N83 10523 D18-44

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 optimum 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 simulted 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 PIM 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.

D. H. Otth (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.

PV ARRAY/POWER-CONDITIONER INTERFACE UPDATE

JET PROPULSION LABORATORY

C.C. Gonzalez

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/cm^2)**

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**

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Correlation of Computer Simulation Results With Weather Atlas Data

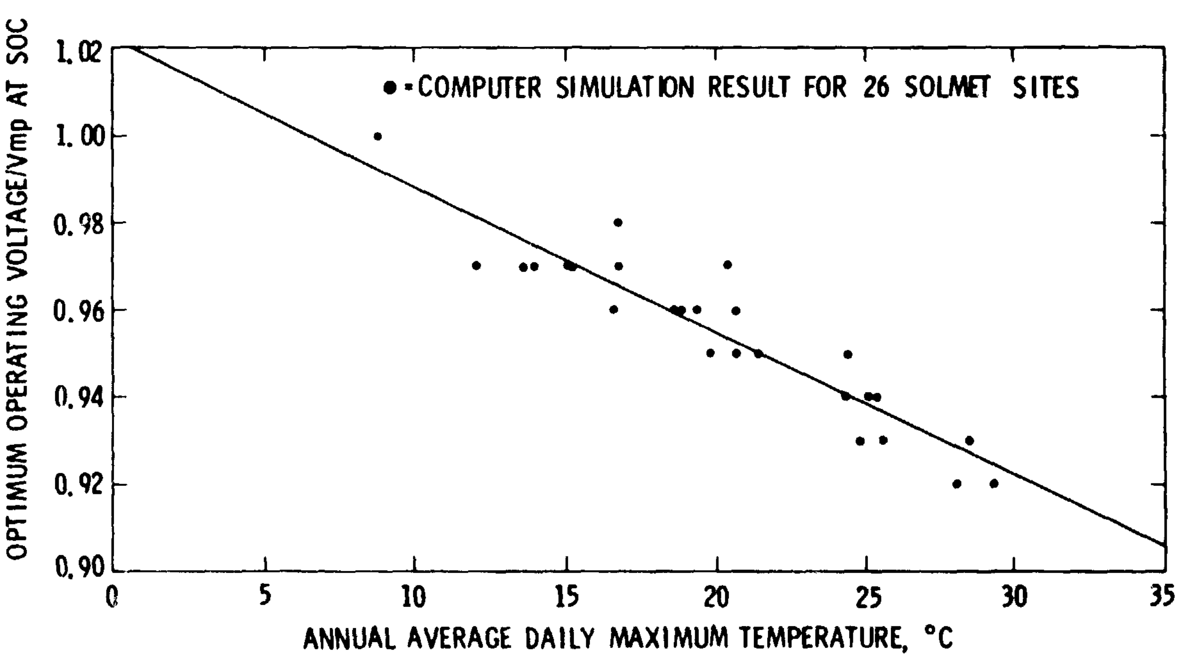
PROBLEM:

- **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**

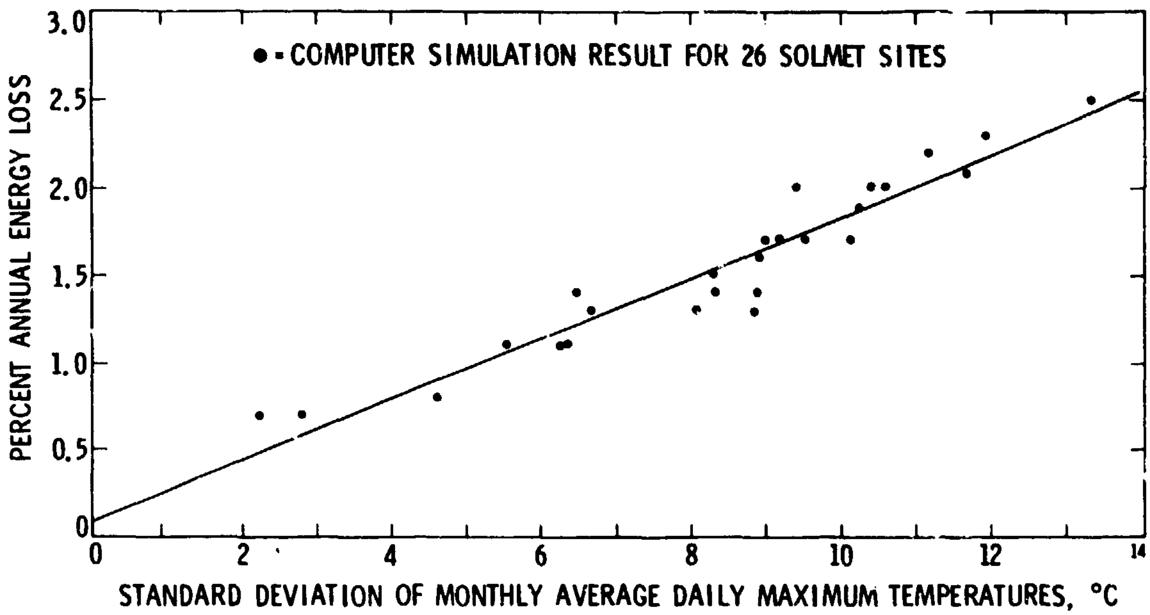
SOLUTION:

- **OBTAIN CORRELATIONS WITH VARIOUS WEATHER ATLAS DATA:**
  - **ANNUAL AVERAGE DAILY MAXIMUM TEMPERATURE**
  - **STANDARD DEVIATION OF DAILY MAXIMUM TEMPERATURE**
  - **K_d = DIFFUSE FRACTION OF EXTRATERRESTRIAL SOLAR IRRADIANCE**
  - **K_d/K_T = DIFFUSE FRACTION OF SURFACE SOLAR IRRADIANCE**
  - **COLDEST RECORDED TEMPERATURE**

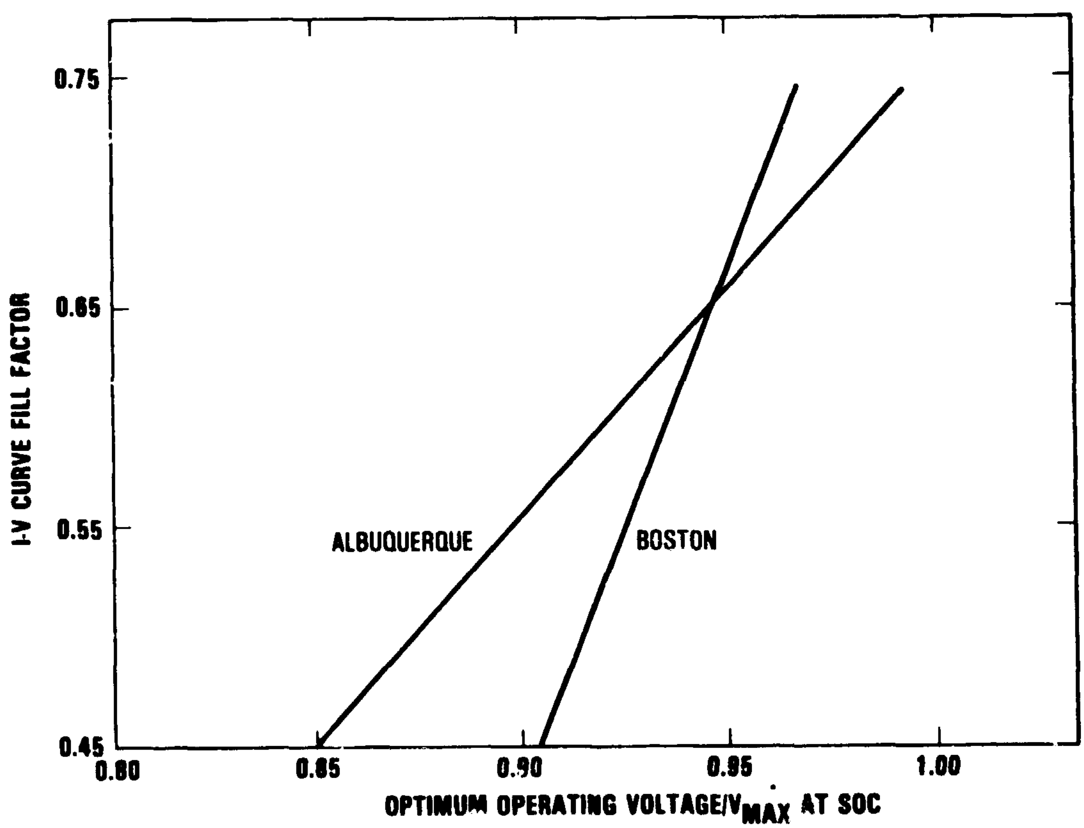
Array Optimum Operating Voltage vs Average Daily Maximum Temperature



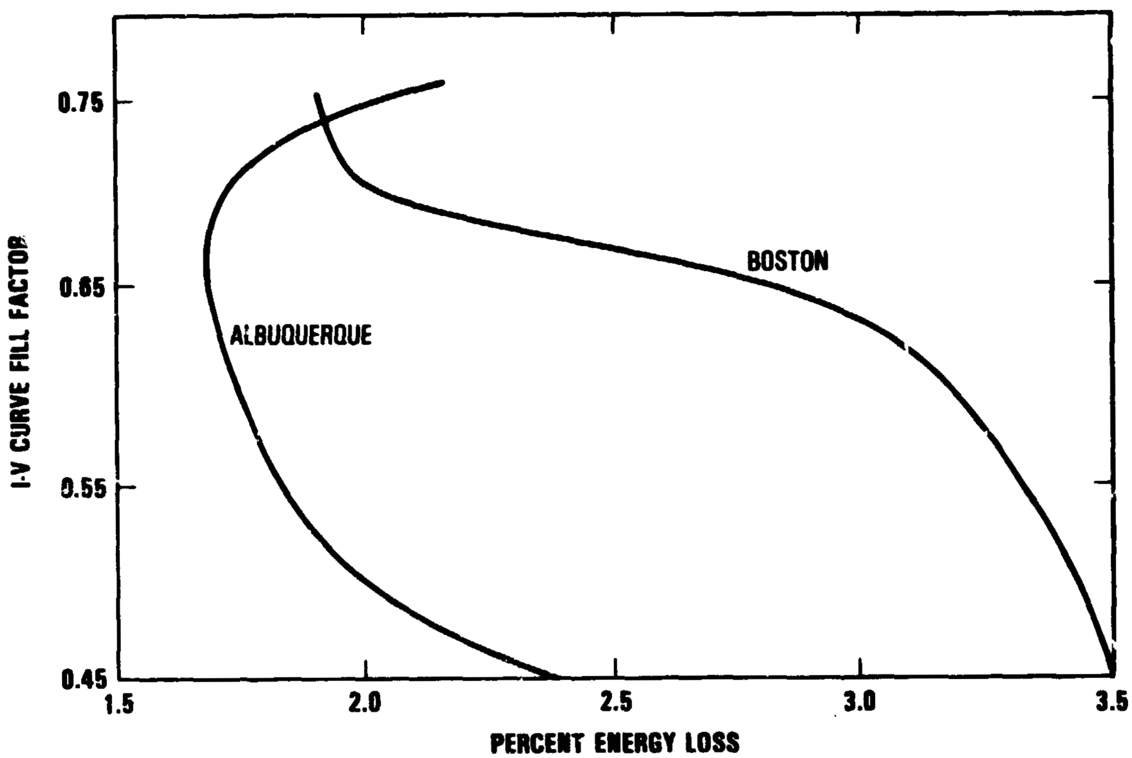
Array Annual Energy Loss With Fixed-Voltage Operation vs Standard Deviation of Daily Maximum Temperature



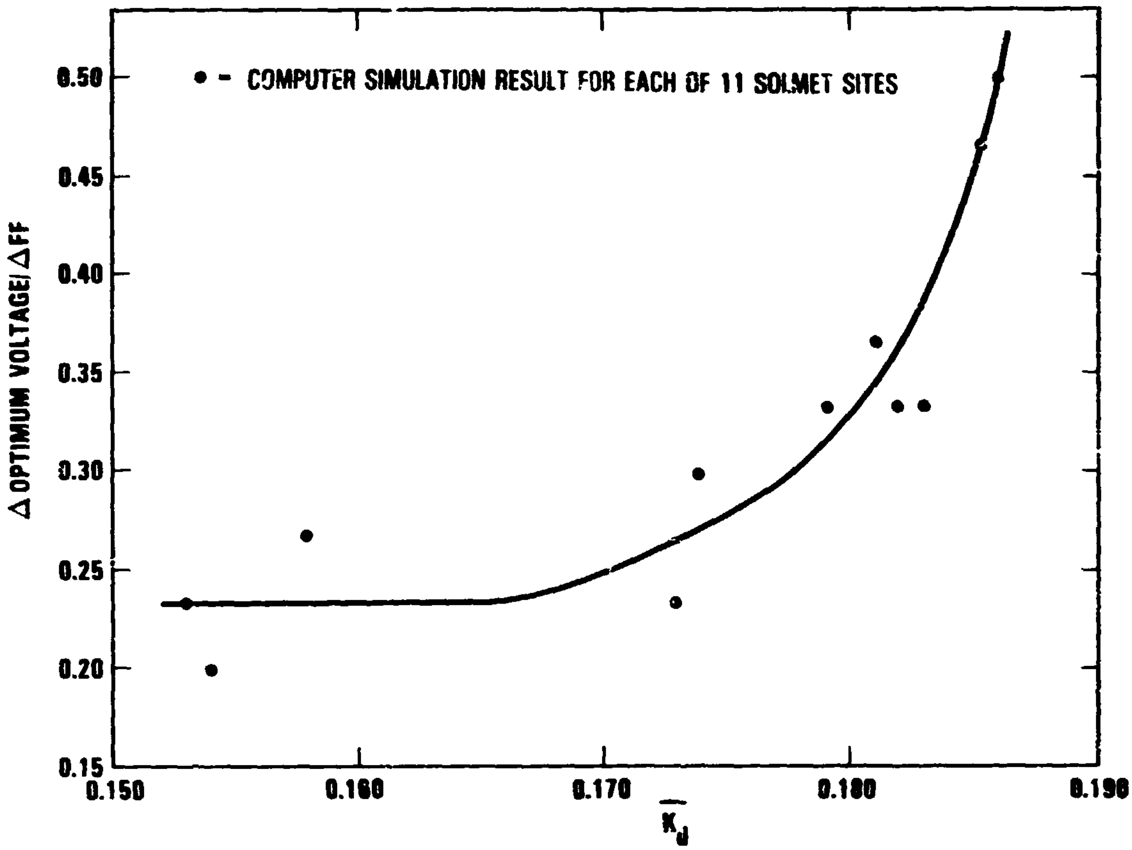
Optimum Operating Voltage vs Fill Factor



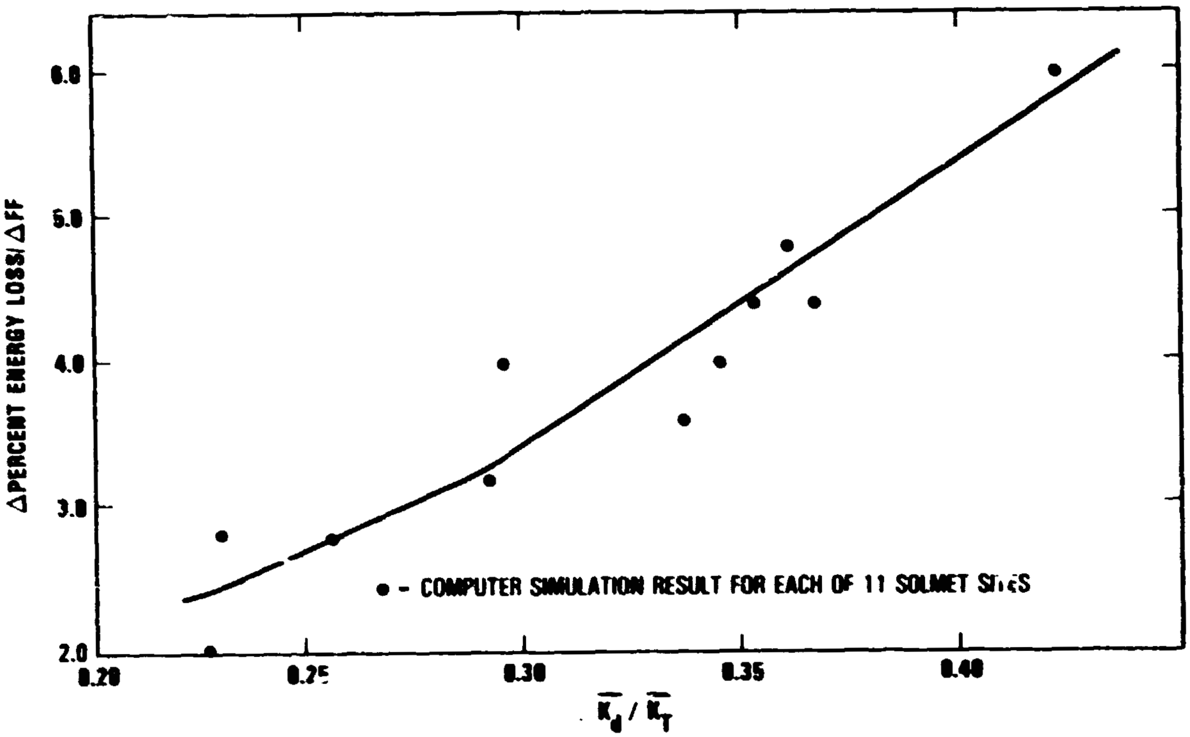
Percentage of Energy Loss vs Fill Factor



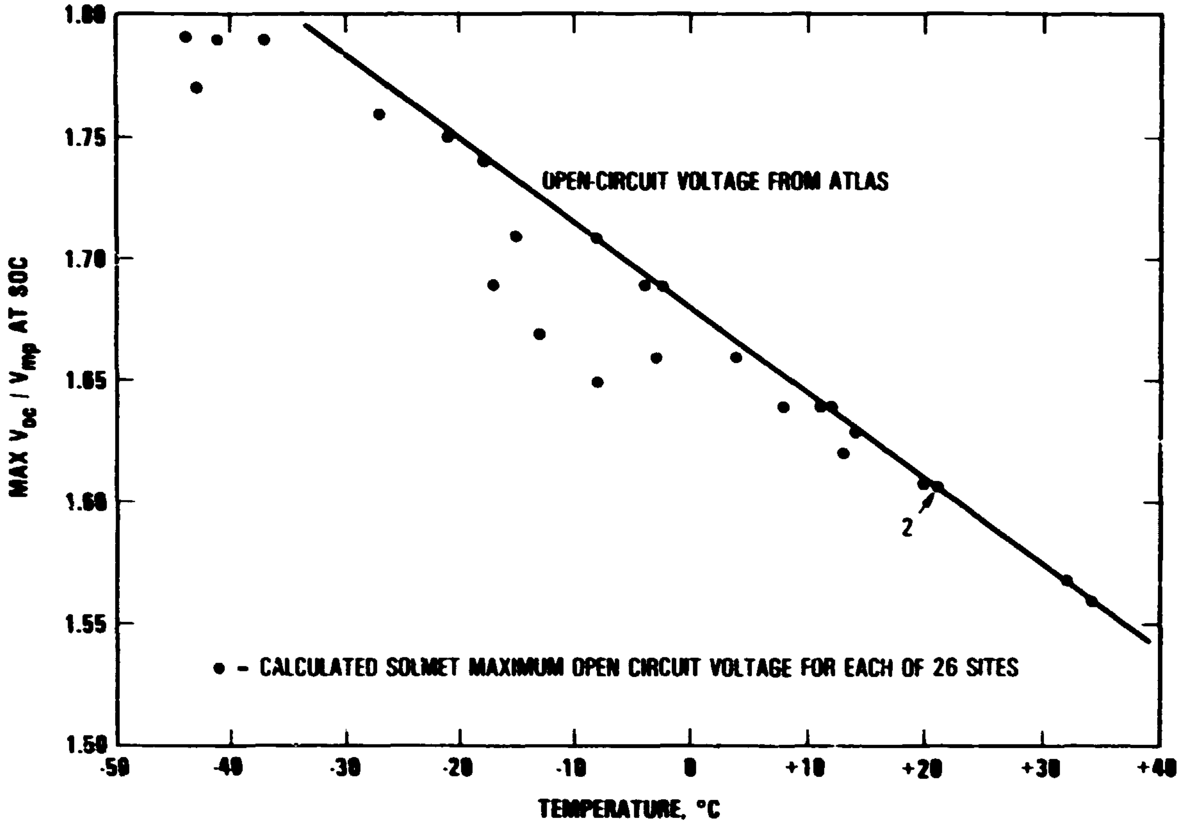
Rate of Change of Optimum Voltage With Fill Factor vs $\overline{K_d}$



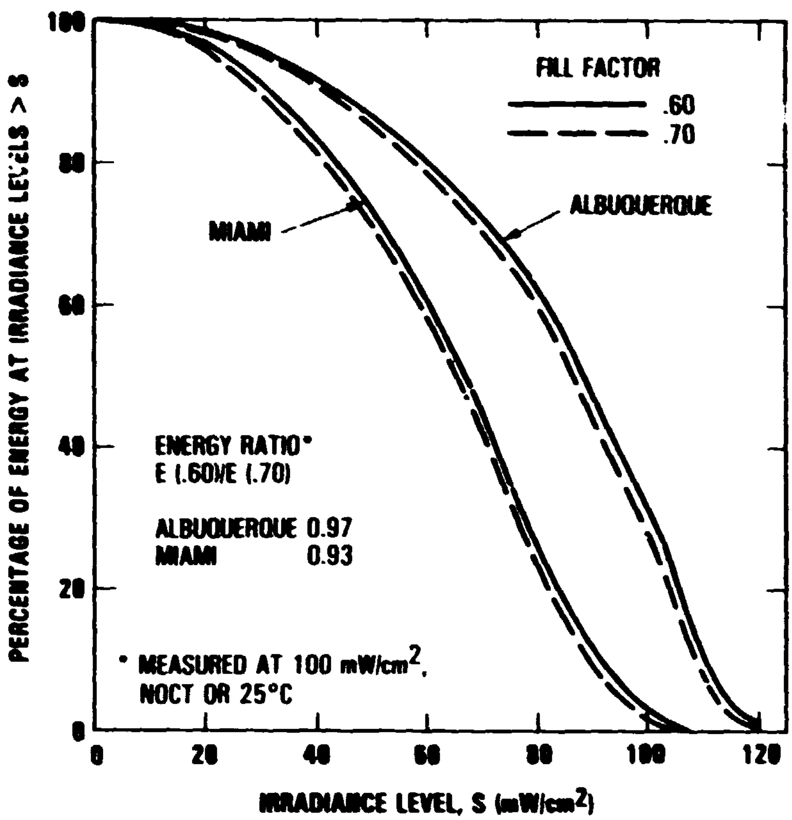
Rate of Change of Energy Loss With Fill Factor vs $\overline{K_d}/\overline{K_T}$



Maximum Open-Circuit Voltage (From SOLMET TMY) vs Atlas Lowest Recorded Temperature



Array Energy Output vs Irradiance

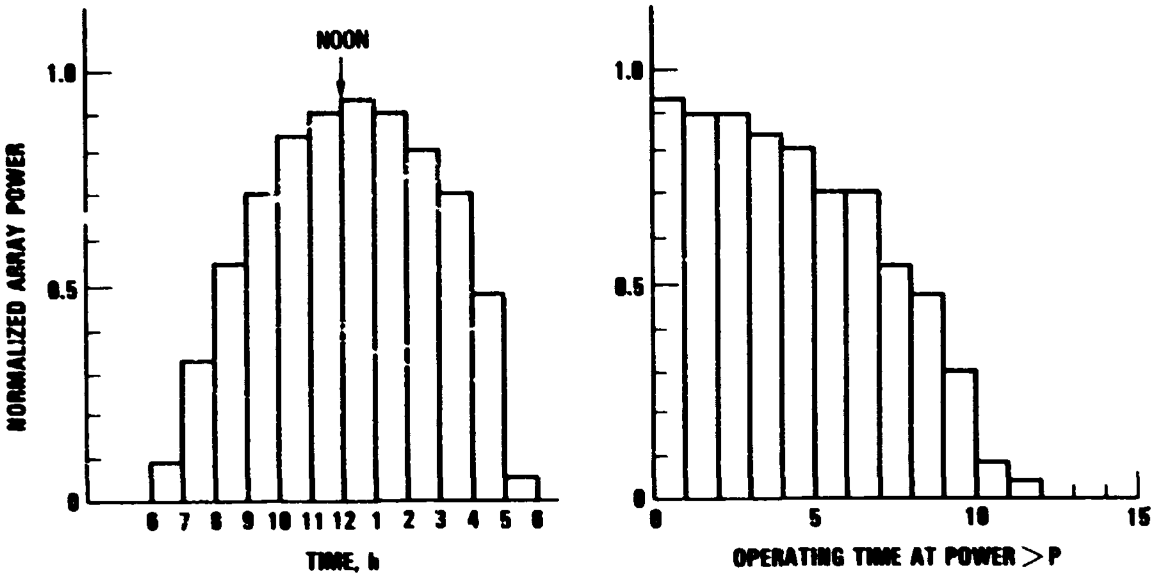


Comparison of Analysis Results With Variation in Array Tilt Angle

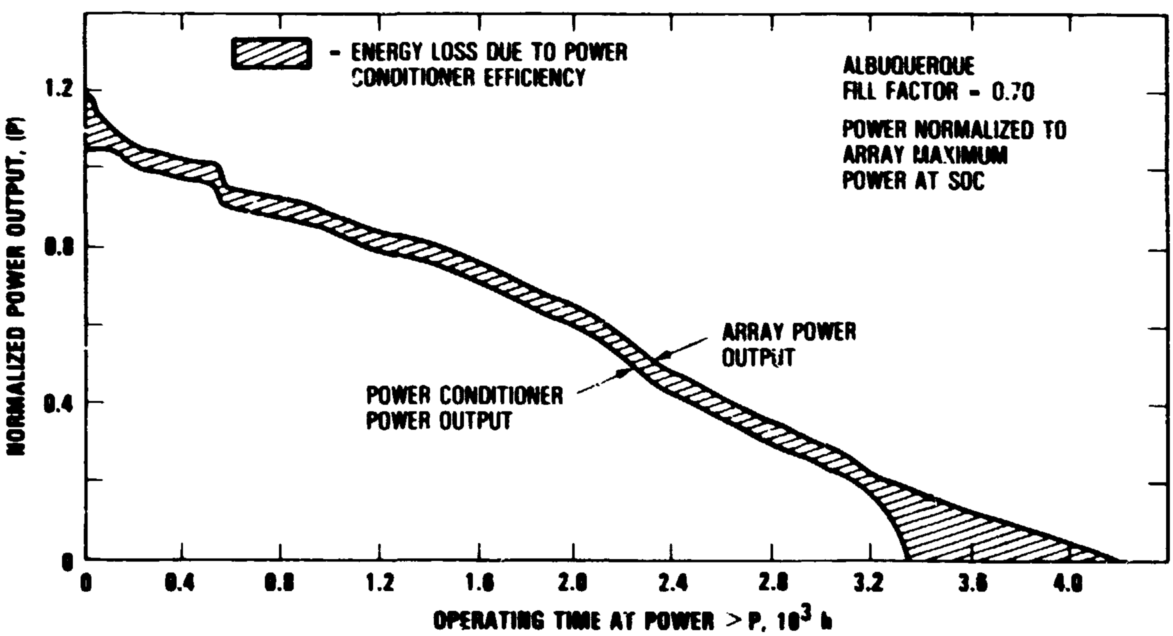
SITE	TILT ANGLE (DEGREES)	OPTIMUM OPERATING VOLTAGE	% ENERGY LOSS	± % VOLTAGE TRACKING WIDTH TO OBTAIN 0.1% LOSS	POWER LIMITS REQUIRED TO OBTAIN % ENERGY LOSS		CURRENT LIMITS REQUIRED TO OBTAIN % ENERGY LOSS	
					99.0	99.9	99.0	99.9
ALBUQUERQUE	35.05*	0.96	1.7	8.5	1.04	1.13	1.06	1.17
	20.05	0.95	1.7	8.5	1.01	1.11	1.04	1.15
	50.05	0.96	1.6	8.5	1.06	1.15	1.06	1.17
MIAMI	25.80*	0.93	0.7	5.5	0.82	0.91	0.86	0.97
	10.80	0.93	0.7	5.5	0.80	0.88	0.88	0.94
	40.80	0.93	0.7	6.0	0.83	0.93	0.87	0.98
BISMARCK	46.77*	0.97	2.5	12.5	0.96	1.08	0.95	1.05
	31.77	0.97	2.4	12.5	0.94	1.06	0.96	1.05
	61.77	0.98	2.7	13.0	0.95	1.10	0.93	1.04

* TILT ANGLE EQUALS SITE LATITUDE

Normalized Power vs Operating Time



Effect of Power Conditioner Efficiency on Array Annual Power Production



Fraction of Annual Array Energy Available in Various Relative Power Intervals

SITE	ARRAY RELATIVE POWER INTERVAL					
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.9	1.0-1.2
ALBUQUERQUE NM	0.0343	0.0782	0.1040	0.2133	0.3693	0.2010
BISMARCK ND	0.0750	0.1363	0.146[illegible]	0.2435	0.3277	0.0739
BOSTON MA	0.0907	0.1383	0.1965	0.2840	0.2741	0.0163
BROWNSVILLE TX	0.0572	0.1393	0.2025	0.3967	0.1905	0.0138
CARIBOU ME	0.0779	0.1734	0.1754	0.2511	0.2542	0.0689
CHARLESTON SC	0.0541	0.1512	0.1996	0.3749	0.2043	0.0158
FORT WORTH TX	0.0590	0.1185	0.1642	0.3184	0.2995	0.0403
FRESNO CA	0.0446	0.0990	0.1213	0.2721	0.4098	0.0533
MIAMI FL	0.0508	0.1554	0.2382	0.4448	0.1073	0.0035
OMAHA NB	0.0682	0.1282	0.1426	0.2723	0.3119	0.0767
PHOENIX AZ	0.0339	0.0679	0.1275	0.3091	0.3821	0.0596
SEATTLE WA	0.1302	0.1603	0.1847	0.2524	0.2692	0.0032
AVERAGE	0.0647	0.1305	0.1667	0.3027	0.2833	0.0522
CUMULATIVE VALUE OF AVERAGES	0.0647	0.1952	0.3619	0.6646	0.9479	1.0000

Summary and Conclusions

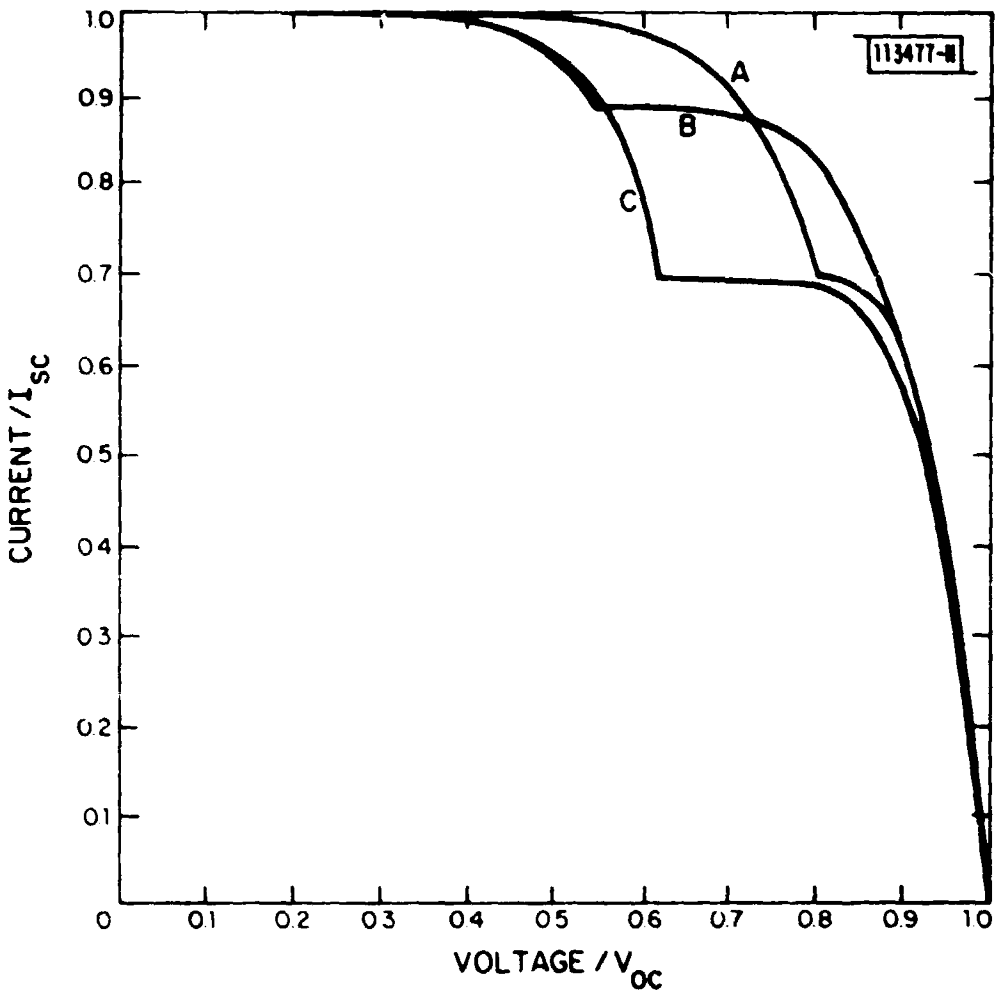
- **EXCELLENT CORRELATIONS OBTAINED WITH RECORDED WEATHER DATA FOR FOLLOWING:**
  - **ARRAY OPTIMUM OPERATING VOLTAGE**
  - **ANNUAL ENERGY LOSS (%)**
  - **VARIATION OF OPTIMUM OPERATING VOLTAGE AND ENERGY LOSS (%) WITH FILL FACTOR**
  - **MAXIMUM OPEN-CIRCUIT VOLTAGE**
- **SENSITIVITY OF ANALYSIS RESULTS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

