. The value of B reflects a thermal activation energy of approximately 0.3 electron volts (7 kilocalories per gram mole). Selection of such a value indicates a judgment that bulk material changes are less likely to cause failure than interface degradation.

Test Conditions for Constant-Temperature Design

Table 8 shows the accelerated test design for the constant-temperature set of tests. The left column indicates that nine different test conditions are to be used. Test Condition 1 represents the highest stress test and is shown to require testing of 10 modules at a temperature, T, of 95 C; relative humidity, R, of 4 percent; and sulfur dioxide concentration, S, of 1.0 ppm. The lowest stress test is shown for Test Condition 9 at (T,R,S) values of 75 C, 7 percent, and 0.3 ppm, respectively. A representation of the test design in the form of a hierarchical tree is shown in Figure 1.

Expected results of the test design are illustrated in Figure 2. The times to failure ($\ln t_F$) are indicated on the abscissa; the ordinate gives the ratio of the rate of power loss in a test to the rate at the center-point test ($\ln(K_i/K^*)$). For purposes of extrapolation to the normal conditions at the Mead site, the following data are used:

TABLE 7. ESTIMATES OF PARAMETERS FOR CONSTANT-TEMPERATURE TEST DESIGN[a]

Parameter	Value/Dimension
B	3500, °K
C	10, dimensionless
D	2330, °K
E	3.09, dimensionless
F	721, K

(a) See Equation 2.

TABLE 8. ACCELERATED TEST DESIGN FOR CONSTANT-TEMPERATURE TEST

Test No.	Test Conditions [a]			No. of Modules to be tested [b]
	Temperature, C	Relative Humidity R, percent	SO_2 Concentration, ppm	
1	95	4	1.0	10
2	95	4	0.3	10
3	95	3	1.0	10
4	95	3	0.3	10
5	85	5	0.6	16
6	75	9	1.0	10
7	75	9	0.3	10
8	75	7	1.0	10
9	75	7	0.3	10

Note: It is recommended that the tests be conducted with the module under a forward-bias current from an external power source equal to a 1-sun current under AM2 illumination, along with the application of a static electric field between the output terminal and module frame.

(a) Row 1 indicates, for example, that 10 modules are to be tested at constant conditions of temperature, relative humidity, and sulfur dioxide (95 C, 4 percent, 1.0 ppm) to determine the times required for the power output of each module to decrease to less than 50 percent of its initial power output.

(b) A total of 96 modules is required for each module design (Solarex and Sensor Technology); the 16 modules associated with the "center point" of the design is intended to allow modules to be removed for tear-down analyses (see text).

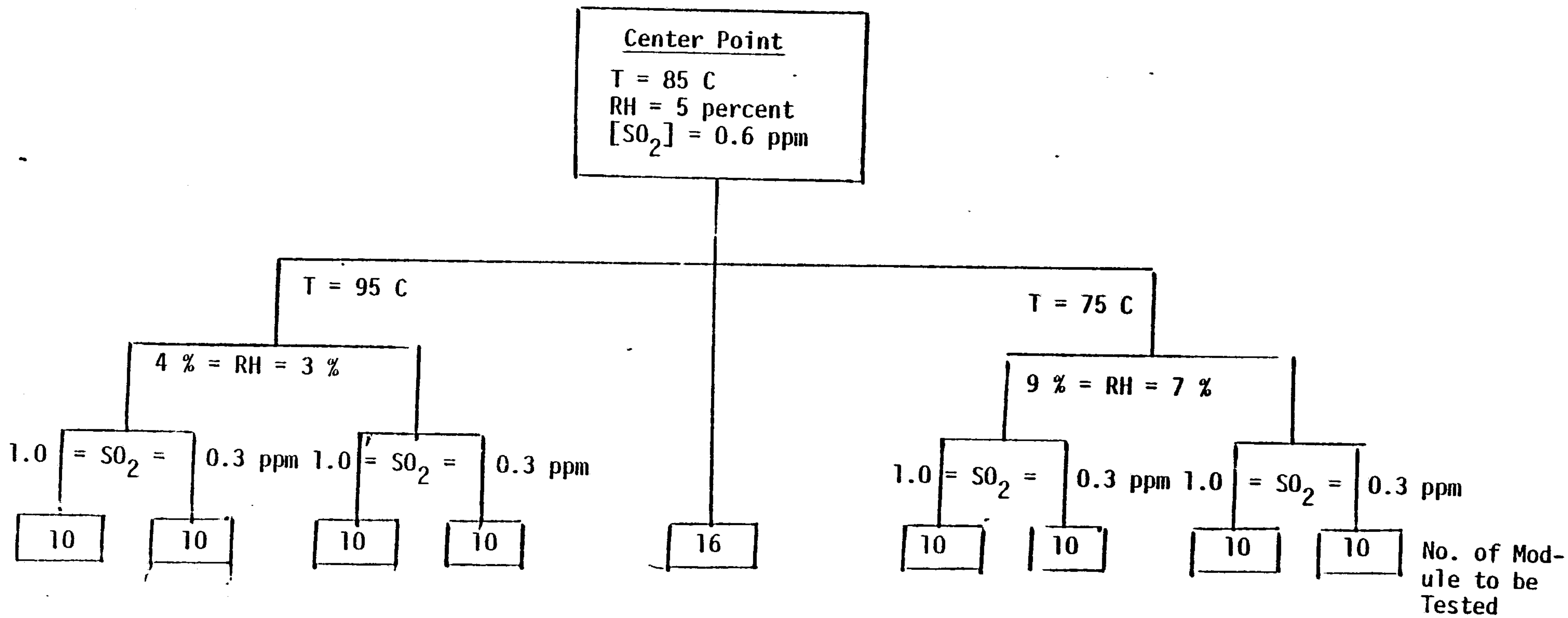

FIGURE 1. HIERARCHICAL TREE REPRESENTATION OF FACTORIAL DESIGN FOR CONSTANT TEMPERATURE ACCELERATED TESTS

See note to Table 8. Tests include an imposed forward bias current, and a static electric field applied to the module.

