ENGINEERING SCIENCES AREA AND MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

R.G. Ross, Jr., and L.D. Runkle, Chairmen

Presentations from the Engineering Sciences Area and Module Performance and Failure Analysis Area were offered in a joint technology session; summaries of the presentations are given below.

C. C. Gonzalez (JPL) presented an update of photovoltaic-array/power-conditioner interface studies. The objective of these studies is to characterize flat-plate arrays by determining significant array operating parameters such as optimal operating voltage. The characterization was obtained by calculating the effect of array/power-conditioner interface parameters on system annual energy production by performing an hour-by-hour array energy simulation using SOLMET weather tapes. The update included correlations of previously reported results with weather atlas data and additional sensitivity studies including effects of array test angle. Also discussed was the effect of power-conditioner efficiency on array annual power production.

George Hart of the Massachusetts Institute of Technology (MIT) described an experiment conducted at the MIT Lincoln Laboratories (MIT-LL) Northeast Residential Experiment Station (NE RES) by MIT-LL and JPL to evaluate different operating-point strategies, such as constant voltage and pilot cells, and to determine array energy losses when the array is operated off the maximum power point. Initial results over a test period of three and a half weeks showed a 2% energy loss when the array is operated at a fixed voltage.

Charles Cox of MIT-LL reviewed degraded-array studies conducted at NE RES that used a range of simulated common types of degraded I-V curves. The additional amount of energy lost at fixed array voltages was compared with outputs from an ideal maximum-power tracker. In a wide variety of degraded arrays the studies found insignificant increases in annual energy losses in tracking arrays.

R. W. Weaver (JPL) described the instrumentation installed at the JPL field-test site to obtain the irradiance data. These include precision spectral pyranometers, normal-incidence pyrheliometers, filtered radiometers, LiCor pyranometers and assorted reference cells. These instruments are appropriately mounted on a sun tracker, horizontally or tilted at 34 degrees. Data is taken every five minutes from sunup to sundown, and the turbidity coefficient, water vapor content and air mass are calculated. It was noted that the turbidity coefficient is a good indicator of the diffuse radiation fraction in the normal plane, but gives poor correlation with the ratio of total horizontal to total tilted irradiance.

C. H. Seaman (JPL) described experiments using an optical filter to adjust the spectral irradiance of the large-area pulsed solar simulator (LAPSS) to AM1.5. A "round-robin" set of intercomparison tests using four different reference cells with matched and unmatched red-blue ratios and using the LAPSS both with and without the Schott GG-4 filter produced the following
conclusions: the red-blue ratio is not a satisfactory criterion for matching reference cells with solar modules for power measurements, and if the LAPSS is used with a filter adjusting the spectral irradiance to approximate AM1.5, then the reference cell need not be matched spectrally with the module.

A. H. Wilson (JPL) reviewed contractor and in-house activity associated with residential-array research. A roof-mounted support structure, designed as a research model and fabricated at JPL, was reviewed and displayed in the PTM lobby. Features of the model were presented, including its lightweight non-conductive frame, simplified configuration for module installation and removal, and an electrical system design consonant with proposed 1984 National Electrical Code requirements. The model will aid JPL efforts in synthesizing solutions to the technological gaps identified by contractor and JPL studies.

G. R. Mon described recent voltage isolation test results that included voltage probability characterization of 22 as-manufactured materials, including pottants, single-layer and multilayer back-surface polymer films, and multilayer composites. The advantages of using multilayer films was emphasized by exhibiting the increased reliability to be gained at the module level. Preliminary test results from a small sample of aged materials has indicated a higher failure probability at a given operating voltage for aged (vs unaged) materials.

A. Shumka (JPL) reviewed experiments performed on one type of module to determine the relationship between leakage current and temperature. The leakage current between the electrically active part of the module and ground was found to be strongly dependent upon temperature in a module using PVB as an encapsulant. As a result of this and other effects, the specification of the voltage-withstanding test is being reviewed.

A presentation by J. W. Lathrop explained the encapsulated-cell testing approach being used at Clemson University. Findings from earlier tests on unencapsulated cells and differences being pursued in the testing of encapsulated cells were summarized. A total of more than 367 encapsulated cells involving more than 25 different metallization-encapsulation combinations will be tested.

R. A. Oth (JPL) and G. R. Mon (JPL) described in a joint presentation the test program, data reduction methods and initial results of long-duration module testing at Wyle Laboratories (Huntsville, Alabama). Although visual encapsulant degradation occurred on several Block II and III PVB modules from temperature-humidity environments, the loss in peak power was on the order of 5% after 112 days of 85°C/85% RH exposure. Other failure mechanisms that identified the need to increase JPL quality test durations to verify module 20-year field-site capability for U.S. environments were reviewed. The need for an intermediate test condition, between the current 40°C/93% RH and 85°C/85% RH temperature-humidity levels, was also discussed. The new test, together with the 85°C/85% temperature soak tests, would support accurate definition of generic module degradation rates.
Objective

TO CHARACTERIZE FLAT-PLATE ARRAYS BY DETERMINING SIGNIFICANT ARRAY OPERATING PARAMETERS:

- OPTIMUM OPERATING VOLTAGE
- OPERATING VOLTAGE RANGE REQUIRED TO OBTAIN A GIVEN AMOUNT OF ENERGY ANNUALLY
- MAXIMUM POWER AND CURRENT LIMITS REQUIRED TO OBTAIN A GIVEN AMOUNT OF ENERGY ANNUALLY
- MAXIMUM OPEN-CIRCUIT VOLTAGE
- CHANGES IN VALUES OF OPTIMUM AND MAXIMUM OPERATING PARAMETERS WITH ARRAY DEGRADATION
- ANNUAL ENERGY OUTPUT VS POWER LEVEL (USED TO CALCULATE POWER CONDITIONER EFFICIENCY)
Approach

- Calculate Effect of Array-Power Conditioner Operational Interface Parameters on System Annual Energy Production:
  - Annual Energy Based on Hour-by-Hour Simulation Using Array Temperature and Irradiance From SOLMET TMY Tapes
  - 26 Site Locations in U.S.
  - All Parameters Normalized to Array Maximum-Power Parameters at Standard Operating Conditions (SOC = NOCT, 100 mW/cm²)

Status of Array/PC Interface Studies

- WORK REPORTED LAST PIM
  - OPTIMUM FIXED OPERATING VOLTAGE AND VOLTAGE TRACKING RANGE
  - MAXIMUM POWER AND CURRENT LIMITS
  - MAXIMUM OPEN-CIRCUIT VOLTAGE

- RECENTLY COMPLETED ACTIVITIES
  - CORRELATION OF COMPUTER SIMULATION RESULTS WITH WEATHER ATLAS DATA
  - COMPARISON OF ANALYSIS RESULTS WITH VARIATIONS IN ARRAY TILT ANGLE
  - DEVELOPMENT OF TECHNIQUE FOR USING ARRAY SIMULATION RESULTS TO OBTAIN POWER CONDITIONER EFFICIENCY
  - REPORT FOR SANDIA PCS SPECIFICATION
  - PAPER FOR AS/ISES MEETING (HOUSTON, TX, JULY 1-4, 1982)
  - COORDINATION OF JPL/MIT PCS STUDIES