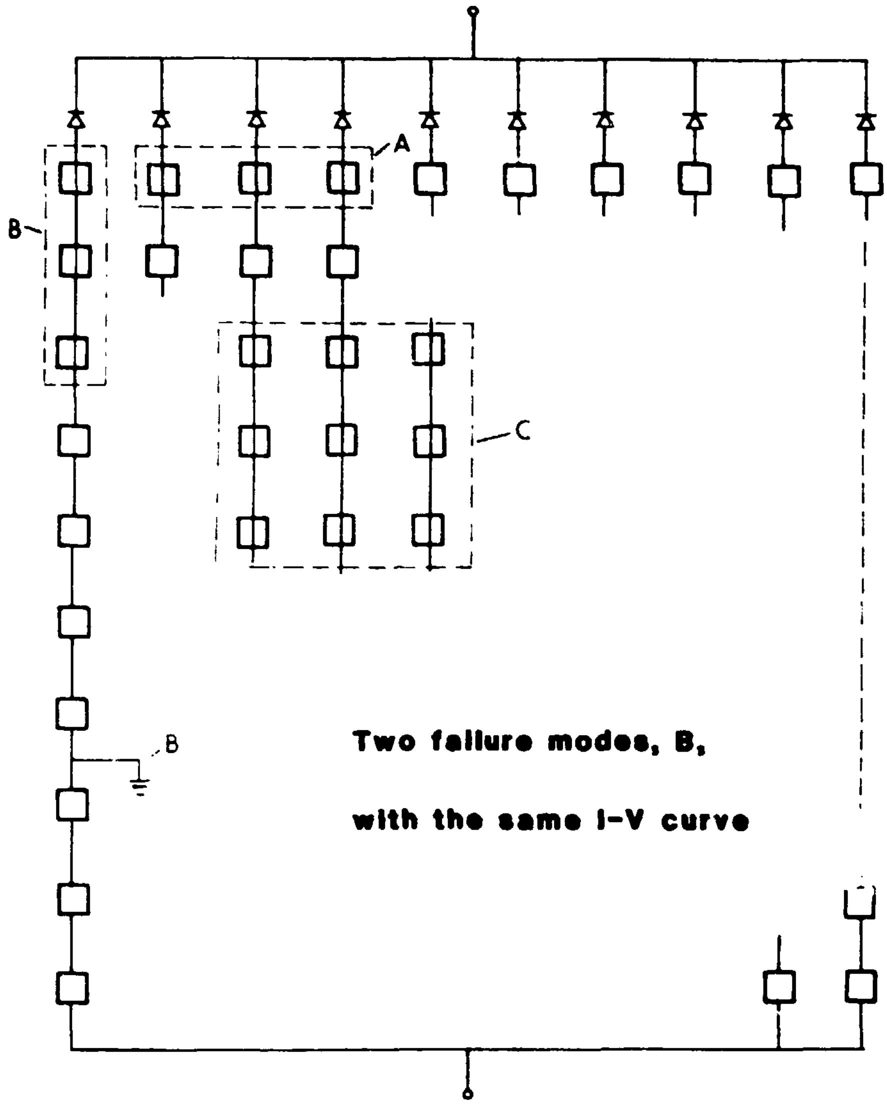
MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

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

Typical Single "Glitch-Point" Curves



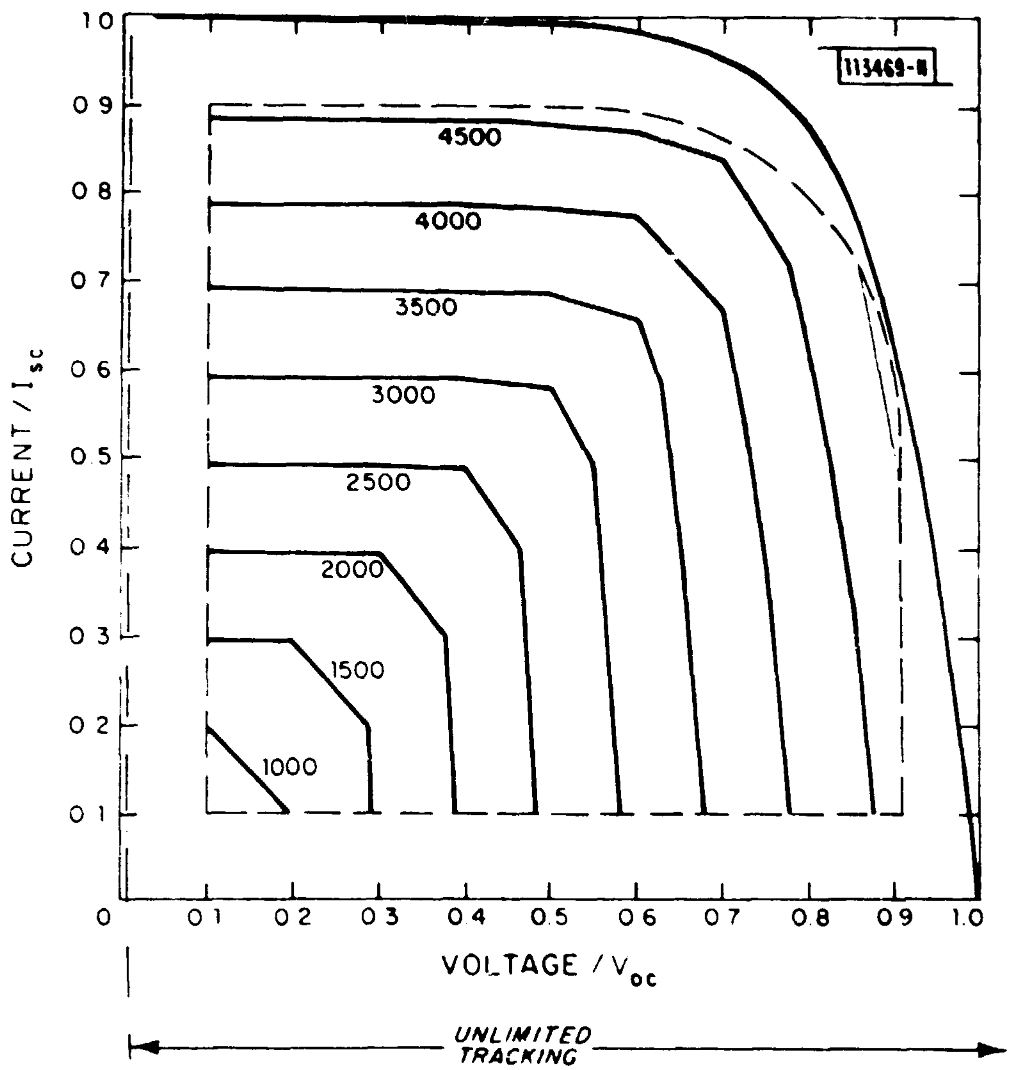
Shorts in a Series-Wired Array

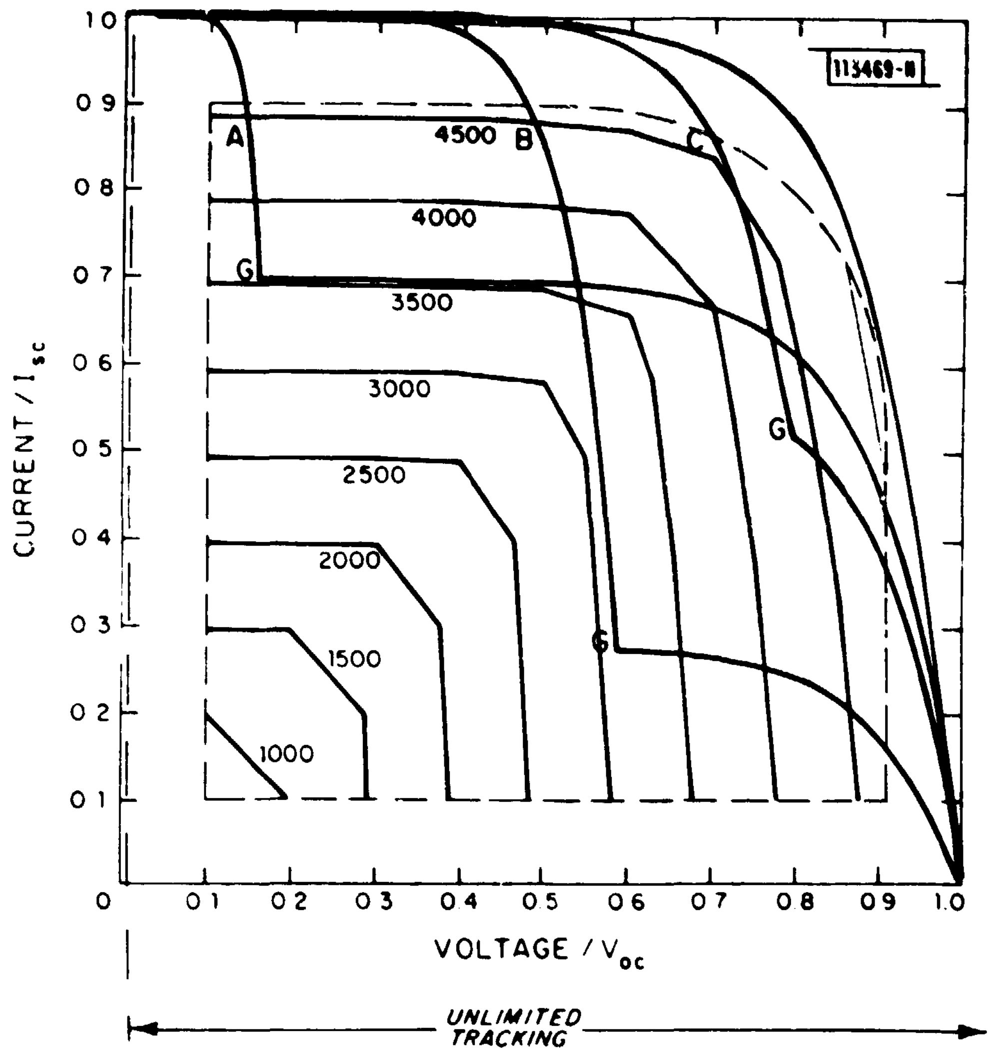


Method

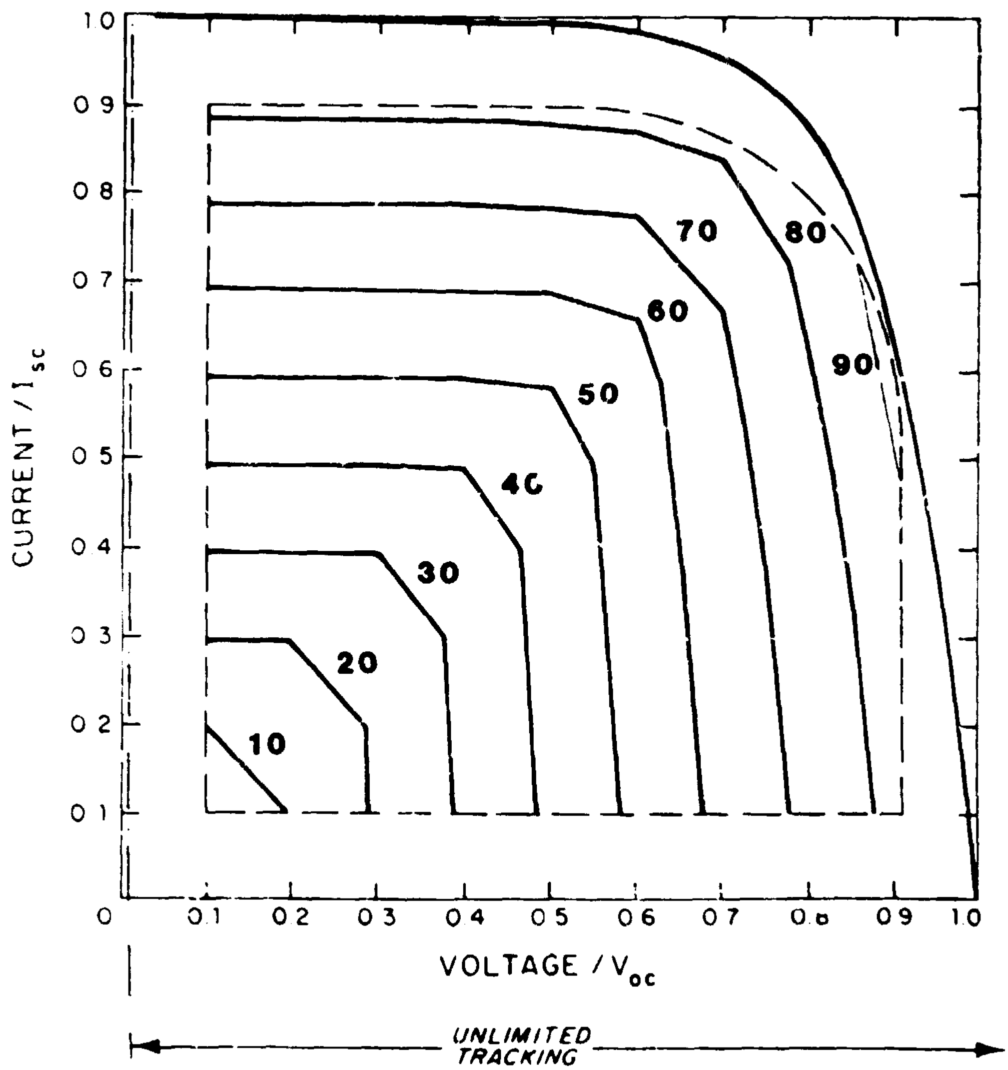
- o Focus on resulting curve shape; not on underlying failure
- o Assume single "glitch-point" curves
- o Simulate using TMY hourly data
- o Compare annual energy between ideal maximum power tracker and best fixed voltage

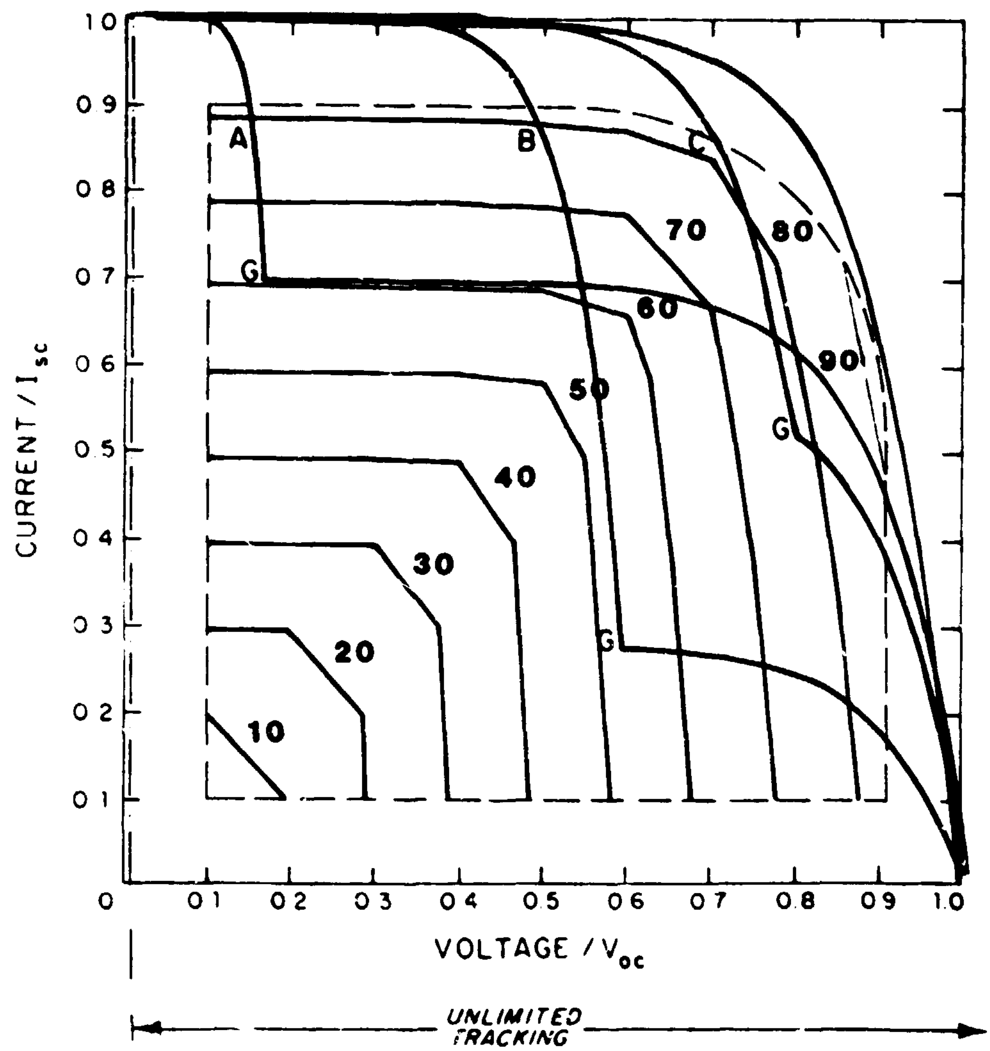
MPT Array Energy as a Function of Glitch-Point Location



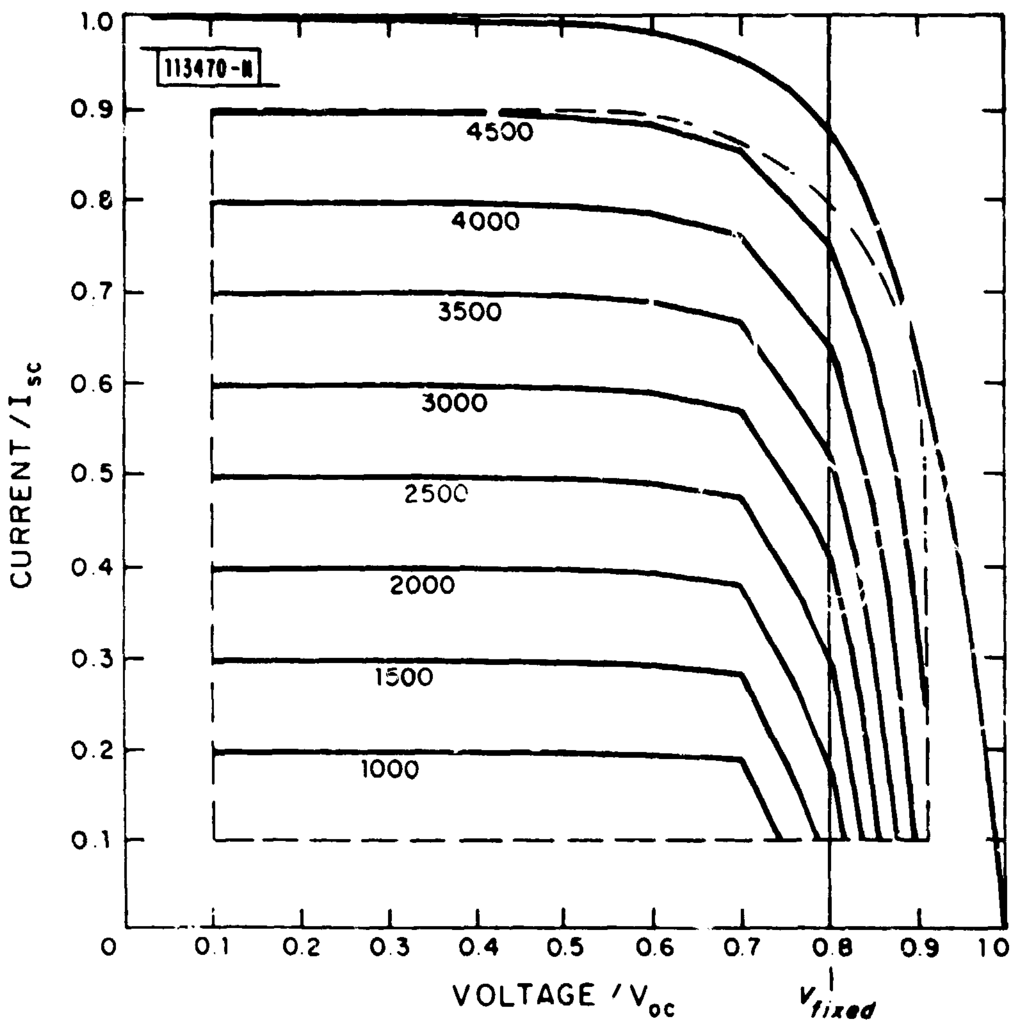

113469-H
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
CURRENT / I_{sc}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
VOLTAGE / V_{oc}
A
B
C
G
G
G
4500
4000
3500
3000
2500
2000
1500
1000
UNLIMITED TRACKING

Percentage of MPT Array Energy vs Glitch-Point Location




CURRENT / I_{sc}
VOLTAGE / V_{oc}
A
B
C
G
10
20
30
40
50
60
70
80
90
UNLIMITED TRACKING

BFV Array Energy as a Function of Glitch-Point Location



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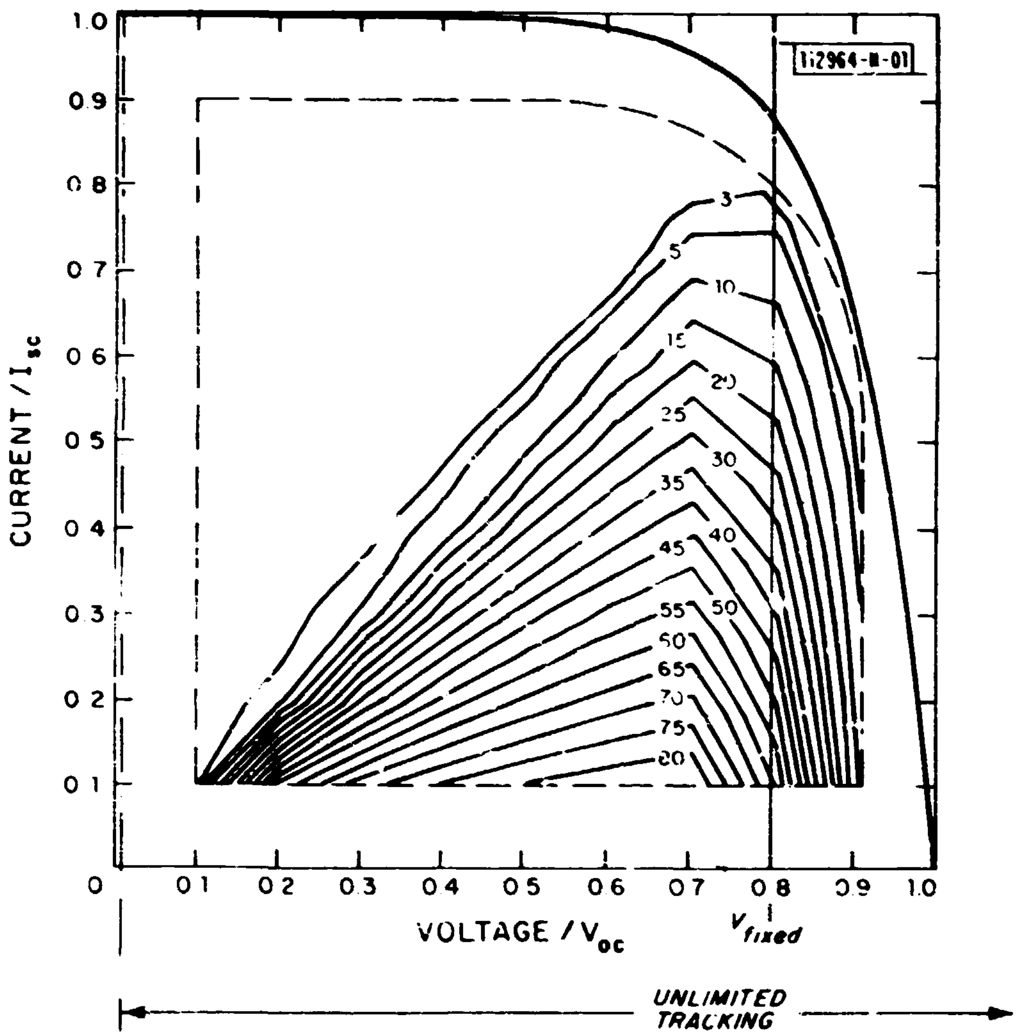
BFV Losses Relative to Full-Range MPT