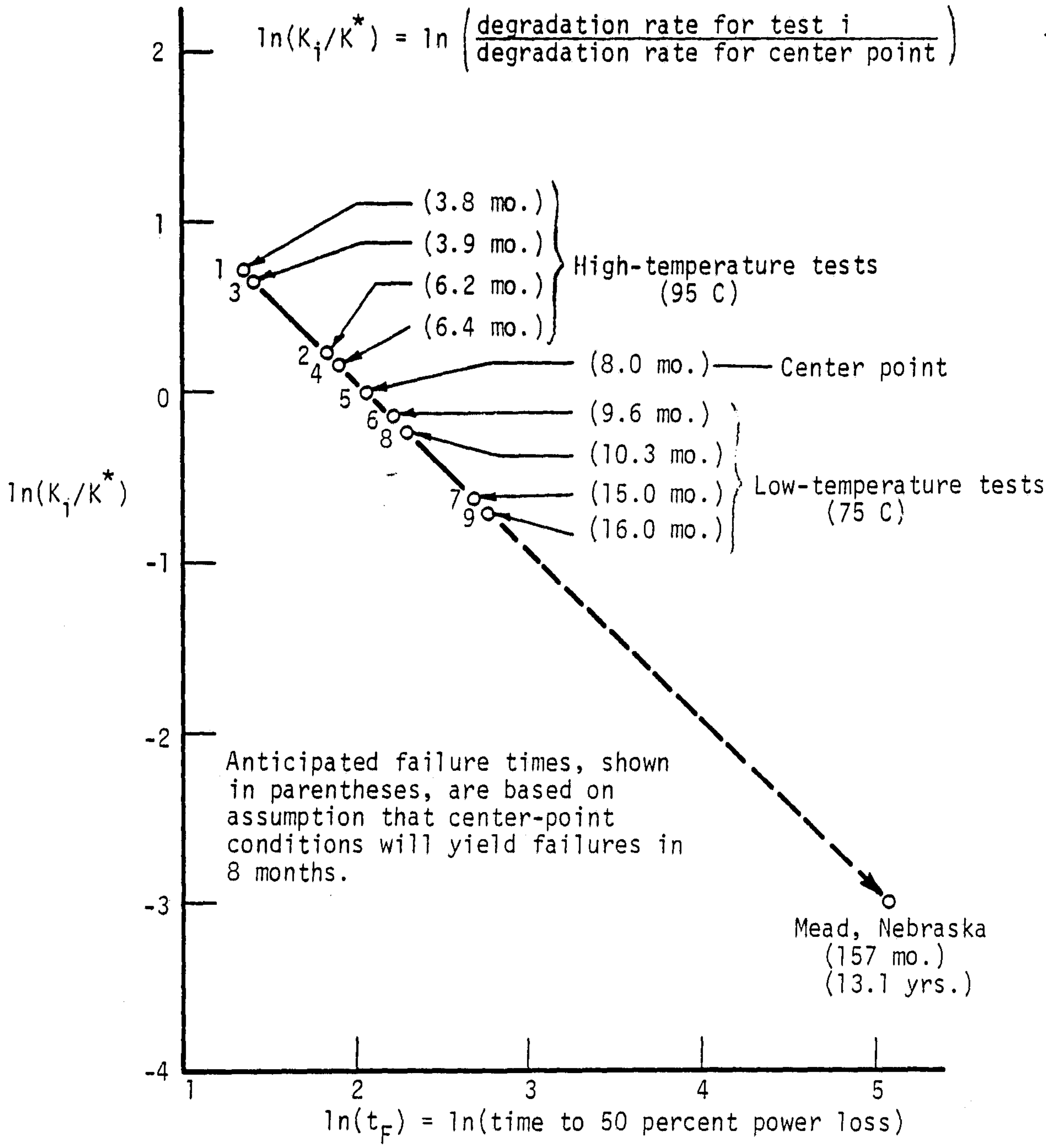

FIGURE 2. TEST DESIGN POINTS, DEGRADATION RATES, AND ESTIMATED TIMES TO 50 PERCENT POWER LOSS FOR CONSTANT-TEMPERATURE TESTS

Temperature - 11.0 C[a]

Relative humidity - 69 percent

SO_2 concentration - 5 ppb .

With these values, the test design predicts a life of 157 months at Mead, Nebraska, neglecting the degradation due to temperature cycling and UV radiation, and is based on the estimation that the average time-to-failure under the center-point conditions is 8 months.

Measurements and Measurement Schedule

Power Measurements: Method/Schedule. The power output characteristics of each module are to be determined before exposure and periodically after exposure according to the schedule given subsequently. At each measurement time, the full IV curve in the power quadrant is to be determined. From this curve, the following values are to be determined: short-circuit current, I_{sc}; open-circuit voltage, V_{oc}; maximum power, P_{max}; current, I_{max}, and voltage, V_{max}, at maximum power; fill factor, F.F.; and effective series resistance, R_S.

Power measurements are to be made under 1 sun (AM2) illumination at an air temperature of 27 C. The illumination intensity over the module should be uniform within 5 percent (3 percent would be preferable if attainable). A pulsed xenon lamp source (LAPS) is preferred as the light source; a bank of ELH lamps is acceptable. A standard cell, appropriate for each manufacturer, calibrated by NASA LeRC, is to be used for each measurement to determine light level.

Measurements of additional IV characteristics are recommended. Because the dominant degradation modes of the modules are uncertain - especially as they relate to power degradation - it is recommended that the dark IV characteristics under forward bias be measured according to the same schedule used for the illuminated characteristics. Limited experience has shown that the modules fabricated by Sensor Technology exhibit IV characteristics that can be fitted rather well to the two-

(a) NOAA, Environmental Data Service, National Climatic Center, Asheville, N.C. This value is the average of the annual average temperature for three surrounding locations to Mead (Lincoln, Omaha, and Columbus, NE).

diode model often used to describe single-cell behavior[a]. From these fitted characteristics, the following "effective" parameters should be measured or calculated: the two diode factors, the shunt resistance, the two saturation currents (I_{01}, I_{02}). Whether the two-diode model fits the Solarex modules has not been determined. Other models also need to be examined.

The measurement schedule to be followed throughout the test will depend to some extent on the expected time to failure of the particular test and the time rate of change on the power output. The experimenter should be guided by the need for short times between measurements for (1) the first period of the test to establish the measurement precision and unavoidable noise in the results, and (2) the period of the test when the power output is changing rapidly. In the intermediate periods, the measurement rate can be relaxed. Subject to modifications based on these considerations, the following schedule is recommended:

Time Period	Time Between Measurements, Hours
First month	72
Second month	120
Third month	168
Fourth month	168
'	168
etc	168
'	168
Near-failure period [(P(t)/P(0) = 0.5]	120

Especially for the high-temperature, high-humidity tests, the times to failure are expected to be 4 months or less. Thus, the modifications suggested would be operative.

