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Flat-Plate
Solar Array Project

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Progress Report 19

for the Period July to November 1981

and Proceedings of the 19th Project Integration Meeting

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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Pasadena, California

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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the Department of Energy and is part of the Photovoltaic Energy Systems Program conducting research in photovoltaic systems.

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ABSTRACT

This report describes progress made by the Flat-Plate Solar Array Project (formerly the Low-Cost Solar Array Project) during the period July to November 1981. It includes reports on project analysis and integration; technology research in silicon material, large-area silicon sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis. It includes a report on, and copies of visual presentations made at, the 19th Project Integration Meeting held at Pasadena, California, on November 11, 1981.

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NOMENCLATURE

ac	Alternating current
A	Ampere(s)
A	Angstrom(s)
ACM	Atmospheric corrosion monitors
AIA/RC	American Institute of Architects Research Corp.
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
CVD	Chemical vapor deposition
Cz	Czochralski (classical silicon crystal growth method)
dc	Direct current
DCS	Dichlorosilane
DLTS	Deep-level transient spectroscopy
DOE	U.S. Department of Energy
EBIC	Electron-beam-induced current
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EMA	Ethylene methylacrylate
EPDM	Ethylene-propylene-diene monomer
EPR	Ethylene propylene rubber
EPSDU	Experimental process system development unit
ESB	Electrostatic bonding
ESGU	Experimental sheet growth unit
EVA	Ethyl vinyl acetate
FAST	Fixed-abrasive slicing technique
FBR	Fluidized-bed reactor
FSA	Flat-Plate Solar Array Project

FSR	Free-space reactor
FTIR	Fourier transform infrared
GC	Gas chromatography
HEM	Heat-exchange method (silicon-crystal ingot-growth method)
HTSA	Hydrothermal stress analysis
I_{sc}	Short-circuit current
I-V	Current-voltage
ID	Inside diameter
ILA	Intermediate-load applications
ILC	Intermediate-load center
IPEG	Interim Price Estimation Guidelines
IPEG4	Improved Price Estimation Guidelines
JPL	Jet Propulsion Laboratory
kW	Kilowatt(s)
LAPSS	Large-area pulsed solar simulator
LAS	Large-Area Silicon Sheet Task
LASS	Low-angle silicon sheet growth method
LeRC	Lewis Research Center
m	Meter(s)
MBS	Multiblade sawing
MEPSDU	Module experimental process system development unit
mgSi	Metallurgical-grade silicon
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MLAR	Multilayer antireflective coating
mm	Millimeter(s)
MT	Metric ton(s)
NASA	National Aeronautics and Space Administration
NBNM	Natural Bridges National Monument

NDE	Non-destructive evaluation
NMR	Nuclear magnetic resonance
NOC	Nominal operating conditions
NOCT	Nominal cell operating temperature
NTE	Nominal thermal environment
O&M	Operation and maintenance
OD	Outside diameter
P	Individual module output power
P_{avg}	Average module output power
P_{avg}	Module rated power at SOC, V_{no}
P_{max}	Maximum power
P_{min}	Minimum acceptable output power
P/FR	Problem-failure report
PDU	Process development unit
PEBA	Pulsed electron beam annealing
PIM	Project Integration Meeting
PMMA	Polymethyl methacrylate
PO	Purchase order
PRDA	Program Research and Development Announcement
PV	Photovoltaic(s)
PV/T	Photovoltaic-thermal
PVB	Polyvinyl butyral
PnBA	Poly-n-butyl acrylate
QA	Quality assurance
QUV	Ultraviolet chamber (trade name)
R&D	Research and development
RES	Residential Experiment Station
RFP	Request for proposal

RTR	Ribbon-to-ribbon (silicon crystal growth method)
RTV	Room-temperature vulcanized
SAIPEG	Sensitivity analysis using IPEG
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SCIM	Silicon coating by inverted meniscus
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute
SERI	Solar Energy Research Institute
SIMS	Secondary ion mass spectroscopy
SOC	Standard operating conditions (module performance)
SOC	Silicon on ceramic (crystal growth method)
SOLMET	Solar radiation surface meteorological observations
TCS	Trichlorosilane
TEM	Transmission electron microscope
TR	Technical Readiness
UCP	Ubiquitous crystallization process
UV	Ultraviolet
V	Volts(s)
V_{dc}	Direct-current voltage
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage
W	Watt(s)
W_p	Peak watt(s)

METRIC CONVERSION FACTORS

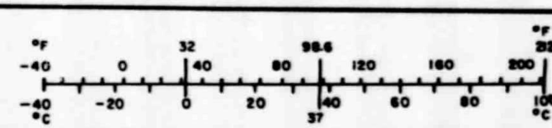
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

PROGRESS REPORT

PROCEEDINGS

PROGRESS REPORT

INTRODUCTION

This report describes the activities of the Flat-Plate Solar Array (FSA) Project (formerly the Low-Cost Solar Array Project) from July to November, 1981, including the 19th FSA Project Integration Meeting (PIM), held on November 11, 1981.

The FSA Project, sponsored by The U.S. Department of Energy (DOE), has the responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources. This responsibility has included developing the technology for producing low-cost, long-life photovoltaic modules and arrays. More than 100 organizations have participated in FSA-sponsored research and development of low-cost solar module manufacturing and mass production technology, the transfer of this technology to industry for commercialization, and the development and testing of advanced prototype modules and arrays. Economic analyses were used to select, for sponsorship, those research and development efforts most likely to result in significant cost reductions. Set forth here is an account of the progress that has been made during the reporting period.

SUMMARY OF PROGRESS

Construction of the Union Carbide Corp. (UCC) experimental process system development unit (EPSDU) was stopped because of a lack of FY82 funding. It is planned to relocate the silane portion of the EPSDU at a UCC site after cost-sharing arrangements have been negotiated. The intent is that UCC will share the data and results that will accrue from operation of the relocated silane facility. Research will continue on silane-to-silicon deposition.

The Hemlock Semiconductor Corp. process development unit (PDU) is operating well, attaining 12.6 mol% conversion of trichlorosilane to dichlorosilane (11 mol% was expected).

A very flat EFG ribbon, 8 mils thick (uniform thickness across the width) and 10 cm wide was grown at 4 cm/min using a new linear cooling plate on the Mobil Tyco No. 17 grower.

The Westinghouse experimental system grower unit (ESGU), now being run on a regular basis for sustained growth testing, is producing a good quality of ribbon. It was designed for and is ready to grow 5.5-cm-wide ribbon.

The final Crystal Systems, Inc., heat exchanger method (HEM) ingot has been grown; solidification time was 40 h and total cycle time was 70 h.

The vibration problems in a Silicon Technology Corp. prototype ID saw were reduced sufficiently so that the cutting speed for 15-cm ingots was raised from 4.5 cm/min to 7.5 cm/min. Using the same saw, 25 wafers/cm were sliced from a 10 x 10-cm ingot.

Springborn Laboratories have developed two pottants, formulated with UV stabilizers, a poly-n-butyl acrylate (PNBA) casting syrup and ethylene methyl acrylate (EMA) in sheet form. These are ready for industrial evaluation.

Anti-soiling fluorosilane coatings on glass and plastic cover films continue to provide significant improvement after five months' exposure.

A preliminary draft of Photovoltaic Module Encapsulation Design and Material Selection, an up-to-date, comprehensive compilation, has been published as JPL Internal Document No. 5101-177.

The two Module Experimental Process Development Unit (MEPSDU) contracts have been further reduced, with emphasis shifted to critical technology and/or improving cell efficiency.

Spire Corp. has demonstrated the pulsed beam annealer at a rate of one 4-in.-dia cell every 3 s.

Results have been obtained from a variety of module tests including exploratory residential roof fires, module hot-spot heating, and voltage breakdown and insulation aging of Mylar and Tedlar films.

Module design data have been generated for interconnect fatigue and on the encapsulation of bypass diodes into module laminates.

Residential integrated photovoltaic array design studies have been performed by the General Electric Co. and by the American Institute of Architecture Research Corp.

An article on photovoltaic array safety has been drafted for incorporation in the 1984 edition of the National Electrical Code by Underwriters Laboratories, Inc.

Initial results have been obtained from a photovoltaic-array and power-conditioner interface requirements study.

Laser scanning technology has matured so that it can now be used to evaluate solar cell performance characteristics from module output data.

Of the 11,000 modules installed by MIT-LL between May 1977 and January 1980, 470 (4.3%) have failed.

Area Reports

ANALYSIS AND INTEGRATION AREA

The function of the Analysis and Integration (A&I) Area is to support the planning, integration, and decision-making activities of the Project. This is done by providing coordinated assessments of Project goals and of progress toward the achievement of the goals by the various activities of the Project, the solar array manufacturing industry, and suppliers; by contributing to the generation and development of alternative Project plans through the assessment of possible achievements and economic consequences; by establishing the standards for economic comparisons of items under Project study; by supporting the integration of the tasks within the Project and between the Project and Program elements through development of procedures, and by developing the analytical capabilities and performing, or participating in, studies of required trade-offs.

SAMIS Release 4 is complete except for some documentation. The SAMICS Cost Catalog pertaining to process waste disposal has been updated, and improved effluent control algorithms have been included. Other significant changes in the Cost Account Catalog include revisions of the indirect staffing algorithms for different-sized manufacturing plants, and updated and improved inflation rates.

The Financial Reports of Release 4 of SAMIS have been completed. The new form of these reports will make them more useful to corporate planners and financial analysts. Revisions in the One-Time Costs Model have also been incorporated.

The User's Manual, Design Document, and the Computer Program Source Code have been updated. Input Formats A, B and C, have also been improved to reduce the possibility of error and to facilitate their use. A new document, a Summary Guide to Using SAMIS, is being prepared to instruct the first-time user of SAMIS.

A short course for industry on SAMICS was offered in conjunction with the 19th FSA PIM. The course described the effective use of the SAMICS and IPEG models.

Other models that have been developed recently incorporate systems performance and financial considerations relevant to assessing a technology. The SAMICS models, which address manufacturing cost estimation, can be used with these models to provide a more comprehensive overview of a technology. They include:

(1) The Peak Power Model, developed by the Engineering Sciences Area, which calculates the power output of modules based on the series-parallel methodology;

(2) The Lifetime Cost and Performance (LCP) Model, which uses the power calculation of the Peak Power Model and other inputs to

generate the cost and technical performance of utility-connected photovoltaic systems;

(3) The Alternative Power System Economic Analysis Model (APSEAM), which uses the technical and economic information generated by LCP along with general economic and detailed investor-specific information to produce a variety of figures of merit for any technology choice.

A description of how the various models can be combined to obtain desired results was presented at the 19th PIM and is contained in the Proceedings of the meeting.

Detailed energy payback analyses have been completed for 1976, 1980 and late 1980 PV technologies. The analyses reveal that PV energy payback times are significantly less than those reported in other published accounts, the latter having been based on obsolete and inaccurate data. A journal article in PV energy payback is being prepared for publication.

A&I has continued to assist the Lead Center in preparing a cost-benefit study of photovoltaics for DOE by describing estimating and documenting LSA spin-off benefits.

FLAT-PLATE COLLECTOR RESEARCH AREA

Silicon Material Task

INTRODUCTION

The objective of the Silicon Material Task is to establish the technical feasibility of critical elements of silicon (Si) purification processes capable of producing Si in a form suitable for use in the manufacture of terrestrial solar cells, so that industry can build a manufacturing base. The program formulated to meet this objective provides for research on processes for obtaining either semiconductor-grade Si or a less pure, but utilizable (i.e., a solar-cell-grade) Si material.

TECHNICAL APPROACH, ORGANIZATION AND COORDINATION

Efforts are now under way to develop technologies that will meet the Task objective in producing semiconductor-grade Si. Another means of meeting this requirement is to devise a process for producing a less-pure, so-called solar-cell-grade Si material. The allowance for the cost of Si material in the overall economics of the solar arrays for the FSA Project is dependent on optimization trade-offs, which concomitantly treat the price of Si material and effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for these trade-offs concurrently with the development of high-volume, low-cost processes for producing Si. This structure has been described in detail in previous Progress Reports. The program also includes economic analyses of silicon-producing processes and supporting efforts, both contracted and in-house at JPL, to respond to problem-solving needs.

Seven contracts in progress are listed in Table 1.

SUMMARY OF PROGRESS

Semiconductor-Grade Silicon Processes

Three contracts in this category were active. Battelle Columbus Laboratories issued its final report on investigating the production of Si by the zinc reduction of silicon tetrachloride (STC). The contract was given a no-cost extension to the end of December to allow Battelle to conduct a conceptual analysis of an improved design developed from a critique of the process development unit (PDU) that was used to investigate the process.

Hemlock Semiconductor Corp. continued to test the dichlorosilane (DCS) PDU integrated with intermediate-size Si deposition reactors. A 5-in.-dia redistribution reactor, for converting trichlorosilane (TCS) to DCS, was installed to replace the 3-in.-dia unit, to increase output and thereby to

Table 1. Silicon Material Task Contractors

Contractor	Technology Area
Semiconductor-grade Silicon Processes	
Battelle Columbus Laboratories Columbus, Ohio JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized-bed reactor
Hemlock Semiconductor Corp. Hemlock, Michigan JPL Contract No. 955533	Dichlorosilane CVD process
Union Carbide Corp. Tonawanda, New York JPL Contract No. 954344	Silane-Si process
Impurity Studies	
C. T. Sah, Associates Urbana, Illinois JPL Contract No. 954685	Effects of impurities on solar-cell performance
Westinghouse R&D Center Pittsburgh, Pennsylvania JPL Contract No. 954331	Definition of purity requirements
Supporting Studies	
Solarelectronics, Inc. Bellingham, Massachusetts JPL Contract No. 956061	Hydrochlorination of metallurgical-grade Si and $SiCl_4$
Texas Research and Engineering Institute Groves, Texas JPL Contract No. 956045	Technology and economic analyses

push the DCS distillation column to its limits. The PDU continues to operate very well. No catalyst degradation or carryover has been noted. The on-line time in a given month has reached as high as 96% and the mole percent conversion of TCS to DCS has gone as high as 12.6%, which is higher than the 10% to 11% range that was expected. It is believed that the higher conversion may be due to higher residence time of the reactants in the larger reactor.

SILICON MATERIAL TASK

In the Si deposition reactor, the goals for deposition rate and conversion efficiency were met, but not simultaneously. A power consumption as low as 80 kWh/kg Si has been attained; the goal is 60 kWh/kg. It is expected that power consumption will be lower for the larger, advanced reactors that will be tested soon. The amount of Si deposited on the bell-jar walls continues to be excessively high. It appears that the amount increases with age of the bell jar, increasing from 1% of the Si produced when the bell jar is new, to about 8% for a bell jar that has been used repeatedly. It is likely that this increase is associated with the increase in surface area that occurs as the deposit becomes rougher.

Purity testing indicates that the product Si is of semiconductor quality.

Design and economic analyses efforts associated with the experimental process system development unit (EPSDU) and the 1000-MT/yr plant were stopped in mid-August because of FY82 budget constraints.

The preliminary economic analysis for the 1000-MT/yr plant was revised and updated. The results indicate a Si price of $19.23/kg Si (1980 dollars, 20% ROI), a small reduction from the earlier figure of $19.85/kg.

In its research on a process for converting metallurgical-grade Si to semiconductor-grade Si using silane, Union Carbide Corp. stopped construction of the EPSDU at East Chicago, Indiana. This action was taken because no DOE funds are available for completion, check-out, and operation of the unit. Funding in FY82 will be limited to research on silane pyrolysis. Alternative means for completing the EPSDU program are being explored with DOE and UCC.

The EPSDU gantry was disassembled, shipped, and reassembled at a new site in the Pacific Northwest. The equipment was repackaged and some of it also was shipped. The operation manual is being prepared.

The fluidized-bed PDU was reactivated in October, after being shut down temporarily because of FY81 funding recisions. New heaters were ordered and the gas distributors are being modified.

The subcontract on consolidation of free-space reactor Si powder was completed. The powder feed, melting, and shotting were operated, but not continuously or simultaneously. Throughput was low and was limited by the powder melting rate. Erosion of the shotting orifice is an area of concern.

Impurity Studies

C. T. Sah Associates are developing a computer model based on the fundamental parameters of solar cells and applying it to the determination of the effects of impurities and defects of Si on solar-cell performance. Analyses were made of the degradation of open-circuit voltage of Si solar cells due to defects and impurities that partially short-circuit the back-surface-field (BSF) junction of high-efficiency cells. A two-region model was used to model edge effects around the cell perimeter and a three-region model was used to model bulk effects that are distributed across the BSF junction area. The reduction of open-circuit voltage by defects across the BSF junction in the bulk is much greater than that around the perimeter.

A draft of the final technical report was written.

Westinghouse R&D Center completed the draft of the final report on its program to determine the effects of impurities on the performance of solar cells.

Supporting Studies

Solarelectronics continued research on the hydrochlorination of metallurgical-grade Si and silicon tetrachloride to form TCS, in support of the UCC program. A 2-in.-dia stainless-steel reactor was designed and constructed. The earlier work at the Massachusetts Institute of Technology on this program was done with a 1-in.-dia unit. The test system was assembled and is being checked out. Experiments are planned for the collection of reactor kinetic data and to study corrosion of various materials of construction for the reactor.

Texas Research and Engineering Institute continued its chemical engineering analysis of the Hemlock process for producing Si from DCS in a 1000-MT/yr plant. The engineering design of the first distillation column, which removes volatile gases from the chlorosilane mixture produced in the hydrochlorination reactor, was prepared. The engineering design of the second distillation column, which separates TCS and higher chlorosilanes from the STC, was initiated.

The JPL in-house effort included work on the fluidized-bed reactor (FBR), direct conversion of silane to molten silicon, and impurity investigations.

Fabrication and installation of a 6-in.-dia FBR and its test facility were completed, and experiments will start soon. Three different gas distributor plates were designed, constructed, and cold-flow-tested. One gave results that were considered suitable, indicating very good mixing and high likelihood of successful operation in the FBR.

In the effort on direct conversion of silane to molten Si, modifications were made that solved a problem that had been encountered: plugging of the silane injector by Si that rapidly formed as silane was injected into the hot reactor. However, molten Si was not obtained as product. Part of the Si produced was used up in transforming the carbon reactor to silicon carbide and in filling the pores, and the rest was in the form of Si powder that was swept out of the reactor without melting. A longer reactor is being designed that is expected to have sufficient length to produce molten Si. The reactor has proven to be capable of repeated operations at very high temperatures (up to 1800°C) without cracking.

In the analysis of electrically active impurities using thermally stimulated capacitance (TSCAP) measurements, it was found that the determination of trapping energy level is very sensitive to temperature measurement. Therefore, modifications were made that enable the system to measure temperature to within 0.01°K, corresponding to a negligible error in trapping energy level. Effort also was spent on preparing samples from process development silicon for impurity testing.

The Zeeman atomic absorption spectrometer was calibrated for iron (Fe), chromium (Cr), and copper (Cu), and it was applied to the analysis of impurities in the submicrometer Si powder produced by the UCC process. The results indicated a range of 3 to 9 micrograms of Fe per gram of Si, and this variation is ascribed to non-uniformity in the Fe content. The corresponding values for Cr and Cu were about an order of magnitude smaller.

Large-Area Silicon Sheet Task

Present solar-cell technology is based on the use of silicon wafers obtained by slicing Czochralski (Cz) or float-zone ingots (up to 10 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single-crystal silicon wafers is tailored to the needs of large-volume semiconductor device production (e.g., integrated circuits, and discrete power and control devices other than solar cells). The small market offered by present solar cell users does not justify industry's development of the high-volume silicon production techniques that would result in low-cost photovoltaic electrical energy.

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several processes for producing large areas of silicon-sheet material suitable for long-life, high-efficiency solar photovoltaic energy conversion. To meet the objective of the FSA Project, sufficient research must be performed on a number of techniques to determine the capability of each of producing large areas of crystallized silicon at a competitive cost. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array industry scheme.

The improvement of the standard Czochralski ingot growth process by reduction of expendable material costs and improvement of ingot growth rate together with improved slicing techniques now produces large areas of silicon at costs approaching the goals of the FSA Project. Growth of large ingots by casting techniques, such as the heat exchanger method (HEM) growth and the ubiquitous crystallization process (UCP), may reduce sheet costs further.

Growth of crystalline silicon material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG) and dendritic-web growth (web), are candidates for such solar-cell material.

Research and development of ribbon and ingot growth, and of multiblade, multiwire, and inner-diameter blade ingot cutting, initiated in 1975-76, are in progress.

ORGANIZATION AND COORDINATION

When the FSA Project was initiated (January 1975) a number of methods potentially suitable for growing silicon crystals for solar-cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is continuing. After a period of accelerated development, these methods will be evaluated and the best will be selected for advanced development. As the growth methods are refined, integrated process schemes will be developed by which the most cost-effective solar cells can be manufactured.

The Large-Area Silicon Sheet Task effort is organized into four phases: research and development of sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype development (1981-82); development, fabrication, and operation of pilot production growth units (1983-86).

Large-Area Silicon Sheet Contracts

Ongoing research and development contracts awarded for growing crystalline sili- con material for solar cell production are listed below. Preferred growth methods for further development have been selected.

Table 2. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
Ingot Technology	
Crystal Systems, Inc. Salem, Massachusetts JPL Contract No. 954373	Heat exchanger method (HEM) ingot growth; fixed-abrasive slicing technique (FAST)
Kayex Corp. Rochester, New York JPL Contract No. 955733	Advanced Cz growth (Adv. Cz)
P.R. Hoffman Co. Carlisle, Pennsylvania JPL Contract No. 955563	Multiblade slurry slicing technique (MBS)
Silicon Technology Corp. Oakland, New Jersey JPL Contract No. 955131	Internal diameter (ID) slicing
Semix Inc. Gaithersburg, Maryland DOE Contract No. DE-F101-80ET 23197	Ubiquitous crystallization process (UCP)
Ribbon Technology	
Mobil Tyco Solar Energy Corp. Waltham, Massachusetts JPL Contract No. 954355	Edge-defined film-fed growth (EFG)
Westinghouse Electric Corp. Pittsburgh, Pennsylvania JPL Contract No. 955843	Dendritic web growth (web)

Table 2 (Cont'd)

Material Evaluation	
Applied Solar Energy Corp. City of Industry, California JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca, New York JPL Contract No. 954852	Characterization of Si properties
Materials Research, Inc. Centerville, Utah JPL Contract No. 957977	Quantitative analysis of defects and impurity evaluation technique

INGOT TECHNOLOGY

Crystal Systems, Inc.: The Schmid-Viechnicki technique (heat-exchanger method or HEM) was developed to grow large single-crystal sapphire. Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This obviates motion of the crystal, crucible, or heat zone. In essence, this method involves directional solidification from the melt where the temperature gradient in the solid is controlled by the heat exchanger and the gradient in the liquid is controlled by the furnace temperature. The overall goal of this program is to determine whether the heat-exchanger ingot casting method can be applied to the growth of large shaped-silicon crystals of 30-cm-cube dimensions of a quality suitable for the fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

Kayex Corp.: In the advanced Cz contracts, efforts are geared to developing equipment and a process to achieve the cost goals and demonstrate the feasibility of continuous-Cz solar-grade crystal production. Kayex has already demonstrated the growth of 150 kg of single-crystal material, using only one crucible, by periodic melt replenishment.

Semix: The semicrystalline casting process is a Semix proprietary process yielding a polycrystalline silicon brick capable of being processed into cells of up to 16% efficiency at AM1.

Crystal Systems, Inc., P. R. Hoffman Co. and Silicon Technology Corp.: Today most silicon is sliced into wafers with an inner-diameter saw, one wafer at a time. Advanced efforts in this area are continuing. The multiwire slicing operation uses reciprocating blade-head motion with a workpiece fed from below. Multiwire slicing uses 5-mil steel wires surrounded by a 1.5-mil copper sheath that is impregnated with diamond as an abrasive.

The multiblade slurry technique is similar to the multiwire slicing technique, except that low-carbon steel blades (typically 1 cm in height and 6 to 8 mils thick) are used in conjunction with an abrasive slurry mixture of SiC and oil.

MATERIAL EVALUATION

Applied Solar Energy Corp. (ASEC): Proper assessment of potential low-cost silicon sheet materials requires the fabrication and testing of solar cells using reproducible and reliable processes and standardized measurement techniques. Wide variations exist, however, in the capability of sheet-growth organizations to fabricate and evaluate photovoltaic devices. It is therefore logical and essential that the various forms of low-cost silicon sheet be evaluated impartially in solar-cell-manufacturing environments with well-established techniques and standards. ASEC has been retained to meet this need.

Materials Research, Inc.: The current MRI sheet defect-structure assessment effort includes a correlation of impurity distributions with defect structures in various sheet materials obtained from the ingot and shaped-sheet manufacturers.

SHAPED-SHEET TECHNOLOGY

Mobil Tyco Solar Energy Corp.: The EFG technique is based on feeding molten silicon through a slotted die. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from a material that is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 4.5 cm/min and a width of 10.0 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic and theoretical analysis of ribbon thermal and stress conditions.

Westinghouse: Dendritic web is a thin, wide ribbon form of single-crystal silicon produced directly from the silicon melt. "Dendritic" refers to the two wirelike supporting dendrites on each side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film between the bounding dendrites. Dendritic web is particularly suited for fabrication into solar cells for a number of reasons, including the high efficiency of the cells in arrays and the cost-effective conversion of raw silicon into substrates.

Environmental Isolation Research Task

INTRODUCTION

The objective of the Environmental Isolation Research Task includes the development and qualification of the total encapsulation system required to protect the active optical and electrical elements of the array from the effects of the field environment. The most difficult technical problem has been the development of high-transparency materials for the photoactive side of the module that meet the Project's cost and lifetime objectives. The approach being used to achieve the overall objective of the Environmental Isolation Research Task includes a combination of contractor and JPL in-house efforts, which can be divided into two technical areas:

(1) Materials and Process Development. This effort includes all of the work necessary to develop, demonstrate, and qualify one or more encapsulation systems to meet the FSA Project goals. It includes the testing of off-the-shelf materials, formulation and testing of new and modified materials, development of automated processes to handle these materials during formulation and fabrication of modules, and systems analysis and testing to develop optimal module designs.

(2) Life Assessment and Material Degradation. This work is directed toward the attainment of the FSA Project 20-year-minimum life requirement for modules by 1986. It includes the development of a life-prediction method applicable to terrestrial photovoltaic modules and validation by application of the method to specific photovoltaic demonstration sites. Material degradation studies are being conducted to determine failure modes and mechanisms. This effort supports both the materials and process development work and the life-prediction model development.

SUMMARY OF PROGRESS

Materials and Process Development

Low-Cost Encapsulants

New encapsulation materials tailored to the specific requirements of the FSA Project are now available for industrial evaluation from Springborn Laboratories. These include ethylene methyl acrylate (EMA) lamination film (Springborn formulation #13439) and poly-n-butyl acrylate (PnBA) casting syrup (Springborn formulation BA 13870). A prototype aliphatic polyurethane casting material by Development Associates, Inc. (formula Z-2591) has also been identified and is available.

Springborn is continuing with work on accelerated aging of candidate materials using the RS-4 sunlamp. New materials that have been added to those currently being evaluated include Korad 63000 white, Tedlar 200 BS30 white, 168-A

(American Cyanamid) and Z-2591 aliphatic polyurethanes, and Scotchpar 20CP white. Clear stabilized ethylene vinyl acetate (EVA) has accumulated 25,600 hours of RS-4 exposure with essentially no change in total integrated transmission, ultimate elongation or tensile strength. Other materials that have shown very little change to date are EMA A11877 and Dupont Tedlar 100 BG 30 UT (both 10,000 hours) Fluorex-A (9000 hours), and Z-2341 polyurethane (3000 hours). After 6000 hours, butyl acrylate (base formulation) exhibits 100% tensile strength and 150% original elongation. By comparison, unstabilized polyethylene and polypropylene retain 10 and 0% elongation respectively after only 500 hours of equivalent exposure.

Current candidates for low-cost panel substrates are still wood-fiber hardboard and cold-rolled mild steel. Methods of protecting these substrates from environmental effects are still being investigated. Results to date (1000 hours of salt spray) indicate that EVA, EVA/Scotchpar and vinylidene fluoride are effective in preventing corrosion of the steel substrate. After two months of outdoor exposure, Scotchpar 20CP appears to perform best as a wood-fiber hardboard coating (less than 0.01% change in weight for either hardboard or complete module.)

Several candidate edge-sealant and gasketing materials have now been identified and are being evaluated. A preliminary recommendation of 3M 5354 Butyl sealant tape has been made. New materials that combine the function of both sealant and gasket are also being evaluated.

Anti-soiling test specimens have now accumulated five months of outdoor aging. General observations indicate L-1668 coating to be preferred for Sunadex glass, E3820 coating to be preferred for Tedlar 100 BG30UT and Ozone/E3820 to be preferred for 3M X-22417 acrylic film.

To date, activities at Springborn have emphasized identifying and/or developing an inventory of the lowest-costing encapsulation materials meeting LSA goals. An output of this activity has been a capability to generalize on functional, performance, and process requirements by which the qualification of future candidate materials for encapsulation application can be readily judged. The need at Springborn, therefore, to continue expanding the inventory of qualified materials is rapidly diminishing, but the need to establish the long-life potential (i.e., 20 years) of the materials we now have is growing. Consequently, activities at Springborn are expected to shift into life-prediction studies, and chemical modifications to existing materials to enhance life (such as chemically attachable UV absorbers and anti-oxidants).

Adhesives and Primers Development

Work continues on the development of a primer system for poly-n-butyl acrylate (PnBA). E. P. Plueddemann of Dow Corning reports that he has essentially identified the requisite chemistry needed for PnBA priming, and that he is now achieving measurable bond strengths to glass. Continuing development now consists of (1) achieving the proper concentrations of the chemical components to maximize the bond strengths, and (2) demonstration of adequate hydrolysis resistance.

ENVIRONMENTAL ISOLATION TASK

UV Absorbers

Work on the copolymerization of 2-hydroxy 5-isopropenyl (2H5P) with various monomers has continued at the University of Massachusetts, but no significant results are reported. A new co-investigator, E. Borsig, has joined O. Vogl on the project, replacing Z. Nir, who left in August.

Module Design and Verification

Spectrolab has continued work on PV encapsulation engineering optimization. Optimization involves structural adequacy, electrical isolation, maximum optical transmission, minimum module temperature, and lowest life-cycle energy cost. To achieve this objective, the program was divided into three phases:

(1) Development of desk-top engineering and design tools (reduced variable master curves).

(2) Experimental evaluation of specific designs.

(3) Preparation of design drawings and specifications for an optimized design.

A report (Cuddihy, E. F., JPL Internal Document No. 5101-182, Development of Reduced-Variable Master Curves for Estimating Tensile Stresses of Encapsulated Solar Cells Caused by Module Deflection or Thermal Expansion) has been published summarizing the Phase I work. Phase II experiments have been completed and the results are now being evaluated.

Ion-Plated Coatings

A critical assessment of the applicability of ion-plated metallization for large-scale cell processing concluded that the process is reproducible, equivalent in performance to competitive methods, and cost-competitive with respect to other processes. A SAMIS cost analysis carried out at JPL indicated that at production levels on the order of megawatts, the add-on cost of metallization and AR coating by ion-plating would be in the range of 5¢ to 6¢ per peak watt.

ITW has successfully metallized (by ion-plating) a p-on-n solar cell, and can metallize the n surface of an n-on-p solar cell. Their current difficulty is in consistently achieving ohmic contact of ion-plated metallization on the p back surface of n-on-p solar cells. Their efforts initially concentrated on direct deposition of aluminum on the back surface. Recently, however, improvements have been observed when a trace deposition of boron is first applied to the back surface, followed by aluminum deposition. This encouraging finding is being pursued in two directions: optimization of the boron deposition, and alternatives to boron. This problem of ohmic contact on n-on-p cells has delayed the start of performance testing of active cells, the purpose of which is to assess various processing methods.

ENVIRONMENTAL ISOLATION TASK

Encapsulation Technology Transfer

A preliminary draft of JPL Document No 5101-177, Photovoltaic Module Encapsulation Design and Material Selection: Volume I, has been completed and distributed for industry use and comment. An updated and revised version will be published late in FY82.

Material Degradation and Life Prediction

Photodegradation Model for EVA

Validation of the computer program allowing the calculation of product species with time (from an initial elementary reaction scheme, arbitrary starting conditions, and corresponding rate data) is continuing at the University of Toronto. The Ecolyte system has been chosen as a model system for validation after preliminary data was studied. This is a patented formulation developed in the laboratories consisting of mixtures of small amounts of ketone-containing polymers blended with other commercial polymers in such a way as to afford programmed lifetimes for the resulting materials.

The elementary reaction matrix for the computer simulation of the photooxidation program has been revised resulting in a new scheme of 31 reactions. Control of integration parameters allowing more program flexibility has also been accomplished. The result is that without any arbitrary adjustment to the reaction rates, the computer simulation now shows lifetimes in excess of 10 years when initiated by very small amounts of ketone, peroxide or some fortuitous alkyl radical generating step.

Interface Degradation, Corrosion Diagnostic and Modeling

Work is continuing at the Rockwell Science Center on identification of criteria and development of design priciples for achieving strong, stable bonding of polymers to metals, such as EVA to solar cell metallization. Some emerging criteria are: the metal surfaces must be clean, readily wetted by the polymer (to eliminate a surface layer of air), and the metal must be activated before priming by exposure to alkaline solutions (i.e., NaOH). The primer, on the other hand, must have acidic character. These principles, and their validation, are still being actively pursued.

Future work will emphasize two critically needed technology tasks:

(1) Requirements of encapsulation systems relative to corrosion protection, either functioning to stop corrosion of such metals as copper, or having a validated model of corrosion which allows the determination of corrosion rates, thereby allowing life prediction.

(2) Theoretical and experimental methods of assuring the quality and life potential of adhesively bonded interfaces (i.e., bond strength, life, resistance to environmental degradation, etc.).

ENVIRONMENTAL ISOLATION TASK

Photodegradation of Polymers

Characterization of the long-term degradation of PnBA in the QUV Tester is continuing at Case Western Reserve University. Swell ratio and gel fraction are being monitored. Gel formation has been observed to decrease exponentially as a function of irradiation time. This has suggested that the cross-linking reaction follows pseudo-first-order kinetics.

Measurement of the fraction of PnBA converted to alcohol, aldehyde and/or ketone during photooxidation was made when the films had been exposed to ultraviolet light for over 2000 hours in the QUV tester at 40°C. Specific products of photooxidation of these films were:

Table 3. Products of Photooxidation of PnBA at 2000 Hours in the QUV

Group	% Change	Method
Ester C-O-C	- 42 ±5	FTIR
COOH	+ 1.4 ±10	Proflavine
CHO, CO	+ .4 ±.2	2,4-dinitrophenyl-hydrazone
CHO	+ .2 ±.2	
COH	+ 5.3 ±2	FTIR
X links (CO)	+ .15 ±0.10	Swell ratio
Monomer	Not measured	
Random cleavage	Not measured	
Mass	+ 25 ±35	

Stress relaxation testing of cured EVA samples from Springborn Laboratories Inc. has been completed at JPL. The data were used in the development of master curves, which are needed for life-prediction modeling. The time and temperature scaling parameter obtained from the stress-relaxation master curve correlates only the time and temperature effect with no chemical degradation or change in the physical state of the EVA. It was found that EVA does not behave like conventional elastomers when the scaling parameter is compared with that of the well-established model in the literature. Evaluation of the change of the scaling parameter with chemical degradation is now in progress. Work has started on fully cured EVA samples prepared at

JPL. Various curing times will be used to evaluate the curing schedule as a function of crosslinking formation.

Photodegradation studies of EMA have been initiated. Photooxidation leading to formation of hydroxyl functionalities on the polymer surface has been detected. Contact angle measurements showed hydrophilic polarity changes on the exposed surface. Photothermal studies of EMA are being planned for the near future.

The report on UV Degradation Rates and Lifetime Potential of polymers is completed and is undergoing internal review at JPL.

Module Field Testing

The validation of the Battelle Accelerated Test Plan was terminated after 120 days (360 cycles). Electrical continuity tests at +95° C indicated that all of the 10 modules had open circuits. A brief study was made of electrical continuity as the temperature was raised and lowered through the Nominal Operating Cell Temperature (NOCT, approximately 45° C). Testing indicated open circuits commenced at 40° C and that all were open at 60° C. Visual inspection continued to contain evidence of progressive fatigue cracking in the interconnects. A report summarizing this work is being prepared.

A memo report on minimodule field testing to date has been completed. Significant events detailed in the report were:

(1) Thermal cycle tests are complete for all modules.
(2) Humidity and freeze tests are 50% complete.
(3) NOCT is complete for six of the 10 modules.
(4) Partial discharge (corona) testing has been completed on all modules.
(5) The Point Vicente field site has been modified and is being reactivated.

The report also includes power output as a function of time for all of the mini-module and sub-module designs for the various field test sites.

CELL AND MODULE FORMATION RESEARCH AREA

INTRODUCTION

The objective of the Cell and Module Formation Research Area is to identify, to assess, and to conduct research on methods for the formation of solar modules, and to make these technologies available to the photovoltaic industrial community.

For convenience, process development is grouped into four categories: surface preparation, junction formation, metallization, and module completion.

SUMMARY OF PROGRESS

The Area's primary contracting effort has been the two MEPSDU (Module Experimental Process Development Unit) contracts, one with the Solarex Corp. and one with Westinghouse Electric Corp. These contracts, originally scheduled for completion in 1982, were modified to reflect a reduced funding rate and were extended into 1984, then were modified again to reduce their funding further and the statements of work are now being modified to reduce the scope of work. Technical readiness was to have been demonstrated at the completion of the contract. This has been changed to one of technical feasibility rather than readiness. The Solarex contract is being reduced in scope to include cell making processes only. Module fabrication work has been deleted from the Solarex contract, in part to save the cost of capitalizing the automated assembly machinery. This machinery was unique to the Solarex MEPSDU in that all other equipment was capitalized by the contractor.

Three requests for proposals (RFPs) were issued requiring response by September 21, 1981. These RFPs are for MEPSDU support activities in metallization, module assembly, and effluent treatment. The proposals are under evaluation and contract awards are scheduled for February 1982.

Surface Preparation

The surface crystal damage removal technique was changed from acid etching to hydroxide some time ago; these newer, cheaper processes are being adopted by the industry. Current attention is being directed toward the reduction of surface recombination velocity of the minority carriers in the diffused layer of the cell junction, as part of an overall effort to increase cell efficiency.

Solarex has achieved a superior sprayed-on anti-reflective coating by heating the cell before spraying, which increases the electrical performance and the mechanical properties of the coating.

Junction Formation

Contaminants during non-mass-analyzed (NMA) ion implantation have been found to come primarily from the metal parts used to fabricate the ion-source mechanism. New materials are being used in the critical areas and the problem is considered to be under control. An increased sensitivity to implantation contaminants has been related to surface microcracks. Apparently there is a gettering action by the microcracks.

Spire Corp. has demonstrated its pulsed electron beam annealer (PEBA). This machine anneals one 4-in.-dia -ion-implanted wafer every three seconds. If operable for 8000 hours per year, this amounts to 9.6 MW/yr. Spire has turned its attention to the construction of a non-mass-analyzed ion implanter with the same production rate. The machine has progressed to the breadboard stage.

Metallization

Bernd Ross Associates have succeeded in formulating a copper-based thick-film ink for metallizing solar cell backs. The projected cost of this process is approximately 4 1/2¢/W. By reducing the amount of AgF fluxing agent, better cell properties have been realized. It was also discovered that the AgF does not function properly in the presence of hydrogen; apparently the hydrogen captures the free fluorine before it can attack the silicon oxides.

The Photowatt International, Inc., contract to develop a nickel-based thick-film paste that will fire through a silicon nitride antireflection coating is progressing with difficulty. Cells made with experimental pastes to date have poor fill factors due to a combination of low shunt resistance and high series resistance.

Solarex is experimenting with ion milling to remove excess metal, which tends to short-circuit the cell at the edge of the n/p junction. After edge cleanup the cells are solder-coated using a wave soldering machine. The uniformity of the resulting solder coating is helpful in reducing cell breakage during lamination with glass superstrate.

Module Completion

Tracor MBA has completed its contract to adapt a programmable industrial robot to assemble and laminate solar cells into modules. The effort was primarily a feasibility activity, using off-the-shelf machines that are programmable and can produce a variety of finished products. The robot selected by JPL was chosen for its size (ability to assemble a 4 x 4-ft module) and is unnecessarily slow. It requires up to 15 seconds per cell, limiting it to less than 2 MW/yr. The use of faster robots, which are currently available, can improve this rate by more than an order of magnitude.

JPL robotics group has successfully added a vision system and a "tactile" capability to an automatic robot. These attributes allow the robot to accommodate placement variations during assembly and to inspect for defects during and after assembly. The robot hand is a many-purpose device that grips, solders, glues, and places the parts.

Westinghouse is having success with its ultrasonic bonding of metal connector strips to silicon solar cells. It has developed a "rolling spot" technique, similar to a single-toothed gear advancing from spot to spot, without damaging the cell between spots.

LABORATORY ACTIVITIES

Experimental cells continue to be processed in the Process Development Laboratory using baseline (repeatable) processes. Performance comparisons are made between cells using the same materials and processes under development, primarily MEPSDU processes.

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ENGINEERING SCIENCES AREA

The overall objective of the FSA Engineering Sciences Area is to develop the design criteria, test methods, analysis tools, and trade-off data that provide the technology base required for technical feasibility with respect to flat-plate modules and arrays.

During the reporting period, activities within the Engineering Sciences Area emphasized array requirements generation, array subsystem development, module development, and array performance criteria and test standards development. A description of the status of each of the Engineering Sciences Area contracts was included in the 19th PIM Handout (JPL Internal Document No. 5101-192). Active contracts and referenced papers and documents are listed in Table 3.

ARRAY REQUIREMENTS

The Array Requirements activity addresses the identification and development of detailed design requirements and test methods at the array level. Continuing areas of activity that addressed improved definition of array requirements include (1) the establishment of module and array electrical safety criteria, (2) the generation of intermediate-load-center building codes as applied to intermediate array design, and (3) the development of array-to-power-conditioner electrical interfaces (coordinated with Sandia and MIT-LL).

Safety Requirements

A necessary element in establishing module technical feasibility, especially for residential and ILC applications, is the early development of safety requirements at the design level. Consistent with this goal, FSA Engineering Sciences Area staff members participated in the fourth meeting of the National Electrical Code (NEC) Ad Hoc Subcommittee Meeting on Photovoltaics August 11 to 13 in Northbrook, Illinois. A result of the meeting was a tentative agreement on a new article for consideration by the NEC Correlating Committee for the 1984 edition of the National Electrical Code. Subcommittee members balloted in September and results were forwarded to the NEC Correlations Committee.

In support of roof-mounted residential-array safety studies, additional roof-covering classification and fire-penetration tests were observed by Engineering Sciences Area staff members at Underwriters Laboratories Inc. (UL) on August 14. These tests were made to determine a PV module's resistance to severe fire exposure from sources outside a building. Shingle and integrally mounted glass-superstrate modules were subjected to spread-of-flame and burning-brand tests. The silicone-based shingle module proved to be highly flame-resistant in the 10-minute spread-of-flame test and withstood both Class

ENGINEERING SCIENCES AREA

Table 3. Engineering Sciences Area Contractors

Contractor	Contract Number	Description
AIA Research Corp. Washington DC	955893	Integrated residential PV array development
Boeing Co. Seattle WA	954833	Wind-loading study on module and array structures
Burt Hill Kosar Rittelmann Associates Butler PA	955614	Residential module O&M requirements study
Clemson University Clemson SC	954929	Solar-cell reliability test
DSET Laboratories, Inc. Phoenix AZ	713131	Accelerated sunlight exposure of modules
General Electric Co. Philadelphia PA	955894	Integrated residential PV array development
IIT Research Institute Chicago IL	955720	Reliability engineering of modules and arrays
Underwriters Laboratories Melville NY	955392	Solar array and module safety requirements

A and Class B burning brands for up to 45 minutes. The EVA-based integral-mount module was resistive to the Class C burning-brand test, but when the Class B brand breached the glass cover it easily ignited the encapsulant, which dropped flaming material into the space below within five minutes.

Commercial and Industrial Building Codes

In support of intermediate-load array design guidelines, Burt Hill Kosar Rittelmann Associates completed their assessment of intermediate-load-center building codes and regulations (initial results were presented at the 17th PIM). An executive summary and clarifying text are being added to the final report, now scheduled for release in December.

Power Conditioning Interface

Work on the array and power-conditioner task focused on (1) comparisons of degraded-array and virgin-array results and how the interface between array and power conditioner is effected, and (2) the determination of the array power-output characteristics for a degraded array. A draft of the interim task report is in preparation; a December release is planned.

Selection of the optimum input voltage window for power conditioning is influenced by the array voltage fluctuations caused by site weather conditions. A JPL in-house analytical study, using SOLMET typical-year data tapes, generated updated input for determining the optimum power-conditioning voltage, current, and power levels versus array parameters. The completed data for residential and intermediate load applications were forwarded to Sandia. Tabulated data on array and power-conditioner interface optimization will be included in Sandia's Power Conditioning Specification.

ARRAY SUBSYSTEM DEVELOPMENT

Array subsystem development activity focuses on the development of conceptual designs for integrated flat-plate array modules and support structures as a key approach to minimizing total array costs. An important output of array conceptual designs is the definition of specific design requirements addressed to functional performance, interface and maintainability (at the array level).

Integrated Residential Arrays

Supporting the development of cost-effective support structures, two residential array design concepts were optimized and evaluated through contracts with the American Institute of Architects Research Corp. (AIA/RC) and General Electric Co. (GE). Design reviews in conjunction with the integrated residential array effort were held at JPL August 25 with AIC/RC and with GE on July 17; a detailed review of their concepts is presented in the Proceedings.

JPL Engineering Sciences Area in-house efforts are developing a prototype residential-array design that obviates a 100% watertight interface between the PV module and the support structure. Low-cost, non-metallic extrusions that include leakage or drainage channels are on order to complete a 5 x 9-ft prototype for verification.

Additional JPL in-house efforts included the determination of the edge vulnerability of 1/8-in. tempered glass sheets to hail impact, using a variety of edge-support conditions. Results showed that 1/8-in. tempered glass panels can survive the JPL Internal Document No. 5101-161 Block V hail-impact test without edge protection. However, tempering techniques do vary among manufacturers, and designers are advised to perform similar ice-ball tests on tempered-glass panels they intend to use.

A viewgraph presentation entitled "Photovoltaics--Electricity from the Sun" was given to the Kansas Society of Architects at the 1981 AIA Kansas State Convention in Topeka on September 4. The seminar overview of photovoltaics, presented jointly by LSA Engineering Sciences Area and AIA/RC staff members, was consistent with the convention theme, "Energy Naturally," and was intended to stimulate interest in photovoltaics.

PV-Thermal Arrays

In the area of photovoltaic-thermal (PV-T) module development, two report drafts were completed for review that document performance and economic studies done on the installation of PV-T collector systems. These included the final task report, Assessment of PV-T Collectors, in press, and a manuscript titled "Evaluation of Unglazed PV-T Collectors in Heat-Pump Applications," submitted to the organizing committee of the American Society of Mechanical Engineers April 1982 conference in Albuquerque, New Mexico.

MODULE ENGINEERING

Module engineering addresses the development of design methods, analysis tools and design concepts necessary to support significant cost and performance improvements at the array-element level. Activities are conducted to clarify design tradeoffs, to develop analysis tools and test methods and to provide generalized design solutions for the PV community. Specific activities included (1) cell reliability testing; (2) module voltage isolation; (3) interconnect fatigue; (4) hot-spot endurance; (5) cell fracture mechanics; (6) module soiling, and (7) module environmental endurance.

Cell Reliability Testing

A joint in-house and contractor-supported test program to stress-test and evaluate encapsulated cells was initiated with the Environmental Isolation Research Task and the Process Development Area. The program includes cells made with different cell-metallization systems and encapsulation systems. A key aspect of this effort is an expanded joint failure-analysis followup phase, which is to be supported by various technical disciplines. Actual testing will take place at Clemson University, which has been generating reliability and accelerated- stress test data on most of the solar-cell types now used in FSA module designs.

Module Voltage Isolation

The voltage isolation task addresses the source and magnitude of leakage currents to ground caused by initial insulation flaws or material aging. The development effort is directed toward predictions of module life and providing for human safety. Activities during the reporting period are given below:

(1) The electrical insulation environmental test chamber for accelerated aging under voltage of minimodules and test coupons (with experimental encapsulants) is nearing completion with installation of data-collection circuitry and instrumentation. The procurement of 100

minimodules, earmarked for the tests, was completed and representative Block IV, PRDA and commercial designs were obtained. The test coupons are being supplied by the Environmental Isolation Task and the Cell and Module Formation Research Area in a joint program for voltage and environmental testing.

(2) The central-station module field-exposure insulation studies continues with data collection on two experimental modules incorporating RTV and EVA encapsulants installed on the new 3000-Vdc test stand. Results will give the responses of those encapsulants to exposures of temperature and humidity variations while under 3000-V electrification.

(3) Characterization of voltage breakdown levels of various contractor and JPL in-house polyester films and multilayer composites using the low-voltage breakdown apparatus is continuing. The data reduction software is being developed for rapid analysis of test results.

Interconnect Fatigue

Examination of the mechanical-fatigue life of cell interconnects is continuing in an effort to obtain a 20-year-life-predictive model. Computer code is being generated to fit interconnect failure data to a Weibull probabilistic function for predicting interconnect failures. The interconnect-fatigue report "Solar-Cell Interconnect Design for Terrestrial Photovoltaic Modules" was completed and forwarded for review by the organizing committee of the ASME April 1982 meeting in Albuquerque, New Mexico.

Fatigue testing of 5-mil-thick clad laminates was initiated with samples received from Texas Instruments (Attleboro, Massachusetts); stainless-steel-and-copper interconnects, on the basis of preliminary testing, appear to have improved fatigue resistance over pure copper.

Hot-Spot Endurance

Development of suitable laboratory-test procedures for evaluation of the hot-spot endurance of a module under severe hot-spot field conditions is this activity's objective. Work included the revision of the hot-spot endurance studies thermal-analysis model to include a family of plots that provide a simple graphic solution for users. The task report on hot-spot heating design guidelines is being revised.

A paper titled "Uses of Infrared Thermography in the Low Cost Solar Array Program" was presented at the annual meeting of the Society of Photo-Optical Instrumentation Engineers in Ottawa, Canada. It dealt with the use of the IR camera in the LSA Module Performance and Failure Analysis Area in connection with photovoltaic array field sites (including Mt. Laguna), and with FSA Engineering Sciences Area work in connection with hot-spot test development.

ENGINEERING SCIENCES AREA

Cell Fracture Mechanics

The fracture-mechanics study of the mechanical strength of silicon solar cells continued, with an examination of loading rates in silicon testing. The measured strength of silicon cells is insensitive to the loading rate and results with Cz wafers from twist and biaxial stress tests have indicated no significant changes in strength with increasing loading rates. A final report, documenting the test and the effect of loading rates, is being prepared for review.

Module Soiling

Engineering Sciences Area staff members gave a presentation on "Low-Cost Methods for Cleaning Photovoltaic Arrays" at the Soiling and Cleaning Conference for Solar Materials at Sandia Livermore on July 21-22.

Module Environmental Endurance

Several environmental endurance development efforts are intended to provide the technical base required to achieve reliable modules with 20-year lifetimes. IIT Research Institute (IITRI) is continuing its work in compiling reliability data on all module-design technologies and their performance in both field use and field tests. A major contribution to the IITRI work was made when the U.S. Coast Guard Research and Development Center agreed to provide FSA with reliability data obtained from different module designs it has tested (see Proceedings).

JPL in-house efforts included the development of a humidity degradation-rate curve based on comparisons of humidity-testing cycles and humidity-temperature data from SOLMET weather tapes. To obtain the required temperature-humidity acceleration factors, a contract was initiated with Wyle Laboratories to subject Block I and Block III module to a six-month humidity test with environments of 40°C, 93% RH, and 85°C, 85% RH. Results derived from inspections at the end of 10- and 20-day exposures have noted color changes in Tedlar and epoxy substrate materials exposed in the 85/85 chamber, but no degradation in electrical performance has occurred.

PERFORMANCE CRITERIA AND TEST STANDARDS

Active interfaces are maintained between the LSA Engineering activities and the SERI Performance Criteria/Test Standards (PC/TS) project to establish Interim Performance Criteria (IPC) and test standards covering both flat-plate and concentrator arrays. Final drafts of 24 test methods were delivered for inclusion in SERI's IPC document (Issue 2), scheduled for release in January 1982. Two working subgroups in support of the SERI effort collated industry and testing laboratory comments, revisions and final additions for the IPC-2 input. The Photovoltaic Environmental Test Subgroup, chaired by FSA Engineering staff members, held their second meeting at the U.S. Coast Guard Research and Development Center at Groton, Connecticut, on September 23 and 24 and reviewed environmental test methods and a visual-inspection procedure. This subgroup's objective is to develop for flat-plate and concentrator array elements a cost-effective set of qualification test procedures that can provide reasonable assurance of reliable performance in a wide range of U.S. and world-wide climates. An October 21 and 22 meeting of the Electrical Performance Task Group (led by Arizona State University) was held at Acurex Corp., Mountain View, California, to complete preparation of test-method drafts for off-axis performance of concentrator modules and optical-element evaluation techniques.

Arizona State University was granted a 90-day no-cost extension of their contract for developing electrical performance test methods for concentrating photovoltaics.

ENGINEERING SUPPORT

Engineering interface activities provide for transfer of array requirements, specifications, design concepts, design guidelines, analysis tools and test methods to the photovoltaic community. Several manuscripts were submitted by Engineering Sciences Area staff members for publication in IEEE Transactions on Reliability, featuring Solar Energy Devices and Systems. Topics included:

--"Photovoltaic Array Reliability Optimization," R.G. Ross.

--"Investigating Reliability Attributes of Silicon Photovoltaic Cells--An Overview," E.L. Royal.

--"Laboratory Testing of Flat-Plate Photovoltaic Modules," A.G. Hoffman, J.S. Griffith and R.G. Ross.

--"A Technique for Determining Solar Irradiance Deficits," C.C. Gonzalez and R. G. Ross.

RECENT CONTRACTOR PUBLICATIONS

1. Integrated Residential Photovoltaic Array Development, Quarterly Report No. DOE/JPL 955894-3, Prepared for JPL by General Electric Co., Advanced Energy Programs, Philadelphia, Pennsylvania, 19101, August 1981.

2. Integrated Residential Photovoltaic Array Development, Quarterly Report No. DOE/JPL 955893-81/1, Prepared for JPL by AIA Research Corp., Washington, D.C., 20006, April 1981.

3. Non-Steady Wind Loads on Flat-Plate Photovoltaic Array Fields, Report No. DOE/JPL 954833-81/4, Prepared for JPL by Boeing Engineering and Construction Co., Seattle, Washington, August 1981.

RECENT ENGINEERING SCIENCES AREA PUBLICATIONS

1. Glazer, S.D., "Uses of Infrared Thermography in the Low-Cost Solar Array Program," Annual Meeting, Society of Photo-Optical Instrumentation Engineers, September 1, 1981.

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MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

INTRODUCTION

The overall objective of the Module Performance and Failure Analysis Area is to evaluate the reliability and durability of modules that are constructed using the improved techniques researched in the other tasks of the project. This is accomplished through a structured program of (1) procurement of modules to a specification, (2) environmental stress testing, (3) detailed failure analysis and (4) operation in a field environment to obtain data that will (a) confirm the reliability and durability of the tested article and (b) confirm the validity of the environmental test regimen imposed in Item (2) above. Accomplishment of this work also requires implementation of an accurate, repeatable and reliable performance measuring system. Activities and accomplishments in this program during the reporting period are described herein.

MODULE DEVELOPMENT

Block IV Design and Qualification

Progress in completing this phase of the Block IV effort continued to be slow. The ARCO Solar, Inc., intermediate-load module passed the prescribed testing program and the drawings and engineering documentation were completed. The ARCO Solar residential module underwent a second iteration in design to overcome a delamination at the bend of the metal substrate, which results from installing the module on a roof. Modules with this problem presumably cured are now in test at JPL. Photowatt International, Inc., has provided JPL a set of modules incorporating design changes deemed necessary. These modules have passed the thermal and humidity cycling tests and, from earlier experience with them, it is expected that the remaining mechanical integrity, twist and hail test requirements will be met. Solarex Corp. modules were delivered that passed the required tests.

Block IV Production Orders

Purchase orders for a few kilowatts of modules as specified under Phase I have been placed with all the contractors. The order for intermediate-load modules at ARCO Solar has been released for production, as has the order for both residential and intermediate-load modules at Solarex. The Photowatt order is on hold pending completion of testing of Phase I modules, and the purchase order for the ARCO Solar residential module has not been released.

Block V Design

Contracts for Block V module designs were executed with six contractors as follows:

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

Intermediate-Load Modules	Residential Modules
ARCO Solar, Inc.	General Electric Co.
RCA Corp.	Mobil Tyco Solar Energy Corp.
Solarex Corp.	Spire Corp.

MODULE TEST AND EVALUATION

Performance Measurements

New reference cells have been selected, fabricated, and calibrated for use by JPL Field Testing for Block IV modules. Spectral response measurements, final sealing and identification of these cells are in process, after which they will be available for use. Seventeen additional new cells are being selected, fabricated and calibrated for use in support of Sandia, the Georgetown Project and other JPL module testing.

The spectral response of cells proposed for the Georgetown Project modules were compared with the spectral response of current Block IV reference cells; it was found that Block IV reference cells can be used for electrical performance evaluation of the Georgetown modules with the exception of the Westinghouse Electric Corp. modules. JPL plans to prepare reference cells to evaluate the Westinghouse modules, provided that candidate cells are received in time; otherwise JPL will select from its supply the reference cell best matched to the Westinghouse module.

During the reporting period, equipment failures in the Large-Area Pulsed Solar Simulator (LAPSS) system forced shutdown of that facility for about a month. The failures have been repaired and both LAPSS 1 and LAPSS 2 are now operating satisfactorily, having been integrated with the PDP 11/60 computer. Simultaneous operation is still being developed. The PDP software has been modified to provide identification of data obtained from the LAPSS 1 and LAPSS 2 systems to eliminate any possible source of confusion over which system was used. In addition, the plotting format was altered to provide simpler interpolation of plotted data.

Environmental Testing

Tests have continued on six types of Block IV modules, and one each of the MIT-LL RES, commercial, and Cell and Module Formation Research Area modules. Malfunctioning of one and sometimes both LAPSSs delayed testing for an appreciable time.

Tables 4 and 5 summarize the test results. As shown in Table 4, the modified Block IV VS module is performing satisfactorily. However, new UR modules must be started into test again because of serious delamination of the latest versions. YR and YS modules have now qualified. Eight of the 10 Block IV types have qualified. GR and US prototype modules were among those previously qualified but the production versions have had test problems recently. This

Table 4. Recent Block IV Test Results

Vendcr Code/Number of Modules Tested	Construction (from Top Down)	Tests Completed	Results
VS/5 Second Set	Glass, PVB, Tedlar/Al/Tedlar, Al frame	T H	Satisfactory
UR/4 Second set	Tedlar, EVA, galv. steel. pan, mounted on JPL wood frame	T	Tedlar edge delamination near terminals, 4 cell cracks
YR/2 YS/1 Fourth sets	Glass, EVA, Craneglas, EVA, Tedlar Same, Al frame	T H	Satisfactory; qualified mdls
GR/2, Production, each mounted on plywood	Glass, adhesive, RTV, weatherproofed paperboard	T	Moderate electrical degradation, encapsulant discoloration, collector contamination
US/2 Test of repair procedure on production mdl	Glass, PVB, Tedlar/steel/Tedlar, Al frame	T H	Repairs OK; after test, encap delaminated from glass
SS/3 Production	Glass, EVA, ripstop, Mylar/Al, back coat; stainless frame	T	Satisfactory
SS/2 Production; repair	Same	T H	Diode leads opened on one mdl

Table 5. Test Results on Other Modules

Vendor Code/Number of Modules Tested	Construction (from Top Down)	Tests Completed	Results
GR-3 (Roof) MIT-LL, RES, SW	Glass, adhesive, RTV, weatherproof paperboard	T last period H this period	Continued electrical degradation, interconnect discoloration and contamination; blank shingles are loose
BV/4 latest design, commercial	Acrylic top and substrate	T	Severe electrical degradation delamination, warping, air bubbles, cell cracks
US/4 PD, Phase 2, automated soldering	Glass, PVB, Tedlar/steel/Tedlar, Al frame	MI Twist Hail	(Previous T caused sealant extrusion); satisfactory except all modules failed final hi-pot

further emphasizes the need for continuing Quality Assurance efforts and follow-up testing.

Table 5 gives data on other modules. The GR version supplied by MIT has failed its tests. The redesign of the commercial BV modules was unsuccessful. The US modules provided by PD passed the latest three qualification tests but failed the final hi-pot test.

The new 85°C/85% RH, -40°C humidity-freeze test was run using seven Block IV qualified modules and one long-lived Block II W-type module. This test is more severe both in the humidity (85°C, 85% RH for 20 hours) and the freezing (-40°C saturated with moisture) than the Block IV test. The test was run to give an indication of the likelihood of Block IV modules passing this more severe Block V test. The Block II W-type module had already had four years' exposure at Table Mountain and most of the others had been exposed to the complete set of Block IV qualification tests. A new type of delamination on the backs of these cells and between cells was found. There are several possible explanations for this; however, it suggests that the test is more severe than four years in the field.