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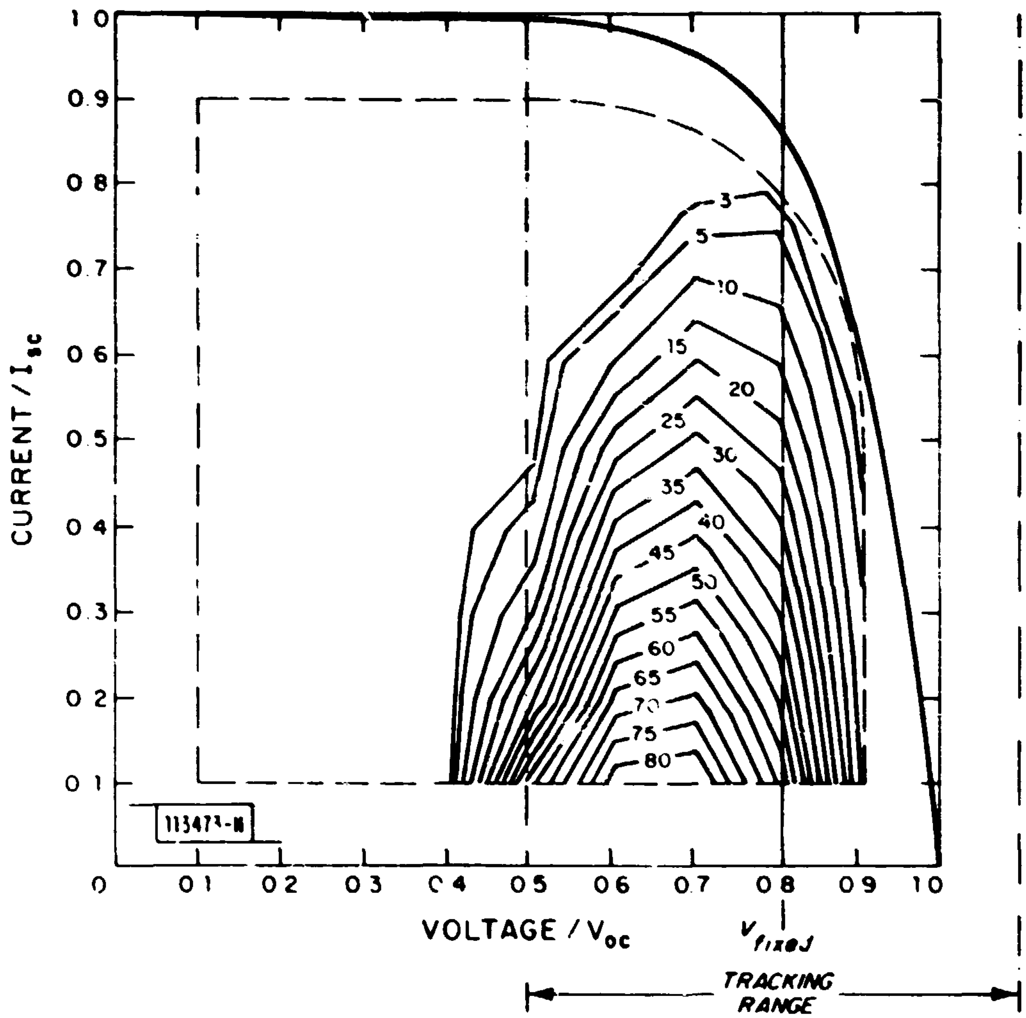
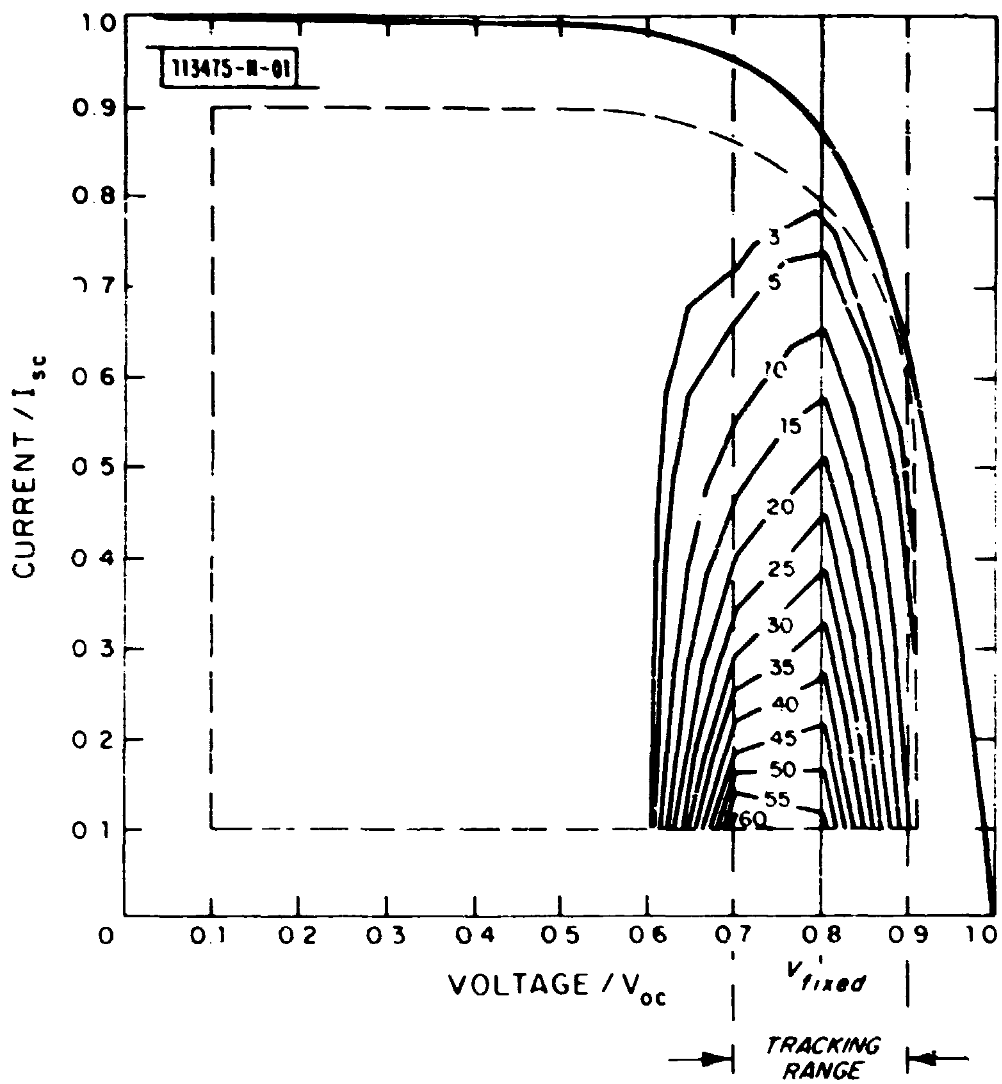
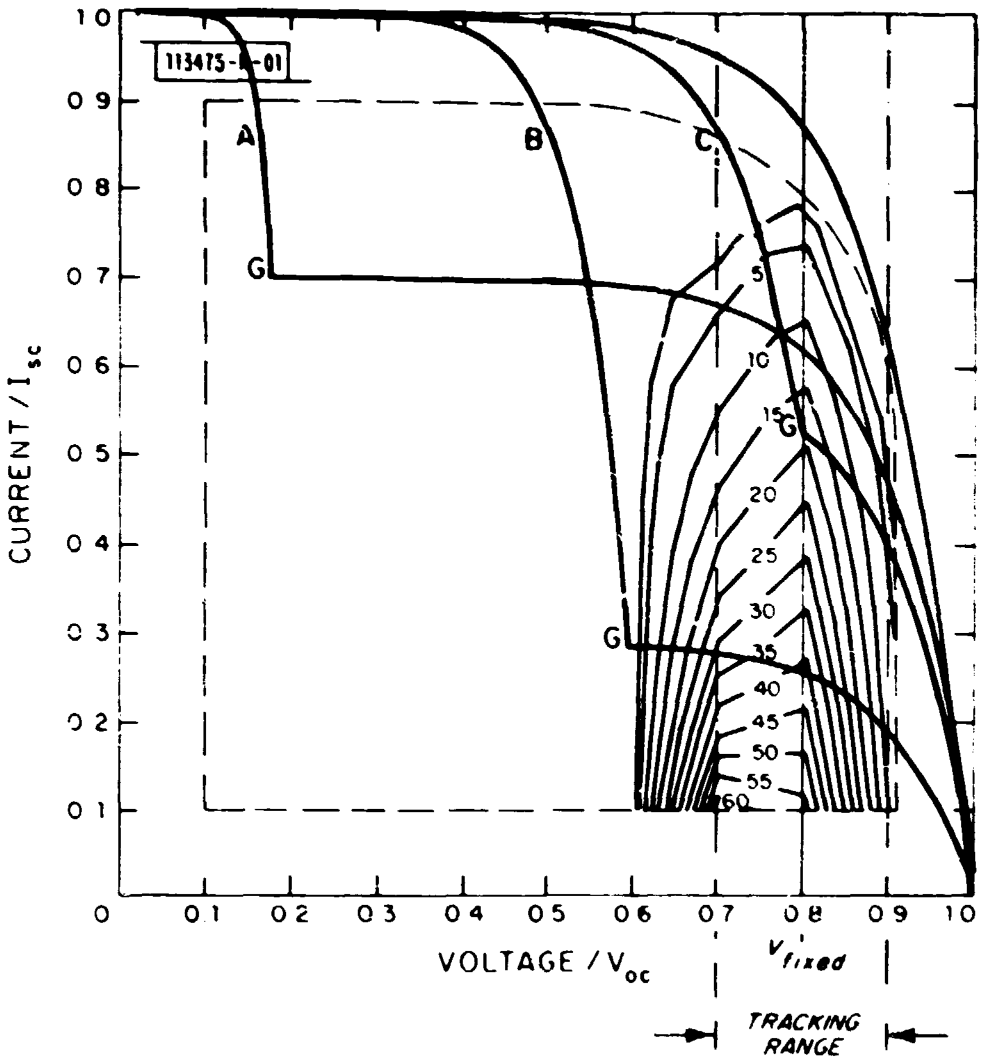
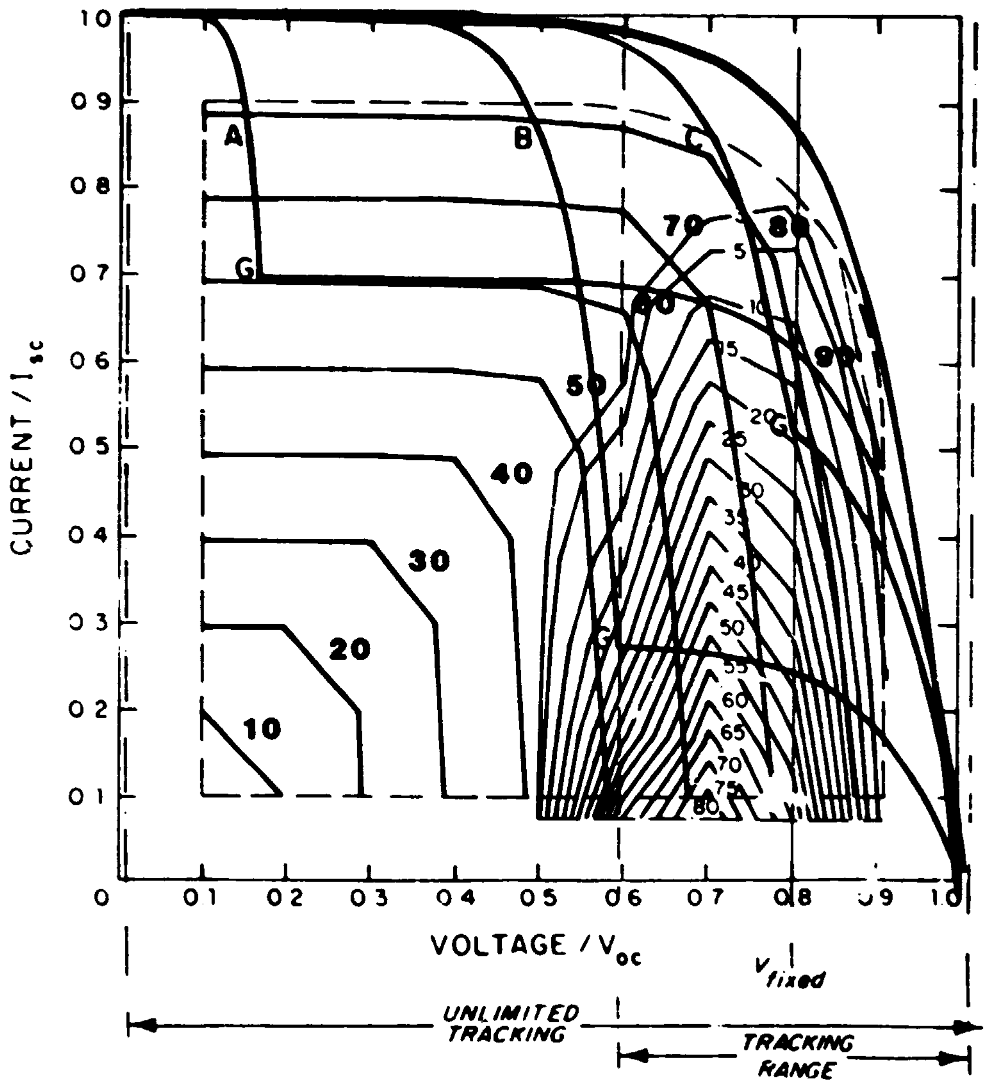
BFV Losses Relative to Limited-Range MPT



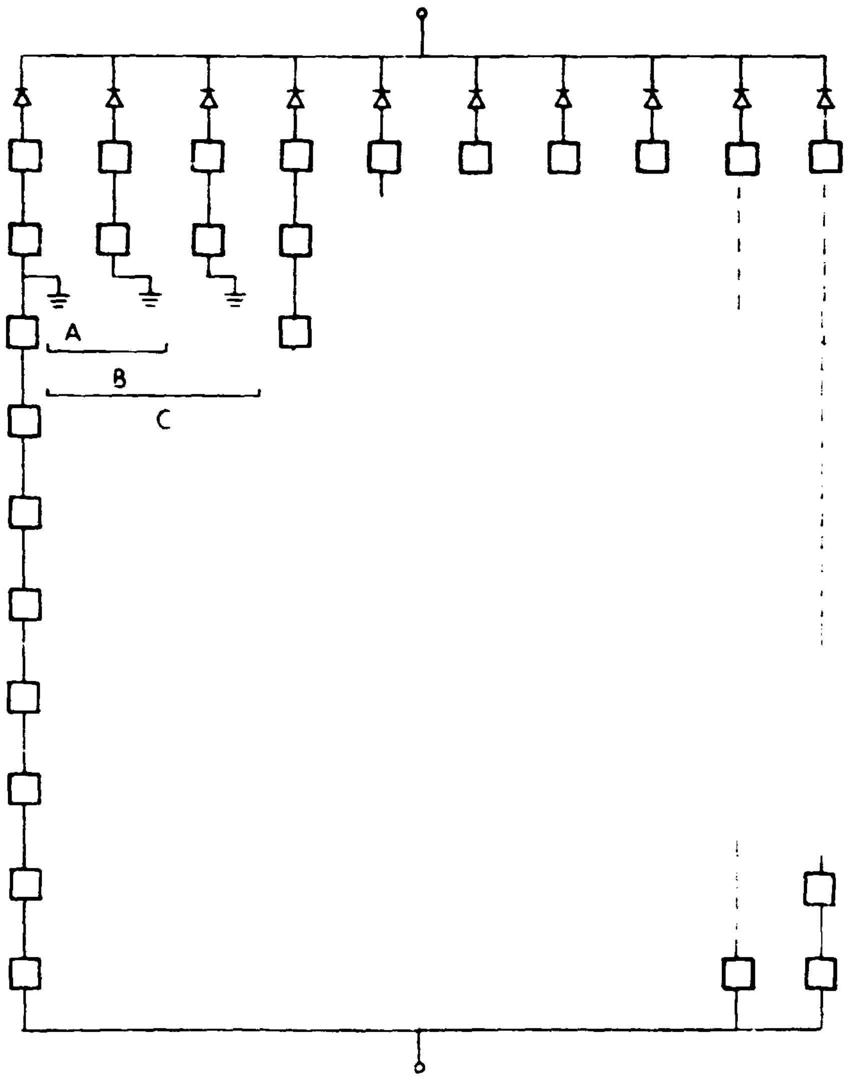

113475-II-01
CURRENT / I_{sc}
VOLTAGE / V_{oc}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
3
5
10
15
20
25
30
35
40
45
50
55
60
V_{fixed}
TRACKING RANGE

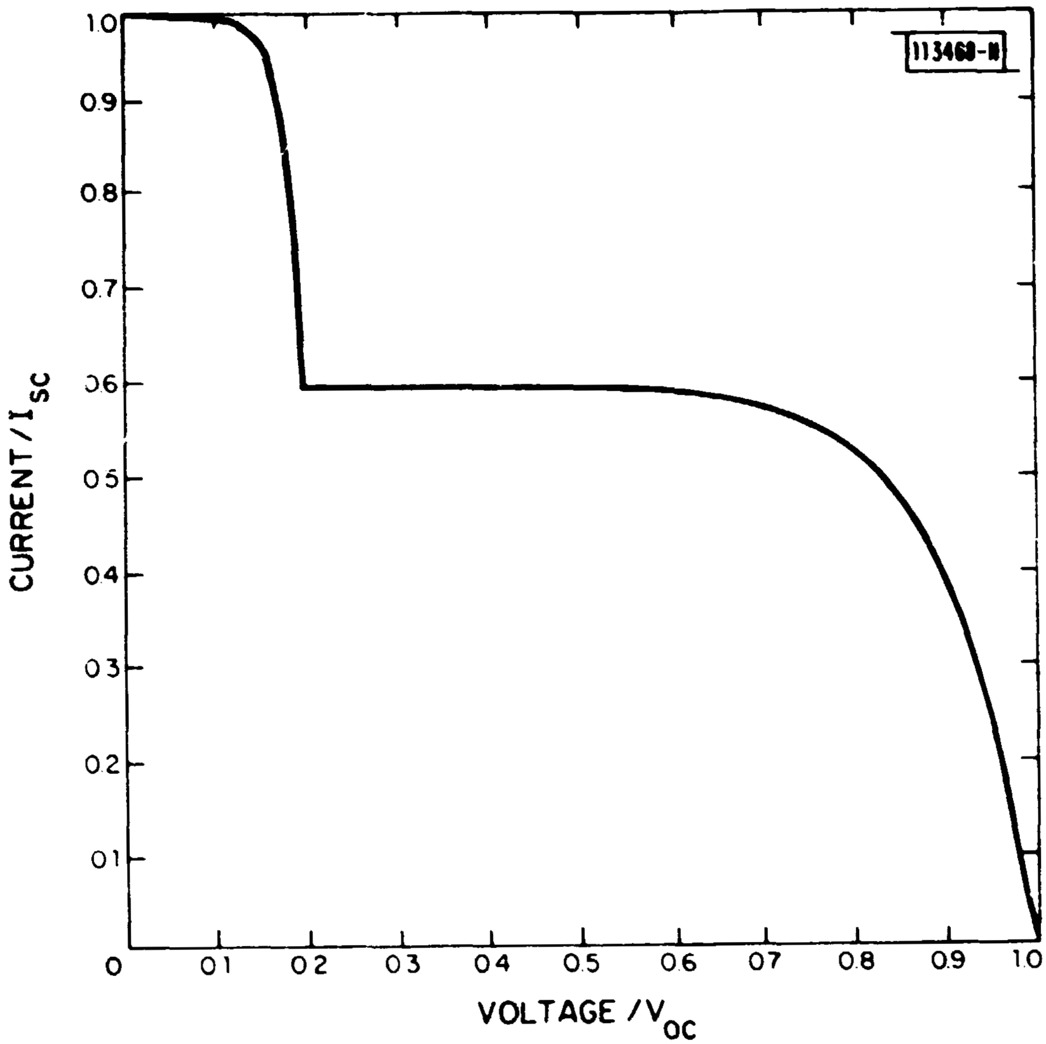

113475-B-01
CURRENT / I_{sc}
VOLTAGE / V_{oc}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
A
B
C
G
G
G
5
10
15
20
25
30
35
40
45
50
55
60
V'_{fixed}
TRACKING RANGE

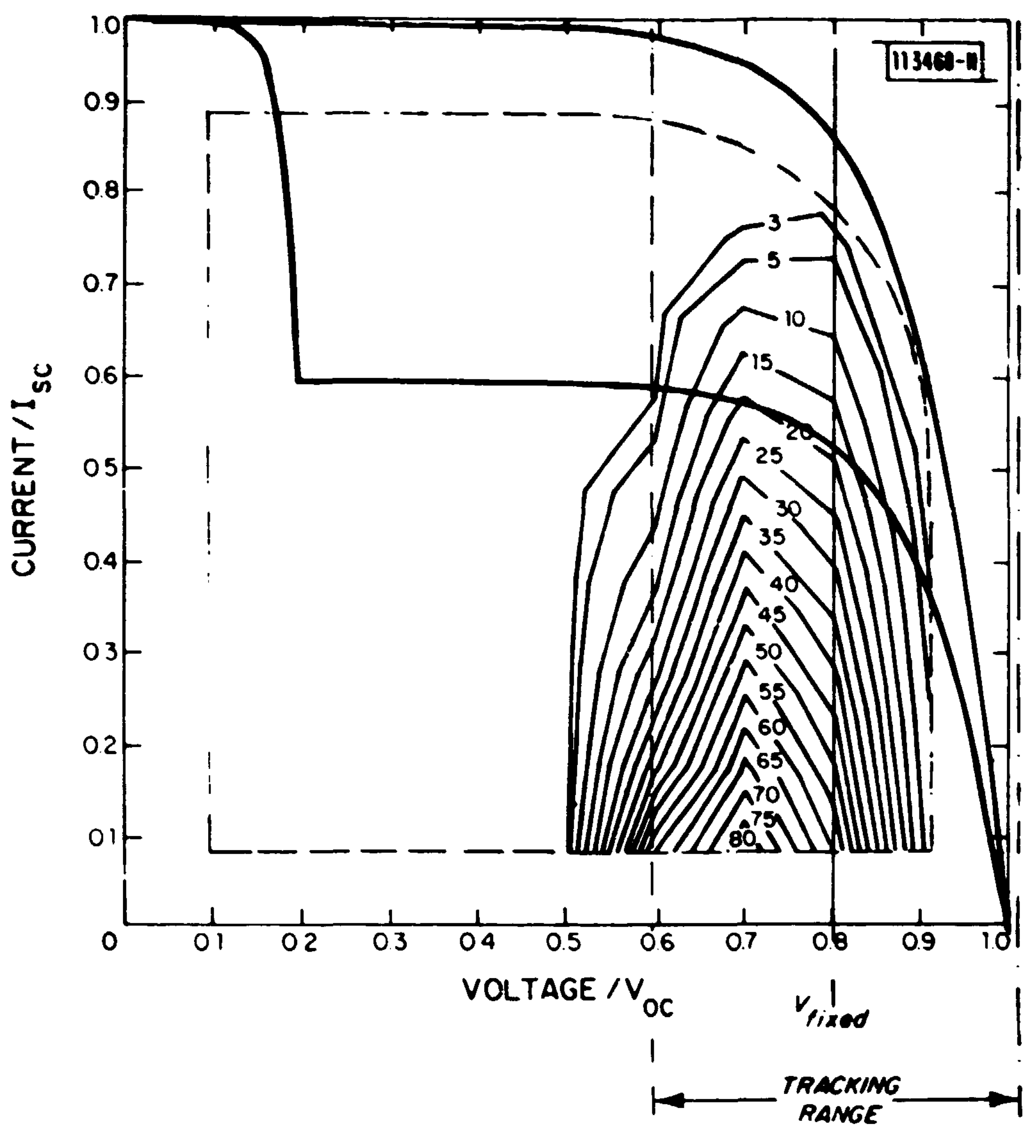
Percent of MPT Array Energy vs Glitch-Point Location



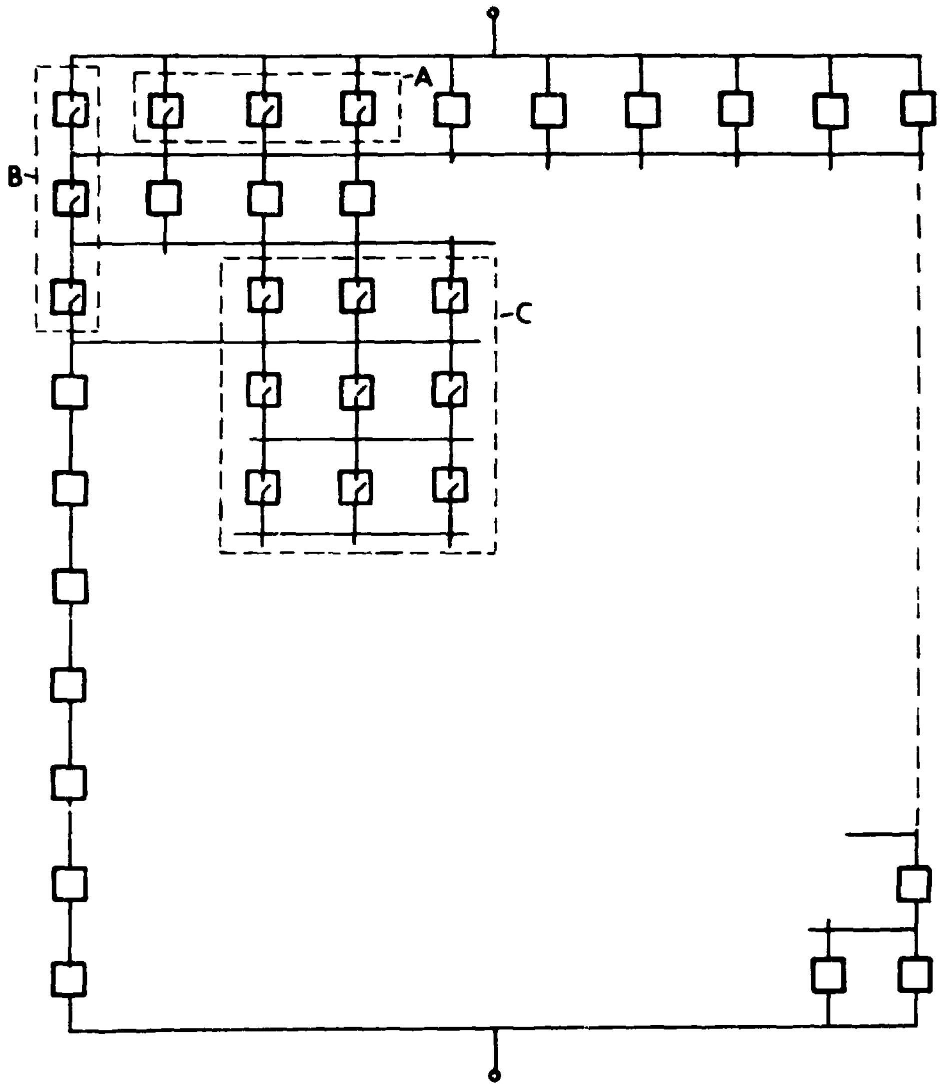
Shorts to Ground in a Series-Wired Array

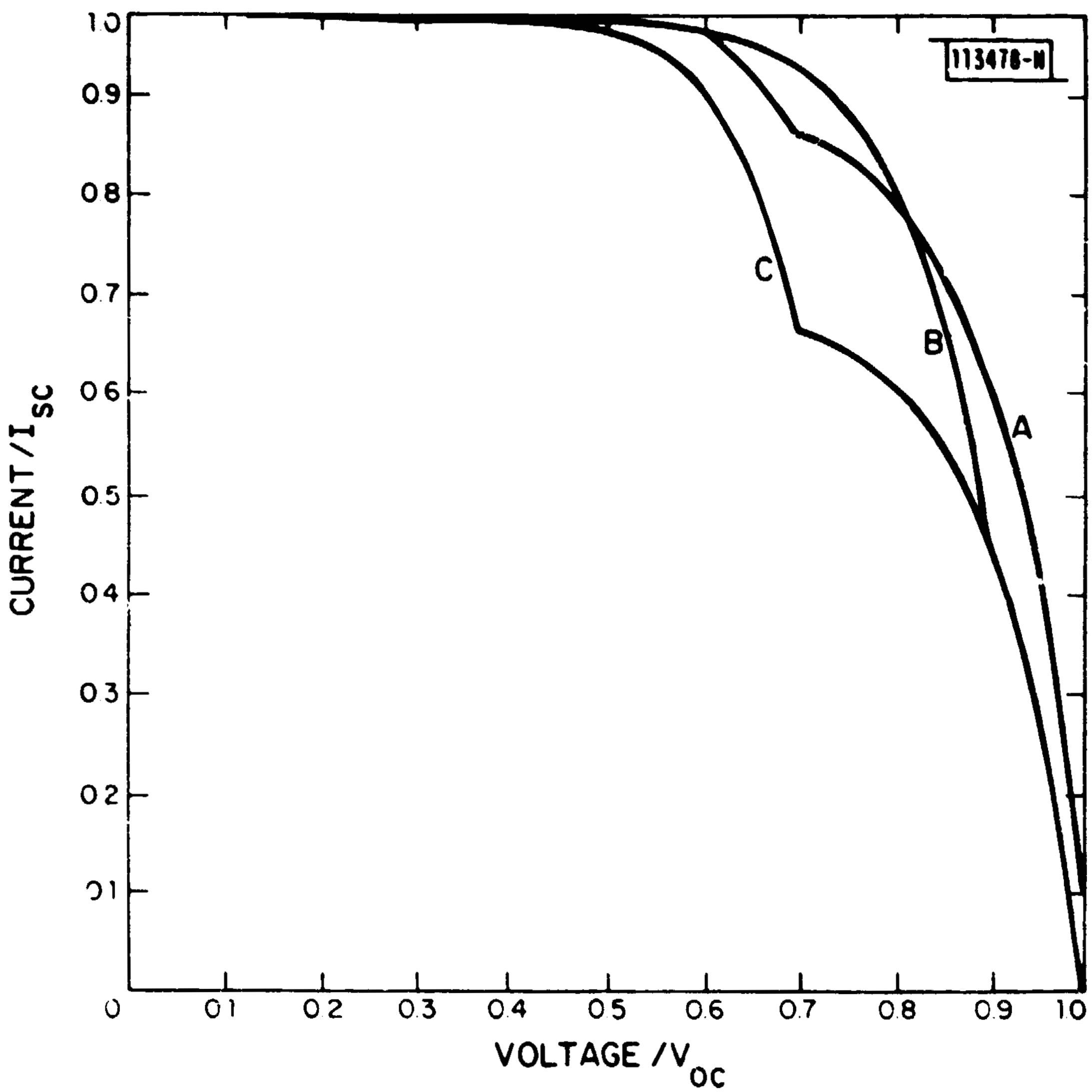


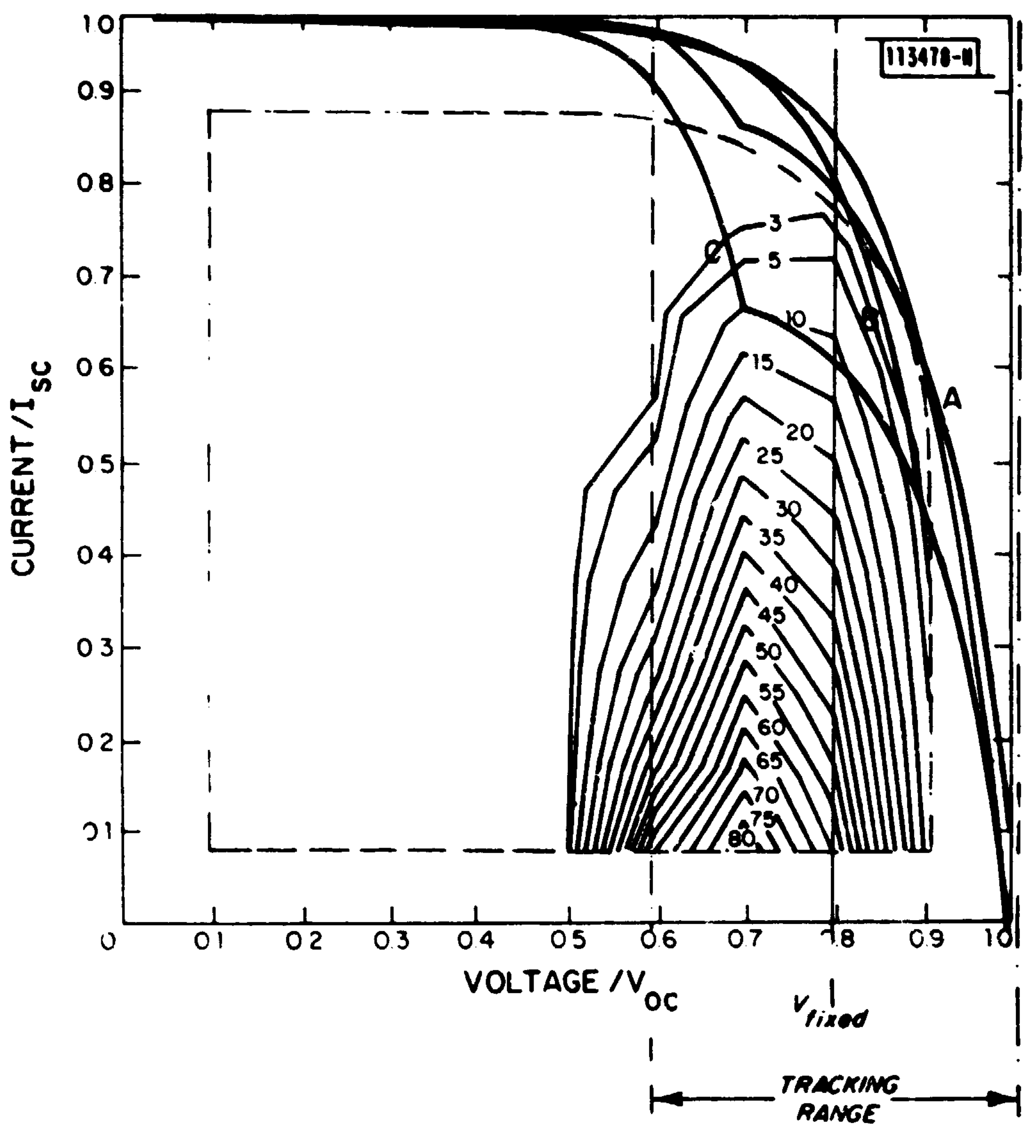

113460-II
CURRENT / I_{SC}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
VOLTAGE / V_{OC}


113460-H
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
CURRENT / I_{SC}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
VOLTAGE / V_{OC}
3
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
V_{fixed}
TRACKING RANGE

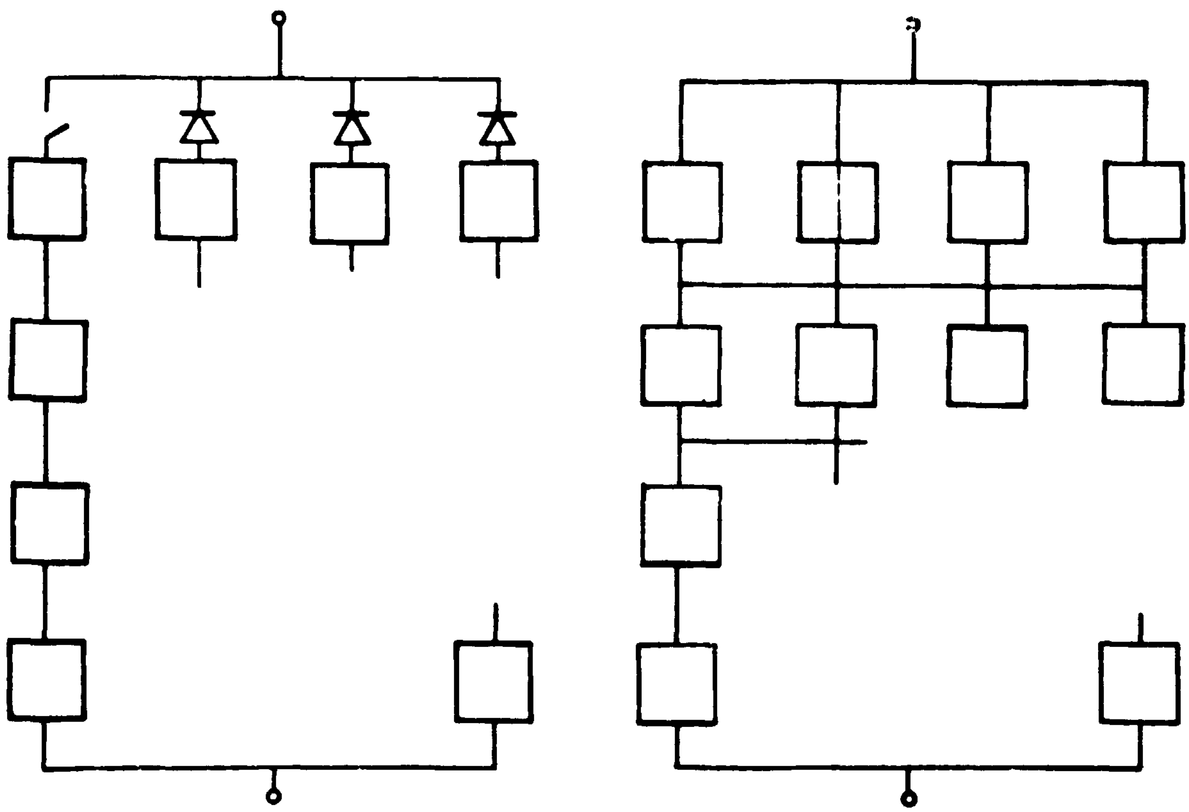
Opens in a Parallel-Wired Array




113478-N
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
CURRENT / I_SC
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
VOLTAGE / V_OC
A
B
C


113478-H
CURRENT / I_{SC}
VOLTAGE / V_{OC}
C
B
A
3
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
V_{fixed}
TRACKING RANGE

Two Special Cases



Conclusions

**Best Fixed Voltage vs
Ideal Maximum Power Tracker**

Small Difference

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

Large Difference

- o Short in parallel connected array
- o Glitch below maxium power radial

ENGINEERING SCIENCES AREA
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

I-V CURVE DATA BASE AND APPLICATIONS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