- FUTURE ACTIVITIES
  - FINAL REPORT IN PREPARATION
  - PROVIDE SUPPORT FOR CONCENTRATOR ANALYSIS
Correlation of Computer Simulation Results With Weather Atlas Data

PROBLEM:
- Lack of hourly data limits usefulness of computer simulation results
  - Optimum operating voltage
  - Energy loss with fixed voltage operation
  - Effect of fill factor on optimum operating voltage
  - Effect of fill factor on energy loss
  - Maximum open-circuit voltage

SOLUTION:
- Obtain correlations with various weather atlas data:
  - Annual average daily maximum temperature
  - Standard deviation of daily maximum temperature
  - $K_d = \text{diffuse fraction of extraterrestrial solar irradiance}$
  - $K_d K_T = \text{diffuse fraction of surface solar irradiance}$
  - Coldest recorded temperature

Array Optimum Operating Voltage vs Average Daily Maximum Temperature
Array Annual Energy Loss With Fixed-Voltage Operation vs Standard Deviation of Daily Maximum Temperature

Optimum Operating Voltage vs Fill Factor
Percentage of Energy Loss vs Fill Factor

- I-V Curve Fill Factor
- Percent Energy Loss
- ALBUQUERQUE
- BOSTON

Percentage of Energy Loss vs Fill Factor.
Rate of Change of Optimum Voltage With Fill Factor vs $K_d$

- COMPUTER SIMULATION RESULT FOR EACH OF 11 SOLMET SITES

ΔOPTIMUM VOLTAGE/ΔFF

$K_d$

0.150 0.160 0.170 0.180 0.190
Rate of Change of Energy Loss With Fill Factor vs $\frac{\bar{K}_d}{\bar{K}_T}$

- COMPUTER SIMULATION RESULT FOR EACH OF 11 SOLMET SITES
Maximum Open-Circuit Voltage (From SOLMET TMY) vs Atlas Lowest Recorded Temperature

- Calculated SOLMET Maximum Open Circuit Voltage for each of 26 sites
Array Energy Output vs Irradiance

Comparison of Analysis Results With Variation in Array Tilt Angle

<table>
<thead>
<tr>
<th>SITE</th>
<th>TILT ANGLE (DEGREES)</th>
<th>OPTIMUM OPERATING VOLTAGE</th>
<th>% ENERGY LOSS</th>
<th>% ELECTRICAL VOLTAGE TRACKING WIDTH TO OBTAIN 0.1% LOSS</th>
<th>POWER LIMITS REQUIRED TO OBTAIN 99% ENERGY LOSS</th>
<th>POWER LIMITS REQUIRED TO OBTAIN 99.9% ENERGY LOSS</th>
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<tr>
<td>ALBUQUEROE</td>
<td>35.05*</td>
<td>0.96</td>
<td>1.7</td>
<td>8.5</td>
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<td>20.05</td>
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<td></td>
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<td>8.5</td>
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<td>1.15</td>
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<td>10.80</td>
<td>0.93</td>
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<td>5.5</td>
<td>0.80</td>
<td>0.88</td>
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<td>40.80</td>
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<td>0.7</td>
<td>6.0</td>
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<tr>
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<td>12.5</td>
<td>0.96</td>
<td>1.08</td>
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<td>31.77</td>
<td>0.97</td>
<td>2.4</td>
<td>12.5</td>
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<td>61.77</td>
<td>0.96</td>
<td>2.7</td>
<td>13.0</td>
<td>0.95</td>
<td>1.10</td>
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</table>

* TILT ANGLE EQUALS SITE LATITUDE
Normalized Power vs Operating Time

Effect of Power Conditioner Efficiency on Array Annual Power Production

ALBUQUERQUE
FILL FACTOR = 0.70
POWER NORMALIZED TO ARRAY MAXIMUM
POWER AT SOC
Fraction of Annual Array Energy Available in Various Relative Power Intervals

<table>
<thead>
<tr>
<th>SITE</th>
<th>ARRAY RELATIVE POWER INTERVAL</th>
<th>0.0-0.2</th>
<th>0.2-0.4</th>
<th>0.4-0.6</th>
<th>0.6-0.8</th>
<th>0.8-1.0</th>
<th>1.0-1.2</th>
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</thead>
<tbody>
<tr>
<td>ALBUQUERQUE, NM</td>
<td></td>
<td>0.0343</td>
<td>0.0782</td>
<td>0.1040</td>
<td>0.2133</td>
<td>0.3893</td>
<td>0.2810</td>
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<td>BISMARCK, ND</td>
<td></td>
<td>0.0750</td>
<td>0.1363</td>
<td>0.1442</td>
<td>0.2435</td>
<td>0.3277</td>
<td>0.0739</td>
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<tr>
<td>BOSTON, MA</td>
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<td>0.0987</td>
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<td>0.2840</td>
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<td>0.0163</td>
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<td>0.1996</td>
<td>0.3749</td>
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<td>0.1105</td>
<td>0.1642</td>
<td>0.3164</td>
<td>0.2995</td>
<td>0.0403</td>
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<tr>
<td>FRESNO, CA</td>
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<td>0.0990</td>
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<td>0.2721</td>
<td>0.4098</td>
<td>0.0533</td>
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<tr>
<td>MIAMI, FL</td>
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<td>0.4448</td>
<td>0.1073</td>
<td>0.0035</td>
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<td>0.1420</td>
<td>0.2723</td>
<td>0.3119</td>
<td>0.0767</td>
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<tr>
<td>PHOENIX, AZ</td>
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<td>0.0339</td>
<td>0.0679</td>
<td>0.1275</td>
<td>0.3091</td>
<td>0.3821</td>
<td>0.0596</td>
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<td>SEATTLE, WA</td>
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<td>0.1302</td>
<td>0.1803</td>
<td>0.1847</td>
<td>0.2524</td>
<td>0.2892</td>
<td>0.0632</td>
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</tbody>
</table>

AVERAGE: 0.0847 0.1305 0.1587 0.3027 0.2833 0.0522

CUMULATIVE VALUE OF AVERAGES: 0.0647 0.1952 0.3019 0.6648 0.9479 1.0980

Summary and Conclusions

- EXCELLENT CORRELATIONS OBTAINED WITH RECORDED WEATHER DATA FOR FOLLOWING:
  - ARRAY OPTIMUM OPERATING VOLTAGE
  - ANNUAL ENERGY LOSS (%)
  - VARIATION OF OPTIMUM OPERATING VOLTAGE AND ENERGY LOSS (%) WITH FILL FACTOR
  - MAXIMUM OPEN-CIRCUIT VOLTAGE

- SENSITIVITY OF ANALYSIS RESULTS TO ARRAY TILT ANGLE IS MINOR

- DETERMINED COMPOSITE ENERGY FRACTION PER GIVEN POWER INTERVAL FROM DATA FOR 26 SITES
ARRAY DEGRADATION
AND VOLTAGE CONTROL STRATEGIES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

H.M. Branz
G.W. Hart
C.H. Cox

Typical Single "Glitch-Point" Curves

![Graph showing typical single Glitch-Point curves with axes labeled CURRENT / $I_{SC}$ and VOLTAGE / $V_{OC}$.]
Shorts in a Series-Wired Array