Other Observations: Methods/Schedule. As noted previously, the dependent variable of primary interest is power output. In designing a test under ideal conditions, the power output would be equated in an appropriate functional form to the contribution of each mechanistic degradation

(a) See M. Wolf and H. Rauschenback, Advanced Energy Conversion, Vol. 3, pp 455-459, April-June 1963.

reaction at the molecular level. Such functional forms are yet unknown. To help provide information for future test designs, as well as for improving module design by increasing knowledge about major mechanisms operating, observations other than power output are recommended. A priori, it is not possible to enumerate a complete list of observations desired. Based upon limited field experience and estimates of those molecular degradation mechanisms that might occur, the following are recommended observations to be made, and the results to be recorded, on the same schedule given previously for the power measurements:

Component or Interface	Observations
1. Delaminations	Site, size, number
2. Silicone top cover	Note any appearance of color
3. Cells	Count number of cracked cells, site of crack; note appearance of AR coating (bleaching and change in reflectance)
4. Interconnects	Note any evidence of corrosion and estimate extent
5. Surfaces and volumes of all components	Measure current between one terminal and the frame at 1000 V d-c under standard room conditions; note any surface or volume damage owing to electrical breakdown or surface currents; record site and visual extent of damage.

These "other observations" are to be augmented by tear-down analysis. By this is meant that detailed laboratory analyses of degradation reactions are to be performed, either destructively or non-destructively, on the modules as they fail during the test and on modules which are included in the test specifically for such analyses. On modules which fail during a test, major emphasis is to be placed on analyzing the apparent cause of failure (broken interconnect, high series resistance, for examples). On other modules, the emphasis is to be placed on measuring the rates of long-term degradation reactions. Correlations of these rates with previously measured power outputs are to be carried out.

The measurements made and the measurement methods used will depend on the test results to some extent. A guide to appropriate methods is given in our previous reports identified earlier as RS5. Some specific measurements or evaluations are judged, a priori, to be important:

1) The transmittance of the silicone top cover. Sample slabs are to be removed from above a cell. Special attention is to be given to the wavelength range from 0.3 to 3 μm.

2) The reflectance of the AR coating. The top cover (silicone) above five cells picked at random in a particular module is to be removed and the reflectance measured between 0.3 and 1.1 μm.

3) The IV characteristics of individual cells. The five cells in 2), above, are to be used (without the silicone top cover). Complete characteristics are to be determined under 1 sun illumination at 27 C.

4) Corrosion products composition. Where corrosion is apparent, identify both metallic and non metallic components by microprobe analysis and by wet chemistry if appropriate. The goal is to determine which metals (cell metallization/interconnects) are acting as the anode and cathode and which material is acting as the electrolyte. Determining if the mode of corrosion is of the pitting type is particularly important.

The schedule for tear-down analysis is based upon the expected time to failure of the center-point test (Test 5). Six modules are added to this test condition specifically for these analyses. One of these modules is to be removed and analyzed after one month exposure, a second after two months, a third after three months, and a fourth at the end of four months. All other modules are to be tested until the power output decreases to 50 percent of the initial power output or until two years of testing have occurred.

Data Analysis

For each test condition, the analysis of the power output ratios obtained from the accelerated tests should begin by optaining an estimate of $\hat{\beta}$. An initial estimate may be obtained by using various trial values to identify a value of $\hat{\beta}$ that yields an approximate linear relation between $[P(t)/P(0)]^{\hat{\beta}}$ and t. If an approximately linear relation is found, more refined regression procedures should be used to determine the value of β that best linearizes the relation[a]. For each test condition, the slopes of the approximating straight lines will provide estimates of the nine degradation rates K(T,R,S).

The degradation rates may be analyzed using statistical procedures employed for analysis of factorial experiments. It is expected that a separate analysis will be required for the high-temperature tests and the low-temperature tests. These analyses will provide standard estimates of the statistical "main effects" and "interactions" to be associated with temperatures, relative humidity, and $[SO_2]$ and their effects on the degradation of power output over time. Selected ratios of degradation rates will provide a basis for estimating the model parameters, A, B, E, F, and G. These estimates will serve to revise those used in deriving the experimental design. In general, the analysis of the data should include an effort to verify or refute the Eyring and Simoni models used to design the accelerated tests.

Cyclic-Temperature Tests

Module Types to be Employed

These should be the same as described under the previous section on the constant-temperature tests.

(a) Data analysis techniques are explored in Report ERDA/JPL-954328-77/1, "Methodology for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays".

Functional Relationship Between Rate Constant and Stresses for Cyclic-Temperature Tests

The following model is assumed to approximate the degradation rate subjected to cyclic-temperature stress as well as other stresses common to the constant-temperature tests

$$K = Af_T f_R f_M f_S f_\omega \quad ,$$

where the factors f_T, ... f_ω are associated with decreases in power output due to effects of temperature, T; relative humidity, R; mechanical stresses, M (due to differences between the interface bonding temperatures and the test temperature); sulfur dioxide concentration, S; and effects due to temperature excursions, ω. These factors are considered to serve as correction factors that relate the degradation rate under some specified stress condition to the degradation rate that corresponds to the stress conditions associated with the Center Point of the test design. The mathematical form of each of these factors is tailored to represent the underlying physical phenomena.

An Arrhenius form is used for f_T:

$$f_T = e^{-B/T} \quad ,$$

where B denotes a constant parameter, and T denotes temperature.

The effect of relative humidity is represented by

$$f_R = \left\{ 1 + R_0 e^{C_0\left(\frac{1}{T_C} - \frac{1}{T_0}\right)} \right\}^{C-D/T}$$

The second term in the bracket corrects the relative humidity as a function of temperature, given a specified relative humidity at T_0. C and D are constant parameters.

Temperature-excursion effects are represented by

$$f_M = \left\{ \frac{e^{G_1\left(\frac{1}{T} - \frac{1}{T_{b'}}\right)} + e^{-G_2\left(\frac{1}{T} - \frac{1}{T_{b'}}\right)}}{D_0} \right\} e^{J_{\Delta\tau}} \quad .$$

The first factor (in brackets) reflects the stresses arising out of differences in expansion coefficients of bonded materials. The constants D_0 and $T_{b'}$, G_1, and G_2 are chosen to give the estimated magnitude of these "fatigue effects", as well as to reflect the judgment that materials fatigue more in tension than in compression (fatigue cracking). The factor $e^{J\Delta\tau}$ estimates the effects of the magnitude of the temperature excursions, $\Delta\tau$, where J is a constant.