G.W. Hart
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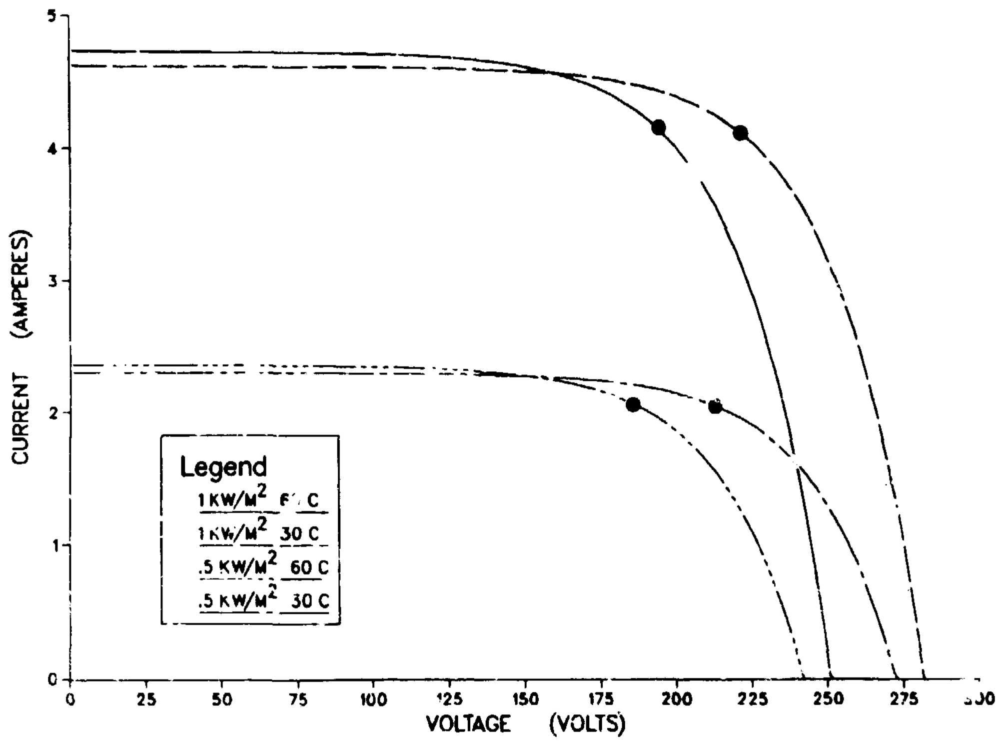
Data Base

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

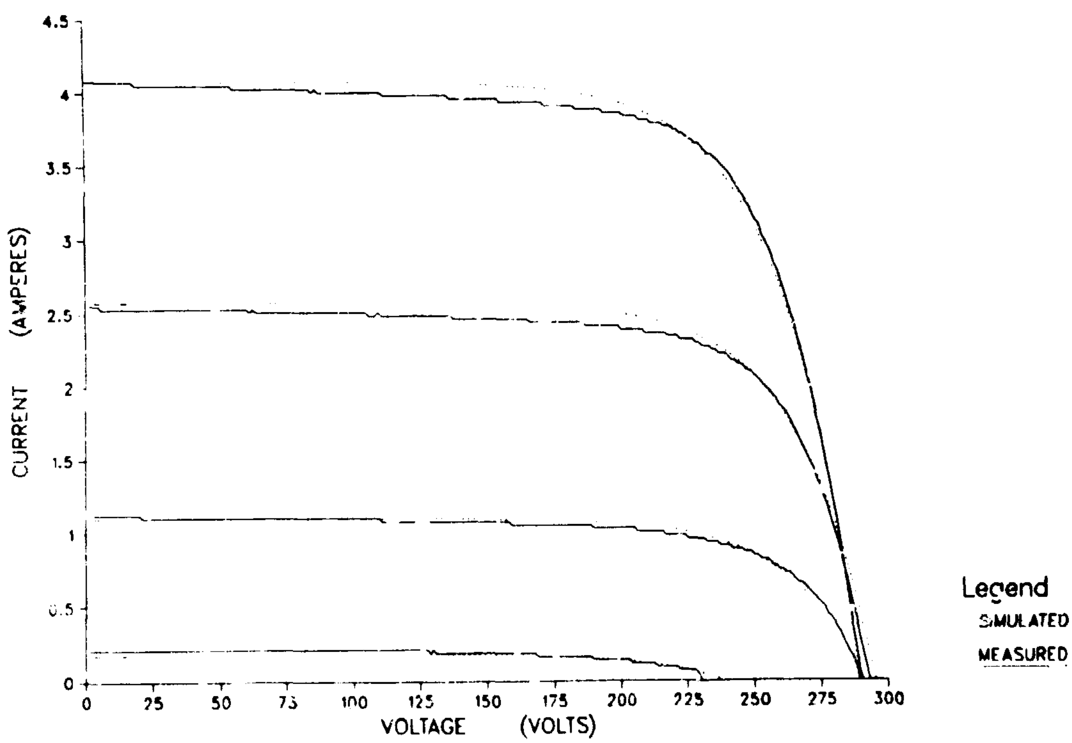
Applications

- IV CURVE TRANSLATION
- VOLTAGE CONTROL STRATEGIES
  - MAX POWER TRACKING
  - FIXED VOLTAGE
  - PILOT CELL

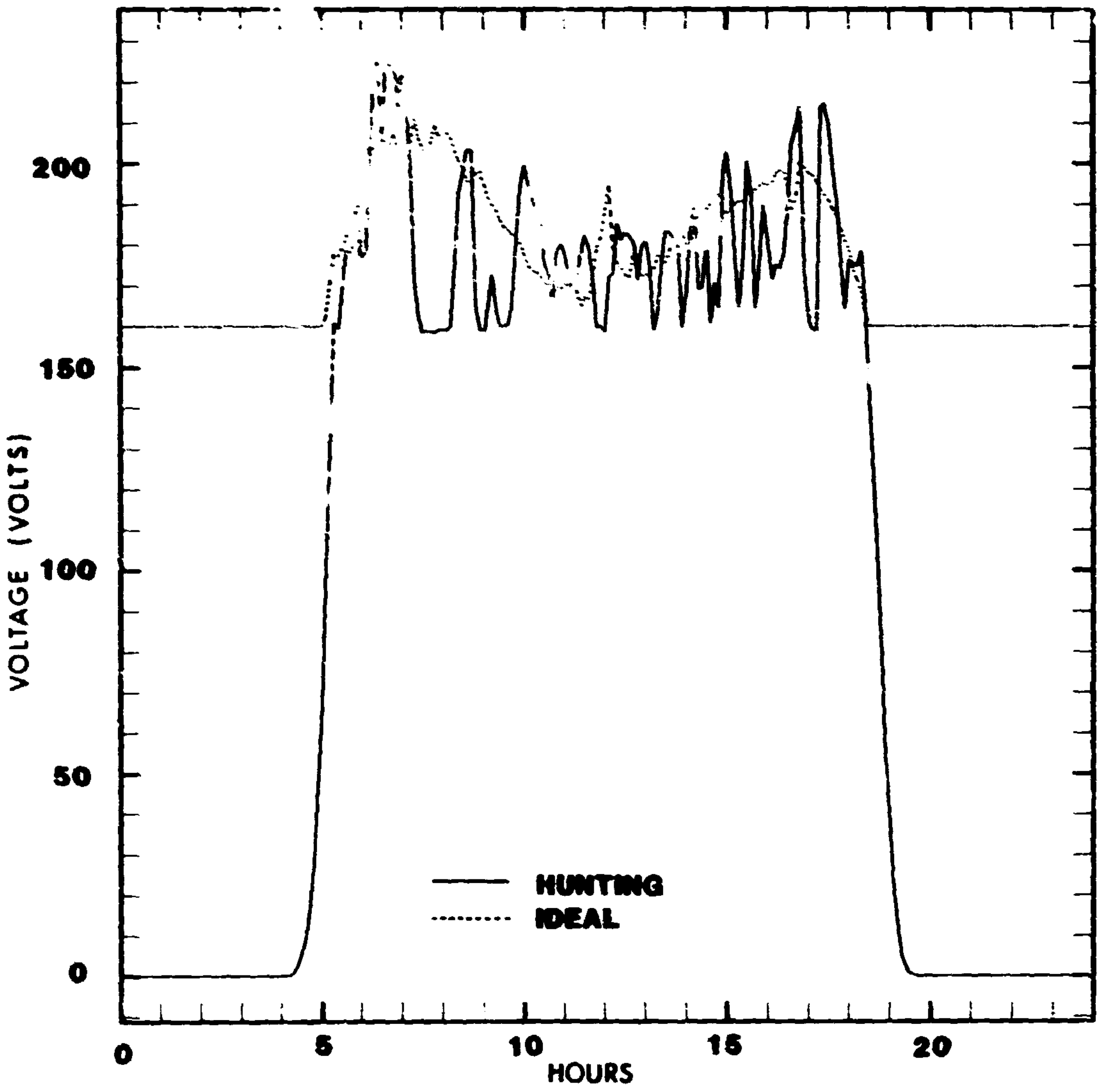
Effect of Insolation and Cell Temperature on I-V Curves



Measured and Simulated I-V Curves

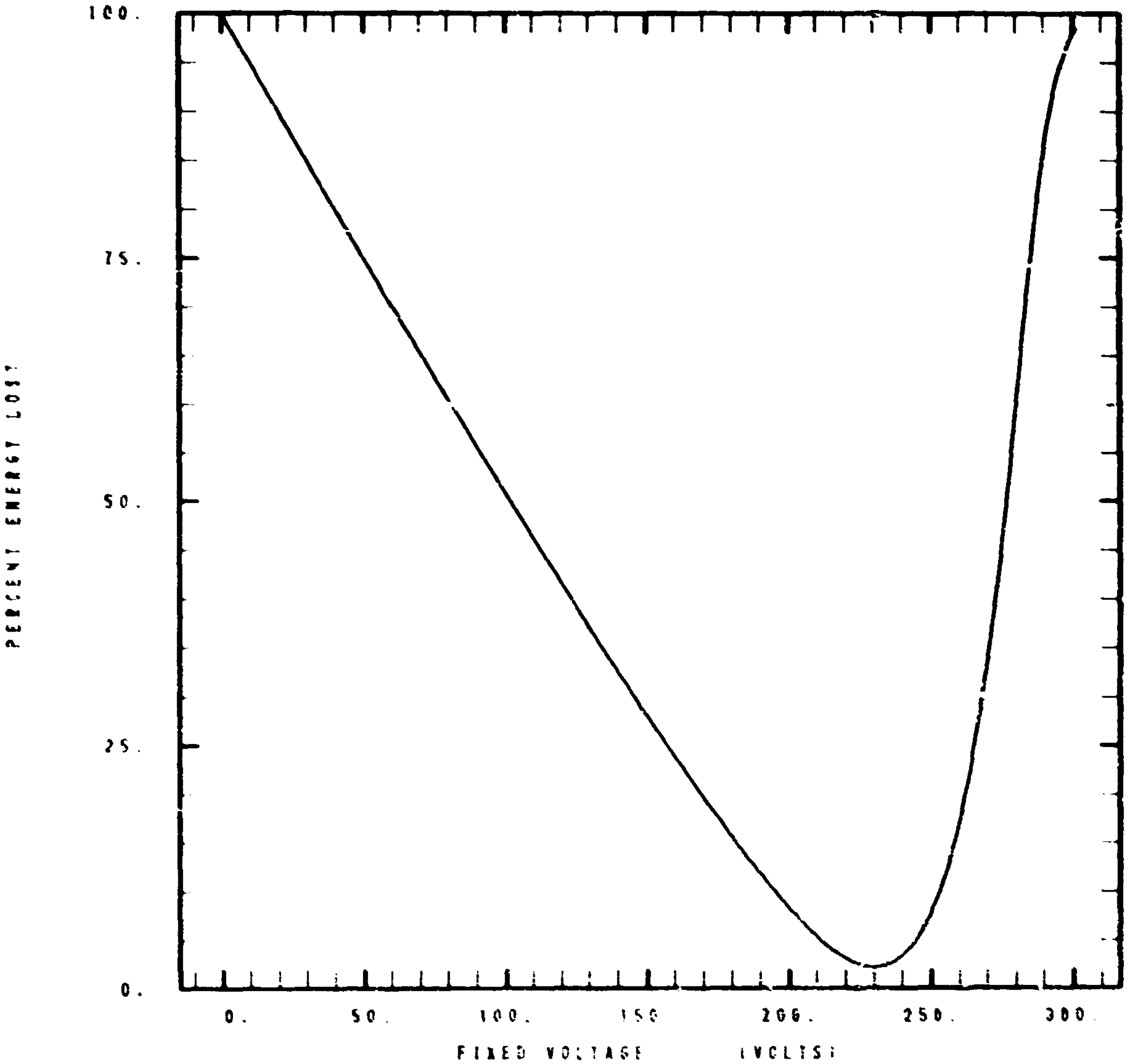


Measured and Calculated Voltages for Abacus Inverter With "Searching" Maximum Power Tracker

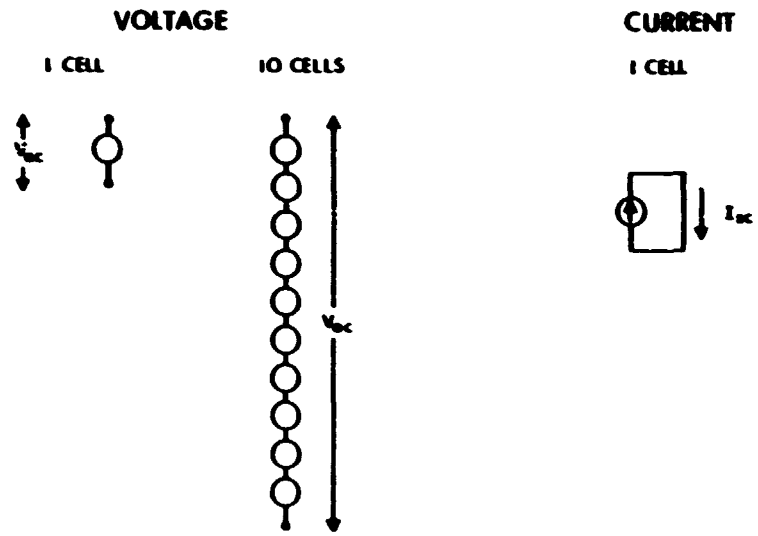


C-6

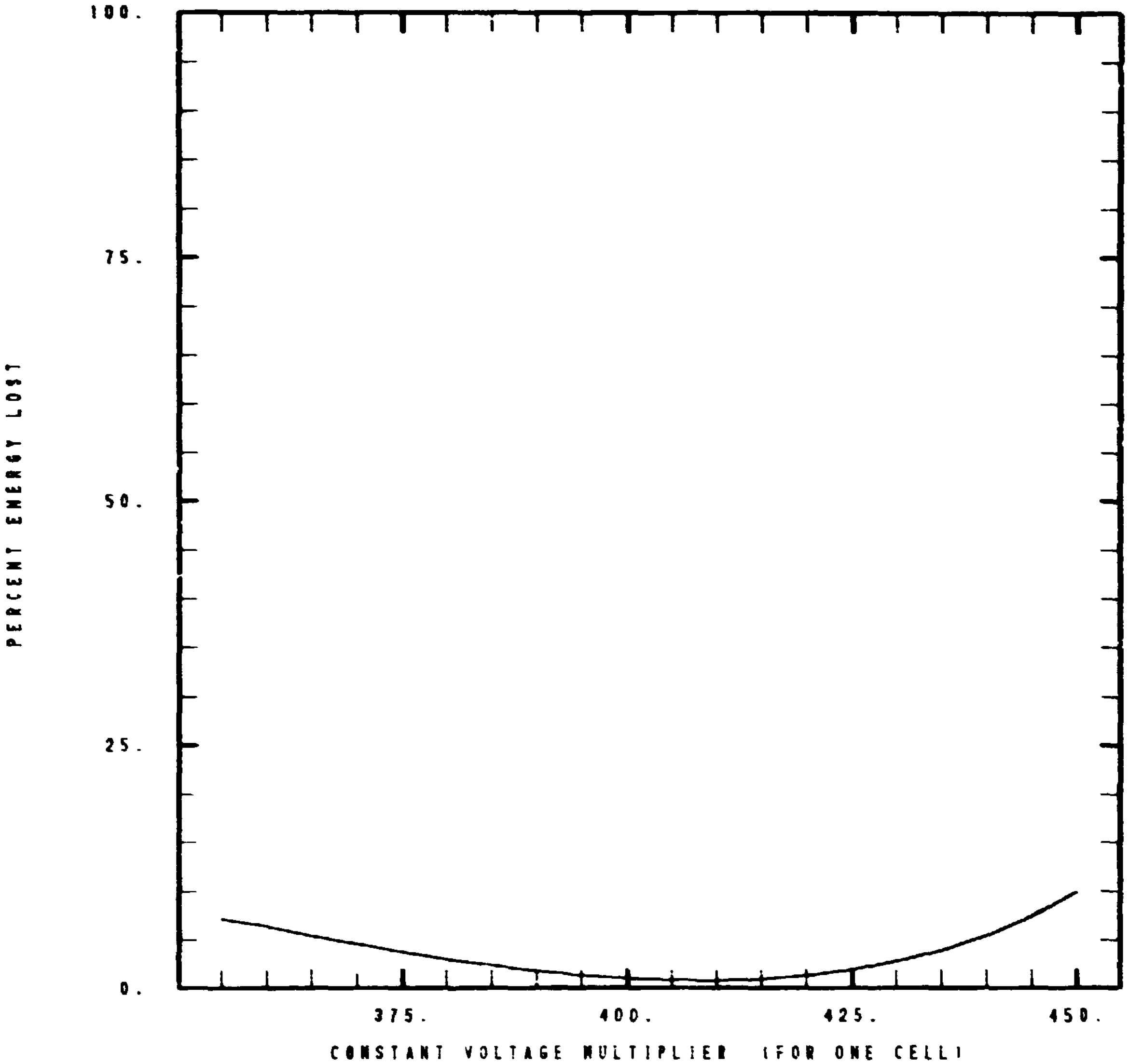
Energy Lost With Fixed-Voltage Operation

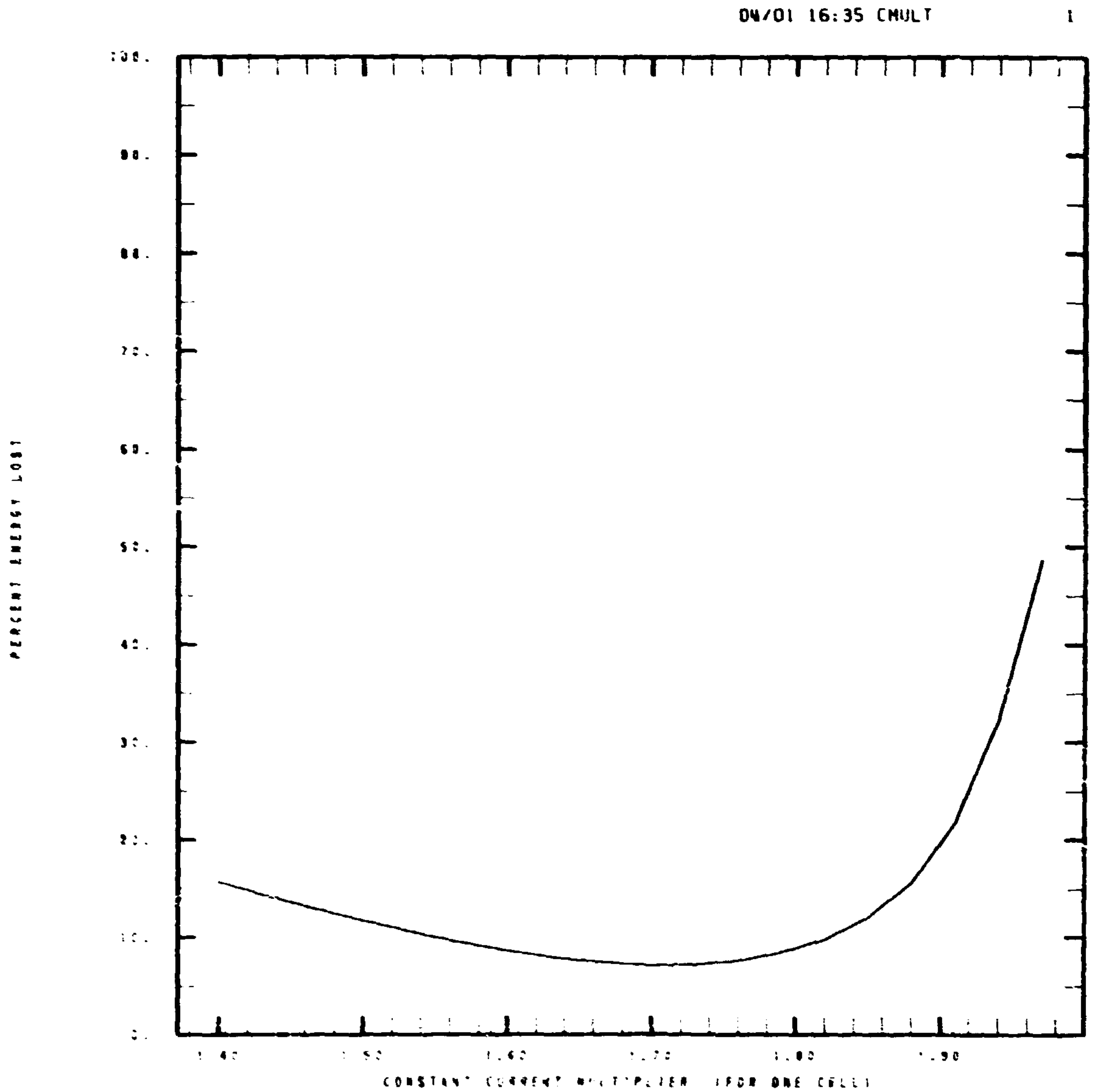


Pilot Cells



Energy Lost With Voltage-Multiplying Pilot Cell





Pilot Cell Experiments

**BASED ON IV CURVES MEASURED EVERY 3 MINUTES
FOR 3 WEEKS IN JANUARY**

TOTAL ENERGY AVAILABLE TO IDEAL MAX POWER TRACKER	67.3	
FIXED VOLTAGE	65.8	2.20% LOSS
VOLTAGE MULTIPLYING (1 CELL)	66.8	0.79% LOSS
VOLTAGE MULTIPLYING (10 CELLS)	66.5	1.17% LOSS
CURRENT MULTIPLYING (1 CELL)	62.5	7.13% LOSS

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, 858 AND 940 NANOMETERS

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

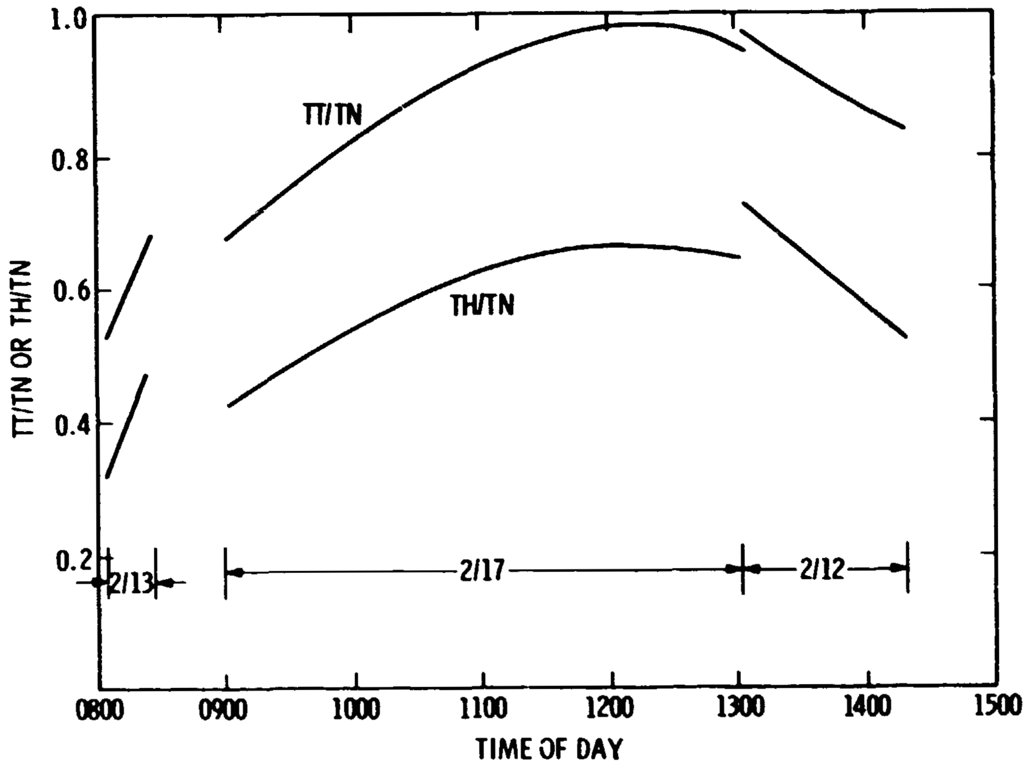
MEASURED: (EVERY 5 MINUTES FROM SUN UP TO SUN DOWN)

- DIRECT NORMAL (DN)
- TOTAL NORMAL (TN)
- TOTAL HORIZONTAL (TH)
- TOTAL TILTED (TT)
- TILTED TOTALS FOR EACH REF. CELL
- RADIOMETER

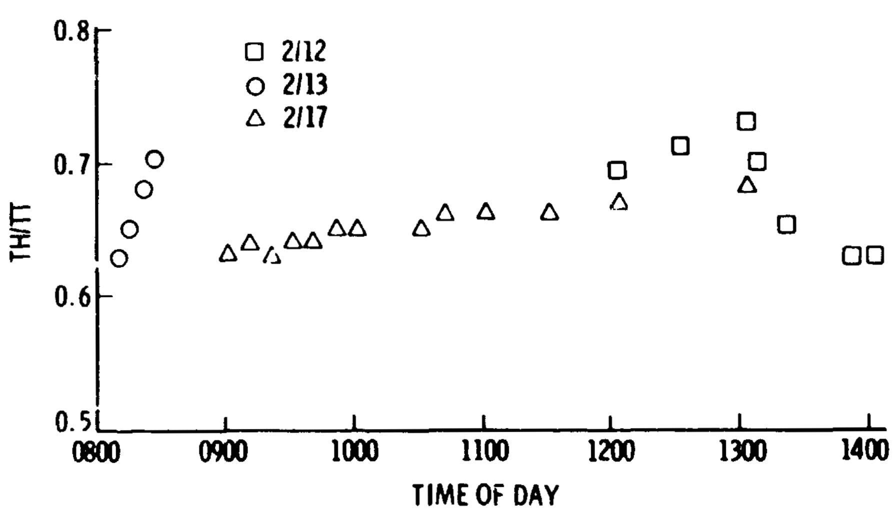
COMPUTED:

- TURBIDITY COEFFICIENT
- WATER VAPOR
- AIR MASS (FROM BAROMETRIC PRESSURE)

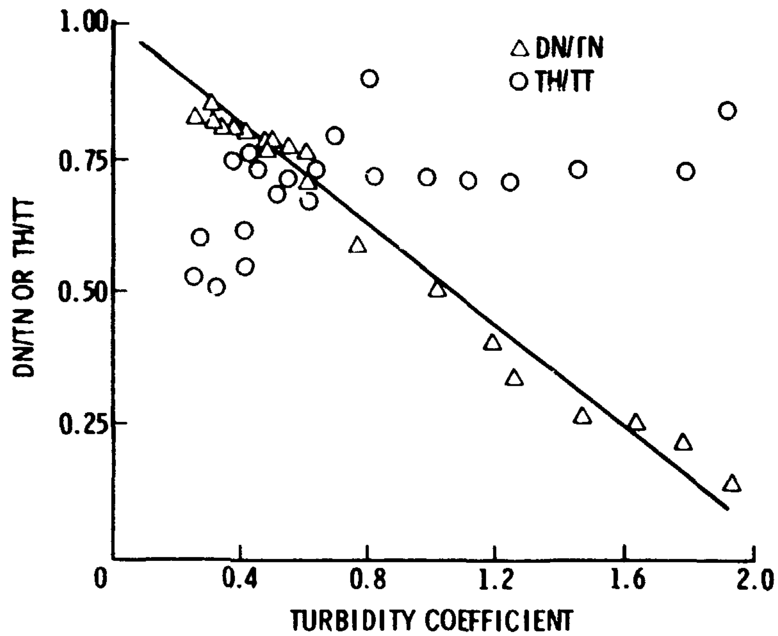
Results: Total Tilt (TT) and Total Horizontal (TH) Fractions



Results: Total Horizontal to Total Tilted Ration vs Time of Day



Results: Direct Normal to Total Normal vs Turbidity Coefficient; Total Horizontal to ‾ ˙ l Tilted vs Turbidity Coefficient



Summary

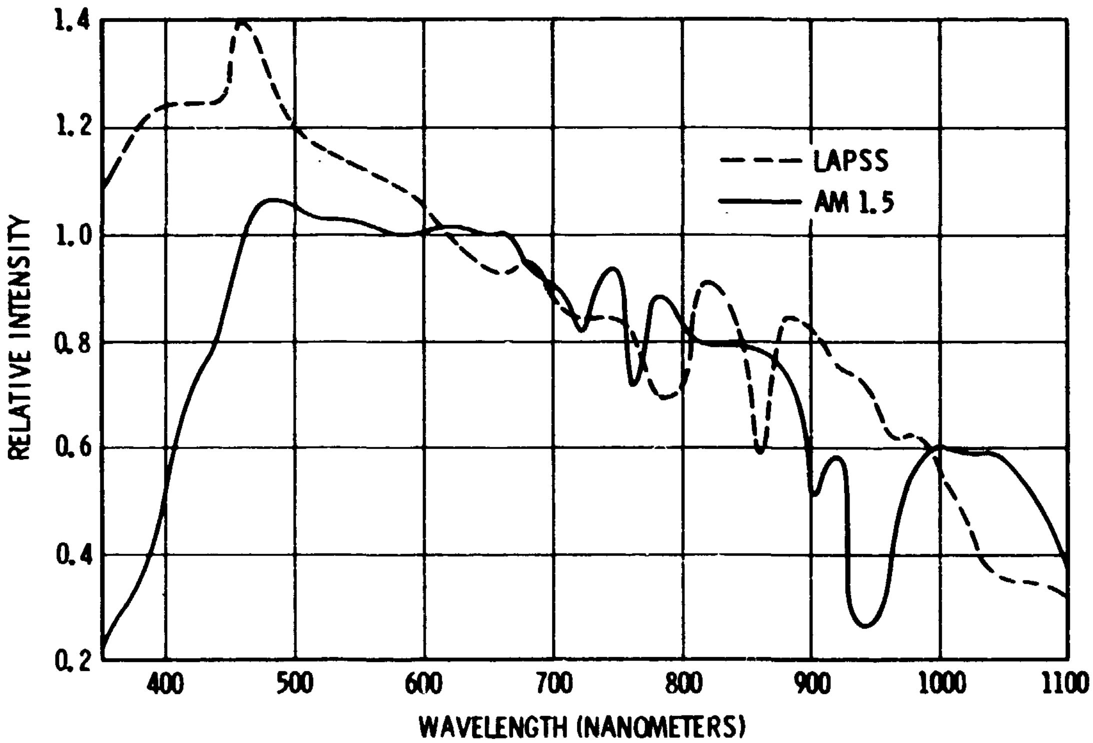
- TURBIDITY COEFFICIENT IS A GOOD INDICATOR OF THE DIFFUSE IRRADIANCE FRACTION IN THE NORMAL PLANE
- POOR CORRELATION BETWEEN TURBIDITY AND THE RATIO OF TOTAL HORIZONTAL TO TOTAL TILTED
- TRANSFORMATIONS BETWEEN THE NORMAL, HORIZONTAL AND TILTED PLANES MAY REQUIRE DIFFUSE SOURCE DATE
- THE REFERENCE 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