Two failure modes, B, with the same I-V curve
Method

- Focus on resulting curve shape; not on underlying failure
- Assume single "glitch-point" curves
- Simulate using TMY hourly data
- Compare annual energy between ideal maximum power tracker and best fixed voltage
MPT Array Energy as a Function of Glitch-Point Location
Percentage of MPT Array Energy vs Glitch-Point Location
BFV Array Energy as a Function of Glitch-Point Location

![Graph showing BFV Array Energy as a Function of Glitch-Point Location](image-url)
BFV Losses Relative to Full-Range MPT
BFV Losses Relative to Limited-Range MPT

CURRENT / \( I_{sc} \) vs. VOLTAGE / \( V_{oc} \)

V_{fixed} TRACKING RANGE

\( 0 \leq V_{oc} \leq 10 \)
Percent of MPT Array Energy vs Glitch-Point Location

![Graph showing percent of MPT array energy vs glitch-point location. The graph has a vertical axis labeled 'CURRENT / \( I_{sc} \)' ranging from 0.1 to 10, and a horizontal axis labeled 'VOLTAGE / \( V_{oc} \)' ranging from 0 to 1. The graph includes several curves labeled with numbers like 10, 20, 30, 40, 50, 60, 70, etc., indicating different percentages of energy. The tracking range is marked between the limits of the voltage axis.]
Shorts to Ground in a Series-Wired Array
Opens in a Parallel-Wired Array
Two Special Cases

Conclusions

Best Fixed Voltage vs
Ideal Maximum Power Tracker

Small Difference
- Open in series connected array
- Short to ground near top of array

Large Difference
- Short in parallel connected array
- Glitch below maximum power radial
I-V CURVE DATA BASE AND APPLICATIONS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

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Data Base

- IV CURVES EVERY 3 MINUTES
- COLLATERAL DATA
  - CELL TEMPERATURE
  - WEATHER CONDITIONS
  - PILOT CELL DATA

Applications

- IV CURVE TRANSLATION
- VOLTAGE CONTROL STRATEGIES
  - MAX POWER TRACKING
  - FIXED VOLTAGE
  - PILOT CELL
Effect of Insolation and Cell Temperature on I-V Curves

Measured and Simulated I-V Curves

Legend

- 1 kW/m² 30°C
- 1 kW/m² 60°C
- 0.5 kW/m² 30°C
- 0.5 kW/m² 60°C

Legend

- SIMULATED
- MEASURED
Measured and Calculated Voltages for Abacus Inverter With "Searching" Maximum Power Tracker
Energy Lost With Fixed-Voltage Operation

![Graph showing energy lost with fixed-voltage operation.](image-url)
Pilot Cells

VOLTAGE

1 CELL

10 CELLS

CURRENT

1 CELL

I_{oc}
Energy Lost With Voltage-Multiplying Pilot Cell

Percent Energy Lost

Constant Voltage Multiplier (for one cell)
### Pilot Cell Experiments

Based on IV curves measured every 3 minutes for 3 weeks in January.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Energy</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy available to ideal max power tracker</td>
<td>67.3</td>
<td></td>
</tr>
<tr>
<td>Fixed voltage</td>
<td>65.8</td>
<td>2.20%</td>
</tr>
<tr>
<td>Voltage multiplying (1 cell)</td>
<td>66.8</td>
<td>0.79%</td>
</tr>
<tr>
<td>Voltage multiplying (10 cells)</td>
<td>66.5</td>
<td>1.17%</td>
</tr>
<tr>
<td>Current multiplying (1 cell)</td>
<td>62.5</td>
<td>7.13%</td>
</tr>
</tbody>
</table>
IRRADIANCE DATA FOR JPL TEST SITE
JET PROPULSION LABORATORY
R.W. Weaver

- JPL TEST SITE HAS BEEN RESTRUCTURED TO OBTAIN DATA FOR THE EARLY DETECTION OF PERFORMANCE PROBLEMS
- PERFORMANCE DATA MUST BE ADJUSTED TO REFERENCE CONDITIONS
- IRRADIANCE VALUES ARE KEY TO ADJUSTMENT PROCESS
- A COMPREHENSIVE SET OF IRRADIANCE MEASURING INSTRUMENTS HAVE BEEN INSTALLED

Irradiance Instruments

Tracker Mounted: (±0.25 deg accuracy)
- EPPLEY PRECISION SPECTRAL PYRANOMETER (PSP)
- EPPLEY NORMAL INCIDENCE PYRHELIOMETER (NIP)
- JPL FILTERED RADIOMETER 500, 850 AND 940 NANO METERS

Fixed:

Horizontal:
- EPPLEY PSP
- LI-COR PYRANOMETER

Tilted at 34 deg.:
- EPPLEY PSP
- LI-COR PYRANOMETER
- 11 REFERENCE CELLS
Instrument Calibration

PYRANOMETERS:
- One Eppley PSP was calibrated by NOAA
- All were mounted horizontally
- Data were taken for all
- The calibrated PSP was used as a standard for all others

NIP:
- Used Eppley calibration values

Filtered Radiometer:
- Used supplied calibration values
  (JPL Solar Energy Conversion Systems Section, 341)

Irradiance Data

Measured: (Every 5 minutes from Sun up to Sun down)
- Direct Normal (DN)
- Total Normal (TN)
- Total Horizontal (TH)
- Total Tilted (TT)
- Tilted totals for each ref. cell
- Radiometer

Computed:
- Turbidity coefficient
- Water vapor
- Air mass (from barometric pressure)
Results: Total Tilt (TT) and Total Horizontal (TH) Fractions

Results: Total Horizontal to Total Tilted Ration vs Time of Day
Results: Direct Normal to Total Normal vs Turbidity Coefficient; Total Horizontal to Tilted vs Turbidity Coefficient

Summary

- TURBIDITY COEFFICIENT IS A GOOD INDICATOR OF THE DIFFUSE IRRADIANCE FRACTION IN THE NORMAL PLANE
- POOR CORRELATION BETWEEN TURBIDITY AND THE RATIO OF TOTAL HORIZONTAL TO TOTAL TILTED
- TRANSFORMATIONS BETWEEN THE NORMAL, HORIZONTAL AND TILTED PLANES MAY REQUIRE DIFFUSE SOURCE DATE
- THE REFERENCE IRRADIANCE SHOULD BE MEASURED IN THE TILT PLANE
AM1.5 FILTERING SYSTEM FOR LAPSS
JET PROPULSION LABORATORY
C.H. Seaman
Spectral Irradiance, Unfiltered LAPSS and AM1.5
Spectral Response Comparisons of Reference and Test Cells

**Reference Cell**: FE431 R/B = 1.81
**Test Cell**: YB451 R/B = 1.70
LAPSS ERROR = +2.0%

**Reference Cell**: UR458 R/B = 2.28
**Test Cell**: MS431 R/B = 1.81
LAPSS ERROR = -3.9%
The Mismatch Factor $M$

$$M = \frac{(\sum \Delta_i) (\sum \Delta_i)}{(\sum \Delta_i) (\sum \Delta_i)}$$

- $E_{Si}$ = LAPSS SPECTRAL IRRADIANCE
- $E_{Al}$ = AM 1.5 SPECTRAL IRRADIANCE
- $R_{CI}$ = TEST CELL SPECTRAL RESPONSE
- $R_{RI}$ = REFERENCE CELL SPECTRAL RESPONSE