The effects of $[SO_2]$ are represented by

$$f_s = (1+S/S_o)^{E-F/T}$$, where the symbolism is the same as in the constant-temperature tests.

The frequency of temperature excursions is represented by

$$f_\omega = (1+\omega/\omega_o)^{P-Q/T} \quad ,$$

where ω is the frequency and P and Q are constant parameters.

In the constant-temperature tests, T is taken to be a specified constant and ω is taken to be zero; in the cyclic temperature tests, reciprocal temperature is considered to be a sinusoidal function of time:

$$T^{-1}(t) = \tau + \Delta\tau \sin(\omega t) \quad ,$$

where

$$\tau = (1/2) \left(\frac{1}{T'} + \frac{1}{T''}\right) \quad ,$$

where T' and T" denote the minimum and maximum temperatures associated with the temperature cycle.

A computation algorithm was written for a Hewlett-Packard 67 in order to evaluate K/A over a wide range of possible test conditions using both constant and cyclic temperature profiles. Numerical values were assumed for the required parameters to obtain results consistent with known physical relationships. The test conditions recommended below were obtained by examining the results of these parametric studies. Estimated values of the parameters are given in Table 9.

Test Conditions for Cyclic-Temperature Tests

Table 10 lists the test conditions for the 17 tests making up this portion of the test design. Note that $[SO_2]$ is held constant at the values denoted in Column 3. The number of modules to be tested are given

TABLE 9. ESTIMATED PARAMETER VALUES FOR MODEL OF DEGRADATION RATES FOR CYCLIC-TEMPERATURE TESTS

Parameter	Value/Dimensions
B	3500, ^oK
(R_o, C_o, T_c)	(85 percent, 5280 ^oK, 300.2 ^oK (75 percent, 5303 ^oK, 298.1 ^oK (65 percent, 5287 ^oK, 295.7 ^oK (21 percent, 5375 ^oK, 278.5 ^oK
C	10, dimensionless
D	2330, ^oK
G_1	864.6, ^oK
G_2	4075.1, ^oK
T_b'	331.0, ^oK
D_o	1.59, dimensionless
J	530. , ^oK
S_o	1.0, ppm
E	3.09, dimensionless
F	721. , ^oK
ω_o	12π, radians
P	1.59, dimensionless
Q	100 , ^oK

TABLE 10. ACCELERATED TEST DESIGN FOR CYCLIC-TEMPERATURE TESTS

Test No.	Test Conditions: Relative Humidity, percent[a]	$[SO_2]$ ppm	Temperature, C[b]: Constant	Duration, hours	Cyclic, one hour	No. of Modules to be Tested
1	85	1.0	95	2	(95, -15)	10
2	85	1.0	95	5	(95, -15)	10
3	65	1.0	95	2	(95, -15)	10
4	65	1.0	95	5	(95, -15)	10
5	85	0.3	95	2	(95, -15)	10
6	85	0.3	95	5	(95, -15)	10
7	65	0.3	95	2	(95, -15)	10
8	65	0.3	95	5	(95, -15)	10
9 (C.P)	75	0.6	85	3	(85, -10)	20
10	85	1.0	75	2	(75, -5)	10
11	85	1.0	75	5	(75, -5)	10
12	65	1.0	75	2	(75, -5)	10
13	65	1.0	75	5	(75, -5)	10
14	85	0.3	75	2	(75, -5)	10
15	85	0.3	75	5	(75, -5)	10
16	65	0.3	75	2	(75, -5)	10
17	65	0.3	75	5	(75, -5)	10
						Total 216

Note: It is recommended that the tests be conducted with the module under a forward-bias current from an external power source equal to a 1-sun current under AM2 illumination, along with the application of a static electric field between the output terminal and module frame.

(a) The water vapor in the test chambers should be set to yield the indicated relative humidities at a temperature of 30 C; lower and higher temperatures will then increase or decrease the relative humidity in accord with this fixed amount of water vapor.

(b) Row 1 indicates, for example, that 10 modules are to be tested at water vapor conditions equivalent to 85 percent RH at 30 C, and an SO_2 concentration of 1.0 ppm. A constant temperature of 95 C is to be held for 2 hours, to be followed by a 1-hour temperature cycle, involving an excursion to -15 C and a return to 95 C. This temperature profile is to be repeated continuously over time until the power output of the module decreases to less than 50 percent of its initial power output.

in the right-hand column. As seen, the tests call for 216 modules of each type (Solarex and Sensor Technology).

It is further to be noted and emphasized that the design calls for holding the modules at constant temperature for a period and then subjecting them to temperature excursions. The temperature profile for each test is given in Figure 3.

In computing the anticipated degradation associated with these tests, the constant-temperature and the cyclic portions were calculated separately and were weighted according to the time spent in each portion. The results of these calculations are listed in Table 11. The time-weighted factor, $\bar{f}$, is listed in the last column. The calculated life under each test condition is given in Table 12. Finally, these rates and times to failure are plotted in Figure 4. Under temperature cycling, the predicted life at Mead is estimated to be 10.5 years.

Measurements and Measurement Schedule

The recommended measurements and their schedule are the same as those described under the section on constant-temperature tests.

Data Analysis

The statistical methods for analyzing the data from these tests are the same as described above for the constant-temperature tests.

Ultraviolet Radiation (UV) Tests

As discussed previously in this report, the UV tests are separated from the constant-temperature and cyclic-temperature tests for both technical and economic reasons. No low-cost UV sources are available with sufficient intensities to flood an area as large as the modules employed in the Mead array. Consequently, the only apparent solution to the testing problem is to employ a single light source for each individual cell. Such a solution is a relatively expensive undertaking if large numbers of cells are to be tested simultaneously. Of course, a few test setups can be used