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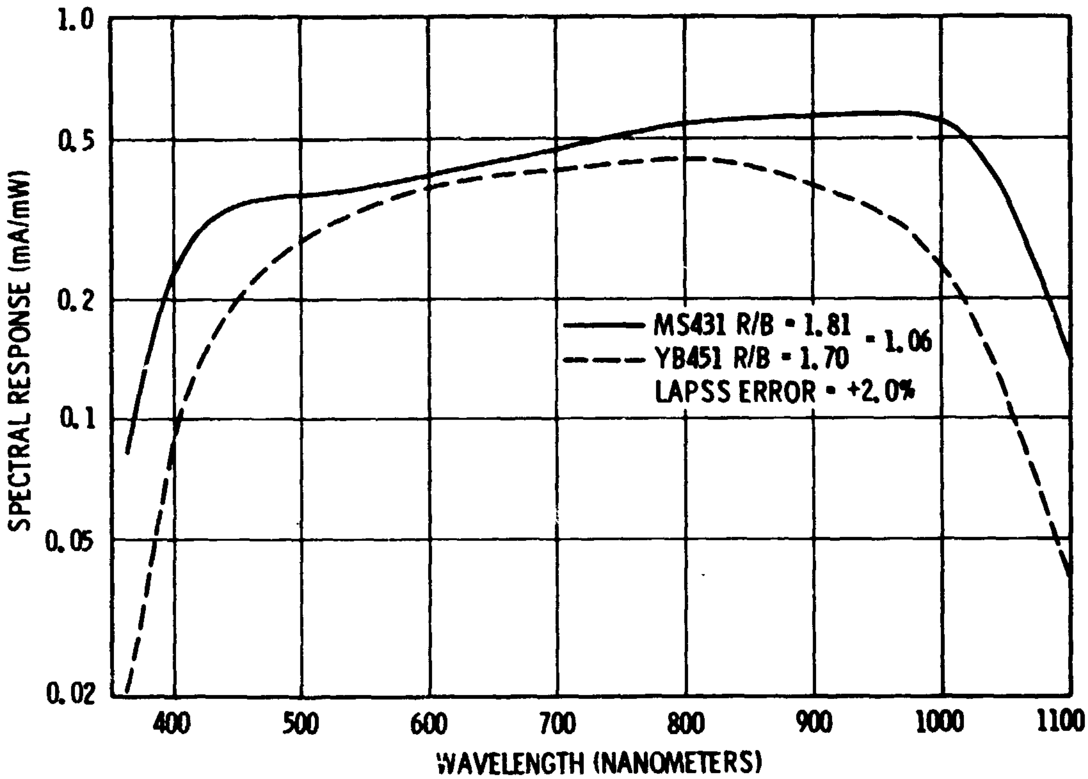
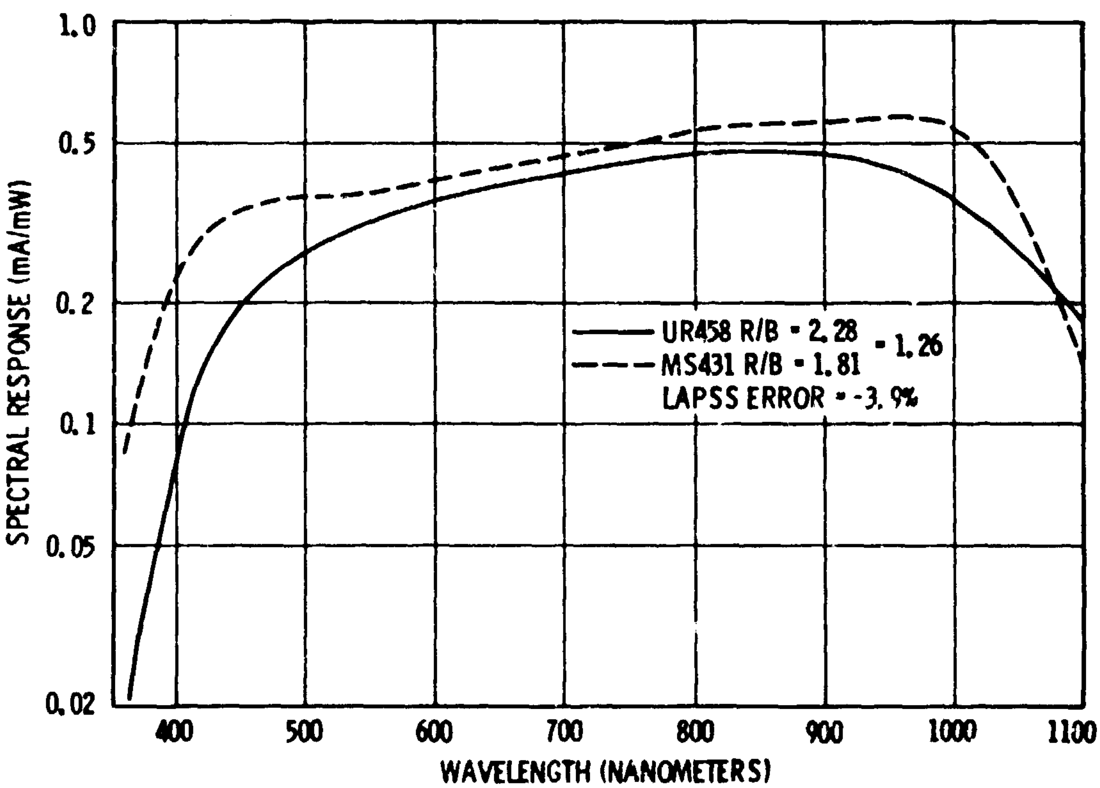
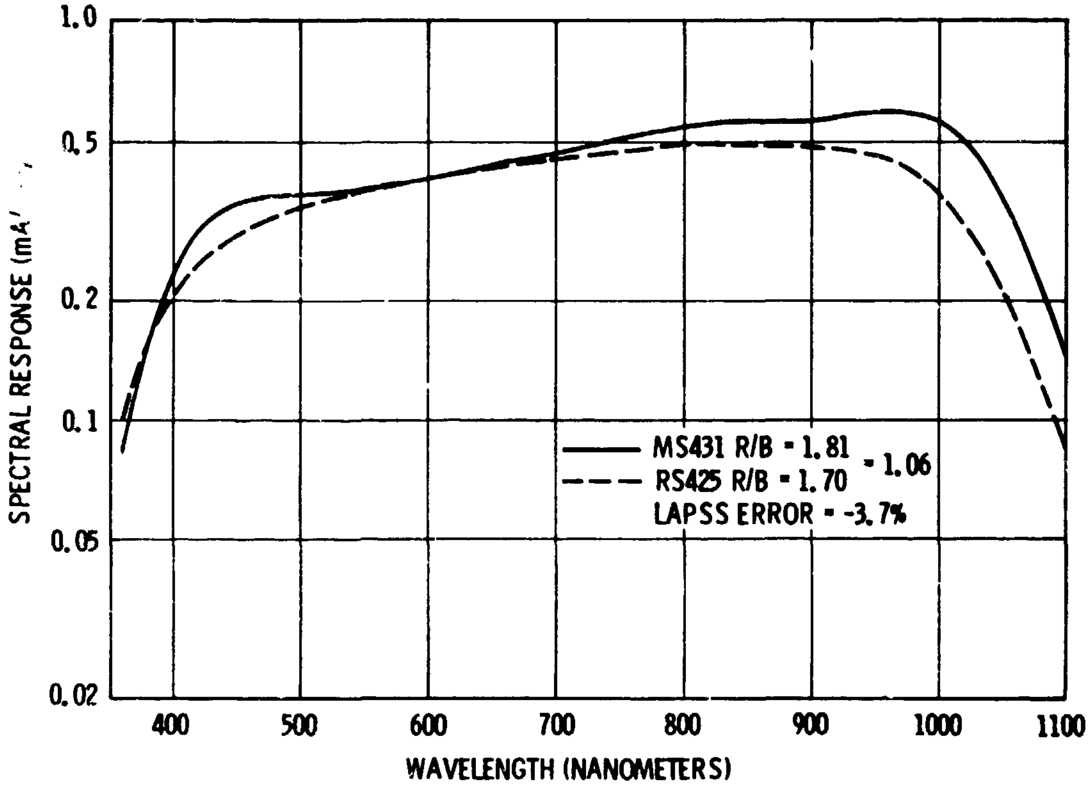
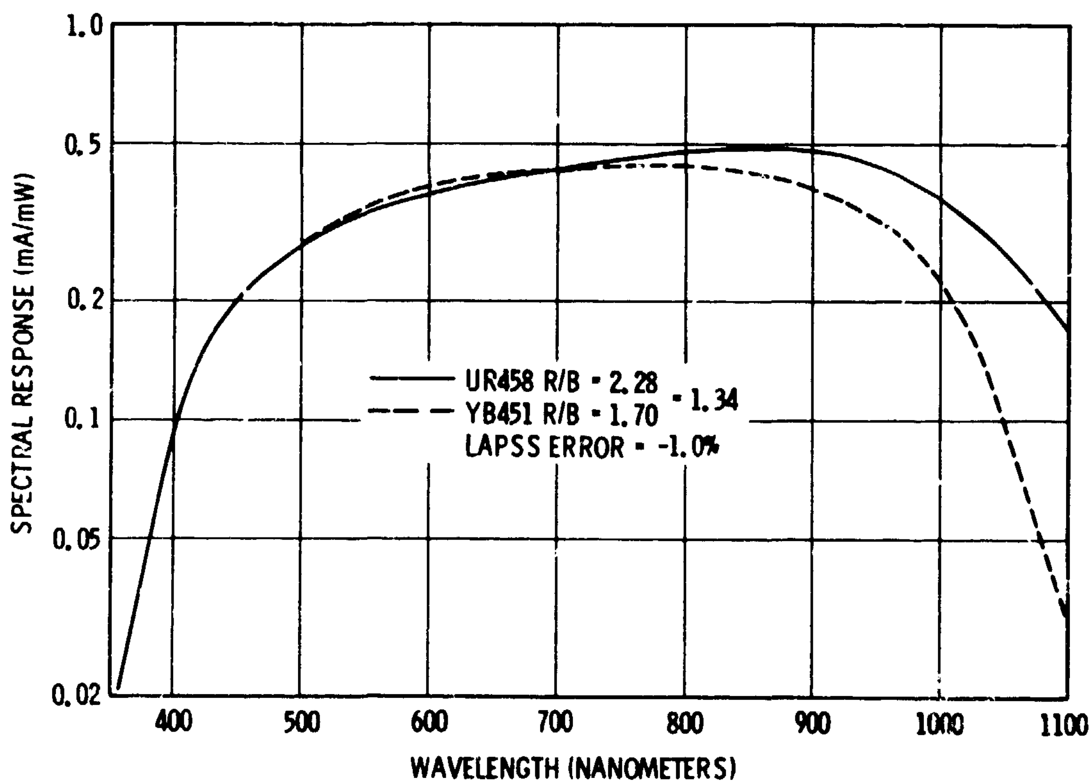
Spectral Response Comparisons of Reference and Test Cells






1.0
0.5
0.2
0.1
0.05
0.02
SPECTRAL RESPONSE (mA/
400
500
600
700
800
900
1000
1100
WAVELENGTH (NANOMETERS)
MS431 R/B = 1.81
RS425 R/B = 1.70
= 1.06
LAPSS ERROR = -3.7%


1.0
0.5
0.2
0.1
0.05
0.02
SPECTRAL RESPONSE (mA/mW)
400
500
600
700
800
900
1000
1100
WAVELENGTH (NANOMETERS)
UR458 R/B = 2.28
YB451 R/B = 1.70
= 1.34
LAPSS ERROR = -1.0%

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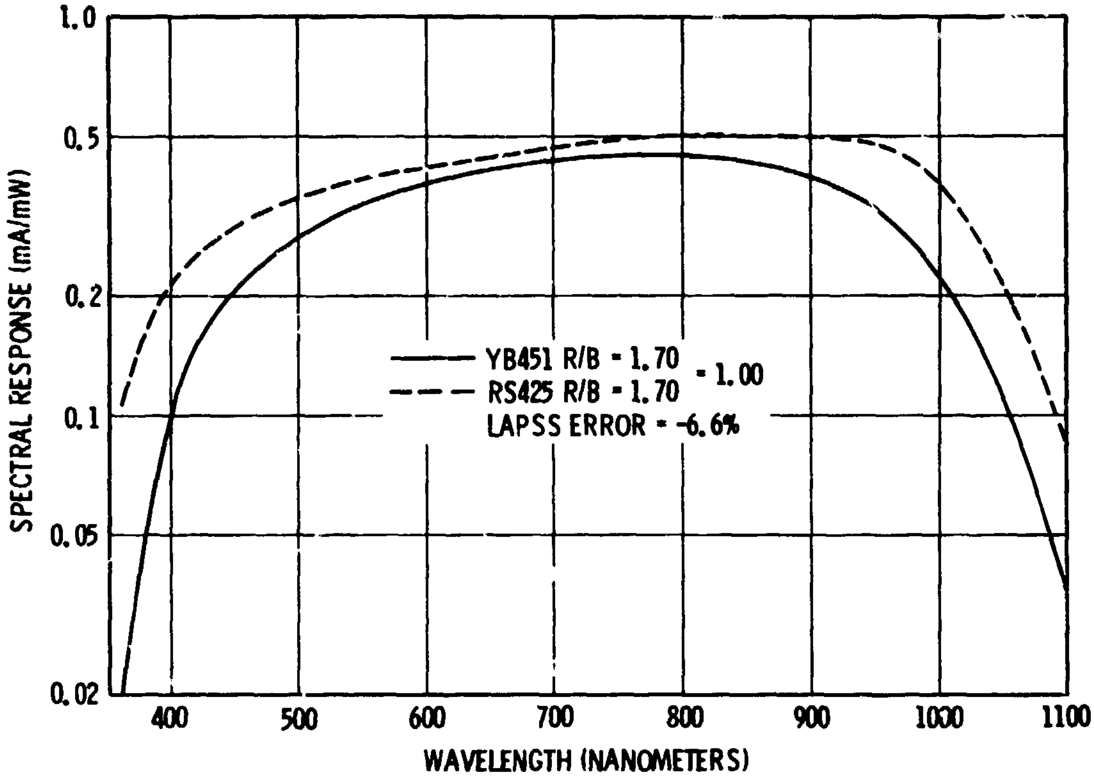
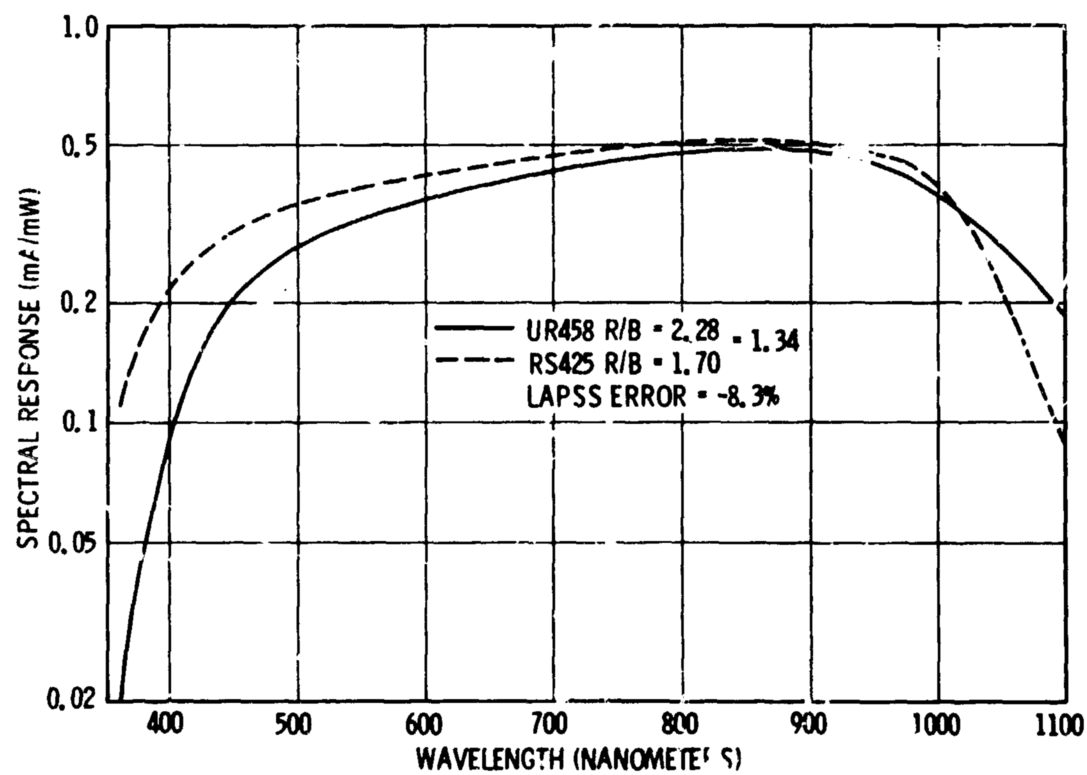




The Mismatch Factor M

$$M = \frac{(\Sigma E_{Si} R_{Ci} \Delta_i)(\Sigma_{Ai} R_{Ri} \Delta_i)}{(\Sigma E_{Si} R_{Ri} \Delta_i)(\Sigma E_{Ai} R_{Ci} \Delta_i)}$$

E_{Si} = LAPSS SPECTRAL IRRADIANCE

E_{Ai} = AM 1.5 SPECTRAL IRRADIANCE

R_{Ci} = TEST CELL SPECTRAL RESPONSE

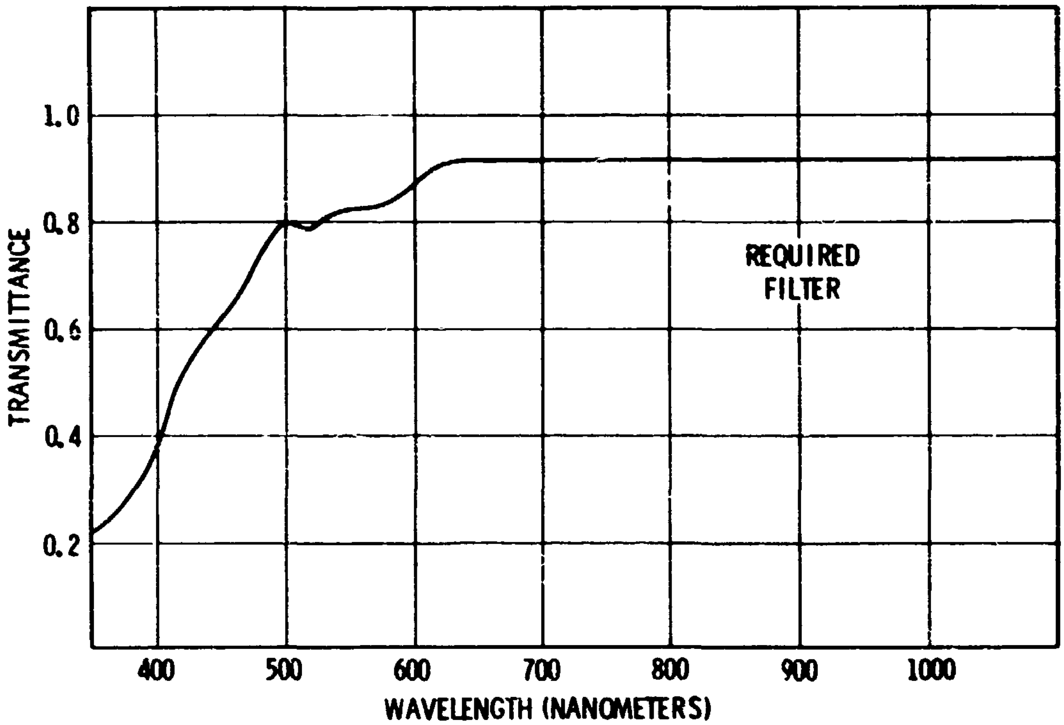
R_{Ri} = REFERENCE CELL SPECTRAL RESPONSE

ERROR = M-1

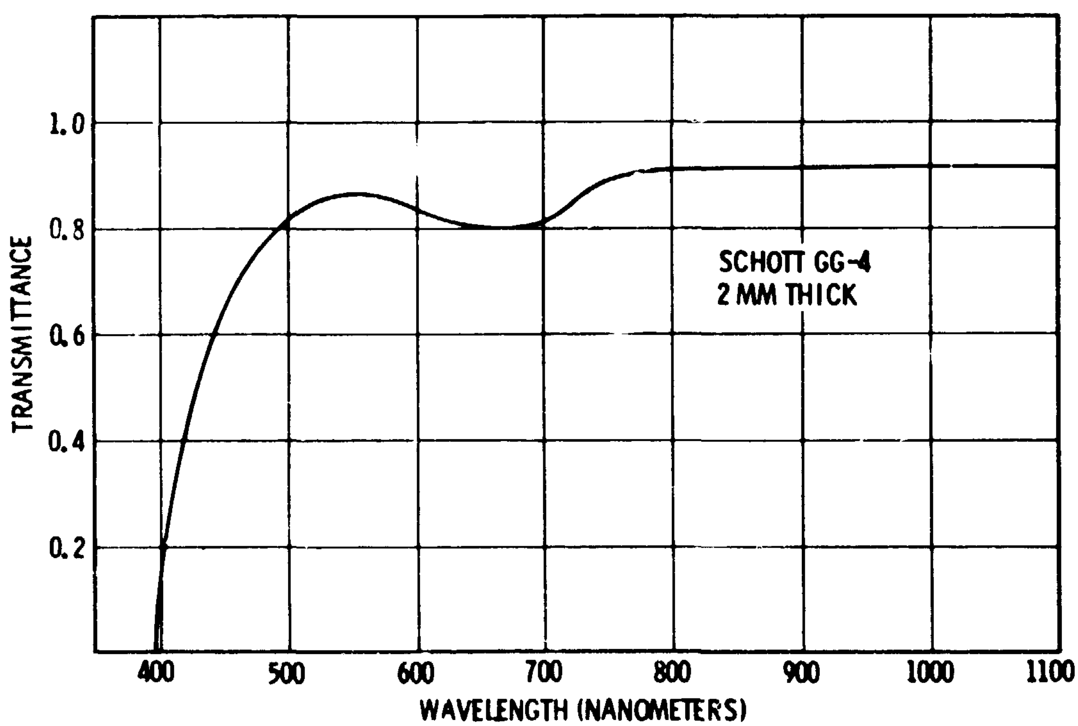
Measured Error Using Unfiltered LAPSS

	PAIR	R/B	$\frac{(R/B)_C}{(R/B)_R}$		% ERROR NO FILTER
C	MS 431	1.81	1.06		+2.0
R	YB 451	1.70			
C	UR 458	2.28	1.26		-3.9
R	MS 431	1.81			
C	MS 431	1.81	1.06		-3.7
R	RS 425	1.70			
C	UR 458	2.28	1.34		-1.0
R	YB 451	1.70			
C	YB 451	1.70	1.00		-6.6
R	RS 425	1.70			
C	UR 458	2.28	1.34		-8.3
R	RS 425	1.70			
ERROR EXPECTATION VALUE					4.3

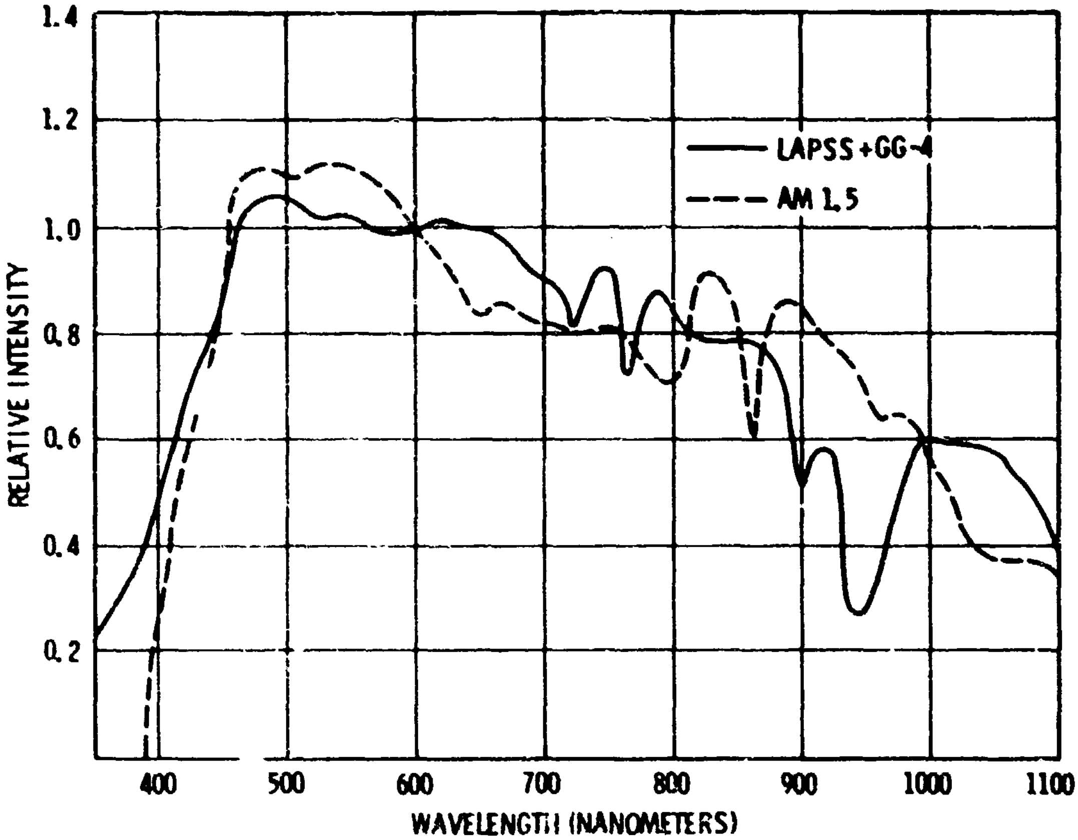
Required Correction Filter



Schott GG-4 Filter



Spectral Irradiance, Filtered LAPSS and AM1.5



Calculated Errors Using Filtered LAPSS

	PAIR	CALCULATED % ERROR
C R	MS 431 YB 451	0.0
C R	UR 458 RS 425	-0.2
C R	MS 431 RS 425	+0.1
C R	UR 458 YB 451	+0.2
C R	YB 451 RS 425	+0.1
C R	UR 458 RS 425	-0.2

Measured Errors Before and After Filtering

	PAIR	R/B	$\frac{(R/B)_C}{(R/B)_R}$		% ERROR NO FILTER	% ERROR FILTER
C R	MS 431 YB 451	1.81 1.70	1.06		+2.0	-0.1
C R	UR 458 MS 431	2.28 1.81	1.26		-3.9	-0.1
C R	MS 431 RS 425	1.81 1.70	1.06		-3.7	+0.2
C R	UR 458 YB 451	2.28 1.70	1.34		-1.0	+1.0
C R	YB 451 RS 425	1.70 1.70	1.00		-6.6	0.0
C R	UR 458 RS 425	2.28 1.70	1.34		-8.3	+0.9
ERROR EXPECTATION VALUE					4.3	0.4

RESIDENTIAL ARRAY RESEARCH

JET PROPULSION LABORATORY

P H. Wilson

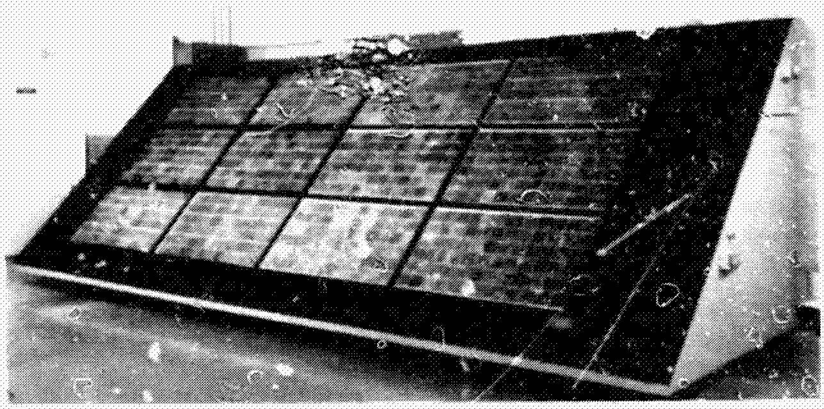
Residential Array Technology Gaps

- **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**

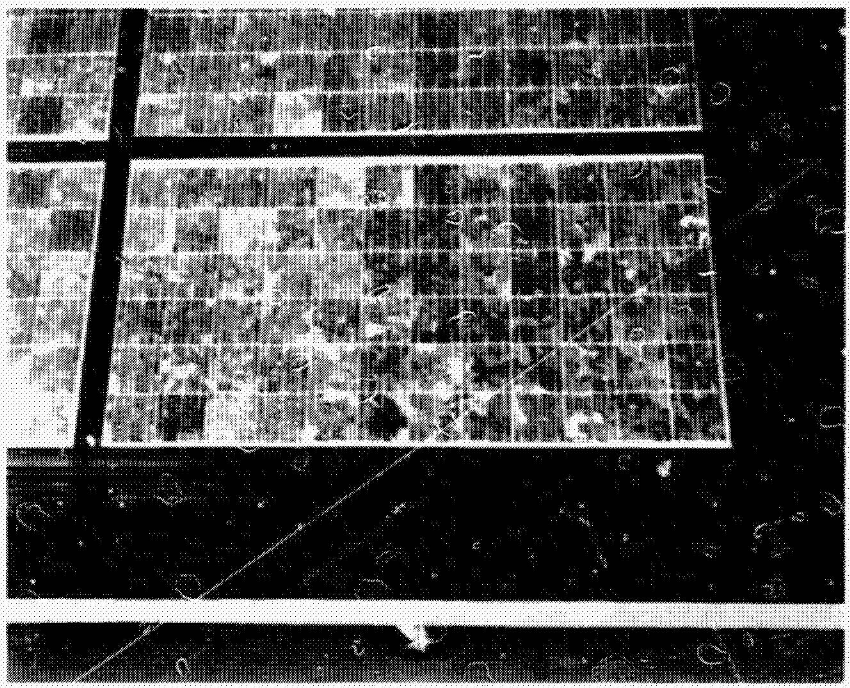
JPL In-House Residential Array Research Activity: Objective and Approach

- **Synthesize Residential Array Solutions 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** } **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**