ERROR = M - 1

Measured Error Using Unfiltered LAPSS

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<thead>
<tr>
<th>PAIR</th>
<th>R/B</th>
<th>$R/B_C$</th>
<th>$(R/B)_R$</th>
<th>% ERROR NO FILTER</th>
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<tr>
<td>C</td>
<td>MS 431</td>
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<td>+2.0</td>
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<tr>
<td>R</td>
<td>YB 451</td>
<td>1.70</td>
<td>1.06</td>
<td>-3.9</td>
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<td>RS 425</td>
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<td><strong>ERROR EXPECTATION VALUE</strong></td>
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Spectral Irradiance, Filtered LAPSS and AM1.5
Calculated Errors Using Filtered LAPSS

<table>
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<th>PAIR</th>
<th>CALCULATED % ERROR</th>
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<tbody>
<tr>
<td>CR</td>
<td>MS 431 YB 451</td>
</tr>
<tr>
<td>CR</td>
<td>UR 458 RS 425</td>
</tr>
<tr>
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<td>UR 458 YB 451</td>
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<td>YB 451 RS 425</td>
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<tr>
<td>CR</td>
<td>UR 458 RS 425</td>
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</table>

Measured Errors Before and After Filtering

<table>
<thead>
<tr>
<th>PAIR</th>
<th>R/B</th>
<th>( \frac{R/B}{C} )</th>
<th>( \frac{R/B}{P} )</th>
<th>% ERROR NO FILTER</th>
<th>% ERROR FILTER</th>
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<tbody>
<tr>
<td>CR</td>
<td>MS 431</td>
<td>1.81</td>
<td>1.76</td>
<td>+2.0</td>
<td>-0.1</td>
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<tr>
<td>CR</td>
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<td>1.70</td>
<td>1.66</td>
<td>+2.0</td>
<td>-0.1</td>
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<td>CR</td>
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<td>1.34</td>
<td>-1.0</td>
<td>+1.0</td>
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<tr>
<td>CR</td>
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<td>1.70</td>
<td>1.34</td>
<td>-1.0</td>
<td>+1.0</td>
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<tr>
<td>CR</td>
<td>YB 451</td>
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<td>1.70</td>
<td>1.34</td>
<td>-8.3</td>
<td>+0.9</td>
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</table>

ERROR EXPECTATION VALUE 4.3 0.4
RESIDENTIAL ARRAY RESEARCH

JET PROPULSION LABORATORY

H. Wilson

Residential Array Technology Gaps

• Water Sealing
  • Techniques for Horizontal Joints
  • Concern Over Seal Durability

• Module Support Structure
  • 2 vs 4 Sides Module Support
  • Edge Protection of Glass
  • Methods to Minimize Field Labor
    • Installation of Frame Structure on Roof
    • Installation and Replacement of Modules

• Electrical Safety
  • Allowable Wiring and Connectors
  • Concern With Conductive Structures
JPL In-House Residential Array Research Activity:
Objective and Approach

- Synthesize Residential Array Solution to Identified Gaps:
  - Light Weight, Non-Conductive Structural Frames
    - Non-Conductive to Eliminate Need for Grounding
    - Factory Pre-Assembly to Minimize Field Labor and
    - Integral Scaffolding to Provide 4-Side Module Support
    - Integral Drain Gutters to Achieve Long-Life Water Sealing
    - Snap-Ring-Type Module Retainer
  - Underground Feeder Cable to Meet Proposed 1984 NEC Code Constraints
  - Module Support Brackets to Facilitate Module Installation

- Fabricate Array Research Model to Evaluate:
  - Structural Loading Capabilities
  - Thermal Expansion Effects
  - Both Parallel and Series Circuit Requirements
  - Module Installation and Replacement Ideas
  - Weathering and Water Sealing Capabilities
  - Aesthetic Appearance

Residential Array Research Model
Detail: Corner of Model

Model With J-Box Exposed
Upper Modules Supported by Brackets

Technician Replacing Module
Details of Model Construction
Details of Model Construction

Modification to Meet UL Requirements
(Connector)
Modification to Meet UL Requirements
(Lead, Underground Feeder Wire)

Cross Section of Plastic Frame Extrusion
UV-Stabilized Extrudable Thermoplastics Properties

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DEFLECTION TEMP °F</th>
<th>TENSILE 10^3 PSI</th>
<th>COMPRESSIVE 10^3 PSI</th>
<th>FLEXURAL 10^3 PSI</th>
<th>FLEXURAL MODULUS 10^3 PSI</th>
<th>SUPPLIER</th>
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<tr>
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<td>225</td>
<td>16.0</td>
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<td>3.0</td>
<td>375</td>
<td>DuPont</td>
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<tr>
<td>Nylon</td>
<td>365</td>
<td>10.0</td>
<td>13.0</td>
<td>14.0</td>
<td>390</td>
<td>DuPont, LNP</td>
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<tr>
<td>Phenylene Oxide</td>
<td>265</td>
<td>9.6</td>
<td>16.4</td>
<td>13.5</td>
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<td>Gen. Elec.</td>
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<td>Polycarbonate</td>
<td>220</td>
<td>7.6</td>
<td>11.0</td>
<td>13.0</td>
<td>300</td>
<td>Mobay</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>400</td>
<td></td>
<td></td>
<td>12.4</td>
<td>330</td>
<td>ICI America, LNP</td>
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<tr>
<td>Chlorinated PVC 21°C</td>
<td>7.5</td>
<td>9.0</td>
<td></td>
<td>14.5</td>
<td>380</td>
<td>Goodrich</td>
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<tr>
<td>PVC (Ref. Point)</td>
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<td>6.0</td>
<td>8.0</td>
<td>10.0</td>
<td>300</td>
<td>Goodrich, Kohinor</td>
</tr>
</tbody>
</table>

Summary

- Array Concepts Have Been Developed and Discussed

Future Work

- Continue Experiments Using Research Model
- Report on Residential Array Research Model Work
VOLTAGE BREAKDOWN OF PV INSULATING MATERIALS

JET PROPULSION LABORATORY

G.R. Mon

Program Objectives

- Characterize Statistical Voltage Breakdown Behavior of Electrical Insulation Materials and Composites Used in Photovoltaic Modules
- Develop Algorithms to Predict Module Field-Failure Probabilities at System Operating Voltage
- Develop Algorithms for Selecting Insulation Systems With Least Life-Cycle Energy Cost

Approach

- Break Down Many Test Areas ($A_T = 0.785\text{ in}^2$) of Candidate Insulation Systems
- Develop Statistical Breakdown Curves for Each System Tested
- Selectively Age Candidate Systems in an Environmental Aging Chamber
- Conduct Additional Breakdown Tests at Reasonable Intervals During the Aging Process to Ascertain the Effects of Aging on the Voltage Breakdown Characteristics of the Candidate Insulation Systems
## Materials Tested to Date