Other modules showed results generally observed in Block IV qualification tests. Delamination and corrosion of frame hardware, cells and interconnects were more severe than in the earlier tests, but electrical degradation was minimal. Two modules survived the humidity-freeze cycle with neither electrical nor visible degradation. Considering the limited field experience available, this test may be nearly optimum.

Field Testing

All field-test activities centered on implementation of the restructuring plan. Table 6 is a milestone chart; below are some additional details.

(1) Decommissioning of the continental remote sites has been completed. One site, the Albuquerque (Sandia Laboratory) site, will remain open by special arrangement with the Sandia Test Facility manager, but no data will be collected by Sandia.

(2) The tasks of reorganizing the Southern California sites and establishing a site at the Florida Solar Energy Center have been completed. About 45% of the modules originally under test at the Southern California sites have been relocated to an enlarged Goldstone site where life-testing continues.

(3) Reorganization of the JPL site is well under way; the old wiring has been removed and new wiring has been installed. Some difficulty has been encountered with the multiplexers (15 are required for the new setup). Random addressing errors that are difficult to track down are being experienced; work is continuing on this problem. Meanwhile, the array-switching controls are being readied for installation.

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

Table 6. Implementation Schedule

	1981												1982											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
FORMULATE RESTRUCTURING PLAN			▼																					
DECOMMISSION CONTINENTAL REMOTE SITES																								
CONTRACT TO DECOMMISSION SITES						▽	▬	▬	▬	▽														
SHIP MODULES AND RECEIVE AT JPL								▽	▬	▬	▽													
OBTAIN FINAL I-V (LAPSS) DATA										▽	▬	▬	▽											
REORGANIZE SOUTHERN CALIFORNIA SITES																								
OBTAIN LAST SET OF IN-SITU I-V DATA							▼																	
INSTALL NEW STANDS AT GOLDSTONE							▼																	
RELOCATE OLD MODULES AT GOLDSTONE								▼																
MODIFY EXISTING STANDS FOR NEW MODULES								▼																
ESTABLISH SITE AT FLORIDA SOLAR ENERGY CENTER									▼															
REWIRE JPL SITE																								
REMOVE OLD WIRING								▼																
WIRE IN NEW MULTIPLEXER AND DORIC STATIONS										▽														
CONNECT DORIC DEVICES										▽	▬	▽												
CONNECT MODULES TO MULTIPLEXERS												▽	▬	▬	▬	▬	▬	▬	▬	▽				
FABRICATE/INSTALL ARRAY-SWITCHING CONTROLS									▽	▬	▽													
FABRICATE ARRAY DATA LOGGER																								
DEFINE REQUIREMENTS					▼																			
COMPLETE DESIGN							▼																	
CONSTRUCT AND TEST								▽	▬	▬	▬	▽												
DEPLOY NEW MODULES																								
RECEIVE MODULES FROM VENDORS	▽	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬	▽						
DEPLOY MODULES AT ALL SITES											▽	▬	▬	▬	▬	▬	▬	▬	▬	▬	▽			
UPDATE JPL SITE SOFTWARE																								
MODIFY INSOLT AND SUMMARY TASKS									▽	▬	▬	▽												
REVISE DATA BASE FOR NEW MODULES											▽	▬	▬	▬	▬	▬	▬	▬	▬	▽				
CODE AND TEST ARRAY1 AND SUMAR5												▽												
START ROUTINE TESTING OF NEW MODULES													▽	▬	▬	▬	▬	▬	▬	▬	▽			

(4) Fabrication of the array data logger, the key instrument in all future array work, has been delayed because of priority and overrun problems. Originally it was to have been completed by the end of September; the revised completion date is now the end of December 1981.

(5) Deployment of new modules is well behind the original schedule because of delays in receiving the modules from the vendors. Only three of the nine different types of new modules to be deployed have been received: Motorola Inc. Block IV intermediate-load modules, ARCO Solar intermediate-load automated assembly-line modules, and GE residential modules.

Most of the remainder will not arrive until next calendar year, and one type probably will not arrive until May or June. The original plan, which called for initiation of testing all the modules at the same time, has been changed; testing will commence as soon as modules are received and have gone through their pre-installation screening and tests.

Work has been started on the annual report. Its theme this year is the restructuring plan; expected publication date is March 1, 1982.

Failure Analysis

Problem-failure activity included the final field analysis of the Mount Laguna array and continued support of JPL block module procurement and of the test and application experiments of MIT-LL and Lewis Research Center.

The Mount Laguna Block III types of modules are showing continued degradation in performance. At the time of a visit in August 1981 the array power output had dropped to below 30 kW at peak insolation. The system operating voltage has been lowered to approximately 200 volts in order to extract maximum power from the array. The cause of the array's degradation is attributed to the hot-spot cell-cracking failure mode shown in Figure 1 for the glass-fiber substrate module.

The other module strings have shown a markedly increased drop in performance, which is attributed to both impact-cracked cells and fractured interconnects that in either case causes the module to become open and to be bypassed in the string by the bypass diode. Table 7 shows the number of degraded modules as related to percentage of degraded modules.

Problem-failure analysis was completed on the Block IV Applied Solar Energy Corp. (ASEC) module. The delamination along the edge of the module was caused by moisture permeation. Another ASEC module was found to be intermittent after environmental test; the problem was diagnosed as an unsoldered contact at the bottom of a cell. Excessive leakage current to ground was noted on an ARCO Solar module in Hawaii by MIT. Preliminary analysis indicates that the pottant material, polyvinyl butyral, is sensitive to temperature with respect to insulation resistance. The leakage increases as the material becomes heated. At 45°C the leakage current appears to be in excess of 50 μA.

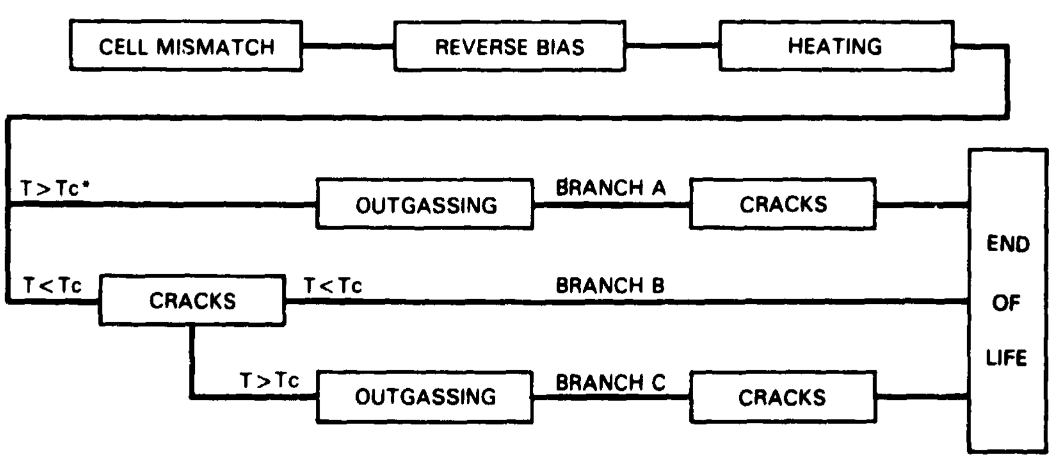
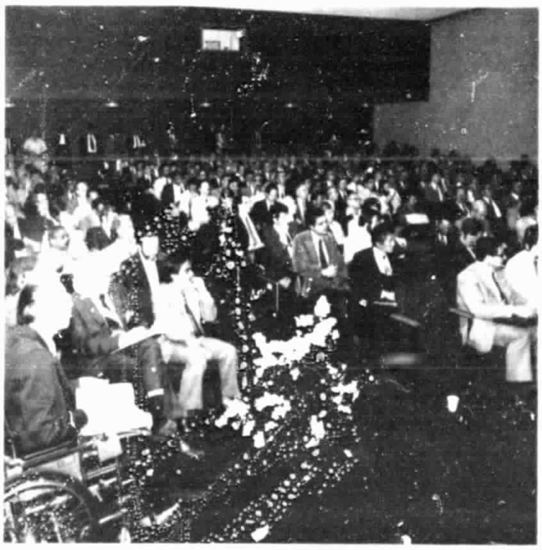


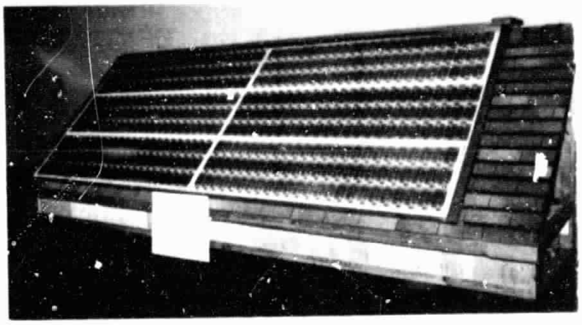
Figure 1. Hot-Spot Cell-Cracking Failure Mode in Glass-Fiber-Substrate Module

Table 7. Degraded Modules: Number vs Percentage

Module	No. of Modules Relating to % Degradation			
	25%	50%	75%	100%
A	130	57	58	94
B	-	-	5	107

Laser scans of modules before test or field deployment have been started to provide a record or fingerprint of each module. This will allow finding defective cells or changing cells after either environmental test or field test.





INTRODUCTION

The 19th Project Integration Meeting (PIM) for the Flat-plate Solar Array (FSA) Project (formerly Low-cost Solar Array Project) was held at the Pasadena Center, Pasadena, California, on November 11, 1981. It was conducted differently from previous PIMS in that it was only a one-day meeting, consisting primarily of parallel technology sessions for an assessment of recent Project progress since the last PIM in July. The usual plenary sessions with emphasis on a theme or themes, special topic sessions, and displays were omitted. Brief summaries of the Critical Technology Workshops and of FSA progress were presented.

Two limited-attendance workshops were conducted on the day before the PIM: one on silicon materials and crystal-growth technology, and one on solar-cell and module technology. The purpose of each was to explore specific critical technical problems that are at present perceived as potential barriers that could limit the achievement of FSA technological objectives.

A number of PIM participants attended the Solar Array Manufacturing Industry Costing Standards (SAMICS) short course held at the Pasadena Center during the two days following that of the PIM. The course offered an overview of the SAMICS methodology, and the effective use of SAMICS was explained in detail and illustrated in real-time applications.

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FLAT-PLATE SOLAR ARRAY PROJECT PLANS FOR 1982

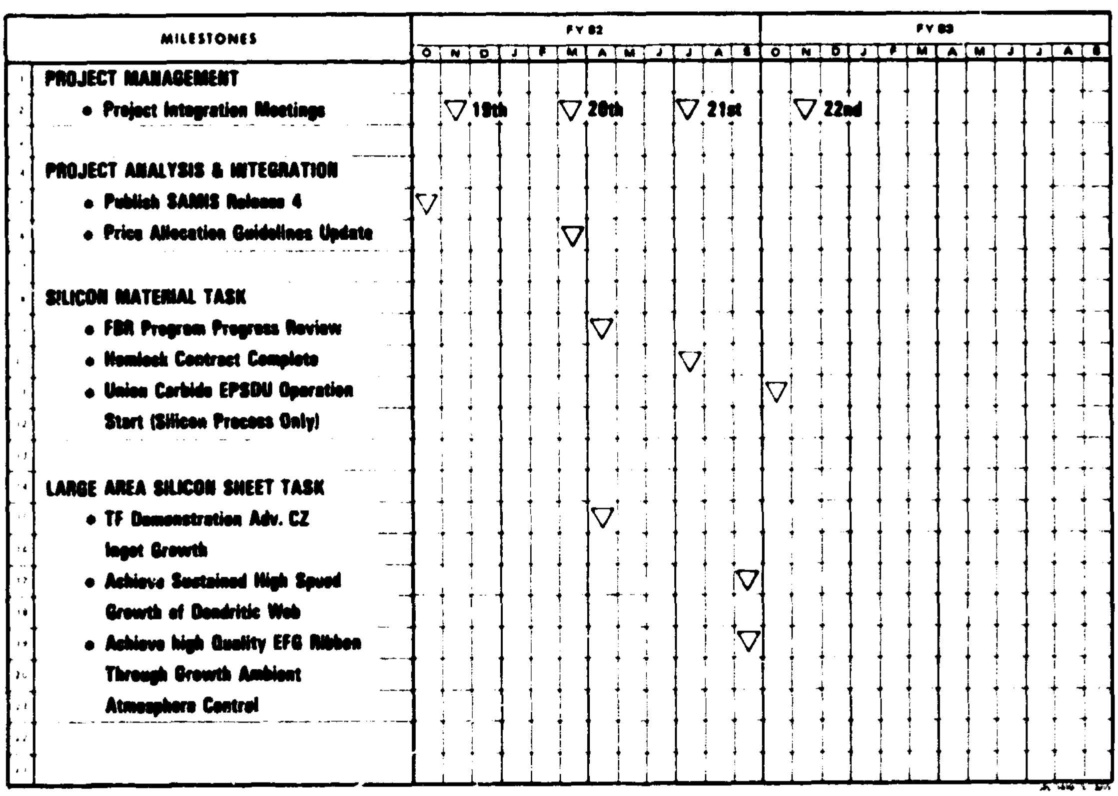
JET PROPULSION LABORATORY

W.T. Callaghan

Basis for FY82 Plans

- **Technical and Commercial Readiness Milestones Removed**
- **Emphasis on Longer-Term Payoff**
- **R&D Content Increased; Industrial Development Activity Decreased**

FSA Key Project Milestone Schedule



FSA Key Project Milestone Schedule (Cont'd)

MILESTONES	FY 82												FY 83											
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
ENCAPSULATION TASK																								
• Report on analysis Methods for Assessing Module Service Life							▽																	
• Publish Summary of Encapsulation Specifications, Properties, and Performance Characteristics										▽														
PROCESS DEVELOPMENT AREA																								
• Execution of PD Contracts						▽																		
• Process Sequence Feasibility Unit Mid-Term Design Review(s)						▽																		
ENGINEERING AREA																								
• UL Module Safety Reqmts Report	▽																							
• Module Hot-Spot Heating Report			▽																					
• Residential Array Design Report												▽												
OPERATIONS AREA																								
• Issue Annual Field Test Report				▽																				
• Award Block V Phase II Contracts					▽																			
• Complete Block V Design and Test Review													▽											

Status

- **FSA FY82 AOP Currently Under Review At DOE**
- **Key Project Activities Are Consistent With FY82 AOP Based on $62.9M DOE Program**
- **FSA FY82 Final Budget Allocation Uncertain**

Technology Sessions

FLAT-PLATE COLLECTOR RESEARCH AREA

Silicon Material Task

R. Lutwack, Chairman

Presentations covering research on silicon (Si) processes and on supporting activities were made by four contractors and by JPL.

Union Carbide Corp. reported on the status of its research into a process that converts metallurgical-grade Si to silane, which is then decomposed to produce pure Si. Construction of the experimental process system development unit (EPSDU) was stopped because no FY82 DOE funding is available for installation and operation. Negotiations are under way by UCC, DOE, and JPL on cost-sharing arrangements. It is planned to relocate the EPSDU at a Pacific Northwest location. In the R&D area, the free-space reactor scale-up and design for the EPSDU is essentially complete, the silicon powder consolidation process was demonstrated on a semicontinuous basis, and work on fluidized-bed pyrolysis of silane was reactivated.

In the investigation of a process for making trichlorosilane by the hydrochlorination of metallurgical-grade Si and silicon tetrachloride, Solarelectronics reported that construction and installation of a test system using a 2-in.-dia reactor is in progress, and samples of various alloys are being prepared for corrosion studies.

Hemlock Semiconductor Corp. described progress in the contract to develop a process wherein Si is deposited from dichlorosilane (DCS) in a Siemens-type reactor. Testing of the DCS process development unit (PDU) integrated with Si deposition reactors continued, the PDU achieving a high (95%) on-line time in October. The Si produced is of semiconductor-grade quality.

Results of analysis on solar cell degradation due to edge defects and bulk defects were presented by C.T. Sah Associates.

In the JPL in-house program, progress was presented for the work on direct conversion of silane to molten Si, on deposition of Si from silane in a fluidized-bed reactor, and on the analysis of impurities in Si by the use of thermally stimulated capacitance measurements.

SILANE-TO-SILICON PROCESS

UNION CARBIDE CORP.

TECHNOLOGY POLYCRYSTALLINE SILICON R&D	**REPORT DATE** NOVEMBER 11, 1981
APPROACH HIGH-PURITY SILANE FROM METALLURGICAL SILICON; SILANE PYROLYSIS & CONSOLIDATION TO FORM SEMICONDUCTOR-GRADE POLYSILICON **CONTRACTOR** UNION CARBIDE CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY & ENGINEERING PRACTICALITY • DEMONSTRATE SILANE PURITY • DEVELOP PRACTICAL SILANE DECOMPOSITION PROCESS FOR SOLAR CELLS • SILICON PRICE OF LESS THAN \$14/KG FOR HIGH VOLUME PROCESS	**STATUS** SILANE PYROLYSIS R&D • FREE SPACE REACTOR SCALE-UP & DESIGN FOR EPSDU IS ESSENTIALLY COMPLETE • SILICON POWDER FEEDING, MELTING & SHOTTING WAS DEMONSTRATED ON A SEMI-CONTINUOUS BASIS • FLUID BED PYROLYSIS R&D WAS REACTIVATED EPSDU ENGINEERING & INSTALLATION • UNION CARBIDE IS CURRENTLY NEGOTIATING WITH DOE/JPL ON COST-SHARING ARRANGEMENTS TO COMPLETE AN EPSDU PROGRAM

Problems and Concerns

EPSDU ENGINEERING, INSTALLATION AND OPERATION

- A PORTION OF THE WASTE TREATMENT SYSTEM DESIGN IS RELATIVELY NOVEL, AND SOME FIELD ADJUSTMENT MAY BE NEEDED FOR PROPER OPERATION.

SILANE PYROLYSIS R & D

- FURTHER R & D WORK WILL BE NEEDED FOR SILICON SHOTTER PRIOR TO USE IN EPSDU.
- FLUID BED R & D HAS JUST BEEN REACTIVATED AND NOT YET DEMONSTRATED.

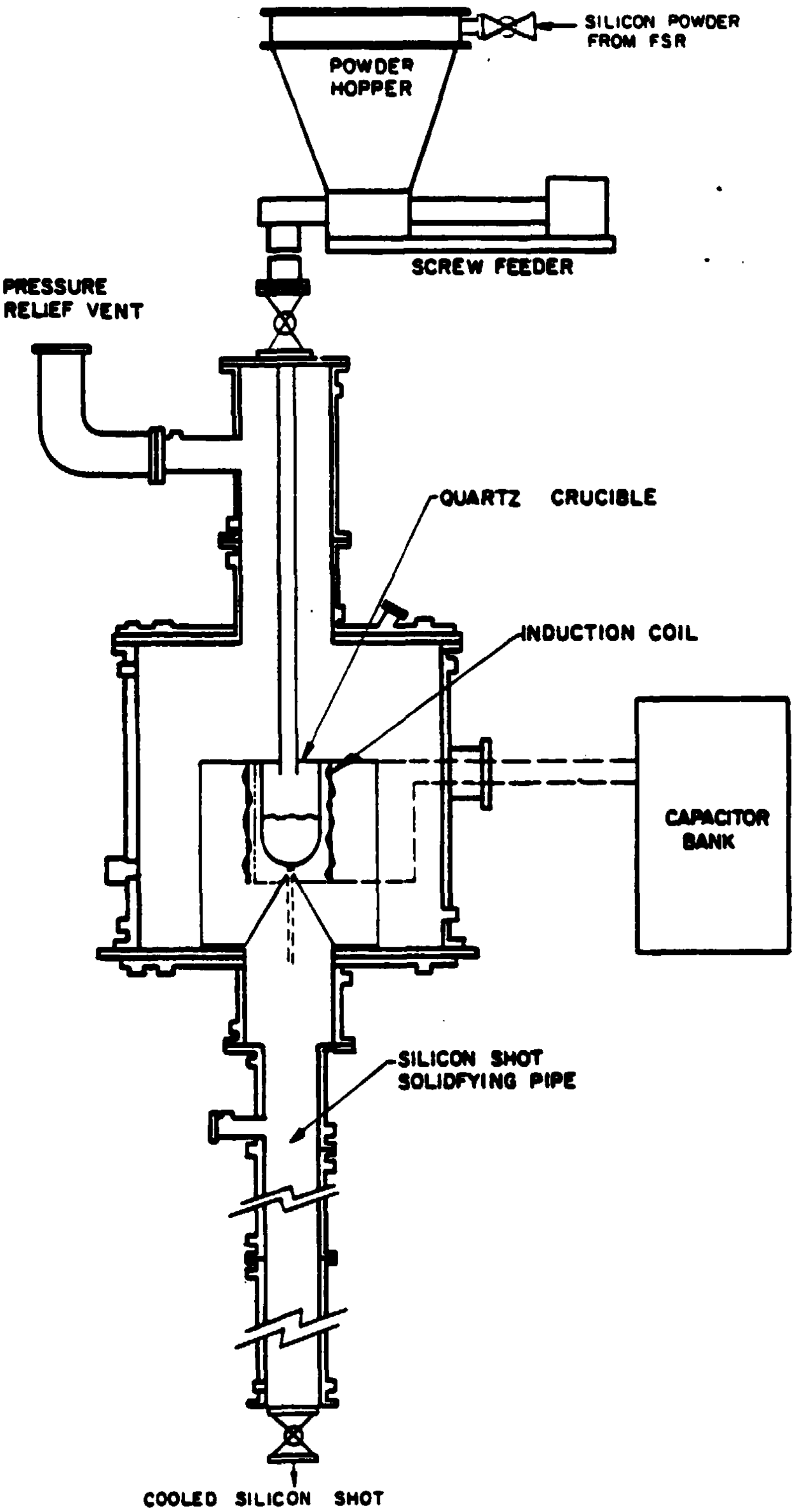
Free-Space Reactor R&D Summary

- DETAILED DESIGN OF EPSDU REACTOR WAS COMPLETED.
- P & I DIAGRAM FOR INTEGRATED REACTOR/SHOTTER SYSTEM WAS PREPARED.
- SUPPORT STRUCTURE FOR REACTOR/SHOTTER WAS DESIGNED.
- RFQ'S & EQUIPMENT PROCUREMENT WILL BE DEFERRED.

Silicon Shotting R&D Summary

- SUBCONTRACT WORK BY KAYEX WAS COMPLETED.
- DEMONSTRATED FEASIBILITY OF SHOT PRODUCTION IN SEMI-CONTINUOUS MODE.
- PRODUCED TOTAL OF ABOUT 10 KG SHOT FROM SILICON POWDER IN 3 SUCCESSIVE RUNS.
- SHOT DIAMETER RANGED 0.4 TO 3 MM.
- RESISTIVITY OF CZOCHRALSKI GROWN INGOT FROM MELTED SHOT WAS 20 OHM-CM.
- PROTOTYPE SHOTTER OPERATION WAS LIMITED BY MELT RATE.
- HOT ZONE MODIFICATION IS REQUIRED TO INCREASE THROUGHPUT.
- FURTHER WORK ON SHOTTER WILL BE DEFERRED.

Silicon Powder Melting and Shotting System



Resistivity of Ingots Grown From Shot

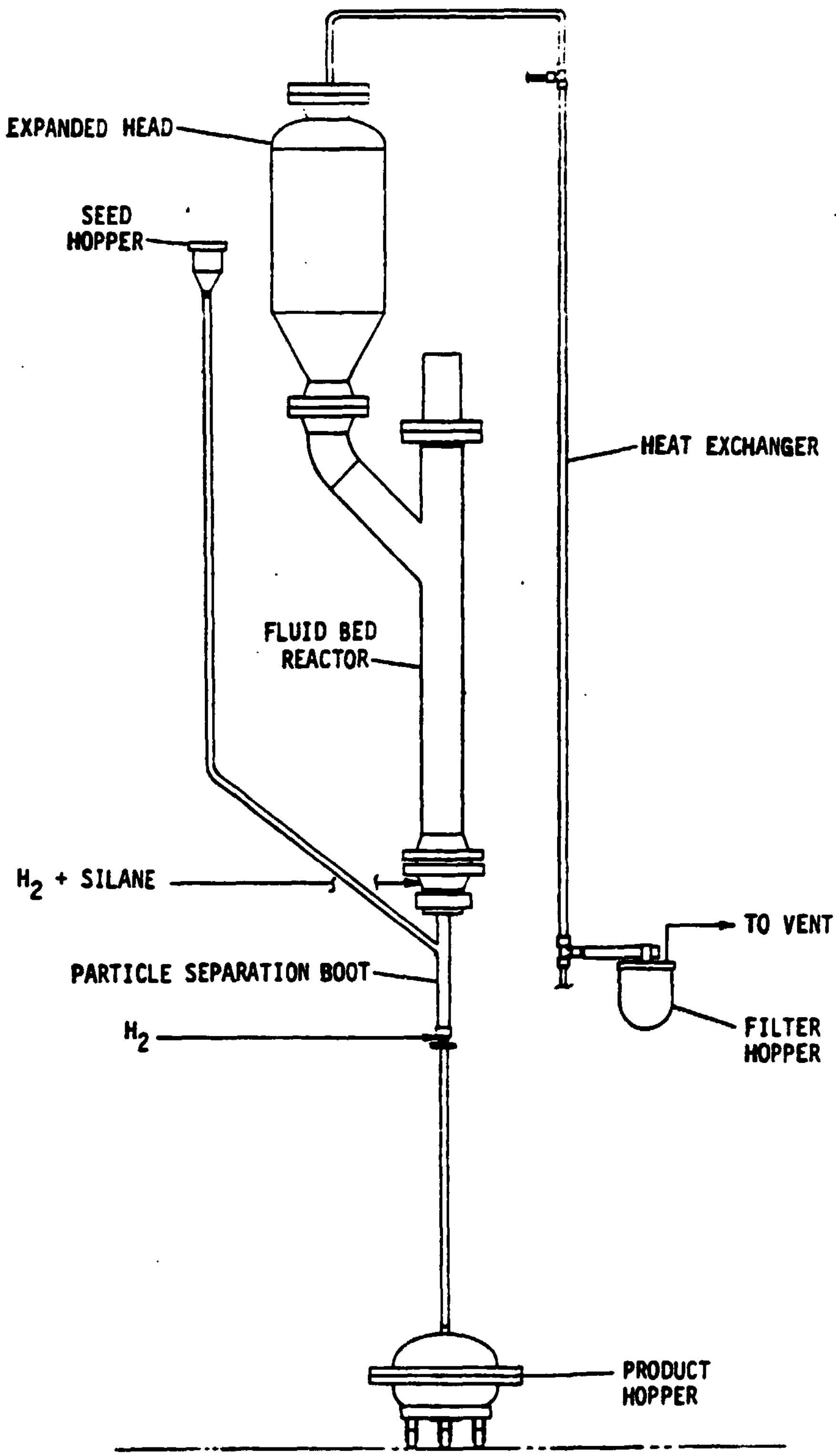
INGOT	NEW POLYSILICON	UNDOPED SHOT	DOPED SHOT
AS GROWN CRYSTAL	45 N	18 P	5.7 P
HEAT TREATED CRYSTAL	200 NEUTRAL	20 P	5.6 P

- 8 KG SHOT CHARGE FROM RUN NO. 24
- UNTREATED SHOT
- FURNACE ATMOSPHERE 20 TORR. ARGON
- CLEAN MELT
- (1,0,0) CRYSTALS
- AVERAGE RESISTIVITY, OHM CM

Fluid-Bed Pyrolysis R&D Summary

- SUCCESSFUL PDU STARTUP RUNS PRIOR TO FUNDING RECISION IN MAY WERE VERY PROMISING.
- FLUID BED PYROLYSIS R & D WAS REVIVED IN OCTOBER.
- PLAN TO CONDUCT PDU TESTS FOLLOWED BY REACTOR SCALE-UP & DESIGN FOR EPSDU IN FY 1982.

Fluid-Bed Reactor PDU



Engineering Summary

- PROCESS & FACILITY DESIGNS ARE COMPLETE.
- MOST MAJOR EQUIPMENT WAS DELIVERED TO EPSDU SITE IN EAST CHICAGO.
- INSTALLATION DESIGN IS COMPLETE.
- SITE & CIVIL WORK IS COMPLETE & CONSTRUCTION IS ON HOLD.
- BIDS FOR MECHANICAL & ELECTRICAL INSTALLATION WERE RECEIVED.
- UCC IS NEGOTIATING WITH DOE/JPL ON COST SHARING ARRANGEMENTS.
- UCC WILL RELOCATE EPSDU FACILITY TO A PACIFIC NORTH-WEST LOCATION.

HYDROCHLORINATION PROCESS

SOLARELECTRONICS, INC.

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON METAL	NOVEMBER 11, 1981. 19TH PIM
APPROACH HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE FOR PRODUCING SILICON **CONTRACTOR** SOLARÈLECTRONICS, INC. **GOALS** TO SUPPORT THE UNION CARBIDE SILANE-TO-SILICON PROCESS BY CONDUCTING EXPERIMENTAL AND THEORETICAL STUDIES, ● OPTIMIZE REACTION CONDITIONS FOR THE HYDROCHLORINATION PROCESS ● CONDUCT CORROSION TESTS FOR MATERIAL OF CONSTRUCTION FOR THE REACTOR ● EVALUATE NEW CONCEPTS FOR WASTE DISPOSAL ● FLUIDIZATION MECHANISM STUDY, MERITS OF A FLUIDIZED-BED, FIXED-BED DESIGN	**STATUS** JPL CONTRACT NO. 956061 (JULY 9, 1981 - JULY 8, 1981) WORK COMPLETED: ● PROGRAM PLAN ● REACTOR DESIGN ● PURCHASE EQUIPMENTS WORK IN PROGRESS: ● CONSTRUCTION AND INSTALLATION OF THE 2 INCH HYDROCHLORINATION REACTOR ● PREPARE TEST SAMPLES OF VARIOUS METAL ALLOYS FOR CORROSION STUDIES ● SAFETY REVIEW, START-UP REACTOR ● CARRY OUT HYDROCHLORINATION EXPERIMENTS

What Is the Hydrochlorination Reaction?

WHAT IS THE HYDROCHLORINATION REACTION ?

REACTION OF SILICON TETRACHLORIDE AND HYDROGEN IN A BED OF SILICON METAL

$$3\ SiCl_4 + 2\ H_2 + Si = 4\ SiHCl_3 \quad (1)$$

- REACTION IS MORE COMPLEX THAN SHOWN IN EQUATION (1)
- OVERALL RESULT OF A NUMBER OF STEP-WISE REACTIONS

$$SiCl_4 + H_2 = HCl + SiHCl_3 \quad (2)$$

$$3\ HCl + Si = SiHCl_3 + H_2 \quad (3)$$

$$3 \times (2) + (3) = (1)$$

EQUILIBRIUM REACTION: MIXTURE OF PRODUCTS

1% SiH_2Cl_2, 26% $SiHCl_3$, 73% $SiCl_4$, UNREACTED H_2

OBJECTIVE: REACTION CONDITIONS TO MAXIMIZE $SiHCl_3$

TEMPERATURE: 400°C - 600°C
PRESSURE : ATM. TO 500PSIG.
$H_2/SiCl_4$: 0.5 - 3.0

The Union Carbide Silane-to-Silicon Process

$$3\ SiCl_4 + 2\ H_2 + Si \xrightleftharpoons{500°C,\ 500\ PSIG} 4\ SiHCl_3 \quad (1)$$

$$2\ SiHCl_3 \xrightleftharpoons{AMINE\ CATALYST} SiCl_4 + SiH_2Cl_2 \quad (2)$$

$$3\ SiH_2Cl_2 \xrightleftharpoons{AMINE\ CATALYST} 2\ SiHCl_3 + SiH_4 \quad (3)$$

$$SiH_4 \xrightarrow{PYROLYSIS} 2\ H_2 + Si \quad (4)$$

$$\text{OVERALL:} \quad \underset{\text{(METALLURGICAL)}}{Si} \longrightarrow \underset{\text{(SEMICONDUCTOR)}}{Si} \quad (5)$$

- HYDROCHLORINATION REACTION GENERATES THE Si-H IN SiH_4
- IT COMPLETES THE RECYCLE OF Si-Cl ($SiCl_4$)
- IT COMPLETES THE RECYCLE OF H_2
- A CLOSED-LOOP PROCESS
- IT CARRIES A HEAVY LOAD, E.G., FOR EVERY LB. OF SiH_4 PRODUCED, APPROXIMATELY 60 LBS. OF $SiCl_4$ ARE PROCESSED IN STEP (1)

Production-Size Reactor for the Hydrochlorination Process

ASSUMPTION: 100 METRIC TONS/ YEAR OF POLYCRYSTALLINE SILICON
CVD REACTOR, $SiHCl_3$ FEED, WITH $SiCl_4$ RECYCLED

CVD REACTOR: INLET 100% $SiHCl_3$, OUTLET 50% $SiCl_4$
NEED 2.2 MM LBS/ YEAR $SiHCl_3$, 2xTHEORECTICAL
OR 255 LBS/ HOUR $SiHCl_3$

REACTION CONDITION: 500°C, 500 PSIG, 1:1 H_2:$SiCl_4$, 60 SECONDS
26% $SiHCl_3$, 74% $SiCl_4$

FEED REQUIREMENT: 1,500 LBS/ HOUR $SiCl_4$, 3,200 SCF/ HOUR H_2
(340 LBS/HOUR) 8.6 CU.FT. GASEOUS FEED/ MIN., 500°C, 500 PSIG.

HYDROCHLORINATION REACTOR SIZE: VOLUME OF Si MASS BED = 8.6 CU.FT.
(AT 75% RATED CAPACITY) TAKE H/D = 12
Si MASS BED = 11.6 IN.DIA. x 11.6 FT.

REACTOR SIZE = 1 FT. DIA. x 18 FT.

CHEMICAL VAPOR DEPOSITION OF POLYSILICON FROM DICHLOROSILANE

HEMLOCK SEMICONDUCTOR CORP.

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	NOVEMBER, 1981
APPROACH CHEMICAL VAPOR DEPOSITION OF POLYSILICON FROM DICHLOROSILANE (DCS) **CONTRACTOR** HEMLOCK SEMICONDUCTOR CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY THROUGH INTERMEDIATE REACTOR EXPERIMENTS • INVESTIGATE PROCESS PROFICIENCY BY OPERATION OF PROCESS DEVELOPMENT UNIT • POLYSILICON PRICE OF LESS THAN \$20/KG (1980 \$, 1000 MT/Y, 20% ROI) AND PURITY APPROACHING OR EQUALLING SEMICONDUCTOR-GRADE POLYSILICON • DEFINE PROCESS ECONOMICS	**STATUS** • INTERMEDIATE REACTOR ACHIEVED GREATER THAN 2.0 $G\text{-}H^{-1}\text{-}CM^{-1}$ DEPOSITION GOAL • DCS-PDU ACHIEVED 95% ON-LINE TIME • SILICON PURITY FROM REDISTRIBUTED TCS EXCELLENT FOR SOLAR CELLS • 3" Ø REDISTRIBUTION REACTOR EVALUATION COMPLETED • 5" Ø REDISTRIBUTION REACTOR EVALUATION IN PROCESS • ECONOMICS INDICATE THAT PRICE OF \$20/KG (1980 \$, 1000 MT/Y, 20% ROI) IS OBTAINABLE

Project Activities

- INTERMEDIATE REACTOR OPERATION USING DICHLOROSILANE FEED STOCK
- POLYCRYSTALLINE SILICON PURITY EVALUATION (BORON, DONOR, CARBON, AND TRACE HEAVY ELEMENTS)
- INTERMEDIATE REACTOR VENT GAS COMPOSITION ANALYSIS
- DCS-PDU 3" DIAMETER REDISTRIBUTION REACTOR EVALUATION
- DCS-PDU 5" DIAMETER REDISTRIBUTION REACTOR INSTALLATION
- 1000 MT/Y COST EVALUATION
- MODEL 11D SITE SELECTION

Reactor Data Evaluation

(Data Normalized for Standard 80-mm Rod Diameter)

SILICON FED $GH^{-1}CM^{-1}$	SILICON DEPOSITED $GH^{-1}CM^{-1}$	CONVERSION MOLE %	POWER KWH/KG
4.2	1.59	37.5	89.6
5.0	1.74	35.0	88.8
5.7	2.00	35.1	82.0
3.9	1.61	41.6	93.9

Dichlorosilane Purity (Average*)

DONOR PPBA	BORON PPBA	CARBON PPMA
1.22	0.07	0.31

*NOTE: HIGH AND LOW VALUES FOR EACH DATA SET HAVE BEEN DELETED.

Intermediate Decomposition Reactor Summary

- DICHLOROSILANE REACTOR OPERATION SIMILAR TO TRICHLOROSILANE OPERATION
- NO VAPOR PHASE NUCLEATION IN THE REACTOR
- ROD SURFACE ACCEPTABLE
- PURITY IS SEMICONDUCTOR GRADE QUALITY

QUESTION:

- CAN DECOMPOSITION GOALS BE ATTAINED USING MIXED FEED?
- CAN CONVERSION AND POWER CONSUMPTION GOALS BE ACHIEVED IN A LARGER DECOMPOSITION REACTOR?

Capital ($k) 1980

1.	DIRECT PLANT INVESTMENT (BATTERY LIMIT)		
	A) MAJOR PROCESS EQUIPMENT	5,244	
	B) INSTALLATION/INSTR./BUILDINGS	6,101	
	TOTAL BATTERY LIMIT INVESTMENT		11,345
2.	OTHER DIRECT PLANT INVESTMENTS		
	A) UTILITIES/INSTALLED	2,300	
	B) OTHER DIRECT (GEN. OFFICES, SHOPS, ETC.) (23% OF MAJOR EQUIP.-1A))	1,204	
	TOTAL OTHER DIRECT PLANT INVESTMENTS		3,504
3.	INDIRET PLANT INVESTMENT		
	A) ENGINEERING OVERHEAD (10% X DIRECT COSTS)	1,485	
	B) NORMAL CONTINGENCY (18% X DIRECT COSTS)	2,673	
	TOTAL INDIRECT PLANT INVESTMENTS		4,158
4.	TOTAL DIRECT & INDIRECT INVESTMENT		19,007
5.	OVERALL CONTINGENCY (20% X TOTAL)		3,802
6.	FIXED CAPITAL PLANT INVESTMENT (TOTAL + CONTINGENCY)		22,809

Manufacturing Costs and Product Pricing

	$/KG SILICON ('80 $)	
1. DIRECT MANUFACTURING COST		
1.1 RAW MATERIALS	2.45	
1.2 DIRECT OPERATING LABOR	0.72	
1.3 UTILITIES		
1.3.1 ELECTRICAL (RX)	1.89	
1.3.2 OTHER	0.61	
1.4 SUPERVISION/CLERICAL	0.18	
1.5 MAINTAINING AND REPAIR		
1.5.1 BELL JAR REPLACEMENT	1.00	
1.5.2 OTHER	1.00	
1.6 OPERATING SUPPLIES	0.40	
1.7 LABORATORY CHARGE	0.18	
TOTAL DIRECT MANUFACTURING COST		$8.43
2. INDIRECT MANUFACTURING COST		
2.1 DEPRECIATION	2.28	
2.2 LOCAL TAXES	0.44	
2.3 INSURANCE	0.22	
TOTAL INDIRECT MANUFACTURING COSTS		$2.94
3. PLANT OVERHEAT (12.3% MFG. COSTS)		$1.40
4. TOTAL MANUFACTURING COST		$12.77
5. GENERAL EXPENSES		
6.1 ADMINISTRATION	0.76	
6.2 DISTRIBUTION & SALES	0.76	
6.3 R&D	0.38	
TOTAL		$1.90
6. PRODUCT COST		$14.67
7. PROFIT (20% R.O.I.)		4.56
8. PRODUCT PRICE		$19.23

SILICON MATERIAL TASK

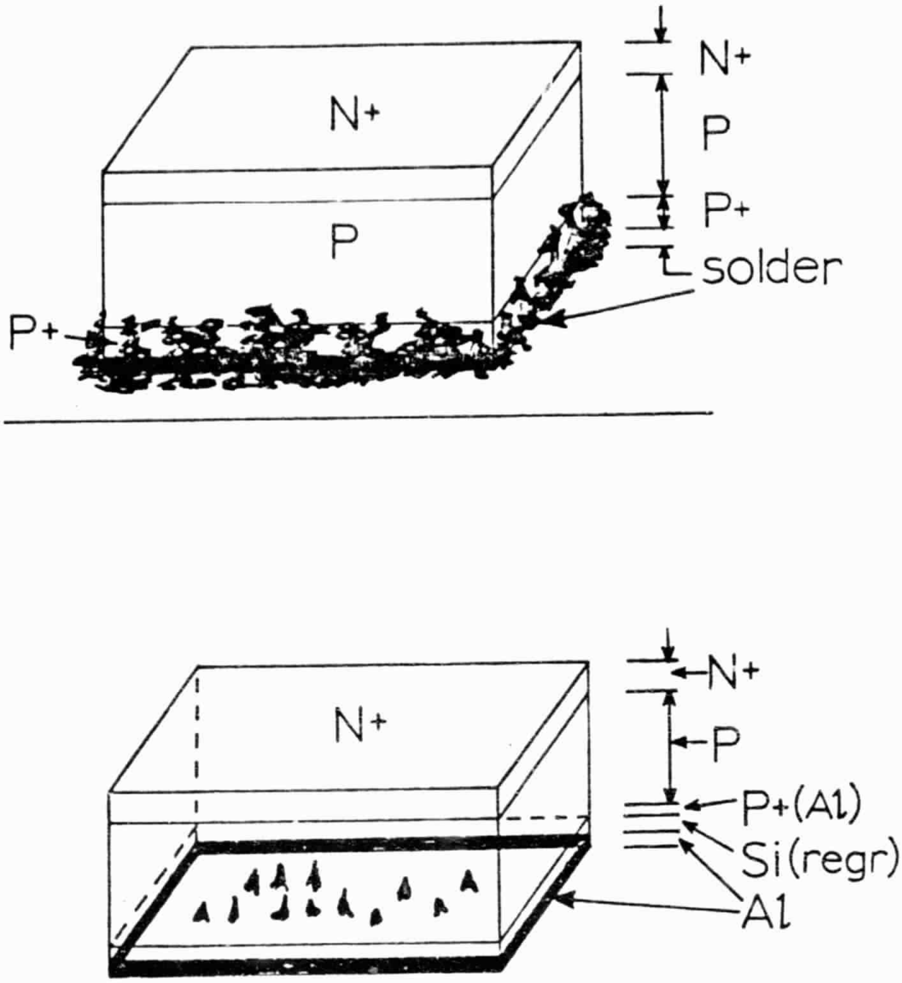
Problems and Concerns

- ACHIEVING CONVERSION EFFICIENCY AND DEPOSITION RATE GOALS SIMULTANEOUSLY
- ACHIEVING A POWER CONSUMPTION AT THE REACTOR OF 60 KWH/KG
- DEPOSITION ON THE QUARTZ REACTOR WALL
- ECONOMICS AND FEASIBILITY OF HYDROGENATION PROCESS

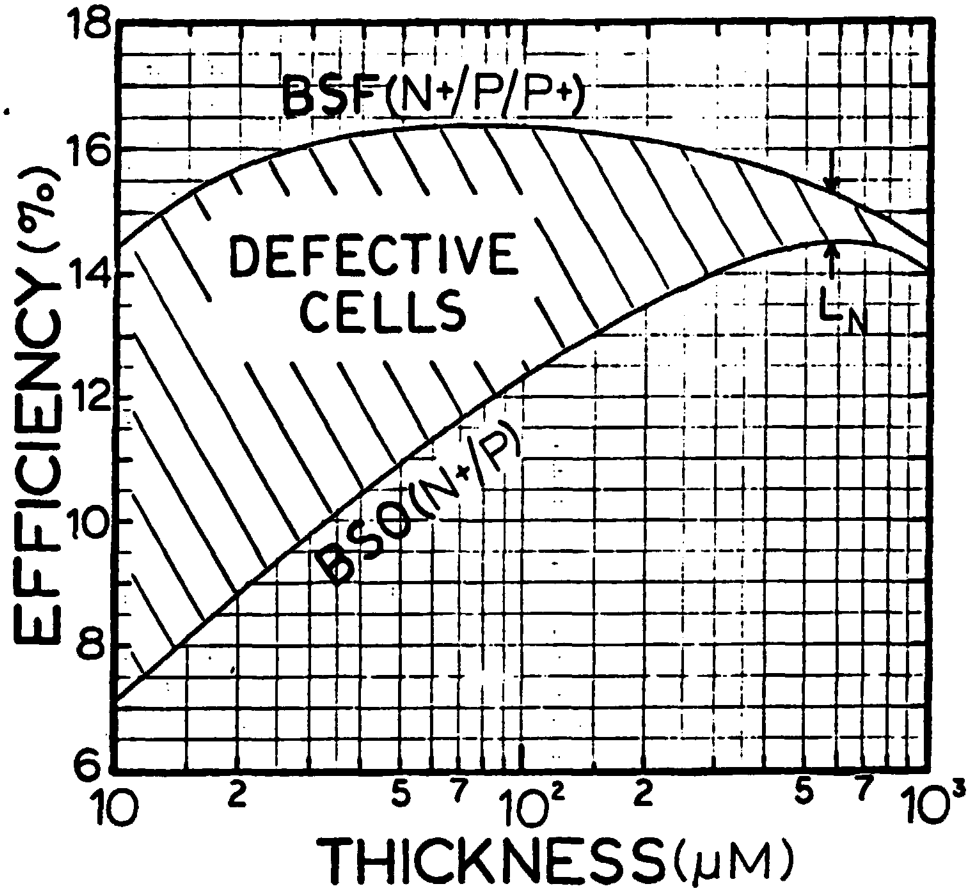
IMPURITY EFFECTS IN SILICON SOLAR CELLS

C.T. SAH ASSOCIATES

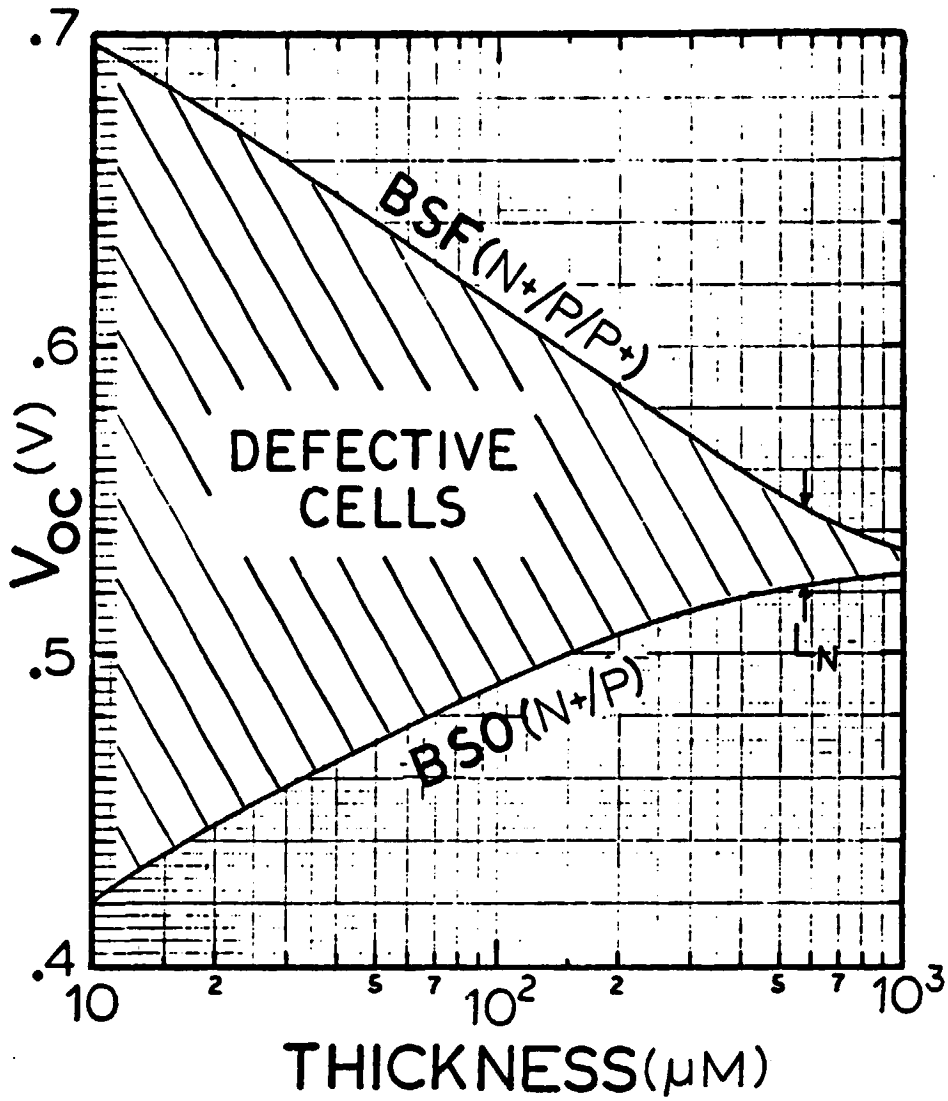
TECHNOLOGY	REPORT DATE
IMPURITY EFFECTS IN SILICON SOLAR CELLS	81/11/11
APPROACH ANALYSIS OF OPEN-CIRCUIT VOLTAGE LIMITED BY RANDOM IMPURITY DEFECTS ACROSS THE BACK-SURFACE-FIELD JUNCTION. **CONTRACTOR** C. T. SAH ASSOCIATES **GOALS** • DETERMINE V_{OC} DEGRADATION DUE TO EDGE DEFECTS ACROSS THE BSF JUNCTION. • DETERMINE V_{OC} DEGRADATION DUE TO BULK DEFECTS ACROSS THE BSF JUNCTION. • CHARACTERIZE IMPURITY RECOMB NATION PARAMETERS FOR PREDICTING MAXIMUM ALLOWABLE IMPURITY CONCENTRATION IN HIGH-EFFICIENCY CELLS.	**STATUS** • EDGE DEFECT CELL DEGRADATION ANALYSES COMPLETED. • BULK DEFECT CELL DEGRADATION ANALYSES COMPLETED. • ZINC RECOMBINATION PARAMETERS OBTAINED AND MAXIMUM ALLOWABLE ZN CONCENTRATION DETERMINED. • TITANIUM RECOMBINATION PARAMETERS ONLY PARTIALLY DETERMINED AND MAXIMUM ALLOWABLE CONCENTRATION ANALYSES TO BE STARTED. • DRAFT OF 5-TH/FINAL TECHNICAL REPORT COMPLETED.



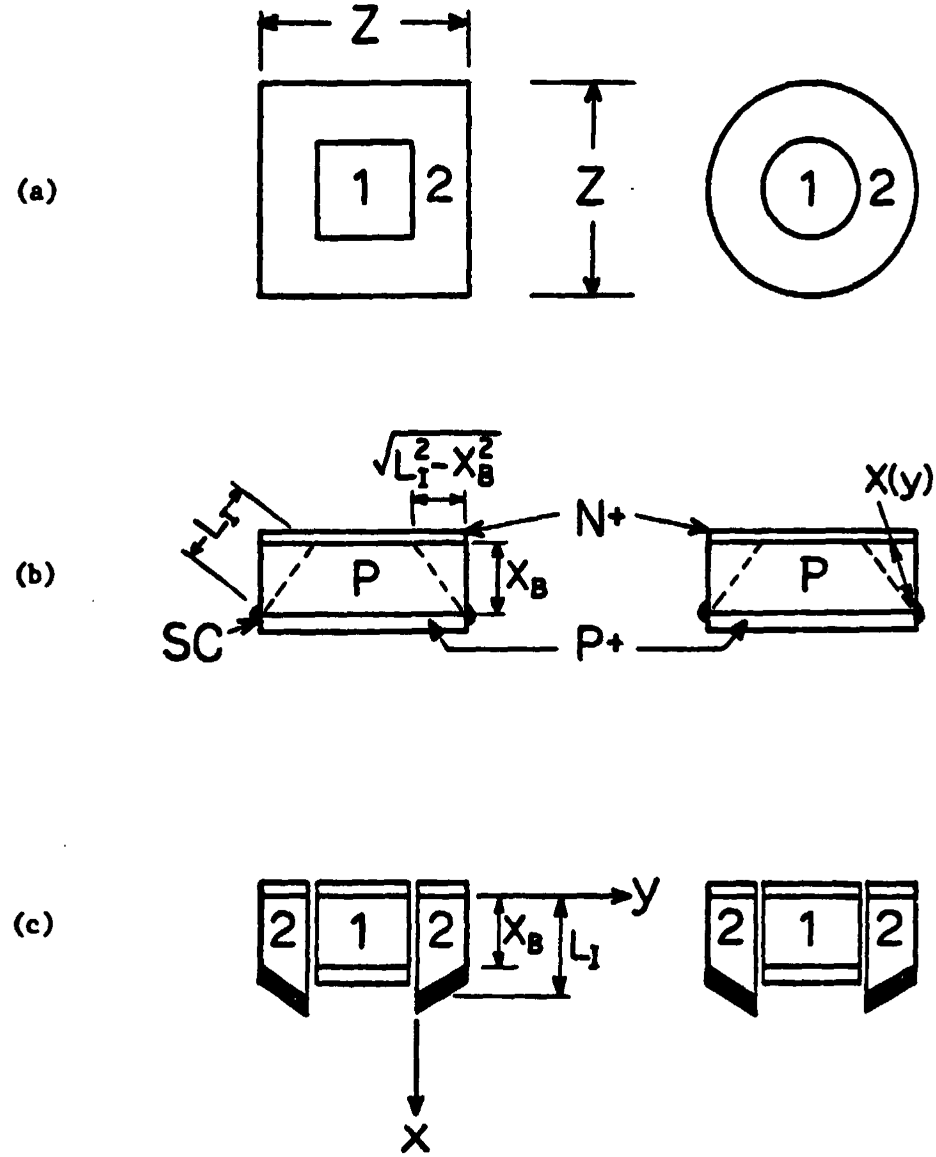
(a) Edge and (b) bulk defects across the back-surface-field junction of a n+/p/p+ junction solar cell.



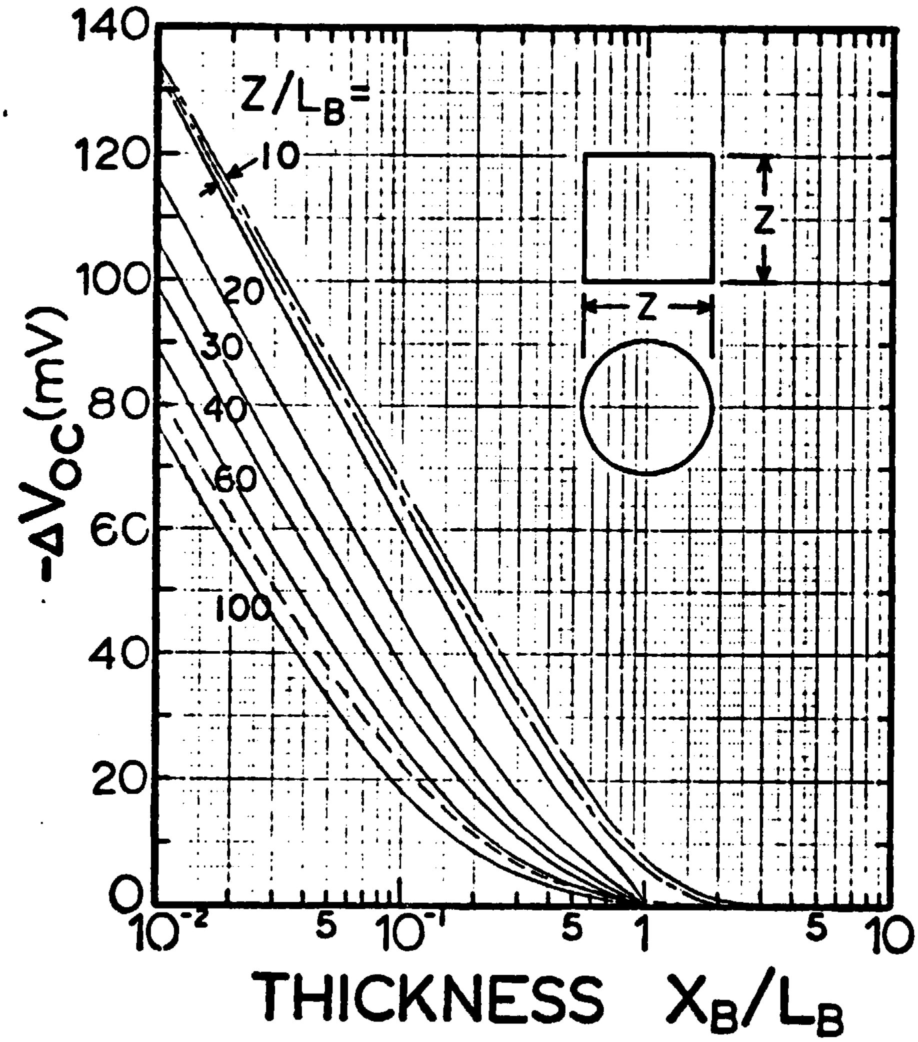
AM1 efficiencies of BSF (back-surface-field) n+/p/p+ and BSO (back-surface-ohmic) n+/p silicon solar cells as a function of cell thickness with 577 μm base minority carrier diffusion length, computed by exact numerical solution of the one-dimensional Shockley Equations. Defective cells with defect across the BSF junction have efficiencies between the BSF and BSO cells.



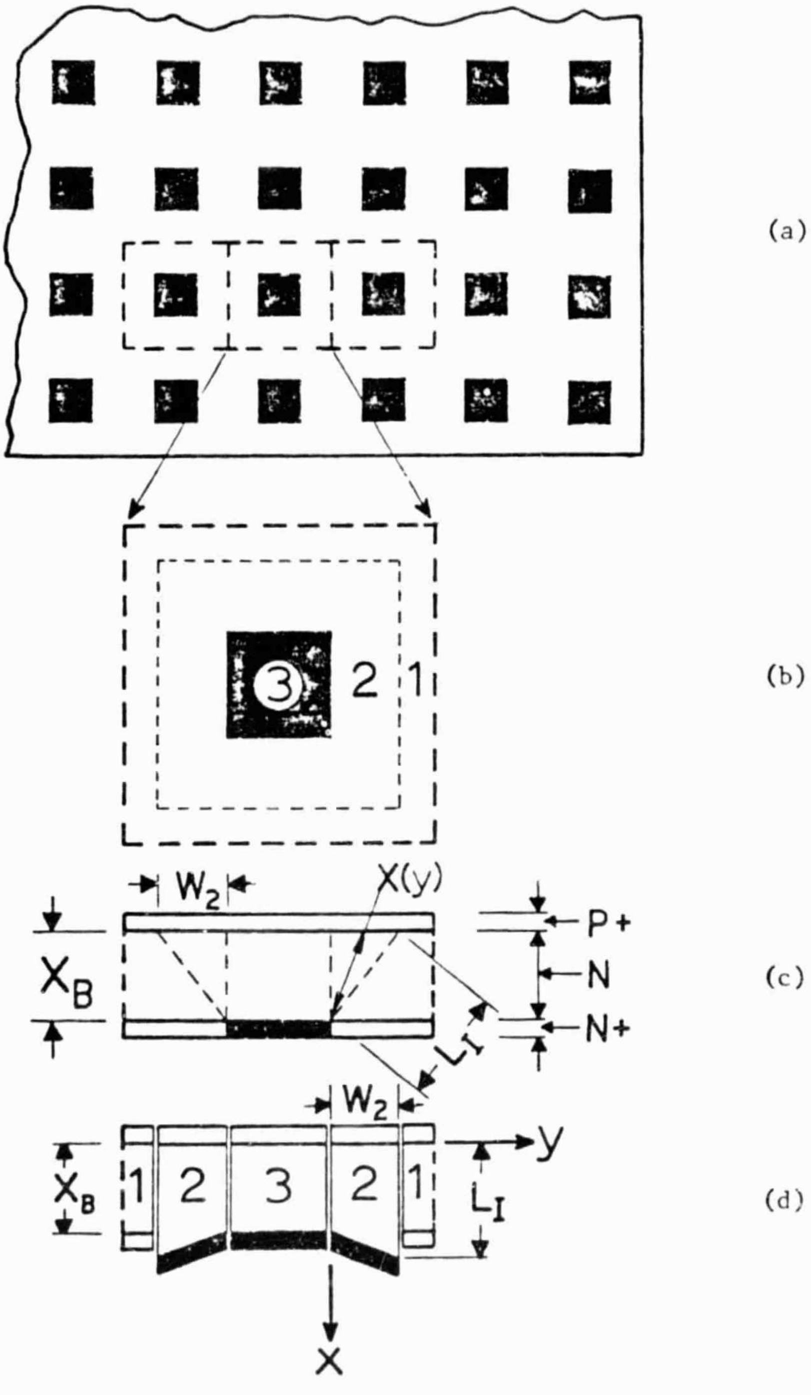
AM1 open-circuit voltage of BSF (back-surface-field) n+/p/p+ and BSO (back-surface-ohmic) n+/p silicon solar cells as a function of cell thickness with 577 μm base minority carrier diffusion length, computed by exact numerical solution of the one-dimensional Shockley Equations. Defective cells with defect across the BSF junction have open-circuit voltages between the BSF and BSO cells.