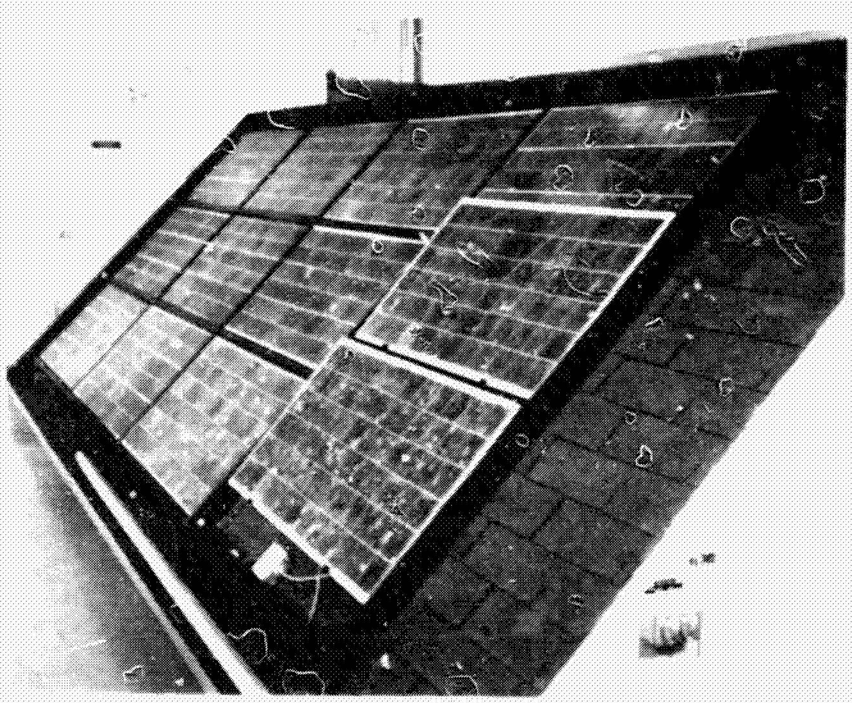
Residential Array Research Model



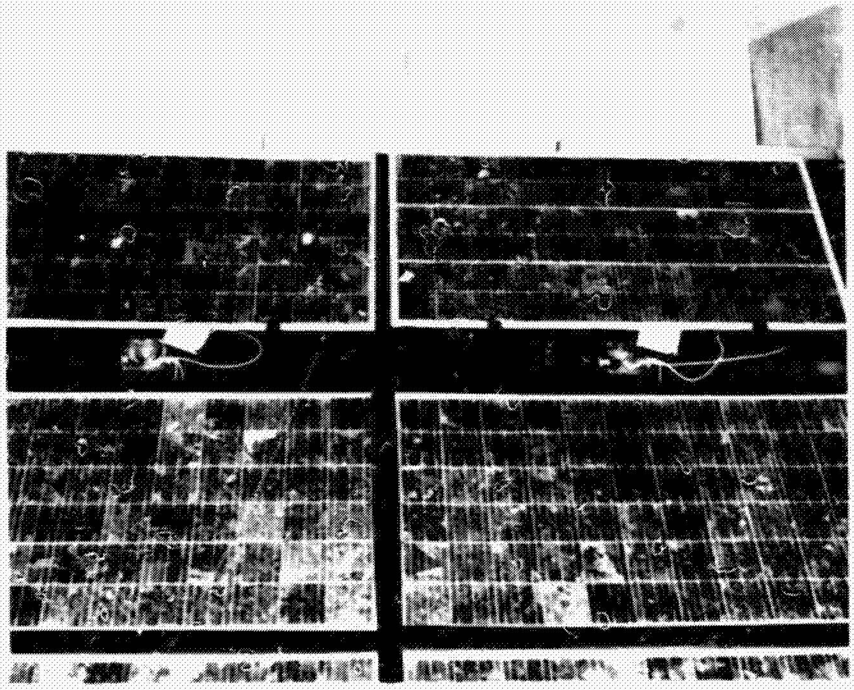
Detail: Corner of Model



Model With J-Box Exposed

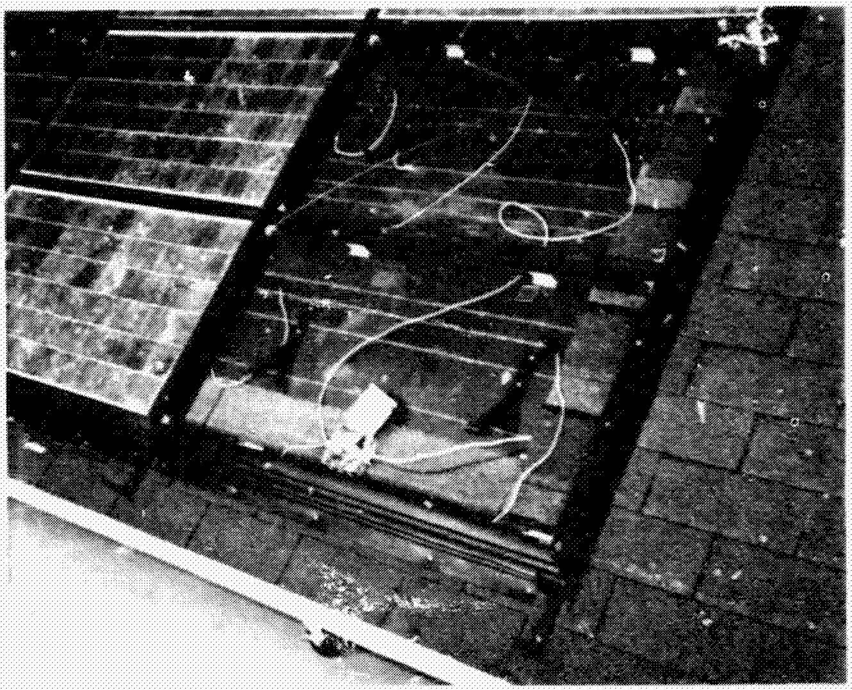


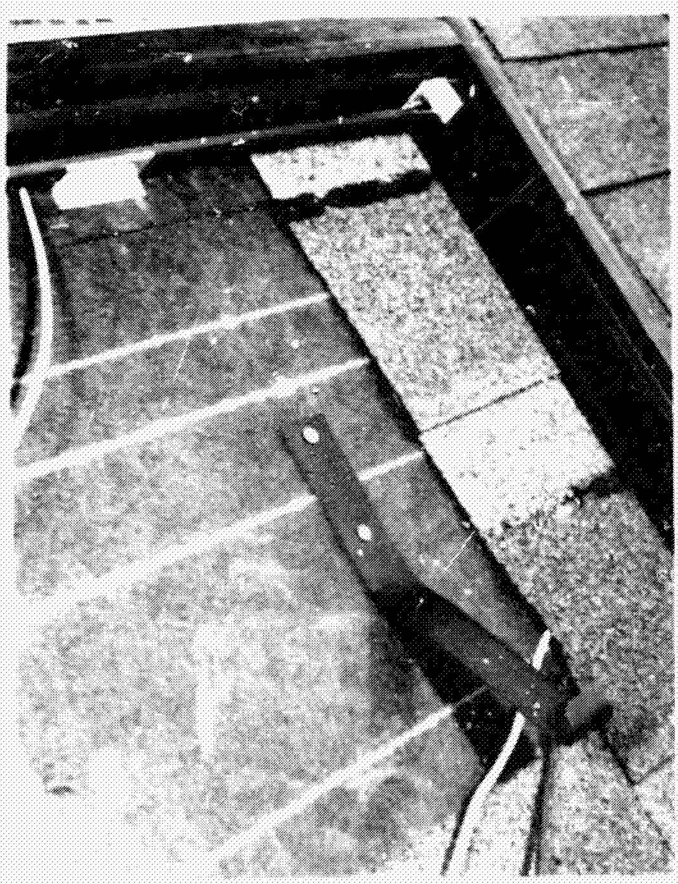
Upper Modules Supported by Brackets



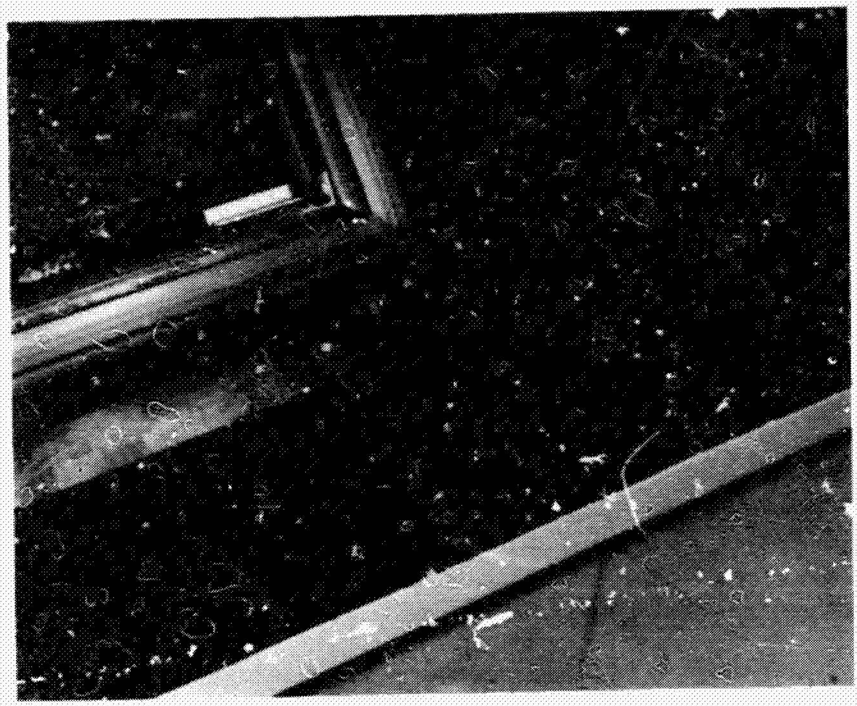
Technician Replacing Module

Details of Model Construction

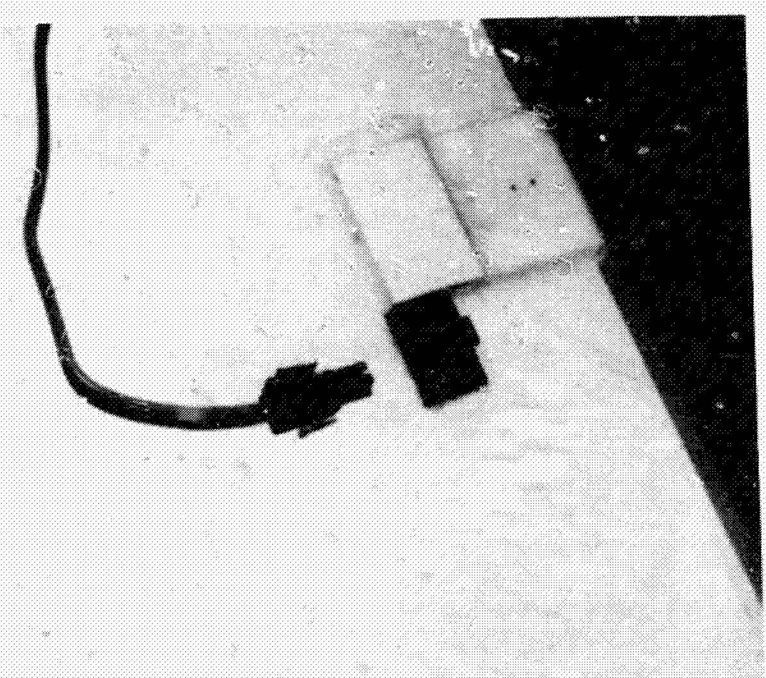




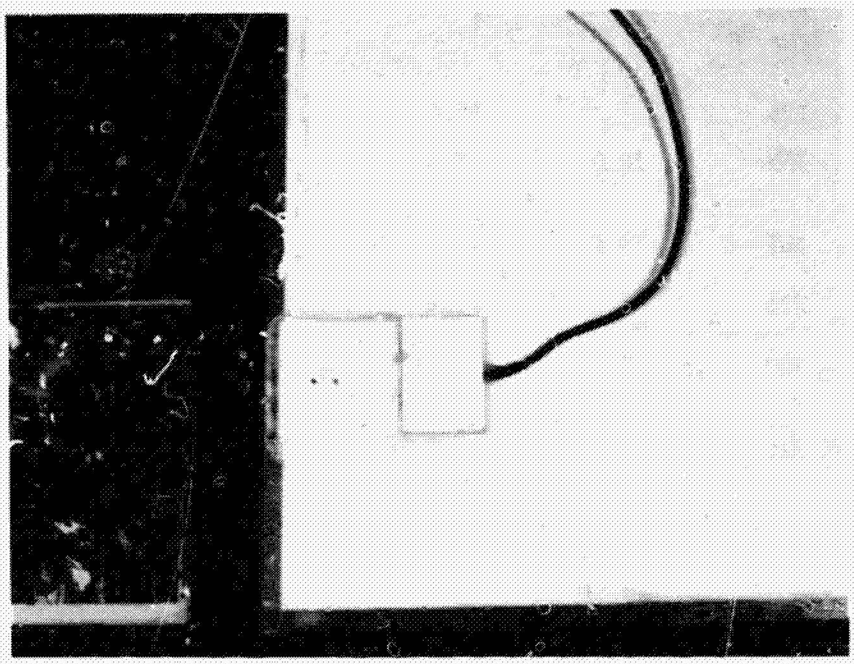
Details of Model Construction



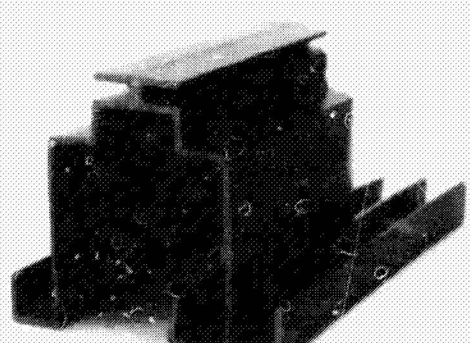
Modification to Meet UL Requirements (Connector)



Modification to Meet UL Requirements
(Lead, Undergro nd Feeder Wire)



Cross Section of Plastic Frame Extrusion



UV-Stabilized Extrudable Thermoplastics Properties

MATERIAL	DEFLECTION TEMP °F	TENSILE 10^3 PSI	COMPRESSIVE 10^3 PSI	FLEXURAL 10^3 PSI	FLEXURAL MODULUS 10^3 PSI	SUPPLIER
ACETAL	225		16.0	13.0	375	DUPONT
NYLON	365	10.0	13.0	14.0	390	DUPONT, LNP
PHENYLENE OXIDE	265	9.6	16.4	13.5	360	GEN. ELEC.
POLYCARBONATE	220	7.0	11.0	13.0	300	MOBAY
POLYSULFONE	400			12.4	330	ICI AMERICA LNP
CHLORINATED PVC	215	7.5	9.0	14.5	380	GOODRICH
PVC (REF. POINT)	155-180	6.0	8.0	10.0	300	GOODRICH, KOHINOR

APRIL, 1982

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 Voltages**
- **Develop Algorithms for Selecting Insulation Systems With Least Life-Cycle Energy Cost**

Approach

- **Break Down Many Test Areas (A_T = 0.785-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**

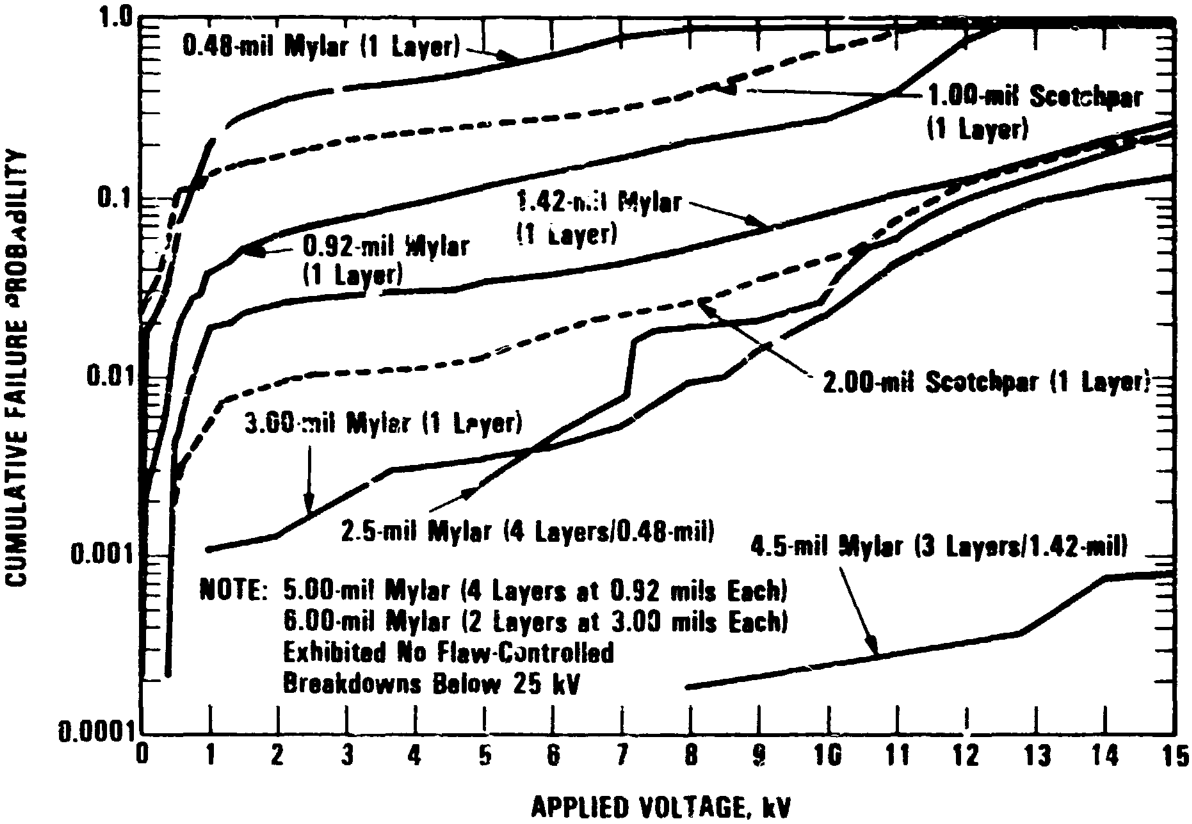
Materials Tested to Date

TEST NO.	MATERIAL	THICKNESS (mils)	NO. OF LAYERS	THICKNESS PER LAYER (mils)	NO. OF TEST POINTS
1	Mylar	0.48	1	0.48	4272
2	Mylar	0.92	1	0.92	4608
3	Mylar	1.42	1	1.42	4608
4	Mylar	3.00	1	3.00	4608
5	Scotchpar: 10 CP 3110	1.00	1	1.00	1034
6	Scotchpar: 20 CP 3110	2.00	1	2.00	968
7	Mylar - Unaged	2.50	4	0.48	385
	Aged*				507
8	Mylar	4.50	3	1.42	5369
9	Mylar	5.00	4	0.92	5280
10	Mylar	6.00	2	3.00	3550
11	EVA	20.00	1	20.00	1037
12	EMA	24.00	1	24.00	429

13	Tedlar: 100BG30TR	1.0	1	1.0	176
14	Tedlar: 100BG30UT 68040 Primer	1.0	1	1.0	1056
15	Tedlar: 100SG30TR	1.0	1	1.0	176
16	Tedlar: 150BL30WH	1.5	1	1.5	1880
17	Tedlar: 200BS30WH 68040 Primer	2.0	1	2.0	2575
18	Tedlar: 200SG40TR	2.0	1	2.0	264
19	Tedlar: Milky	4.0	1	4.0	1959
20	Tedlar: Experimental WH	4.0	1	4.0	
	- Unaged				381
	- Aged*				876
21	Polyester	4.0	1	4.0	441
22	Tedlar/Aluminum/Polyester/Tedlar	8.0	4	1.5/0.7/4.0/1.5	
	TAPT				1840
	TPAT				1421

*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: $A_T = 0.785\ in^2$)



Theoretical Film and Module Failure Probabilities

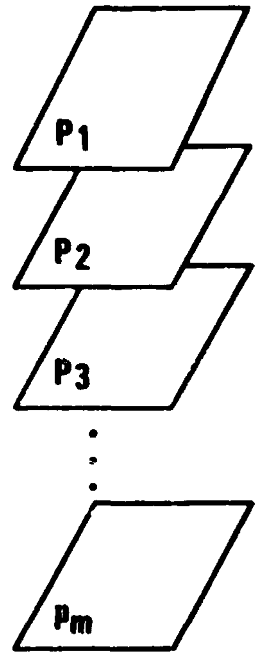
- **The Breakdown Probability of a Single Test Area ($A_T = 0.785\text{-in}^2$), Determined by Measurement, Is p.**

  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**

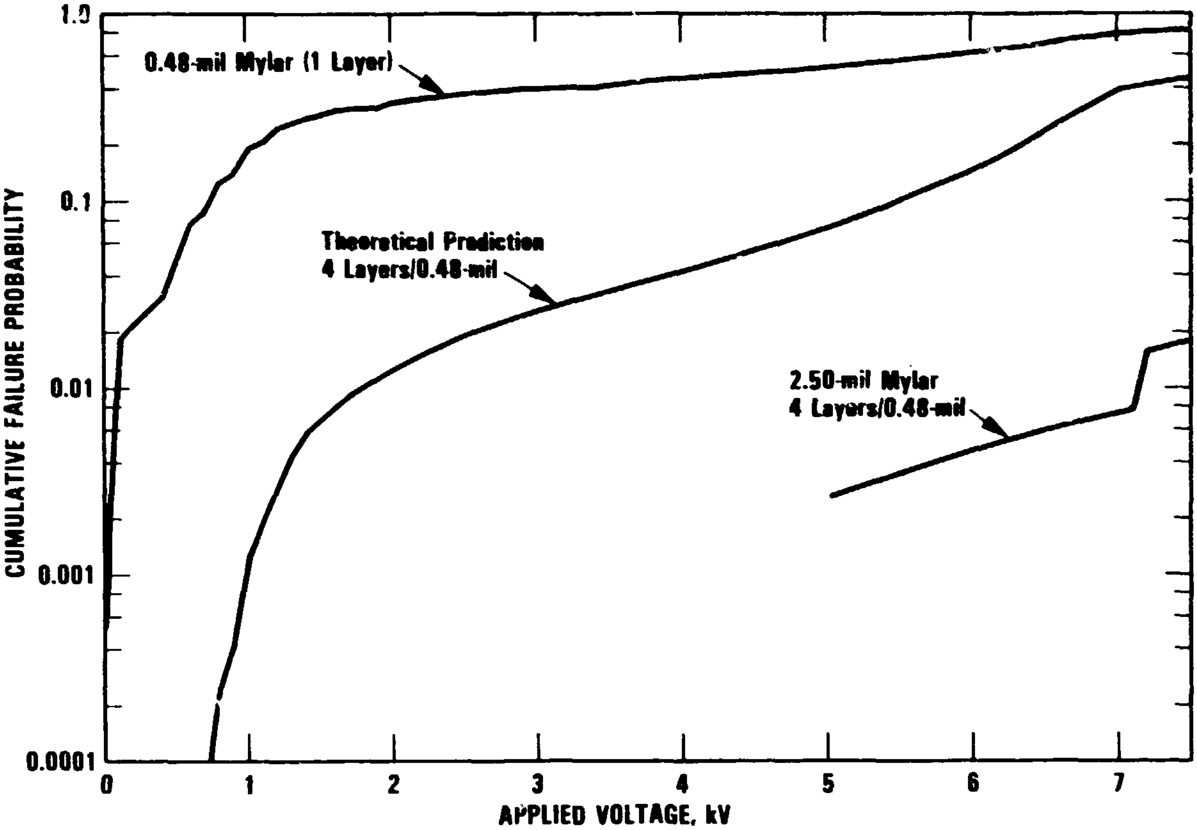


- **If All of the Layers Are Identical, Then** $p_m = p^m$

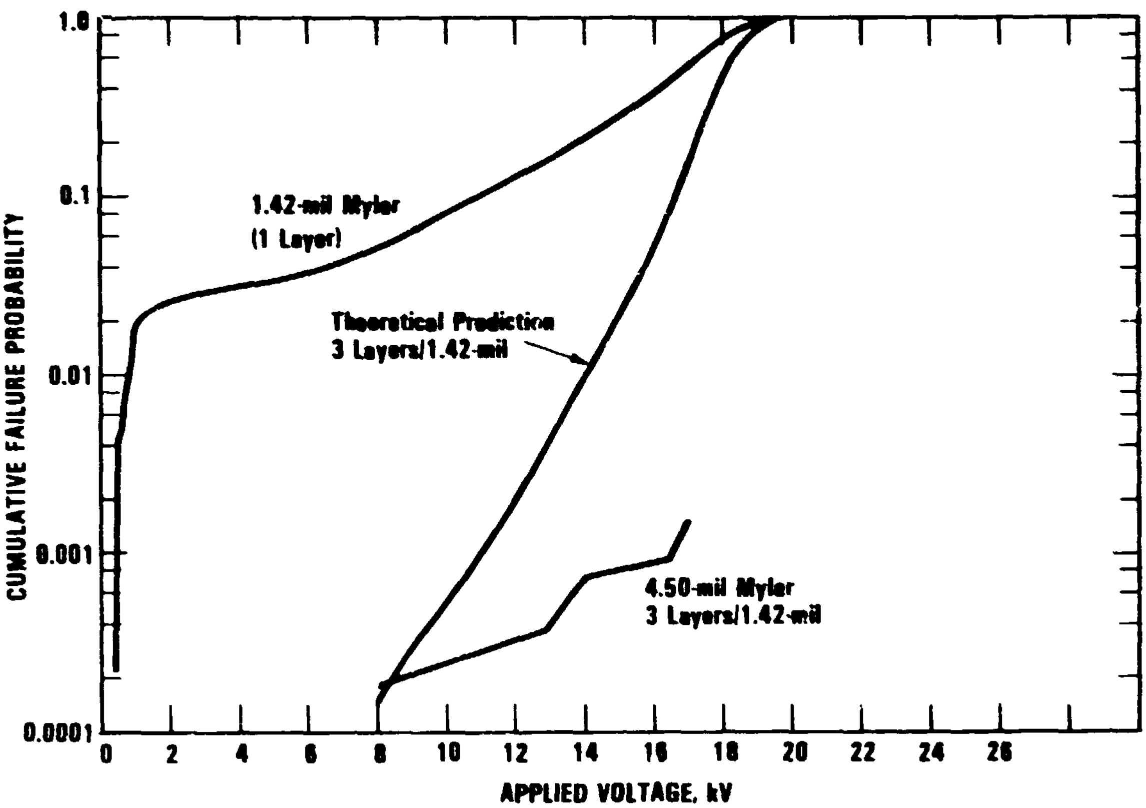
- **The Breakdown Probability of a Module Using Multilayer Insulating Films is** $p_{MOD} = 1 - (1-p_m)^n$

  Where $n = \begin{Bmatrix} 1467 \\ 2934 \\ 5867 \end{Bmatrix}$ **for** $\begin{Bmatrix} 2X4\text{-ft} \\ 4X4\text{-ft} \\ 4X8\text{-ft} \end{Bmatrix}$ **Modules**

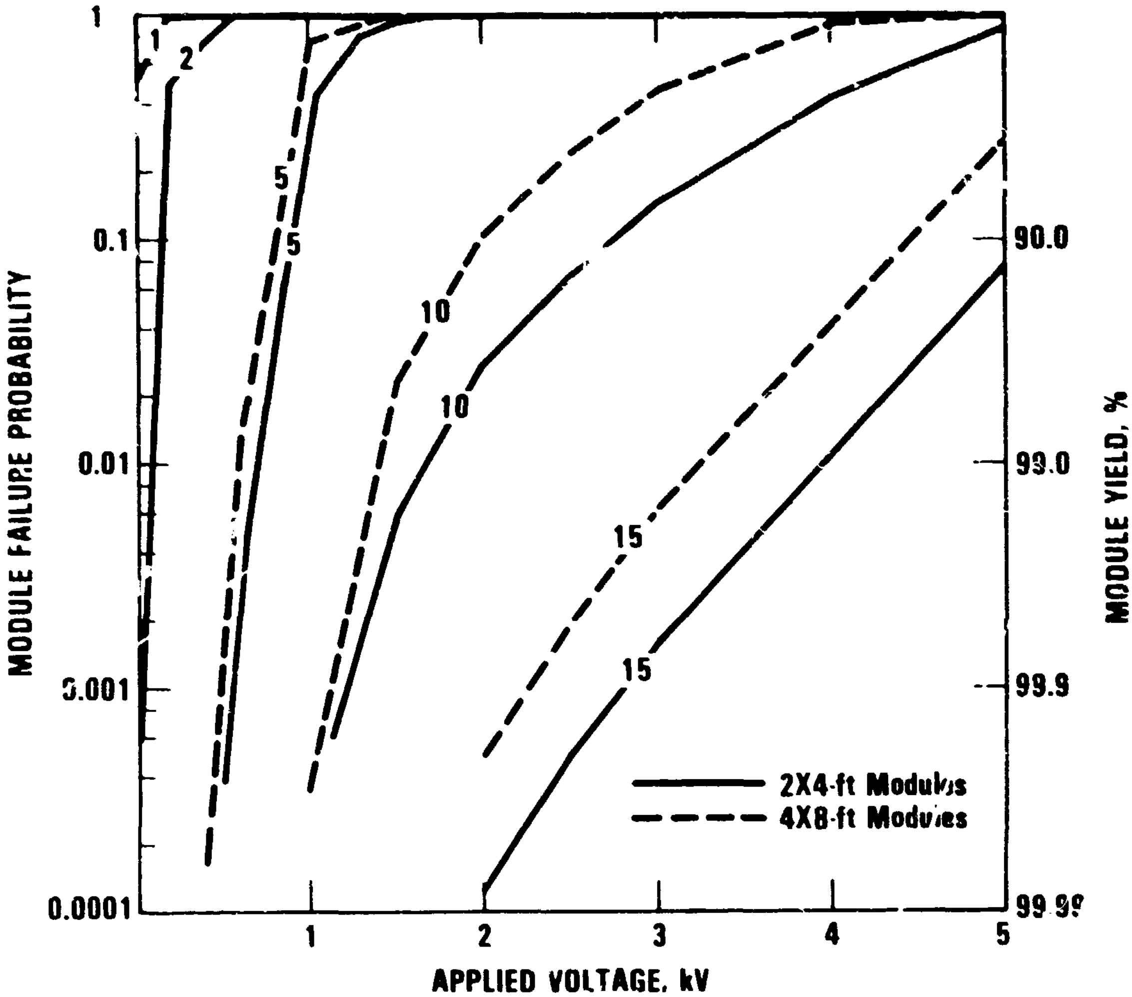
Theoretical vs Measured Voltage Breakdown Characteristics of Multilayer Mylar Insulation Films: Single Layer, 0.48 mils



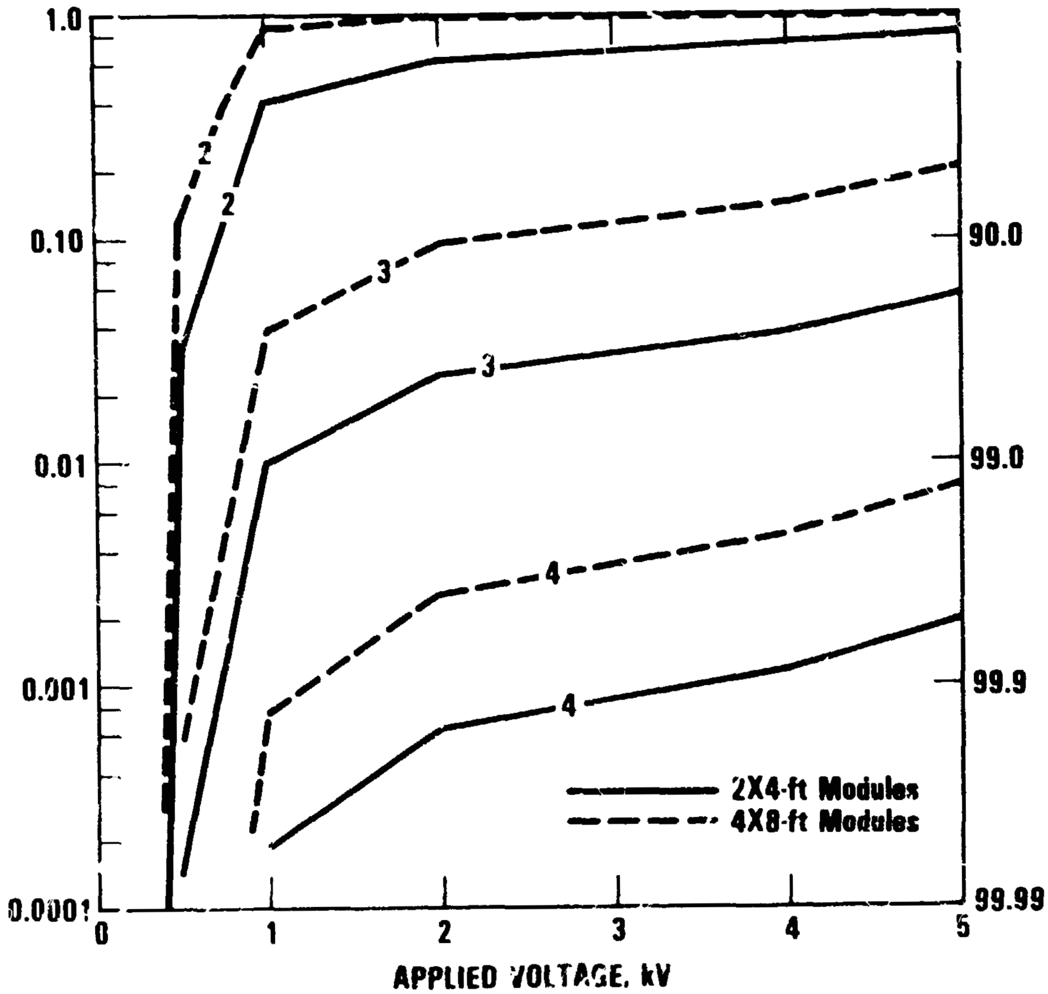
Theoretical vs Measured Voltage Breakdown Characteristics of Multilayer Mylar Insulation Films: Single Layer, 1.42 mils



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



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**
  - **Reference: G. Mon, "Defect Design of Insulation Systems for Photovoltaic Modules," 15th IEEE Photovoltaic Specialists Conference, pp. 964-971, 1981**