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>MATERIAL</th>
<th>THICKNESS (mils)</th>
<th>NO. OF LAYERS</th>
<th>THICKNESS PER LAYER (mils)</th>
<th>NO. OF TEST POINTS</th>
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<tbody>
<tr>
<td>1</td>
<td>Mylar</td>
<td>0.48</td>
<td>1</td>
<td>0.48</td>
<td>4272</td>
</tr>
<tr>
<td>2</td>
<td>Mylar</td>
<td>0.92</td>
<td>1</td>
<td>0.92</td>
<td>4008</td>
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<tr>
<td>3</td>
<td>Mylar</td>
<td>1.42</td>
<td>1</td>
<td>1.42</td>
<td>4608</td>
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<tr>
<td>4</td>
<td>Mylar</td>
<td>3.00</td>
<td>1</td>
<td>3.00</td>
<td>4608</td>
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<tr>
<td>5</td>
<td>Scotchpar: 10 CP 3110</td>
<td>1.00</td>
<td>1</td>
<td>1.00</td>
<td>1034</td>
</tr>
<tr>
<td>6</td>
<td>Scotchpar: 20 CP 3110</td>
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<td>1</td>
<td>2.00</td>
<td>968</td>
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<tr>
<td>7</td>
<td>Mylar: Unaged*</td>
<td>2.50</td>
<td>4</td>
<td>0.63</td>
<td>385</td>
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<tr>
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<td>Mylar: Aged*</td>
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<td>5369</td>
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<td>3.00</td>
<td>3550</td>
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<tr>
<td>10</td>
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<tr>
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<td>EMA</td>
<td>24.00</td>
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<td>12</td>
<td>Tedlar: 100BG20TR</td>
<td>1.0</td>
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<td>1.0</td>
<td>176</td>
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<td>68040 Primer</td>
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<td>1.5</td>
<td>1880</td>
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<td>16</td>
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<td>17</td>
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<td>1959</td>
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<tr>
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<td>Tedlar: Experimental</td>
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<td>4.0</td>
<td>381</td>
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<tr>
<td>19</td>
<td>Tedlar: Milky</td>
<td>8.0</td>
<td>4</td>
<td>1.5/0.7/4.0/1.5</td>
<td>1840</td>
</tr>
<tr>
<td>20</td>
<td>Polyester</td>
<td>4.0</td>
<td>1</td>
<td>4.0</td>
<td>441</td>
</tr>
<tr>
<td>21</td>
<td>Tedlar/AIuminum/Polyester/</td>
<td>8.0</td>
<td>4</td>
<td>1.5/0.7/4.0/1.5</td>
<td>1840</td>
</tr>
<tr>
<td>22</td>
<td>TAPT</td>
<td>4.0</td>
<td></td>
<td></td>
<td>1421</td>
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</table>

*Aged 1600 h at 40°C/93% RH, Then Dehumidified*
Voltage Breakdown Characteristics of Single-Layer and Multilayer Polyethylene Terephthalate Insulation Films (per Unit Test Area: $A_T = 0.785 \text{ in}^2$)

**NOTE:**
- 5.00-mil Mylar (4 layers at 0.92 mils each) exhibited no flaw-controlled breakdowns below 25 kV.
- 6.00-mil Mylar (2 layers at 3.00 mils each) exhibited no flaw-controlled breakdowns below 25 kV.
Theoretical Film and Module Failure Probabilities

- The Breakdown Probability of a Single Test Area \((A_T = 0.785\text{-in}^2)\), determined by measurement, is \(p\).

- The Breakdown Probability of a Test Area of a Multilayer Film is \(p_m = \prod_{i=1}^{m} p_i\), where:
  - \(p_i\) = Breakdown Probability of a Test Area of Layer \(i\)
  - \(m\) = Number of Layers

- If All of the Layers Are Identical, Then \(p_m = p^m\)

- The Breakdown Probability of a Module Using Multilayer Insulating Films is \(p_{MOD} = 1 - (1-p_m)^n\), where:
  - \(n = \begin{cases} 1467 & \text{for 2X8-ft Modules} \\ 293 & \text{for 4X4-ft Modules} \\ 5867 & \text{for 4X8-ft Modules} \end{cases}\)
Theoretical vs Measured Voltage Breakdown Characteristics of Multilayer Mylar Insulation Films: Single Layer, 0.48 mils
Theoretical vs Measured Voltage Breakdown Characteristics of Multilayer Mylar Insulation Films: Single Layer, 1.42 mils
Failure Probability of Modules Using Indicated Number of Layers of 0.48-mil Mylar Insulating Film
Failure Probability of Modules Using Indicated Number of Layers of 1.42-mil Mylar Insulating Film

![Graph showing failure probability vs. applied voltage for different numbers of layers of Mylar insulating film. The graph has two sets of curves labeled 2x4-ft Modules and 4x8-ft Modules.](image-url)
Conclusions From Multilayer Studies

- Multilayer Mylar Films Perform Better Than Theoretically Expected, Perhaps Because of the Presence of Bonding Layers

- Minimum Life-Cycle Costing, in Conjunction With the Module Failure Probability Curves, Can Be Used to Determine the Least Number of Film Layers That Will Ensure Acceptable Hi-Pot Yields

- With Knowledge of How Environmental Exposure (Aging) Changes a Materials Voltage Breakdown Characteristics, These Same Design Tools Can Determine Dielectric Design to Yield Acceptable Module Performance Over the Life of the Array Field

Aging Studies

- Purpose:
  - To Ascertain Changes in Dielectric Voltage Breakdown Characteristics Resulting From Environmental Exposure
  - To Enable Realistic Prediction of 20-Year Failure Probabilities

- Aging Apparatus
  - HIVEC
  - Associated Humidity Chambers and Ovens

- Procedure
  - Break Down Selected Films Both Before and After Aging
Voltage Breakdown Characteristics of 4.00-mil Experimental White Tedlar: Unaged vs Aged (1704 h at 40°C/93% RH)

Conclusions Based Upon Aging Studies

- Preliminary Results Indicate That Environmental Exposure Can Significantly Alter Single-Layer, and Hence Module, Failure Probabilities

- Much Additional Testing Is Necessary Before Final Conclusions Can Be Made
Additional Test Results

- **Encapsulants**
  - EVA
  - EMA

- **Back-Cover Films**
  - Tedlar
  - Polyester
  - Tedlar/Polyester/Aluminum/Tedlar

Voltage Breakdown Characteristics of Single-Layer Tedlar Films (per Unit Test Area: \( A_T = \pi/4 \text{ in}^2 \))
Comparison of Voltage Breakdown Characteristics of EVA and EMA
Voltage Breakdown Characteristics of Tedlar/Polyester/Aluminum/Tedlar (1.50/4.0/0.7/1.5 mils)

- Surface Discharges
- Volume Discharges
- TAPT
- Polymer

**Actions for Future Research**

- Continuation of Voltage Breakdown Characterization Program
  - Test Composite Insulation Systems
  - Develop Cost-Optimal Module Design Algorithms Based Upon Voltage-Probability Data

- Conduct Fundamental Degradation Studies of Photovoltaic Insulation Systems
  - Partial Discharge (Corona)
  - Pulse-Height Analysis
  - Middle ac/dc Test Equipment Can Measure Microscopic Erosion of Dielectric; May Enable Long-Term Prediction of Module Electrical Service Life Without Extensive Testing
LEAKAGE CURRENT IN ENCAPSULANTS