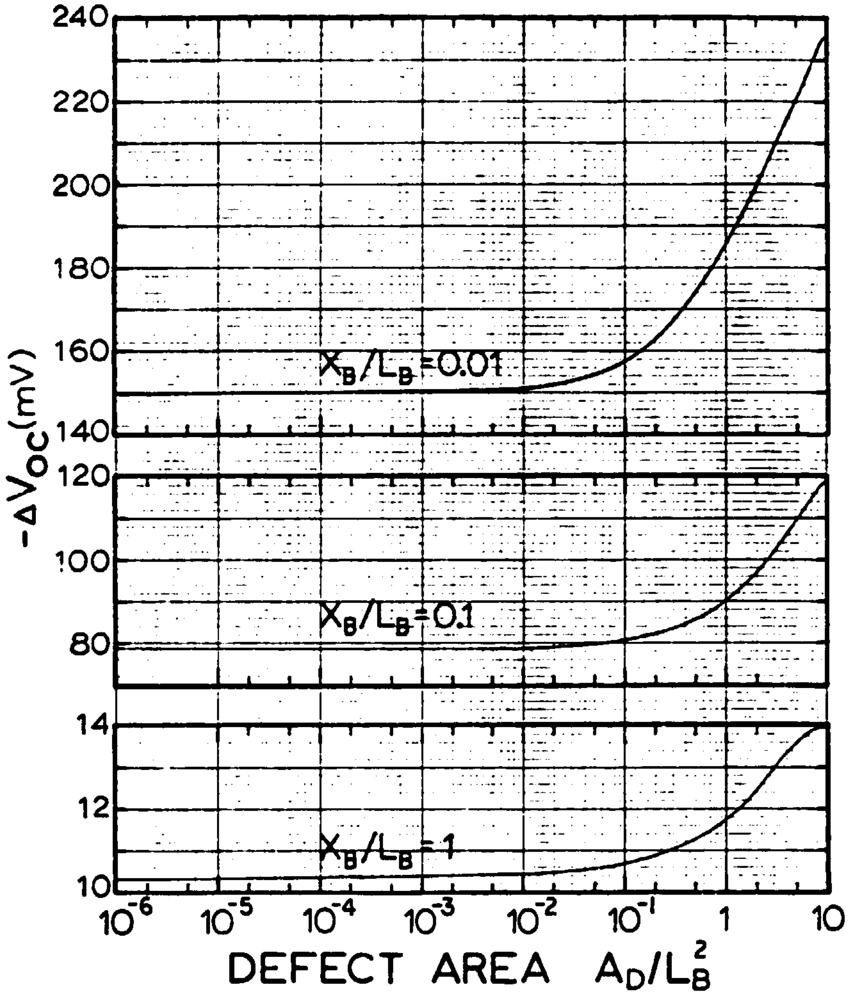
(a) The top view, (c) the cross sectional view and (c) the cross sectional view of the developed perimeter model of a n+/p/p+ back-surface-field solar cell with edge defect across the back-surface-field junction.



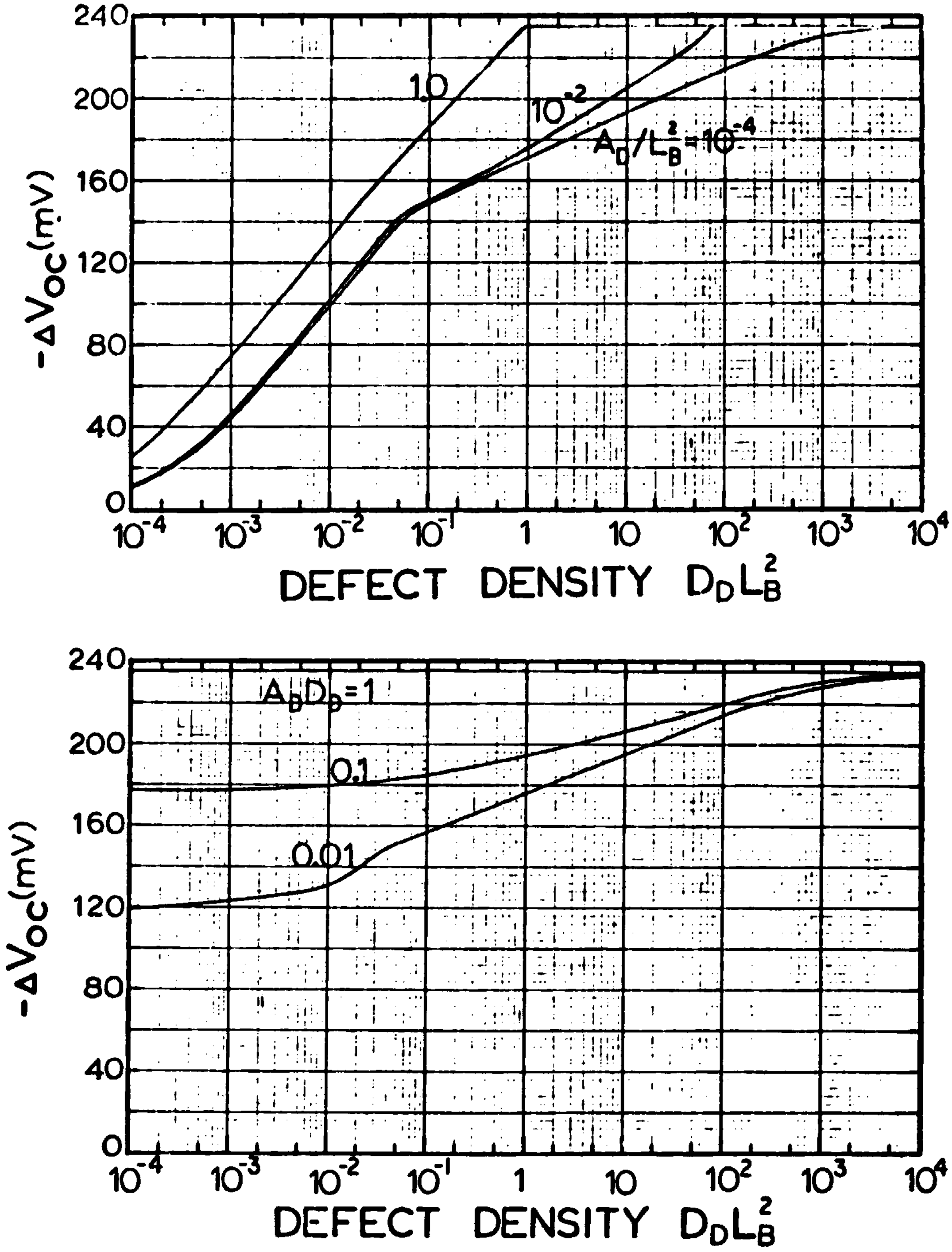
The reduction of the open-circuit voltage as a function of the cell thickness of back-surface-field solar cells with edge defects across the BSF junction. The constant parameter is the cell diameter or cell edge normalized to base minority carrier diffusion length.



(a) Top view, (b) expanded unit cell top view, (c) expanded cross sectional view, and (d) developed perimenter cross sectional view of a defective back-surface-field solar cell.



Reduction of the open-circuit voltage of *t* BSF solar cell as a function of defect area with cell thickness as the constant parameter.



The reduction of the open-circuit-voltage of BSF solar cells as a function of defect density with defect area as the constant parameter (top figure) and fractional defective area as the constant parameter (lower figure).

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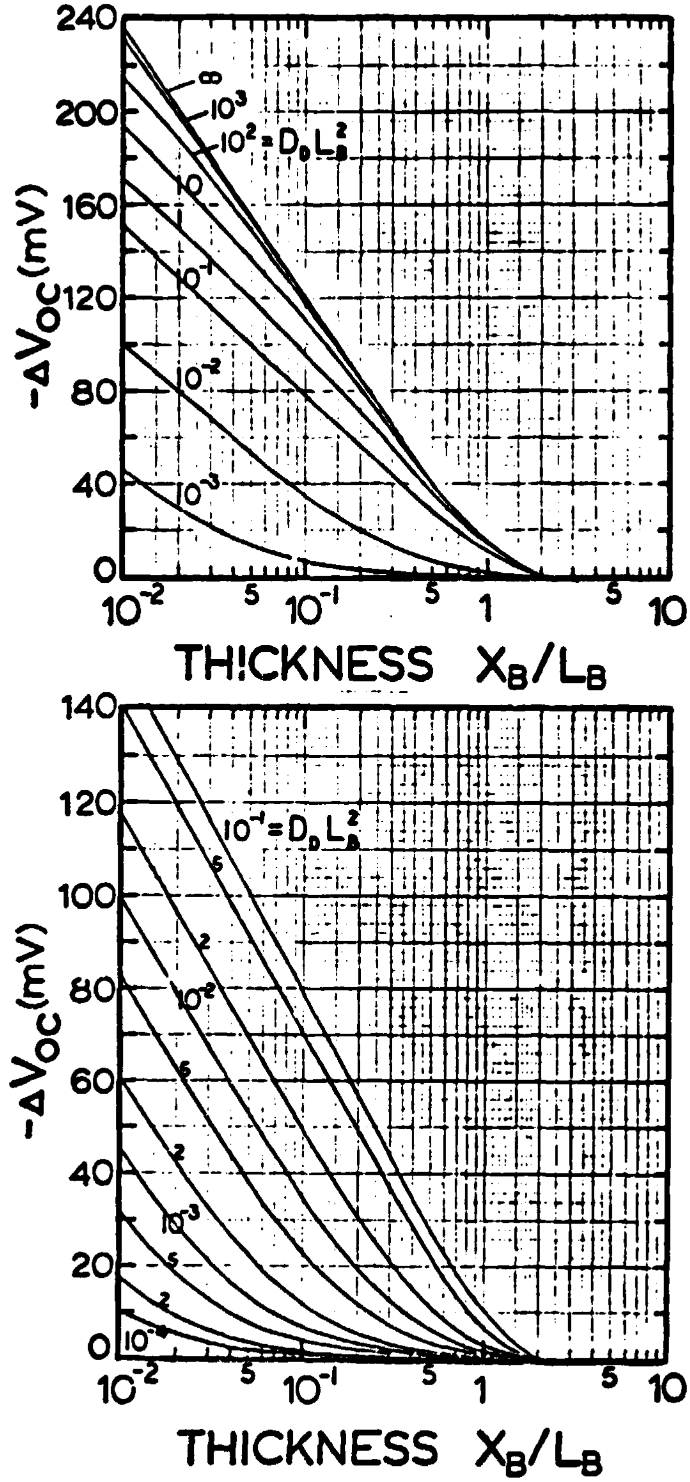
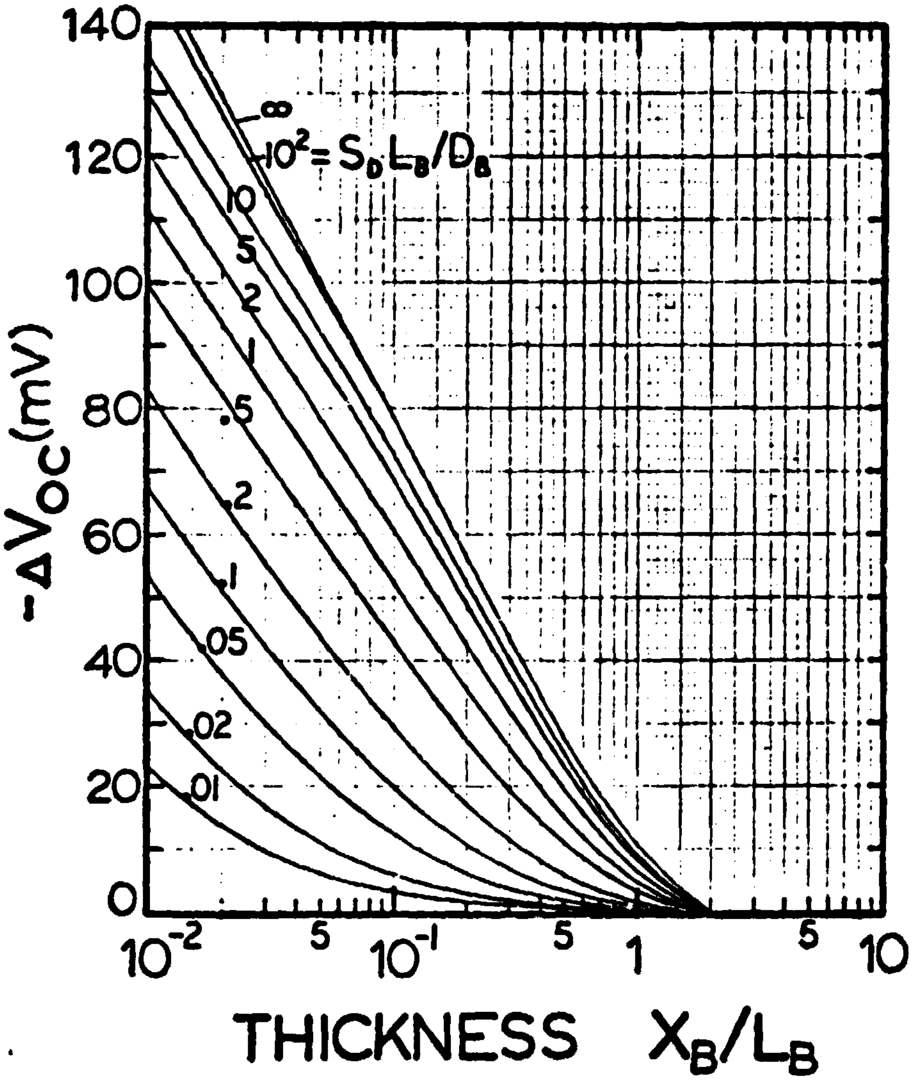


The reduction of the open-circuit-voltage of BSF solar cells as a function of cell thickness with the defect density as the constant parameter.



The reduction of the open-circuit voltage of BSF solar cells as a function of cell thickness with the defect surface recombination velocity as the constant parameter.

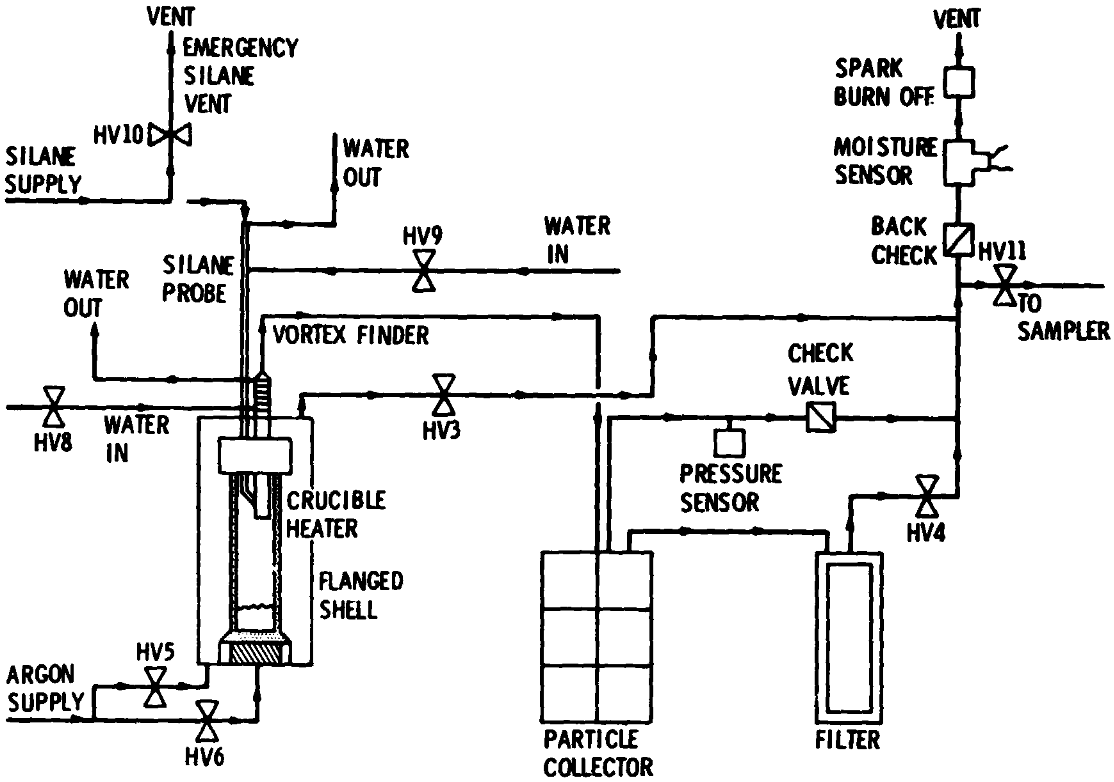
POLYCRYSTALLINE SILICON

JET PROPULSION LABORATORY

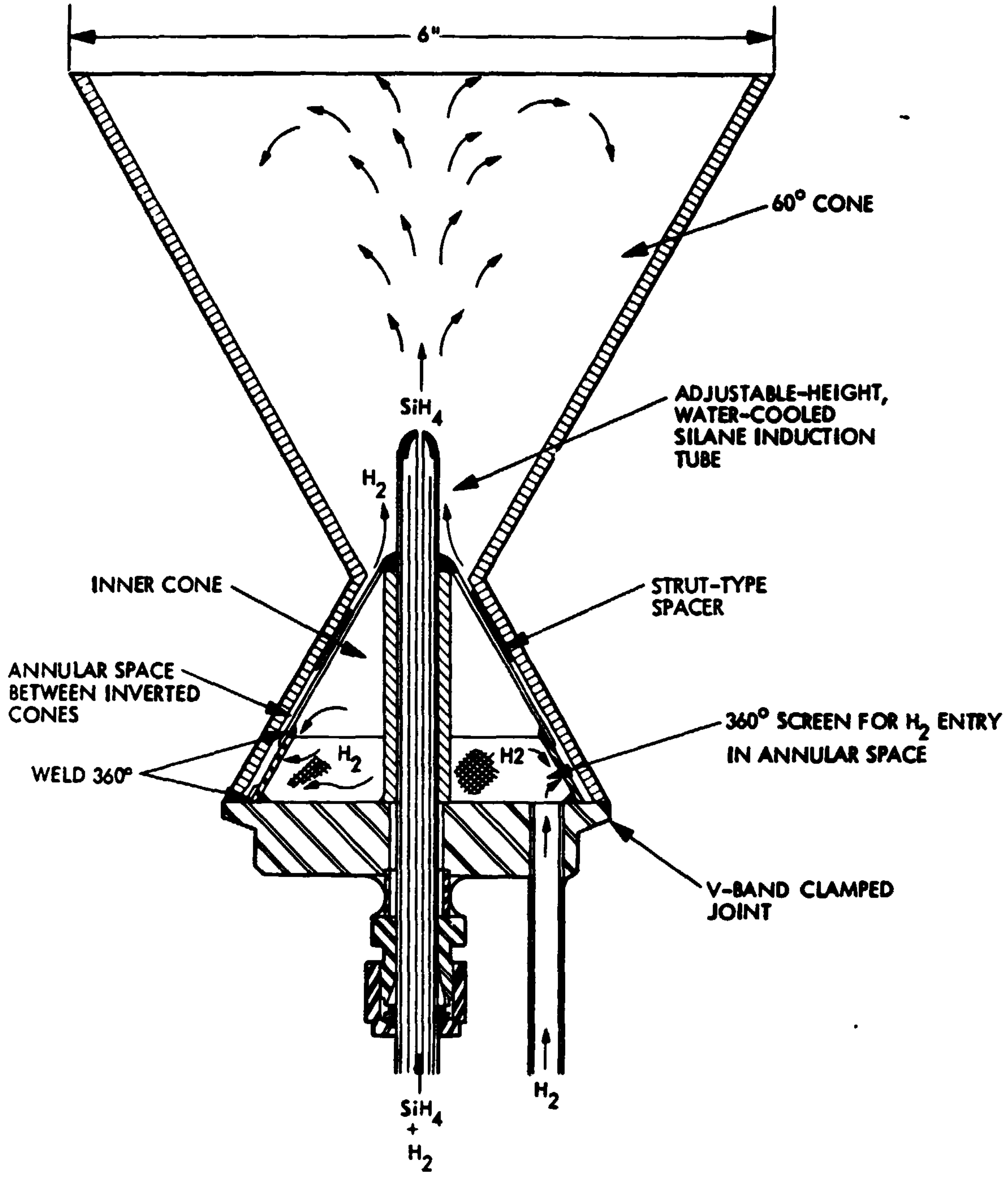
TECHNOLOGY	REPORT DATE
Polycrystalline Si Production R & D	November 11, 1981

APPROACH 1) Fluidized Bed Si Deposition (FBR) 2) Direct Conversion from Silane to Molten Si (SMS) **CONTRACTOR** JPL In-house Si Processing Program	**STATUS** 1) Established feasibility for FBR Si deposition. 2) Identified operating guidelines in 2-in FBR: a) less than 10% fine loss in T≤800°C. b) u/u_{mf} ≥3 for clog-free operation. c) up to 100% high silane conc. is feasible. 3) Selected conditions for deposition kinetics experiments in 2-in FBR. 4) Completed design, fabrication and installation of 6-in FBR system. 5) Conducted safety review for 6-in FBR system. 6) Cold-flow tests for distributor are underway. 7) The tests pointed out conceptual feasibility for the SMS. Detailed report and program are being formulated.
GOALS Conduct Complementary R&D to the Task Program in Process Development Contractual Efforts: 1) Identify operating window in 2-in-dia FBR. 2) Conduct fundamental R&D including studies on Si Deposition kinetics and distributor. 3) Design, construct & operate 6-in-dia FBR system to collect engineering R&D data. 4) Determine SMS feasibility; and develop R&D technologies for SMS as a Silicon production alternate.	

SMS Converter System



Pattern I Distributor



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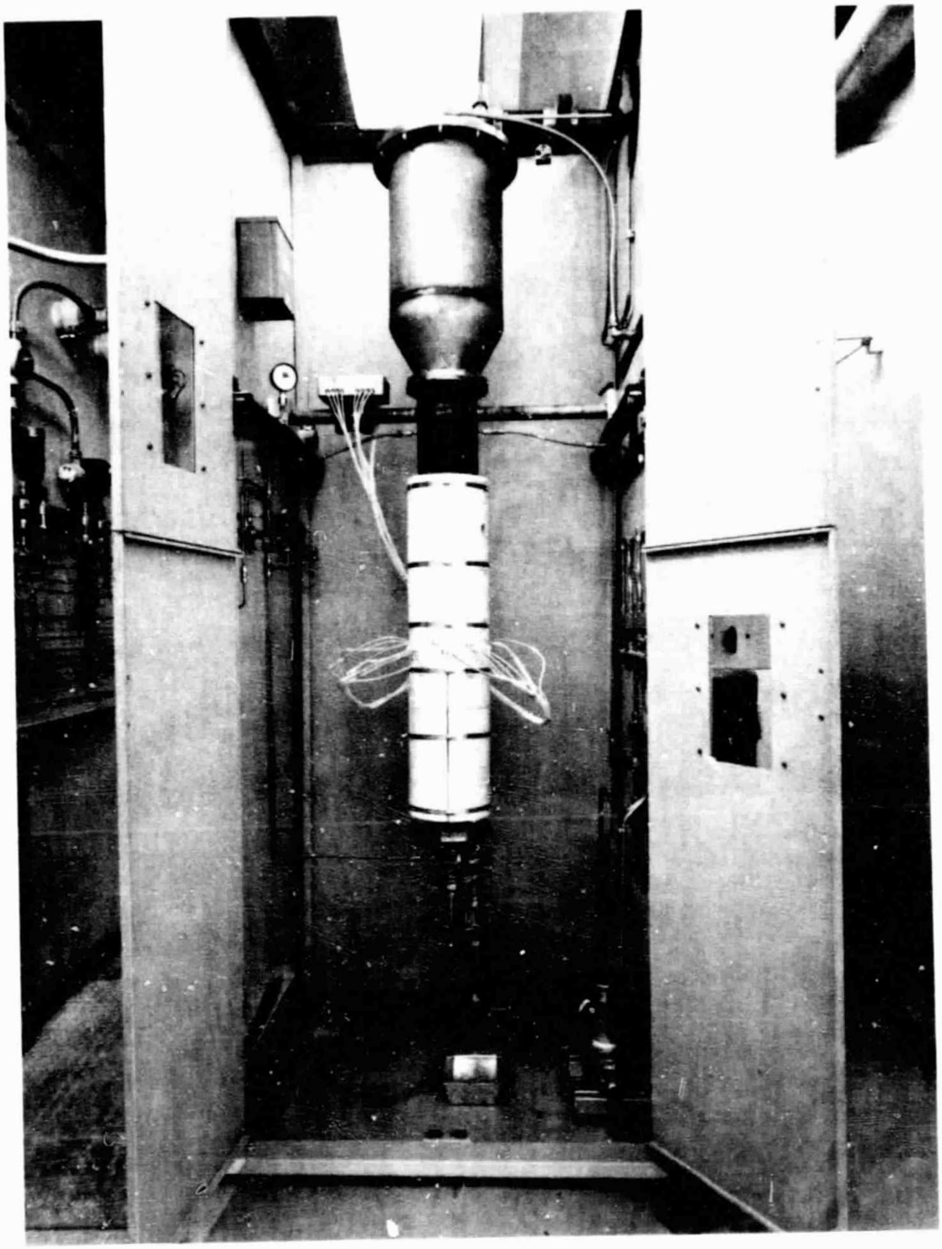
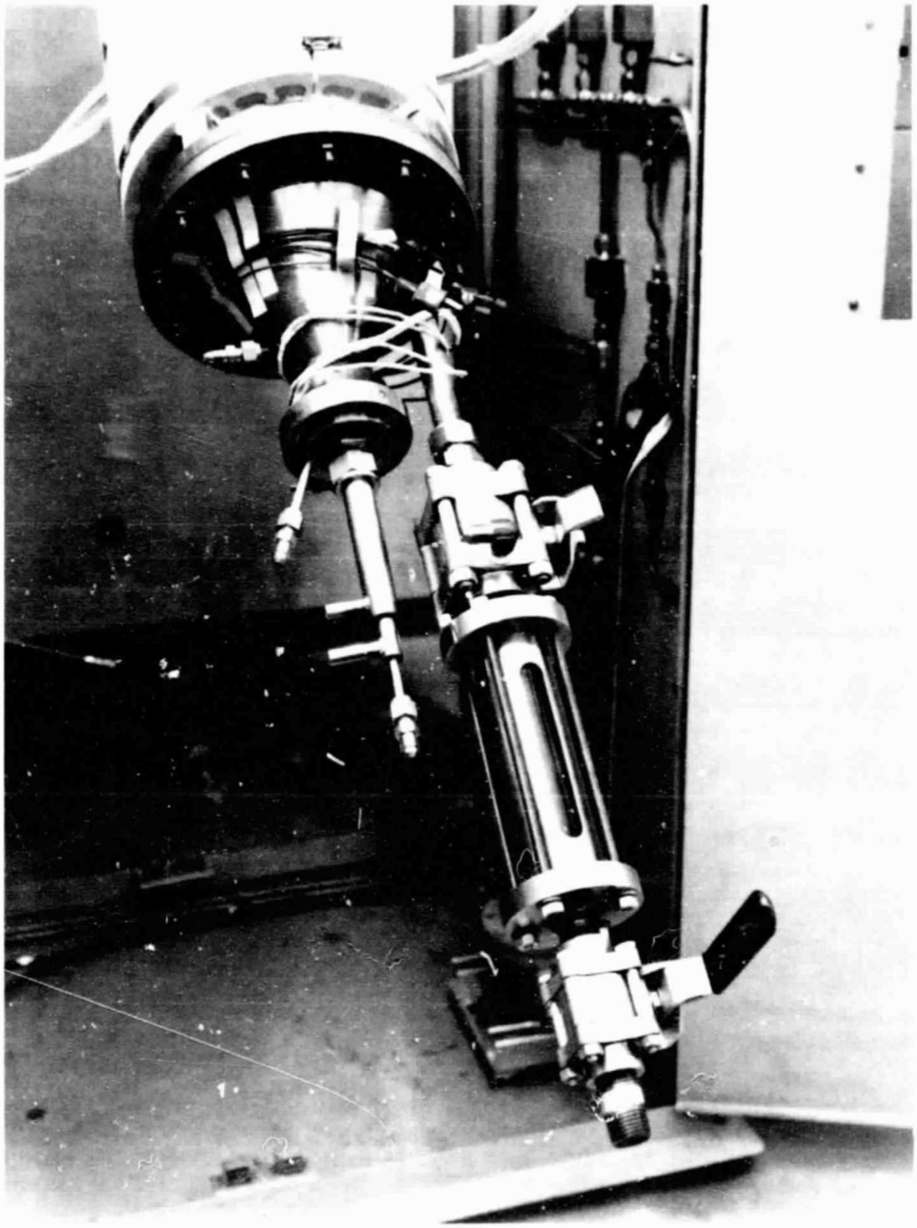
6-in. Fluidized-Bed Reactor



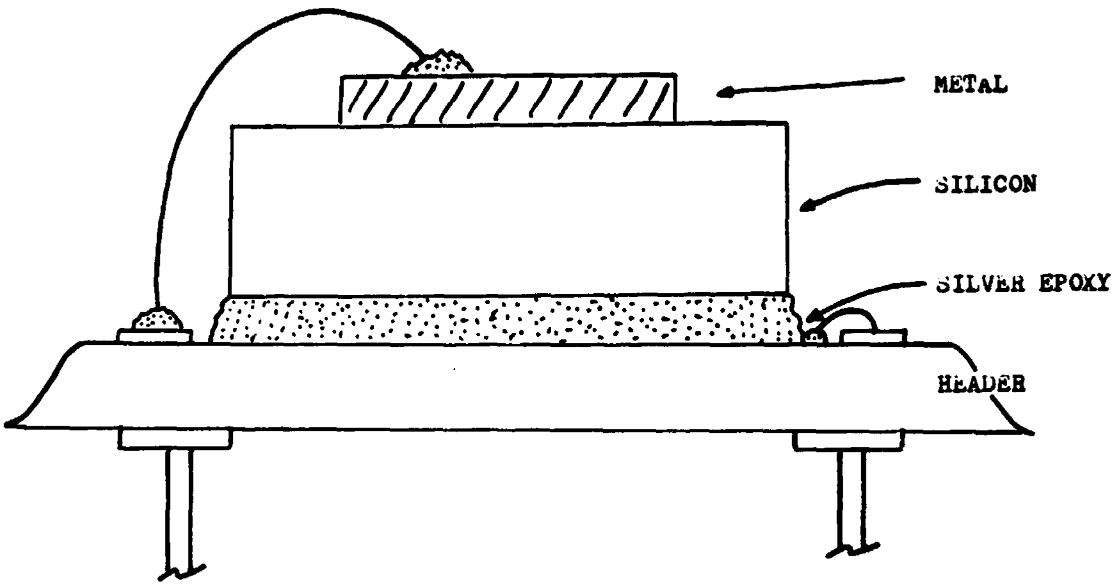
Particle Sampler for 6-in. FBR



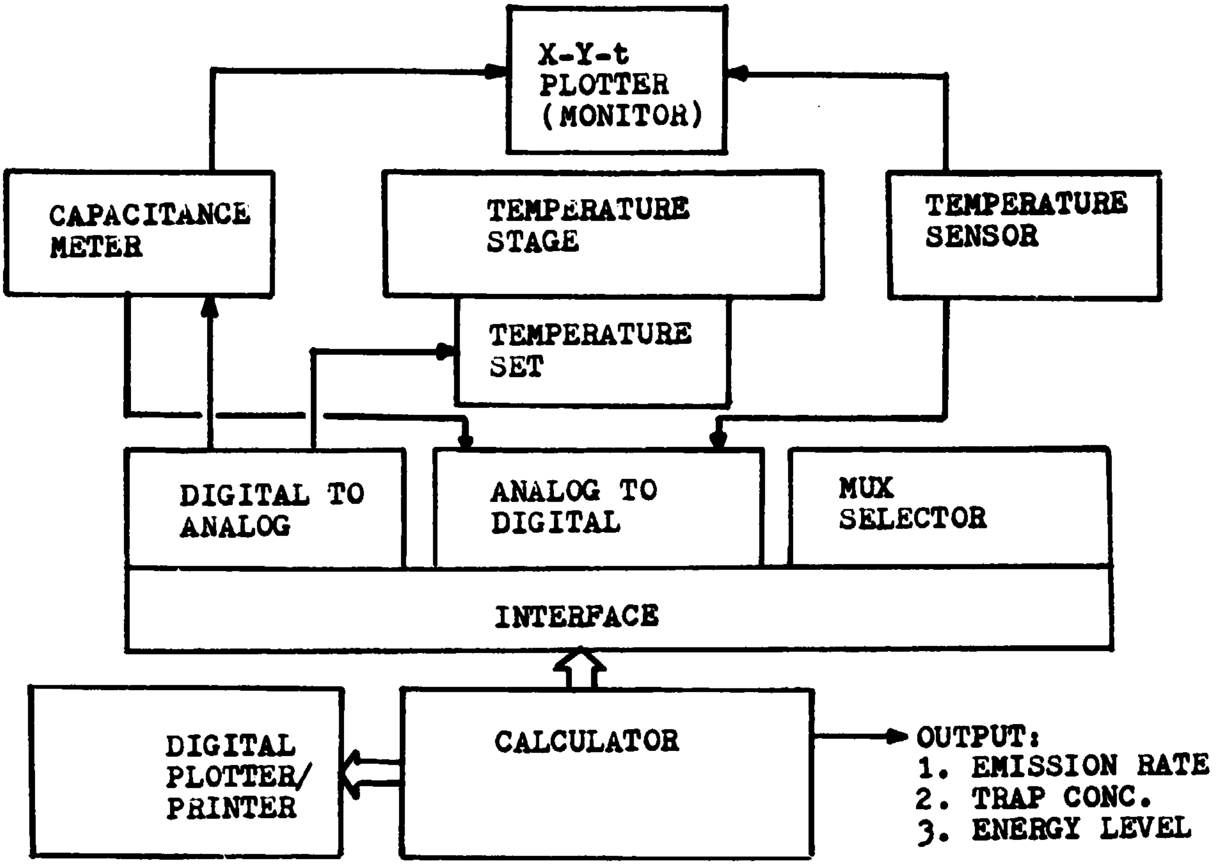
Impurity Analysis by Thermally Stimulated Capacitance (TSCAP) Measurements

IN THE TASK FOR ANALYSIS OF IMPURITIES USING THERMALLY STIMULATED CAPACITANCE MEASUREMENTS, EFFORT WAS SPENT IN IMPROVING THE AUTOMATION OF THE EXPERIMENTS AND MEASURING KNOWN IMPURITIES IN SILICON USING SAMPLES FROM THE WESTINGHOUSE IMPURITIES PROGRAM.

TSCAP Test Device



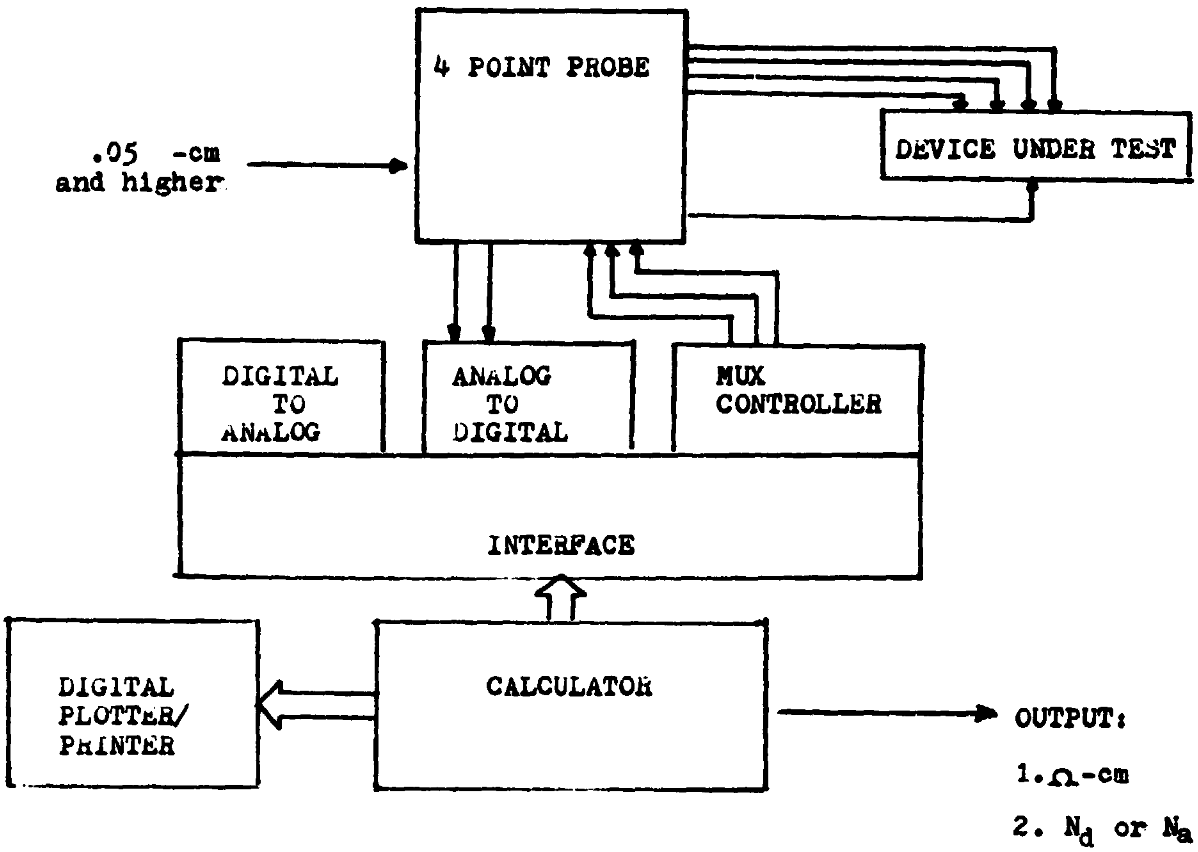
Automated TSCAP



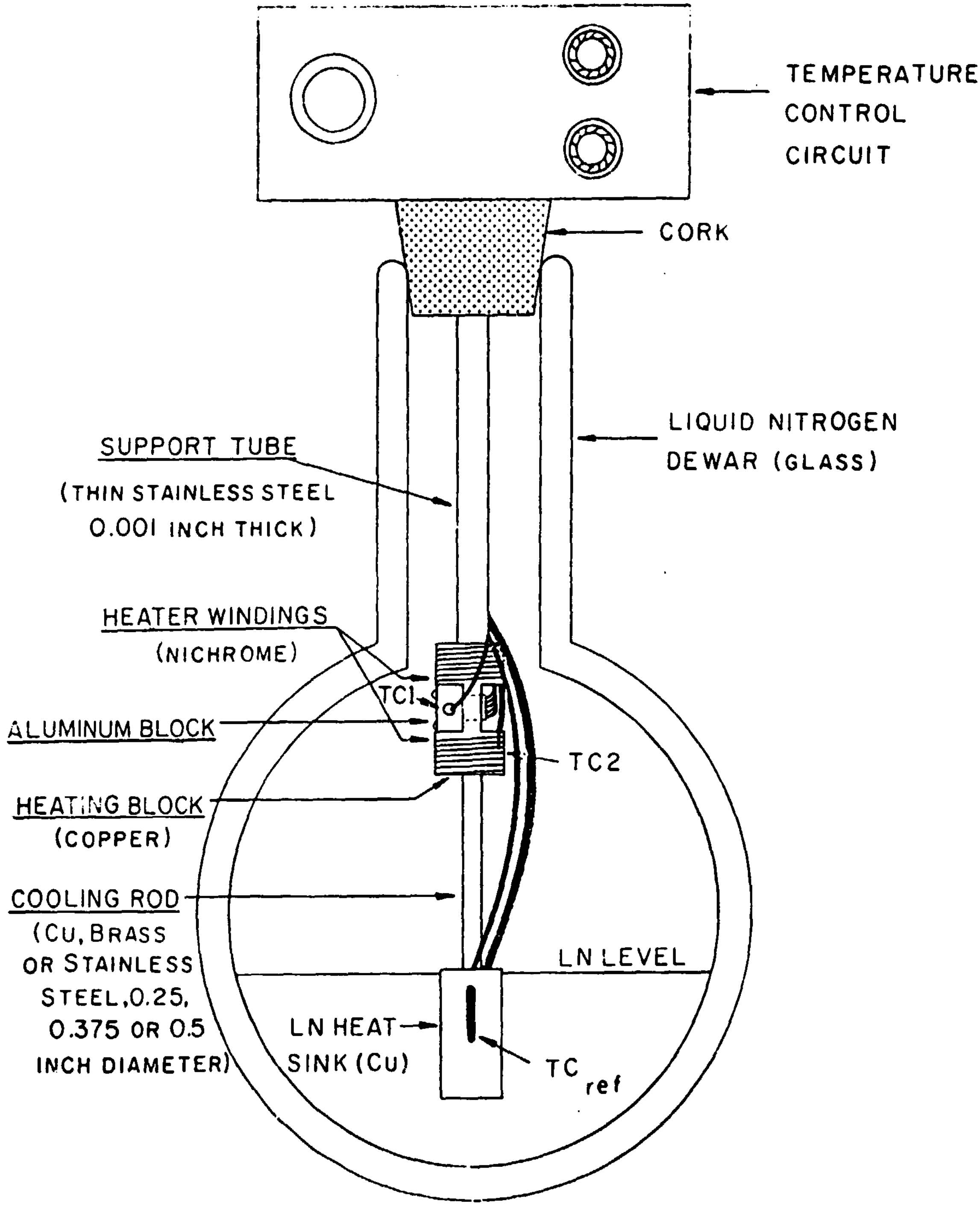
Experimental Procedure

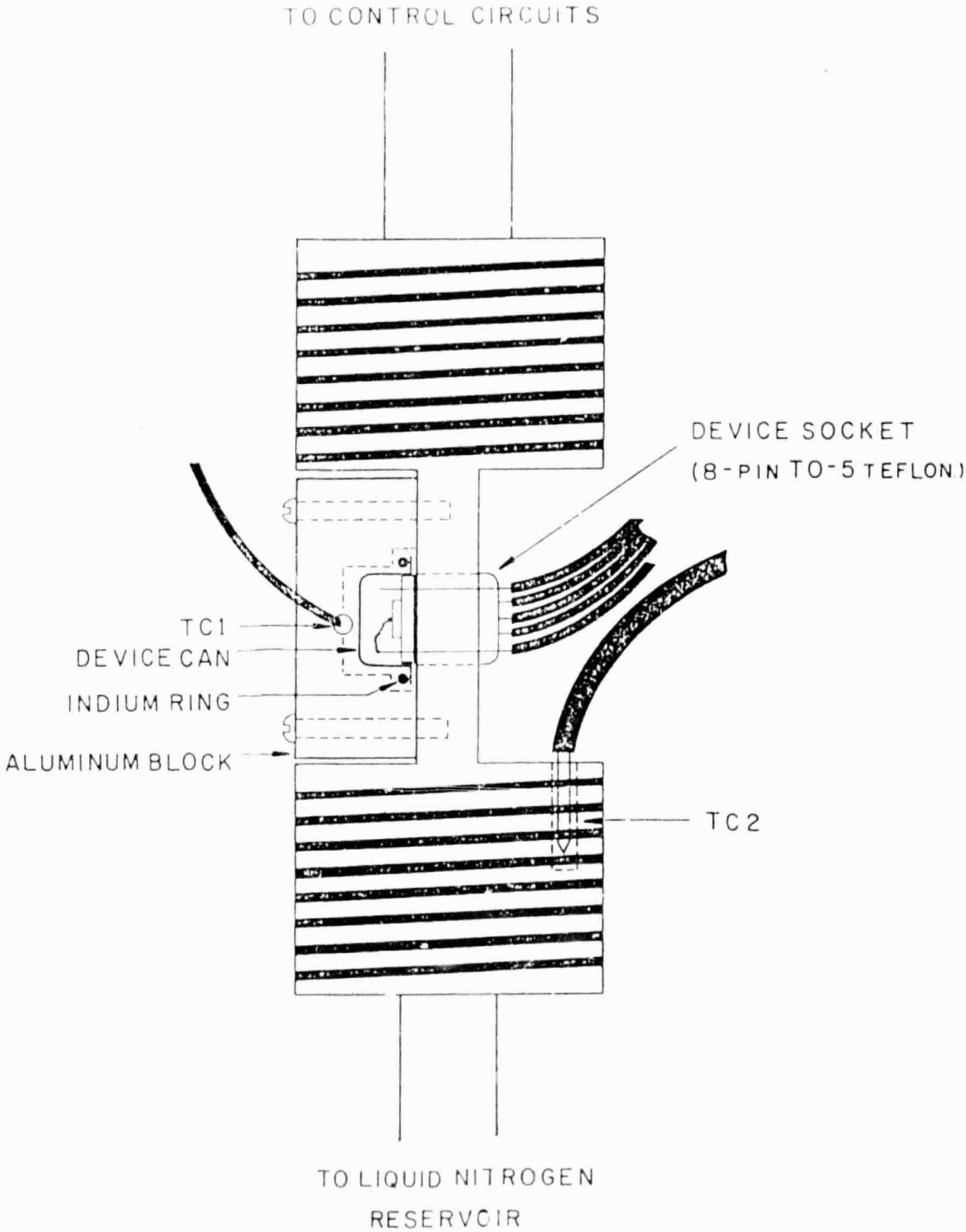
1. MAKE IV CURVE
2. MAKE TSCAP CURVE
3. MAKE CAPACITANCE CURVE
4. CALCULATE EMISSION RATE
5. CALCULATE ΔE
6. CALCULATE CONCENTRATION

Automated Four-Point Probe



Temperature Stage





The sample holder and heating block of the capacitance transient

Plans

1. COMPLETE AUTOMATION HARDWARE

2. TEST PROCESS DEVELOPMENT SI

3. ADD NEW MEASUREMENT TECHNIQUES

Large-Area Silicon Sheet Task

J.K. Liu, Chairman

SHAPED-SHEET TECHNOLOGY

Mobil Tyco Solar Energy Corp. (EFG)

A gas-tight ribbon seal for Machine No. 16 was made. It controls the ambient gas in the cartridge, to achieve repeatable ambient-growth conditions. Cartridges longer than 10 cm for Machine No. 16 have been designed.

Four runs were made using Machine No. 17 to evaluate new linear cooling plates used to provide a linear thermal gradient in the cartridge. Additional runs were made to evaluate flatness, uniformity and higher growth rate. One run was successfully made for 60 minutes at a growth rate of 4.1 cm/min. All available melt was used during this run. To improve flatness, a new linear cooling-plate arrangement was implemented. The buckling pattern was modified and fewer kinks were observed. Three runs were made, using a new, longer cartridge. An extremely flat ribbon, 8 mils thick and 10 cm wide, was grown at 4 cm/min growth rate. The buckle pattern seems to be related to cartridge-exit conditions. Ribbon thickness was uniform across its width. Optimum spacing between the cooling plates and growth slot width is being evaluated. A cooling-plate spacing of 30 mils and cooling-plate height of from 6.25 to 1.25 cm provide the optimum arrangement for ribbon growth.

Several runs were made with Machine No. 18 with no cold shoe. Two-piece dies and special shield were used. The center-to-edge thickness of the ribbons was not uniform; the ribbons produced were thinner at the center. Runs were made without end cold shoes to optimize the thermal profile at the die top. Slight enhancement of diffusion-length data on annealed EFG samples were obtained and are being analyzed.

Construction of Machine No. 21, which is contractor-owned, is proceeding on schedule. This machine will not be included in the FY82 Program because of budget constraints.

Westinghouse Electric Corp. (Web)

Experimental growth runs to identify a thermal geometry suitable for high-speed growth of low-stress ribbons were continued. Design of a wide format to allow the growth of a ribbon wider than 1 inch is under way.

The modeling effort has developed an improved integration procedure that has been used with selected lid geometries. Systematic experiments were run to relate modeling to the effect of top-shield modifications. Lids and heat shields are instrumented. Temperature measurements throughout the system are needed.

The elongated-crucible design is being tested and thermal trimming for it has been developed empirically. Variable time-constant control for the melt-level sensor has been breadboarded and tested, and was installed on the experimental system growth unit (ESGU) during September.

LARGE-AREA SILICON SHEET TASK

The ESGU furnace, now mechanically and electronically complete, was demonstrated at the final design and performance review during the first week of October. Thermal refinements of the long-crucible setup now permit high replenishment rates, and the system is ready for wide-ribbon runs. Lid and shield temperature measurements have been made; the resulting data will be used to develop and verify models for low-stress ribbon growth. A zero-stress experimental configuration, however, is unobtainable. An experimentally obtainable profile, calculated to yield a less-than-critical stress in the growing ribbon, will be manufactured and experimentally tested.

Stress distribution calculations for mathematically defined thermal profiles were made and related to data taken from actual runs. Some simplifying relationships have been established. Lid and shield setup will be made according to theoretically determined dimensions. Test runs are being made to evaluate work coil positions relative to existing setup configurations.

The experimental sheet grow unit (ESGU) is being run on a regular basis for sustained growth procedure testing. The machine has produced good quality ribbon from the very first run. It has been designed to grow 5.5-cm-wide ribbon.

INGOT TECHNOLOGY

Kayex Corp. (Advanced Cz)

After the successful 150-kg growth run reported in June, the machine was shut down for retrofitting of the Kayex-developed microprocessor hardware for process automation. The interfacing with the microprocessor (dubbed by Kayex AGILE, for Automatic Grower Logic) was completed in August.

A satisfactory final design and performance review of the advanced Czochralski experimental sheet-growth unit was held at Kayex Research Center. The review consisted of presentations to JPL by members of the Kayex staff, discussions, and a demonstration growth run.

Two growth runs were made to deal with the recurring problem of ingot corkscrewing, a subtle 1 to 2 mm helical offset in ingot dimension, often observed. This phenomenon was demonstrated to be independent of machine alignment.

Substantial effort was spent running and calibrating the ambient gas analyzer on the growth system.

The choice of materials for the radiation shield/purge cone was studied. Based on prior experience, cost, and delivery, a single molybdenum-sheet cone was chosen.

The possibility of using synthetic rather than fused-quartz crucibles was explored. Crucibles with 12 to 15-in.-dia are not now available (projected prices are too high), but quotations have been requested for synthetic quartz-lined fused quartz crucibles.

Experimental activity was limited to automation of melt-dip temperature trimming, using an Ircon sensor viewing the melt at 90° to avoid thermal-signal noise.

The major emphasis during October was on the microprocessor control development. Dip temperature trimming for 18-kg melts (full 30-cm-dia crucible charge) was achieved. This required hardware modifications of the sensor mounting and sighting systems, angles of sight, dimensions, etc., which are virtually complete.

The ambient gas analysis system has been augmented to analyze water and oxygen content. It has also been retrofitted with an automatic rotary sampling valve and data reduction hardware.

Crystal Systems, Inc. (HEM)

The final 35-kg ingot required under the current contract has been grown. Solidification time for the ingot was 40 hours; total cycle time was 70 hours. The ingot was sectioned into nine bricks for use in the continuing fixed-abrasive slicing technique (FAST) wafering program at CSI.

The CSI contract for the growth of silicon ingots by the heat-exchanger method has been completed. A draft of the final report is being prepared.

Semix Inc. (Semicrystalline Casting)

A revised technology projection for $0.70/W and a continuation program plan for FY82 and beyond continue to be reviewed. Negotiations continue to produce a plan consistent with technology requirements, budget limitations, and Administration philosophy.

Cells manufactured by Applied Solar Energy Corp. (ASEC), using an unsophisticated baseline process, gave efficiencies comparable to other polycrystalline sheet materials. Advanced processing methods are being applied by ASEC and Semix to determine material limits.

The second and third quarterly reports have been released. The second phase of the program has been negotiated to include only critical elements of the $0.70/W technology. Efforts involving casting, wafering, ingot quality evaluation, and performance improvements are included.

The fourth quarterly report has been received, reviewed, and revisions recommended to Semix. The present module price analysis (the basis for the technical goals) is being reviewed critically. Preliminary analysis suggests that the projected price will be fairly close to $0.70/W.

A group of 100 2 x 2-cm cells, processed by Solarex from Semix material, has demonstrated efficiencies of 13.7% to 15% (AM1). The cells were produced by high-technology methods on material provided by Semix. The performance was confirmed by JPL.

A group of cells, processed by Solarex using high-technology methods from material selected by JPL, has been returned. Analysis of performance and results is under way.

A program review was held at Semix October 21 and 22. The effort on conventional multiblade wafering has been completed and a draft summary report has been submitted for review. The proof-of-concept report, designed to establish the potential of polycrystalline silicon for photovoltaics, has been reviewed and returned with recommended changes.

Silicon Technology Corp. (ID Wafering)

A new 12-month R&D contract with STC was signed on July 1. The final report from the previous purchase order was rewritten and is being prepared for delivery to JPL.

Changes in the 32-in.-bladehead machine, including replacing the air bearings with mechanical bearings, were completed, and the machine was operating in the first week of September. Slicing runs on the new 27-in.-bladehead saw began after the installation of the microprocessor system.

Efforts centered on elimination of vibration problems in the prototype RD-140 saw. By installing new bearings and machine supports, the previous cutting speed of 4.5 cm/min was increased to 6.3 cm/min for a 15-cm-dia ingot. The kerf thickness for these runs was 13 mils and the wafer thickness ranged from 15 to 10 mils. The yields for all of these runs were greater than 95%.

Continued efforts to eliminate vibration in the RD-140 saw have effected a reduction in the problem by a factor of 2. Other changes, including modifying the coolant delivery by repositioning the jets, increasing the fluid pressure and changing the coolant mixture, have also improved slicing performance. Cutting rates, which were increased last month to 6.3 cm/min, were further increased to 7.5 cm/min for 15-cm-dia ingots. (The objective is 9 cm/min for 15-cm-dia ingots.)

Crystal Systems, Inc. (FAST)

A series of unsuccessful runs were made in July 1981. Two attempts were made to slice 10-cm-square cross-section ingots but were aborted by alignment problems. A third 10-cm-square cross-section ingot was sliced, resulting in a poor yield of only 19%. An unusual cutting profile was cited by CSI as the reason for the failure.

Two 15-cm-dia ingot-wafering runs were aborted, the first due to excessive wire breakage and the second due to diamond pull-out in the wire.

Two slicing runs were completed under the new FAST contract, which started in August 1981. The first run used a CSI electroplated wire pack that had 30-μm diamonds around the wire. A 10-cm-dia poly-HEM ingot was sliced at 25 wafers/cm with an average cutting rate of 1.6 mils/min and a yield of 73%.

The average wafer thickness was 8.2 mils and the kerf was 7.4 mils. The second run used a wire pack electroplated only on one side by an outside vendor with a 73% yield and a cutting rate of 1.6 mils/min, using a wire pack of 19/cm.

After the second run a problem with the bladehead slides developed. Many of the ball bearings inside the slides had flat sides that interfered with the smooth motion of the bladehead. The balls were replaced and a major misalignment problem occurred. The cause of the alignment problem is still unknown.

Five slicing runs were done, all cutting 10 x 10-cm polycrystalline heat-exchanger method (HEM) ingots at 25 wafers/cm. The cutting rates varied from 1.38 mils/min to 2.87 mils/min, and the yields ranged from a low of 15% to a high of 47%. Emphasis was placed on varying the diamond-plating time to find an optimum nickel thickness, and varying the feed force on the wires to increase the cutting rates. Unfortunately, the recurring problem of blade run-out reappeared, causing a fifth run to be aborted.

The first slicing attempt using an electroformed wire pack was made in October. The pack sliced a 10-cm ingot at 25 wafers/cm with an average cutting rate of 2.5 mils/min and a yield of 57%. Two more runs were done using the same wire pack. The first of the two additional runs had an average cutting rate of 2.8 mils/min and a yield of 95%. The second run with the same pack was aborted after 75% of the ingot was sliced because the cutting rate became unreasonably low. An attempt to dress the pack was made, but this only slowed the cutting rate. (The objective for 10-cm ingot is 4.1 mils/min average and 5 cuts/wire pack.)

Norlin Industries, Inc. (MBS)

Possible joint efforts are being discussed between Norlin and Diamotec Inc., and between Norlin and Scomac, Inc., to evaluate the feasibility of fixed-abrasive multiblade sawing. Although the bladehead speed of the present MBS saws is low, high workpiece-tool pressures are attainable using MBS. With contoured blades or rotating workpieces in the MBS system, substantially improved cutting rates may be achieved.

The alternative cutting oils received in June were evaluated against the standard PC oil. Gardoil and Lubrizol, both of them petroleum-based rather than fat-based fluids, seem to be superior to the PC oil. Lubrizol, especially, has price, clean-up, and surface-tension advantages. Filtration, rather than centrifugation, is being considered for the oil-recycling process because of the high costs of the heavy liquids used in centrifugation.

Five saw-test runs were made during August. Three runs dealt with abrasive slurry volume and delivery. The delivery system was converted from the headbox configuration to a curtain, with improved results. Two runs involved a feed-force measuring device. A newly introduced force gauge on the workpiece die-set provided a continuous feed force readout and, inadvertently, some useful workpiece rocking.

C-2

Runs cutting 2 x 3-in. sections, using the feed-force gauge and wear-contoured blades, yielded average cutting rates of 3 mils/min with a maximum of 5.2 mils/min at the bottom of the cut. These runs were made on the JPL saw that had been precisely aligned by Varian Associates on a previous contract. These are excellent rates and are attributed to the alignment, worn blades, ingot rocking, and the slurry content.

A water-based (50%) vehicle additive from Lubrizol has been tested for over 25 hours in the Varian MBS saw. No blade corrosion or breakage was observed, blade wear rate seems low, cutting rate is normal, and cleanup is easy and inexpensive. The quality of the wafers obtained was as good as or better than that of wafers sliced using oil-based slurries. Some problems encountered using the water-based slurry include water loss by evaporation and slurry thickening and hardening during interruption of wafering for any extended time. Norlin also has a water-based slurry additive from Process Research Corp. for evaluation.

The wafer lift-off mechanism is being redesigned before fabrication. The improved design is simpler and less expensive.

Five cutting experiments were run, including blade loading, blade size, baseline, and the water-based slurry run. Blades 4 mils thick have been determined to be unsuitable for wafering because they lack the necessary rigidity to resist blade wander.

MATERIAL EVALUATION

Applied Solar Energy Corp. (Cell Fabrication)

Fabrication of solar cells from ubiquitous-crystallization-process (UCP) silicon with an extra diffusion glass-gettering step revealed that there is no significant difference in efficiencies of cells with and without a gettering step. Diffusion lengths of baseline cells predictably correlated with the short-circuit current.

Material that was sent to Semix for correlation of its cell fabrication results with those of ASEC did not yield useful data due to Semix processing problems. More material was sent with data and cells to be returned to JPL.

Fabrication runs for high-efficiency solar cells from Semix UCP material provided no useful information because of extreme shorting of most cells, probably during the back-surface field (BSF) step. The highest efficiency obtained was 13.2%, but this is not representative of the quality of the UCP material. Light-spot scanning of cells, which have been studied by EBIC, has begun. Cells are being fabricated on low-angle silicon sheet (LASS) ribbon, but have not been measured.

Cells fabricated from Semix UCP silicon, using a shallow junction and multilayer antireflective coating (MLAR), yielded cells averaging 12.0% AM1 (controls were 13.8% AM1). This compares well with the 13.1% AM1 average of cells fabricated from this material by Solarex (controls were 15.2% AM1), which have BSF shallow junction and multilayer AR.

Cells fabricated on UCP silicon by ASEC displayed severe shunting with the BSF processing, but it is not known if this was caused by the material processing.

An ingot of Semix UCP silicon (10 x 10 x 17 cm) was wafered and cells were fabricated from four sections of the ingot: top, two middle sections, and bottom. Results of the baseline processing indicate that the bottom of the ingot yields the best cells, with an average efficiency of 10.1% AM1 (Cz controls averaged 12.3% AM1). Cells from the top of the ingot suffered from low V_{oc} and CFF, while cells from the middle sections had low J_{sc}. A diffusion glass gettering step before baseline fabrication improved the J_{sc} of the cells from the center of the ingot, but did not affect the performance of cells from top and bottom. High-efficiency cells of UCP material with an evaporated aluminum BSF averaged 13.2% AM1 efficiency (controls were 15.1%).

Cells fabricated on LASS ribbon yielded an average efficiency of 10.7% AM1 (controls were 13.4%), using shallow junction and MLAR. The material proved to be fragile; most of the cells were broken during processing.

Cornell University (Characterization)

Cornell continued its studies of high-order twins and low-angle boundaries using high-resolution transmission electron microscopy (TEM).

A program was initiated to study hydrogen-plasma passivation of grain boundaries in EFG materials using conventional hydrogen-plasma generators and Cornell's high-power plasma diode. The latter is a plasma machine that can provide a high-current beam of hydrogen ions on the order of several thousand amperes. Under the high-current bombardment, the top level of the material will be melted and regrown in a hydrogen-rich environment.

Experiments on processed edge-defined film-fed growth (EFG) materials using transmission electron microscopy (TEM) and electron-beam-induced current (EBIC) have been performed. Preliminary results indicate a possibility of enhanced diffusion of phosphorus along some grain boundaries.

A report on the study of structured defects in HEM, using a combined technique of EBIC and optical-end etching has been finished.

A preliminary study of phosphorus-diffusion-induced effects on structured defects in EFG silicon is completed. The results show that:

(1) A variation in the depth of the p-n junction was observed, which can be attributed to some enhanced diffusion along planar defects (mainly grain boundaries).

(2) Spiral dislocations were found in the processed EFG, but not in as-grown samples. These spiral dislocations are formed by interaction between dislocations originally in the material and point defects created during diffusion. The properties of the spiral dislocations reflect some of the types of point defects generated during the diffusion (e.g., vacancy or interstitial). The observation provides a new way to study process-induced effects on silicon material.

Micro-diffraction experiments are being performed on process-induced precipitates at dislocation modes using scanning TEM (EFG material).

More TEM and EBIC experiments were performed on HEM samples and found alternating {111}/{111} -- {111}/{115} twins in the samples cut from the corners of the ingot. The observation is similar to those obtained previously in EFG samples.

It was discovered that the electrical activity of dislocation networks at twin boundaries in web samples is mainly associated with the jogs in dislocation lines.