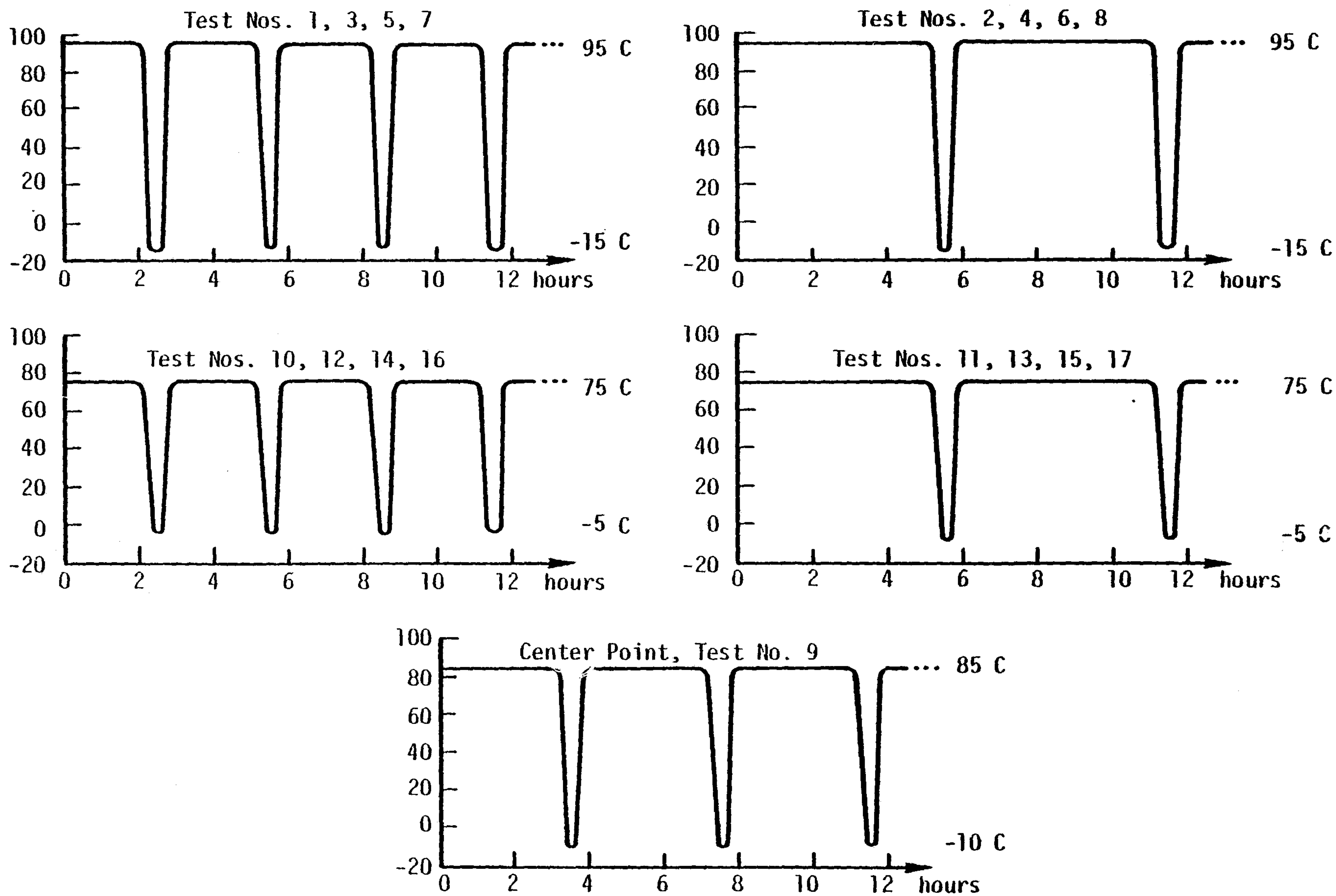

FIGURE 3. TEMPERATURE PROFILES FOR CYCLIC-TEMPERATURE TESTS

TABLE 11. CALCULATION OF CORRECTION FACTORS FOR CYCLIC-TEMPERATURE TESTS

Test No.	Relative Humidity, percent	$[SO_2]$, ppm	Temperature, C		Fraction of Time Under[(a)]		Computed Correction Factor[(b)]		Time-weighted Correction Factor, $\bar{f}$[(c)]
			Constant	Cyclic	Constant	Cyclic	Constant	Cyclic	
1	85	1.0	95	(95,–15)	2/3	1/3	495	179	353
2	85	1.0	95	(95,–15)	5/6	1/6	495	117	389
3	65	1.0	95	(95,–15)	2/3	1/3	479	167	337
4	65	1.0	95	(95,–15)	5/6	1/6	479	110	375
5	85	0.3	95	(95,–15)	2/3	1/3	304	132	230
6	85	0.3	95	(95,–15)	5/6	1/6	304	86	246
7	65	0.3	95	(95,–15)	2/3	1/3	294	123	220
8	65	0.3	95	(95,–15)	5/6	1/6	294	81	237
9 (C.P.)	75	0.6	85	(85,–10)	3/4	1/4	236	115	197
10	85	1.0	75	(75,–5)	2/3	1/3	196	163	184
11	85	1.0	75	(75,–5)	5/6	1/6	196	106	177
12	65	1.0	75	(75,–5)	2/3	1/3	184	149	172
13	65	1.0	75	(75,–5)	5/6	1/6	184	98	166
14	85	0.3	75	(75,–5)	2/3	1/3	126	120	124
15	85	0.3	75	(75,–5)	5/6	1/6	126	78	116
16	65	0.3	75	(75,–5)	2/3	1/3	118	110	115
17	65	0.3	75	(75,–5)	5/6	1/6	118	72	109
Mead[(d)]	21	0.005	11	(17,4)	0	1	12	15	15

(a) Source: See Figure 3.
(b) Source: Obtained by evaluating model (Equation 1) under constant and cyclic temperature conditions.
(c) The first row, for example, yields $\bar{f} = (495)^{2/3}(179)^{1/3} = 353$; the remaining entries are calculated in a similar manner.
(d) The corresponding entries for Mead, Nebraska are shown for comparative purposes.

TABLE 12. CALCULATION OF PREDICTED LIFE FOR CYCLIC-TEMPERATURE TESTS

Test No.	(a) $t_F = (236/\bar{f}) \cdot (8\ \text{months})$	(b) $\ln\ (K/K^*)$	(c) $\ln\ t_F$
1	5.4	0.402	1.677
2	4.9	0.499	1.580
3	5.6	0.357	1.723
4	5.0	0.464	1.616
5	8.2	-0.026	2.105
6	7.7	0.042	2.038
7	8.6	-0.070	2.150
8	8.0	0.004	2.075
9(d)	9.6	-1.181	2.260
10	10.3	-0.249	2.329
11	10.7	-0.287	2.367
12	11.0	-0.316	2.396
13	11.4	-0.352	2.432
14	15.2	-0.643	2.723
15	16.3	-0.710	2.789
16	16.4	-0.719	2.798
17	17.3	-0.772	2.852
Mead	125.9 (10.5 yr)	-2.756	4.835

(a) The value of $\bar{f}$ is obtained from Table 11. It is assumed that the constant-temperature stress conditions for the Center Point will cause a 50 percent loss in power output to occur after 8 months of testing.