JET PROPULSION LABORATORY

A. Shumka

Objectives

• CHARACTERIZE THE LEAKAGE CURRENT BETWEEN CELLS AND A MODULE GROUND PLANE AS A FUNCTION OF VOLTAGE AND TEMPERATURE FOR ONE PARTICULAR TYPE OF COMMERCIALYL USED ENCAPSULATION SYSTEM

• EVALUATE LEAKAGE CURRENT RESULTS IN TERMS OF CURRENT PROCUREMENT SPECIFICATION REQUIREMENTS

• INDICATE WHERE AN UPGRADING OF THESE SPECIFICATIONS MAY RESULT IN MODULE DESIGNS WITH IMPROVEMENTS IN LONG LIFE AND SAFETY

Module Procurement Specification for Leakage Current

• REQUIREMENT OF SPECIFICATION

  • ROOM TEMPERATURE LEAKAGE CURRENT NOT TO EXCEED 50 μA AT 2000 Vdc (HI-POT TEST)

• LIMITATION OF SPECIFICATION

  • TYPICAL NOCT FOR BLOCK IV MODULES RANGES FROM 50 TO 60 C
  • NO SPECIFICATION FOR LEAKAGE CURRENTS ABOVE ROOM TEMPERATURE
  • NO SPECIFICATION FOR MAXIMUM ALLOWABLE TEMPERATURE COEFFICIENT FOR LEAKAGE CURRENT
Test Approach

- Selected three Block IV modules of same design and manufacture - one of which had a reported temperature sensitive leakage current.

- Measure capacitance and dissipation factor at room temperature.

- Measure partial discharge (corona) breakdown voltage at room temperature.

- Measure and characterize module leakage currents at seven different voltages (100, 200, 500, 1000, 1500, and 2000 Vdc) and at seven temperatures (24, 35, 45, 55, 65, 75 and 85°C).

Exploded View of Module Structure
Capacitance Dissipation Factor at Room Ambient, 1 kHz

<table>
<thead>
<tr>
<th>MODULE S/N</th>
<th>CAPACITANCE VALUE IN (µF)</th>
<th>DISSIPATION FACTOR VALUE IN (%)</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02231</td>
<td>5.30</td>
<td>SUBJECT MODULE RETURNED FROM HAWAII</td>
</tr>
<tr>
<td>2</td>
<td>0.02149</td>
<td>4.95</td>
<td>COMPARISON MODULE JPL SPARE</td>
</tr>
<tr>
<td>3</td>
<td>0.01976</td>
<td>4.60</td>
<td>COMPARISON MODULE JPL SPARE</td>
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Partial Discharge (Corona) at Room Ambient, 60 Hz

<table>
<thead>
<tr>
<th>MODULE S/N</th>
<th>PARTIAL DISCHARGE &quot;INCEPTION&quot; LEVEL</th>
<th>PARTIAL DISCHARGE AT 100 pC LEVEL</th>
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<tbody>
<tr>
<td></td>
<td>(pC)</td>
<td>TEST VOLTS (kV PEAK)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>4.4</td>
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</table>

REMARKS                  |
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<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>MODULE RETURNED FROM HAWAII</td>
</tr>
<tr>
<td>COMPARISON MODULE - JPL SPARE</td>
</tr>
<tr>
<td>COMPARISON MODULE - JPL SPARE</td>
</tr>
</tbody>
</table>

NOT: THE 100 pC LEVEL OF PARTIAL DISCHARGE IS EQUIVALENT TO ≈10 nA AVERAGE CURRENT.
DC Leakage Current Test Results vs Temperature and Voltage: Module No. 1

TEMPERATURE IN DEGREES CENTIGRADE

DC LEAKAGE CURRENT IN MICROAMPERES

Polarity of Test Voltage | Test Connection
--- | ---
Positive | Module End Terminations Shorted Together
Negative | Module Metal Frame

Temperature: Module No. 1
- 2000 Vdc
- 1500 Vdc
- 1000 Vdc
- 500 Vdc
- 200 Vdc
- 100 Vdc
GC Leakage Current Test Results vs Temperature and Voltage: Module No. 1

DC LEAKAGE CURRENT IN MICROAMPERES

TEMPERATURE IN DEGREES CENTIGRADE
Voltage as a Function of Temperature for a 50 $\mu$A Leakage Current

<table>
<thead>
<tr>
<th>VOLTAGE (VOLTS)</th>
<th>MODULE #1 WITH TERMINAL POLARITY</th>
<th>MODULE #2 WITH TERMINAL POLARITY</th>
<th>MODULE #3 WITH TERMINAL POLARITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>2000</td>
<td>42</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>1500</td>
<td>44</td>
<td>44.5</td>
<td>42.5</td>
</tr>
<tr>
<td>1000</td>
<td>52</td>
<td>49.5</td>
<td>47</td>
</tr>
<tr>
<td>500</td>
<td>59.5</td>
<td>58</td>
<td>56</td>
</tr>
<tr>
<td>200</td>
<td>65</td>
<td>71</td>
<td>62.5</td>
</tr>
<tr>
<td>100</td>
<td>71</td>
<td>77.5</td>
<td>69</td>
</tr>
</tbody>
</table>

+ POLARITY - MODULE FRAME CONNECTED TO GROUND
- POLARITY - TERMINALS CONNECTED TO GROUND
Insulation Resistance Test Results vs Temperature and Voltage: Module No. 1

![Graph showing insulation resistance test results vs temperature and voltage for Module No. 1. The graph includes lines for different temperatures: 24°C, 35°C, 45°C, 55°C, 65°C, 75°C, and 85°C. The graph shows the relationship between DC test voltage in volts and insulation resistance in megohms.]
Conclusions

- LEAKAGE CURRENT IN THE ENCAPSULATION SYSTEM TESTED - PVB/TEDLAR - EXHIBITED A VERY STRONG DEPENDENCE ON TEMPERATURE AND MAY REPRESENT POTENTIAL LONG TERM PROBLEMS

- NEED TO SIMILARLY CHARACTERIZE OTHER ENCAPSULATION SYSTEMS

- NEED TO UNDERSTAND CONDUCTION MECHANISM IN TERMS OF TIME AND TEMPERATURE. THIS MAY PROVIDE INFORMATION IMPORTANT FOR QUALITY CONTROL

- NEED TO DETERMINE EFFECT OF LEAKAGE CURRENT ON LONG TERM LIFE

- NEED TO REVIEW EFFICACY OF BLOCK IV LEAKAGE CURRENT SPECIFICATION - <50 µA AT 2000 Vdc AT ROOM TEMPERATURE

- NEED TO ESTABLISH SPECIFICATIONS FOR ACCEPTABLE LEVELS OF LEAKAGE CURRENT FOR LONG TERM RELIABILITY AND SAFETY
CELL RELIABILITY TESTING

CLEMSON UNIVERSITY

J.W. Lathrop

Accelerated Stress Tests

<table>
<thead>
<tr>
<th>FORM</th>
<th>TEST</th>
<th>LIMIT</th>
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<tr>
<td>UNENCAPSULATED</td>
<td>BIAS-TEMPERATURE</td>
<td>SOLDIER MELTING</td>
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<tr>
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<td>PRESSURE COOKER</td>
<td>T &lt; 175°C</td>
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<tr>
<td></td>
<td>85°C/85% RH</td>
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<td>ENCAPSULATED</td>
<td>THERMAL SHOCK</td>
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<tr>
<td></td>
<td>85°C/85% RH</td>
<td>ORGANIC DECOMPOSITION</td>
</tr>
<tr>
<td></td>
<td>THERMAL CYCLE</td>
<td>T &lt; 95°C</td>
</tr>
<tr>
<td></td>
<td>ENVIRONMENTAL</td>
<td></td>
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### Anticipated Failure Mechanisms