Materials Research, Inc. (Si Sheet Microstructure)

The final report on this activity has been received.

University of Illinois (Wafering Fundamentals)

A detailed program plan has been received from UI. Experiments have begun to establish normal-force-to-the-surface and speed-of-rotation baselines for abrasion of p-type single-crystal silicon at room temperature in deionized water, acetone, and ethanol. Future experiments will involve varying the speed of rotation and abrading the silicon in the presence of mixtures of n-alcohols with water.

Experiments have established baseline conditions for abrasion of p-type single-crystal silicon at room temperature in deionized water, acetone and ethanol. During these experiments, the frequency spectra experienced by the abrasion stylus are quite distinct, depending on the mechanism of silicon wear (ductile ploughing, brittle chipping, etc.). The statement of work was modified to include a deeper study of this phenomenon.

A fixture has been obtained to angle-lap samples and measure the depth of damage from abrasion. Polishing and etching of abraded silicon slices has begun.

A spectrum analyzer is being used to determine the differences in the frequency spectra of the output of the diamond-stylus abrading (100) p-type silicon. The frequency output changes significantly after hundreds of abrasions.

A mechanical spectrometer is being modified so that it will be possible to measure the energy used in the abrasion process. This setup will also allow easy measurement of abrasion phenomena as a function of temperature.

An experimental set-up for abrading silicon has been completed and numerous runs have proven its reliability and repeatability. Modification of the mechanical spectrometer and purchase of a new spectrum analyzer will complete the experimental facilities required for this study.

LARGE-AREA SILICON SHEET TASK

Work for the next few months will concentrate on depth and character of damage to the silicon under various experimental conditions. The long-term objective of the contract is to develop a model for the abrasion of silicon by diamond.

IN-HOUSE ACTIVITIES

Crystal Growth

Seven (100) silicon single crystals and one 211/211 10^{o} bicrystal were grown. All of the (100) ingots were 5- to 10-cm squares.

Czochralski-crystal growth efforts concentrated on the growth of shaped-cross-section ingots. Runs were made to investigate the configuration of the cooling-gas delivery system and the above-the-melt heat shields. This empirical work has led to a spiral gas manifold and an inverted-hat shield design, that together effectively produced crystals with shaped cross-sections and with reduced wall freezing, previously a problem.

Material Characterization

Deep-level transient spectroscopy (DLTS) experiments on silicon bicrystal samples continued to obtain more information concerning electronic states associated with grain boundaries and their effects on carrier trapping and recombination.

Several experiments on carrier trapping and releasing effects on grain boundaries in silicon were performed. The processes associated with the effects are complex, depending not only on the voltage and the time of the voltage applied, but also on the history of the sample thermal treatment and light exposure.

The material from square cross-section ingots is characterized by measuring resistivity, etch-pit density and current-voltage (I-V) curves. Resistivity measured by a four-point probe method indicates that the square wafers have uniform resistivity across their cross-sections. The etch-pit density measurement after Secco etching is less than 10^4 cm^2, suggesting the material is nearly dislocation-free. Solar cells on square wafers have efficiencies as good as those of control cells. Dark forward I-V data indicates that there is some partial shunting effect in the junction region of these cells.

When a grooving-and-staining technique and SEM method were used to do EBIC studies of wafer cross sections, enhanced phosphorus diffusion has been observed along grain boundaries in Wacker silicon sheets. The enhanced diffusion was only observed along regular grain boundaries, but not along twin boundaries. The depth of enhanced diffusion varies considerably from boundary to boundary. The largest observed depth in Wacker samples, diffused at $850^{o}C$ for 30 min, was about 0.6 m.

EBIC and light-spot scanning on corresponding Semix wafers showed little correlation. EBIC of the actual solar cell confirmed structural continuity between the solar cell and the EBIC sample (two slices away during growth). Work continues to try to resolve the differences in response of the EBIC sample and the solar cell.

Dark- and light-current-voltage measurements were made on cells made from EFG ribbons grown with and without CO_2-ambient atmospheres. Spectral response measurements on cells made from HEM materials are made to evaluate their junction behavior. Oxygen and carbon concentrations in the square cross-section material grown by Czochralski growth technique were measured using infrared transmission spectroscopy.

The photoconductivity of grain boundaries in p-type silicon was studied. The result demonstrates the applicability of the photoconductivity technique for the measurement of minority carrier recombination velocity at the grain boundary. The experimental data seem to support the hypothesis that the recombination velocity increases with the density of intergrain states and the intensity of light.

Wafering

First attempts to run the instrumented Varian MBS wafering machine resulted in a gear-box failure. A new gear was ordered. The instrumented Varian multiblade wafering machine includes all-electronic controls and digital force readout (in pounds).

Several experiments were performed during one water-based-slurry multiblade saw (MBS) wafering demonstration run, using the recently modified electronic-feed wafer-cutting machine. The run was terminated during the third day of experiments when several wafers broke loose. It is believed that separation of the slurry caused the cutting difficulty experienced on the third day.

Because of difficulties in maintaining SiC abrasive suspension in water-soluble oil solutions, efforts have been concentrated on identifying appropriate suspension agents. The following materials are being procured or have recently been procured for multiblade slurry characterization (suspension tests, initially): agar-agar, bentonite, methyl cellulose, propylene laurate, and Suspendex. Agar-agar is a dried bleached gelatinous extract of seaweed. Bentonite is a fine powdered clay. The grade purchased was Volclay HPM-20; it sold for $0.08/lb. Initial concentrations were high (8% Suspendex, 5% soluble oil and 2% bentonite by weight in 2 gal of water plus 2 lb SiC) and will be optimized. Suspendex is a proprietary product originally designed to keep alumina polishing powder suspended in water. Methyl cellulose and propylene laurate are noted for their suspension-agent characteristics as listed in chemical handbooks.

During the month of October considerable testing was made on a Varian MBS saw with a batch of water-based slurry (containing Bentonite, Suspendex, water-soluble oil and 2 lb of No. 600 grit and water). Four separate cuts of 12 wafers each were made in polycrystalline silicon block. These wafers were all of good to excellent surface quality (visual inspection) indicating that water-based slurry remains a feasible approach to lowering silicon wafering costs without sacrificing quality.

Some of the problems encountered were: (1) need to add water, perhaps 200 ml per day, to the slurry; (2) the need to scrape away dried-up slurry from the workpiece before restarting the cut, and (3) the need to allow time for slurry to stabilize after restarting the cut, expecially after several days of standing idle. All of these conditions indicate that a continuous cutting operation is better than an intermittent one.

High-carbon blades, cut in length to fit the Varian saw at JPL, are being prepared for diamond plating on one edge of the blades. Two different diamond plating designs will be used. All blade cutting edges will be straight. Investigation of contour blade cutting may be initiated, depending on results of these initial tests.

Fracture of Silicon

An infrared polariscope system was set up to measure residual stress of unconventional Si sheet and relate the amount of residual stress to the fracture strength of these materials.

Eight-mil-nominal-diameter Laser Technology, Inc., Super Wire, a candidate for the FAST saw, was studied. Evaluation consisted of tensile-strength testing and scanning electron microscopy examination. Super Wire consists of a high-tensile core material and an electrolyte copper sheath for holding 45- m diamond. Three tensile pull tests were performed on as-received wire. There was very little scatter in the load value at failure. This is one indication of uniform-quality material. The average failure load was 8.34 lb. At the nominal 8-mil diameter, this corresponds to a tensile strength of about 170 x 10^3 lb/in.^{2}. However, the core diameter measures out at about 5 mils. The tensile strength of the core material is then about 427 x 10^3 lb/in.^{2}.

Two sets of Semix square polycrystalline-silicon wafers were tested by the four-point twisting method. The 50% fracture probability of Semix's polywafer is about 12 x 10^3 lb/in.^{2}; of Motorola's 3-in.-dia Cz wafers, about 15 x 10^3 lb/in.^{2}, and of ASEC's 4-in.-dia Cz wafers, about 10^3 lb/in.^{2}. Preliminary results indicate that Semix polycrystalline wafers have lower strength than Cz single-crystalline wafers.

The design of a double-torsion test jig for measuring crack growth in silicon has been completed. The jig was designed to facilitate testing wafer samples of sizes 50 x 100 mm and 5 x 75 mm with conventional thickness (i.e., 17 mils). Wafer samples will be grooved longitudinally to guard the crack path. The double-torsion test jig will be used to determine crack growth rate vs stress intensity factor of several types of silicon sheet materials, including Cz in several crystalline orientations, Semix, HEM, web and EFG materials.

Miscellaneous

Reports titled "Investigation of Saw Damage vs Plunge Speed for Silicon Wafers Using an ID Saw" and "Sheet and Module Price Sensitivities to Silicon Price" have been completed and distributed internally.

ID WAFERING

SILICON TECHNOLOGY CORP.

Goals

(1) GOALS FOR 15 CM (6-INCH) DIAMETER INGOTS

SLICING PARAMETER	PLUNGE CUT SLICING
-# WAFERS/CM	18
-SLICING YIELD	95 %
-SLICING RATE	2.5 INCH/MINUTE
-MINIMUM SLICE THICKNESS	12 MILS
-MAXIMUM KERF	10 MILS
-# SLICES/BLADE	4,000
-#WAFERS/DAY	590

(2) GOALS FOR 10 CM X 10 CM INGOTS

SLICING PARAMETER	PLUNGE CUT SLICING
- # WAFERS/CM	25
- SLICING YIELD	95%
- SLICING RATE	1 WAFER/MINUTE
- MINIMUM SLICE THICKNESS	8 MILS
- MAXIMUM KERF	8 MILS

Work to Date

MACHINE DEVELOPMENT

-NEW FEED BEARING DESIGN

-STRUCTURAL ANALYSIS AND CHANGE

-REDUCTION OF VIBRATION LEVELS
(0.48 TO 0.25 MM/S TYPICAL)

-DOUBLED FEED RATE (UP TO 3 INCHES/MINUTE)

-MICROPROCESSOR CONTROLS

COOLANTS

-IMPROVEMENTS IN WETTING AND SURFACANT PROPERTIES

BLADES

-ACQUISION OF SPECIAL CORE MATERIAL

Recent Achievements

(1) ACHIEVEMENTS FOR 6 INCH DIAMETER INGOT

- 15 WAFERS/CM
- 95% SLICING YIELD
- 3 IN/MIN. SLICING RATE
- 14 MIL MINIMUM SLICE THICKNESS
- 13 MIL MAXIMUM KERF
- 124 SECOND CYCLE TIME = 580 WAFERS/20 HOUR DAY
- ADD ON COST = $16.56/M^2

(2) ACHIEVEMENTS FOR 10 CM x 10 CM

- 25 WAFERS/CM
- 95% SLICING YIELD
- 1.25 INCHES/MINUTE SLICING RATE
- 5.5 MIL SLICE THICKNESS
- 10 MIL KERF
- 200 SECOND CYCLE TIME = 360 WAFERS/20 HOUR DAY
- ADD ON COST = $51.72/M^2

15-cm Round Ingot

ADD ON COST BASED ON THE IPEG 2 EQUATION
USING DEMONSTRATED COSTS AND TECHNOLOGY FOR 6" ROUND CRYSTAL

E = EQUIPMENT COST = $50,000.

FT^2 = EQUIPMENT AREA IN SQUARE FEET = 84 FT^2

L = DIRECT LABOR COST/MACHINES PER OPERATOR = 5875

U = UTILITY COST PLUS SUPPLIES = $1,676./YEAR

S = SLICING SPEED (CM/MIN.) = 7.62 CM/MIN.

R = RETURN SPEED OF BLADE (CM/MIN.) = 100 CM/MIN.

D = DIAMETER OF ROUND INGOT (CM) = 15 CM

T = WAFER THICKNESS (MM) = 0.36 MM

K = KERF (MM) = 0.33 MM

BLADE LIFE = NUMBER OF SLICES/BLADE = 4000

20 HOURS/DAY

360 DAYS/YEAR

BLADE COST = $50.

YIELD = 95%

ADD ON COST $16.56/$M^2$

Plans

MACHINE DEVELOPMENT

AUTOMATED MONITORING
PROGRAM FEED
AUTOMATED RECOVERY

BLADE DEVELOPMENT

4 MIL CORE 32 INCH AND 27 INCH
(10 MIL KERF)

NEW MATERIAL

VARIATIONS IN I.D. O.D. RATIOS

10 x 10 cm Ingot

ADD ON COST BASED ON THE INPEG 2 EQUATION
FOR 10 CM X 10 CM INGOT

E = \$50,000.

FT^2 = 84 FT^2

L = (12,500/YR. X 4.7 SHIFTS/YR.)/(10 SAWS PER OPERATOR) = 5875

U = \$1,676.

S = 3.18 CM/MINUTE

V = 61 CM/MINUTE

L x W = 100 CM^2

L 1 = 11.6 CM

T = 0.14 MM

K = 0.25 MM

BLADE LIFE = 4000 WAFERS/DAY

20 HOURS/DAY

360 DAYS/YEAR

95% YIELD

ADD ON COST = \$51.72/M^2

Wafering Tests

DEPTH OF DAMAGE STUDIES
MEASURE NORMAL AND TANGENTIAL FORCES

EFFECT OF PARAMETERS ON WAFERS:
NORMAL FORCE
TANGENTIAL FORCE
VIBRATION
THICKNESS
CUTTING RATE
COOLANT
BLADE TYPE

MULTIWIRE SLICING: FAST

CRYSTAL SYSTEMS INC.

F. Schmid and C.P. Khattak

Blade Development

1. PLATING TIME AND NICKEL THICKNESS CORRELATION
2. EFFECT OF DRESSING
3. ELECTROFORMED WIRES
4. TEST BLADEPACK SUPPLIED BY VENDOR
5. 22 MICRON SIZE DIAMOND
6. DIAMOND CONCENTRATION

Machine Development

1. FLYWHEEL FOR COUNTERBALANCE
2. NEW WIRES AND BALLS IN SLIDES
3. NEW GEARBOX
4. NEW BEARING, CASE HARDENED CRANK PIN AND DRIVE BELT
5. SHOCK ABSORBER
6. DOWNFEED OF WORKPIECE

Silicon Slicing Summary

Run# (SX)	Purpose	Ingot Size (cm)	Slices cm	Slices #	Wire Type	Slicing/Blade Force (gm)	Slicing/Blade Rate (mm/min)	Yield %	Average kerf mm	Average slice mm	Remarks
501	Effect of increased wire tension and rocking angle	10 ∅	25	224	0.125 mm W core 30μm diamonds electroplated	24.7	0.04	73	0.186	0.204	Wires pulled to 250,000 psi. Rocking angle ±20°.
502	To test vendor supplied plated wirepack	10 ∅	19	167	0.125 mm W core 45μm natural diamond on cutting surface only	29.5	0.041	72.9	0.27	0.26	Low diamond concentration resulted in slow cutting rate
503	To test effect of low feed forces	10 ∅	25	223	0.125 mm W core 30μm natural diamond on cutting surface only	22.2	0.035	63.1	0.25	0.14	Lowered feed force did not increase yield
504	To test cutting effectiveness of 22 μm natural diamond	10 ∅	25	221	0.125 mm W core electroplated with 22 μm diamond	26.7	0.043	15.4			
505	Effect of high feed force on cutting rates and yield	10 ∅	25	222	0.125 mm W core electroplated with 30 μm diamonds	32.0	0.073	33.8			Considerable wire wander observed
506	Study effect of varying nickel buildup	10 ∅	25	222	Same as 505	32.0	0.061	47.3			
507	Same as 506	10 ∅	25	222	Same as 505	32.0	0.069	aborted			Wires slipped in clamp
508	Test electroformed wire	10 ∅	25	222	Same as 505	26.8	0.063	57.2			
509	Slice 25/cm from 10 cm ∅ ingot	10 ∅	25	221	Same as 505	26.6	0.071	94.6	0.19	0.21	
510	Life test	10 ∅	25	220	Same as 505	26.7	0.039	*			*89% at time aborted. Dressing sticks removed diamonds from wire
511	Test downfeed system	10 ∅	25	222	Same as 505	26.6	0.074	70.0	0.14	0.25	Wafers broke loose at end of run and were lost

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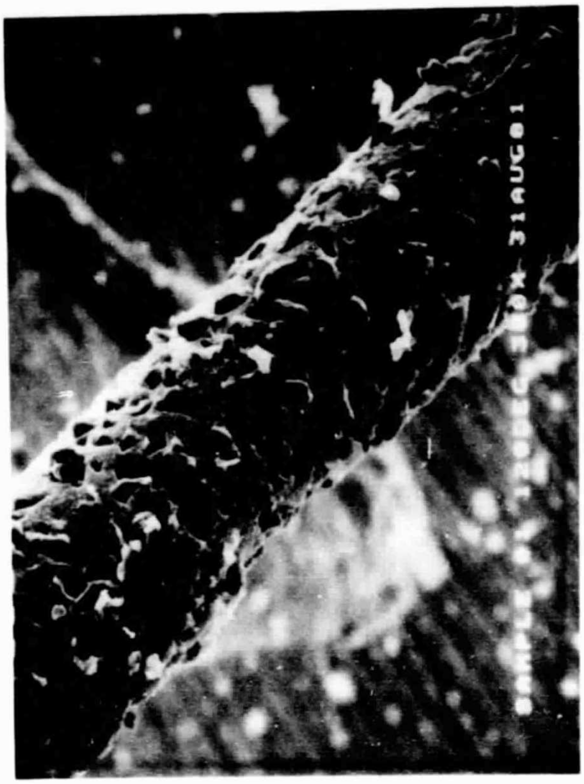
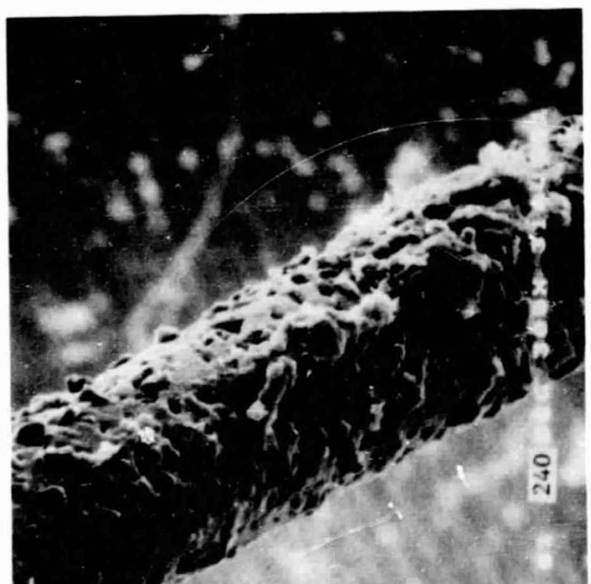


THREE VIEWS OF WIRE PRIOR TO USE IN RUN
456-SX IN WHICH 99% YIELD WAS PRODUCED
AT 25 WAFERS/CM



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EXAMINATION OF A WIRE AFTER
USE IN RUN 456-SX

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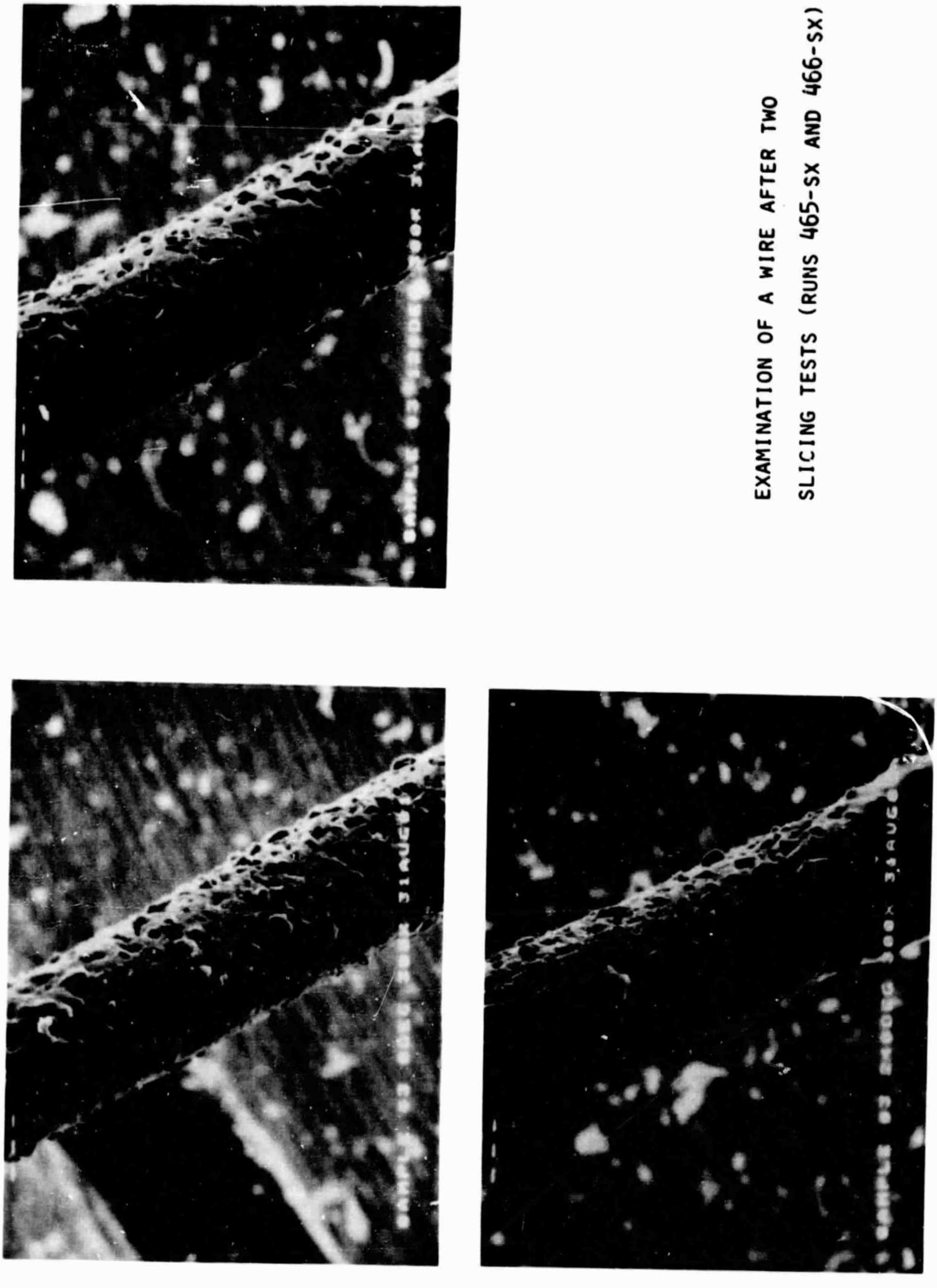

EXAMINATION OF A WIRE AFTER TWO
SLICING TESTS (RUNS 465-SX AND 466-SX)

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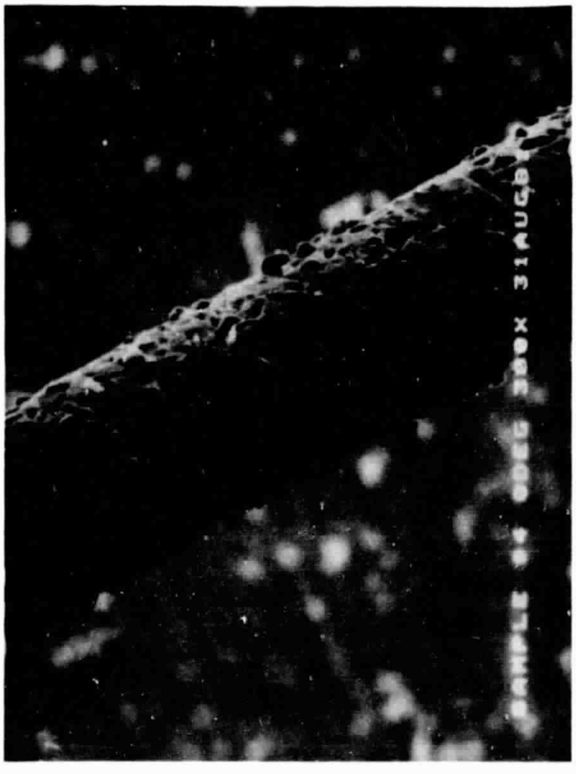
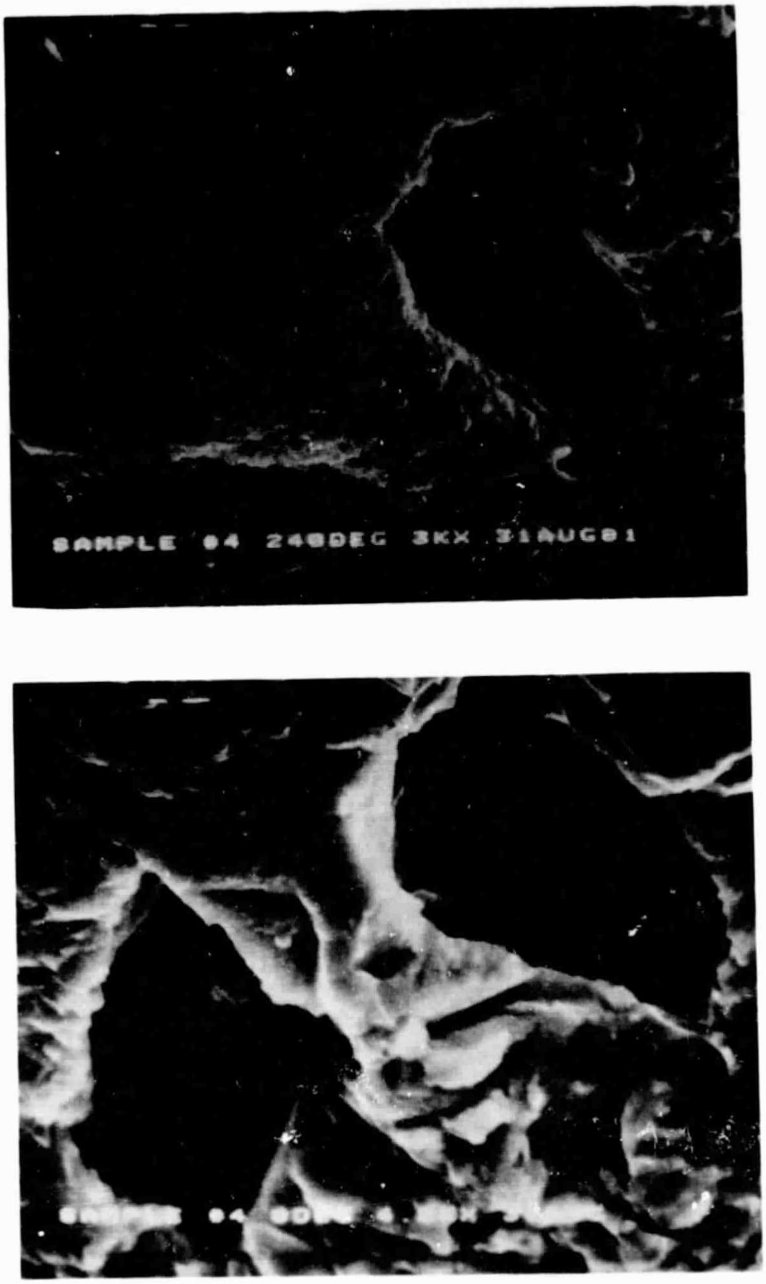
EXAMINATION OF A WIRE AFTER USE IN THREE SLICING TESTS (RUNS 465-SX. 466-SX AND 467-SX)





HIGHER MAGNIFICATION OF DIAMOND SITES

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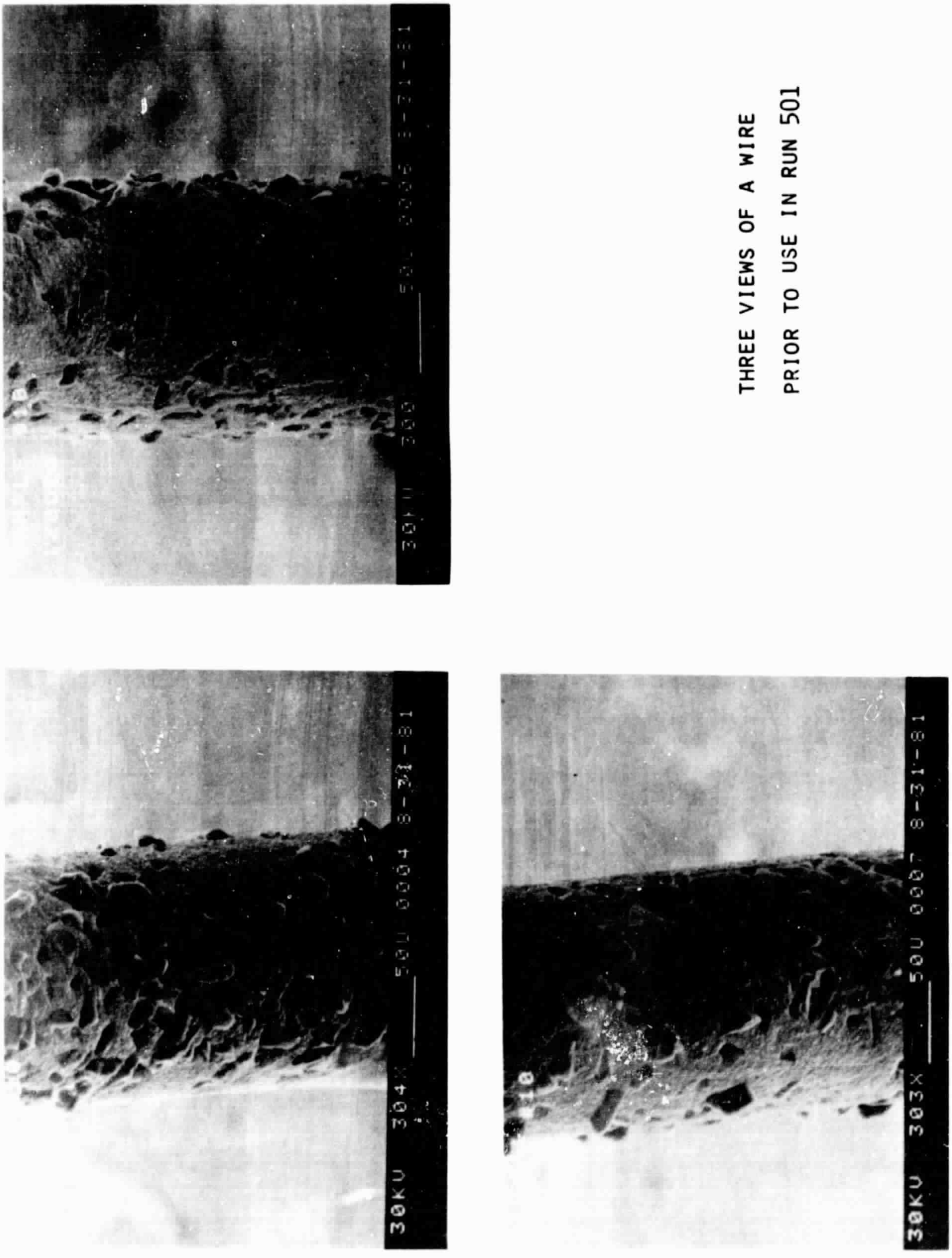
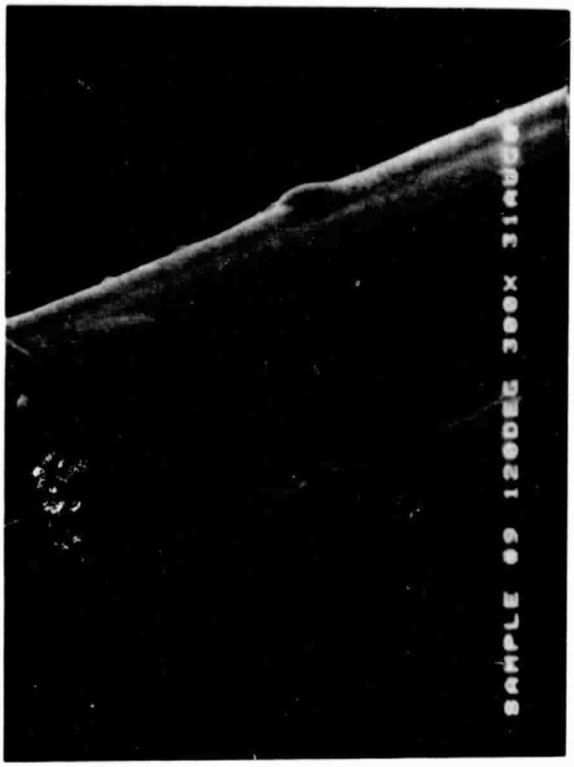
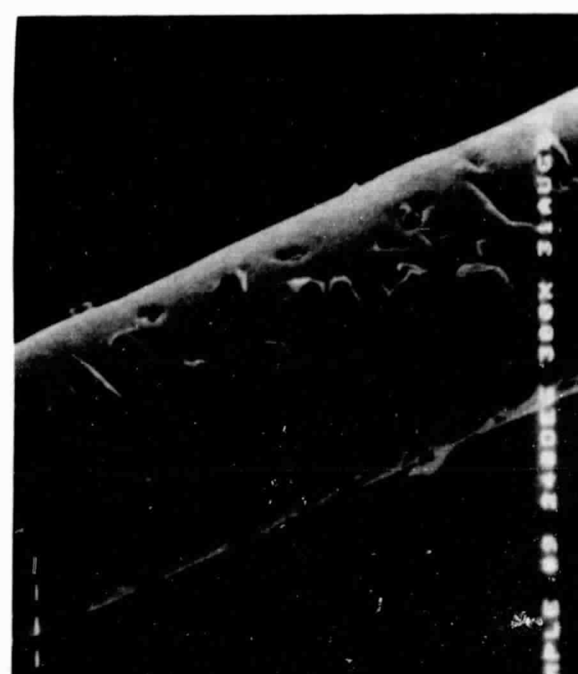


THREE VIEWS OF A WIRE
PRIOR TO USE IN RUN 501



THREE VIEWS OF UNUSED WIRE
SHOWING HEAVY NICKEL BUILD-UP
AND LOW DIAMOND CONCENTRATION



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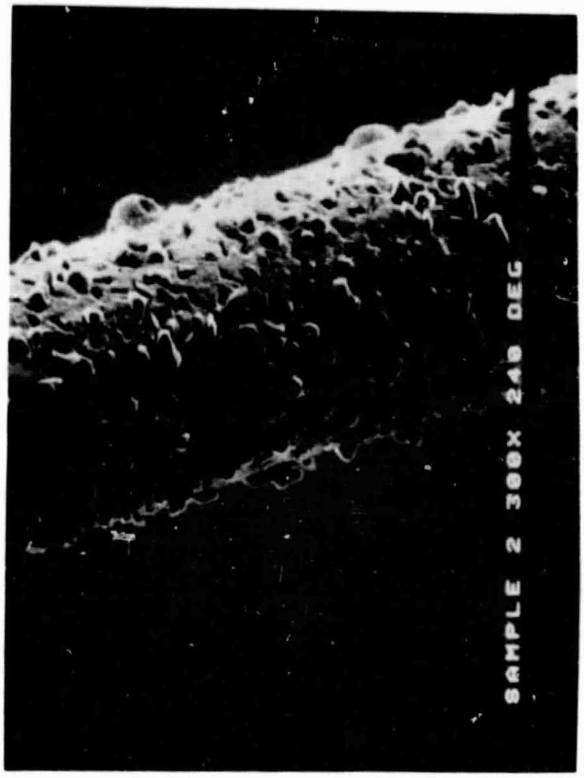
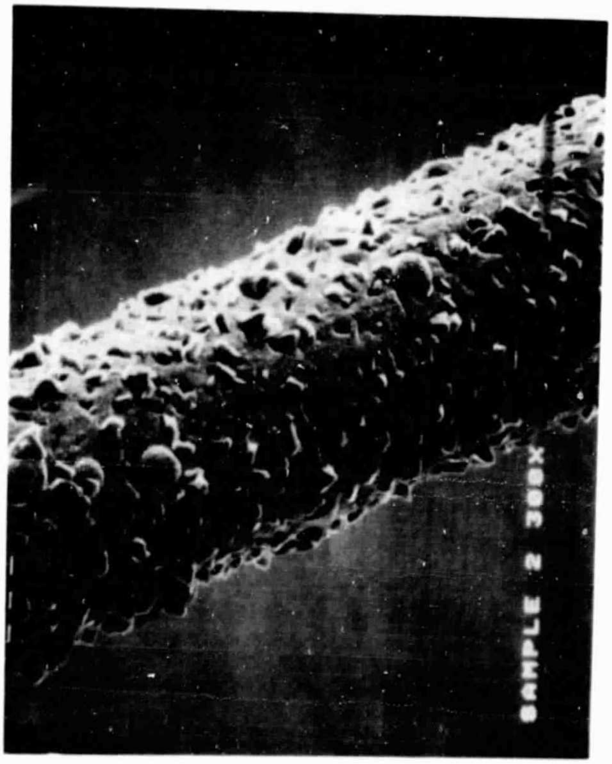
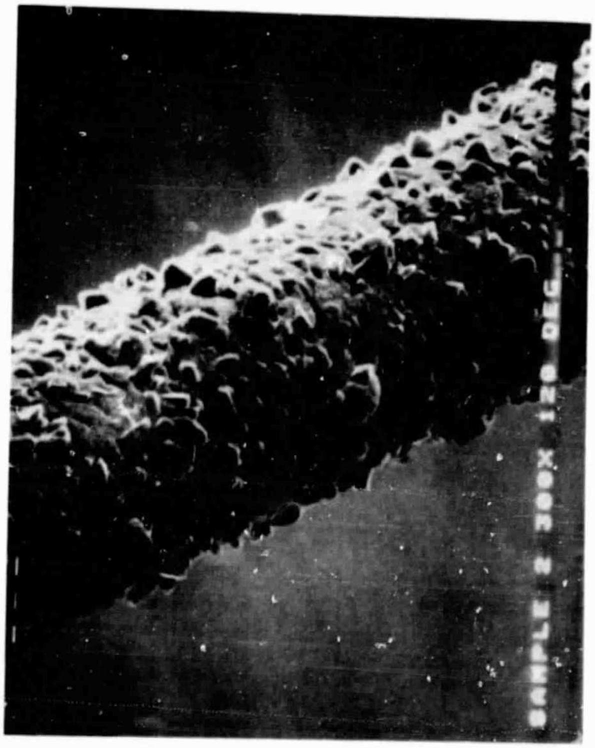
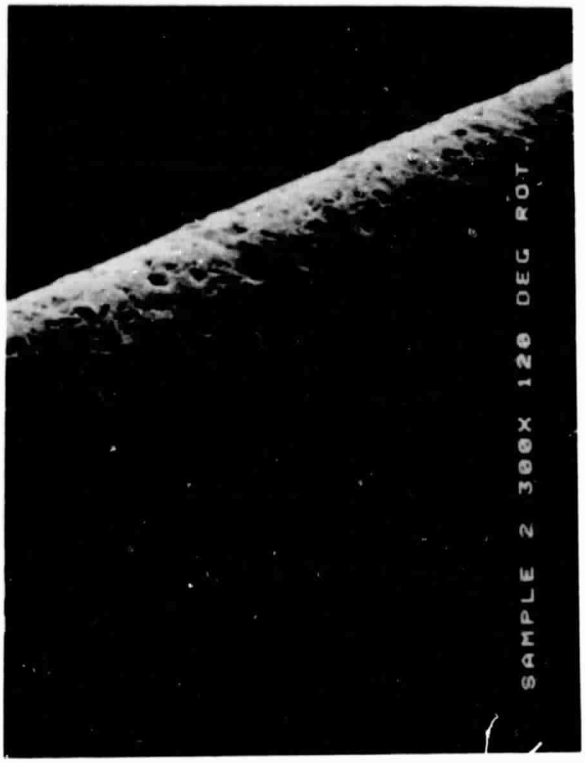


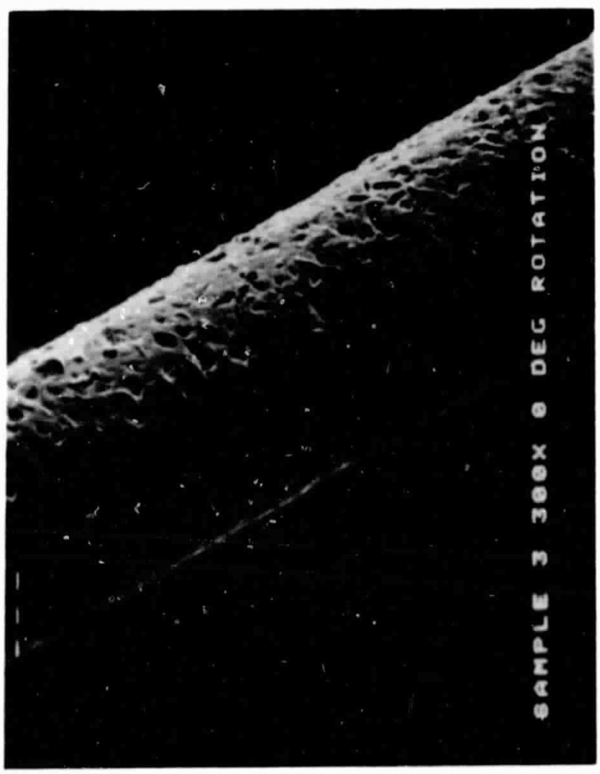
UNUSED WIRE -- 22 UM DIAMOND

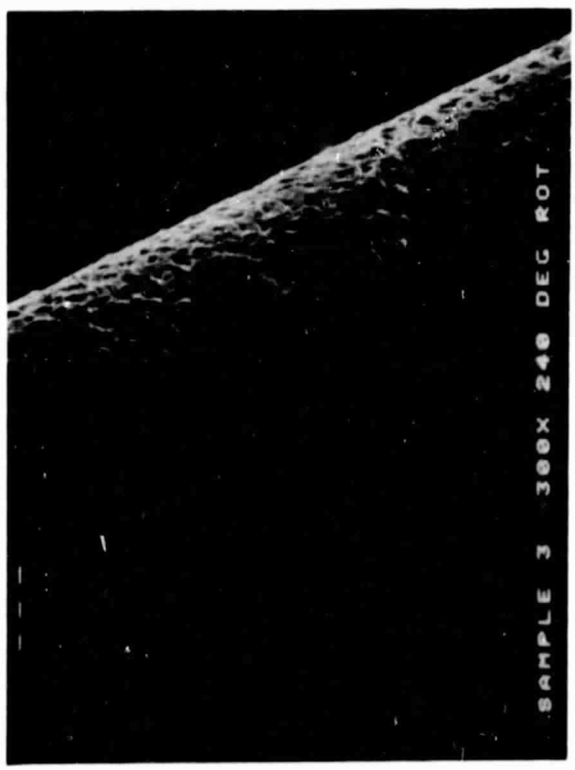


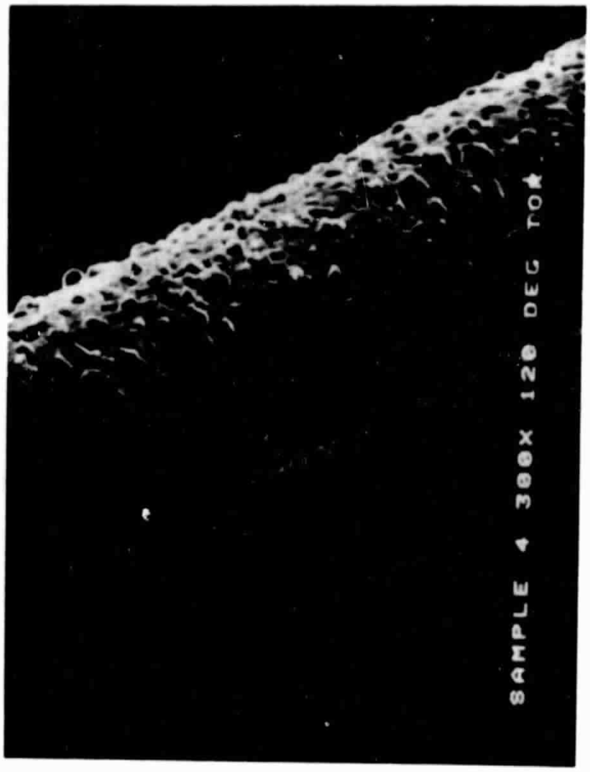




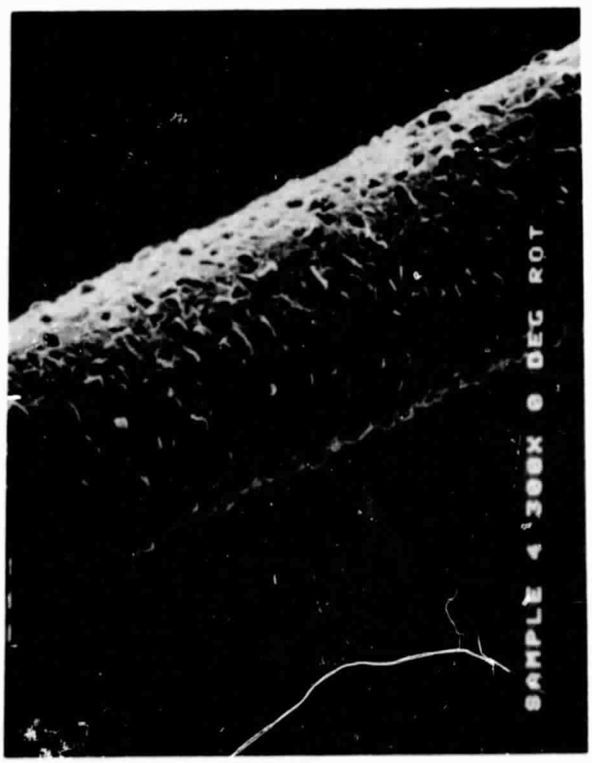
WIRE WITH 22 UM DIAMOND TAKEN FROM
REGION OF POOR YIELD IN RUN 504

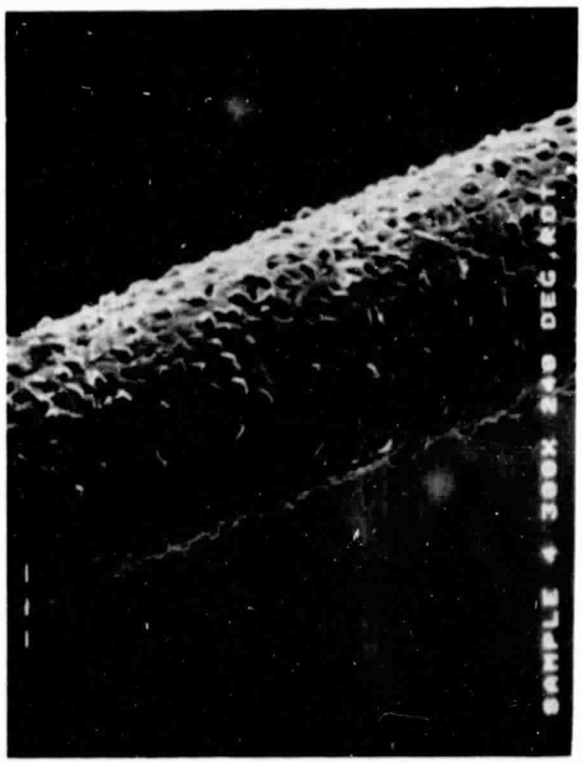






WIRE WITH 22 UM DIAMOND TAKEN
FROM REGION OF HIGH YIELD IN RUN
504





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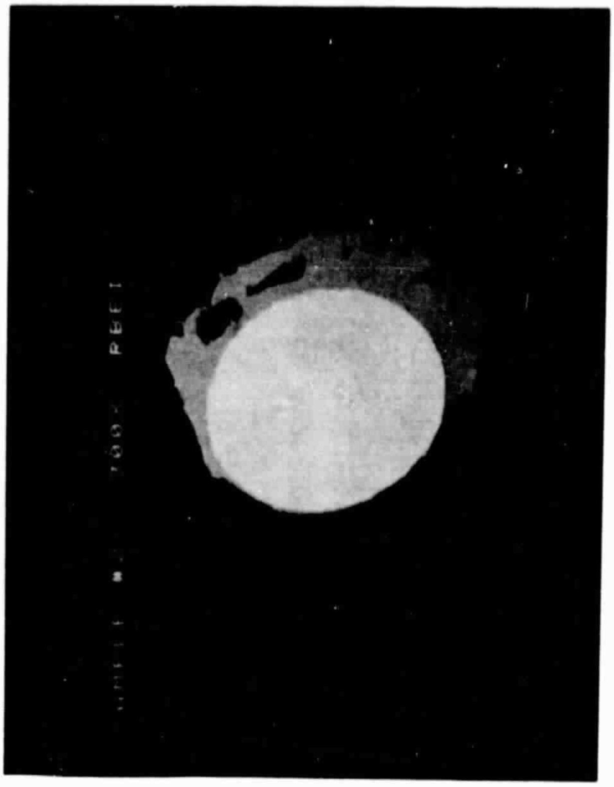
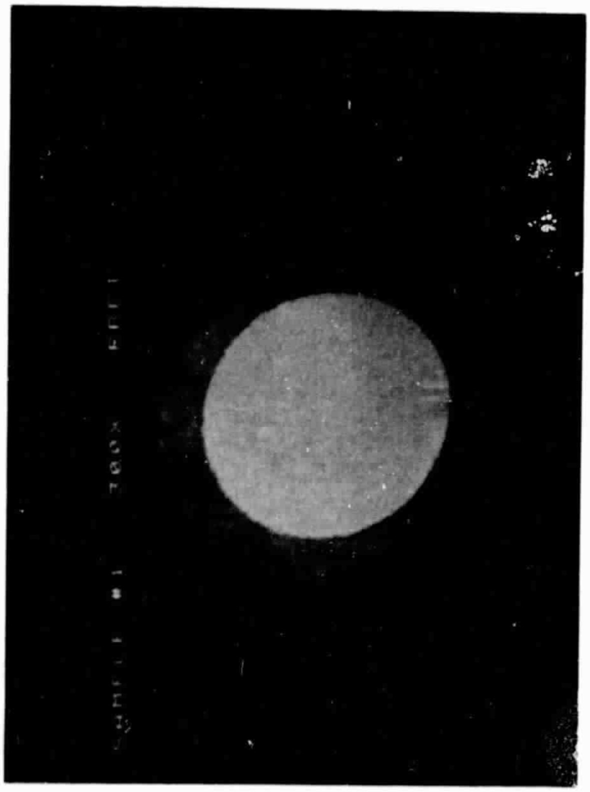
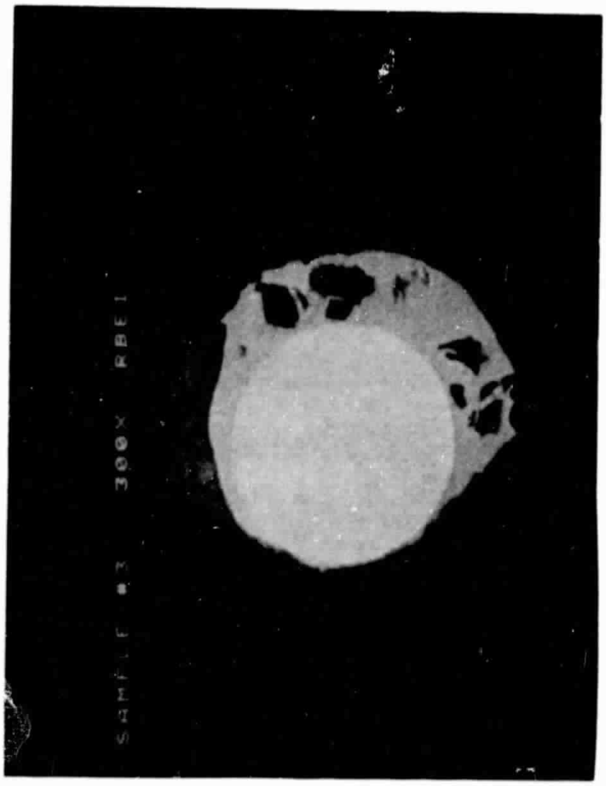


CROSS-SECTIONS OF
ELECTROFORMED WIRES





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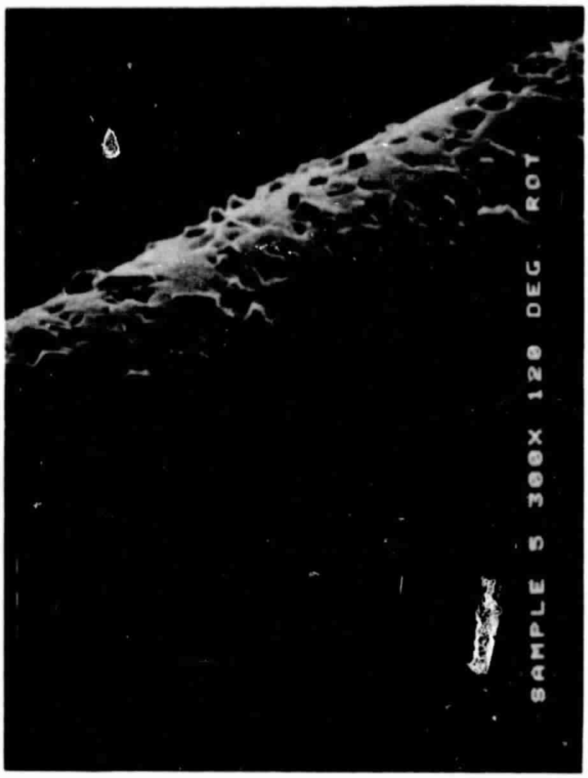
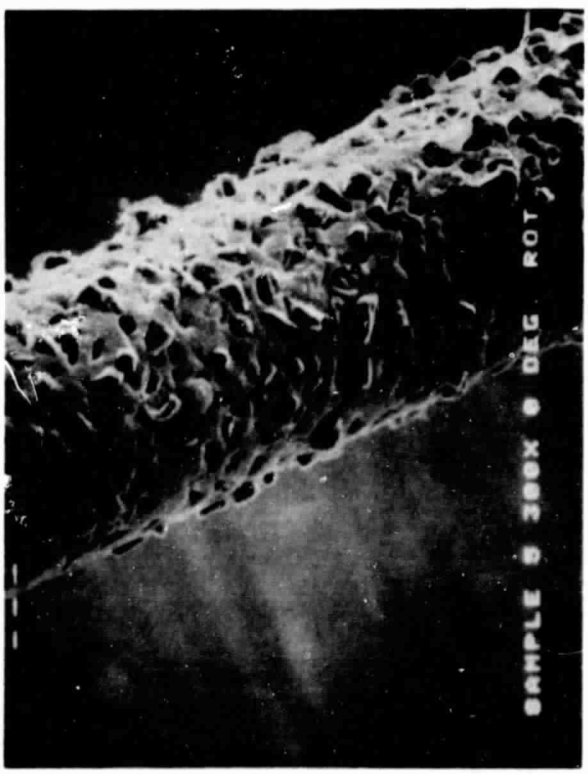
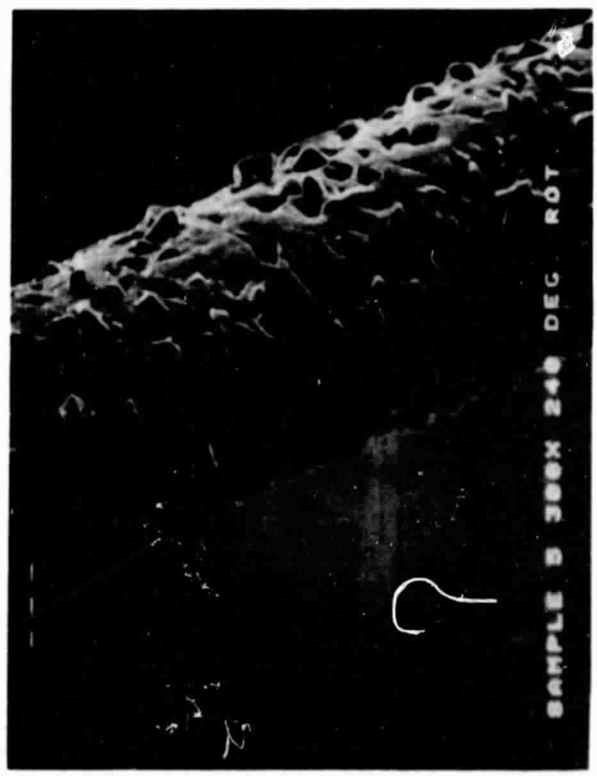
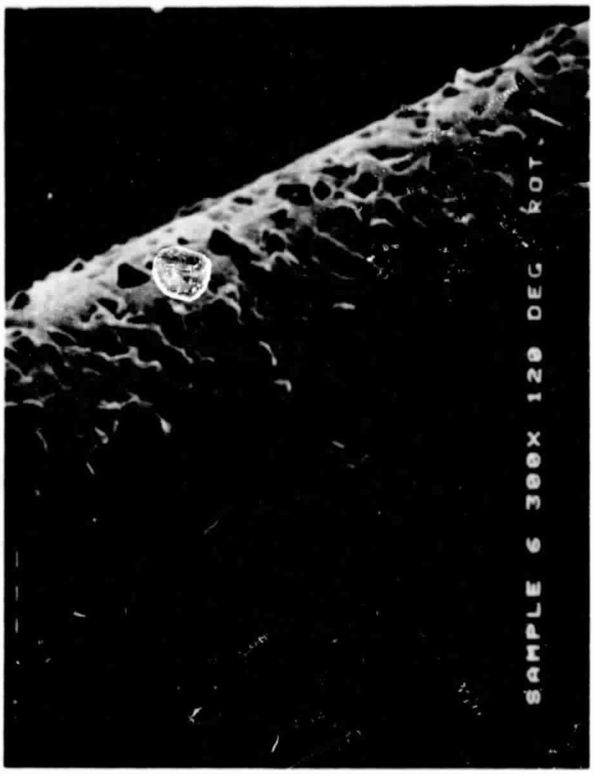


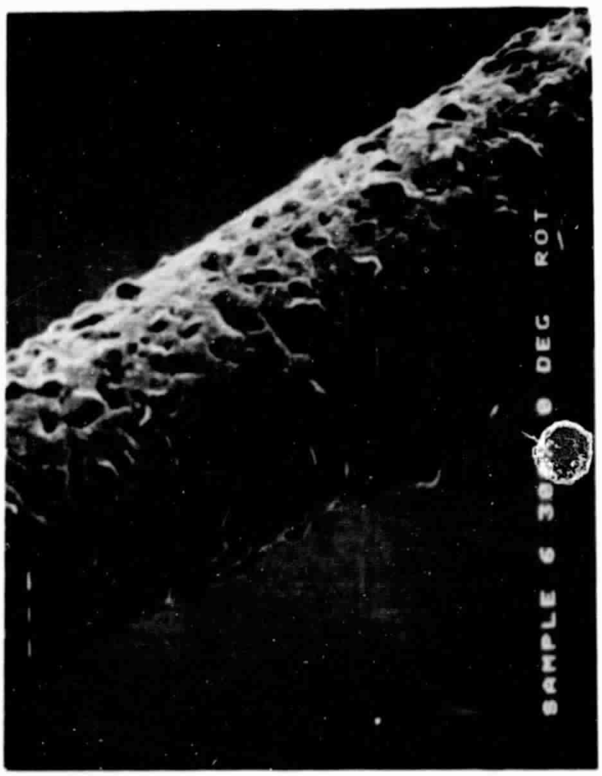
UNUSED WIRE PRIOR TO USE IN RUN 509
THAT PRODUCED 95% YIELD AT 25 WAFERS/CM

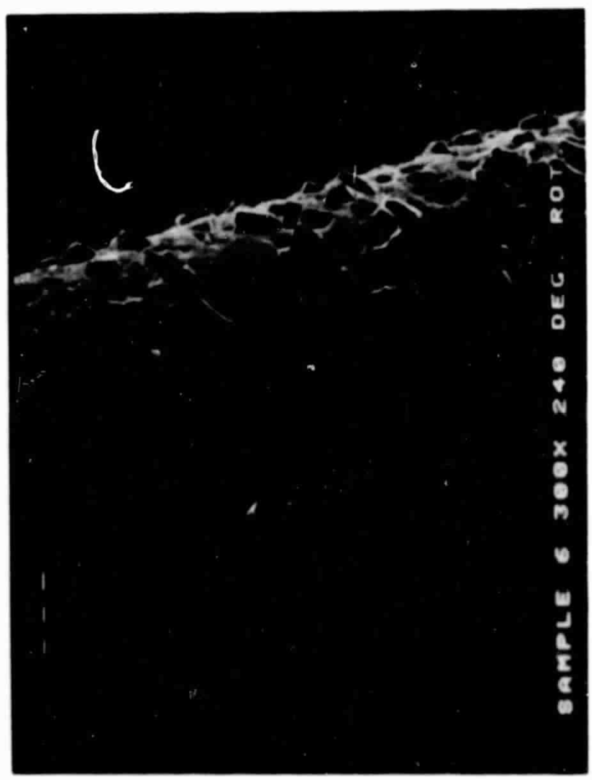






WIRE THAT PRODUCED 95% YIELD
AT 25 WAFERS/CM IN RUN 509





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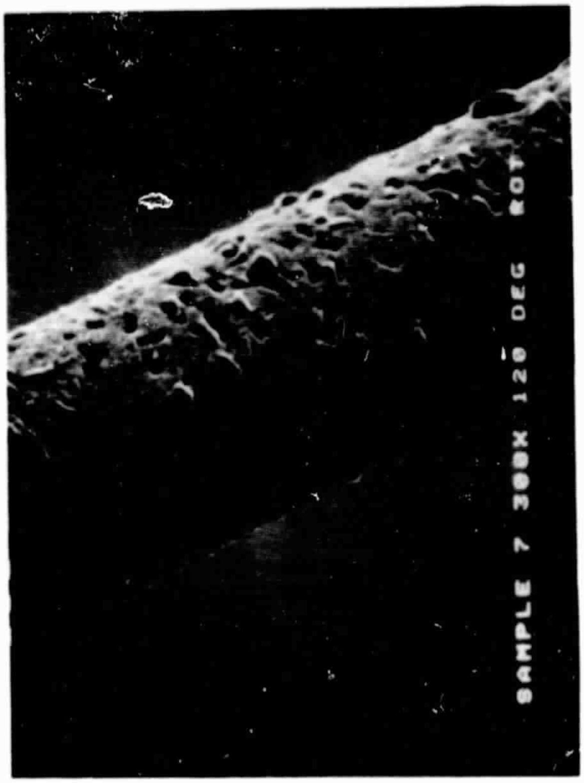
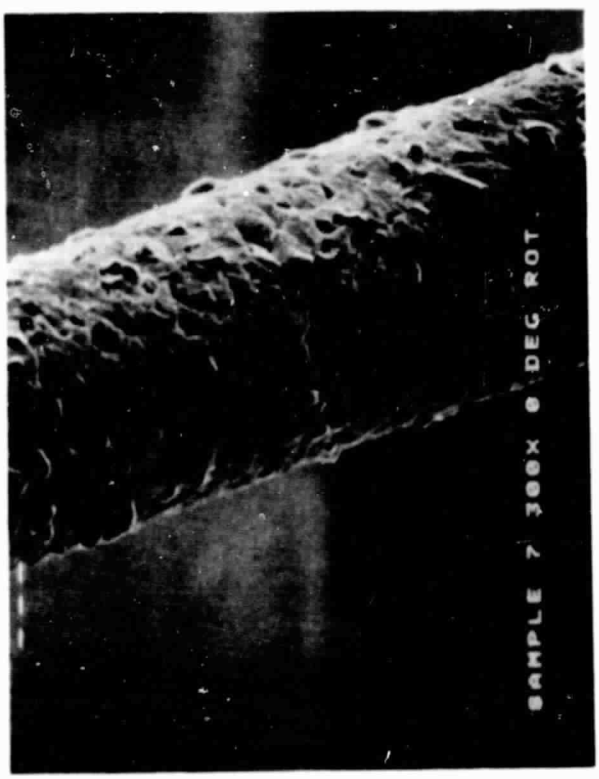
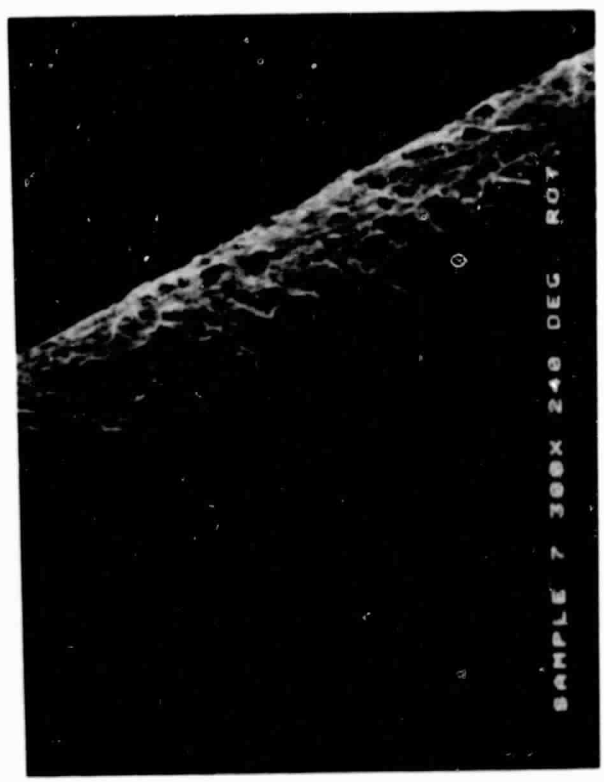


WIRE DRESSED AFTER PRODUCING
95% YIELD IN FIRST RUN (RUN 509)





Conclusions

1. HIGH YIELDS HAVE BEEN DEMONSTRATED DURING FIRST SLICING TESTS WITH WIRES.

2. SLICING TESTS WITH ELECTROFORMED WIRES HAVE BEEN DEMONSTRATED AT 25 WAFERS/CM.

3. HIGH DIAMOND CONCENTRATION IS VERY IMPORTANT FOR HIGH SLICING RATE AND LIFE OF WIRES. TRADITIONAL APPROACHES DO NOT GIVE THE UNIFORMITY DESIRED.