(b) Obtained by computing $\ln(\bar{f}/236)$.

(c) Columns 3 and 4 are plotted as shown in Figure 4.

(d) This test represents the Center Point of the design.

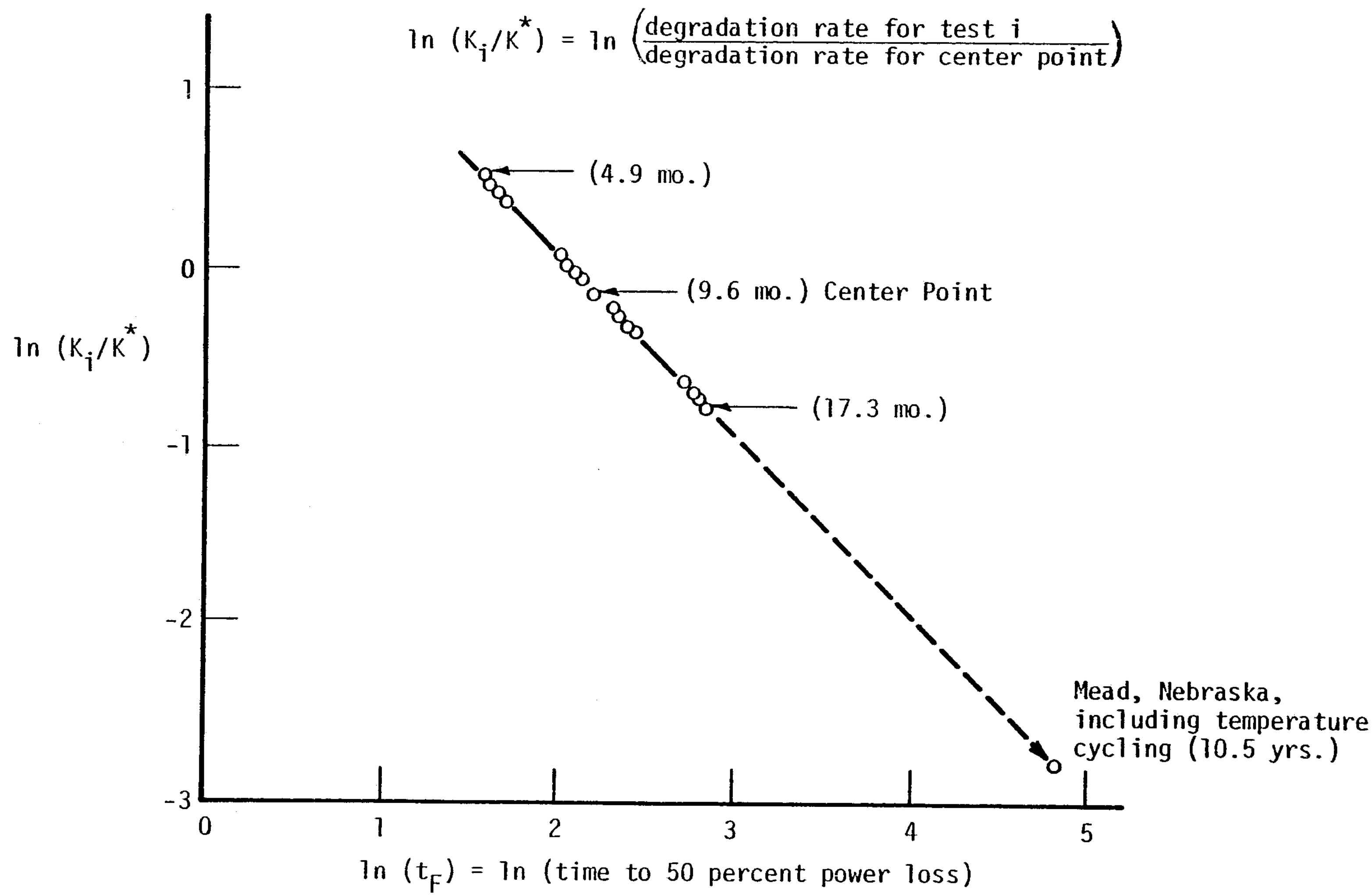

FIGURE 4. TEST DESIGN POINTS, DEGRADATION RATES, AND ANTICIPATED TIMES TO 50 PERCENT POWER LOSS FOR CYCLIC-TEMPERATURE TESTS

but the period required for testing a sufficient quantity for statistical validity is large, given that the interactive effects of several stresses are important.

Testing of individual cells also has some advantages. Changes in the power output can be followed without interactive effects among cells, an important point if some cells in the module are back-biased. Effects can more likely be ascribed to definable causes. Both destructive and nondestructive tests can be made easier and in more detail with individual cells.

Cells to be Employed

Cells used in these UV tests are to be of the same type as found in the Sensor Technology and Solarex modules. They can be made up separately or they can be cut out of the existing modules. Those cut out can be sealed around the cut edges with the same silicone products used in the original module. Electrical leads can be added and sealed with the silicone. During the tests, care must be exercised in assessing degradation attributable to the resealing of the cut edges.

Functional Relationship Between Rate Constant and Stresses for UV Tests

Stresses judged to be of major importance in the UV tests - in addition to the UV intensity - are temperature and water vapor. Other stresses must be considered - thermal cycling, for example. At this stage of the total accelerated test design, adding thermal cycling and its attendent mechanical stressing would complicate the test design unnecessarily. Insufficient information is available to detail the mechanisms of degradation. Moreover, extending the test to include another stress would add substantially to equipment cost since individual light sources are necessary.

Special attention must be given to the spectral content of the light striking the cell. The ideal source would be one which would furnish the specrral content (intensity vs wavelength) of the sun (AM 1-2). Such can be simulated reasonably well, but not easily in the laboratory at multisun intensities. The best compromise appears to be the use of light sources which have strong line spectra added to a rather strong continuum. Where there is line absorption by the materials in the light path to the cell, the use of strong line emission threatens adequate simulation of aging processes under normal environments. With the materials under consideration, narrow-line absorption is not expected between wavelengths of 300 and 400 nm, the range generally considered as the terrestrial ultraviolet. Thus, it is expected that high-intensity sources with strong line emission are acceptable, though not ideal.