<table>
<thead>
<tr>
<th>PHYSICAL PHENOMENON</th>
<th>OBSERVED EFFECT</th>
<th>ACCELERATING TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOSS OF COLLECTION EFFICIENCY</td>
<td>BULK RESISTIVITY INCREASE</td>
<td>B-T</td>
</tr>
<tr>
<td>CONTACT RESISTANCE INCREASE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>METAL REMOVAL</td>
<td>METAL PLATING</td>
<td>PC</td>
</tr>
<tr>
<td>CORROSION</td>
<td>AR COATING REMOVAL</td>
<td>85/85</td>
</tr>
<tr>
<td>DIFFERENTIAL EXPANSION</td>
<td>METAL PEELING</td>
<td>TC/TS</td>
</tr>
<tr>
<td></td>
<td>CELL FRACTURE</td>
<td></td>
</tr>
</tbody>
</table>
Proposed $\text{SO}_2$ – $85^\circ\text{C}$ – 85% RH Test
ENGINEERING SCIENCES AREA
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

Modules for Encapsulated Cell Testing

CELL METALLIZATION SYSTEMS

<table>
<thead>
<tr>
<th>Ni-SOLDER 7 TYPES</th>
<th>Cu PLATE 2 TYPES</th>
<th>Ag SCREEN 1 TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>M</td>
<td>S</td>
</tr>
</tbody>
</table>

| G/EVA/G  | 12 | 50 | 2 | 3 |
| G/EVA/T  | 18 | 50 | 2 | 24 | 3 |
| G/EMA/T  | 18 | 50 | 2 | 3 |
| G/EVA/F  | 15 | 50 | 3 |
| T/EVA/S  | 15 | 2 | 3 |
| G/EVA    |     |   |   | 25 |
| G/SR/G   | 12 |   |   |   |

<table>
<thead>
<tr>
<th>Ni-SOLDER</th>
<th>Cu PLATE</th>
<th>Ag SCREEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>M</td>
<td>S</td>
</tr>
</tbody>
</table>

| G/EVA/G  | 78 | 162 | 13 | 99 | 15 | 106 | 261 |
| G/EVA/T  |    |     |    |    | 240 | 112 |   |
| G/EMA/T  | 15 | 367 |

S = SPRINGBORN FABRICATED
M = MANUFACTURER FABRICATED
LONG-TERM MODULE TESTING AT WYLE LABORATORIES

JET PROPULSION LABORATORY

D.H. Otth

Objectives

- Understand Temperature/Humidity-Bias Failure Mechanisms of Typical Photovoltaic Modules and Materials
  - Cells, Encapsulants, Interconnects
  - Back Covers, Edge Seals

- Establish Generic Functional Relationships Among Temperature, Humidity, Bias and Time for Observed Failure Mechanisms

- Determine Relative Lifetimes of Roof-Mounted vs Ground-Mounted Arrays

- Understand Relative Severity (Acceleration Factor) of Candidate T/H-B Qualification Tests and Define Recommended Levels
Long-Term Module Testing

Original page is of poor quality.

- Temperature
- Humidity

85°C/5%RH, 100°C/5%RH, 40°C/93%RH, 85°C/85%RH

- Brownsville
- 20-Yr Site Environment
- Phoenix
- French Temp. $\text{SOAK}$
- French
- CEC
- BLK V
- BLK II-IV
- BLK I
- Field Test Results
- Laboratory Test Results
- Qualification Test Level
- Degradation Rate Curve from RTC

- Time (h)
- Temperature + RH (%)
Module Materials

- Encapsulants
  Silicone, RTV, PVB, EVA

- Cell Metallization
  Ni-Solder, Ti-Pd-Ag, Print Ag, Pd-Ni-Solder

- Cell Types
  Semi-XTL, Silicon (p/n, n/p)

- Substrate/Superstrate Structure
  Glass, FRP, Aluminum

- Back Covers
  Tedlar, Mylar, Tedlar-Fe-Tedlar, Tedlar-Al-Tedlar

- Frames
  Al, Stainless Steel

Blocks II and III Modules in Wyle Testing
Block I Type Module in Wyle Testing
Block IV Modules in Wyle Testing
Block IV Minimodule With Semicrystalline Cells
## Schedule

<table>
<thead>
<tr>
<th>Test</th>
<th>1981</th>
<th>1982</th>
<th>1983</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>93% RH 40°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interim Test Condition (Current, Undefined)</td>
<td></td>
<td></td>
<td>TBD</td>
</tr>
<tr>
<td>Inspection Points</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Legend

- BLKS I, II, III
- BLK IV
- BLKS III, IV

---

518
Visual Degradation Mechanisms

<table>
<thead>
<tr>
<th>Encapsulants</th>
<th>DISCOLORATION</th>
<th>DELAM</th>
<th>DISCOLORATION</th>
<th>DELAM</th>
<th>DISCOLORATION</th>
<th>DELAM</th>
<th>DISCOLORATION</th>
<th>DELAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone/RTV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metalization</th>
<th>GRID YELLOW</th>
<th>GRID CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRINT Ag</td>
<td></td>
<td>INCR</td>
</tr>
<tr>
<td>Ni SOLDER</td>
<td></td>
<td>INCR</td>
</tr>
<tr>
<td>Ti-Pd-Ag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pd-Ni-SOLDER</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate/Backcover</th>
<th>DISCOLORATION</th>
<th>CORROSION</th>
<th>DIFFUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mylar</td>
<td>EMBRITTLEMENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tedlar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus Bar/Interconnects</td>
<td></td>
<td></td>
<td>INCR (40/93)</td>
</tr>
<tr>
<td>Seals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PRELIMINARY LONG-TERM TESTING RESULTS

JET PROPULSION LABORATORY

G.R. Mon

Presentation Outline

- VISUAL OBSERVATIONS
  - ROAD MAPS
  - PHOTOGRAPHS

- ELECTRICAL MEASUREMENTS
  - I-V CURVE
  - INSULATION (DIELECTRIC) DATA

- DATA INTERPRETATION
  - IDENTIFICATION OF DEGRADATION MECHANISMS
  - QUANTIFICATION OF DEGRADATION RATES
  - COMPARISON OF RESULTS WITH RESULTS FROM OTHER LABORATORY TESTS AND FIELD EXPERIENCE
### Visual Observations From Long-Duration Module Tests (112 Days)