4. DOWNFEED OF WORKPIECE PREVENTS TRAPPING OF WAFER PIECES.

MULTIBLADE SAWING

P.R. HOFFMAN CO.

TECHNOLOGY: INGOT SLICING

APPROACH: MULTI-BLADE SLURRY TECHNIQUE (MBS)

CONTRACTOR: P. R. HOFFMAN CO.

OBJECTIVE: 1 METER^2/KG. CONVERSION RATE
VALUE ADDED < \$14.00/M^2 (1980\$)

STRATEGY: IMPROVE PROCESS TECHNOLOGY
REDUCE PROCESS COSTS
IMPROVE EQUIPMENT DESIGN VIA INCORPORATION OF PROCESS IMPROVEMENTS

TACTICS: DETERMINE PROCESS/COST VARIABLES WHICH MOST SIGNIFICANTLY AFFECT COSTS VIA SENSITIVITY ANALYSIS.
DIRECT R & D EFFORTS IN SYNC WITH COST/BENEFIT PRIORITIES.

ACTIVITY TO DATE

Process Technology

- EFFECT FEED FORCE
- RELATIVE BLADE HEAD SPEED
- VEHICLE/ABRASIVE RATIO
- SLURRY DELIVERY AND VOLUME
- BLADE PACKAGE SPECIFICATIONS
- BLADE CONTOURING

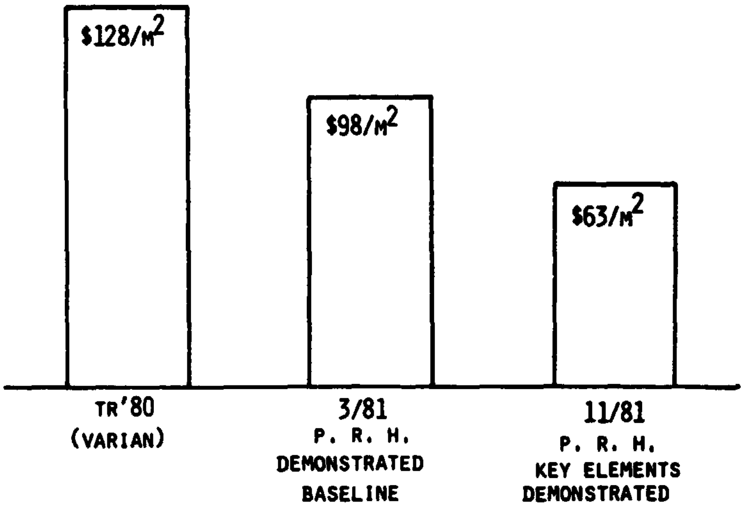
Cost Reduction

- SLURRY RECLAMATION
- ALTERNATIVE ABRASIVE
- ALTERNATIVE VEHICLE
- WATER-BASED VEHICLE

Design Improvements

- FEED FORCE CONTROL
- INGOT MOUNTING TECHNIQUES
- WAFER SUPPORT/LIFT-OFF
- ROCKING MOUNT

Ingot-to-Sheet Value Added (1980 $)



Demonstrated--Status

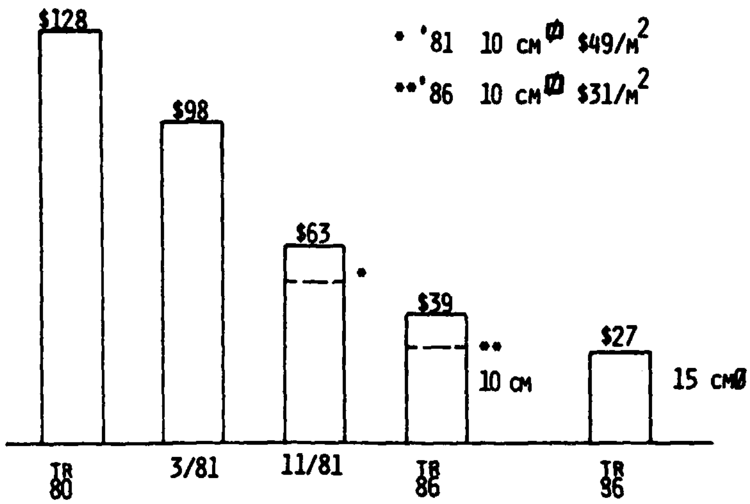
- VEHICLE/ABRASIVE RECLAIM CAPABILITY
- FEED FORCE CONTROL
- IMPROVED CUTTING RATE - 3 MIL/MIN AVG
  (1/3 WAFER/MIN)
- REDUCED VEHICLE COST (ALTERNATE OIL-BASED)
- WATER-BASED SLURRY (EQUIV >15 CMØ RUN)

Cost Analysis 11/81 Technology (1980 $) IPEG

ASSUMPTIONS:

EQUIPMENT COST - $42K/MACHINE
FLOOR SPACE - 36 SQ. FT.
1 OPERATOR/15 UNITS
EXPENDABLES/RUN - $109.32 (BLADE PACK, OIL, ABRASIVE)
455 WAFERS/RUN (20 WAFERS/CM) 10 CM Ø
22 HOUR RUN TIME
95% YIELD 95% DUTY CYCLE

PROJECTION:
$62.80/M^2 VALUE ADDED



1986 Cost Projections (1980 $) IPEG

ASSUMPTIONS:

EQUIPMENT COST - $30K/MACHINE
FLOOR SPACE - 36 SQ. FT.
1 OPERATOR/15 UNITS
EXPENDABLES/RUN - $85.00 (BLADE PACK, OIL, ABRASIVE)
500 WAFERS/RUN (22 WAFERS/CM) 10 CMØ
15 HOUR RUN TIME
95% YIELD 95% DUTY CYCLE

PROJECTION:

$39.45 VALUE ADDED

ASSUMPTIONS:

EQUIPMENT COST - $30K/MACHINE
FLOOR SPACE - 36 SQ. FT.
1 OPERATOR/20 UNITS
EXPENDABLES/RUN - $89.50 (BLADE PACK, OIL, ABRASIVE)
432 WAFERS/RUN (19 WAFERS/CM)
33 HOUR RUN TIME
95% YIELD 95% DUTY CYCLE

PROJECTION:

$27.40 VALUE ADDED

Concerns

FURTHER REDUCTION OF WAFERING COST REQUIRES:

* Improvements in Blade Cost/Life
* Improvements in Vehicle Cost (water based)
* Process Improvements re high Blade Speed and various Mechanical Improvements
* Increased Saw Capacity/Throughput
* Feasibility of Square Ingot

SEMICRYSTALLINE CASTING

SEMIX INC.

J.R. Anderson

Goals

1. DEMONSTRATION OF COMMERCIAL READINESS OF SEMICRYSTALLINE SHEET CONSISTENT WITH ARRAY PRICE OF $2.80/WP.

2. DEMONSTRATION OF TECHNICAL READINESS OF SEMICRYSTALLINE SHEET CONSISTENT WITH ARRAY PRICE OF $0.70/WP.

Phase I Results (June 18, 1980 to June 18, 1981)

- DEMONSTRATED TO SATISFACTION OF DOE AND JPL TECHNICAL READINESS TO REACH $2.80/WP

- SAMIS ANALYSIS: PLANT CAPACITY: 10 MW/YEAR

SILICON ($56/KG)	0.939
CRYSTALLIZATION VALUE-ADDED	0.26
BRICK FINISHING VALUE-ADDED	0.04
WAFERING VALUE-ADDED	0.39
WAFER RINSE VALUE-ADDED	0.006
QUALITY ASSURANCE VALUE-ADDED	0.014
TOTAL $/WP	1.649

Phase II (June 19, 1981 to June 18, 1982)

- DOE OBJECTIVES RESTRUCTURED

- FOCUS NOW ON CRITICAL ELEMENTS OF SEMIX UBIQUITOUS CRYSTALLIZATION PROCESS TO REACH TECHNICAL FEASIBILITY OF $0.70/WP

Critical Elements

A. HIGH VOLUME, LOW COST UCP TECHNICAL FEASIBILITY

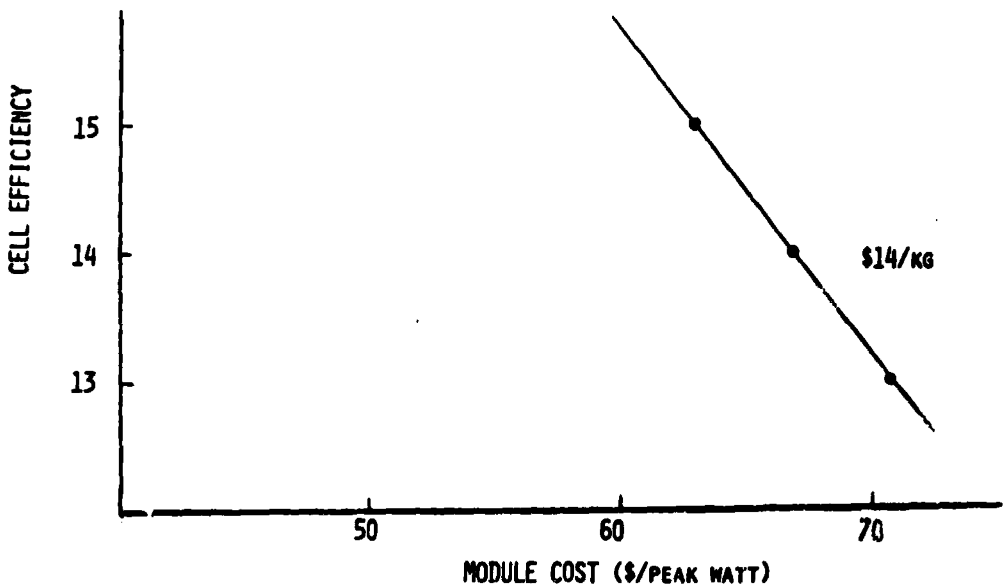
B. HIGH VOLUME, LOW COST WAFERING TECHNICAL FEASIBILITY

C. HIGH EFFICIENCY SEMICRYSTALLINE SOLAR CELLS

Results of SAMIS Analyses

PROCESS STEP	$14/KG SI AND 15% AM1 EFFICIENCY
SIL-BUY	20.178 $/KG = .1716 $/WP
UCP	54.832 $/INGOT = .0111 $/WP
SIZE	2.582 $/BRICK = .0032 $/WP
BRICK QC	.266 $/BRICK = .0003 $/WP
WAFER 10X15	.221 $/WAFER = .1044 $/WP
RINSE	.001 $/WAFER = .0003 $/WP
SHIPPING	.697 $/BOX = .0003 $/WP
CLEAN	.007 $/WAFER = .0035 $/WP
DIFFUSIO	.018 $/WAFER = .0084 $/WP
BCONTACT	.008 $/WAFER = .0038 $/WP
2 CLEAN	.007 $/WAFER = .0034 $/WP
FCONTACT	.246 $/WAFER = .1126 $/WP
ARCOAT	.007 $/WAFER = .0030 $/WP
ETCH	.009 $/CELL = .0042 $/WP
ATTACH 4X4	.716 $/SUBSTRATE = .0319 $/WP
PPREP 4X4	17.071 $/MODULE = .0951 $/WP
LAYUP 4X4	4.719 $/MODULE = .0263 $/WP
MODCLN	2.408 $/SUBSTRATE = .0134 $/WP
BOND	1.136 $/MODULE = .0063 $/WP
TRIMSEAL	1.289 $/MODULE = .0072 $/WP
FINALTES	.055 $/MODULE = .0003 $/WP
PKGMODUL	25.153 $/CRATE = .0140 $/WP
TOTAL	.6246 $/WP

Effect of Cell Efficiency on Module Cost Using $14/kg Si



Ubiquitous Crystallization Process (UCP)

- o HEART OF SEMIX'S TECHNOLOGY
- o EXHIBITS HIGH TOLERANCE FOR IMPURITIES
- o LENDS ITSELF TO AUTOMATION
- o UTILIZES RELATIVELY LOW ENERGY
- o LOW MATERIALS COSTS
- o LARGE AREA CELLS
- o HIGH PACKING DENSITY

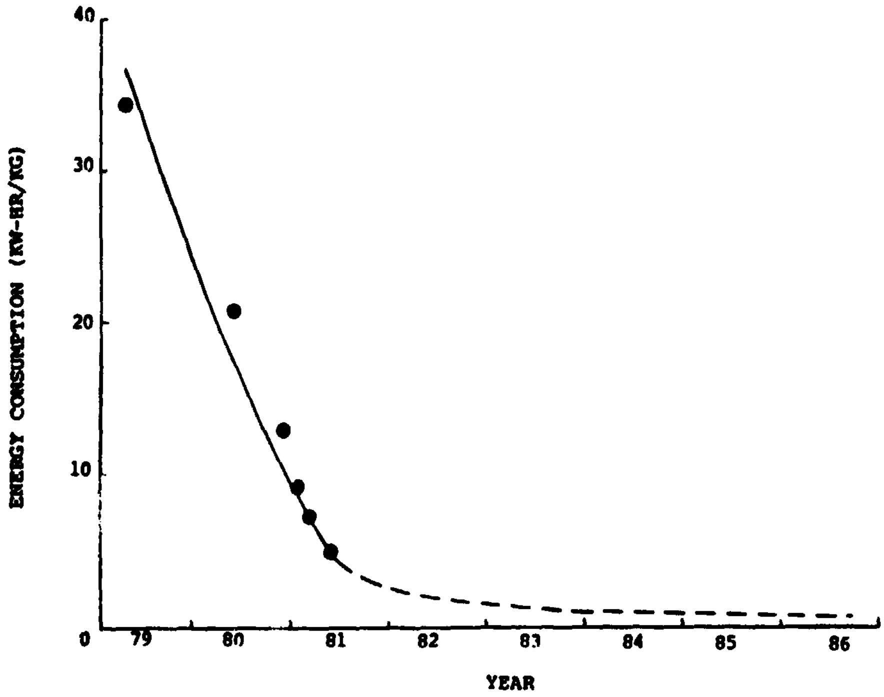
Critical Elements of UCP

A. LARGE VOLUME - PRESENTLY 17 KILOGRAM BRICKS WITH 42 KILOGRAM GOAL

B. REDUCED ENERGY CONSUMPTION

C. HIGH YIELD

Total Average Energy Consumption



Critical Elements of Wafering Technology

A. HIGH THROUGHPUT (M^2/HR)

B. HIGH SILICON YIELD (M^2/KG)

Investigating Three Wafering Technologies

1. STANDARD MULTI BLADE SLURRY (MBS) SAWING
2. HIGH SPEED MULTI BLADE SLURRY (HSMBS) SAWING (PROTOTYPE)
3. INTERNAL DIAMETER (ID) SAWING

MBS and High-Speed MBS Wafering

	BEST TO DATE		PROGRAM
	MBS	HSMBS	GOALS
PROCESS YIELD, %	95	99	95
MATERIAL YIELD, M^2/KG	0.57	0.60	0.92
WAFER SIZE, MM	100 x 100	100 x 100	100 x 150
WAFER THICKNESS, MM	0.381	0.381	0.229
(INCH)	(0.0150)	(0.0150)	(0.009)
KERF LOSS, MM	0.330	0.330	0.229
(INCH)	(0.0130)	(0.0130)	(0.009)
RUN TIME, HR	11.5	7.6	6.3
MACHINE OUTPUT, M^2/HR	0.22	0.25	0.99
FINISHED WAFER COST*, $/$M^2$	84.	84.	46.

*BASED ON IPEG ANALYSIS, INTERIM STANDARD PRICE ESTIMATING EQUATION. AMORTIZED ONE TIME COSTS HAVE BEEN OMITTED. THE PRICE OF SILICON INGOTS IS ASSUMED TO BE $25/KG. THIS ANALYSIS IS FOR COMPARISON ONLY.

ID Wafering

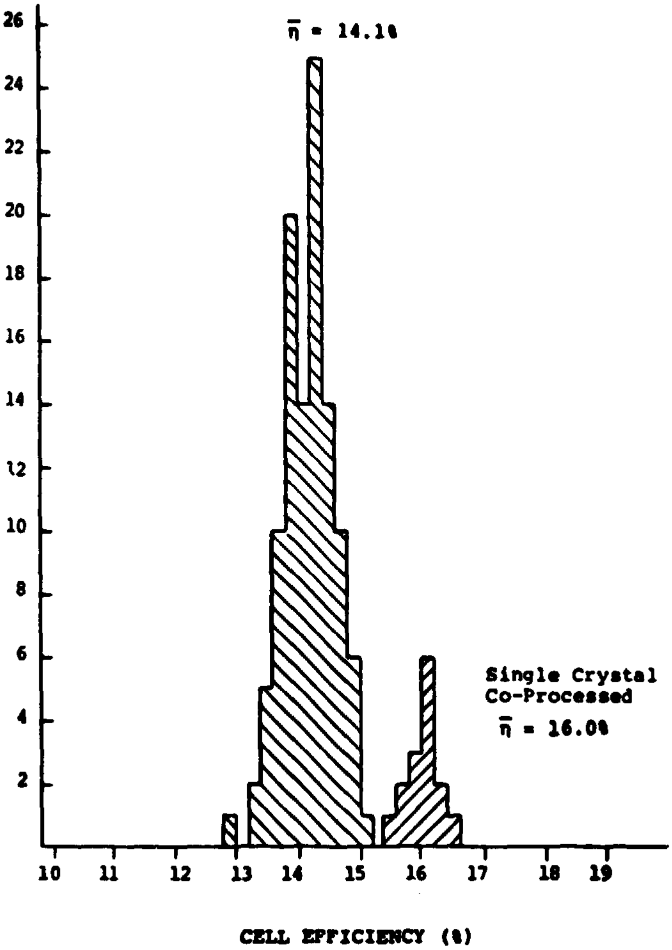
	BEST TO DATE	PROGRAM GOALS
PROCESS YIELD, %	100	95
MATERIAL YIELD, M^2/KG	0.89	0.92
WAFER SIZE, MM	100 x 100	100 x 150
WAFER THICKNESS, MM	0.208	0.229
(INCH)	(0.0082)	(0.009)
KERF LOSS, MM	0.274	0.229
(INCH)	(0.0108)	(0.009)
CYCLE TIME, MIN	2.4	3.0
MACHINE OUTPUT, M^2/HR	0.22	0.30
FINISHED WAFER COST*, $/$M^2$	64.	39.

*BASED ON IPEG ANALYSIS, INTERIM STANDARD PRICE ESTIMATING EQUATION. AMORTIZED ONE TIME COSTS HAVE BEEN OMITTED. THE PRICE OF SILICON INGOTS IS ASSUMED TO BE $25/KG. THIS ANALYSIS IS FOR COMPARISON ONLY.

High-Efficiency Semicrystalline Solar Cells

- SEMIX GOAL - 15% EFFICIENCY (AM1) TO MEET $0.70/WP COST GOAL
- 250 10 X 10 CM - 14% EFFICIENCY TO BE DELIVERED
- 100 2 X 2 CM - 15% EFFICIENCY TO BE DELIVERED
- 100 2 X 2 CM - 14.2% EFFICIENCY DELIVERED AND VERIFIED
- BEST CELL TO DATE 17% AM1 EFFICIENCY (MEASURED BY SOLAREX)

Total Sample: 108 2 x 2 cm Cells



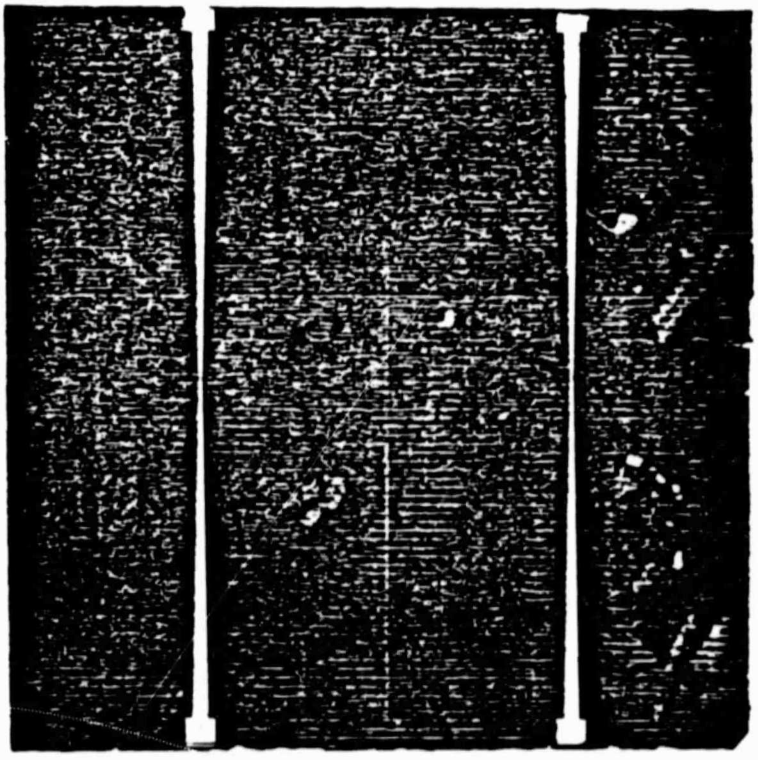
Best Semicrystalline Si Solar Cells to Date (AM1, 26.5°C)

CELL	I_{sc} (MA)	V_{oc} (MV)	FF (%)	P_{max} (MW)	EFFICIENCY
A	144	604	78.2	68	17.0%
B	143	599	78.2	67	16.8%
C	140	592	77.2	64	16.0%
D	139	595	78.0	64.5	16.1%

High-Efficiency Cell Processing Sequence

THINNING ETCH TO ~200 µM	GOAL THICKNESS
↓	
PHOSPHORUS DIFFUSION	HIGH BLUE RESPONSE
↓	
AL PASTE APPLICATION, ALLOY	BSF FORMATION
↓	
CONTACT FORMATION Ti-Pd-Ag	LOW SERIES RESISTANCE
↓	
DICING	(2 CM X 2 CM SAMPLES ONLY)
↓	
MULTI-LAYER AR COATING	MINIMIZE REFLECTANCE

High-Efficiency Semicrystalline 10 x 10 cm Pattern



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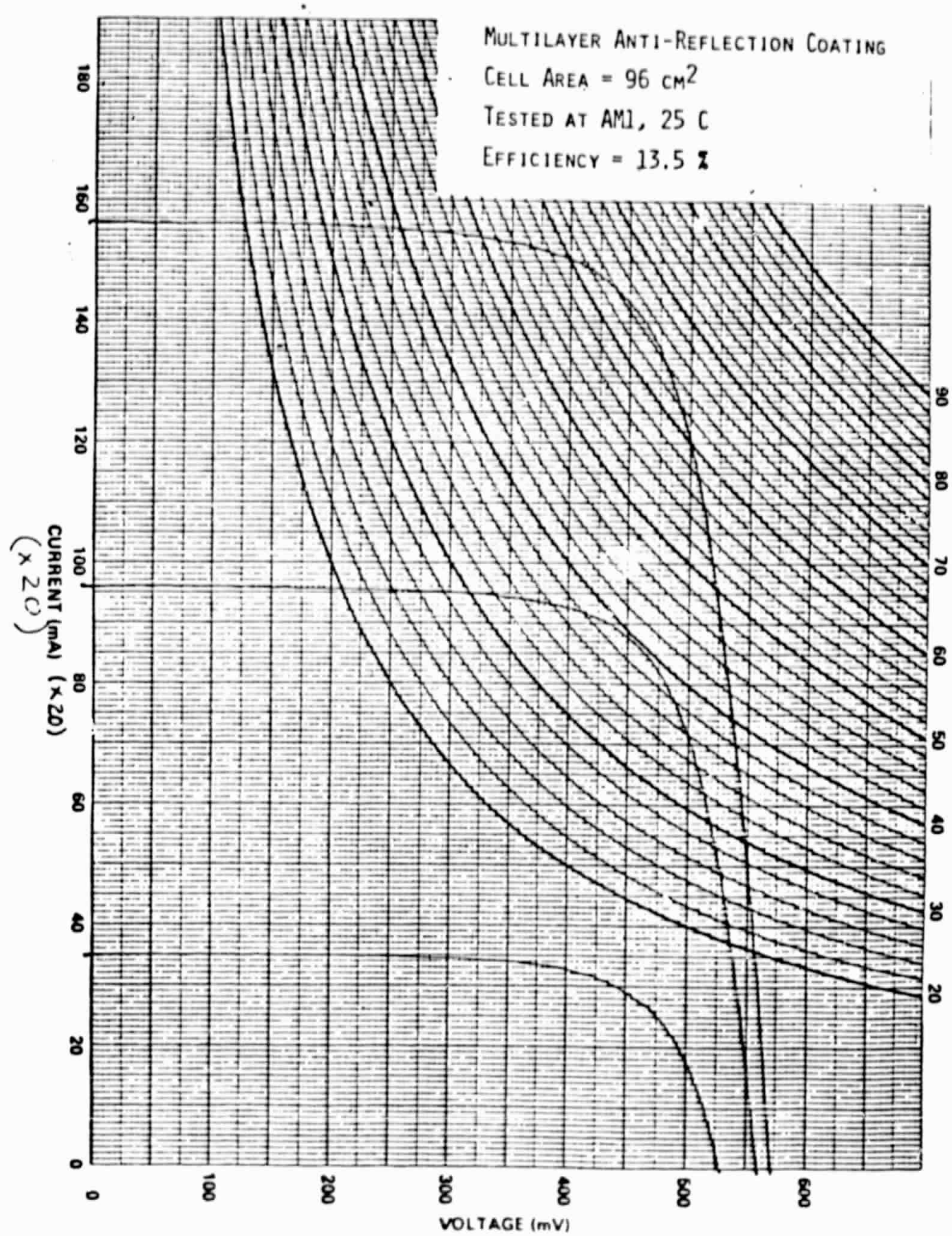
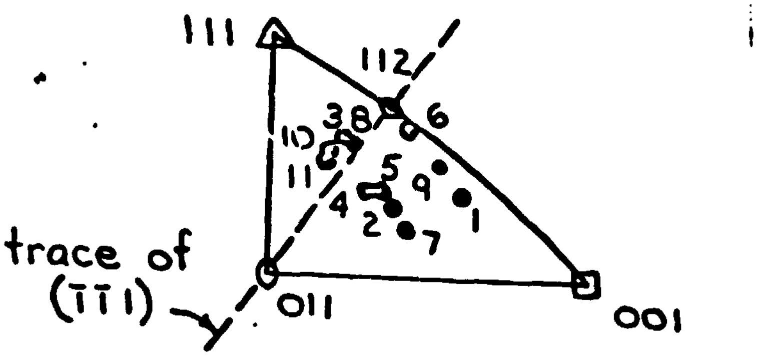


Other Areas of Investigation

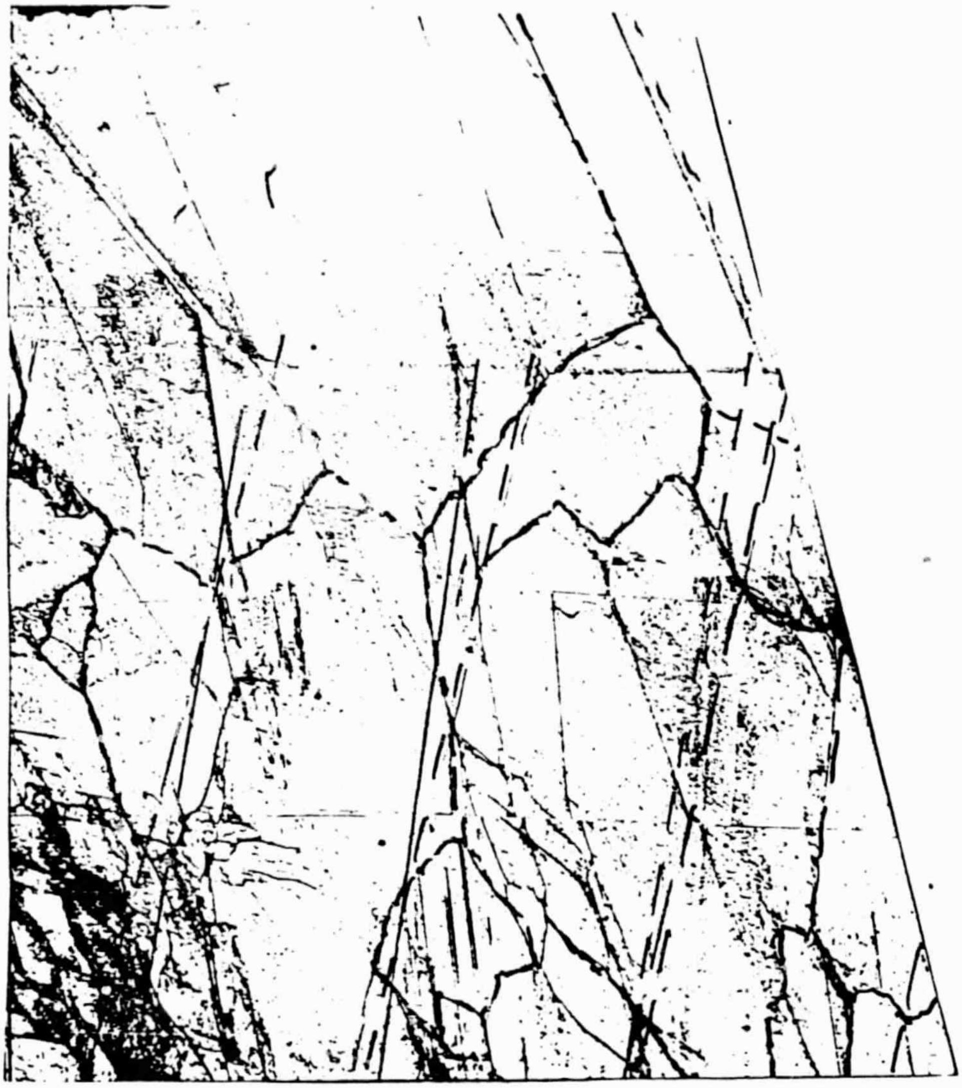
- VARIABLE GRAIN SIZE
- VARIABLE GRAIN ORIENTATION
- GRAIN BOUNDARIES/INTERNAL GRAIN ORDER
- RESISTIVITY MEASUREMENT TECHNIQUES

Summary of Light I-V Characteristics of Co-Processed Cells From Material With Dissimilar Grain Size

CRYSTAL SIZE	CELL #	SHORT CIRCUIT CURRENT DENS. (mA/CM^2)	OPEN CIRCUIT VOLTAGE (mV)	AM1 CONVERSION EFFICIENCY %	FILL FACTOR (%)
LARGE (CM)	1	31	585	14.28	79
	2	31	5[illegible]2	13.32	73
	3	30	577	13.44	77
	4	29	573	13.20	78
SMALL (MM)	1	31	580	14.04	77
	2	31	579	13.92	78
	3	32	582	14.28	77
	4	31	577	13.80	78



Surface Normals of Selected Large Grains in 20x20 cm^2 Cross Section of Semicrystalline Brick



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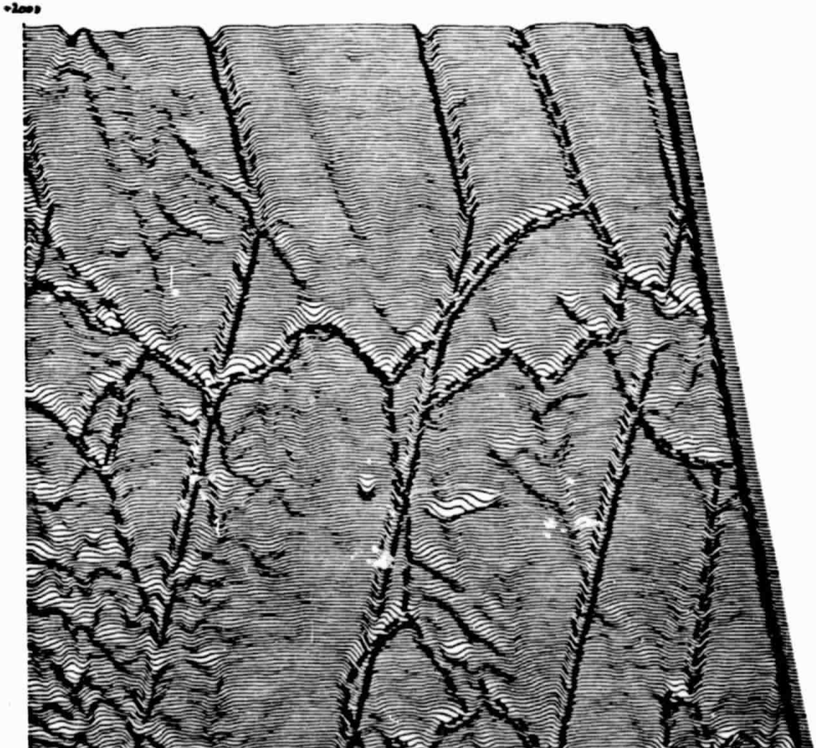
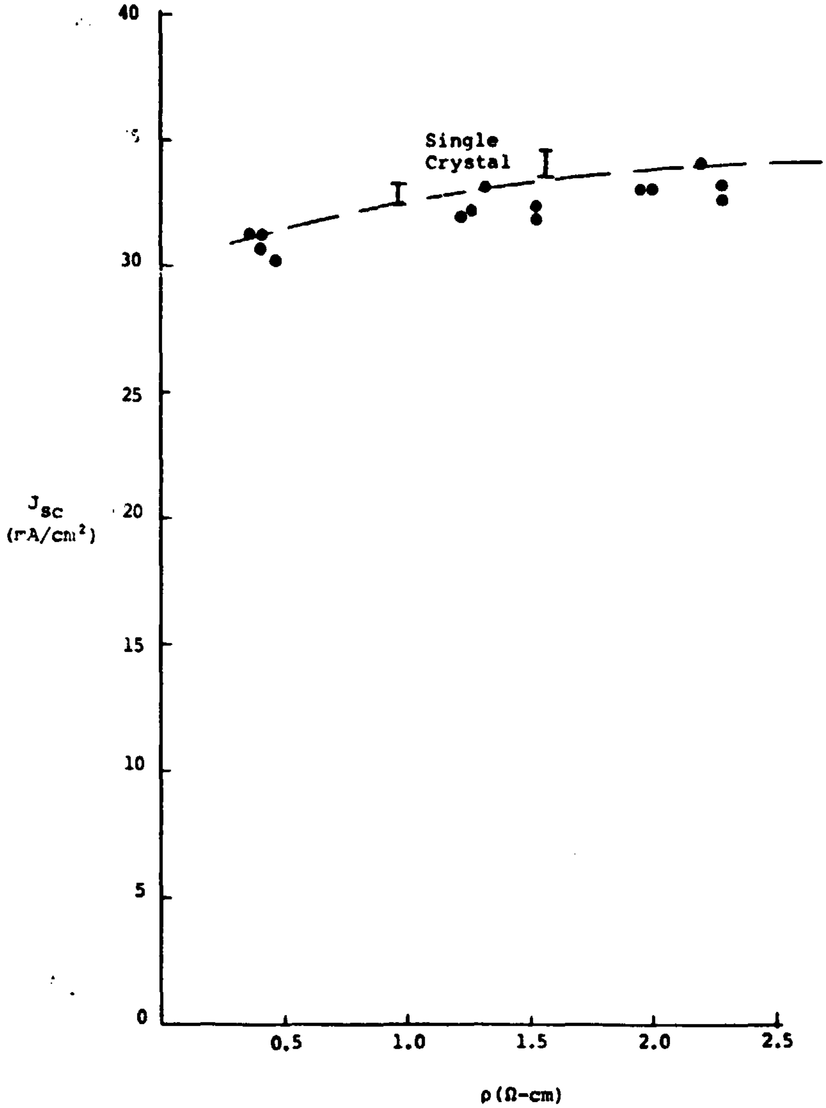
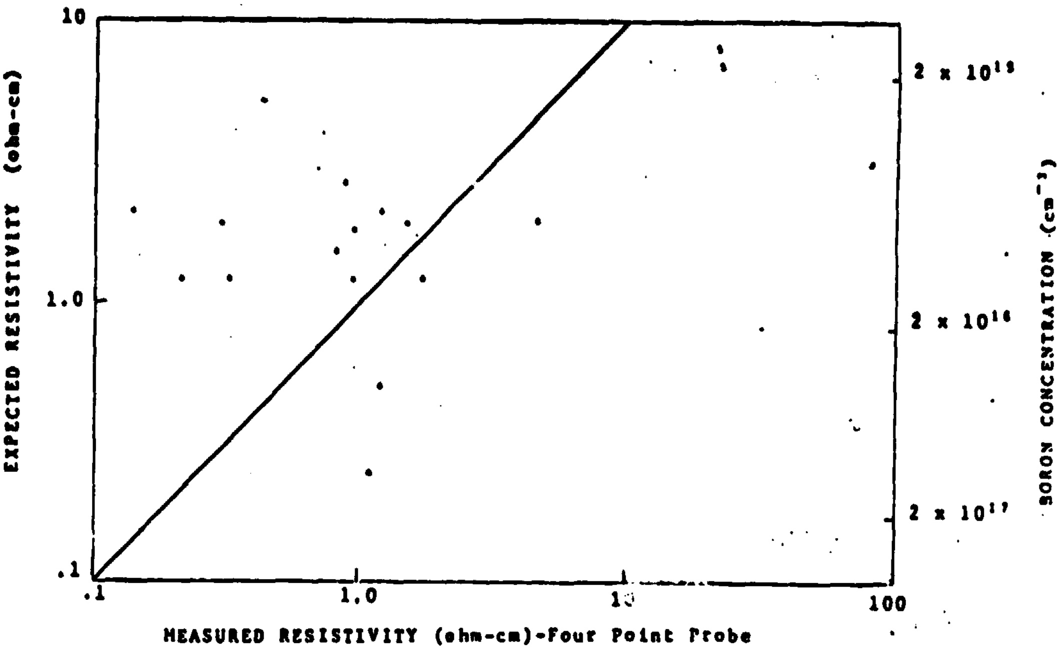
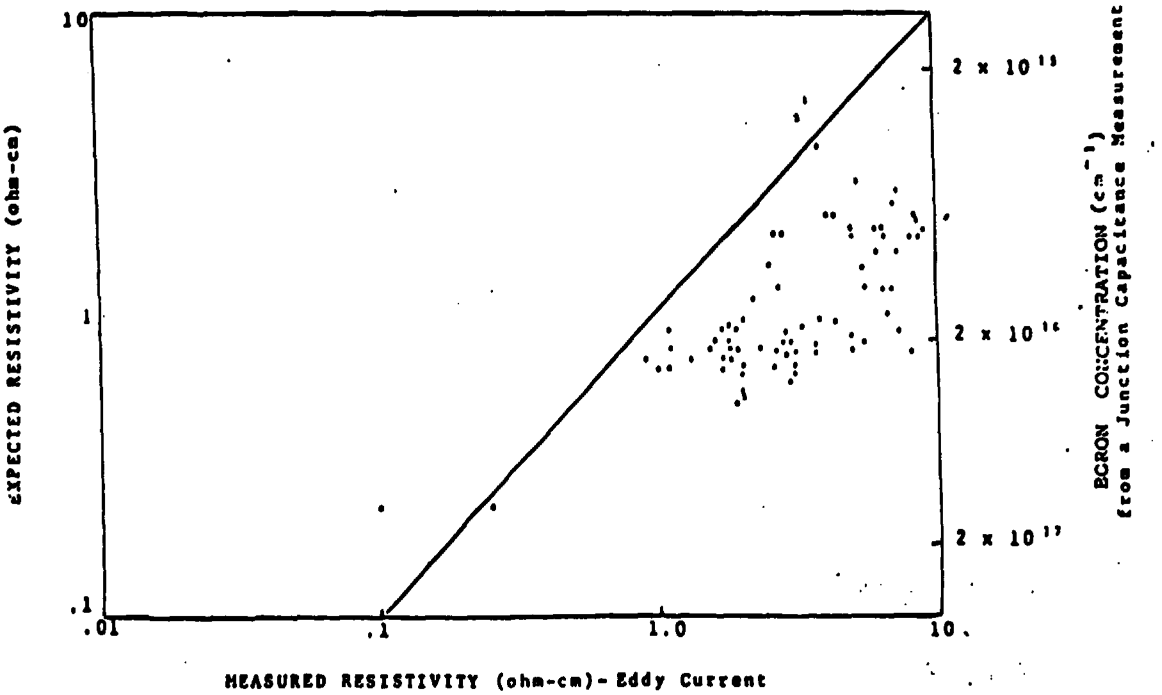


Influence of Base Resistivity on the AM1 Short Circuit Current Density of Semicrystalline and Single Crystal Silicon Solar Cells





Comparison of the base resistivity of UCP Semicrystalline silicon as measured by a four point probe and by junction capacitance



Comparison of the base resistivity of UCP semicrystalline silicon as measured by an eddy current and by junction capacitance

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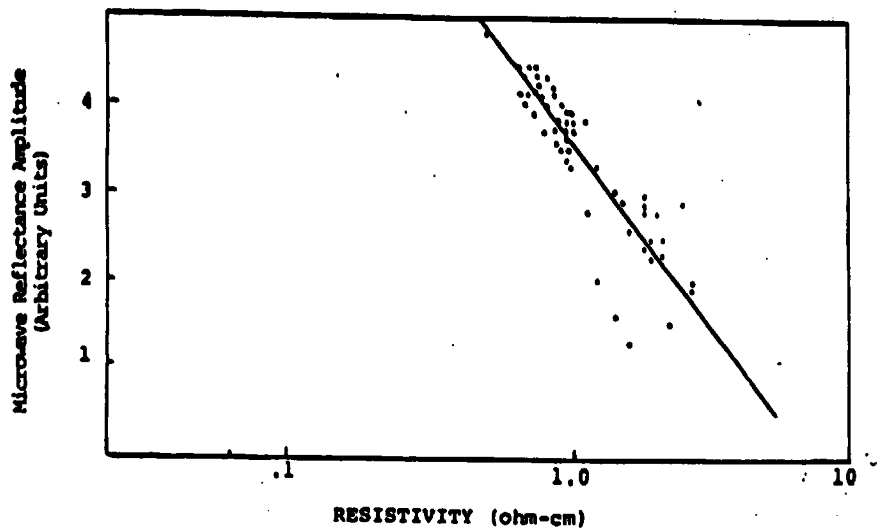

Comparison of the Microwave Reflectance as a Function of the Base Resistivity of Semicrystalline Material

ADVANCED CZOCHRALSKI INGOT GROWTH

KAYEX CORP.

Presentation Format

1. OBJECTIVES OF CONTRACT
2. APPROACH
3. PROGRAM PLAN
4. PRESENT STATUS
5. AREAS OF CONCERN
6. PLANS

Goals

- GROWTH OF 150 KG OF INGOTS FROM ONE CRUCIBLE USING PERIODIC MELT REPLENISHMENT
- DIAMETER - 15 CM
- THROUGHPUT - 2.5 KG/HR
- RECHARGE MELTING RATE - 25 KG/HR
- AFTER GROWTH YIELD - 90%
- MICROPROCESSOR CONTROLS PLUS IMPROVED SENSORS FOR MELT TEMP, INGOT DIAMETER, AND MELT LEVEL
- PROTOTYPE EQUIPMENT SUITABLE FOR HIGH VOLUME SILICON PRODUCTION, TRANSFERABLE DIRECTLY TO INDUSTRY

Approach

- CONSTRUCT AN IMPROVED CRYSTAL GROWER HAVING THE PERFORMANCE REQUIRED TO ACHIEVE GOALS
- CONSTRUCT AN AUTOMATED SYSTEM WHICH WILL OFFER RELIABLE PERFORMANCE LEADING TO IMPROVED YIELDS AND REDUCED LABOR COST
- CONDUCT PROCESS DEVELOPMENT ON LARGE SIZE CRYSTAL GROWTH, MELT REPLENISHMENT AND IMPROVED THROUGHPUT AND YIELDS
- CONDUCT A PARALLEL ANALYTICAL PROGRAM TO HELP UNDERSTAND THE PROCESS

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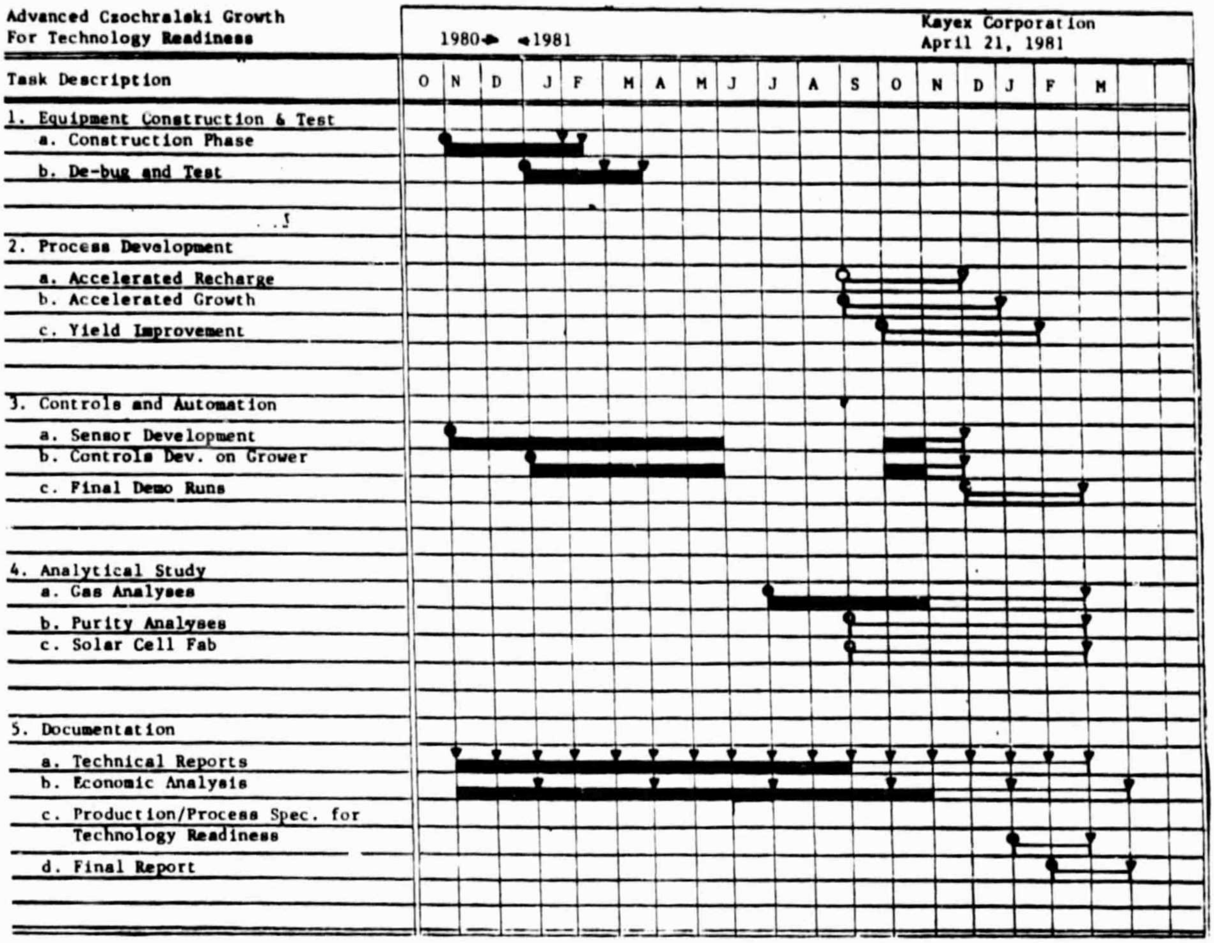
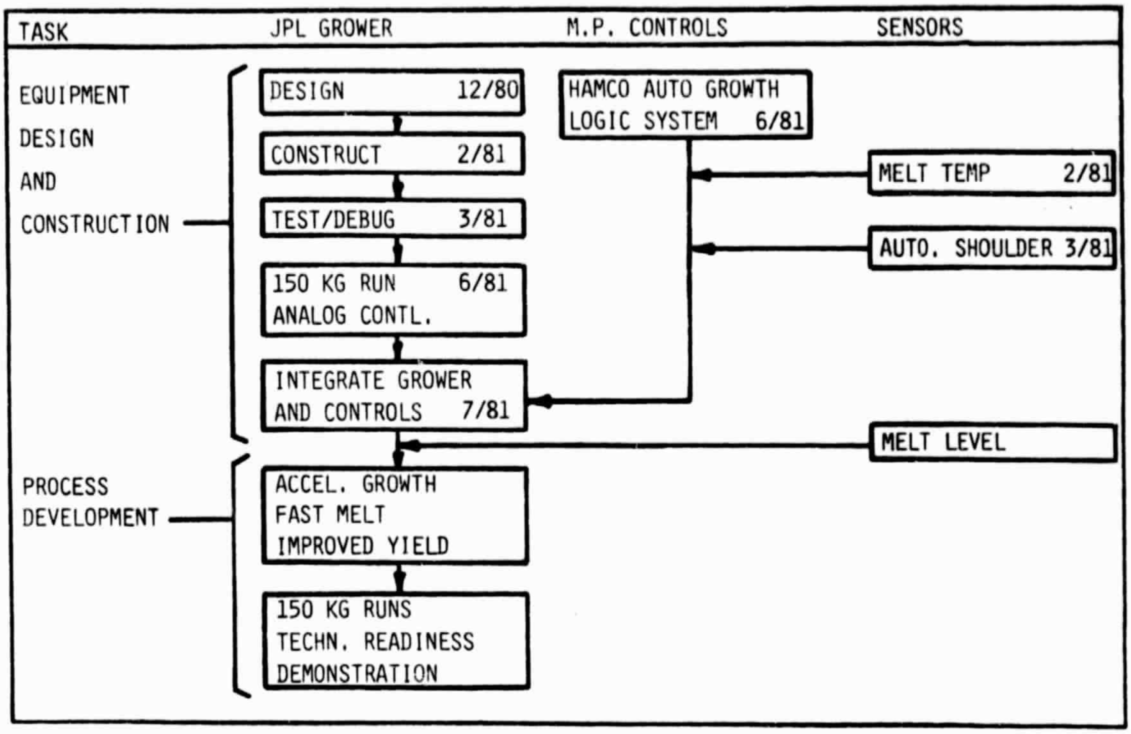
LARGE-AREA SILICON SHEET TASK

Program Plan, Rev. 2



Kayex-Hamco Automatic Grower Logic



EQUIPMENT DESIGN AND CONSTRUCTION	COMPLETE
GCA DESIGN AND CONSTRUCTION	COMPLETE
150 KG QUALIFICATION RUN	COMPLETE
AGL CONTROLS	INTERFACE TO JPL GROWER COMPLETE
SENSORS	
MELT TEMP	DEMONSTRATED ON 18 KG MELT
AUTO SHOULDER	DEMONSTRATED ON 150 MM DIAM
MELT LEVEL	SCHEDULE COMPLETION 11/81
PROCESS DEVELOPMENT	ONGOING
ANALYTICAL STUDY	ONGOING

Automation and Sensors

AUTOMATION

- HAMCO AGILE COMPUTER-BASED CONTROL SYSTEM INTEGRATION COMPLETED.
- TWO CRYSTALS GROWN WITH AUTOMATIC CONTROL OF NECK, CROWN, SHOULDER AND BODY.

SENSOR DEVELOPMENT

- TESTING OF DIAMETER, SHOULDER AND MELT TEMPERATURE SENSORS CONCLUDED ON CG2000 GROWER.
- NEW MELT TEMPERATURE "PERISCOPE" MOUNT DESIGNED AND IMPLEMENTED. IMPROVED DIP TEMPERATURE REPRODUCIBILITY VERIFIED.