With respect to the UV intensity, the variable used in the relationship between stress and UV radiation is the integral over the 300-400 nm wavelength range of the power per unit wavelength. This assignment, of course, takes into account the assumption that the aging is not wavelength sensitive. This assumption is likely not valid, but each cell is to be irradiated with identical sources so that at least relative effects can be reckoned.

The design of this test is based on the following model:

$$K = Ae^{-B/T}(1+R)^{C-D/T}(1+I/I_0)^{U-V/T} ,$$

where A is a parameter in units of reciprocal months, T denotes absolute temperature, R denotes relative humidity, and I/I_0 denotes an intensity ratio for UV radiation in the range 300 to 400 nm. The normalizing value of I_0 is taken to be 7.5 suns, so that I/I_0 varies between 15/7.5 = 2 for the tests at relatively high levels of UV radiation to 5/7.5 = 0.67 for the tests at relatively low levels of UV radiation. The assumed values for parameters B, C, D, U and V are:

B - 3500, °K
C - 10, dimensionless
D - 2300, °K
U - 3.35, dimensionless
V - 642.5, °K

<u>Light Sources</u>

Appropriate light sources for UV radiation at multisun intensities present some problems, as previously stated. Two major choices are available to the experimenter. A xenon lamp - 1 kW - gives a preferable spectrum in the 300-400 nm wavelength range; the output is essentially a continuum. Some difficulty can be experienced in obtaining sufficient intensity. A 1-kW mercury lamp can furnish the intensity desired but much of the power is in line spectra.

Discussions with light source manufacturers reveal that sufficient intensity can be obtained for a 2-inch by 2-inch beam - adequate for the Sensor Technology cell - but for the 4-inch Solarex cell the mercury lamp would have to be used.

Filters are available (from Oriel Corporation, for example) for confining the spectral range reaching the cell to the 300 to 400 nm range. The cutoff at 300 nm is sharp, as desirable. The cutoff above 400 nm is not as sharp, but the consequences are judged not to be significant. It is envisioned that the light source will either be inside of a test chamber containing an individual cell, or the light will be passed through an appropriate window in the test chamber. The test chamber temperature and the relative humidity of the enclosed atmosphere would be set and regulated according to the test conditions. Since the solar cell has some response in the 300-400 nm range, the current output should be monitored as a control and as a measure of the changes in the cell.

Test Conditions for UV Radiation, Constant Temperature, and Relative Humidity

Table 13 shows the accelerated test design for UV radiation, constant temperature, T, and relative humidity, RH. Test Number 1 represents the highest stress test and is shown to require 5 cells at T = 95 C, RH = 85 percent, and UV - 15 suns. The lowest stress test is shown for Test Number 9 at (T, R, UV) values of 50 C, 60 percent, and 5 suns, respectively.

TABLE 13. ACCELERATED TEST DESIGN FOR UV RADIATION, CONSTANT TEMPERATURE, AND RELATIVE HUMIDITY

		Test Conditions[a]		
Test No.	Temp., C	Relative Humidity, R, percent	UV Radiation, suns	Number of Cells to be Tested[b]
1	95	85	15	5
2	95	85	5	5
3	95	60	15	5
4	95	60	5	5
5 (C.P.)	71	72	9.3	10
6	50	85	15	5
7	50	85	5	5
8	50	60	15	5
9	50	60	5	5

(a) Row 1 indicates, for example, that 5 cells are to be tested at constant conditions of temperature, relative humidity, and UV radiation (95 C, 85 percent, 15 suns) to determine the "failure" times required for the power output of each cell to decrease to less than 50 percent of its initial power output.

(b) A total of 50 cells is required of each manufacturer's type, the 10 cells of each type required at the center point (Test No. 5) is intended to allow cells to be removed for teardown analyses prior to failure.

Anticipated results of the test design are illustrated in Figure 5. The times to failure ($\ln t_F$) are indicated along the abscissa; the ordinate gives the ratio of the computed rate of power loss for the i th test conditions to the computed rate for the center point test condition (Test No. 5); ($\ln(K_i/k^*)$). For purposes of extrapolation to conditions at Mead, Nebraska, the following values are used:

Temperature: 11.0 C
Relative Humidity: 69 percent
UV Radiation: 1/3 sun

With these values the model used to drive the test design predicts a life of approximately 40 years at Mead, Nebraska. This result neglects the expected effects of cyclic temperature and SO_2 considered in separate