<table>
<thead>
<tr>
<th>Generic Module Type</th>
<th>Visual Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>85/85</td>
</tr>
<tr>
<td>Glass/PVdMylar Ag Paste</td>
<td>Discoloration PVd</td>
</tr>
<tr>
<td></td>
<td>Corrosion: Circuitry Grid lines</td>
</tr>
<tr>
<td>RTV Aluminum in Solder</td>
<td>Discoloration RTV</td>
</tr>
<tr>
<td></td>
<td>Microcracks RTV</td>
</tr>
<tr>
<td>Glass/RTV Aluminum in Solder</td>
<td>Discoloration RTV</td>
</tr>
<tr>
<td></td>
<td>Delamination at Terminals</td>
</tr>
<tr>
<td>Glass/PbTeAG Ag Paste</td>
<td>Discoloration PVd</td>
</tr>
<tr>
<td></td>
<td>Corrosion: Circuitry Grid lines</td>
</tr>
<tr>
<td>Glass Fiber RTV Reinforced Polyester</td>
<td>Discoloration Substrate</td>
</tr>
<tr>
<td></td>
<td>Corrosion: Circuitry</td>
</tr>
<tr>
<td>RTV/Glass Fiber in Solder</td>
<td>Discoloration Substrate</td>
</tr>
<tr>
<td></td>
<td>Slight corrosion: Circuitry</td>
</tr>
</tbody>
</table>

### Electrical Measurements

- **I-V Curve Data**
  - $V_{oc}$
  - $I_{sc}$
  - $P_{mp}$
  - $V_{mp}$
  - $I_{mp}$

- **Dielectric Data**
  - $R_{insul}$
  - $C_{insul}$
  - $\tan \delta$
Example I-V Curve Results (85/85 vs 93/40)

Summary of I-V Curve Findings (112 Days)

<table>
<thead>
<tr>
<th>GENERIC MODULE TYPE</th>
<th>(\Delta l_{oc} %)</th>
<th>(\Delta R_s %)</th>
<th>(\Delta P_{mp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLASS/PVB/MYRAR Ag PASTE</td>
<td>-5 0</td>
<td>+100 10</td>
<td>-40 1</td>
</tr>
<tr>
<td>RTV/ALUMINUM IN SOLDER</td>
<td>-2.5 0</td>
<td>+20 0</td>
<td>-2.5 1</td>
</tr>
<tr>
<td>GLASS/RTV/ALUMINUM IN SOLDER</td>
<td>0 0</td>
<td>0 0</td>
<td>0 1</td>
</tr>
<tr>
<td>GLASS/PVB/TEFLON Ag PASTE</td>
<td>-5 0</td>
<td>+60 10</td>
<td>-20 1</td>
</tr>
<tr>
<td>RTV/GLASS FIBER REINFORCED POLYESTER Ti-Pe Ag</td>
<td>-4 0</td>
<td>+100 10</td>
<td>-15 1</td>
</tr>
<tr>
<td>RTV/GLASS FIBER IN SOLDER</td>
<td>-3 0</td>
<td>+100</td>
<td>-20 1</td>
</tr>
</tbody>
</table>

* AFTER SUBTRACTING THE CONTRIBUTION DUE TO \(l_{oc} \) LOSS, THE POWER LOSS RATE IS FOUND TO BE ROUGHLY ONE TENTH THE RATE OF SERIES RESISTANCE INCREASE.
Comparison Overview of Wyle and Clemson Tests

<table>
<thead>
<tr>
<th>TEST SPECIMENS:</th>
<th>WYLE</th>
<th>CLEMSON</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINIMODULES</td>
<td></td>
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</tr>
<tr>
<td>TESTS:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>65/85 - FB</td>
<td>85/85 - FB</td>
</tr>
<tr>
<td></td>
<td>65/65 - UB</td>
<td>85/85 - UB</td>
</tr>
<tr>
<td></td>
<td>93/40 - FB</td>
<td>15 psig STEAM/121 - FB</td>
</tr>
<tr>
<td></td>
<td>93/40 - UB</td>
<td>15 psig STEAM/121 - UB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UNENCAPSULATED CELLS</th>
<th>WYLE</th>
<th>CLEMSON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0/85 - FB</td>
<td>0/75 - FB</td>
</tr>
<tr>
<td></td>
<td>0/85 - UB</td>
<td>0/75 - UB</td>
</tr>
<tr>
<td></td>
<td>0/100 - FB</td>
<td>0/135 - FB</td>
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<tr>
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<td>0/100 - UB</td>
<td>0/135 - UB</td>
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<td>0/150 - FB</td>
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<td></td>
<td>0/150 - UB</td>
<td>0/165 - FB</td>
</tr>
<tr>
<td></td>
<td>0/165 - UB</td>
<td></td>
</tr>
</tbody>
</table>
Mean Percentage Decrease in $P_m$ vs Stress Time
(85°C/85% RH Test)
Behavior of $R_s$ With B-T Stress Time: Typical Type A Cells

![Graph showing the behavior of $R_s$ with B-T stress time for typical Type A Cells at different temperatures.](image-url)
Acceleration of Humidity and Temperature

![Graph showing acceleration of humidity and temperature](image)

- **20-yr SITE ENVIRONMENT**
- **BROWNSVILLE**
- **PHOENIX**
- **FRENCH**
- **RS, B CELLS, WYLE**
- **RS, GLASS/PVB/MYLLAR WYLE**
- **RS, A CELLS, CLEMSON**

**Time, h**

**Cell Temperature °C + % RH**

**Legend:**
- △ FIELD TEST RESULTS
- ○ LABORATORY TEST RESULTS
- □ QUALIFICATION TEST LEVEL
- □ DEGRADATION RATE CURVE FROM RTC
Wyle-Clemson Test Comparisons: Conclusions

• SERIES RESISTANCE INCREASES ARE COMPARABLE IN THE WYLE AND CLEMSON TESTS

• THE MAXIMUM POWER LOSSES DUE TO $I_{sc}$ DECREASE AND $R_s$ INCREASE ARE SEPARATELY DETERMINABLE

• IGNORING SHUNT, RESISTANCE EFFECTS, THE RATE OF $R_s$ INCREASE IS APPROXIMATELY TEN TIMES THE RATE OF ASSOCIATED $P_m$ DECREASE

• ACCELERATION CURVES SUGGEST THAT, BASED UPON DEGRADATION OF SERIES RESISTANCE, THE FRENCH AND THE BLOCK V QUALIFICATION TESTS ARE EQUIVALENT

• 85/85 TEST CONDITIONS REQUIRE 40-250 DAYS OF OPERATION TO QUALITY MODULES FOR 20-YEAR FIELD SERVICE

• ALL RESULTS ARE PRELIMINARY. ADDITIONAL TESTING AND ANALYSIS IS NECESSARY TO ESTABLISH:

  • PRECISE DEGRADATION MECHANISMS AND RATES

  • RELIABLE HUMIDITY/TEMPERATURE-BIAS QUALIFICATION TEST PARAMETERS
Research Plans

- ADDITIONAL TESTING
  - LONGER DURATION 93/40
  - CONTINUE TEMPERATURE-ONLY TESTS
  - NEW INTERMEDIATE HUMIDITY/TEMPERATURE TEST LEVELS
  - POSSIBLE RETESTING WITH NEW GENERIC MODULE TYPES

- DETAILED FAILURE MECHANISM ANALYSIS AND DETERMINATION OF FUNCTIONAL DEPENDENCE

- CORRELATION OF LONG-DURATION TEST DATA WITH PAST AND FUTURE CLEMSON CELL TESTS

- REPORTING
  - FAILURE-MECHANISM STUDY RESULTS
  - RECOMMENDATIONS FOR IMPROVED QUAL TEST PROCEDURES
    - BLOCK VI
    - INTERNATIONAL STANDARDS (IEC)