IMPLEMENTATION

- DIGITAL CONTROLLERS FOR DIAMETER, TEMPERATURE, GROWTH
- PROCESS RECIPES
- CRITICAL DECISIONS BY OPERATOR
- PARAMETERS CONTROLLED BY COMPUTER

FUNCTIONS

- MELTDOWN - RECIPE CONTROL, TERMINATED BY OPERATOR
- STABILIZATION TO SEEDING TEMP - CLOSED LOOP
- NECK GROWTH - RECIPE CONTROL, TERMINATED BY OPERATOR
- CROWN AND SHOULDER - FULLY AUTOMATIC, RECIPE, AND SENSOR
- BODY - CLOSED LOOP DIAMETER AND GROWTH RATE CONTROL
- FINAL TAPER - AUTOMATIC START, RECIPE

Gas Analysis System

OBJECTIVE	-	TO QUANTITATIVELY ANALYZE GASEOUS COMPONENTS OF THE CRYSTAL GROWTH ENVIRONMENT DURING GROWTH. OPERATING PRESSURE, 7.6 TORR (1/100 ATM)
APPROACH	-	GAS CHROMATOGRAPHY FOR CO AND H_2 CALCIUM STABILIZED ZIRCONIA FOR O_2 ALUMINUM OXIDE HYGROMETER FOR H_2O
STATUS	-	GCA OPERATING PRELIMINARY MEASUREMENTS OF CO OBTAINED ALL SENSORS INSTALLED AUTOMATIC GAS SAMPLING FUNCTIONAL

AREAS OF CONCERN	PLANS
- YIELD OF QUALITY INGOT	- CORRELATE FURNACE ATMOSPHERE TO INGOT QUALITY AND CRUCIBLE PERFORMANCE
- CRUCIBLE DEGRADATION	- PURITY ANALYSES AND EVALUATION OF VENDOR - SUPPLIED CRUCIBLES
- GROWTH RATE IMPROVEMENT	- INSTALL RADIATION SHIELD

Economic Analysis

CZ ADD-ON COST PROJECTIONS BASED ON
GROWER THROUGHPUT GOAL OF 2.5 KG/HR

CONDITIONS	1	2	3
CRUCIBLE DIAMETER (IN)	16	16	16
CRYSTAL DIAMETER (IN)	6	6	6
TOTAL POLY MELTED (KG)	158	158	158
TOTAL CRYSTAL PULLER (KG)	150	150	150
AVG STRAIGHT GROWTH RATE (IN/HR)	4.05	3.5	3.1
PULLED YIELD (%)	94.9	94.9	94.9
YIELD AFTER CG (% OF MELT)	83.5	85.4	87.3
INDIVIDUAL CRYSTAL WT (KG)	30	37.5	50
NO. CRYSTALS/CRUCIBLE	5	4	3
CYCLE TIME (HR)	60	60	60

PROCESS CYCLE TIMES

OPERATION	TIME (MINS)		
1. PREPARATION			
LOAD POLYSILICON	15	20	25
CLOSE FURNACE	5	5	5
PUMP DOWN	15	15	15
MELTDOWN	105	115	135
SUBTOTAL	140	155	180
2. GROWTH CYCLE (INITIAL)	1	2	3
LOWER SEED	*	*	*
STABILIZE TEMPERATURE	30	30	30
NECK GROWTH	20	20	20
CROWN GROWTH	55	55	55
STRAIGHT GROWTH	347	515	795
TAPER END	60	60	60
SUBTOTAL	512	680	960
3. RECHARGE/GROWTH CYCLE	(X4)	(X3)	(X2)
COOL CRYSTAL	30	30	30
REMOVE CRYSTAL	10	10	10
LOAD HOPPER, VAC DOWN (X2)	60	60	60
LOWER HOPPER (X2)	10	10	10
DUMP AND MELT	80	85	90
	(22.5 KG/HR)	(26.5 KG/HR)	(33.3 KG/HR)
LOWER SEED	*	*	*
STABILIZE TEMPERATURE	30	30	30
NECK GROWTH	20	20	20
CROWN GROWTH	55	55	55
STRAIGHT GROWTH	347	515	795
TAPER END	60	60	60
SUBTOTAL	702	875	1160
	(X4) 2808	(X3) 2625	(X2) 2320
4. SHUT DOWN CYCLE			
COOL FURNACE	80	80	80
REMOVE CRYSTAL	**	**	**
CLEAN, SET UP	60	60	60
SUBTOTAL	140	140	140
TOTAL CYCLE TIME (MINS)	3600	3600	3600

*COMPLETED DURING MELT STAB. TIME; **COMPLETED DURING FURN. COOL.TIME

GROWTH RATE CALCULATION	1	2	3
GROW DIAMETER (IN)	6.2	6.2	6.2
STRAIGHT CRYSTAL WT (KG)	27	34.5	47
STRAIGHT GROWTH TIME (HR)	5.78	8.58	13.25
AVG GROWTH RATE (KG/HR)	4.67	4.02	3.55
WT PER UNIT LENGTH (KG/IN)	1.153	1.153	1.153
AVG PULL RATE (IN/HR)	4.05	3.49	3.08

SAMICS/IPEG INPUT DATA AND COST CALCULATION

1. CAPITAL EQUIPMENT COST (EQPT)	\$ 247,560	\$ 247,560	\$ 247,560
2. FLOOR SPACE (SQFT)	120	120	120
3. ANNUAL DIRECT SALARIES			
PROD. OPERATOR (0.65 MAN @\$13160/YR)	8,554	8,554	8,554
ELECT. TECH. (0.3 MAN @\$16940/YR)	5,082	5,082	5,082
INSPECTOR (0.1 MAN @\$11550/YR)	1,155	1,155	1,155
TOTAL (DLAB)	14,791	14,791	14,791
4. DIRECT MATERIALS USAGE BASED ON MACHINE UTILIZATION OF 85% = 124 CYCLES/YR			
CRUCIBLES 16 x 12 @\$345 EA	42,780	42,780	42,780
SEED (\$25/CYCLE)	2,480	2,480	2,480
DOPANT (\$25/CYCLE)	3,100	3,100	3,100
ARGON (60 FT^3/HR @\$0.05/FT^3)	22,320	22,320	22,320
GRAPHITE (4 SETS 16" GRAPH.	35,556	35,556	35,556
MATERIALS TOTAL (MATS)	\$ 106,236	\$ 106,236	\$ 106,236

5. UTILITIES	1	2	3
ELECTRICITY @$0.04/KW HR)			
MELTDOWN @100 KW	3,513	3,058	2,604
AVG GROW @75 KW	18,600	18,910	19,220
WATER @¢0.7/FT^3			
30 GPM FOR 97% CYCLE	12,106	12,106	12,106
UTILITIES TOTAL (UTIL)	$ 34,219	$ 34,074	$ 33,930

IPEG PRICE	5 x 30 KG CRYSTALS	4 x 37.5 KG CRYSTALS	3 x 50 KG CRYSTALS
C1 EQPT X $0.57/YR = $EQPT	141,109	141,109	141,109
C2 SQFT X $109/YR = $SQFT	13,030	13,080	13,080
C3 DLAB X $2.1/YR = $DLAB	31,061	31,061	31,061
C4 MATS X $1.2/HR = $MATS	127,483	127,483	127,483
C5 UTIL X $1.2/YR = $UTIL	41,063	40,889	40,716
TOTAL ANNUAL COST	$ 353,796	$ 353,622	$ 353,449
QUAN (TOTAL CHARGED X YIELD AFTER CG) KG =	16,360	16,732	17,104
ADD-ON COST $/KG =	21.62	21.13	20.66
ADD-ON COST ¢/PEAK WATT = (ASSUMES 1 KG = 1 M^2)	15.25¢/W_p	14.90¢/W_p	14.57¢/W_p

ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

Major Activity in This Reporting Period

Development Of Greater Sustained Growth Width

- **Reduce Thermally Generated Stress To Permit Increased Width Of Growth**
- **Provide Experimental Web Growth Machine To Support Development Of Increased Growth Width**

Reduce Thermally Generated Stress–
Increase Width of Growth

- **Control Thermal Stress**
  - **Develop Criteria For Buckling Stress**
  - **Identify Acceptable Thermal Profile In Web**
  - **Design Lid/Shield System To Generate This Profile**
- **Maintain Control Of Thermal Profile In Melt**

Develop Criteria for Buckling Stress

Identify Temperature Profile In Web

- Thermal Model Of Temperature Distribution Developed
- Model Verified By Velocity/Thickness Prediction And Stress Data

Compute Thermal Stress Distributions

- Computer Finite Element Code Used To Compute Stress Fields
- Results Verified Via Buckling Results And Residual Stress Data In Experimental Web Growth

Identify Buckling Parameters

- Finite Element Code Used For Predicting Buckling Conditions
- Procedure Verified By Agreement With Observed Web Growth Behavior

Identify Acceptable Thermal Profile in Web

- Finite Element Code Used To Compute Stresses In Synthetic Temperature Profile Of Known Mathematical Properties
- Zero Stress Temperature Profile Identified
- Finite Stress Conditions Being Evaluated Via
  - Mathematically Defined Temperature Profile
  - Comparison Of Experimental Web Growth Temperature Profiles
- Composite Curves Being Evaluated

Design Lid–Shield System to Generate Desired Thermal Profile

Development Approach:

- **Measure System Temperatures For Various Geometries**
- **Quantify Growth Effects Of Temperatures And Geometry In Experimental System**
- **Investigate Active Thermal Elements If Needed**
- **Combine Appropriate Elements**

Status of Stress Reduction

- **Computer Models Developed And Verified By Correlation With Experimental Results**
- **Application Of Models Under Way To Identify Acceptable Web Temperature Profiles**
- **Development Of Web Growth Thermal Configuration Started**
- **Control Of Melt Profile Routinely Maintained**

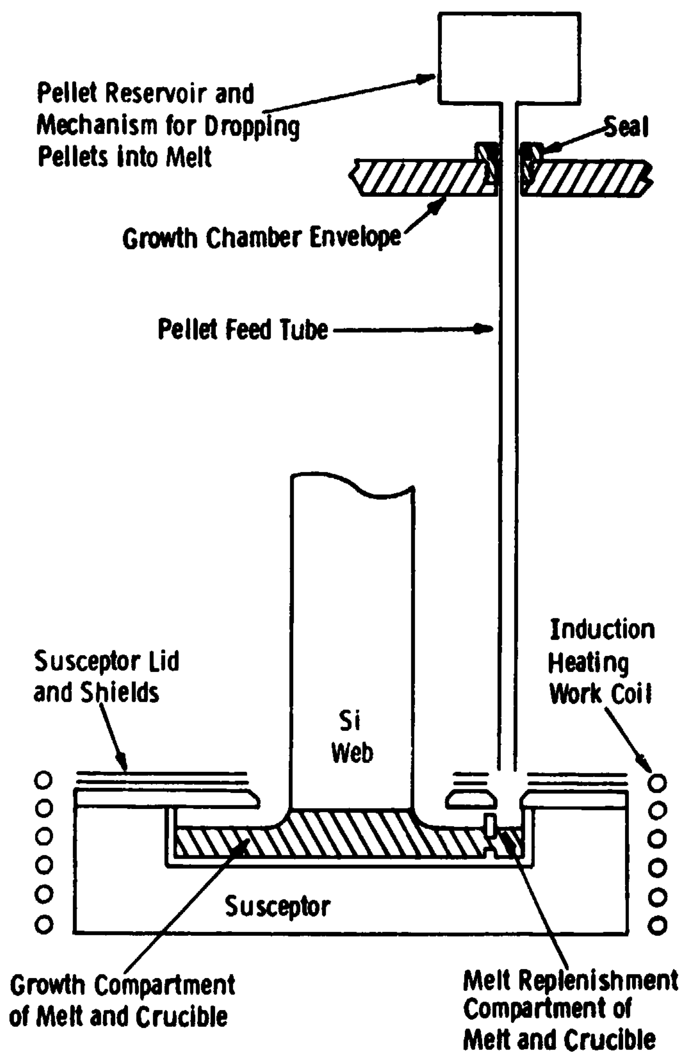
Key Features of Sustained Web Growth

- **Constant Melt Level**
- **Constant Temperature**
- **Constant Width Of Growth**
- **Constant Thickness Of Growth**
- **Programmed Start Of Growth**

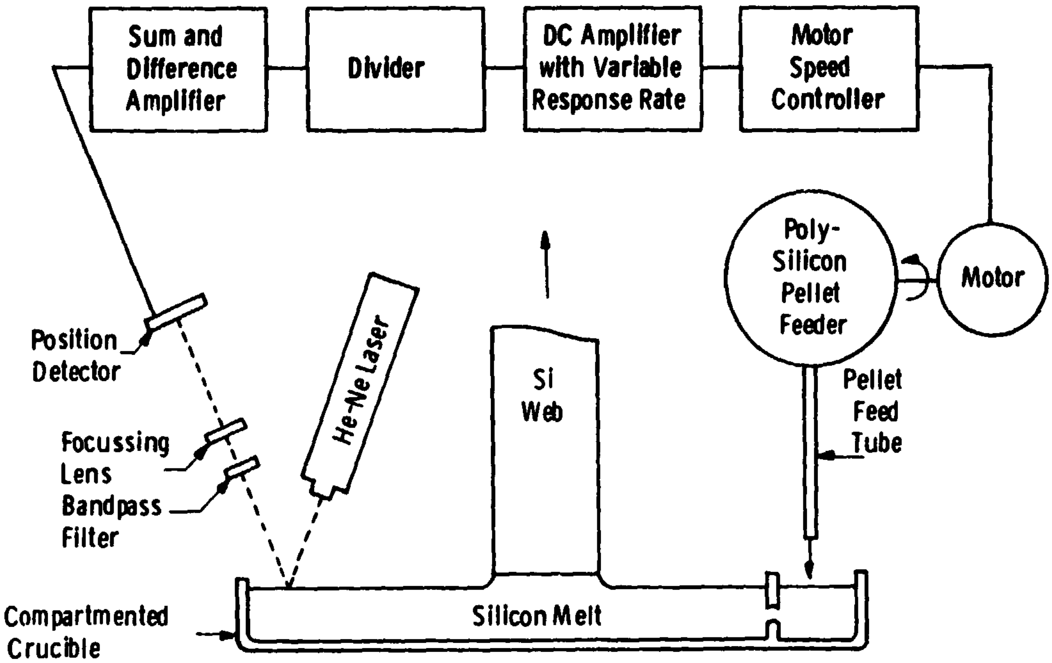
Constant Melt Level

- **Uses Reflected Laser Beam And Solid State Position Detector**
- **Maintains Melt Level To Within One Tenth Millimeter**
- **Continuously Variable Polysilicon Feed Rate**
- **Insensitive To Changes In Laser Beam Intensity**

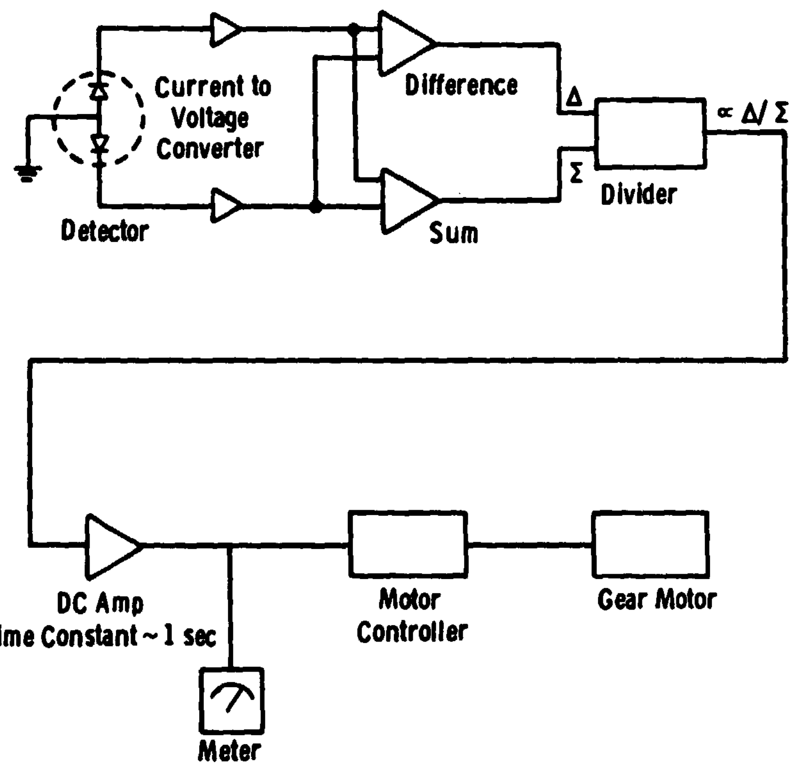
Simplified Sketch of Melt Replenishment System



Closed-Loop Circuit for Control of Melt Level



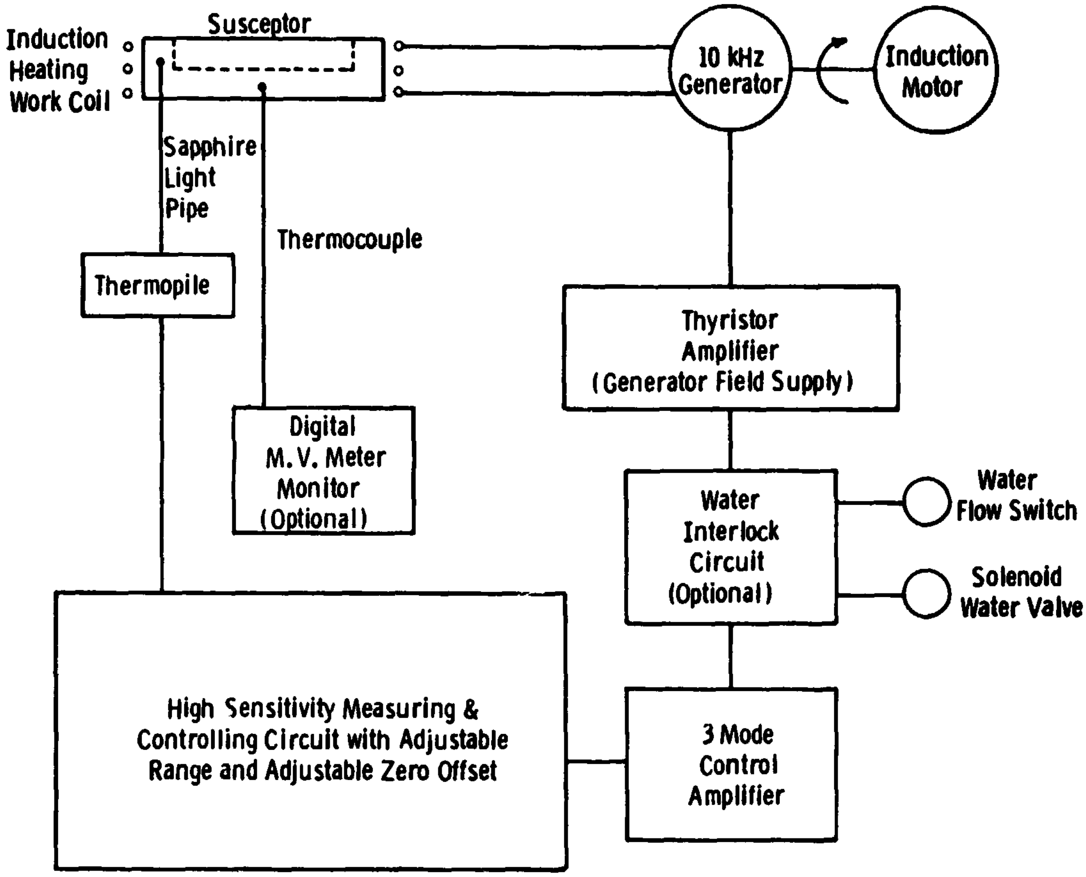
Melt Replenishment Control System



Constant Temperature

- **Uses Low-Cost Commercial Controller**
- **Controller Factory Modified For Web Growth**

Web Temperature Control System

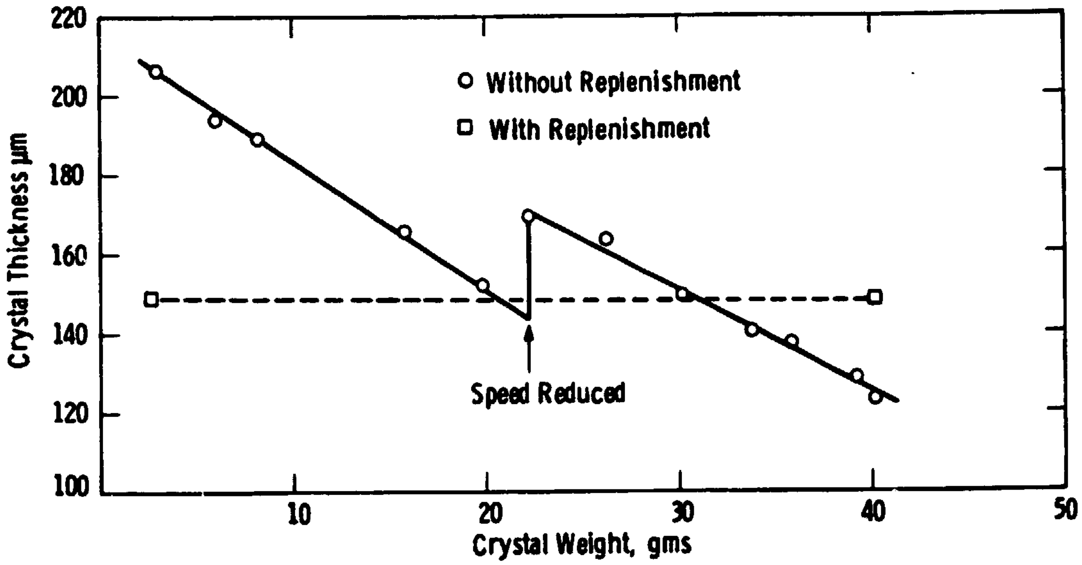


Constant Width of Growth

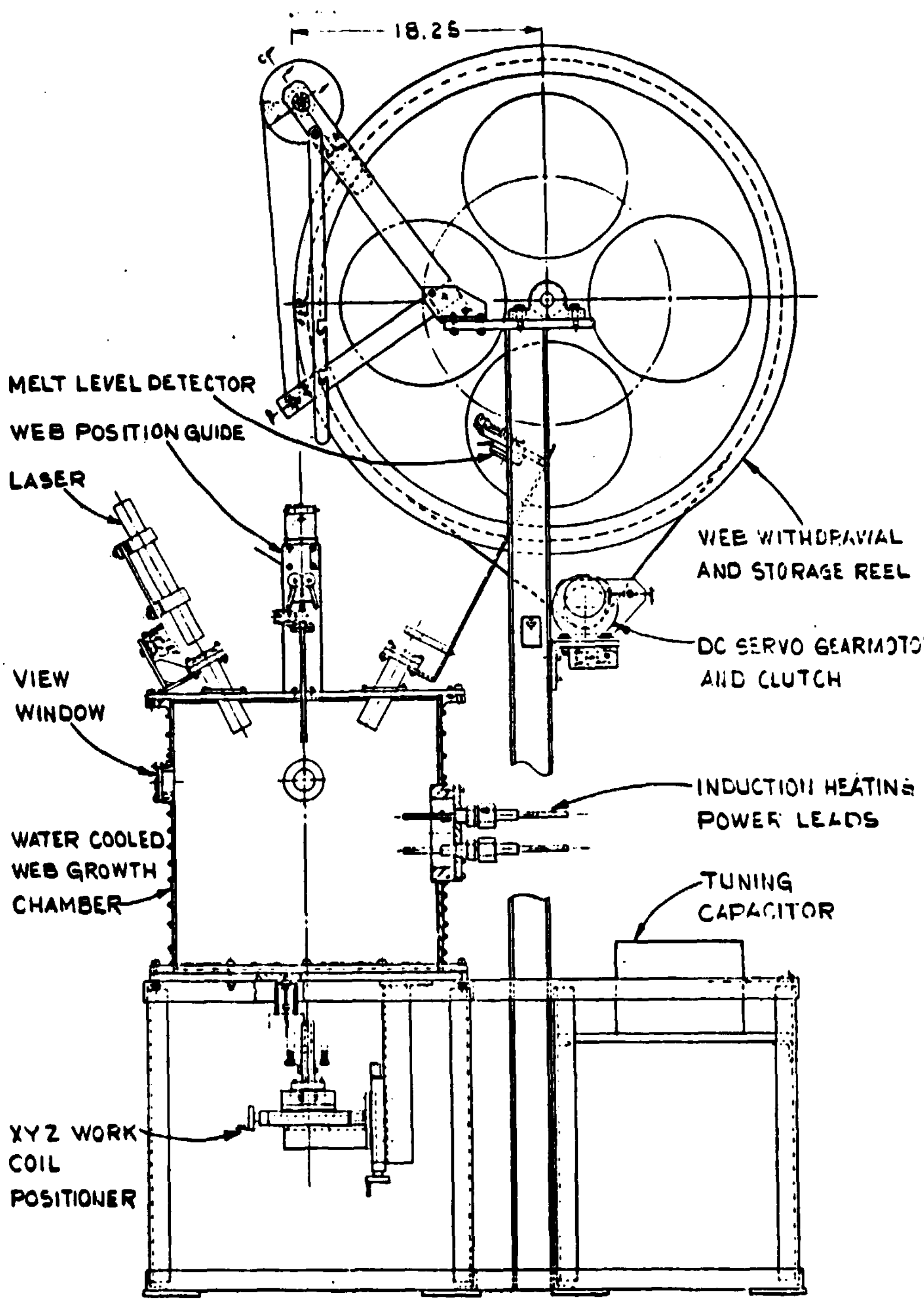
- **Uses Low-Cost Passive Thermal Shields - No Electronics, No Moving Parts**
- **Controls To Within One Millimeter**
- **Simplified Operation - Requires Little Operator Skill Or Training**
- **Proven In Widths To 3 Centimeters**
- **Development Of Greater Width In Progress**

Constant Thickness of Growth

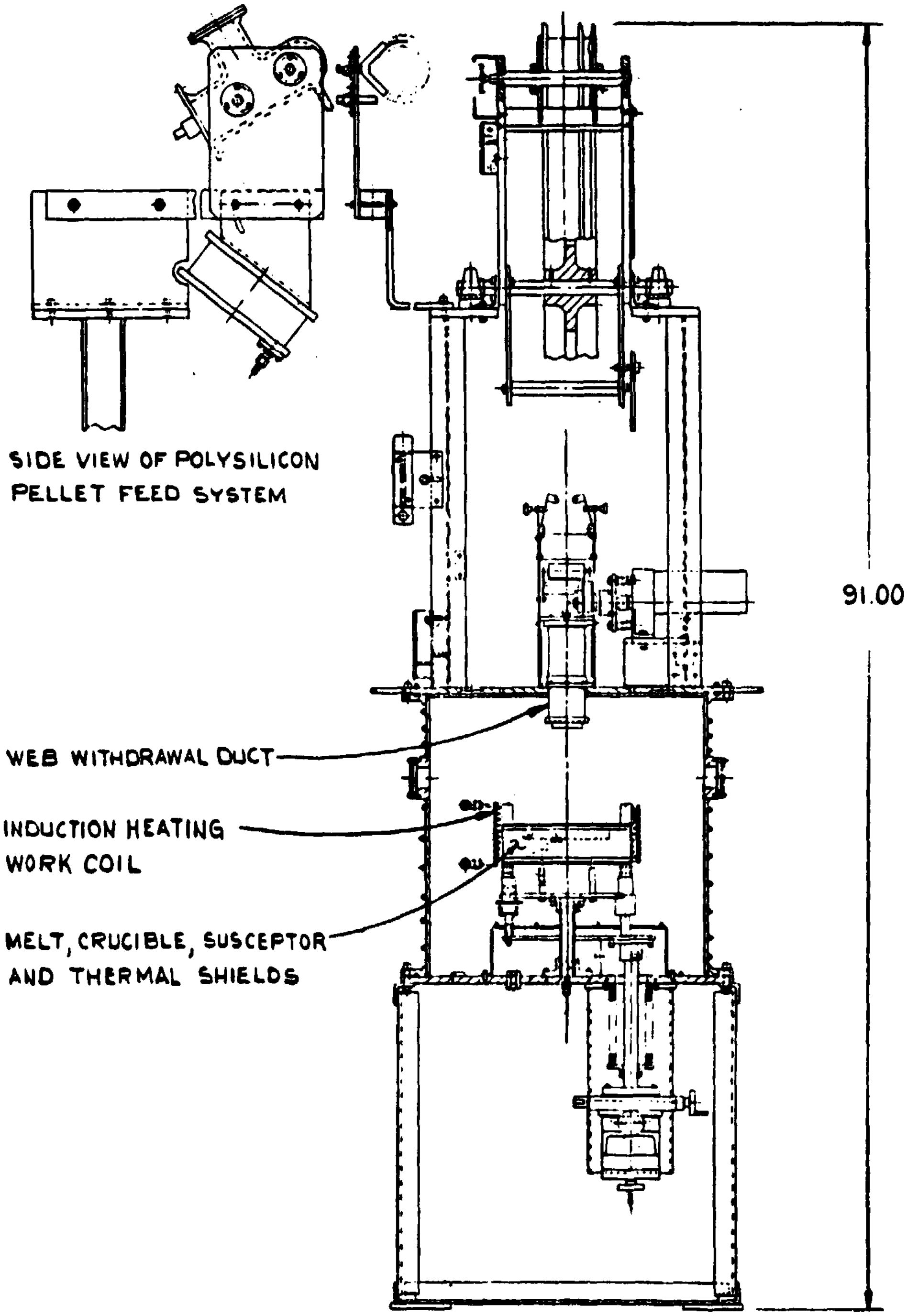
- **Based On Thickness/Speed Relationship At Constant Melt Level**
- **Uses Commercial DC Servo Motor To Produce Constant Pull Speed And Thickness**

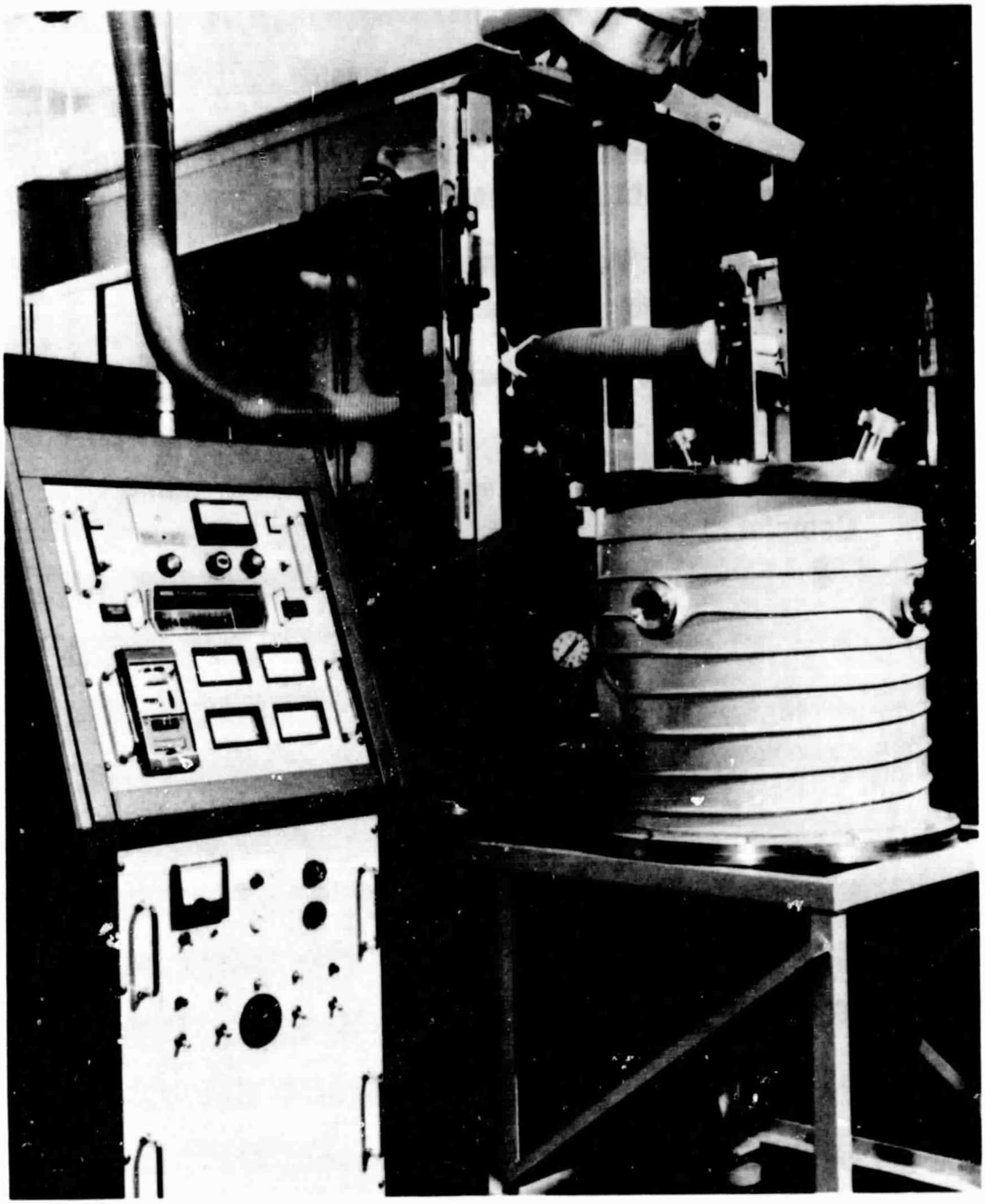


Experimental Web Growth Furnace: Side View



Front View


SIDE VIEW OF POLYSILICON
PELLET FEED SYSTEM
WEB WITHDRAWAL DUCT
INDUCTION HEATING
WORK COIL
MELT, CRUCIBLE, SUSCEPTOR
AND THERMAL SHIELDS
91.00



Experimental Silicon Web Growth Machine Nearing Completion of Assembly

Summary

Wider Growth Development

- Computer Models Developed And Verified By Correlation With Experimental Results
- Application Of Models Under Way To Identify Acceptable Web Temperature Profiles
- Development Of Web Growth System Thermal Configuration Started
- Construction Of Experimental Web Growth Machine Completed

LARGE-AREA SILICON SHEET BY EFG

MOBIL TYCO SOLAR ENERGY CORP.

1981 Goals

- STUDY OF MEANS TO REDUCE STRESS IN EFG RIBBON GROWN AT 4 cm/MIN AND IMPROVE FLATNESS AT 200 μm THICKNESS
- DEMONSTRATE 12% EFFICIENCY ON LARGE AREA CELLS MADE FROM RIBBON GROWN AT HIGH SPEEDS
- DESIGN, FABRICATION AND TESTING OF NEW MULTIPLE RIBBON FURNACE (LARGELY AT MOBIL TYCO'S EXPENSE).

Multiple-Ribbon Furnaces: Status

MULTIPLE RIBBON FURNACE WORK ON THE CONTRACT HAS BEEN TERMINATED AS OF OCTOBER 1, 1981.

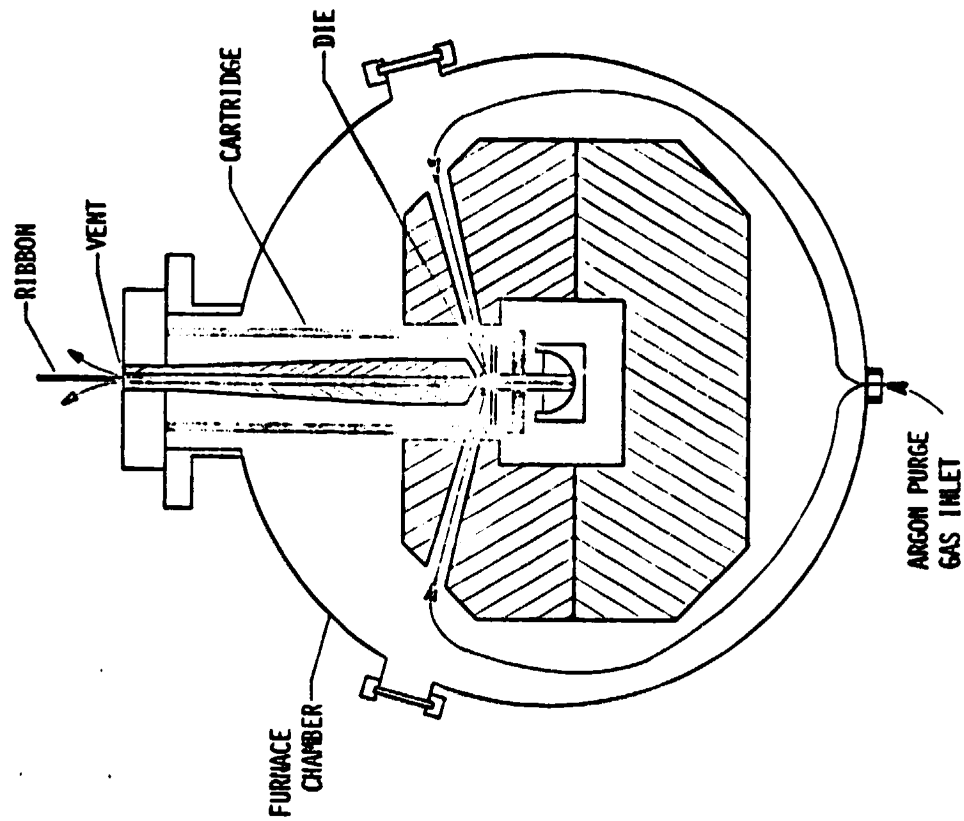
- FURNACE 16 OPERATION ALREADY CEASED IN JULY DUE TO START-UP OF FURNACE 21 CONSTRUCTION.
- FURNACE 21 CONSTRUCTION IS ON SCHEDULE AND IS NOW SUPPORTED ENTIRELY BY MOBIL TYCO.

  THIS FURNACE PROVIDES FOR GROWTH OF FOUR 10 cm WIDE RIBBON

New Multiple-Ribbon Furnace 21 Comparison With Furnace 16

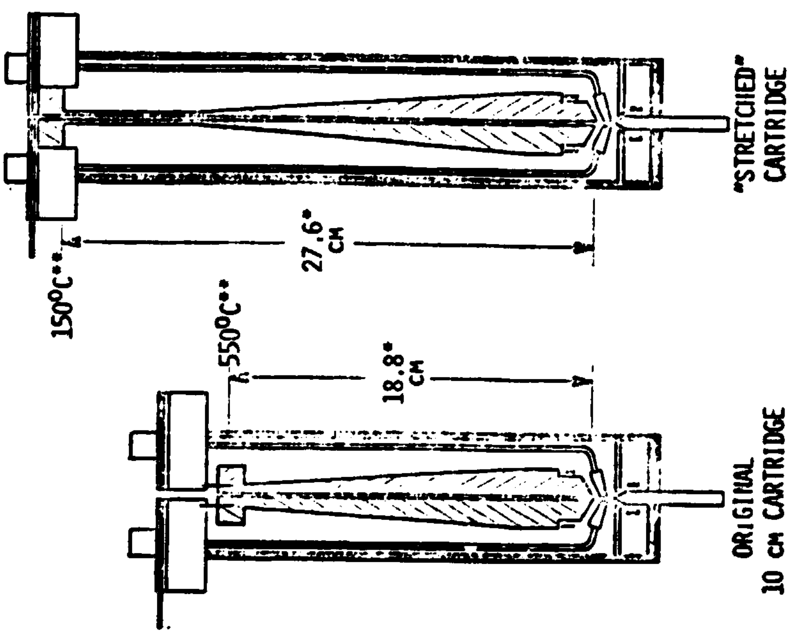
ITEM	FURNACE 16	FURNACE 21
NUMBER OF 10 cm CARTRIDGES	3	4
CARTRIDGE DESIGN	STANDARD	NEW DESIGN (DEVELOPED IN FURNACE 17)
SILICON FEEDSTOCK	SOLID RODS	CHIPS (NEW REPLENISHMENT SYSTEM)
AMBIENT CONTROL	MAIN ZONE ARGON PURGE	CARTRIDGE (DEVELOPED IN FURNACE 17)

ORIGINAL PAGE IS
OF POOR QUALITY



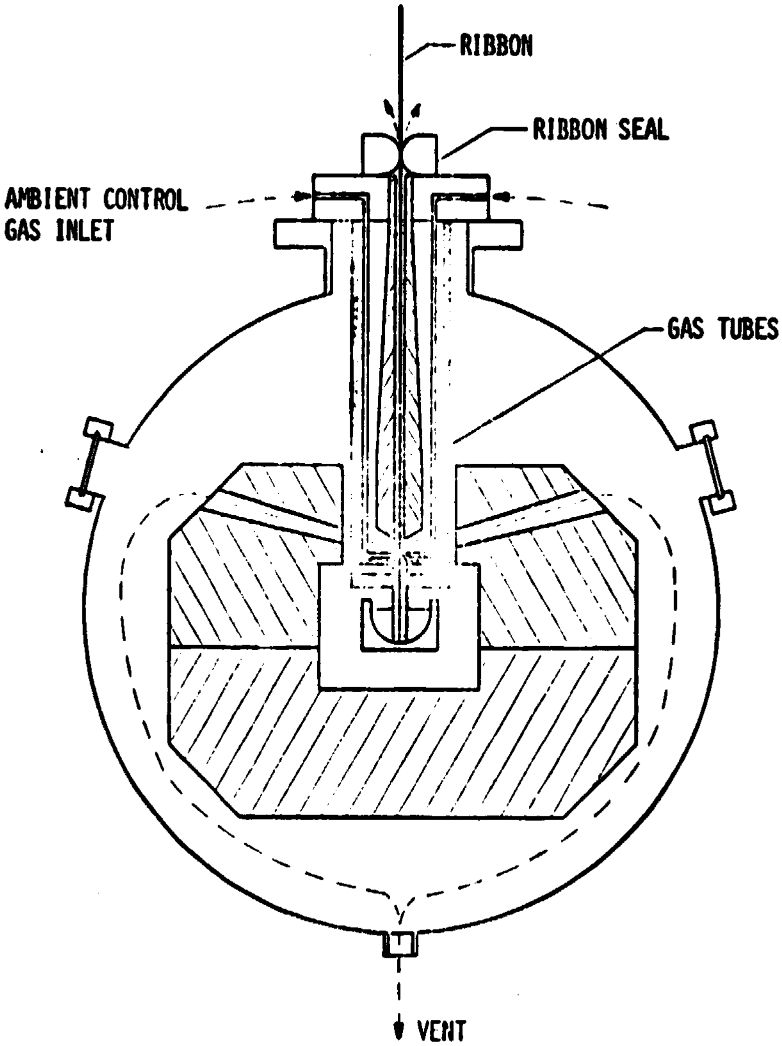
EFG FURNACE WITHOUT RIBBON SEAL

A LARGE PURGE GAS FLOW PREVENTS BACKSTREAMING, BUT ENTRAINS ALL GAS SPECIES PRESENT IN THE FURNACE PAST MENISCUS AND HOT RIBBON.



*EFFECTIVE LENGTH OF LINEAR COOLING PLATES.

**ENDING TEMPERATURE OF CONTROLLED GRADIENT REGION.



EFG FURNACE WITH RIBBON SEAL

PURGING GAS OF CONTROLLED COMPOSITION IS ADDED THROUGH THE CARTRIDGE AND DIRECTED AT THE GROWTH INTERFACE

New Multiple Ribbon Furnace Features

- GROWTH CONTROLS:
  - SAME TV SYSTEM AS ON FURNACE 16, BUT WITH VIDEO ANALYSIS CONTROLS ON PANEL IN FRONT OF OPERATOR, AND ONE MONITOR WITH SWITCHING SYSTEM
  - BUILT-IN POWER MEASURING SYSTEM FOR CARTRIDGE HEATERS
- GENERAL REFINEMENTS:
  ALL SYSTEMS IMPROVED FOR GREATER RELIABILITY AND EASE OF OPERATION/MAINTENANCE
- DOCUMENTATION:
  ALL SYSTEM AND COMPONENTS OF MACHINE FORMALLY DOCUMENTED TO A DEGREE WHICH WOULD PERMIT FUTURE MACHINES TO BE BUILT BY OUTSIDE VENDORS.
- FACILITIES:
  NEWLY CONSTRUCTED ROOM WITH HUMIDITY CONTROL, FILTERED AIR, AND NON-PARTICULATING SURFACES

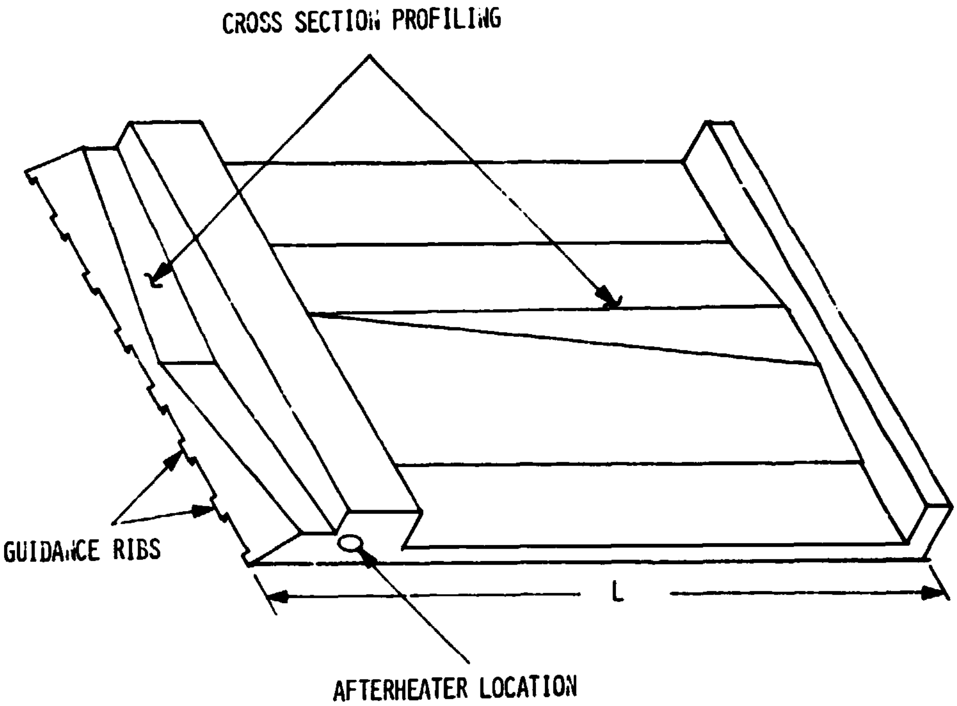
Basic Studies: 10-cm-Wide Ribbon

- OPTIMIZATION STUDIES ARE IN PROGRESS IN FURNACE 17:
  - GOOD GROWTH CONDITIONS HAVE BEEN ACHIEVED AT 4 CM/MINUTE AND PROGRESS MADE IN REDUCING NON-FLATNESS AND STRESS-INDUCED BUCKLING FOR 200 μm (8 MILS) RIBBON.
  - LARGE (~50 cm^2) AREA CELL EFFICIENCIES OF 10-11% HAVE BEEN OBTAINED.
- DEVELOPMENT OF CARTRIDGE WITHOUT CONVENTIONAL COLD SHOES IN FURNACE 18:
  - FURNACE AND CONTROL ELECTRONICS REFURBISHED.
  - GROWTH AT 2-2.5 CM/MINUTE ACHIEVED.
- CHARACTERIZATION STUDIES WILL EXAMINE PARAMETERS NEEDED TO OPTIMIZE RIBBON PROPERTIES
  - GROWTH PARAMETERS SUCH AS CO_2 CONCENTRATION, CO_2/O_2 MIX, RESISTIVITY, QUARTZ IN THE MELT.
  - HEAT TREATMENT CONDITIONS: TEMPERATURE, AMBIENT AND TIME, AND RIBBON SURFACE CONDITION.
  - COMPARISON OF RIBBON FROM FURNACES 17 (COLD SHOES) AND FURNACE 18 (NO COLD SHOES) IS PLANNED.

Approaches in Stress Studies

- CHANGES IN LINEAR COOLING PLATE HORIZONTAL ISOTHERMS HAS CHANGED BUCKLE PATTERN.
- STRETCHED CARTRIDGE HAS BEEN SUCCESSFULLY OPERATED AND RESULTED IN REDUCED STRESSES AND BUCKLE AMPLITUDE.
- WAYS TO IMPROVE ALIGNMENT HAVE BEEN DEFINED AND IMPLEMENTED.
- GUIDANCE INFLUENCE, RELATED TO CONSTRICTION IN GROWTH SLOT, IS UNDER STUDY.
- <u>FUTURE PLANS:</u>
  - MEASURE TEMPERATURE FIELDS WITH DIFFERENT LINEAR COOLING PLATE GEOMETRIES.
  - DEVELOP MODEL FOR STRESSES IN RIBBON.

Linear Cooling Plate Design Modifications



Ribbon Quality Basic Studies

GOAL: ACHIEVE 12% EFFICIENT CELLS ON RIBBON GROWN AT HIGH SPEEDS.

FACTORS UNDER CONSIDERATION:

- GROWTH PARAMETERS (AMBIENT, SPEED, DIE DESIGN).
- IMPURITIES CONTRIBUTED BY COLD SHOES, MOLYBDENUM PARTS.
- COLD SHOES VERSUS NO COLD SHOES THERMAL EFFECTS.
- MENISCUS HEIGHT (BULK MELT LEVEL, DIE DESIGN).

Summary of Averaged Solar-Cell Data for 10-cm-Wide Ribbon Grown With Varying Melt Doping Levels
(ELH Light, 100 mW/cm2, 28°C, No AR Coating)

RUN NO.	MELT DOPING (Ω-cm)	MEASURED ρ (Ω-cm)	SPEED (cm/min)	GROWTH AMBIENT (% CO_2/ppm O_2)	CELL PARAMETERS			
					J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
17-177-1A	0.2	0.3	3.5	0 / 0	11.7	0.510	0.753	4.5
17-179-1B		0.3	3.5	0.5 / 50	14.7	0.540	0.745	5.9
17-117	1.0	1.2	3.8	0 / 0	13.7	0.486	0.747	5.0
17-162-1A		1.1	3.2	0 / 0	15.6	0.503	0.762	6.0
17-175-1C		1.2	3.5	0.3 / 30	17.3	0.534	0.732	6.8
17-178-1B		1.6	3.5	0.5 / 50	16.8	0.524	0.750	6.6
17-178-1E		1.6	3.5	1.0 /100	16.0	0.518	0.723	6.0
17-139-1B	4.0	5.4	3.2	0 / 0	15.5	0.470	0.734	5.4
17-136-2A		5.9	3.1	0 / 0	15.8	0.472	0.681	5.1
17-136-2B		6.0	3.0	0.14/ 14	18.6	0.519	0.717	6.9
17-181-1B		3.5	3.5	0.23/ 23	18.2	0.512	0.736	6.9
17-139-2A		5.0	3.3	0.23/ 0	19.0	0.513	0.753	7.3
17-136-2C		5.9	3.1	0.33/ 33	19.2	0.524	0.746	7.5
17-181-1D		3.5	3.5	1.0 /100	17.4	0.512	0.745	6.6

Large-Area (50 cm^2) Solar Cell Data for 10-cm-Wide Ribbon From Several Growth Runs
(ELH Light, 100 mW/cm^2, 28°C, AR Coated)

RUN NO.	MELT DOPING (Ω-cm)	SPEED (cm/min)	GROWTH AMBIENT	CELL PARAMETERS J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
BEST PREVIOUS RESULTS - APRIL, 1981							
17-143	1	2.5	0.2% CO_2	26.5	0.523	0.608	8.4
				26.5	0.531	0.705	9.9
				27.7	0.534	0.677	10.0
				26.2	0.530	0.699	9.7
				25.7	0.495	0.407	5.2
				28.6	0.538	0.634	9.7
				30.3	0.528	0.521	8.3
				26.2	0.529	0.717	9.9
				26.6	0.533	0.696	9.9
OPTIMIZED CO_2/O_2 - OCTOBER, 1981							
17-175	1	3.5	0.3% CO_2 + 30 ppm O_2	26.8	0.539	0.735	10.6
				27.7	0.545	0.706	10.7
				26.1	0.537	0.720	10.1
				27.5	0.547	0.641	9.7
17-181	4	3.5	0.23% CO_2 + 23 ppm O_2	29.0	0.525	0.603	9.2
				28.8	0.522	0.713	10.7

MATERIAL EVALUATION

APPLIED SOLAR ENERGY CORP.

1. UCP (SEMIX)
   A. BASELINE PROCESS
   B. GETTERING TEST
   C. ADVANCE PROCESS
   D. INGOT #5848-13C (BASELINE PROCESS)

2. LASS (ENERGY MATERIAL)
   A. ADVANCE PROCESSES

Baseline Process

1. DEEP JUNCTION (0.3∼0.4um) BY $POCl_3$.
2. METALLIZATION (BOTH FRONT AND BACK) BY EVAPORATION THROUGH METAL SHADOW MASK.
   - Ti-Pd-Ag
3. SiO AR COATING: ∼ 35% CURRENT GAIN.
4. NO BSF

Advanced Process

1. SHALLOW JUNCTION (∼ 0.2um)
2. NARROW FRONT GRIDLINE BY PHOTORESIST PROCESS.
3. BSF
4. MULTI-LAYER AR COATING: ∼42% CURRENT GAIN.

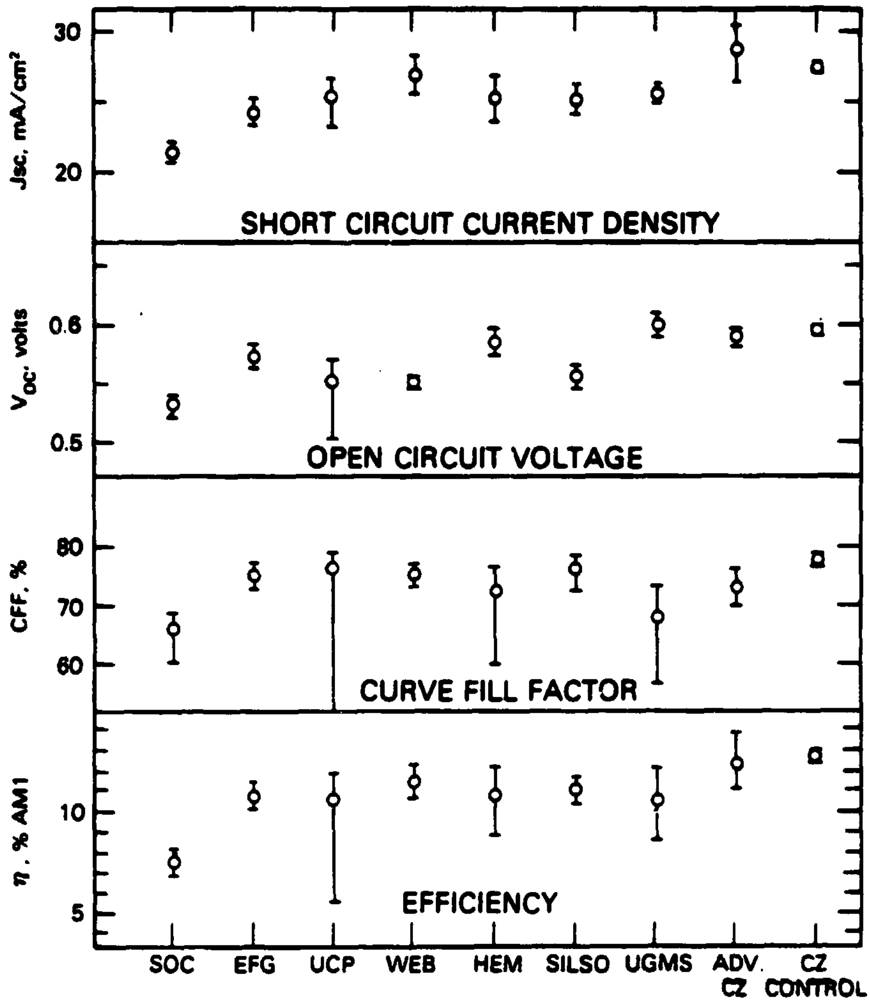
Summary of Results: Semix Materials

WAFER #		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)	NO.OF CELLS
A-5	Ave. S.D. Range	559 6 546-570	25.1 0.9 23.0-26.4	78 1 74-79	10.9 0.5 9.9-11.8	14
B-3	Ave. S.D. Range	554 9 540-568	25.1 1.2 23.1-26.9	76 2 70-79	10.6 0.7 9.6-12.0	15
C-1	Ave. S.D. Range	550 5 542-558	25.5 0.5 24.4-26.4	76 1 73-77	10.7 0.4 9.7-11.1	12
D-3	Ave. S.D. Range	557 8 542-568	26.0 0.7 25.0-26.8	76 2 70-78	11.0 .6 9.5-11.7	12
E-7	Ave. S.D. Range	543 14 504-558	25.4 0.6 24.0-26.1	72 10 44-78	9.9 1.5 5.5-11.2	12
F-3	Ave. S.D. Range	555 7 540-570	24.9 0.8 23.1-26.1	75 2 72-78	10.4 0.5 9.4-11.5	13
Combining All Wafers	Ave. Range	553 504-570	25.3 23.0-26.9	76 44-79	10.6 5.5-12.0	78
CZ Control	Ave. S.D. Range	586 - -	28.7 0.2 28.5-28.9	78 1 77-79	13.1 0.1 13.0-13.2	3

Effective Minority Diffusion Length Of Solar Cells Made From UCP Wafers

	CELL NO.	L_D(um)	Jsc(mA/cm^2) (No AR)
GOOD CELLS	A-5-10	48	18.6
	B-3-5	72	19.2
	D-3-1	63	18.7
AVE.CELLS	A-5-15	44	17.6
	C-1-14	48	17.6
	E-7-1	46	17.6
BAD CELLS	A-5-12	28	16.3
	B-3-2	23	16.2
	F-3-6	37	16.3
	CONTROL #2	177	20.5

Baseline Solar Cell Parameters



Summary of Gettering Results

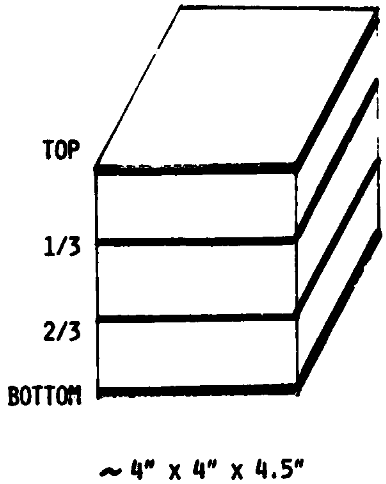
SILICON SHEETS

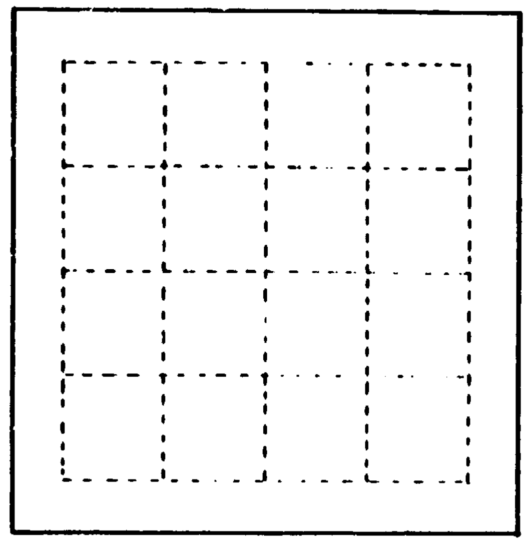
		Voc(mV)	Jsc(mA/cm^2)	CFF(%)	η (%)
D5	AVE. S.D. RANGE	557 7 546-564	25.8 .8 24.4-26.9	73 7 50-77	10.5 1.14 6.9-11.4
E5	AVE. S.D. RANGE	543.8 24.9 470-558	25.4 .7 23.6-26.4	67.7 12.7 31-76	9.4 2.0 3.6-10.8
T5	AVE. S.D. RANGE	554.6 16.9 498-570	25.0 .88 23.9-26.5	72 9 40-79	10.0 1.5 4.9-11.2
CZ CONTROL	AVE. S.D. RANGE	580 2.8 576-582	27.9 .46 27.4-28.5	75.5 2.1 73-78	12.2 .36 11.9-12.7

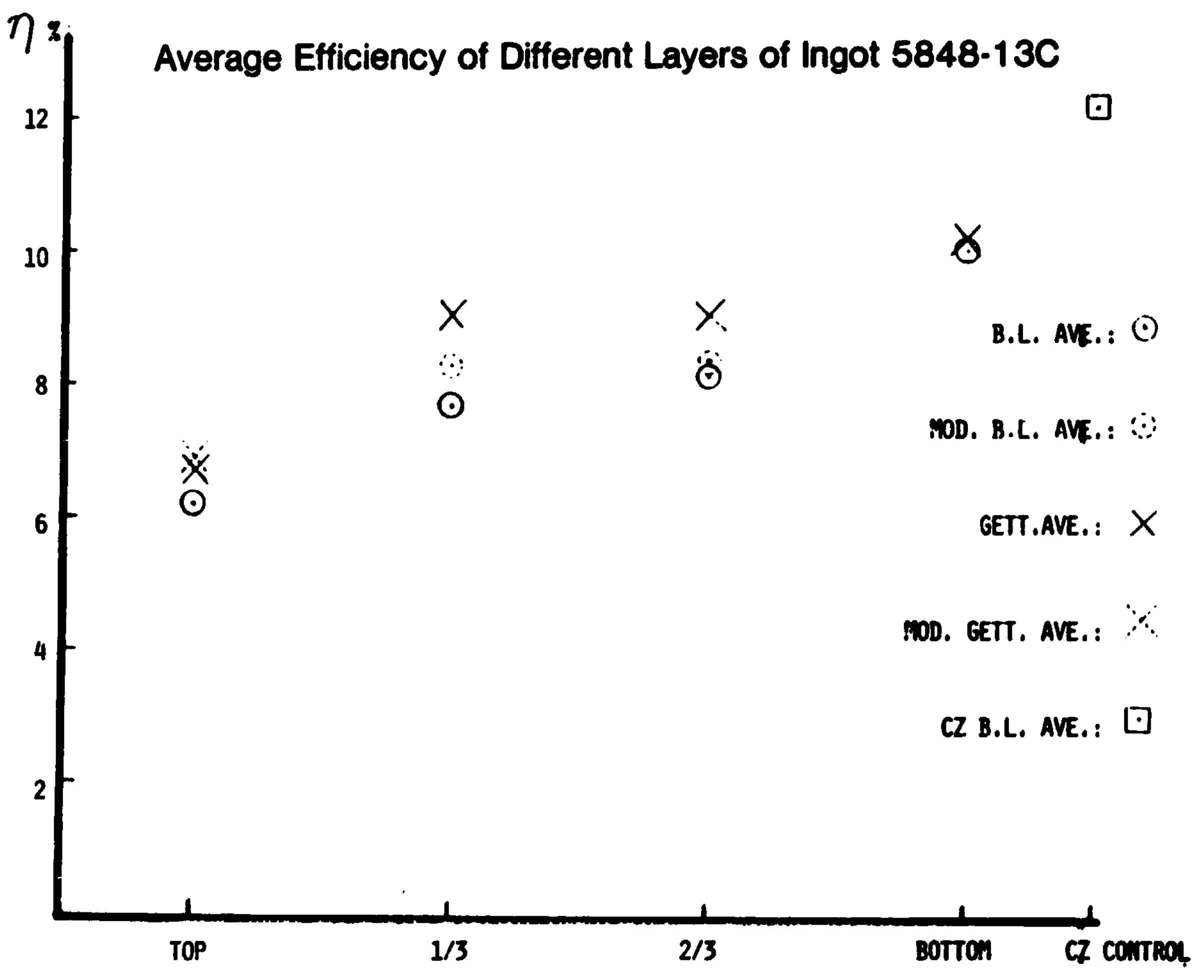
UCP Solar Cells With SJ, BSF by Evaporated Al, MLAR

		Voc(mV)	Jsc(mA/cm^2)	CFF (%)	(%)	BEST
UCP (12 CELLS)	AVE.	572	29.5	78	13.2	14.1%
	S.D.	7	.9	1	.6	
	RANGE	560-584	28.2-31.1	77-80	12.4-14.1	
CZ CONTROL CELLS	AVE.	595	31.7	80	15.1	15.4%
	S.D.	1	.4	1	.2	
	RANGE	594-596	31.2-32.2	79-81	14.7-15.4	