- **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**

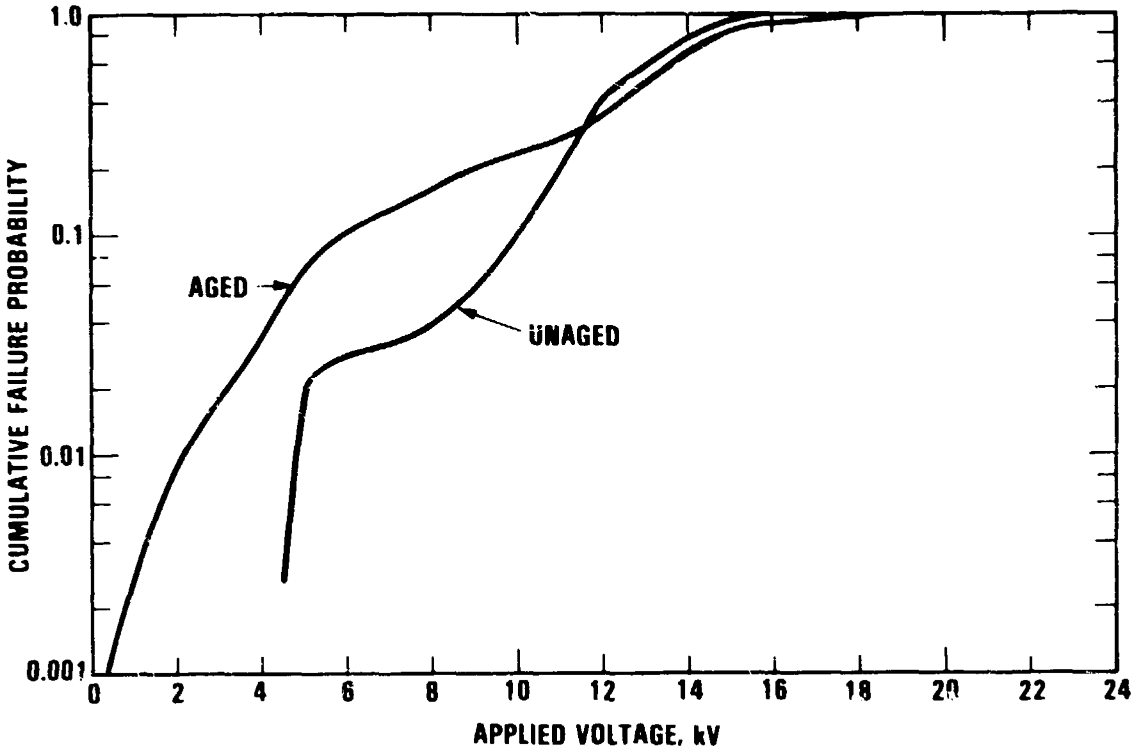
Aging Studies

- **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

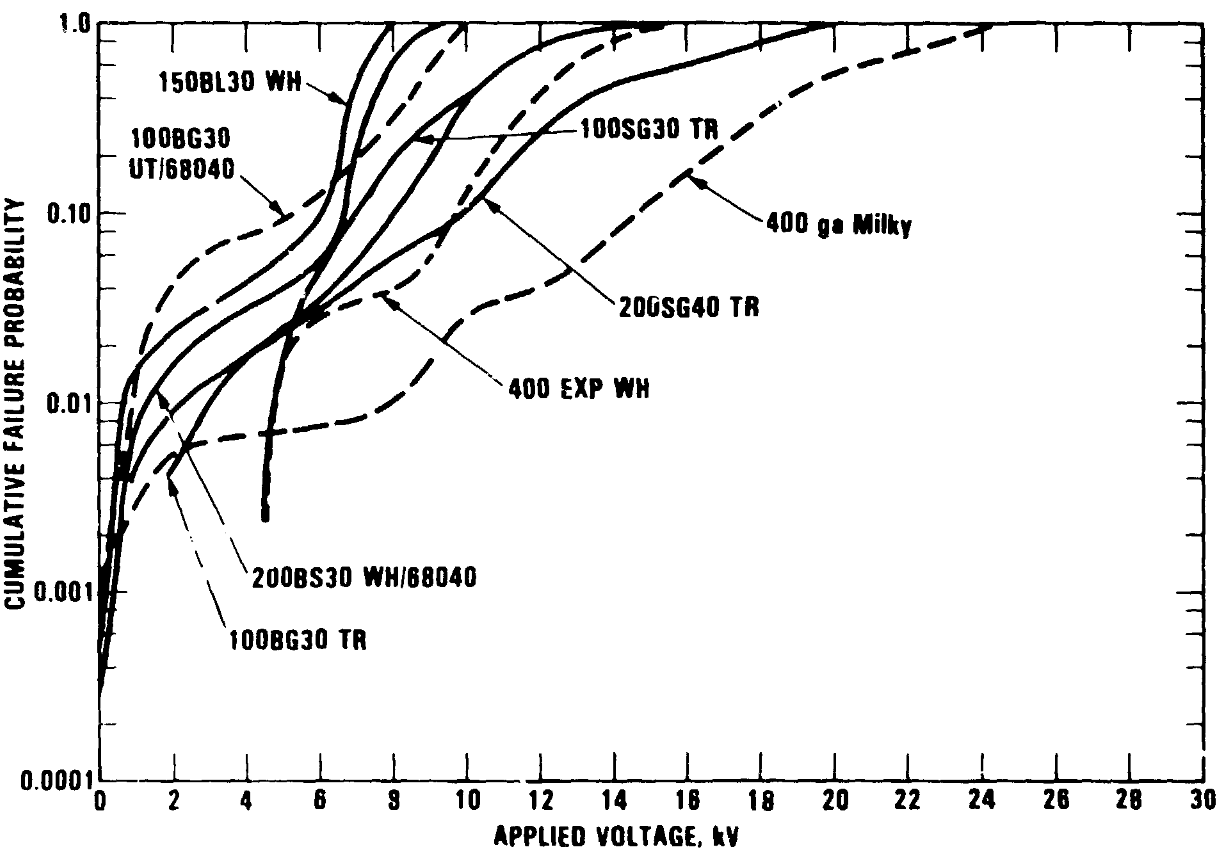
- **Preliminary Results Indicate That Environmental Exposure Can Significantly Alter Single-Layer, and Hence Module, Failure Probabilities**
- **Much Additional Testing Is Necessary Before Final Conclusions Can Be Made**

Additional Test Results

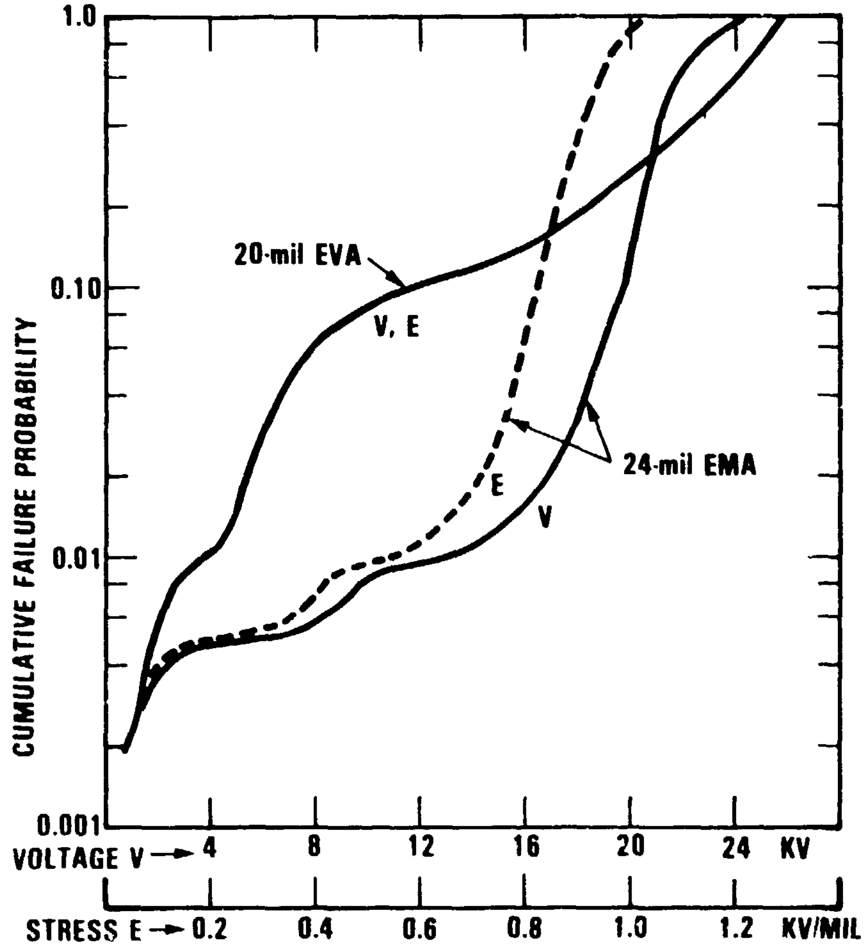
- **Encapsulants**
  - **EVA**
  - **EMA**

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

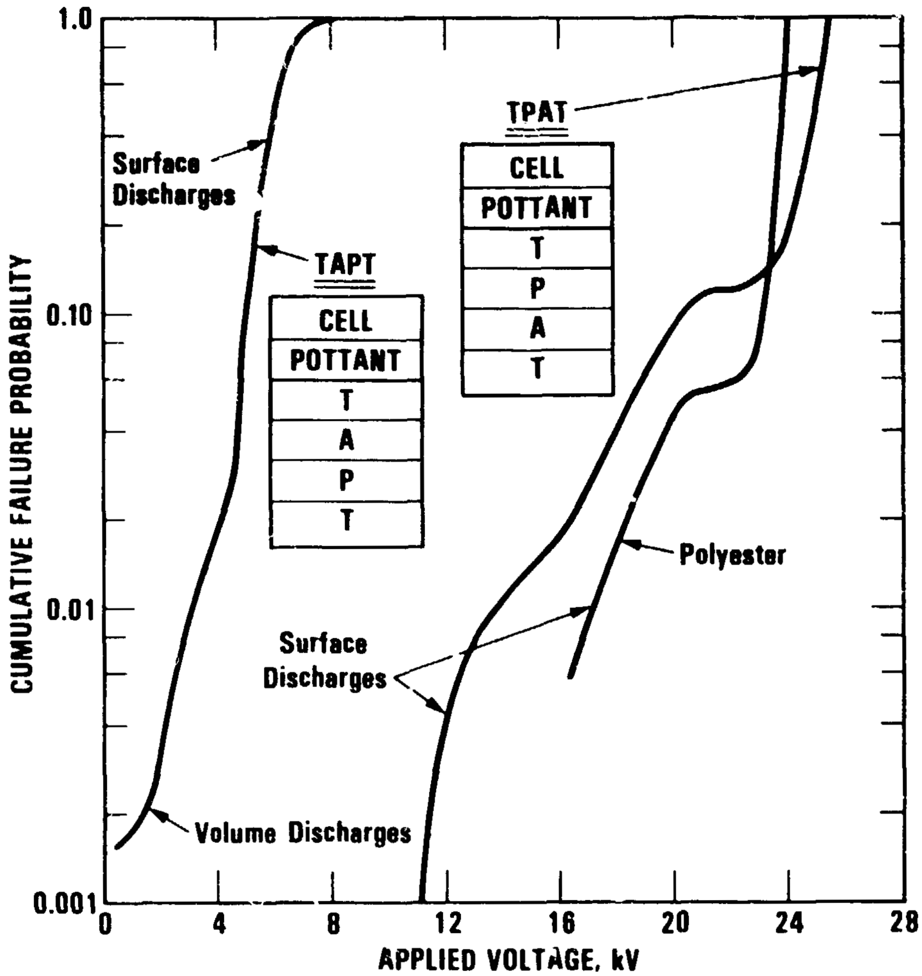
Voltage Breakdown Characteristics of Single-Layer Tedlar Films (per Unit Test Area: $A_T = \pi/4 \text{ in}^2$)



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)



Directions 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
  - Biddle 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 COMMERCIALLY 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

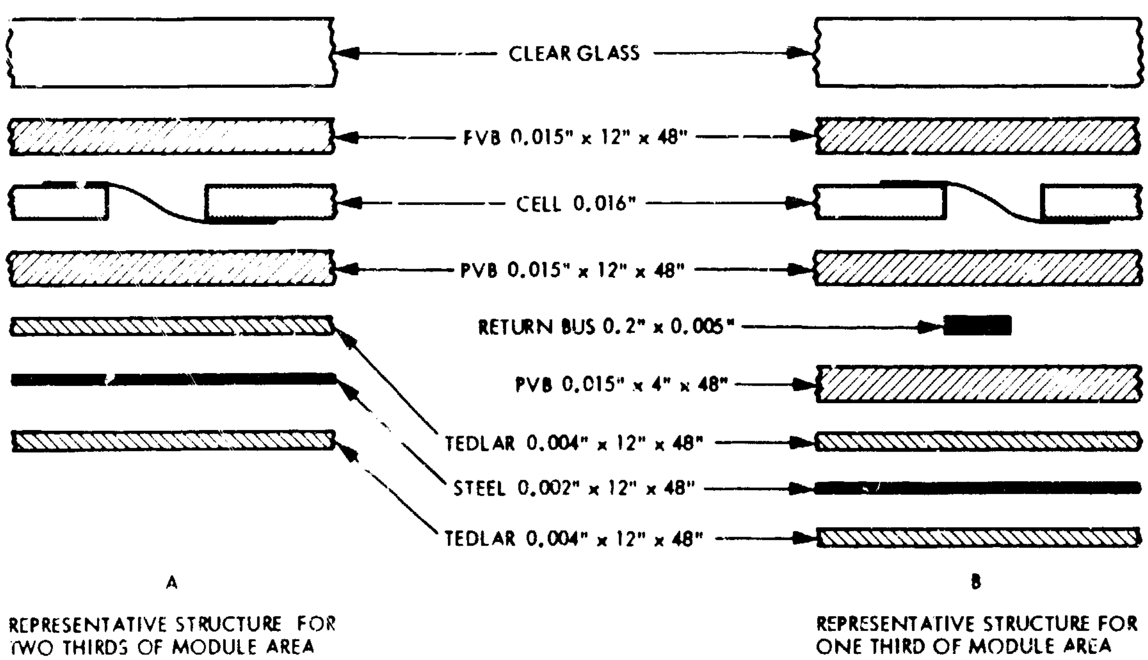
- REQUIREMENT OF SPECIFICATION
  - ROOM TEMPERATURE LEAKAGE CURRENT NOT TO EXCEED 50 μA AT 2000 Vdc (HI-POT TEST)

- 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 85C)

Exploded View of Module Structure



Capacitance Dissipation Factor at Room Ambient, 1 kHz

MODULE S/N	CAPACITANCE VALUE IN (μF)	DISSIPATION FACTOR VALUE IN (%)	REMARKS
1	0.02231	5.30	SUBJECT MODULE RETURNED FROM HAWAII
2	0.02149	4.95	COMPARISON MODULE JPL SPARE
3	0.01976	4.60	COMPARISON MODULE JPL SPARE

Partial Discharge (Corona) at Room Ambient, 60 Hz

MODULE S/N	PARTIAL DISCHARGE "INCEPTION" LEVEL		PARTIAL DISCHARGE AT 100 pC LEVEL		REMARKS
	(pC)	TEST VOLTS (kV PEAK)	(pC)	TEST VOLTS	
1	20	6.6	124	7.9	MODULE RETURNED FROM HAWAII
2	22	5.8	103	6.3	COMPARISON MODULE - JPL SPARE
3	23	4.4	105	5.1	COMPARISON MODULE - JPL SPARE

NOTE: THE 100 pC LEVEL OF PARTIAL DISCHARGE IS EQUIVALENT TO ≈ 10 ηA AVERAGE CURRENT.

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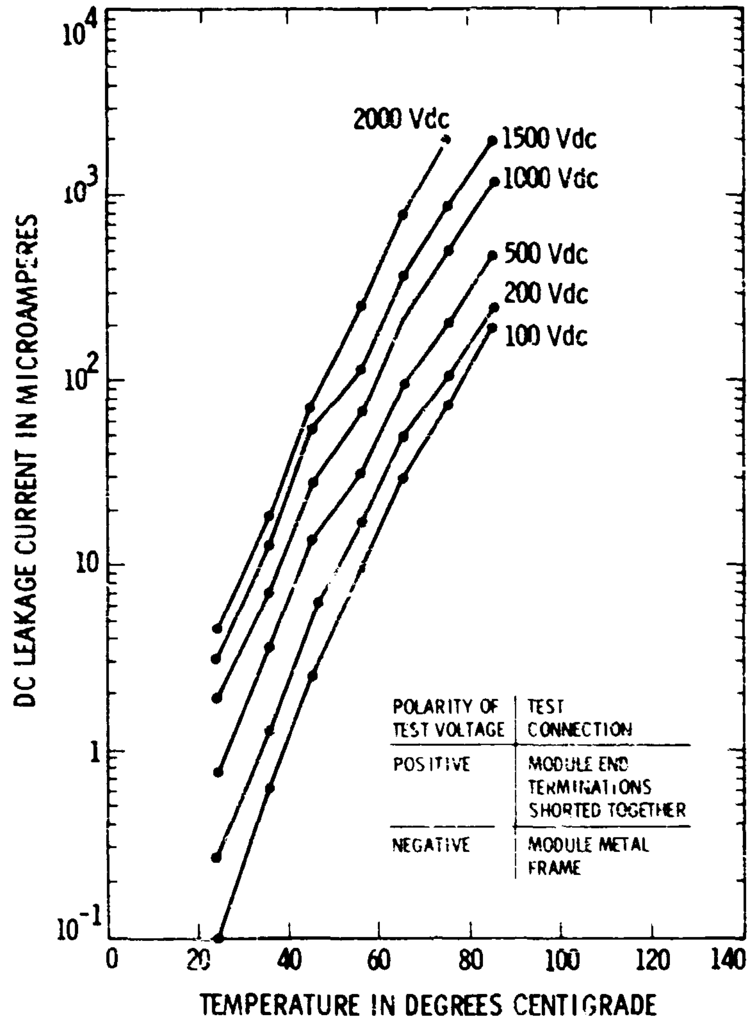
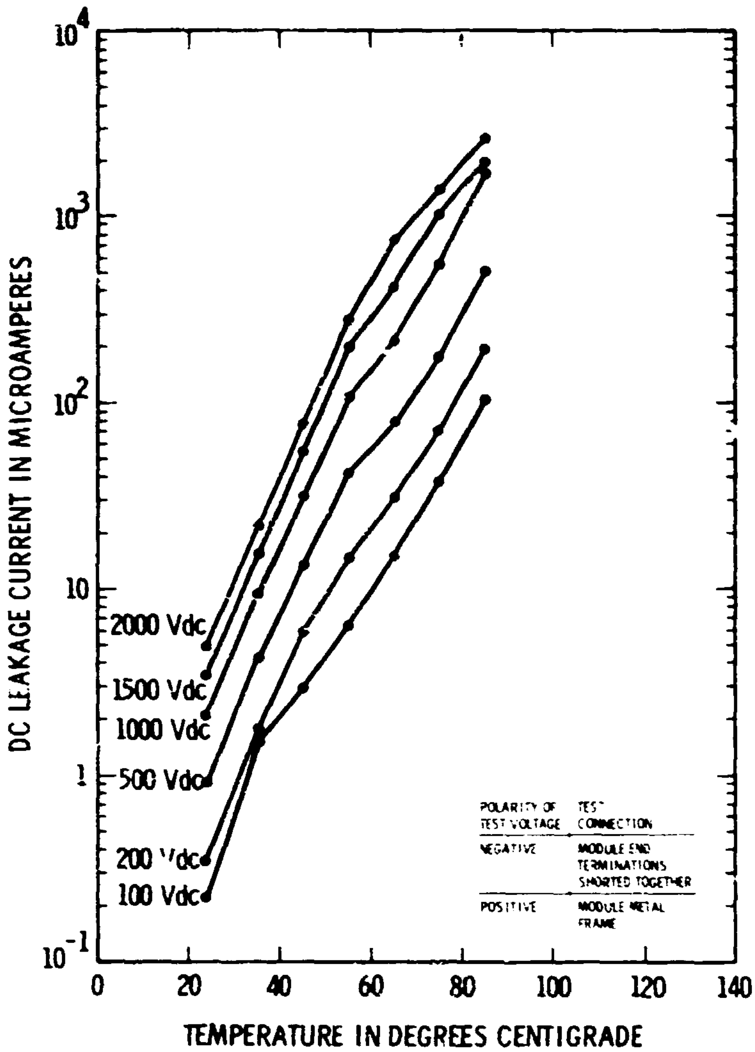
DC Leakage Current Test Results vs Temperature and Voltage: Module No. 1



DC Leakage Current Test Results vs Temperature and Voltage: Module No. 1



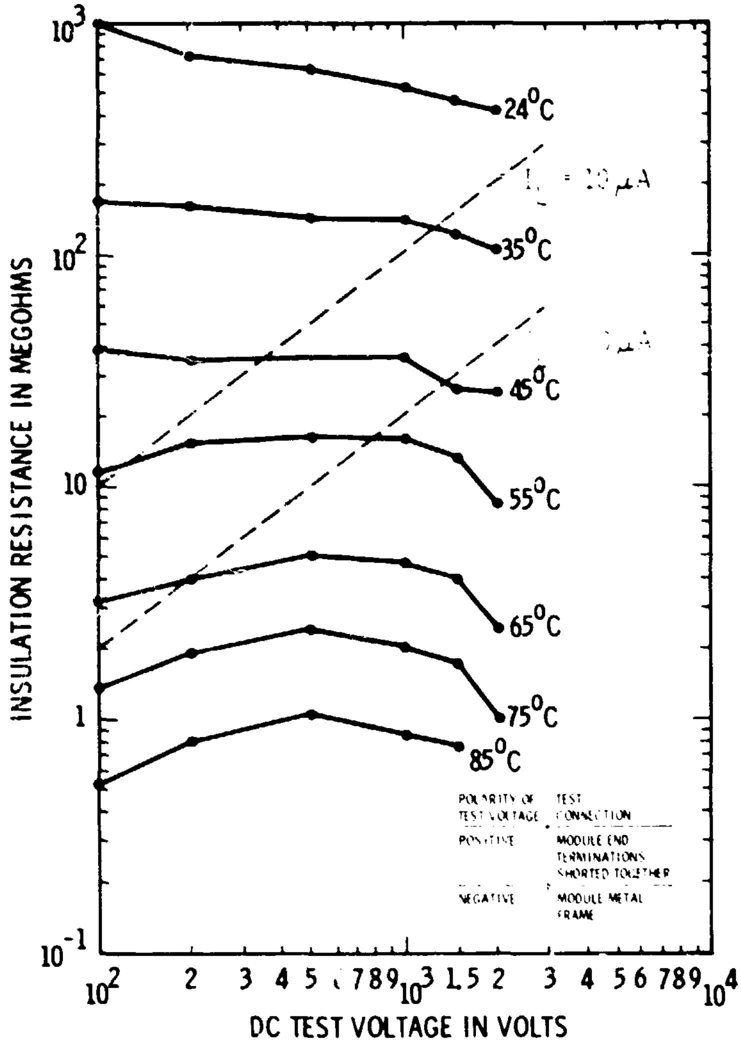
Voltage as a Function of Temperature for a 50 μA Leakage Current

VOLTAGE (VOLTS)	MODULE TEMPERATURE (DEG C) FOR A 50 μA DC LEAKAGE CURRENT					
	MODULE #1 WITH TERMINAL POLARITY		MODULE #2 WITH TERMINAL POLARITY		MODULE #3 WITH TERMINAL POLARITY	
	+	-	+	-	+	-
2000	42	42	40	40	41	40.5
1500	44	44.5	42.5	42	45	46
1000	52	49.5	47	47	52.5	55
500	59.5	58	56	59.5	59.5	62.5
200	65	71	62.5	69.5	68	72
100	71	77.5	69	76.5	74	79

+ POLARITY – MODULE FRAME CONNECTED TO GROUND

- POLARITY – TERMINALS CONNECTED TO GROUND

Insulation Resistance Test Results vs Temperature and Voltage: Module No. 1



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 - $<50\,\mu A$ AT 2000 Vdc AT ROOM TEMPERATURE
- NEED TO ESTABLISH SPECIFICATIONS FOR ACCEPTABLE LEVELS OF LEAKAGE CURRENT FOR LONG TERM RELIABILITY AND SAFETY

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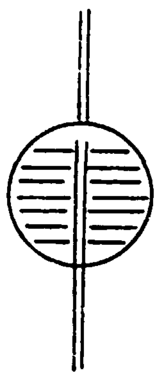
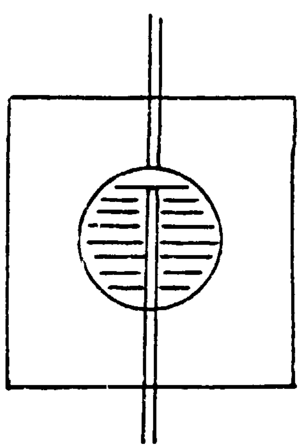
CELL RELIABILITY TESTING

CLEMSON UNIVERSITY

J.W. Lathrop

Accelerated Stress Tests

FORM	TEST	LIMIT
 UNENCAPSULATED	BIAS-TEMPERATURE PRESSURE COOKER $85^{\circ}C/85\%$ RH THERMAL CYCLE THERMAL SHOCK	SOLDER MELTING $T < 175^{\circ}C$
 ENCAPSULATED	$85^{\circ}C/85\%$ RH THERMAL CYCLE ENVIRONMENTAL	ORGANIC DECOMPOSITION $T < 95^{\circ}C$

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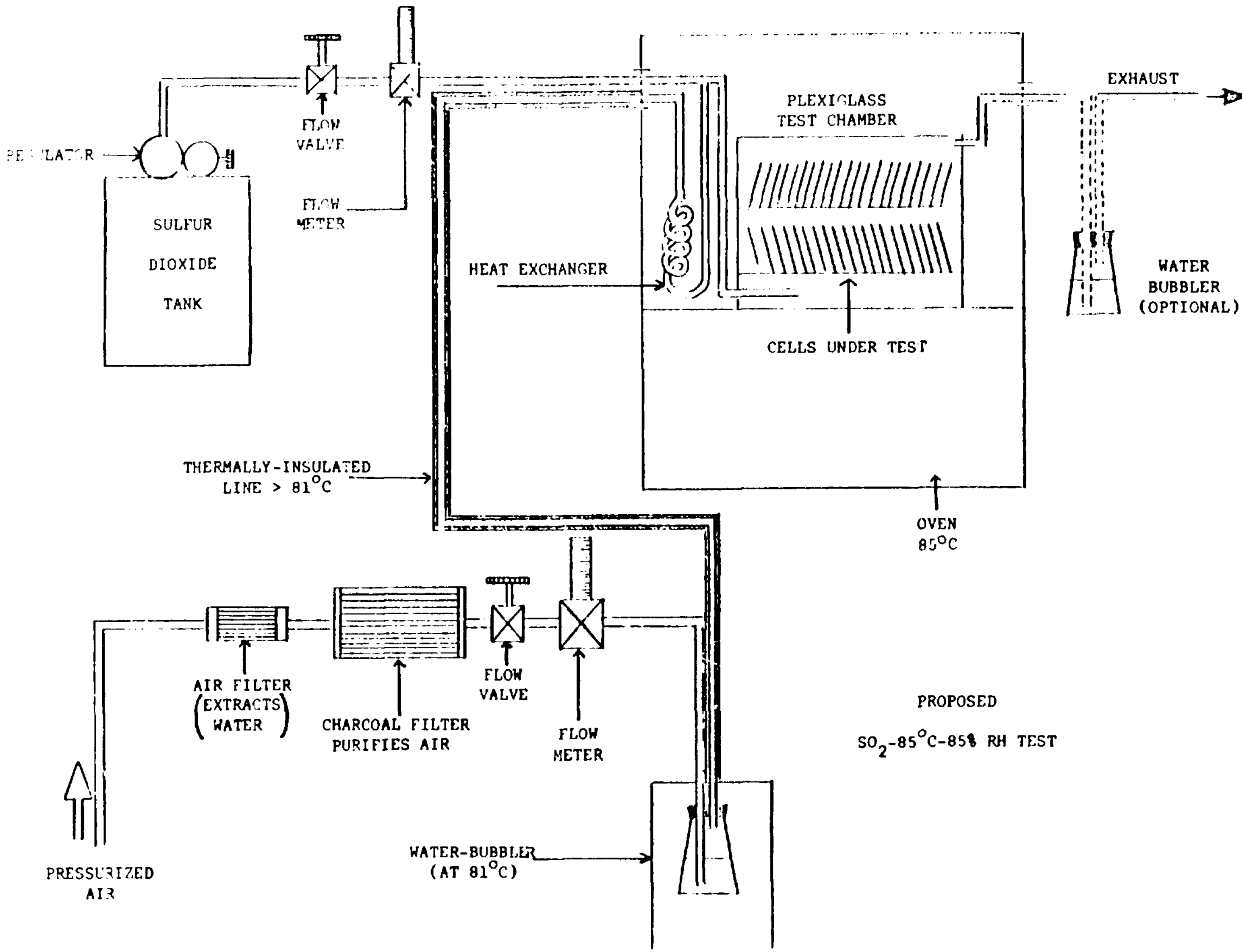
Anticipated Failure Mechanisms

PHYSICAL PHENOMENON	OBSERVED EFFECT	ACCELERATING TEST
DIFFUSION	LOSS OF COLLECTION EFFICIENCY BULK RESISTIVITY INCREASE CONTACT RESISTANCE INCREASE	B-T
CORROSION	METAL REMOVAL METAL PLATING AR COATING REMOVAL	PC 85/85
DIFFERENTIAL EXPANSION	METAL PEELING CELL FRACTURE	TC/TS

Proposed SO_2 – 85°C – 85% RH Test



PROPOSED

SO_2-85°C-85% RH TEST

Modules for Encapsulated Cell Testing

CELL METALLIZATION SYSTEMS

	Ni-SOLDER 7 TYPES		Cu PLATE 2 TYPES		Ag SCREEN 1 TYPE			
	S	M	S	M	S	M		
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		5	50	3			
T/EVA/S	15		2		3			
G/EVA				25				
G/SR/G		12						
	78	162	13	99	15		106	261
	240		112		15		367	

S = SPRINGBORN FABRICATED

M = MANUFACTURER FABRICATED

LONG-TERM MODULE TESTING AT WYLE LABORATORIES

JET PROPULSION LABORATORY

D.H. Otth

Objectives

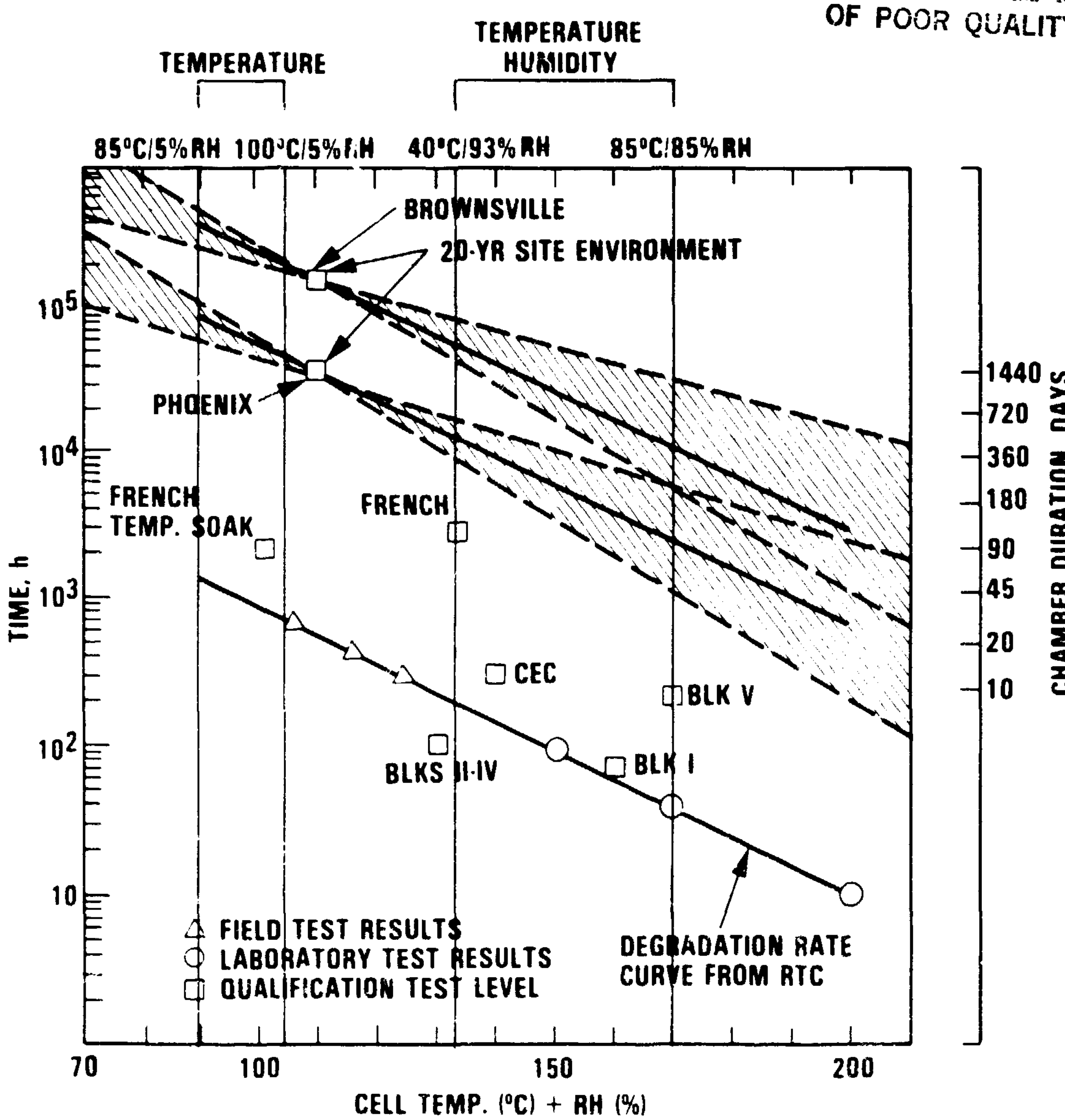
- **Understand Temperature/Humidity-Bias Failure Mechanisms of Typical Photovoltaic Modules and Materials**
  - **Cells, Encapsulants, Interconnects**
  - **Back Covers, Edge Seals**