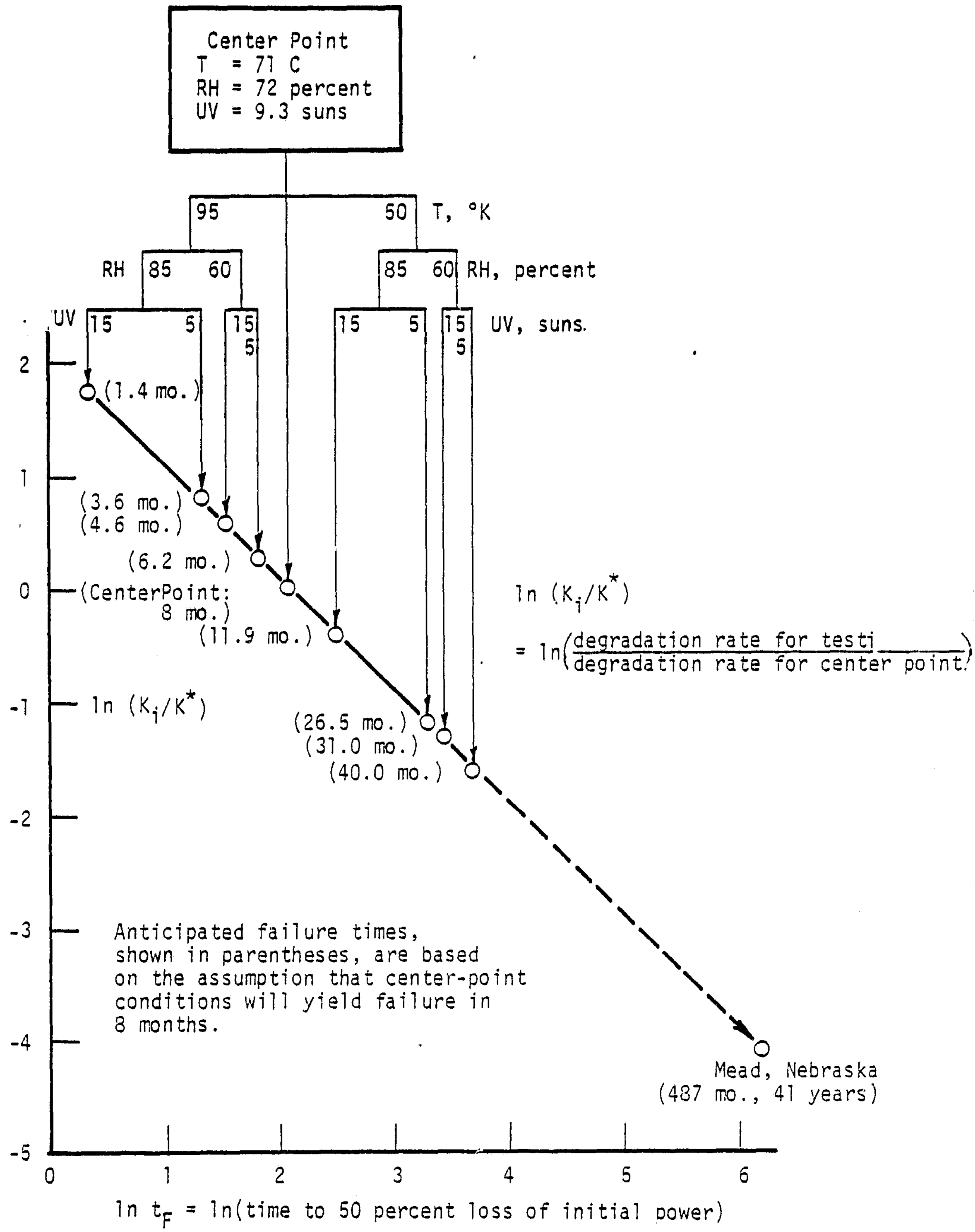

FIGURE 5. TEST DESIGN POINTS, DEGRADATION RATES, AND ESTIMATED TIMES TO 50 PERCENT POWER LOSS FOR CONSTANT-TEMPERATURE, RELATIVE-HUMIDITY, AND UV-RADIATION TESTS

accelerated tests, and is based on an assumed life of 8 months at the conditions of the center point (Test No. 5). The test conditions for each point of the curve are indicated by the hierarchical tree shown above the plotted points.

Measurements and Data Analyses for UV Tests

For the essential features of the measurements and data analyses to be carried out for the UV tests, see the appropriate sections of this report for the constant-temperature tests. The experimenter should be able to follow detail changes in the IV characteristics more closely since individual cells are being employed. Moreover, the consequences of delamination and "bleaching" of the AR coating can and should be examined closely. Further weight is put on detailed analysis in these UV tests because the number of cells to be tested is restricted to a bare minimum because of the cost of the tests.

RECOMMENDATIONS CONCERNING ACCELERATED TESTS AND JPL TOTAL TEST PLAN

In the development of a new device from conception to maturity, many tests are commonly carried out to assure both adequate initial performance and an acceptable service life. Based on discussions with JPL personnel, the authors understand that JPL has developed a testing hierarchy for photovoltaic modules. Without attempting to reproduce the terminology of the JPL hierarchy but listing them in somewhat their order of increasing development toward device (photovoltaic module) maturity, these tests (laboratory) include:

- Initial performance - normal environment
- Acceptance - short-term, overstressed environment
- Weak link - intermediate-term, highly overstressed environment
- Failure mode - intermediate-term, intermediate-stress environment
- Accelerated - life prediction paramount

Note that the last test in the list, the accelerated test, generally is carried out, if at all, when the device is developed to a reasonable state of maturity; that is, after most other tests have been completed. For the photovoltaic module, the other tests have not been completed but they are in various states of completion for various module designs and materials. Moreover, photovoltaic module designs are not in a state of maturity. These circumstances would mitigate against running a full-scale accelerating test at this time. On the other hand, the economics of the modules require a long service life - in the neighborhood of 20 years. Estimating the service life early, then, becomes of critical importance, even in light of a lack of module maturity and the lack of the identification of long-term failure modes. The authors have undertaken the development of an accelerated test for life prediction under these circumstances which lead to the practical necessity for considerable simplification of the total test design and to certain recommendations for the near term, particularly with regard to testing of the models employed.

Recommendation I: Center-Point Testing

As discussed previously in this report, the models used for expressing the rate constant, K, in terms of the stresses and their magnitudes, were chosen on the basis of the known aging mechanisms for possible failure modes and, at the same time, on the basis of realizing as simple a relationship as can adequately describe the power response of the module under the stresses used. A simple relationship requires less testing. This point is important because accelerated testing is expensive. On the other hand, the testing matrix for the three-part test employs only three levels of stresses: a "high", a "low", and a "center point". Requiring few levels puts a large burden on choosing an appropriate model. These considerations lead to the first recommendation:

> *Carry out the center-point conditions for each of the three tests.*

These actions carried out prior to a commitment of a full-scale accelerated test will serve the following purposes:

1. The resulting data will serve model evaluation studies recommended in later paragraphs.
2. The results will identify potential degradation modes, both with respect to power output and other parameters. With failure modes identified, simplifying modifications of the test design may be possible.
3. The tests can be carried out in a reasonable time since the center-point conditions are rather stressful.
4. With failure times identified at the center-point conditions, the stress levels for the remainder of the tests could be appropriately modified.

Recommendation II: Model Evaluation

Two of the main and interdependent features of the model, again, are: 1) simplicity, so as to require a minimum number of tests for economic viability and, 2) the concept of capturing the interactive features among the stresses through temperature dependence of the effect of each nonthermal stress. Because the test design is essentially a minimum one in terms of the number of tests required, the validation of the model will be realized only if all the tests are run and appropriate parameters calculated to fit the resulting data. If the model does not fit the data satisfactorily, the test results are not wasted; additional tests would be required as dictated by a more complex model. A significant step in the validation of the model, however, can be realized by running the most stressful tests early in the program, perhaps simultaneously with the center-point tests. So the recommendation is

> *Carry out the most stressful tests for the cyclic-temperature tests.*

The test results from this test would serve the following purposes:

1. Test results will be obtained quickly.
2. One can determine early if failure modes are the same as the center-point tests. That is, are the most stressful tests causing degradation for the same reasons as those obtained in lower stresses? If so, the high-stress conditions can be modified early.
3. One can estimate the effects of temperature on the main effects of nonthermal stresses, even though as noted previously, the interactions could not be fully realized.
4. Temperature cycling is judged to make an important contribution to module degradation.