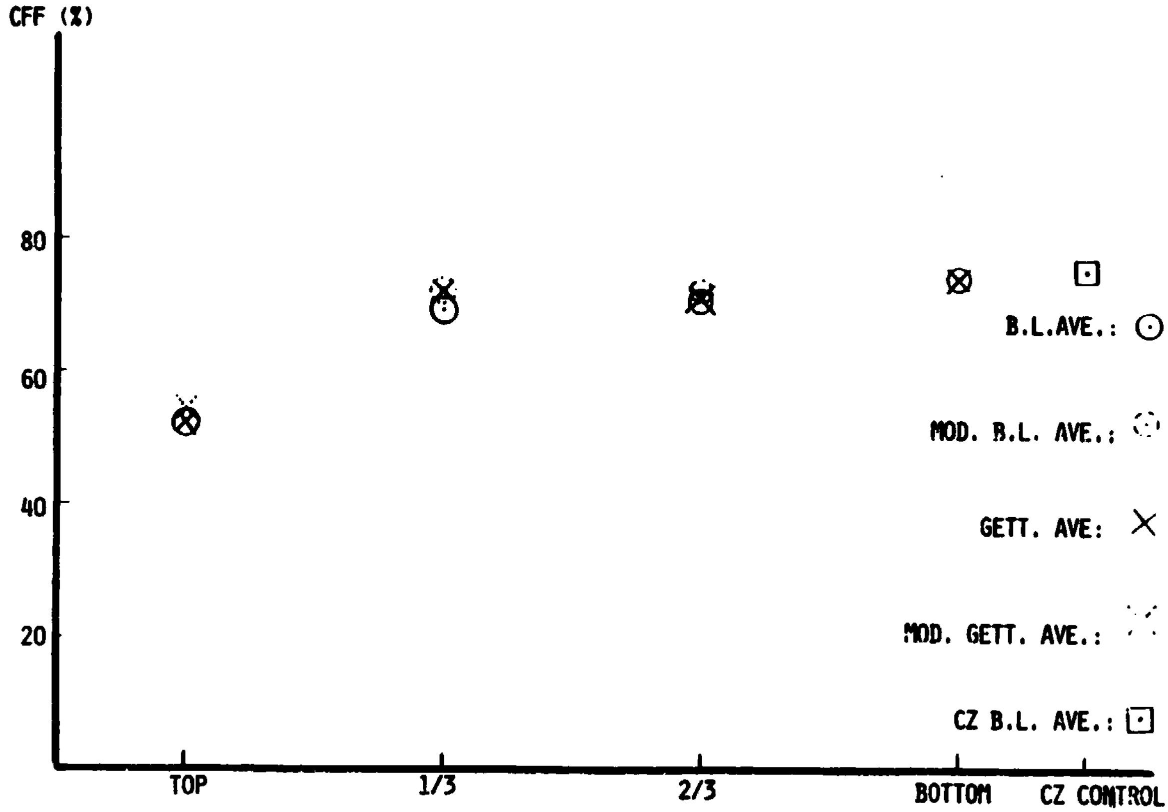
UCP ingot No. 5848-13C



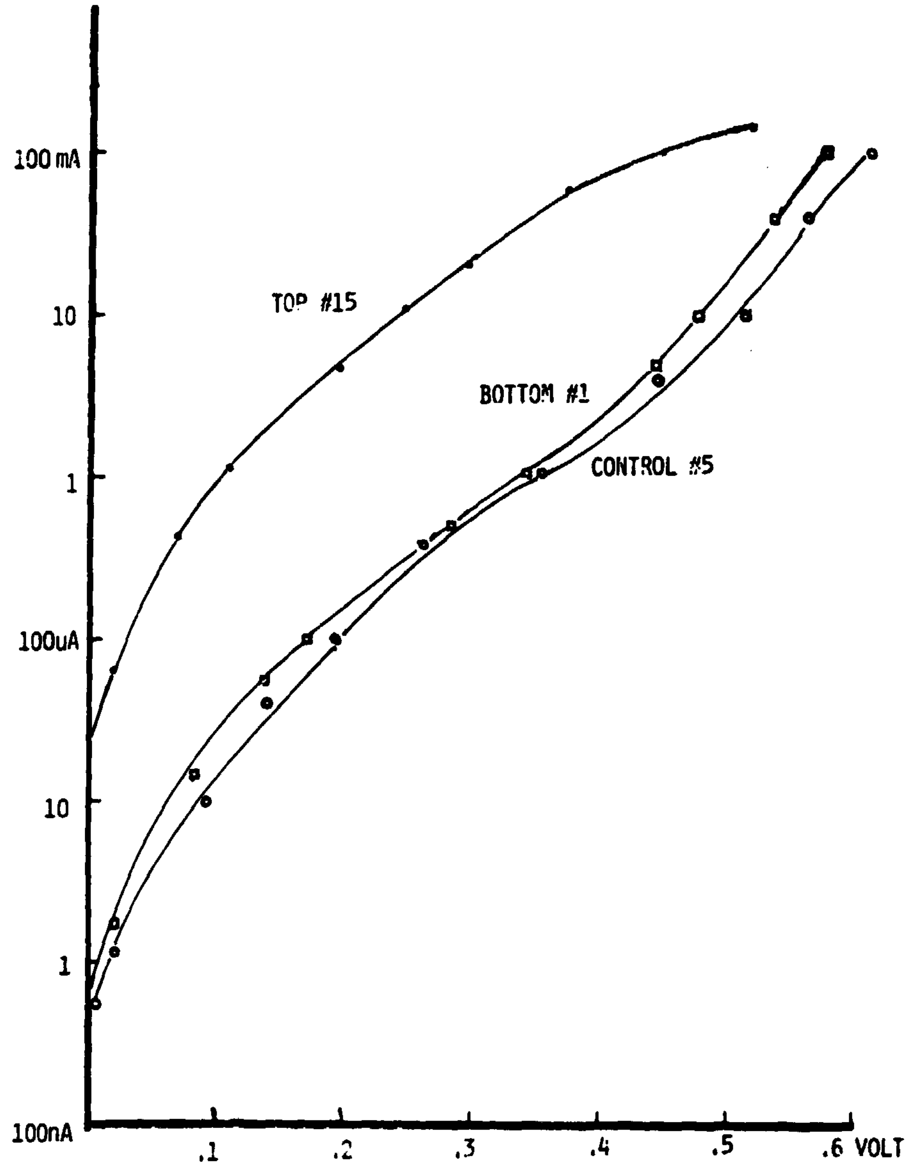




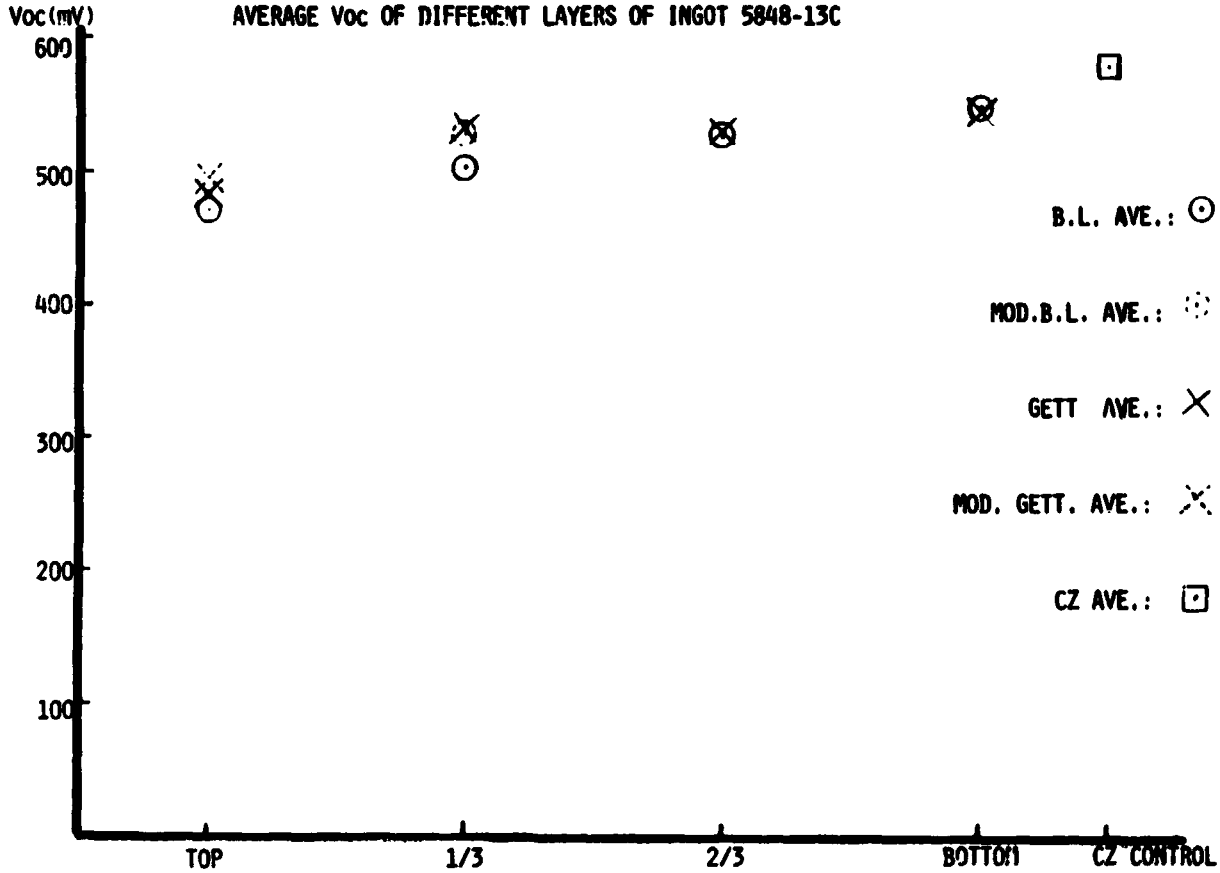
Average CFF (%) of Different Layers of Ingot 5848-13C



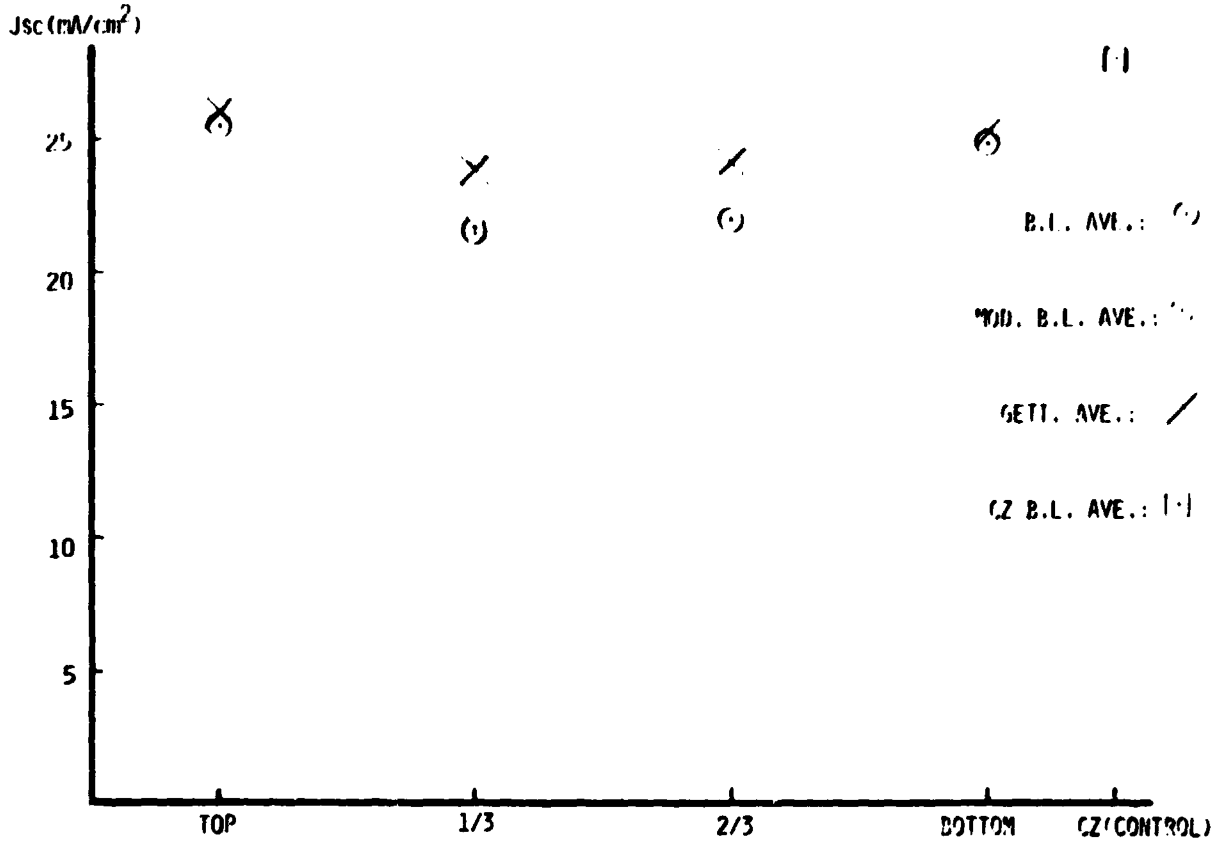
Dark Current of UCP Solar Cells



Average V_{OC} of Different Layers of Ingot 5848-13C



Average J_{SC} of Different Layers of Ingot 5848-13C



Minority Carrier Diffusion Length Of Selected Cells From Ingot 5848-13C

	BASELINE		GETTER PROCESS	
	CELL NO.	L_D (um)	CELL NO.	L_D (um)
TOP	1-2-8	26	1-4-8	51
	1-2-13	35	1-4-13	53
	1-2-15	31	1-4-15	57
1/3	2-9-2	22	2-10-2	51
	2-9-3	9	2-10-3	22
	2-9-16	22	2-10-16	29
2/3	3-9-5	15	3-10-5	34
	3-9-6	14	3-10-6	17
	3-9-12	19	3-10-12	41
BOTTOM	4-9-1	27	4-10-1	51
	4-9-8	31	4-10-8	47
	4-9-15	22	4-10-15	42
CZ CONTROL	1	133		
	3	135		
	5	133		

Summary of Results of the LASS Materials SJ, BSR, MLAR

		Voc (mV)	Jsc (mA/cm^2)	CFF (%)	η (%)
LASS	AVE.	562	26	73	10.7
	S.D.	9	1.3	5	1.16
	RANGE	552-574	24.1-27.4	65-77	9.4-11.8
CONTROL	AVE.	581	30.8	75	13.4
	S.D.	2	0.5	2	0.2
	RANGE	580-584	30.4-31.3	73-76	13.2-13.5

STUDY OF ABRASIVE WEAR RATE OF SILICON USING n-ALCOHOLS

UNIVERSITY OF ILLINOIS

R. Reaves, J. Clark and S. Danyluk

INTRODUCTION

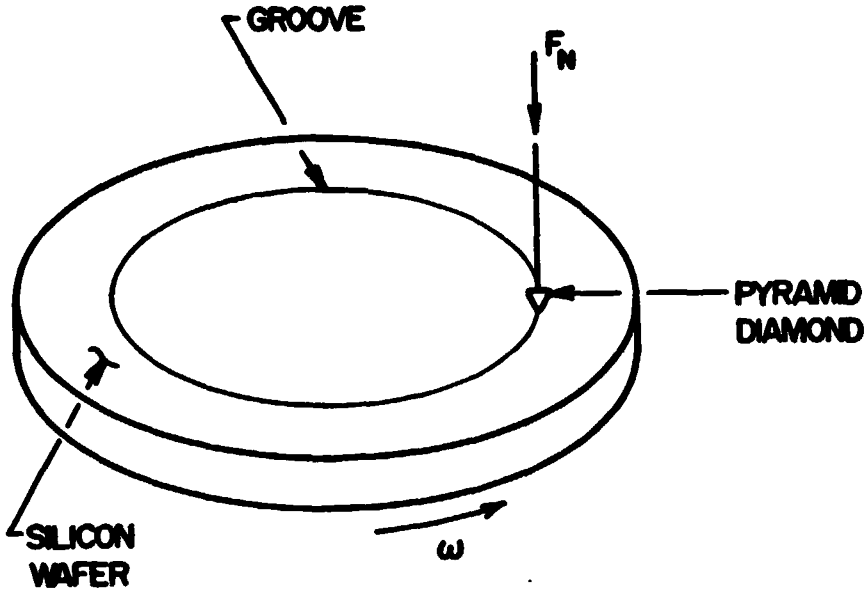
The abrasion wear rate of (100) p-type silicon is found to depend on fluids in contact with the silicon surface. An experiment was designed for abrading silicon by a pyramid diamond and the effects of fluid and force on the abrading pyramid diamond were examined. The abraded surfaces were examined by scanning electron microscopy which revealed a change in surface deformation mechanism with type of fluid. Acoustic signals produced during abrasion can also be used to distinguish between changes in mechanism when the fluid is varied.

OBJECTIVE

1. Study Wear Rate as Influenced by Fluid Adsorption.
2. Identify Critical Parameters in Wear Rate.
3. Develop a Model for Abrasive Wear.

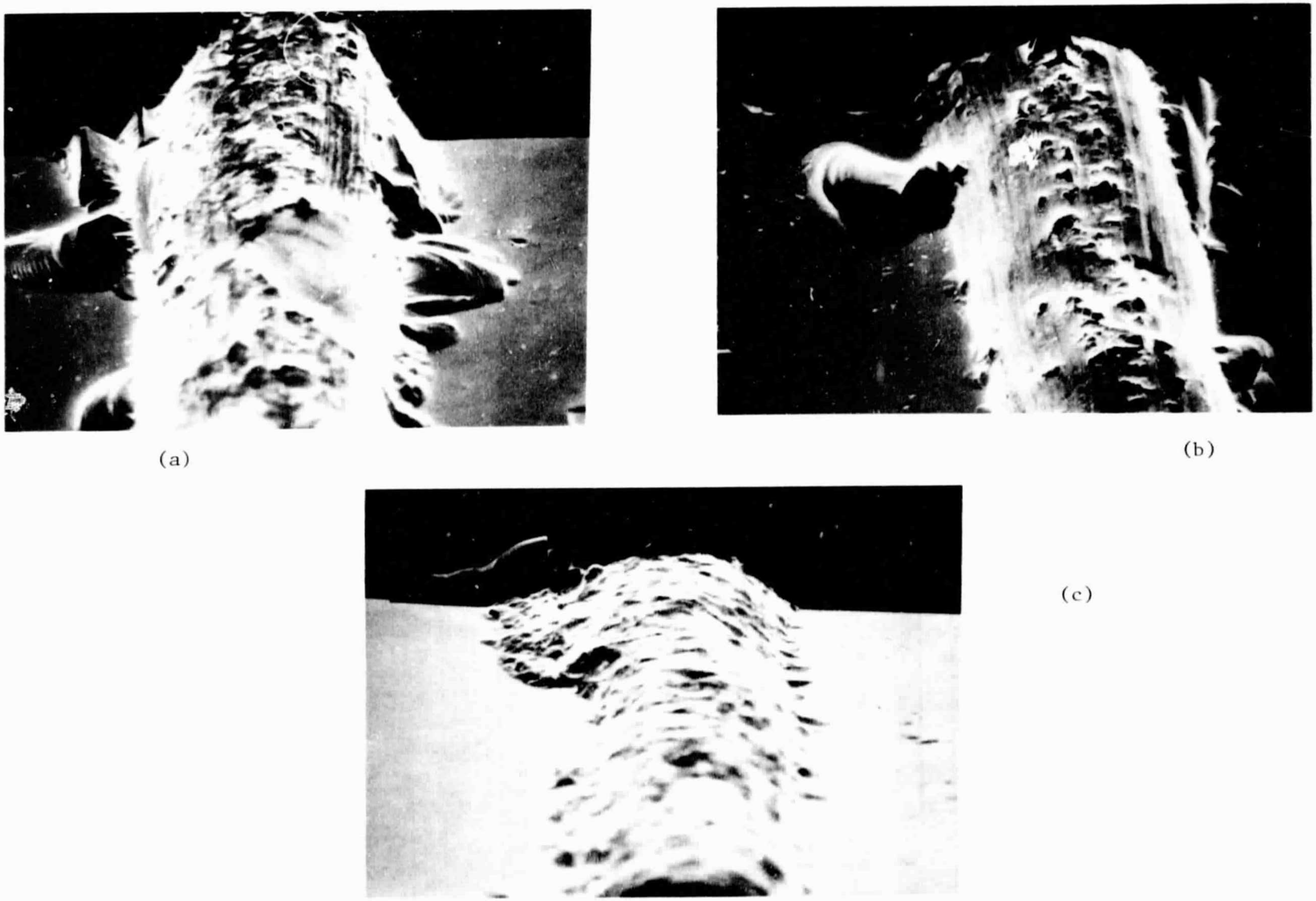
APPROACH

1. Simulate abrasive cutting by a Multiple Scratch Test Measure Wear Rate as a function of systematically controlled variables.
2. SEM; optical microscopy; acoustic signatures examination of wear.



A schematic representation of the experiment for abrading silicon by diamond. Grooves are produced on the silicon wafer and the groove depth is measured as a function of time, fluid environment and normal force on the diamond. The surface of the silicon is examined by scanning electron microscopy (SEM) for mode of silicon removal.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

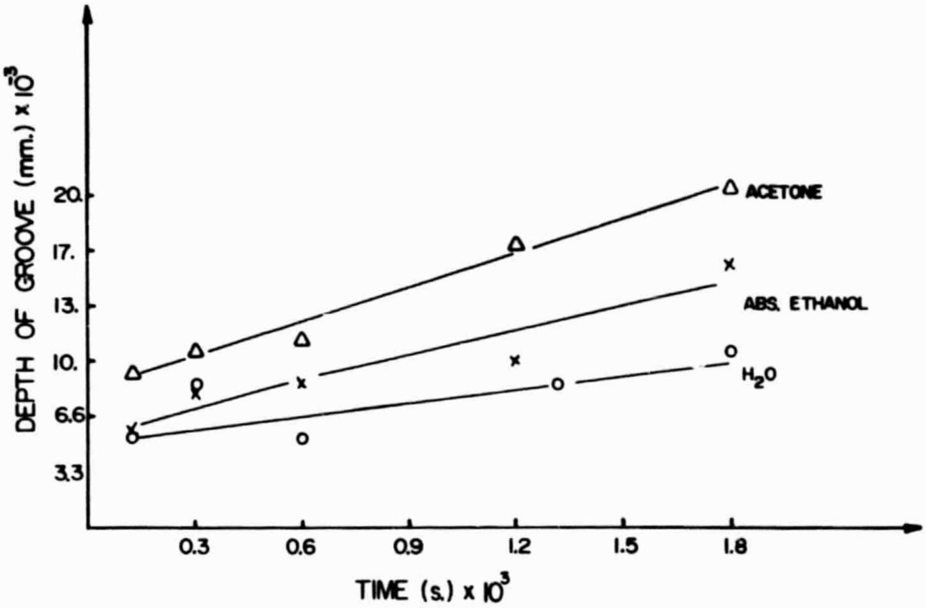


(a)

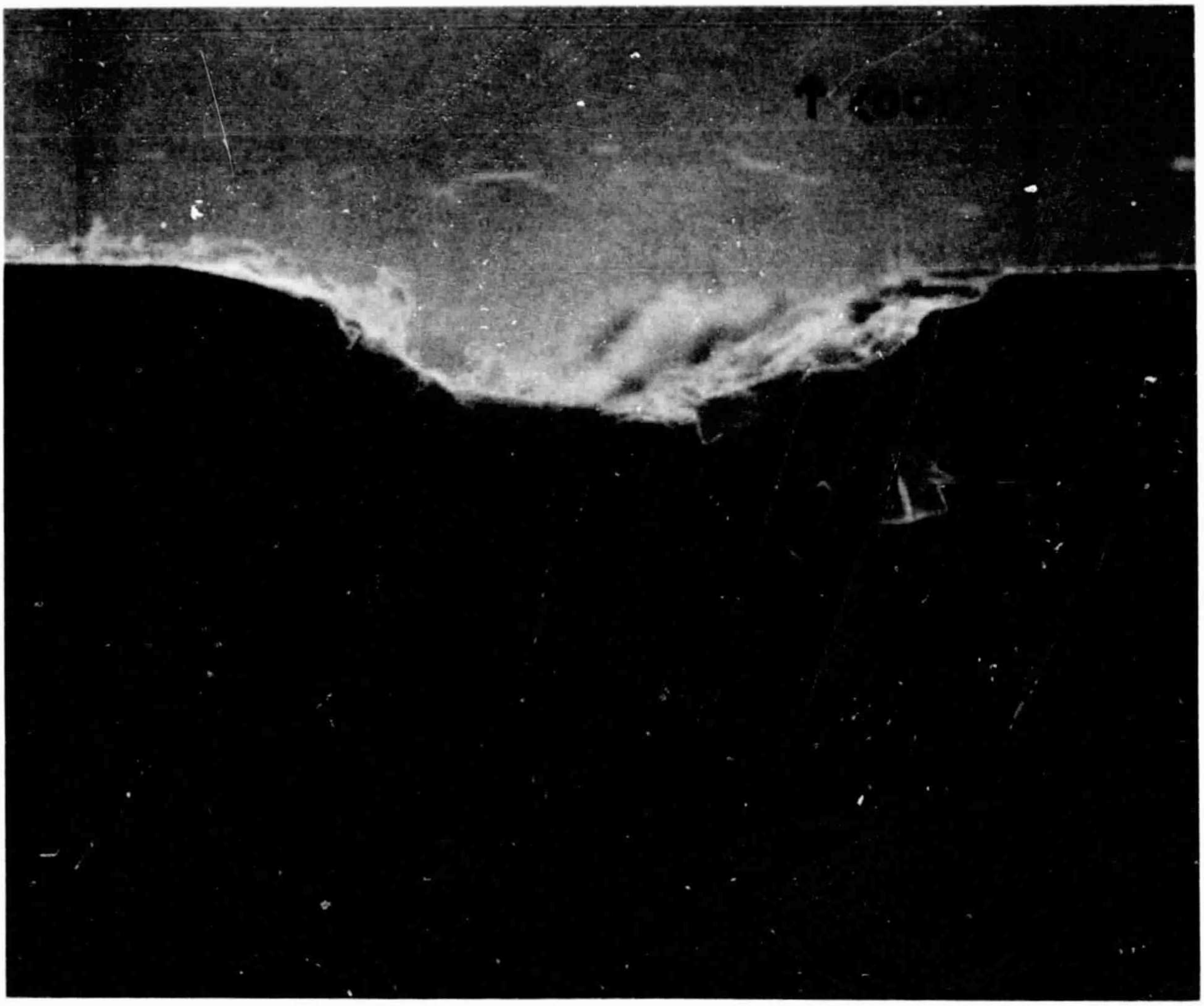
(b)

(c)

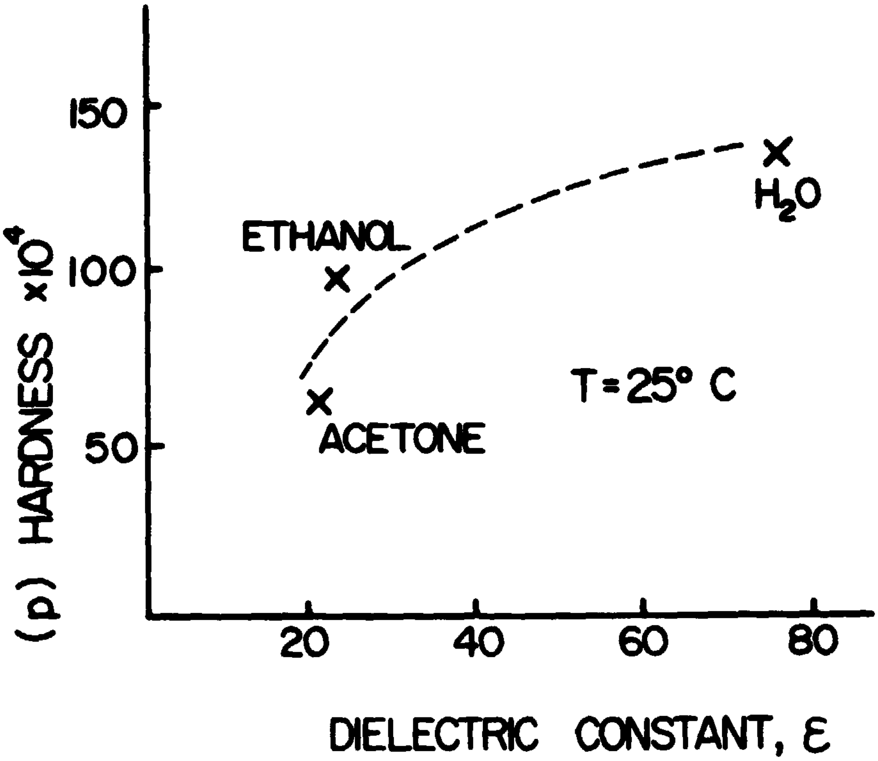
SEM photographs of Si abraded at room temperature by a pyramid diamond in the presence of (a) H_2O, (b) absolute ethanol and (c) acetone. Normal force on the diamond = 62g; abrasion time = 1.8×10^3 s, all other conditions constant. Mechanism changes from brittle (a) to ductile (b) and a mixture of the two (c).



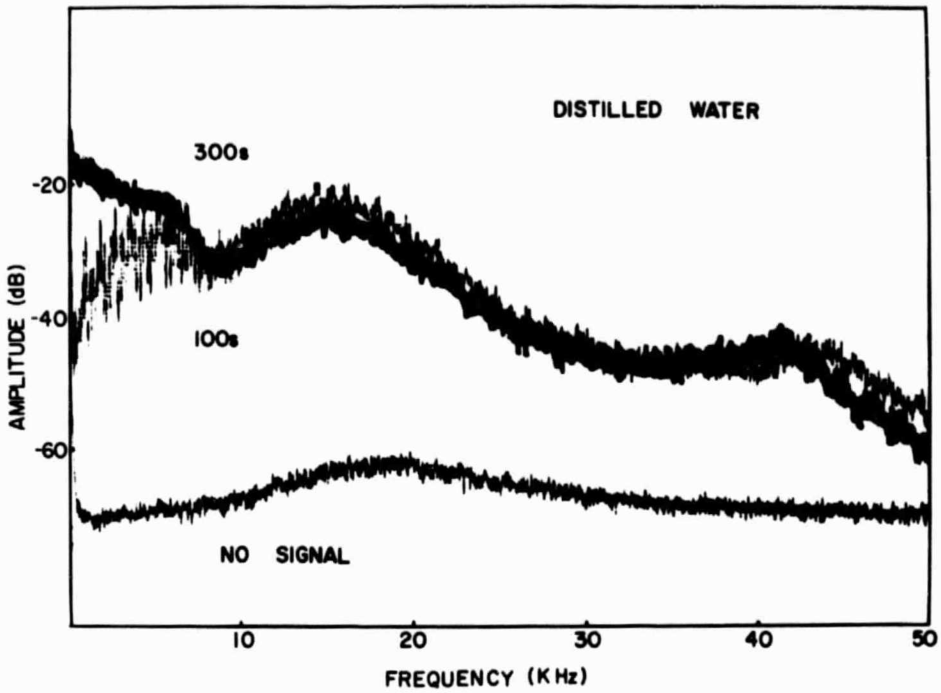
The depth of the groove in silicon formed by a pyramid diamond at room temperature vs abrasion time. The fluid environment was varied. Normal force was F_N = 62 g.



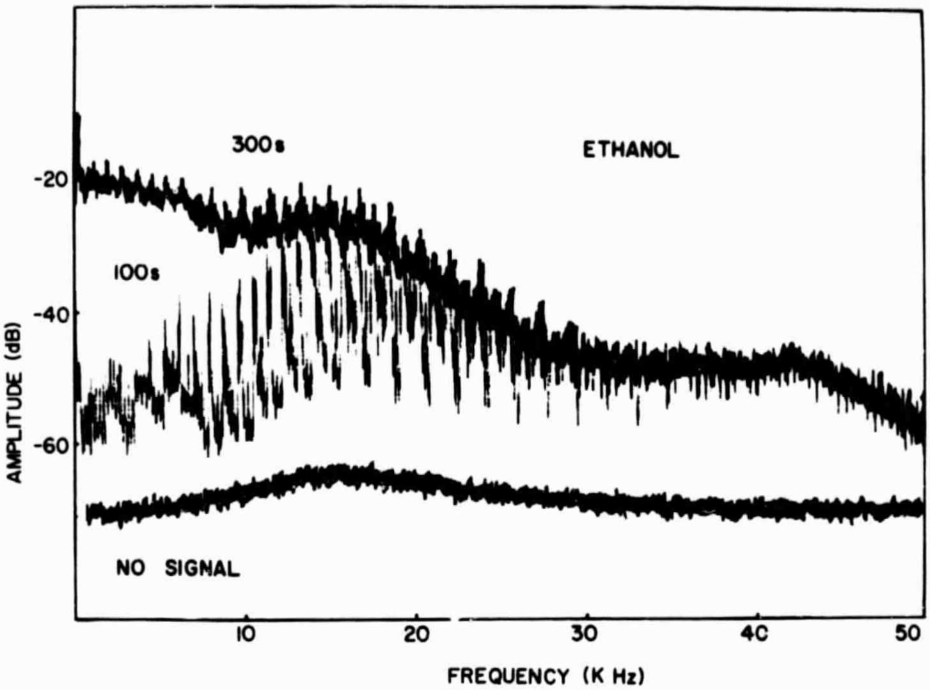
SEM micrograph of a cross section of a silicon wafer with cracks emanating from the groove bottom. Conditions were: F_n = 62 g, distilled water and 600 s abrading time.



The surface hardness of silicon (kg/mm^2) versus the dielectric constant of the fluid in contact with the silicon during the abrading process. The normal force F_N was 62 g and the abrading time was 1.8×10^3 s. The silicon surface is softened by ~70% in the presence of acetone.



Log Amplitude (dB) vs. frequency (Hz) of a pyramid diamond stylus abrading (100) p-type silicon. The three curves are for (a) no-signal (b) signal after 100s of abrasion and (c) signal after 300s of abrasion. $F_n = 40_g$, ω = 0.56 rps, distilled water.



Log Amplitude (dB) vs. frequency (Hz) of a pyramid diamond stylus abrading (100) p-type silicon. The three curves are for (a) no-signal (b) signal after 100s of abrasion and (c) signal after 300s of abrasion. F_n= 40s, ω = 0.56 rps, absolute ethyl alcohol.

SUMMARY OF RESULTS

1. Wear rate may vary by 100% (acetone - Ethanol - H_2O).
2. Mechanism changes due to fluid-surface effects.
3. Acoustic signature can distinguish between changes in mechanism.

ENVIRONMENTAL ISOLATION RESEARCH TASK

C.D. Coulbert, Chairman

ENCAPSULATION ENGINEERING

Development and characterization of pottants, covers, adhesives and sealants continues at Springborn Laboratories (Enfield, Connecticut). Development of an industrially ready butyl acrylate casting syrup was completed. The formulation is UV-stabilized and may be cured with a non-hazardous initiator. The catalyzed syrup is stable at room temperature and cures in 18 minutes at 60°C. The investigation of aliphatic polyurethane syrups was also continued and prototype formulations are available that exhibit rapid cure, low modulus, low mixed viscosity and good optical transmission.

A series of anti-soiling treatments on glass and plastic cover films were deployed outdoors to determine the efficiency of soil resistance. Based on standard cell measurements, fluorosilane coatings were found to give significant improvement over control after five months' exposure.

Continuing studies of adhesion chemistry for bonding pottants to cther module components resulted in primers for EVA, butyl acrylate and urethane to glass, Tedlar and Mylar cover materials.

Experiments to evaluate outdoor protective coatings for hardboard and mild-steel substrate candidates were started and test specimens were put into field exposure.

Evaluation of materials under RS/4 radiation is continuing. After 9000 hours' exposure the new EMA formulation shows no change in optical or mechanical properties. The outer cover candidates, X-22417 acrylic film and Tedlar 100BG, have also survived unchanged. The butyl acrylate and aliphatic urethane pottants are also undamaged after 4000 hours' exposure. Outdoor photothermal aging racks are being constructed for studying the heat-accelerated degradation of polymers in natural sunlight.

In the Spectrolab program to develop and validate a module design analysis methodology to predict the optical, thermal, structural, and electrical isolation response of module encapsulation systems, testing of the experimental hardware has been completed. Workup of the raw data is in process. Initial results of the optical and electrical isolation data show good correlation with the model predictions.

The Illinois Tool Works (ITW) contract was initiated to investigate, develop and demonstrate the capability of producing operational solar cells with metallizations and AR coatings deposited by gasless ion plating.

Metallization of 100-mm-dia, 5-mm thick p/n wafers has resulted in producing cells with an average efficiency of 12.49% (AM1). The ion-plated metallizations consisted of a nickel-copper front electrode pattern and a titanium-copper back contact, which were then solder dipped.

Efforts to metallize n/p-type wafers have concentrated on improving the ohmic contact made to the back surface of the wafer (base wafer with boron impurity 2 cm). A 65Ti/35Al alloy has been shown to produce good ohmic contacts of 160 m2-cm^2 when deposited on nondegenerate p-type silicon, but not consistently enough yet to allow production of cells from n/p wafers.

Results from a SAMIS analysis based on the production of 50 MW/year of 100-mm-diameter round cells (p/n wafers) with nickel-copper front and titanium-copper back metallizations plus SiO_x AR coating indicate a cost of \$.056/W_p (1980 \$) for the metallization and AR coating.

JPL Document No. 5101-177, <u>Photovoltaic Module Encapsulation Design and Material Section: Vol. I</u> (internal document) has been published in preliminary form. Recipients are requested to review and notify the authors at JPL of any errors or omissions by the end of January 1982. New information and revisions will be incorporated in an updated report to be published in the summer of 1982.

MATERIAL DURABILITY AND LIFE ASSESSMENT

Photothermal characterization of EVA (Springborn 9918), EMA (Gulf) and PVB (Monsanto) have been completed for up to 800 hours of testing. A detailed description of these tests will be incorporated in a JPL report. Results have been used to rank candidate pottants and outer covers materials and also to obtain data to validate and refine degradation mechanisms of EVA (Springborn 9918) being developed by the University of Toronto.

Testing of polymerizable UV absorbers and UV-absorbing acrylic copolymers has resulted in understanding of degradation mechanism of 2¼(2-hydroxy 5-vinylphenyl) 2H-benzotriazole ½-co-mma, supplied by the University of Massachusetts, and Acrylar films obtained from 3M Corp.

Controlled-environment-reactor (CER) testing of these materials and of Tedlar UTB 300 (Du Pont) is in progress.

Construction of the full-scale UV gradient tester is nearly complete. Components have been procured and received. Design of the chamber has been completed. The effect of photothermal stresses in 2 x 4-ft modules in presence of water vapor and of liquid water will be investigated in this chamber. These tests will be used to refine and validate the photohydrothermal interface degradation and corrosion model proposed by the Rockwell Science Center.

An experimental technique for measuring ac impedance has been used by Rockwell Science Center to characterize the changes in the electrical properties of modules exposed to simulated environments. Corrosive attack or moisture-induced mechanical failure of current-carrying components effectively places additional resistances in series with the module and leads to high I^2R power loss. The ac impedances of a number of modules undergoing the Battelle accelerated test have been analyzed. The results showed that an equivalent resistor and capacitor representing failed interconnects lie in series with the cells.

Experiments designed by Rockwell to study the influence of moisture diffusion on solar cell performance have shown that conducting paths develop at cracks, within the encapsulant, or at the encapsulant-substrate interface. By decreasing the shunt resistance, R_{sh}, these additional paths may dissipate the photo-excited state and limit the power of the cell. A fiber-board-backed, EVA-encapsulated and fluorocarbon-covered two-cell module was subjected to a controlled cyclic hydrothermal stress. Analyses of the module at intervals during the treatment showed irreversible decrements in R_{sh} correlating with the hydrothermal cycle. Introduction of an artificially produced crack also decreased R_{sh}.

Additional work has demonstrated the specific influence of corrosion on delamination of an encapsulant from a metal surface. Results of experiments initiated during this period suggest that the loss of adhesion at metal-encapsulant interfaces gives rise to a particular set of problems not encountered for non-conducting interfaces. A simple test to assess the significance of separate anodic or cathodic processes has been applied to primed (A11861-1) and unprimed EVA-encapsulated metal surfaces to study the effects on interface bond integrity.

The photodegradation of EVA at ambient temperatures as predicted by the University of Toronto computer model is essentially that of the ethylene segments. The mechanical model for photooxidation consists of 31 or 32 elementary reactions, which include photochemical decomposition of ketone and hydroperoxide (since these are early culprits in degradation). No allowance has yet been made for (1) the different reactivities of secondary and tertiary C-H groups, (2) the restricted diffusion of polymeric radicals in the solid state, (3) temperature cycling in an outdoor environment, (4) light and dark periods in a daily cycle, (5) the effect of additives and residues, or (6) the crosslinking of EVA before application. However, results from the simulation (using the best available rate data) show:

(1) The photooxidation process has a long induction period of up to several years, followed by a rapid deterioration.

(2) The chemical changes that result lead to:

- (a) The formation of polar alcohols and acids that could affect wettability and electrical resistance of the polymers.
- (b) The formation of ketones that could become conjugated, leading to discoloration and further molecular scission which also affects physical properties.
- (c) Possible crosslinking through alkoxy radicals coupling in a cage to form peroxide linkages that could cause the polymer to shrink and hence tear or pull away from connections and supports in a module-failure mode.

MATERIALS DEVELOPMENT

SPRINGBORN LABORATORIES, INC.

P. Willis

Ethylene Methyl Acrylate (EMA)

FORMULA NO. 13439

- INDUSTRIAL EVALUATION SAMPLES AVAILABLE FROM SPRINGBORN LABORATORIES
- PILOT PLANT QUANTITIES AVAILABLE FROM SPRINGBORN AT $0.40 PER SQUARE FOOT
- STANDARD SIZE: 24 INCH WIDTH, 0.018 INCH THICK
- ROLLS OF APPX. 230 LINEAR FEET W/NO RELEASE INTERLEAF
- PRIMER: SPRINGBORN A11861 (TO GLASS)

<u>THERMAL CREEP:</u>

- BLOCKS OF CURED EMA AND UNCURED RESIN HUNG IN AIR OVEN AT 90° C - NO CREEP IN EITHER
- MODULES UNDER TEST AT 90° C SHOW NO SIGNS OF CREEP AFTER THREE MONTHS
- EMA HAS NO ESTABLISHED GEL REQUIREMENT, MAY NOT REQUIRE CURE.
- POSSIBLE POTENTIAL FOR HIGH SPEED LAMINATION

Aliphatic Urethane (Prototype)

DEVELOPMENT ASSOCIATES, INC.

DESIGNATION: Z-2591

MIXED UNCURED SYRUP:		
VISCOSITY, CPS		500
GEL TIME, MINUTES (20°)		15
CURE	90°C /	15 MINUTES
CURED PROPERTIES:		
TENSILE STRENGTH, PSI		160
ELONGATION, %		115
YOUNG'S MODULUS, PSI		254
HARDNESS, SHORE D		60
INTEGRATED TRANSMISSION,%		91
GLASS TRANSITION, ° C		-30
COLOR		NONE
CUTOFF WAVELENGTH, NM		360*
FIELD PERFORMANCE		6 YEARS

* CONTAINS UV STABILIZER SYSTEM

- AVAILABLE - DEVELOPMENT ASSOCIATES, INC.
  NORTH KINGSTOWN, R.I.
- COST: APPX. $3.00 PER POUND
  (MIXED SYSTEM)
- CONTACT: MR. BUD NANNIG
- PRIMER:
  - TENTATIVE RECOMMENDATION
    DOW CORNING Z-6020
    (10% SOLUTION IN METHANOL)
  - BAKE PRIMERS ALSO
    AVAILABLE - DEVELOPMENT
    ASSOCIATES, INC.

Adhesion Experiments

EVA TO GLASS, SUBSTRATE, COVER FILMS:

EVA TO:	PRIMER	ADHESION, LBS/IN WIDTH CONTROL	2 HOURS BOILING WATER	2 WEEKS WATER IMMERSION
TEDLAR 100 BG-UT	11861	4.5	0	0
SUNADEX	11861	32.0	28.0	30.0
ACRYLAR	11861	APPX. 1	0	0
TEDLAR 200BS-WH	68040	>30	>30	>30
TEDLAR 100BG-UT	68040	6.5	6.5	7.8
SCOTCHPAR 10CP	107D	12	APPX. 3	27
KORAD - WHITE	107D	2.0	0	0
TEDLAR 100BG	107D	>30	13	>30
MILD STEEL	107D	2.5	2.5	3.0
MILD STEEL	11861	>30	>30	>30
ACRYLAR	107D	APPX. 10	0	0

- GOOD PRIMERS FOR STEEL, GLASS, TEDLARS AND SCOTCHPAR
- NEED PRIMER FOR ACRYLAR

EMA

EMA TO:	PRIMER	ADHESION, LBS/IN WIDTH CONTROL	2 HOURS BOILING WATER	2 WEEKS WATER IMMERSION
SUNADEX	11861	30	27.7	30
MILD STEEL	11861	12	14	15
TEDLAR 100 BG	68040	0.5	0	0
TEDLAR 200BS-WH	68040	2.0	LOW	LOW
SCOTCHPAR 20CP	107D	1.0	1.2	0.4

- GOOD PRIMERS FOR GLASS AND STEEL
- NEED PRIMERS FOR FILMS

CASTING TYPE POTTANTS

POLYURETHANE Z-2591

TO:	PRIMER	CONTROL	2 HOURS BOILING WATER	2 WEEKS WATER IMMERSION
SUNADEX	Z-6020 (10%)	31	45	37
TEDLAR 100	Z-6020	5	2.5	0
SCOTCHPAR 10CP	Z-6020	0.2	0	0
KORAD - WHITE	X-6020	5	3	2

BUTYL ACRYLATE A13870

TO:	PRIMER	CONTROL	2 HOURS BOILING WATER	2 WEEKS WATER IMMERSION
SUNADEX	Z-6032W	0.9	0.4	0.6
TEDLAR 100BG	Z-6032W	3.0	3.0	3.0
SCOTCHPAR 10CP	Z-6032W	2.0	0	0
KORAD - WHITE	Z-6032W	0.7	0	0
SUNADEX	14588	3.0	1.5	1.5

- PU - GLASS PRIMER, GOOD
- BA TO GLASS, TEDLAR, OK

C-3

SELF PRIMING POTTANTS[A.]

POTTANT/ PRIMER	SURFACE	BOND STRENGTH, LBS/IN CONTROL	2 WEEKS WATER IMMERSION	2 HOURS BOILING WATER
EVA A9918 Z-6030	SUNADEX	> 30	> 30	30
	MILD STEEL	30	30	30
EMA 13439 Z-6030	SUNADEX	V. HIGH	> 30	10
	MILD STEEL	10	10	>30
PU Z-2591 Z-6020	SUNADEX	2	1	0
	MILD STEEL	3	1	0
BA 13870 Z-6030	GLASS	0	NT	NT
	MILD STEEL	0	NT	NT

A. PRIMER COMPOUNDED IN AT A LEVEL OF 0.5%

- SELF PRIMING MODIFICATIONS EFFECTIVE IN EVA & EMA
- LONG TERM BOND DURABILITY?

RS/4 Sunlamp Exposure

MATERIAL	HOURS	% PROPERTY RETAINED (ASTM D-638) TENSILE	ELONGATION
3M ACRYLIC FILM X-22417	12,000	54%	100%
EMA BASE RESIN (UNCOMPOUNDED)	8,000	10%	10%
EMA A11877 (COMPOUNDED)	10,000	100%	100%
DUPONT TEDLAR 100 BG 30 UT	10,000	100%	100%
BUTYL ACRYLATE BASE FORMULATION	6,000	100%	150%
FLUOREX - A	9,000	100%	100%
POLYURETHANE * Z - 2341	3,000	100%	100%
REFERENCE:			
POLYETHYLENE UNSTABILIZED	500		10%
POLYPROPYLENE UNSTABILIZED	500		0%

*SLIGHT HAZE, TRANSMISSION OK

EVA POTTANT
(NO COVER FILM)

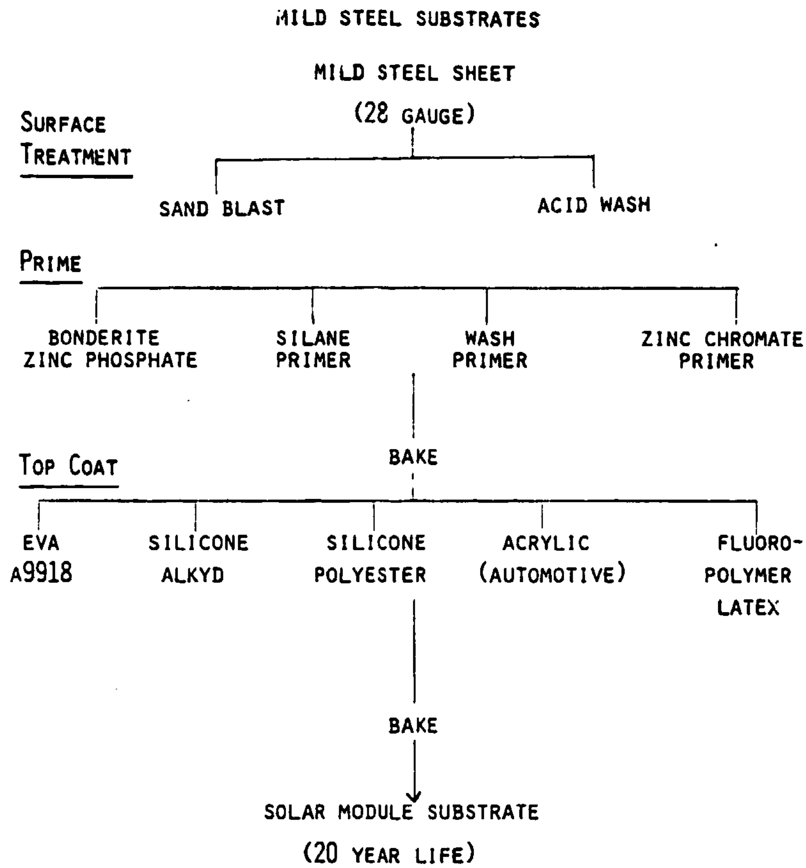
- CLEAR STABILIZED EVA EXPOSED 25,600 HOURS
  NO OBSERVABLE CHANGE

	TOTAL INTEGRATED TRANSMISSION (%)	ULTIMATE* ELONGATION (%)	TENSILE* STRENGTH (PSI)
CONTROL	91	510	1890
EXPOSED 25,600 HRS.	90	560	1870

- UNSTABILIZED ELVAX 150 (EVA) BECOMES SOFT, TACKY, - LOSES PHYSICAL PROPERTIES IN LESS THAN 1,000 HOURS

* ASTM D-638

Corrosion Protection Scheme



Corrosion Experiments

MILD STEEL SUBSTRATES

"MODULES" PREPARED WITH COATED STEEL
BUTYL SEALANT AND GASKET

		1,000 HOURS	
COATING	ADHESIVES	SALT SPRAY	OUTDOORS
ACRYLAR	ACRYLIC	2, 3	1
SCOTCHPAR	ACRYLIC	2, 3	3
ALUM. FOIL	ACRYLIC	1, 3	0
KORAD (WHITE)	ACRYLIC	3	3
EVA	SILANE	1	1
CLEAR KORAD	ACRYLIC	1, 3	3
ACMITITE	ACRYLIC	1	0
WHITE TEDLAR	ACRYLIC	3	1
302 STAINLESS	ACRYLIC	2, 3	0
EVA/SCOTCHPAR	SILANE	0	0
EVA/STAINLESS	SILANE	1	0
EVA/TEDLAR	SILANE	1	0
SCOTCHCLAD	NONE	2, 3	2, 3
EVA	CHROMATE/ SILANE	0	0
VINYLIDENE FLUORIDE	EPOXY	0	0

0 = NO CHANGE　　1 = LIGHT CORROSION

2 = MODERATE CORROSION　　3 = DELAMINATION

Anti-Soiling Experiments

SURFACE UNDER INVESTIGATION:

- SUNADEX GLASS
- 3M ACRYLIC FILM, X-22417
- TEDLAR 100BG30UT - DU PONT

SURFACE TREATMENTS UNDER INVESTIGATION:

- 3M FLUOROSILANE TREATMENT L-1668[A.]
- PERFLUORODECANOIC ACID BASED COATING[A.]
  DOW CORNING E-3820
- OWENS ILLINOIS GLASS RESIN 650
- GENERAL ELECTRIC SHC - 1000
- ROHM & HAAS WL-81
  ACRYLIC COATING

A. ALSO USED WITH OZONE TREATMENT TO COUPLE TO ORGANIC SURFACES

Anti-Soiling Test Results

TWO MONTH EXPOSURE,
ENFIELD, CONN.

CHANGE IN SHORT CIRCUIT CURRENT, I_{SC}

TREATMENT	SUNADEX		ACRYLIC X-22417		TEDLAR 100 BG 30 UT	
	INITIAL	Δ %	INITIAL	Δ %	INITIAL	Δ %
CONTROL NO TREATMENT	90.5	-3.0	84.0	-5.1	87.7	-4.7
L-1668	89.7	-0.4	80.3	-3.5	88.4	-3.8
L-1668/OZONE	A.	-	84.5	-3.4	88.1	-2.8
PFDA E-3820	90.0	-1.5	80.0	-2.8	86.0	-1.5
PFDA E-2820/OZONE	A.	-	84.1	-2.5	86.0	-3.9
GLASS RESIN 650	91.0	-3.3	81.1	-3.7	89.0	-4.5
SHC -1000	91.9	-3.9	82.1	-6.5	89.0	-3.7
WL-81	90.7	--4.4	83.6	-3.1	87.7	-4.9

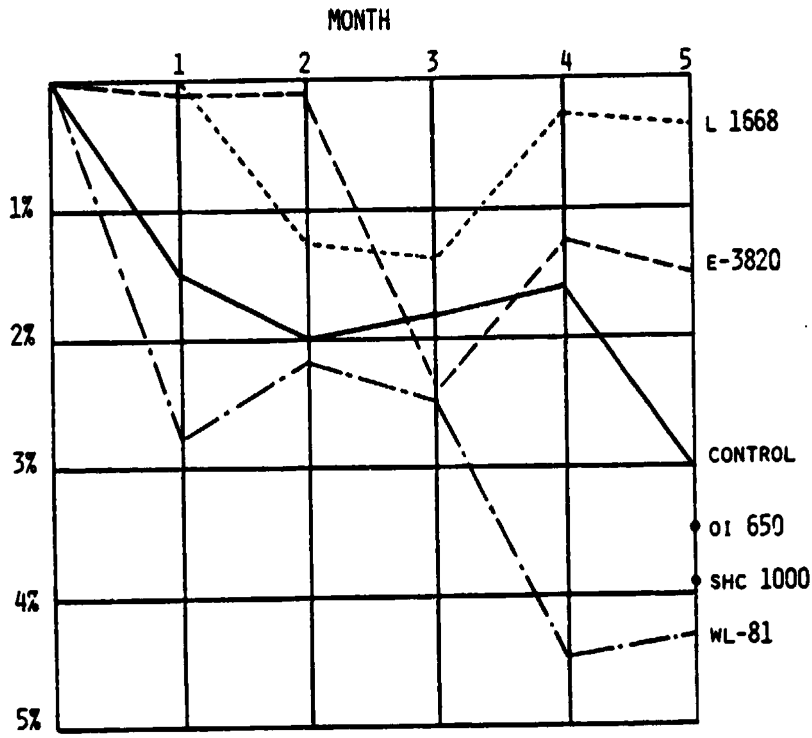
A. NOT PREPARED

Anti-Soiling Experiments

FIVE MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL

TREATED SUNADEX GLASS



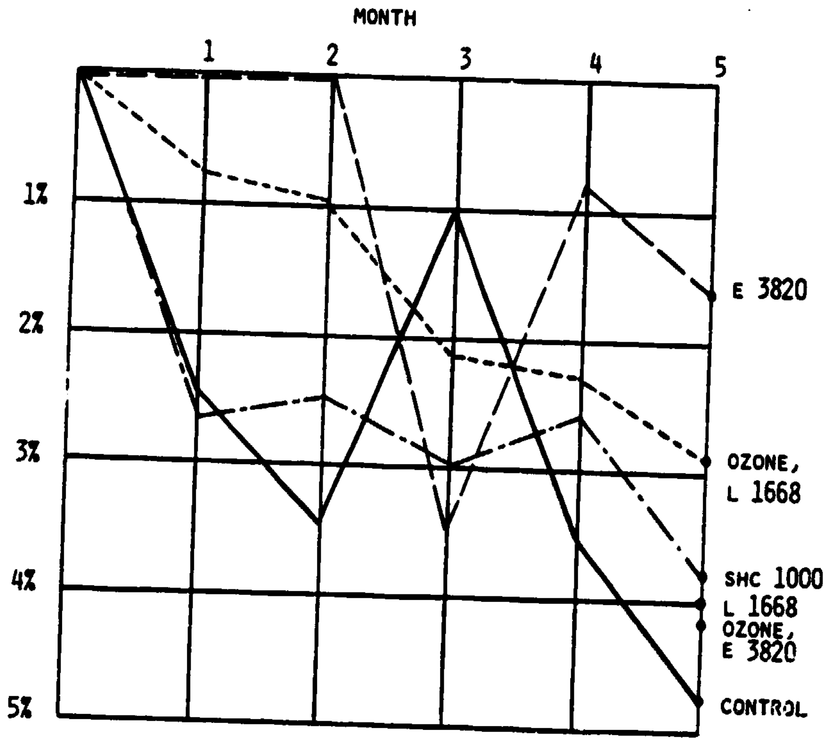
BEST TREATMENT, L 1668

FIVE MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL

TREATED TEDLAR 100BG300UT

(SUPPORTED ON GLASS)

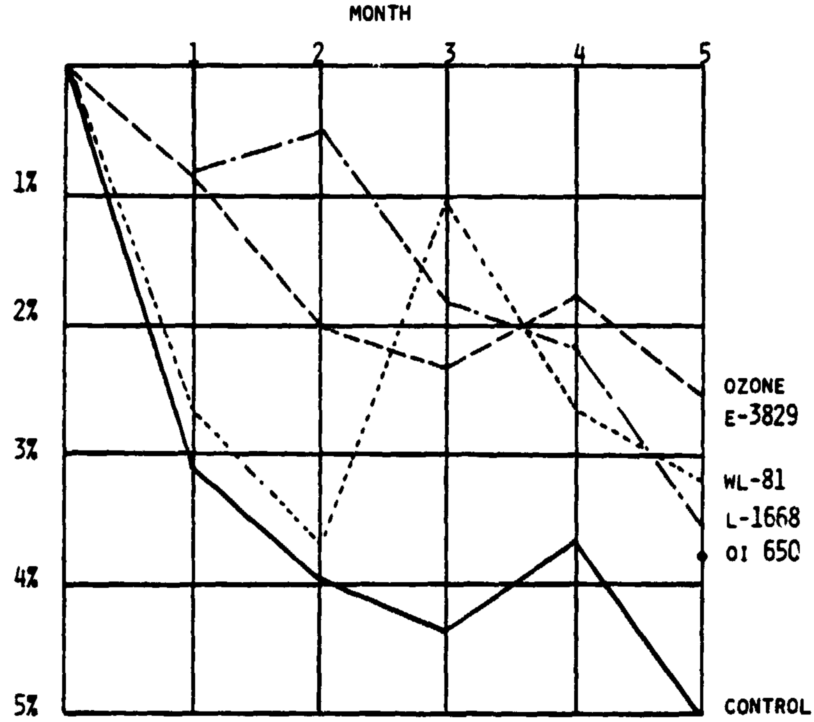


• BEST TREATMENT, E-3820

FIVE MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL

TREATED ACRYLAR
(SUPPORTED ON GLASS)



- BEST TREATMENT, OZONE WITH E-3829 (FLUOROSILANE)

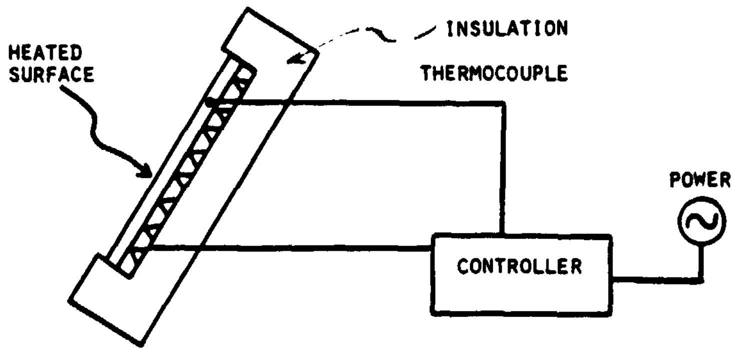
GENERAL OBSERVATIONS:

- SUNADEX HAS BEST CONTROL VALUES (-3.0%)
- SUNADEX: BEST COATING, L-1668 (-0.5%)
- TEDLAR: BEST COATING, E 3820 (-1.5%)
- ACRYLAR: BEST COATING, OZONE + E 3820 (-2.4%)
- GOOD CORRELATION WITH NATURAL "CLEANING" CONDITIONS

Accelerated Aging Test Program

OUTDOOR PHOTOTHERMAL AGING

- USE NATURAL SUNLIGHT, AVOIDS SPECTRAL DISTRIBUTION PROBLEMS WITH ARTIFICIAL LIGHT SOURCES
- USES TEMPERATURE TO ACCELERATE THE PHOTOTHERMAL REACTION
- INCLUDES DARK CYCLE REACTIONS
- INCLUDES DEW/RAIN EXTRACTION
- SILICONE RUBBER HEATERS - IN OPERATION ONLY DURING SUNLIT HOURS



- CURRENTLY UNDER CONSTRUCTION

ENVIRONMENTAL ISOLATION TASK

MODELING OF POLYMER PHOTOOXIDATION

UNIVERSITY OF TORONTO

J. Guillet

A. Somersall

J. Gordon

The Problem

- LIFETIME PREDICTABILITY
- LIFETIME CONTROL

ISSUES

- WHAT IS THE INITIATOR ?
  - KETONE
  - AROMATICS
  - HYDROPEROXIDE
  - SINGLET O_2
- WHAT IS THE MECHANISM ?
  - COMPLEX CHAIN PROCESSES
- HOW TO MONITOR ?
  - EXTENDED LIFE
  - WEATHEROMETER
  - EXTRAPOLATION
- CORRELATION OF PHOTOOXIDATION / FAILURE

Our Approach

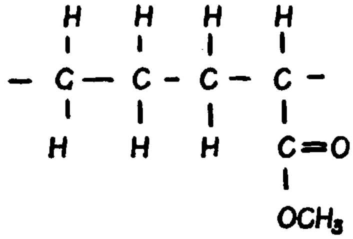
COMPUTER SIMULATION OF POLYMER PHOTOOXIDATION

- *DEFINE THE SYSTEM CHEMICALLY*
- *ELUCIDATE THE MECHANISTIC MODEL*
- *SET STARTING CONDITIONS*
  INTEGRATION PARAMETERS
- *PERFORM NUMERICAL INTEGRATION*
- *VALIDATE THE PROCEDURE*
- *CORRELATE CHEMICAL CHANGE WITH FAILURE*
- *GAIN CONTROL THROUGH UNDERSTANDING*

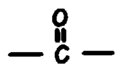
Defining the System

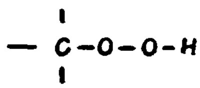
- ETHYLENE-VINYL ACETATE (EVA)

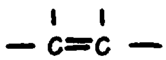
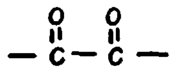
  UV STABILISER
  ANTIOXIDANT
  CROSSLINKING RESIDUE
  ETC.