- **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**

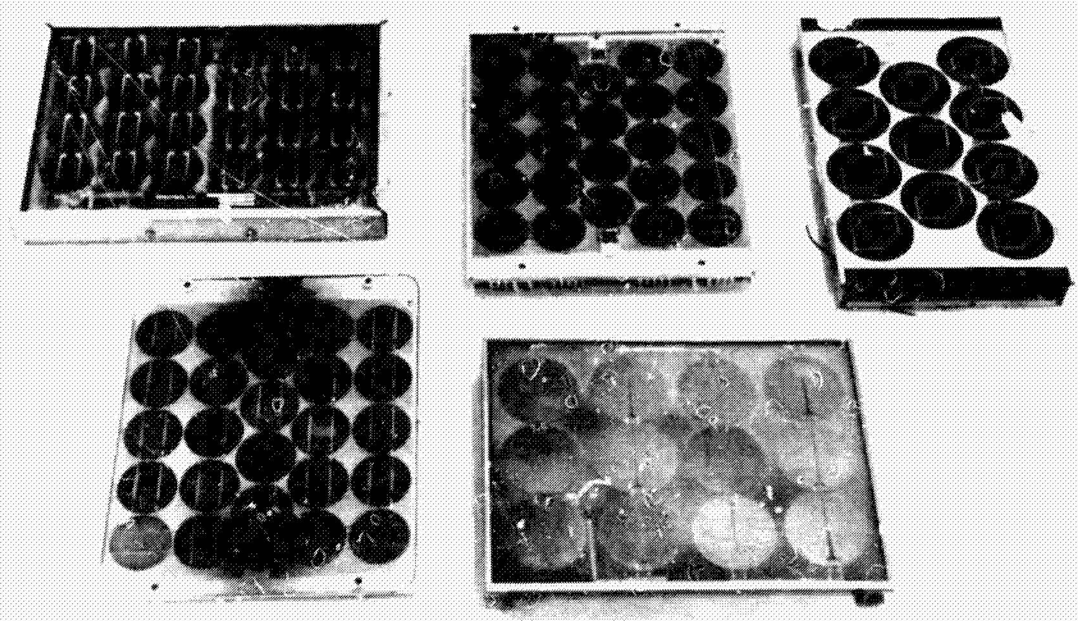
Long-Term Module Testing



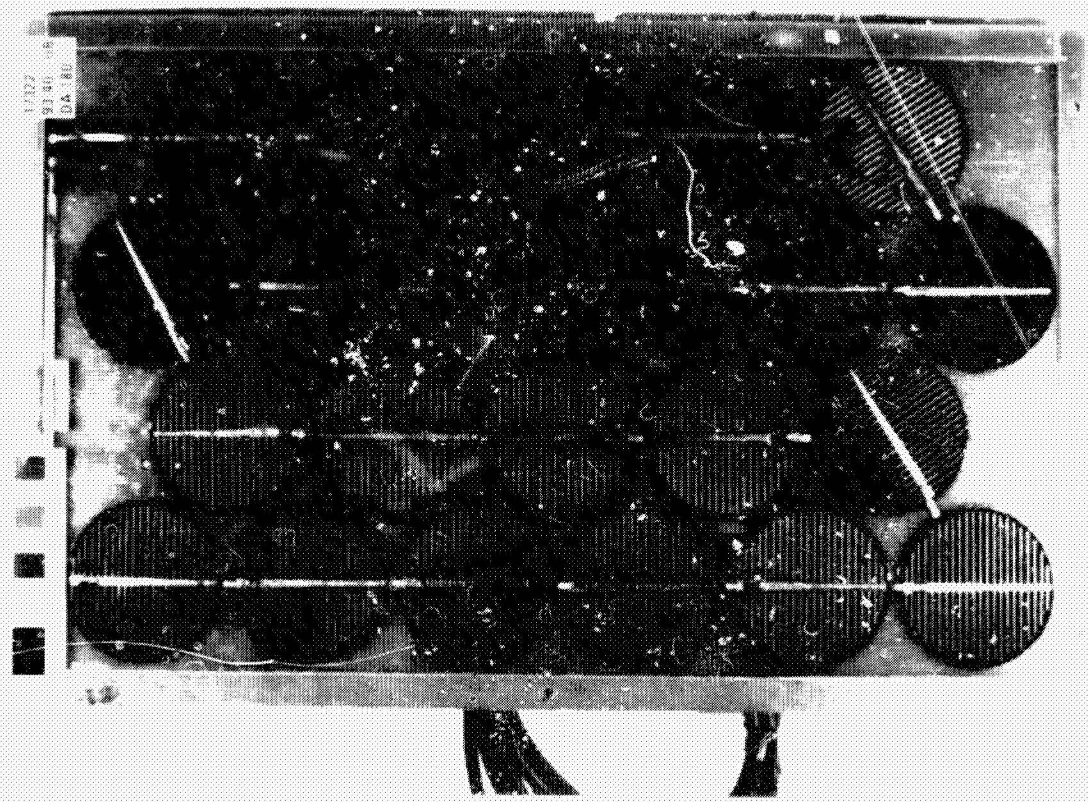
Module Materials

- **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

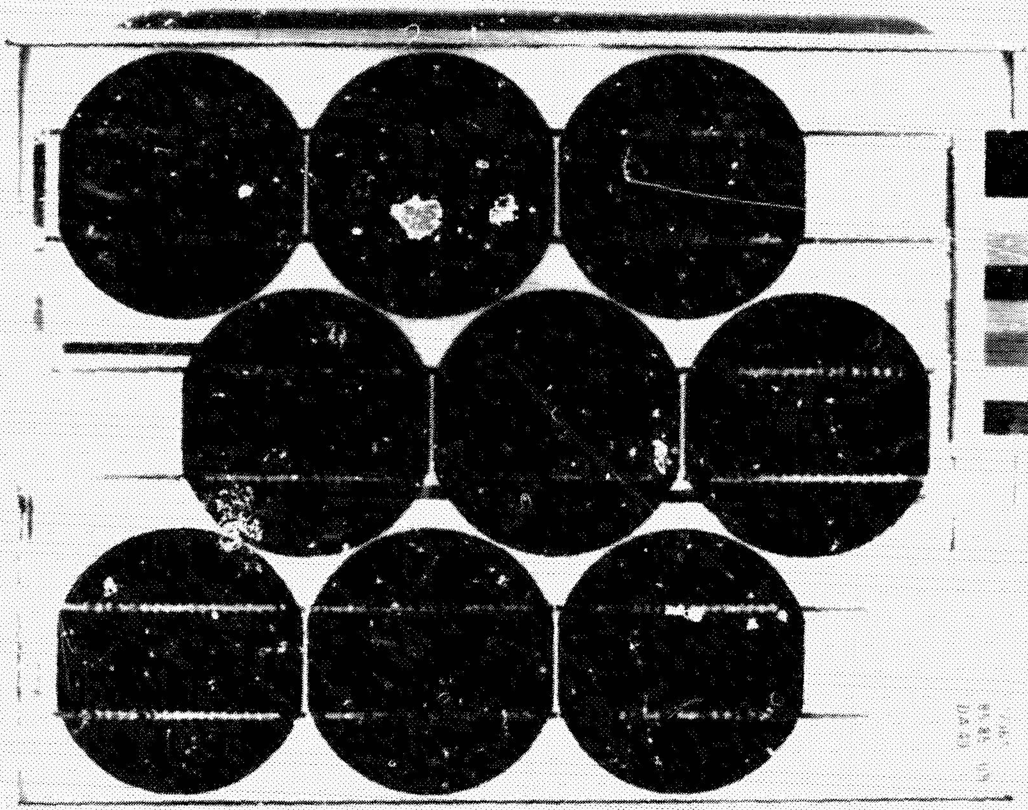
Blocks II and III Modules in Wyle Testing



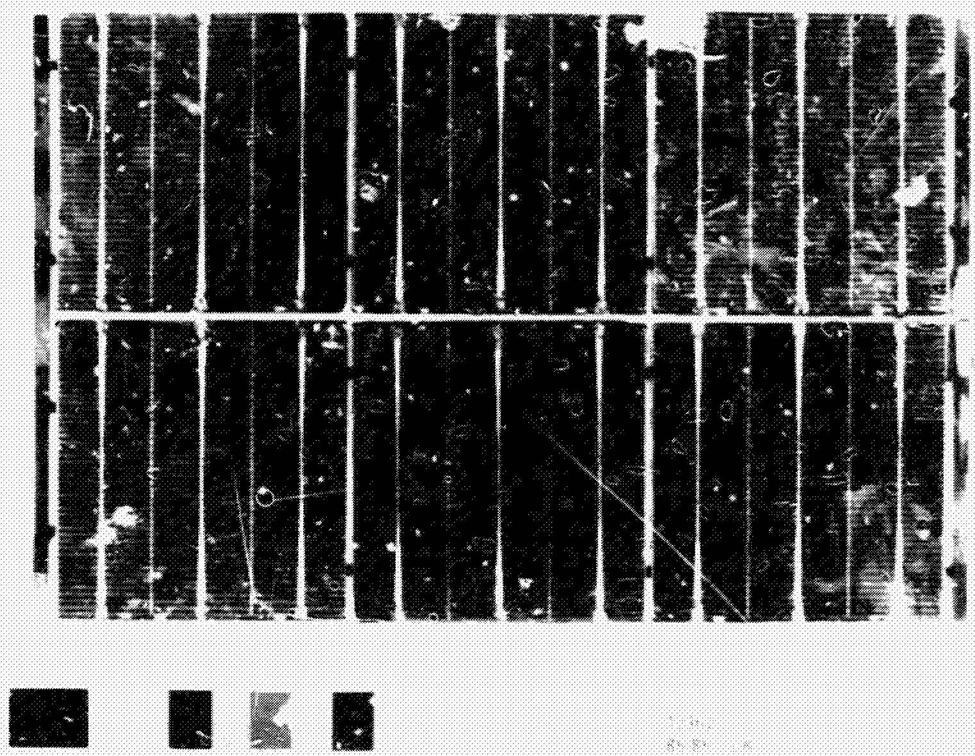
Block I Type Module in Wyle Testing



Block IV Modules in Wyle Testing



Block IV Minimodule With Semicrystalline Cells



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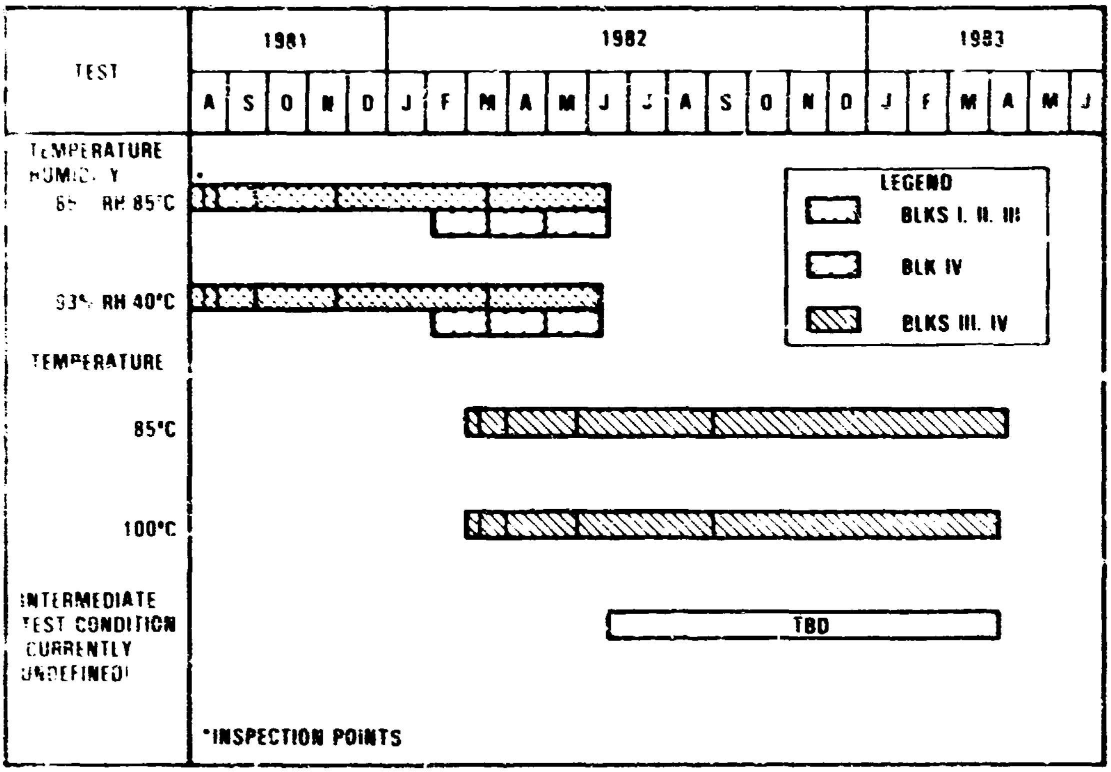
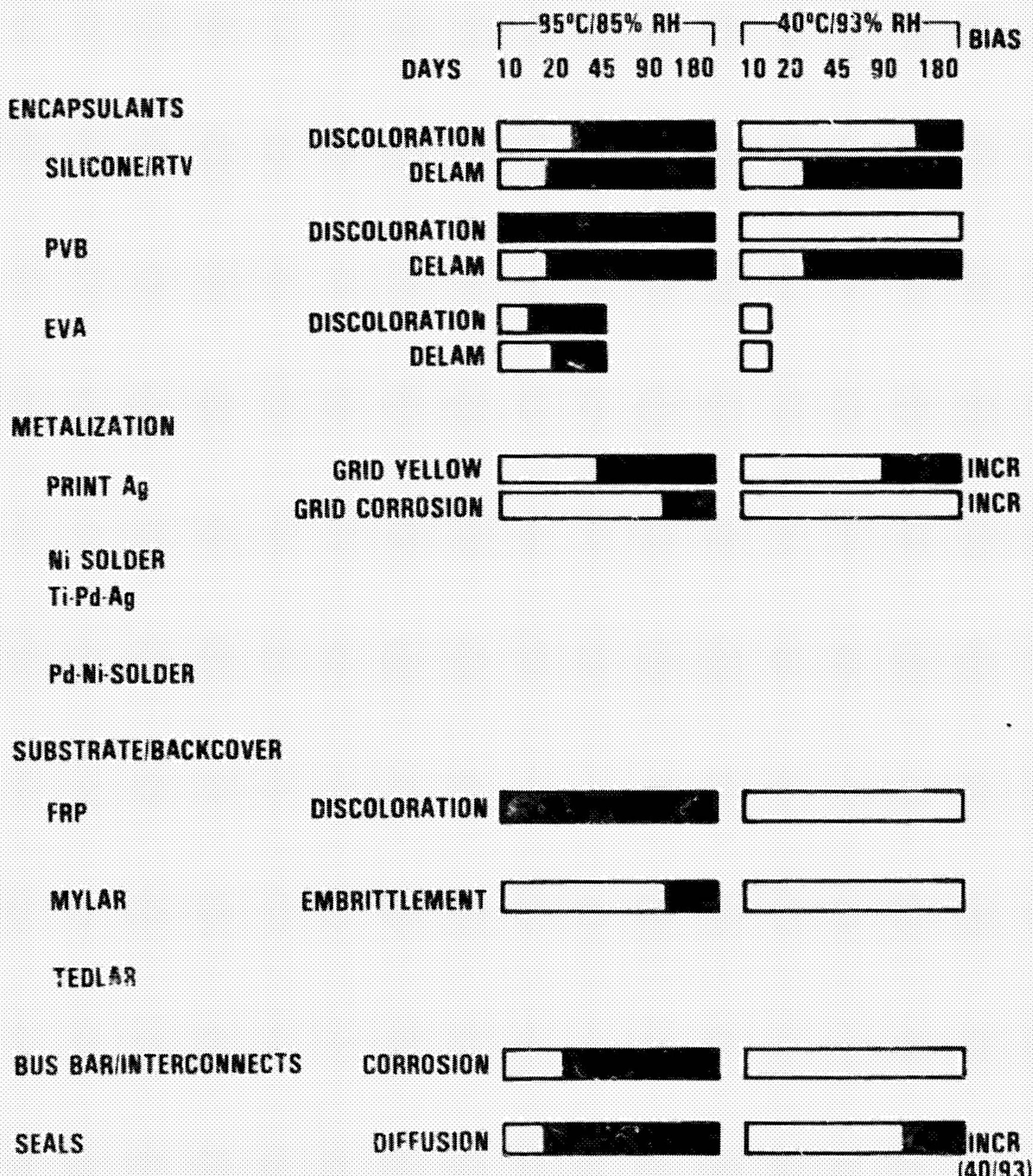


Visual Degradation Mechanisms



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**

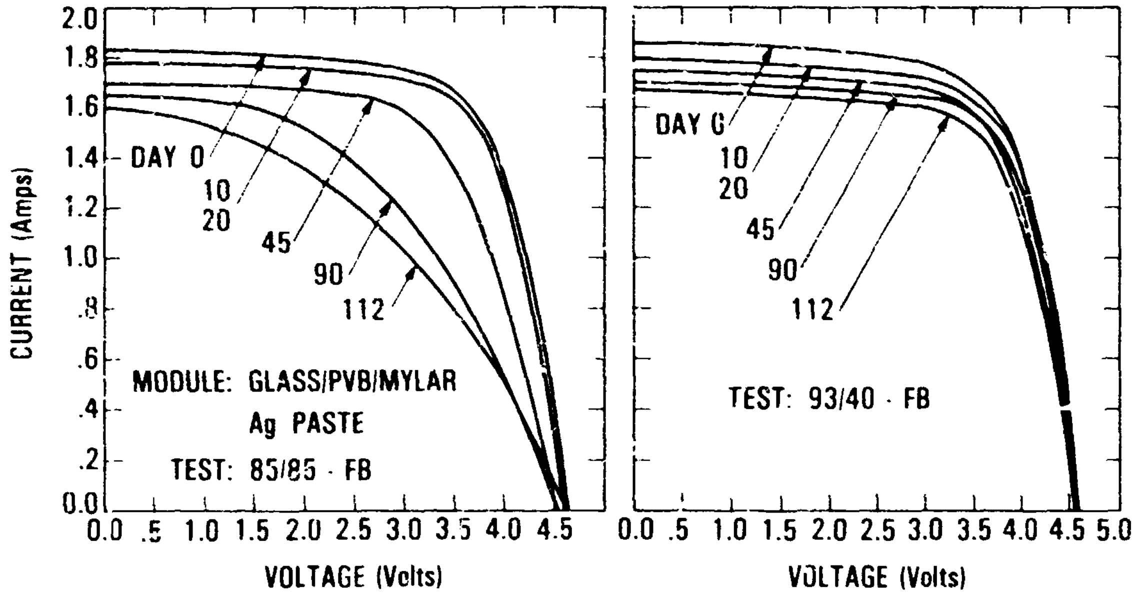
Visual Observations From Long-Duration Module Tests (112 Days)

GENERIC MODULE TYPE	VISUAL OBSERVATIONS	
	85/85	93/40
GLASS/PVB/MYLAR Ag PASTE	DISCOLORATION: PVB CORROSION: CIRCUITRY GRID LINES	
RTV/ALUMINUM Ni SOLDER	DISCOLORATION: RTV MICROCRACKS: RTV	SLIGHT DISCOLORATION: RTV
GLASS/RTV/ALUMINUM Ni SOLDER	DISCOLORATION: RTV DELAMINATION AT TERMINALS	SLIGHT DISCOLORATION: RTV
GLASS/PVB/TEDLAR Ag PASTE	DISCOLORATION: PVB CORROSION: CIRCUITRY GRID LINES	DISCOLORATION: GRID LINES DELAMINATION: EDGE SEAL
RTV/GLASS FIBER REINFORCED POLYESTER Ti-Pd-Ag	DISCOLORATION: SUBSTRATE CORROSION: CIRCUITRY	SLIGHT CORROSION: CIRCUITRY
RTV/GLASS FIBER Ni SOLDER	DISCOLORATION: SUBSTRATE SLIGHT CORROSION: CIRCUITRY	

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)

GENERIC MODULE TYPE	ΔI_{sc}, % 85/85	ΔI_{sc}, % 93/40	ΔR_s, % 85/85	ΔR_s, % 93/40	ΔP_{mp}, % 85/85	ΔP_{mp}, % 93/40
GLASS/PVB/MYLAR Ag PASTE	-5	0	+300	+10	-40	1
RTV/ALUMINUM Ni SOLDER	-2.5	0	+20	0	-2.5	1
GLASS/RTV/ALUMINUM Ni SOLDER	0	0	0	0	0	1
GLASS/PVB/TEDLAR Ag PASTE	-5	0	+60	+10	-20	1
RTV/GLASS FIBER REINFORCED POLYESTER Ti-Pd-Ag	-4	0	+100	+10	-15	1
RTV/GLASS FIBER Ni SOLDER	-3	0	+100	—	-20	1
	$I_{sc}\downarrow$		$R_s\uparrow$		$P_{mp}\downarrow$	

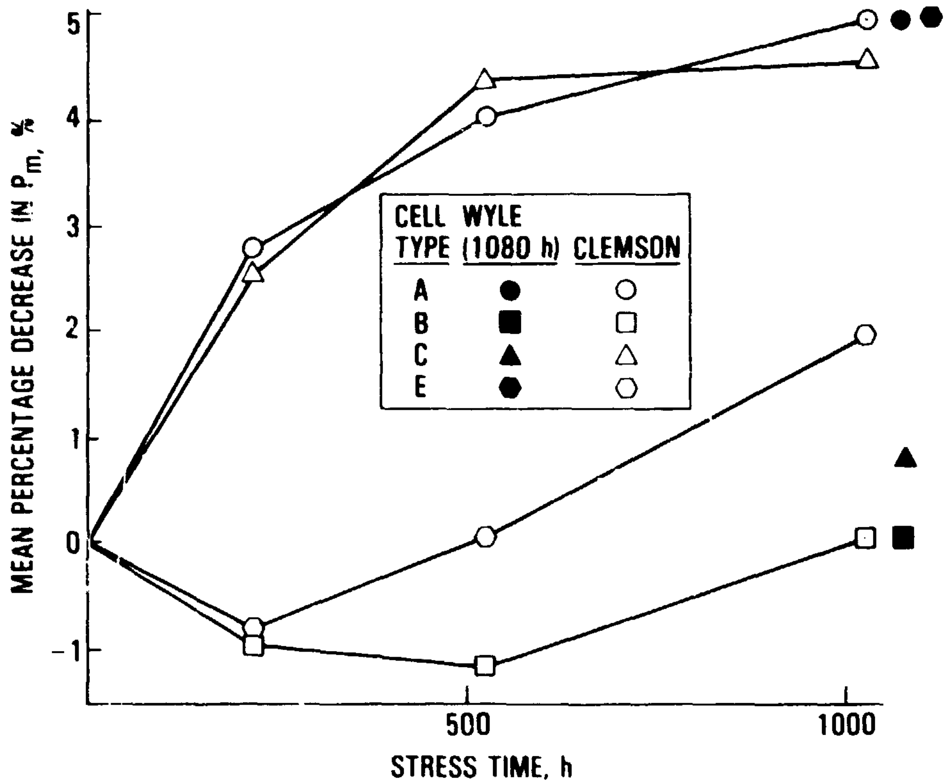
- AFTER SUBTRACTING THE CONTRIBUTION DUE TO I_{sc} LOSS, THE POWER LOSS RATE IS FOUND TO BE ROUGHLY ONE TENTH THE RATE OF SERIES RESISTANCE INCREASE.

Comparison Overview of Wyle and Clemson Tests

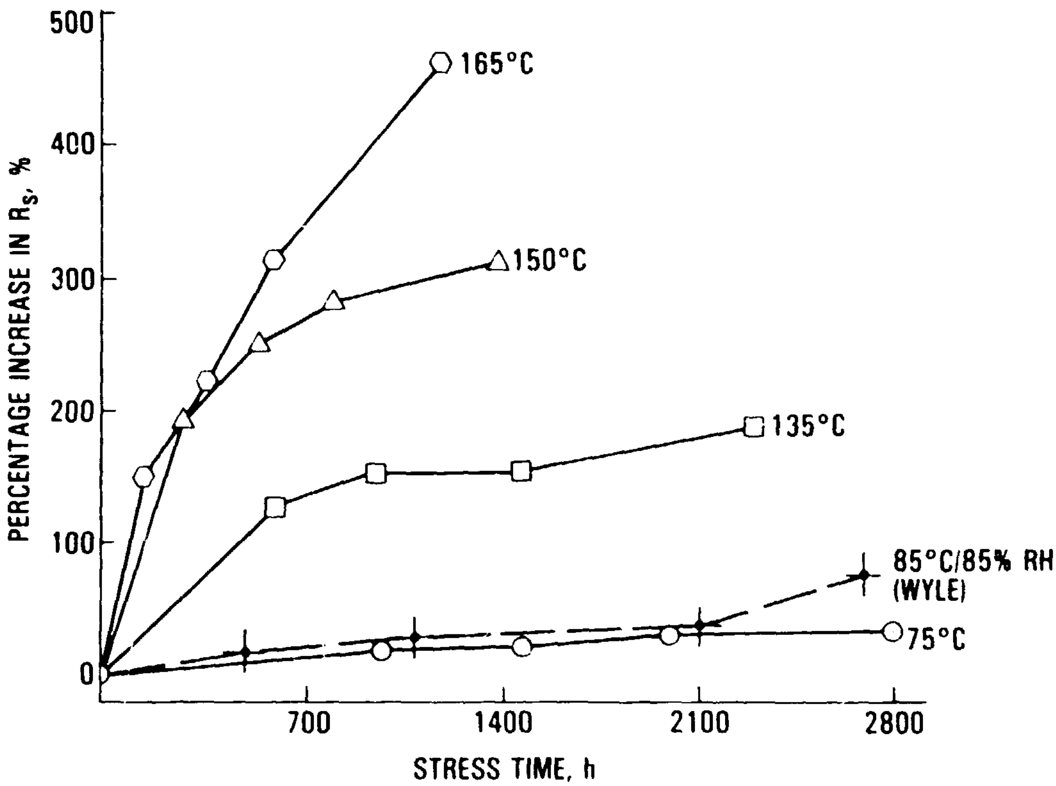
	WYLE	CLEMSON
TEST SPECIMENS:	MINIMODULES	UNENCAPSULATED CELLS
TESTS:	85/85 - FB	85/85 - FB
	85/85 - UB	85/85 - UB
	93/40 - FB	15 psig STEAM/121 - FB
	93/40 - UB	15 psig STEAM/121 - UB
	0/85 - FB	0/75 - FB
	0/85 - UB	0/75 - UB
	0/100 - FB	0/135 - FB
	0/100 - UB	0/135 - UB
		0/150 - FB
		0/150 - UB
		0/165 - FB
		0/165 - UB

GENERIC MODULE TYPE	CLEMSON CELL TYPE
GLASS/PVB/MYLAR Ag PASTE	—
RTV/ALUMINUM Bi SOLDER	C
GLASS/RTV/ALUMINUM Bi SOLDER	C
GLASS/PVB/TEDLAR Ag PASTE	E
RTV/GLASS FIBER REINFORCED POLYESTER Ti Pd Ag	B
RTV/GLASS FIBER Bi SOLDER	A

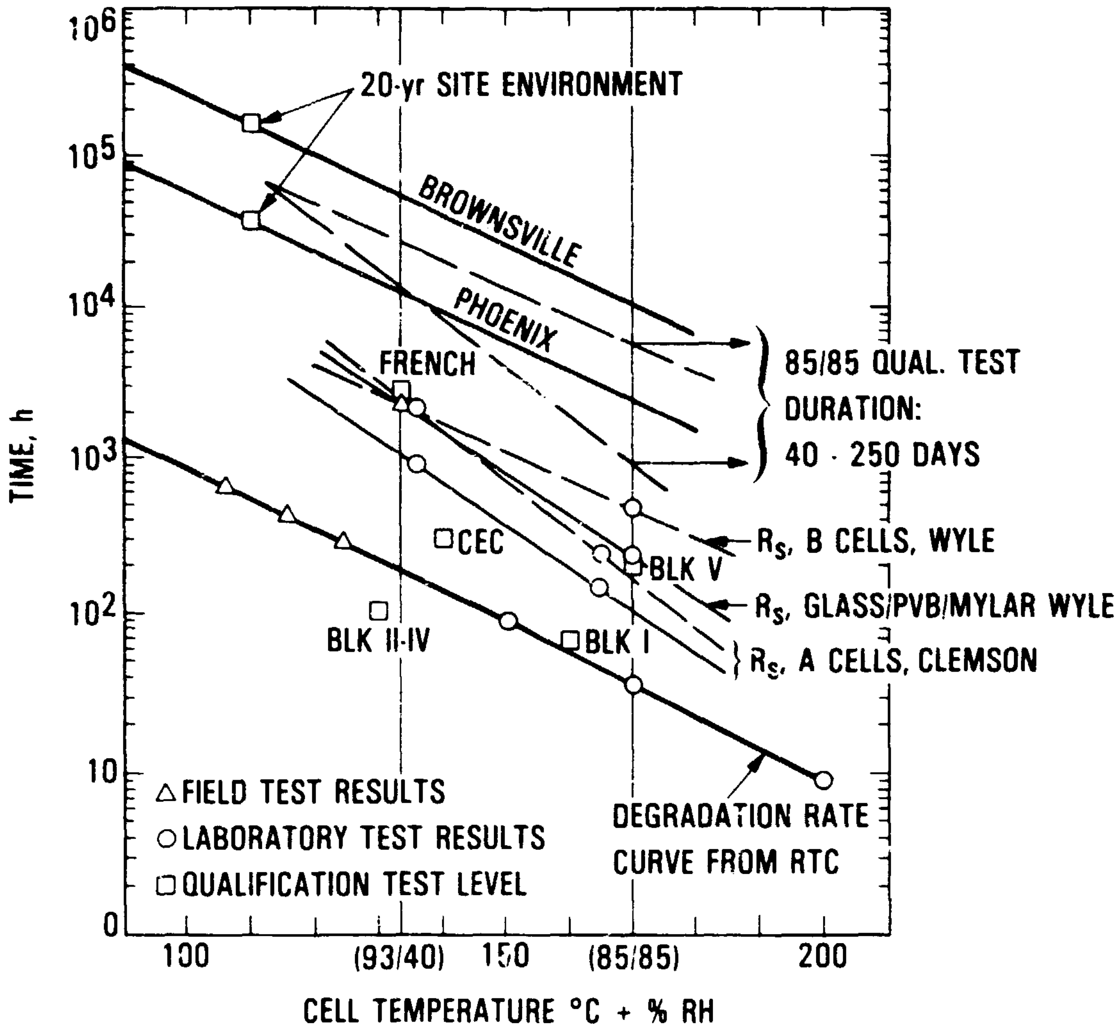
Mean Percentage Decrease in P_m vs Stress Time (85°C/85% RH Test)



Behavior of R_S With B-T Stress Time: Typical Type A Cells



Acceleration of Humidity and Temperature



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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

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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)