- OTHER SPECIES:

  KETONE 

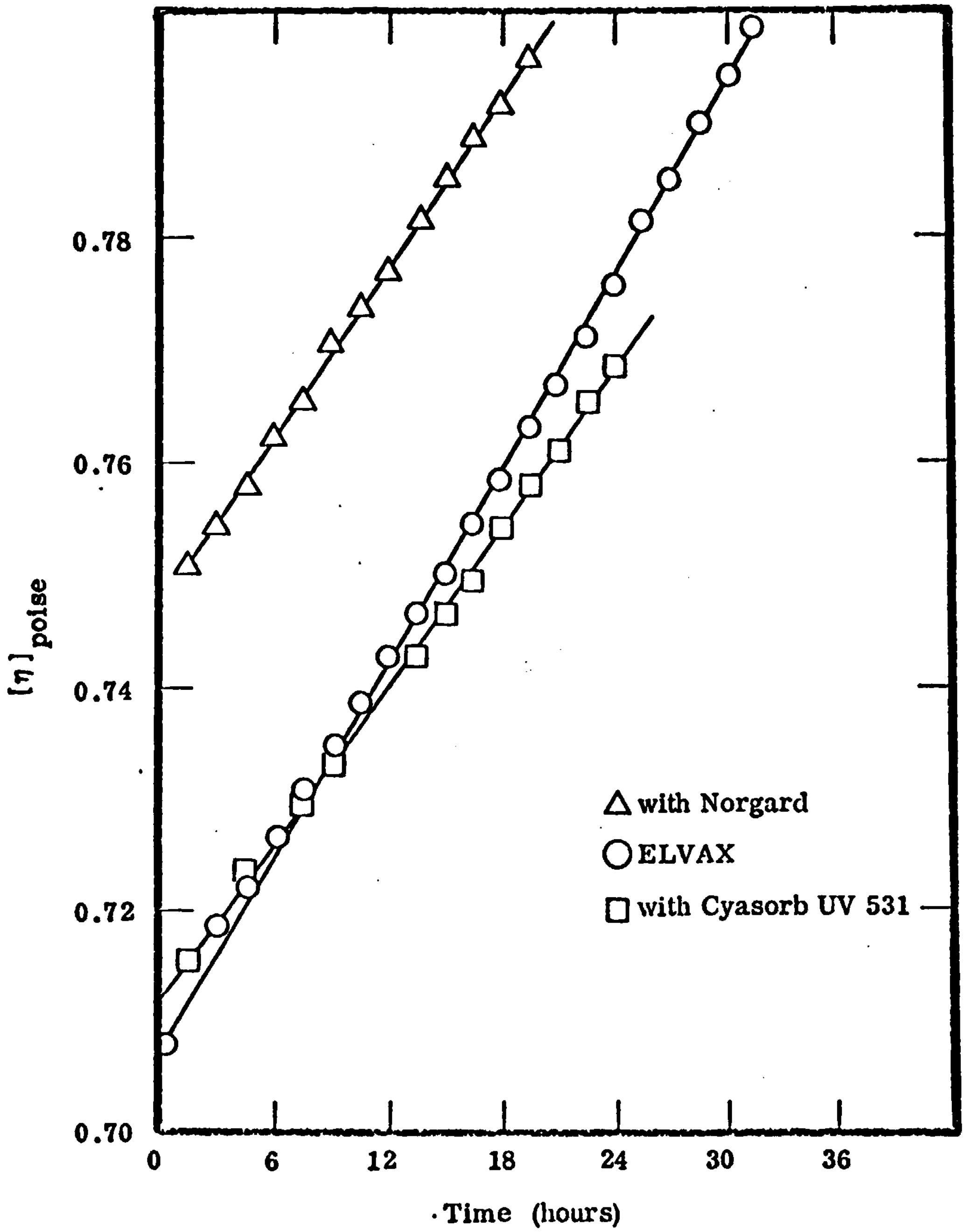
  HYDROPEROXIDE 

  UNSATURATION  

  OXYGEN, MOISTURE

– STARTING POINT : LINEAR POLYMER (RH) –

Intrinsic Viscosity vs Irradiation Time
(Elvax 0.47 g/100 ml CH_2Cl_2)



The Mechanism

MODEL : 31 ELEMENTARY REACTIONS

KEY: *INITIATION*

$$RH \xrightarrow{?} R^{\bullet}$$

$$R-\overset{O}{\overset{\|}{C}}-R \xrightarrow{h\nu} R-\overset{O}{\overset{\|}{C}}^{\bullet} \qquad R^{\bullet}$$

$$R-O-O-H \xrightarrow{h\nu} R-O^{\bullet} \qquad {}^{\bullet}O-H$$

PROPAGATION

$$R^{\bullet} \longrightarrow RO_2^{\bullet}$$

$$RO_2^{\bullet} + RH \longrightarrow ROOH + R^{\bullet}$$

$$OH^{\bullet} + RH \longrightarrow HOH + R^{\bullet}$$

TERMINATION

$$RO_2^{\bullet} + RO_2^{\bullet} \longrightarrow RO^{\bullet} \longrightarrow \text{ALCOHOL}$$

$$RO^{\bullet} \longrightarrow R-O-O-R \quad (\text{CROSSLINK})$$

$$RO_2^{\bullet} + RO_2^{\bullet} \longrightarrow \text{KETONE} \xrightarrow{h\nu} \text{SCISSION}$$

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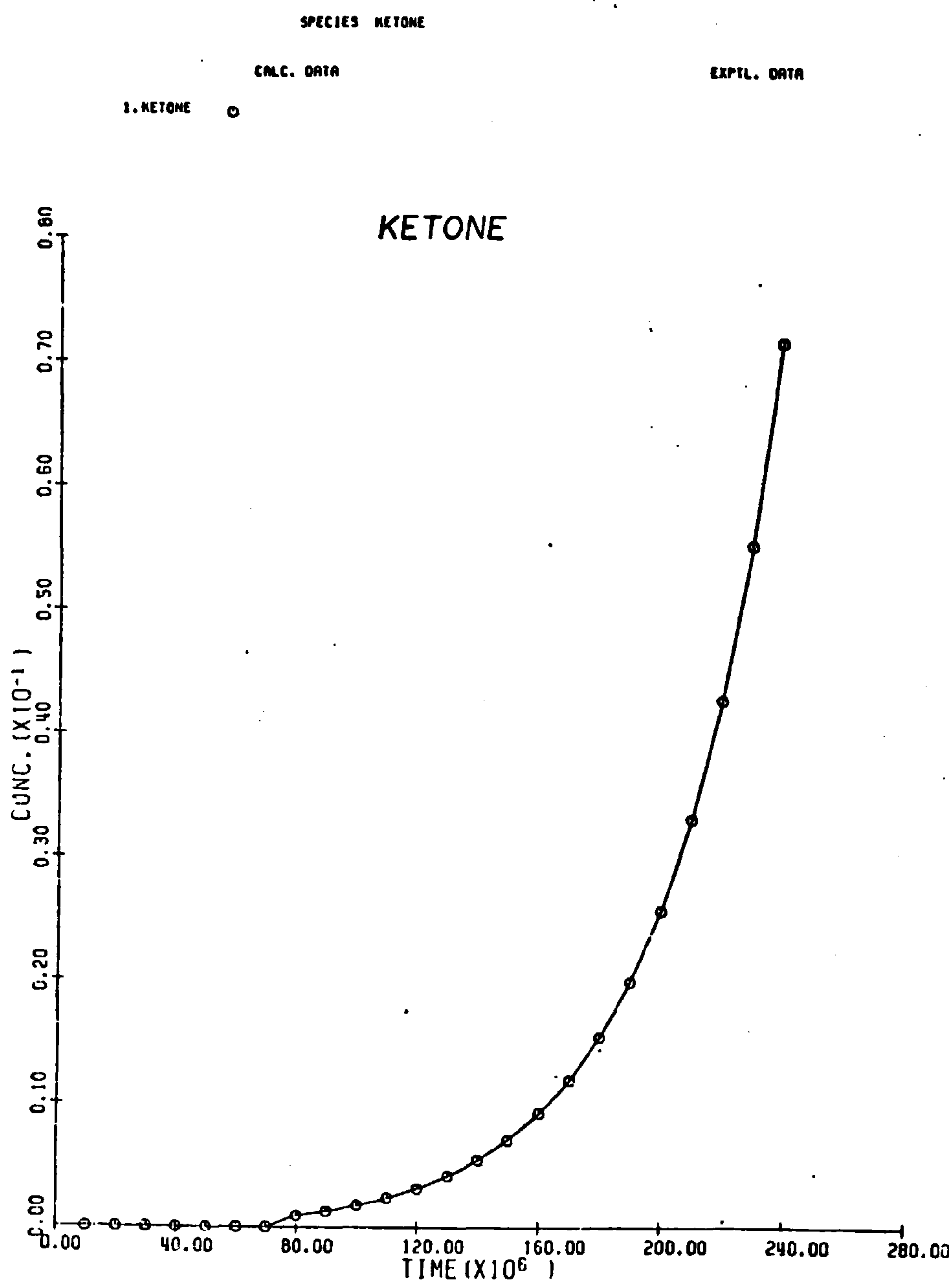

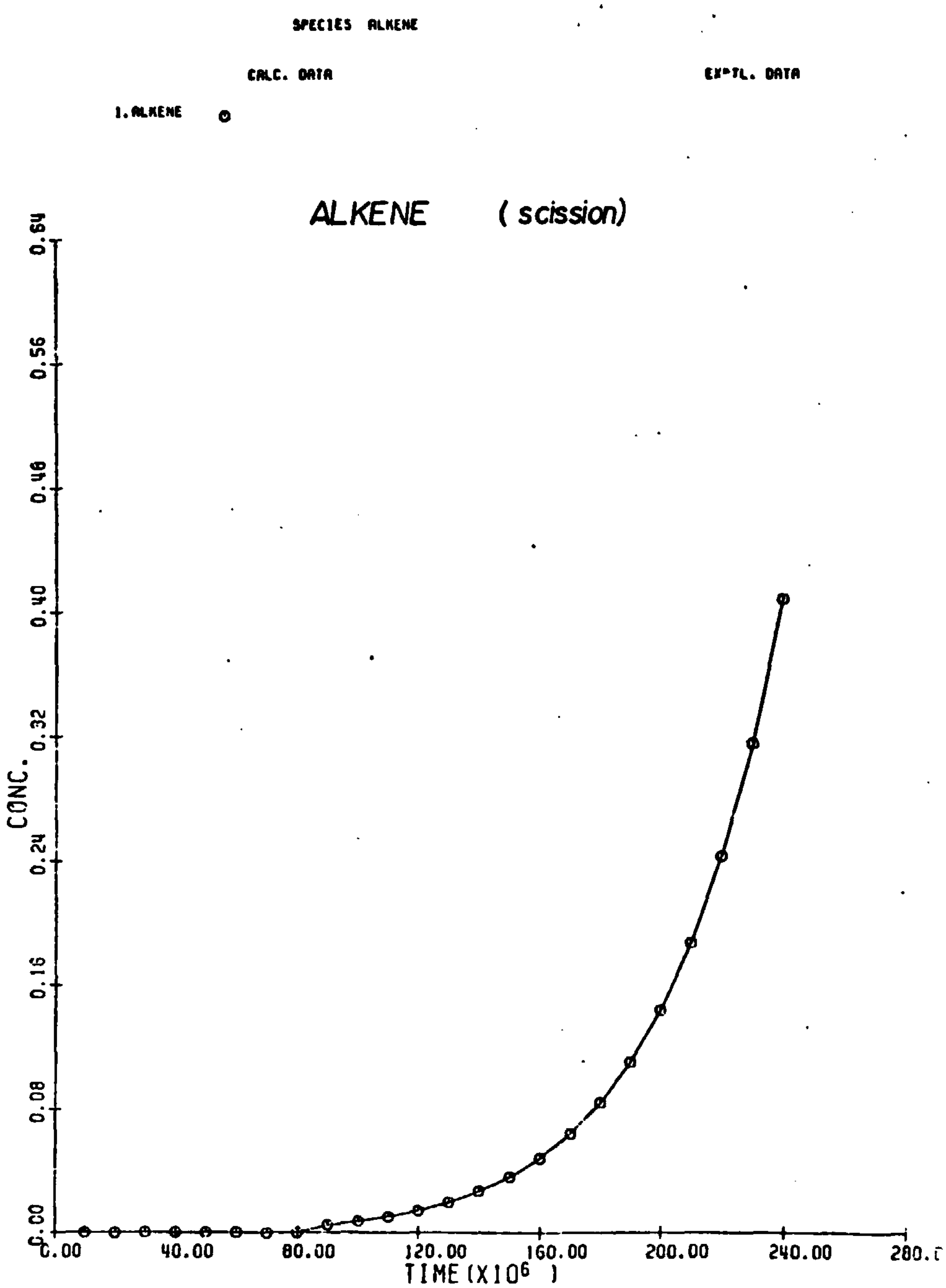
SPECIES ALKENE
CALC. DATA
EXPTL. DATA
1. ALKENE
ALKENE (scission)
CONC.
0.00
0.08
0.16
0.24
0.32
0.40
0.48
0.56
0.64
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.0
TIME (X10⁶)

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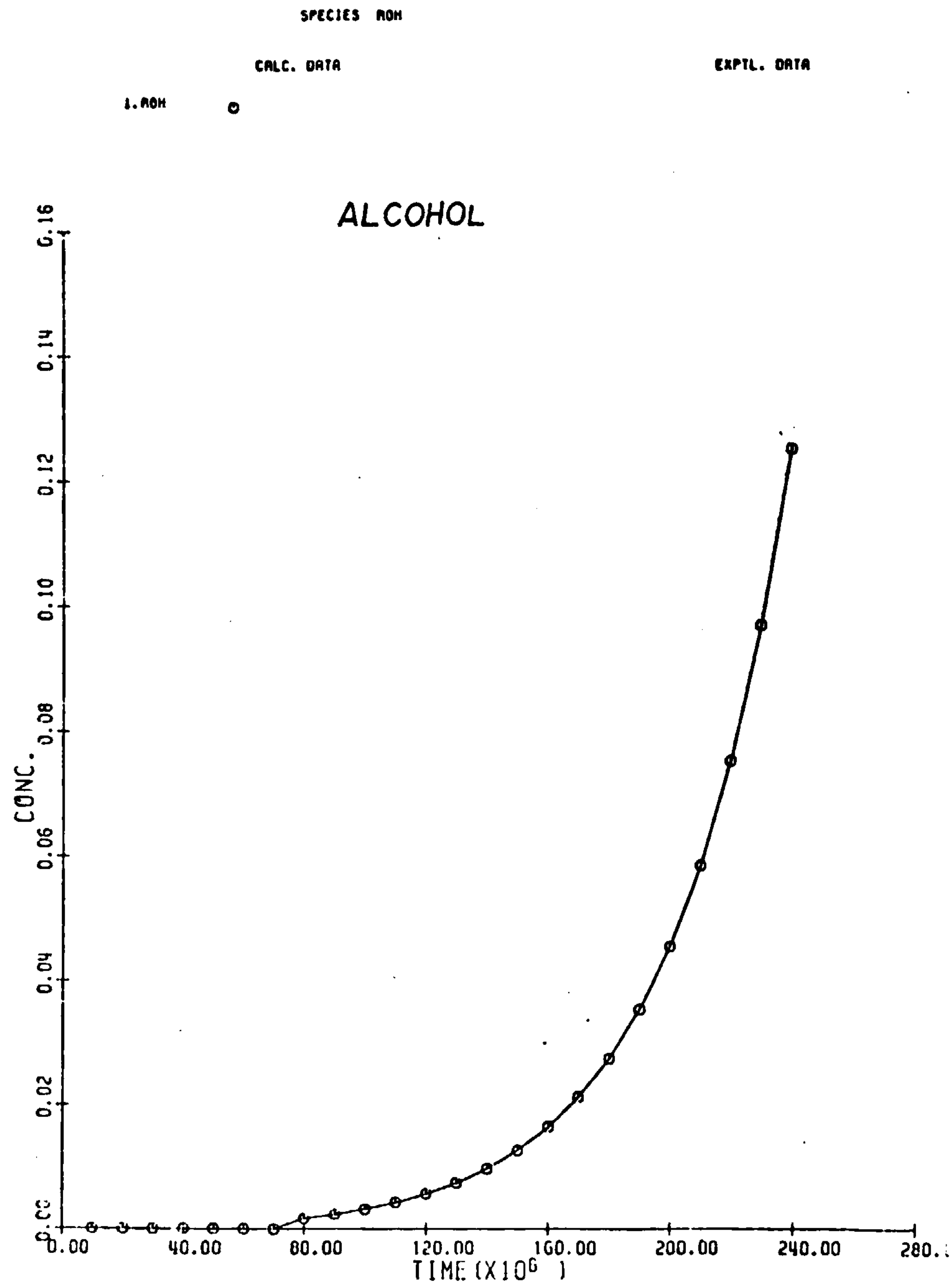


CELL AND MODULE FORMATION RESEARCH AREA

D.B. Bickler, Chairman

The Cell and Module Formation Research Area technology session began with the two Module Experimental Process Sequence Development Unit (MEPSDU) contracts. Both contractors, Solarex and Westinghouse, were further reduced in funding rate since the last PIM. This is the second funding-level reduction and a reduction in scope of effort is being negotiated as a result. The main thrust of the contracts, to demonstrate technical readiness by 1982, has been changed to the development of technical feasibility by 1984.

Westinghouse has reduced the level of experimentation from 1 MW to 0.5 MW and has increased the proportion of Westinghouse funding. Several of the pieces of equipment (all capital equipment is being funded by Westinghouse) have been specified and placed on order. Alternative processes are still being studied. More emphasis is being placed upon plasma cleaning of the dendritic-web-grown silicon. Sample modules were fabricated and subjected to environmental tests, which they passed. Process costing details have been perfected in complete agreement with JPL. Some revision was necessary on the part of JPL also, in order to update details.

Solarex Corp. has ceased development work on the processing of cells into modules for their MEPSDU as a result of funding reductions. The cell processing work has been extended from 26 months to 45 months to accommodate the reduced funding rate. Several cell processing steps are being reviewed with an effort to improve the final cell efficiency. Solarex has consistently had low processing costs with options that are also low in cost. Considerations are being given to any optimizing that may benefit polycrystalline cells. A new method of applying a polymer-based antireflective coating has been developed: cells are heated before and during the spraying of the coating. The company is experimenting by ion milling the edges of stacks of cells in an effort to improve upon the laser edge treatment for junction cleanup, and is successfully solder-coating cell metallization with a wave soldering machine.

Spire Corp. has demonstrated the pulsed electron beam annealer (PEBA) at a rate of one 4-in.-dia cell every 3 seconds. The ion-implanted cells that were pulse-annealed were measured at AM1 in simulated sunlight with no antireflection coating. Correcting for terrestrial sunlight and an AR coating gives an average 13.6% cell efficiency. The cells had an ion-implanted boron back-surface field, resulting in open-circuit voltages around 550 mV. This is considerably below the open-circuit voltages experienced with fired-in aluminum back surface fields; it is assumed that this 13.6% efficiency could be improved accordingly. Spire has developed its non-mass-analyzed (NMA) ion implanter to the breadboard stage. Efficiencies of cells implanted by the machine using an unanalyzed ion beam are comparable to those with conventional implants using an analyzed beam.

JPL in-house work with ion implantation was the starting point of the non-mass-analyzed implantation activity. The basic technology may be thought of as a spinoff of deep-space propulsion work using ion-thruster engines. The in-house work deals with the basic feasibility of the process; current work is being done on the effect of "knock on" impurities left on the silicon surface after cleaning. Another source of impurities being investigated is the ion source apparatus itself. Sources are being fabricated of carbon as part of this investigation.

JPL robotics work is being cancelled as a result of fund reduction. The PIM presentation was a videotape of the robot equipped with a video system and tactile sensors. The video system is coupled with a computer system that increases contrast so that geometric edges and surfaces can be identified and digitalized. The processed visual data allows the robot to "see"; it can move to a randomly placed object and can inspect for position, defects, etc. The tactile sensors allow the robot to "feel" mechanical shapes and find positions while applying only the force necessary, thus avoiding breakage. The robot's hand was a multipurpose tool that permitted the gripping of parts and heating for soldering, while holding in position; the extruding of adhesive beads under automatic visual control, and picking up, holding and placing parts during assembly.

Bernd Ross Associates reported further developments in the design of thick-film metallization systems using base metals. Substantial evidence shows that an excess of the silver fluoride fluxing agent is detrimental to the bonding integrity. An alternate source of fluorine is a powdered fluorocarbon (a type of Teflon). Hydrogen, used as a furnace atmosphere, prevents the fluorine from reducing the silicon oxide. Other non-oxidizing atmospheres must be used during the firing of these formulations. The systems are not repeatable in that an electrically rectifying barrier occasionally appears at the silicon-to-metal interface. Solving this problem is the focus of the present effort. Cost analysis shows that the copper-based system will cost about $.045 per watt; a little more than two-thirds of the cost lies in the copper powder.

Tracor MBA reported the final details of its recent effort to adapt and program the industrial robot to assemble cells and laminate them in glass-superstrate modules. The advantages of this approach are relatively little special tooling, with off-the-shelf robots; maximum versatility by simply reprogramming, and low initial cost accompanied by resale value. The major disadvantage, slowness of operation (12 to 15 seconds/watt), would not be true of other robot models currently available. The robot and its fixturing will ultimately be delivered to the JPL processing laboratory.

Photowatt is experiencing some difficulty in its development of an interrelated antireflection coating and metallization system. The metal is silk-screened over the AR coating and fired through it. Subsequently, the metal pattern is built up by brush-plating with copper until sufficient electrical conductivity results. Two subcontractors are involved: Electro-Science Laboratory is working on the nickel paste and Vanguard Pacific is assisting in the adapting of copper brush-plating. The primary problem is excessive series resistance. Excess firing can cure the series resistance problem but shunting of the junction results. The best firing to date is 10 minutes at 650°C.

The University of Pennsylvania has completed evaluation of metallization designs with the analysis of Westinghouse's fan-shaped pattern. The effort has been focused upon the modeling of other efficiency drivers. Heavy doping effects and surface passivations are being assessed.

MEPSDU

WESTINGHOUSE ADVANCED ENERGY SYSTEMS DIVISION

C.M. Rose

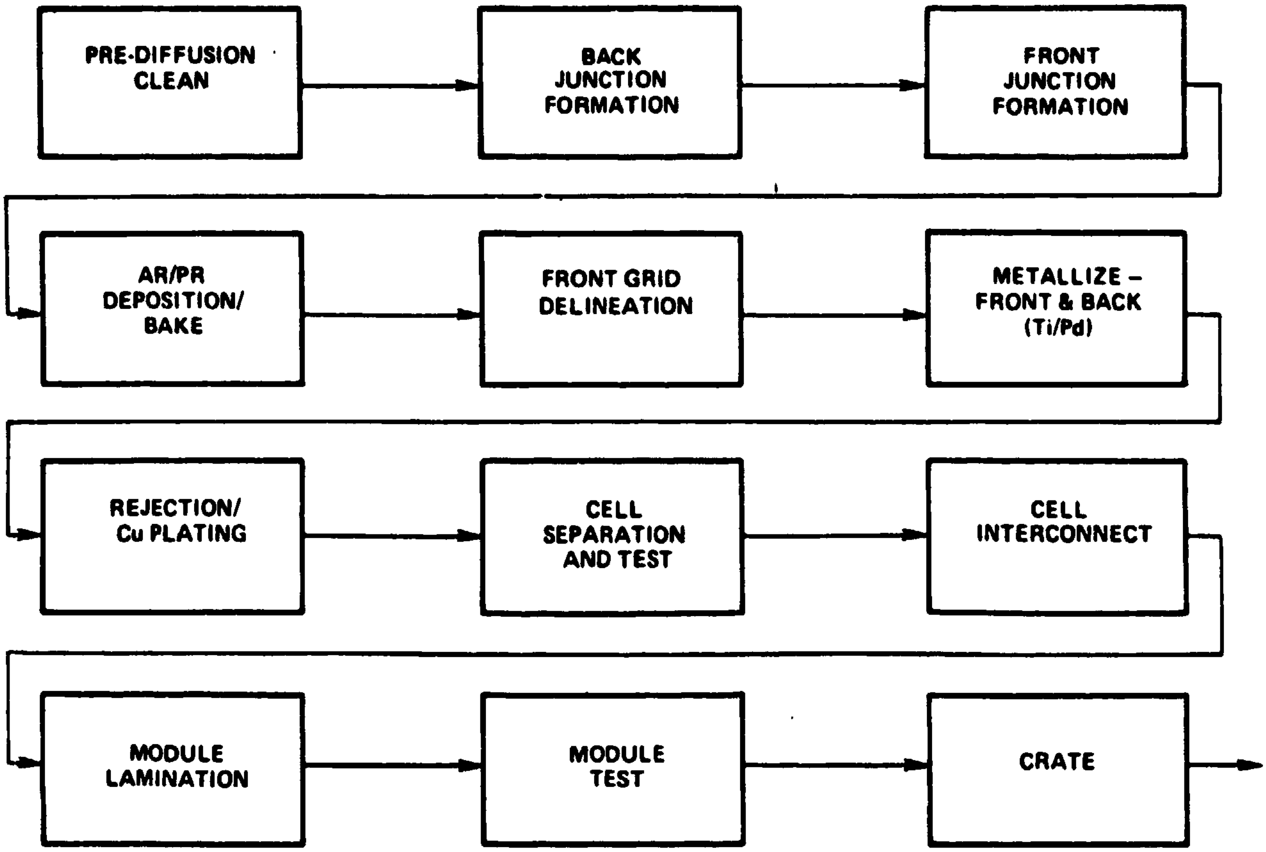
Goals and Approach

- DESIGN MODULE MEETING JPL 5101-138 SPECIFICATIONS
- SELECT AND VERIFY PROCESS SEQUENCE FOR FABRICATING MODULES
- DESIGN AND BUILD A TEST FACILITY TO FABRICATE MODULES USING SELECTED PROCESS SEQUENCE
- PERFORM TECHNICAL FEASIBILITY EXPERIMENTS
- ACCEPTANCE AND QUALIFICATION TESTING OF MODULES PRODUCED
- DETERMINATION OF 1986 MODULE PRODUCTION COSTS

Milestone Schedule

MILESTONE	CURRENT PROGRAM PLAN
START DATE	NOV. 26, 1980
PRELIMINARY DESIGN REVIEW	MAR. 3, 1981
PROTOTYPE MODULE DESIGN REVIEW	JULY 14, 1981
MEPSDU DESIGN REVIEW	MAY 15, 1982
MEPSDU INSTALLATION	JAN. 31, 1983
TECHNICAL FEASIBILITY EXPERIMENTS	DEC. 15, 1983
FINAL REPORT	DEC. 31, 1983

Baseline Process Sequence



Equipment Procurement Status

ITEM	STATUS
PRE-DIFFUSION CLEANING EQUIP.	BEING DEFINED
DIFFUSION FURNACE	PRELIM. E-SPEC PREPARED
SILOX REACTOR	PRELIM. E-SPEC PREPARED
AR/PR APPLICATION EQUIP.	PRELIM. E-SPEC PREPARED
EXPOSURE/DEVELOPMENT STATION	BEING DEFINED
METAL EVAPORATION EQUIP.	PRELIM. E-SPEC PREPARED
REJECT/PLATING STATION	PRELIM. E-SPEC PREPARED
LASER SCRIBE	ON ORDER
CELL TESTER	ON ORDER
INTERCONNECT STATION	E-SPEC FINALIZED
LAMINATOR	BEING DEFINED

Alternative Metallization Experiments

OBJECTIVE:

- IDENTIFY A MORE COST EFFECTIVE METALLIZATION PROCESS.

RESULTS:

- UNIFORM/REPRODUCIBLE LAYERS OF Ni ON Si NOT ACHIEVED.
- RESULTS OF W R & D PROGRAM SUGGEST Ni-Cu SYSTEM NOT STABLE.
- VACUUM EVAPORATION OF Ag ELIMINATED FROM BASELINE PROCESS.

Dry Processing Experiments

OBJECTIVE:

- REPLACE WET CHEMICAL CLEANING STEPS WITH PLASMA PROCESSING.

RESULTS:

- OPTIMUM CLEANING GAS COMPOSITIONS DETERMINED.
- PLASMA PROCESS WILL REPLACE CHELATING CLEANING.
- "MEGASONIC" CLEANING BEING INVESTIGATED TO REPLACE WET CHEMICAL OXIDE REMOVAL.

Liquid Dopants

OBJECTIVES:

- TO ACHIEVE COST REDUCTION IN JUNCTION FORMATION BY REDUCING PROCESSING TIME.

RESULTS:

- CELL EFFICIENCIES GENERALLY LOWER BY LESS THAN 1% ABSOLUTE AS COMPARED TO GASEOUS DIFFUSION.
- CONTINUED EXPERIMENTS TO BE PERFORMED WITH W FUNDING.

Application of AR and PR

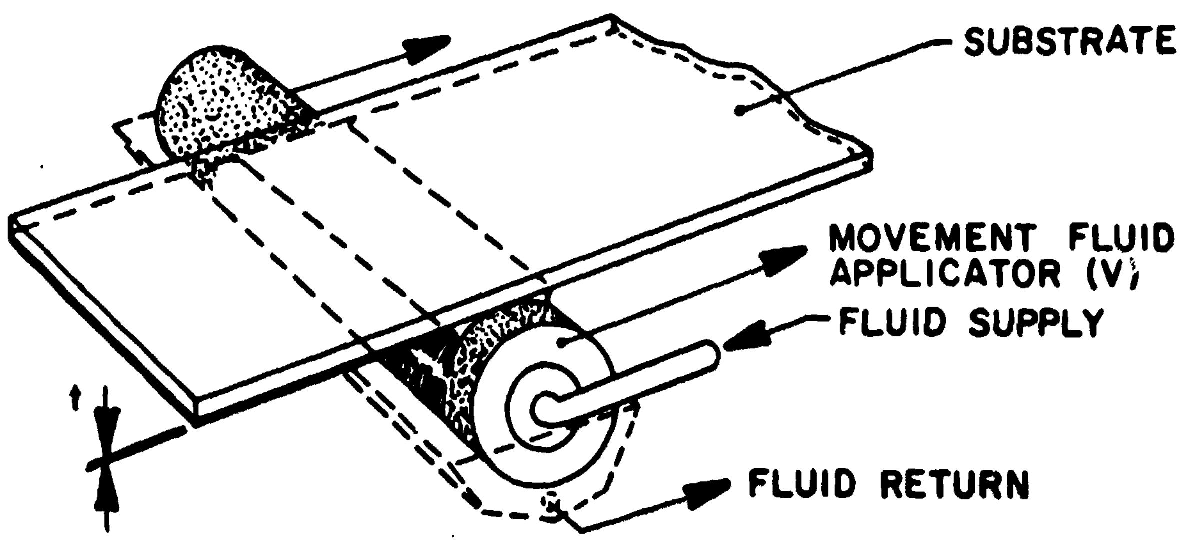
OBJECTIVE:

- INVESTIGATE IMPROVED METHODS FOR APPLYING AR/PR COATINGS.

RESULTS:

- SPRAYING OR ROLLER COATING RESULTS UNSATISFACTORY. "MENISCUS" COATING GIVES REPRODUCIBLE THICKNESS OF BOTH AR AND PR.

Meniscus Coater



Junction Formation by Ion Implantation

OBJECTIVE:

- TO ACHIEVE HIGH EFFICIENCY CELLS WITH MORE UNIFORM DISTRIBUTION OF CELL PARAMETERS.

RESULTS:

- AVERAGE CELL EFFICIENCIES FELL IN RANGE 12.7 ± 1.04%.
- EFFICIENCY DATA COMPARABLE TO DIFFUSION PROCESS.
- SPIRE ION IMPLANTATION PROCESS COMPATIBLE WITH MEPSDU PROCESS SEQUENCE.

Module Environmental Tests

OBJECTIVE:

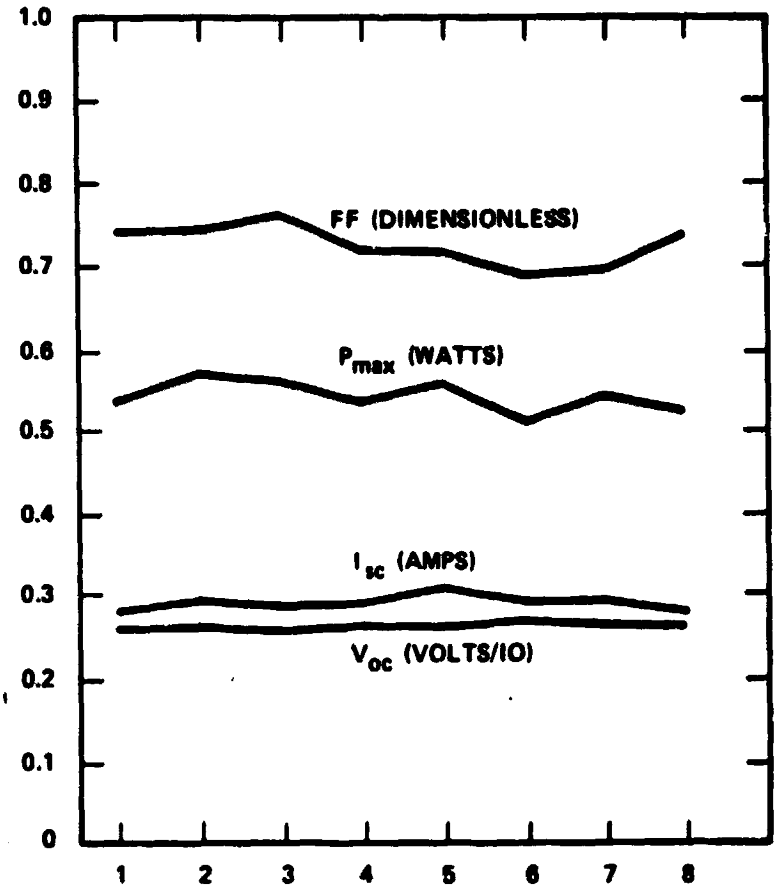
- TO VERIFY THAT THE MEPSDU MODULE CONFIGURATION MEETS ALL ENVIRONMENTAL SPECIFICATIONS OF JPL 5101-138

RESULTS:

- 250 THERMAL CYCLES SUCCESSFULLY COMPLETED
- HUMIDITY CYCLE TESTS SUCCESSFULLY COMPLETED
- POSITIVE/NEGATIVE WIND LOADING TESTS SUCCESSFULLY COMPLETED
- SIMULATED HAILSTONE IMPACT TEST SUCCESSFULLY COMPLETED

Environmental Test Data

1 AS LAMINATED
2 AFTER 25 THERMAL CYCLES
3 AFTER 50 THERMAL CYCLES
4 BEFORE HUMIDITY TEST
5 AFTER HUMIDITY TEST
6 AFTER 100 THERMAL CYCLES
7 AFTER 150 THERMAL CYCLES
8 AFTER 200 THERMAL CYCLES



Cell Shading Tests

OBJECTIVE:

- MEASURE EFFECTS OF SHORT CIRCUIT MODULE OPERATION WITH SHADED CELL.

RESULTS:

- WITH 15 CELL STRING DESIGN NO MEASURABLE TEMPERATURE INCREASE OBSERVED DURING SHADED/SHORT CIRCUIT OPERATION.
- NO DIODES REQUIRED.

Cell Interconnect Failure Test

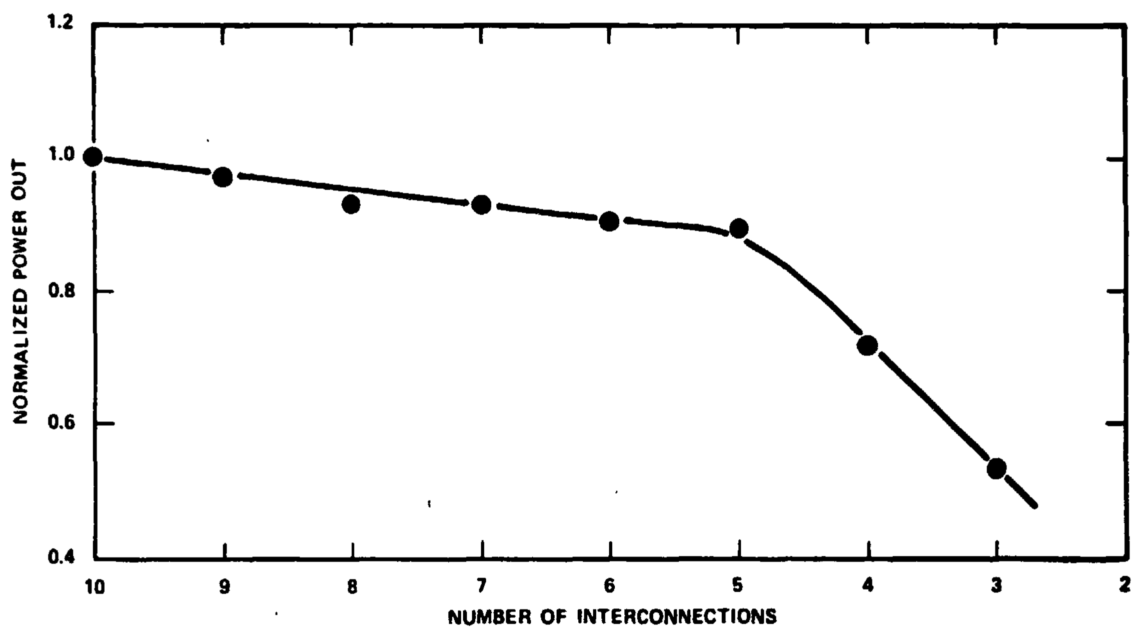
OBJECTIVE:

- TO DETERMINE EFFECTS OF MULTIPLE CELL INTERCONNECT FAILURES ON MODULE PERFORMANCE.

RESULTS:

- UP TO 30% OF INTERCONNECTS CAN BE BROKEN WITH A CELL POWER DEGRADATION LESS THAN 7%.
- MODULE POWER DEGRADATION UNMEASURABLE.

Normalized Output Power From Solar Cell
As a Function of Number of Interconnects



SAMICS Cost Analysis

- NEW OR RE-VERIFIED VENDOR QUOTES USED FOR CAPITAL EQUIPMENT AND COMMODITY COSTS.
- COMMODITY USAGE RE-CALCULATED.
- PRE-PILOT FACILITY EXPERIENCE UTILIZED.
- UTILITY USAGE BASED ON VENDOR INPUT.
- YIELD DATA ACCOUNTED FOR IN EACH PROCESS STEP.
- OPERATIONAL UP-TIME BASED ON INDUSTRY EXPERIENCE.

SAMICS Cost Analysis Assumptions

- 3 SHIFT, 345 DAY/YEAR OPERATION
- INPUT SHEET MATERIAL: DENDRITIC WEB
- 12% MODULE EFFICIENCY AT 28°C AND 100 mW/cm^2 INSOLATION
- 1 mW/YR AND 25 mW/YR PRODUCTION LEVELS

CELL AND MODULE FORMATION RESEARCH AREA

1 MW/yr Production Facility Cost Analysis Results

PROCESS STEP	PROCESS	VALUE ADDED (1980 $/PEAK WATT)	% OF TOTAL
1	PREPARE INPUT WEB	0.615	18.9
2	BORON DIFFUSION	0.192	5.9
3	PHOSPHOROUS DIFFUSION	0.181	5.6
4	APPLICATION OF AR/PR	0.182	5.6
5	DEFINE GRID PATTERN	0.193	5.9
6	METALLIZE WEB	0.366	10.9
7	REJECTION AND PLATING	0.307	9.4
8	CELL SEPARATION AND TEST	0.545	17.7
9	CELL INTERCONNECTION	0.254	7.8
10	LAMINATION	0.345	10.6
11	CRATING	0.061	1.9

TOTAL FOR PROCESS – 3.26 $\frac{\text{1980 \$}}{\text{PEAK WATT}}$

25 MW/yr Production Facility Cost Analysis Results

PROCESS STEP	PROCESS	VALUE ADDED (1980 $/WATT)	% TOTAL
1	PREPARE INPUT WEB	0.353	49.73
2	BORON DIFFUSION	0.032	4.51
3	PHOSPHOROUS DIFFUSION	0.023	3.33
4	APPLICATION OF AR/PR	0.016	2.24
5	DEFINE GRID PATTERN	0.017	2.40
6	METALLIZE WEB	0.037	5.18
7	REJECTION AND PLATING	0.037	5.26
8	CELL SEPARATION AND TEST	0.029	4.06
9	CELL INTERCONNECTION	0.026	3.67
10	LAMINATION	0.121	17.02
11	CRATING	0.019	2.62

TOTAL FOR PROCESS – 0.709 $\frac{\text{1980 \$}}{\text{PEAK WATT}}$

CELL AND MODULE FORMATION RESEARCH AREA

Cost Factors for 1 MW/yr and 25 MW/yr Simulations

	1 MW/YR	25 MW/YR
DIRECT LABOR	0.820	0.060
DIRECT MATERIALS	0.539	0.388
DIRECT UTILITIES	0.033	0.008
INDIRECT LABOR	0.469	0.038
INDIRECT MATERIALS	0.060	0.004
INDIRECT UTILITIES	0.044	0.005
CAPITAL EXPENSES	0.770	0.111
TAXES/MISC	0.521	0.095

*COSTS IN 1980 $

Module Fabrication Progress Results

DATE	AVG. CELL EFFICIENCY	MODULE EFFICIENCY
MAR. 1981	10.8	7.5
SEPT. 1981	10.5	9.0
OCT. 1981	12.3	10.6

Conclusions

- (W) MEPSDU PROJECT CURRENTLY ON SCHEDULE AND BUDGET.
- PROGRAM REVISION PROPOSAL HOLDS SCHEDULE WHILE GREATLY REDUCING COSTS.
- MODULE/CELL ENVIRONMENTAL TESTS SUCCESSFULLY COMPLETED.
- PROCESS SEQUENCE STUDY TASKS HAVE IMPROVED DETAILS OF BASELINE PROCESS SEQUENCE.
- UPDATED ECONOMIC ANALYSIS (SAMICS) COMPLETED VERIFYING EFFECTIVENESS OF BASELINE PROCESS SEQUENCE.

MEPSDU

SOLAREX CORP.

John H. Wohlgemuth

Change in Program Emphasis

JPL IMPOSED

- ELIMINATION OF ALL MODULE BUILDING EFFORTS INCLUDING TABBING, STRINGING, MODULE LAY-UP AND LAMINATION.
- SPREAD OUT OF THE PROGRAM FROM ORIGINAL 26 MONTHS TO 45 MONTHS WITH A MUCH REDUCED FUNDING RATE GEARED ONLY TO CELL FABRICATION.

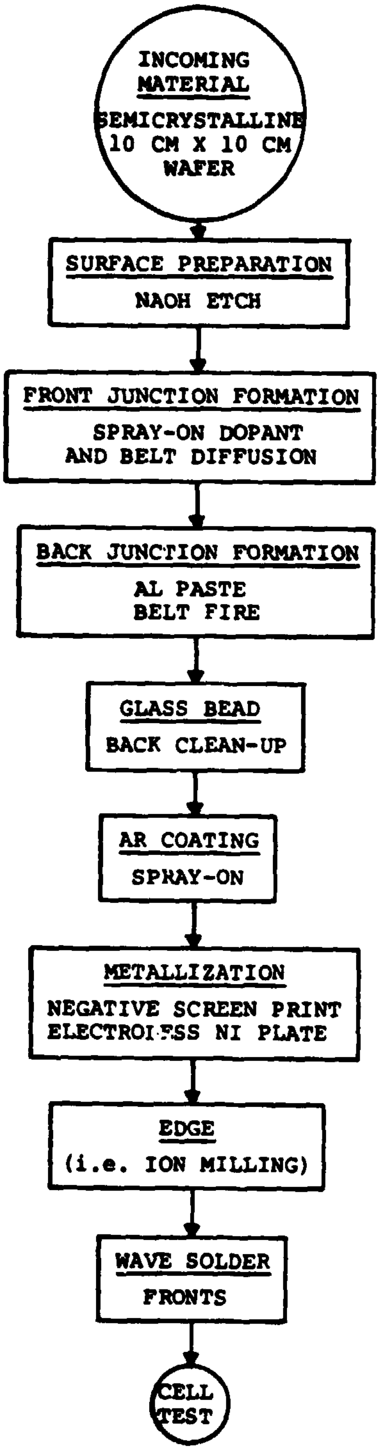
SOLAREX PROGRAM PLAN

- EMPHASIS ON TECHNICAL FEASIBILITY OF PROCESSES AND MATERIAL TO MEET PRICE GOAL OF 70¢ OR LESS PER PEAK WATT IN 1980 DOLLARS.
- DEVELOP OPTIMUM CELL PROCESSING.
- IDENTIFY EQUIPMENT THAT CAN BE USED FOR AUTOMATED CELL PROCESSING.
- VERIFY THAT PROCESSES CAN BE PERFORMED IN AN AUTOMATED MODE.

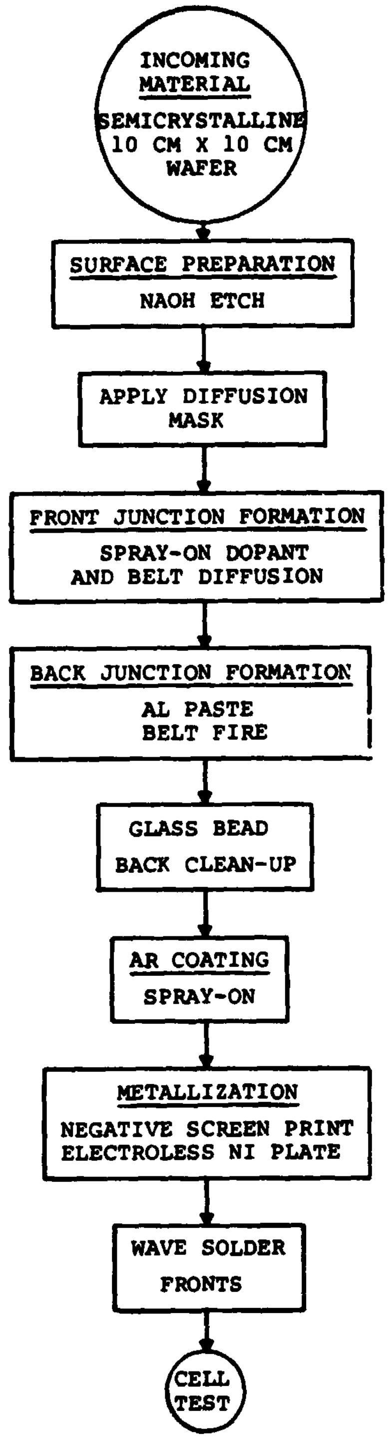
CELL AND MODULE FORMATION RESEARCH AREA

General Process Description

OPTION A



OPTION B



CELL AND MODULE FORMATION RESEARCH AREA

Technical Progress

CELL AREA

- PILOT LINE CELL FABRICATION
- AR COATING DEVELOPMENT
- ION MILLING
- WAVE SOLDERING

MODULE AREA - TERMINATED

- IDENTIFICATION AND TESTING OF INSULATOR TAPE AND EDGE SEAL MATERIALS.
- EVALUATION OF ENCAPSULATION MATERIALS.
- INITIATION OF SUBCONTRACT WITH MB ASSOCIATES TO BUILD TABBING AND STRINGING MACHINE - SUBSEQUENTLY TERMINATED.

GENERAL

- IDENTIFICATION, DISCUSSIONS, DEMONSTRATION AND VISITS WITH CANDIDATE EQUIPMENT VENDORS.
- UPDATING THE DRAWING PACKAGE.
- COLLECTING DATA FOR PRELIMINARY SAMICS COST ANALYSIS.

Spray AR

STANDARD SPRAY AR TECHNIQUE USES TITANIUM ISOPROPOXIDE
BUTYL ACETATE
2ETHYL 1HEXANOL
ISOPROPYL ALCOHOL

ON POLISHED SURFACES RESULTS IN UNIFORM 1/4 WAVE LENGTH BLUE AR COATING.

ON TEXTURED SURFACES (I.E., SEMICRYSTALLINE SILICON) RESULTS IN VARIABLE THICKNESS GREY AR.

EFFORTS TO FIND PRESPRAY OR DIP TREATMENT WERE UNSUCCESSFUL AT IMPROVING AR COATING.

New Development

SPRAY TITANIUM ISOPROPOXIDE UNDILULTED ONTO HEATED WAFERS.

TITANIUM ISOPROPOXIDE DISSOCIATES ON CONTRACT.

RESULT IS UNIFORM THICKNESS AR COATING.

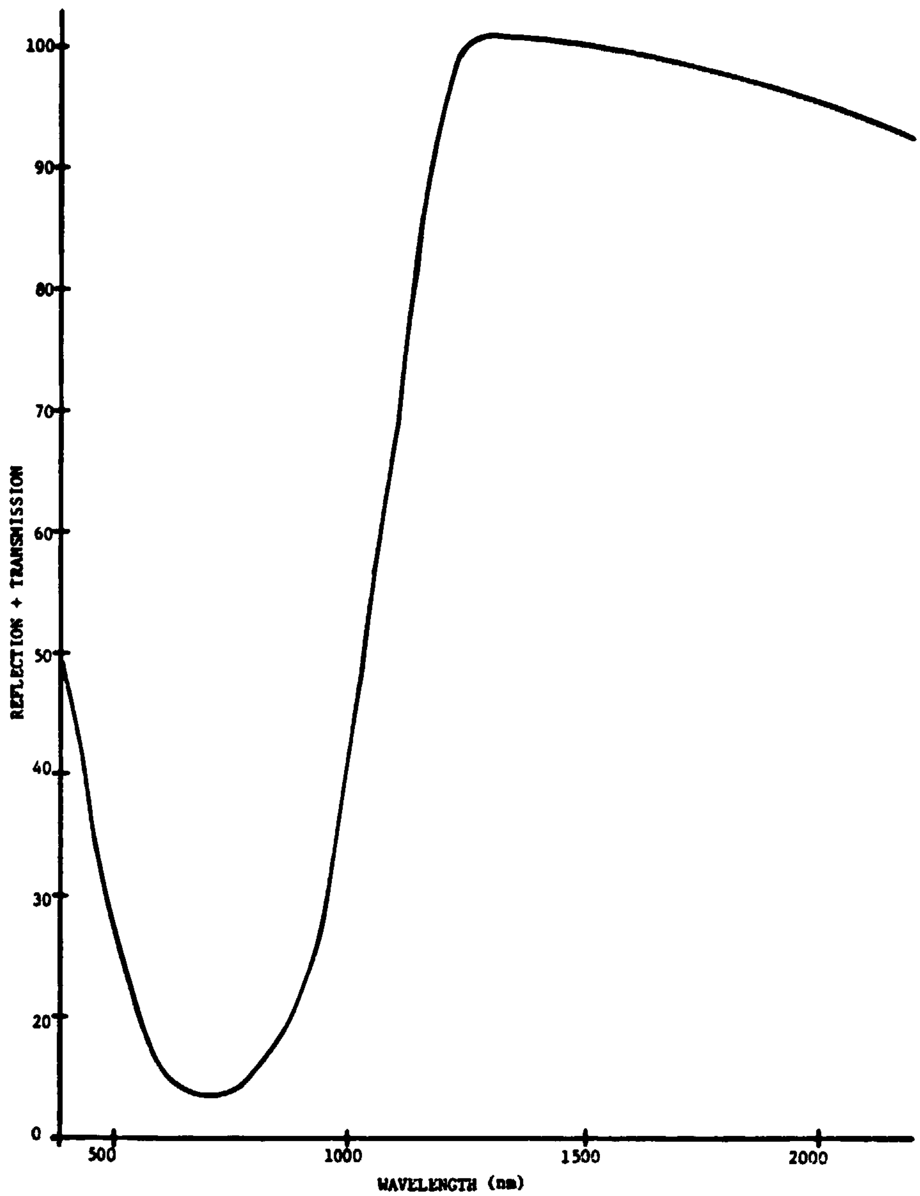
UNIFORM BLUE AR LAYERS OBTAINED ON TEXTURED SURFACES.

PLOT OF R & T VS WAVE LENGTH SHOWS HOW GOOD AR COATING IS.

EVAPORATED TA_2O_5 - 25% INCREASE IN ISC.

SPRAYED TIOX - 23% INCREASE IN ISC.

Hot-Spray AR Coat, Ti Isopropoxide



Ion Milling

VIABLE TECHNIQUE FOR REMOVING NI AND DIFFUSED SILICON FROM EDGE.

DO IN STACKS OF 1,000 WAFERS.

BEAM VOLTAGES OF 1,000 - 2,000 VOLTS.

BEAM CURRENTS OF $\approx$ 1.0 MA/CM^2.

MILL TIMES OF $\approx$ 1 HOUR.

PRELIMINARY RESULTS ENCOURAGING.

Cost

COST ESTIMATE BASED ON THROUGHPUT OF 1,000 WAFERS PER HOUR PER MACHINE - 50 MW PER YEAR FACTORY.

IPEG APPROXIMATION

EQUIPMENT	=	$0.0054	PER WATT
FLOOR SPACE	=	0.00096	PER WATT
DIRECT LABOR	=	0.0031	PER WATT
MATERIAL	=	0.0012	PER WATT
UTILITIES	=	0.00027	PER WATT
TOTAL	=	$0.0109	PER WATT

FOR COMPARISON: USING SAME FACTORY ASSUMPTIONS

LASER SCRIBING TOTAL = $0.0139 PER WATT

CELL AND MODULE FORMATION RESEARCH AREA

Wave Soldering

EXCELLENT TECHNIQUE FOR SOLDERING TO ONE SIDE OF SQUARE OR RECTANGULAR PART.

PRELIMINARY EXPERIMENTS INDICATE IT WORKS WELL FOR SEMICRYSTALLINE SOLAR CELLS.

NO BREAKAGE DUE TO THERMAL SHOCK HAS BEEN OBSERVED.

SOLDER THICKNESS CONTROLLABLE BY SPEED, ANGLE AND SOLDER TEMPERATURE.

SOLDER THICKNESS UNIFORMITY EXCELLENT.

REMAINING EFFORT - TO DESIGN CARRIERS FOR CELLS THAT CAN BE AUTOMATICALLY LOADED AND UNLOADED.

Equipment Suppliers

WAFER HANDLING - CASSETTE LOADERS/UNLOADERS

KINEMATICS
AMI
DEHAART
PROA

ETCH SYSTEMS

CONVEYOR ENGINEERING
FREDERICK MANUFACTURING
WESTERN TECHNOLOGY
CREST ULTRASONICS

CELL AND MODULE FORMATION RESEARCH AREA

Spray Coaters

ITI

Advanced Concepts Corporation

Belt Furnaces

BTU Engineering

Thermco

Infrared Furance Systems

Screen Printers

AMI

DeHaart

Sand Blasting

MTI

Empire

Plating Transport Equipment

Conveyor Engineering

Branson Corporation

Crest Ultrasonics

Wave Solder Equipment

Electrovert

Hollis

Ion Milling

Technics

Tabbing and Stringing Machines

MB Associates

Kulicke and Soffa

Spire

PROA

Module Lay-Up Systems

MB Associates

Laminators

Spire

JUNCTION FORMATION

SPIRE CORP.

Pulsed Electron Beam Annealing Tests

- o SOLAR CELLS
  1) First anneals made into cells
  2) Tests to improve uniformity
  3) Second anneals made into cells

- o HIGH THROUGHPUT TRANSPORT
  1) 50 wafer cassette operated through system
  2) Needs modification to improve alignment consistency

- o CHARGE TIME
  1) Machine operated at up to 3 second rep. rate
  2) Installing improved voltage monitor to define firing time

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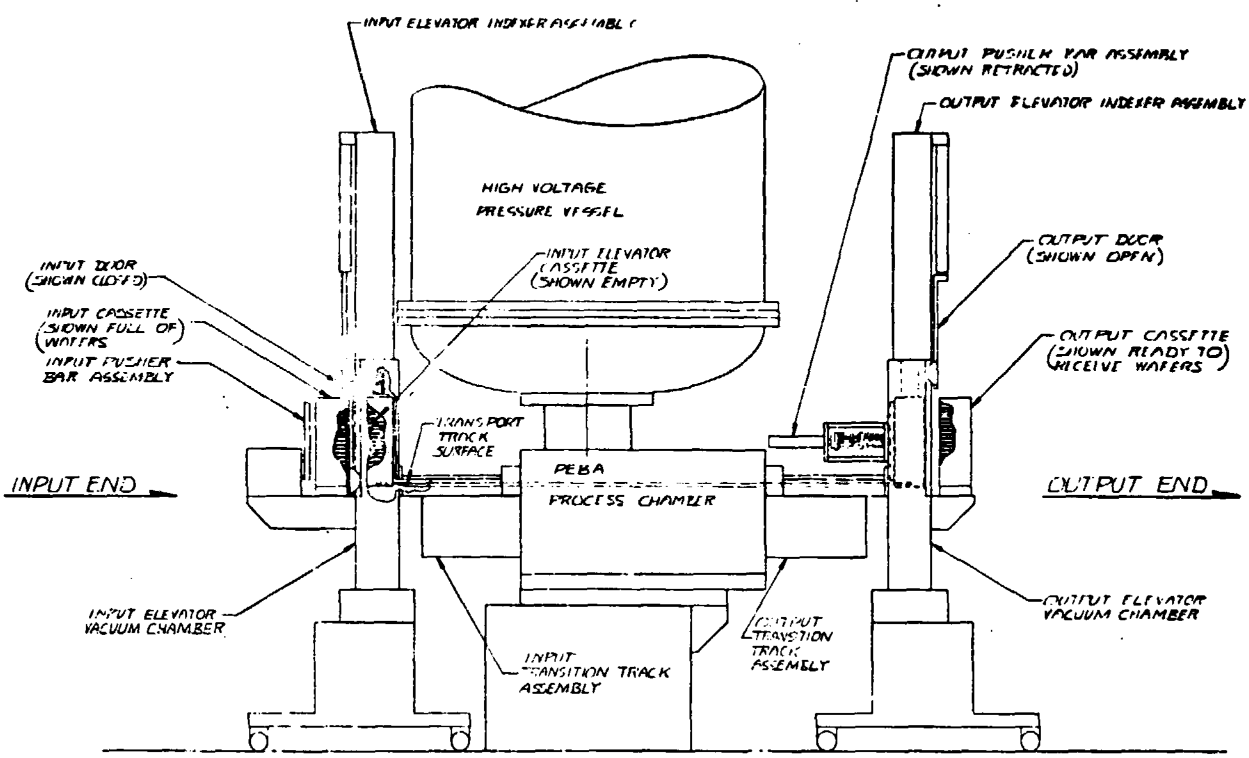
Elevator-Chamber Integration



Junction Processor Cells, Lot 4031: Comments

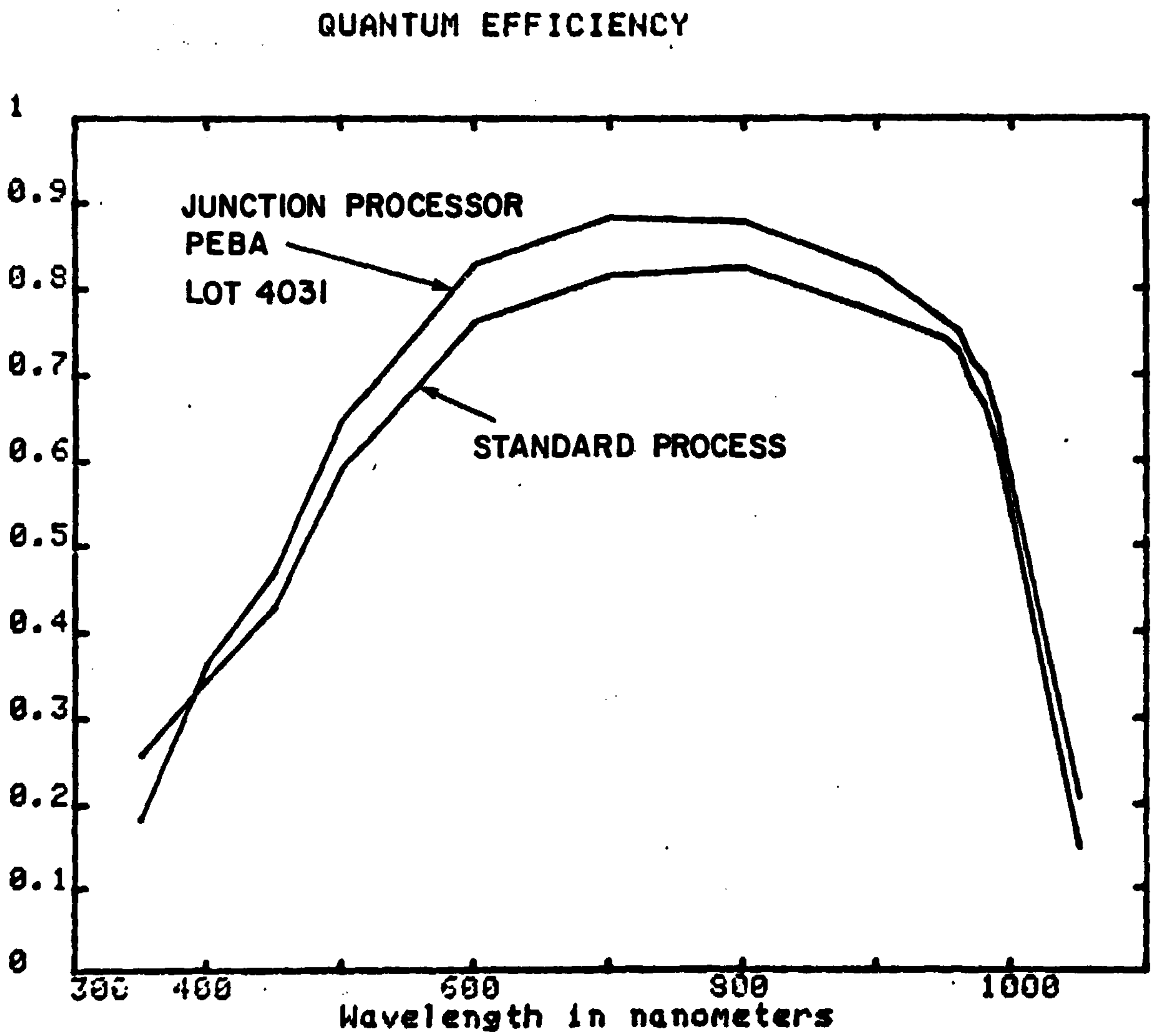
- No post-PEBA thermal treatment to simulate BSF process - this should increase Voc
- J_{sc} is higher than control lot
- Efficiency uniformity on 4" wafer is 11.2 ± 0.2% (AMO)

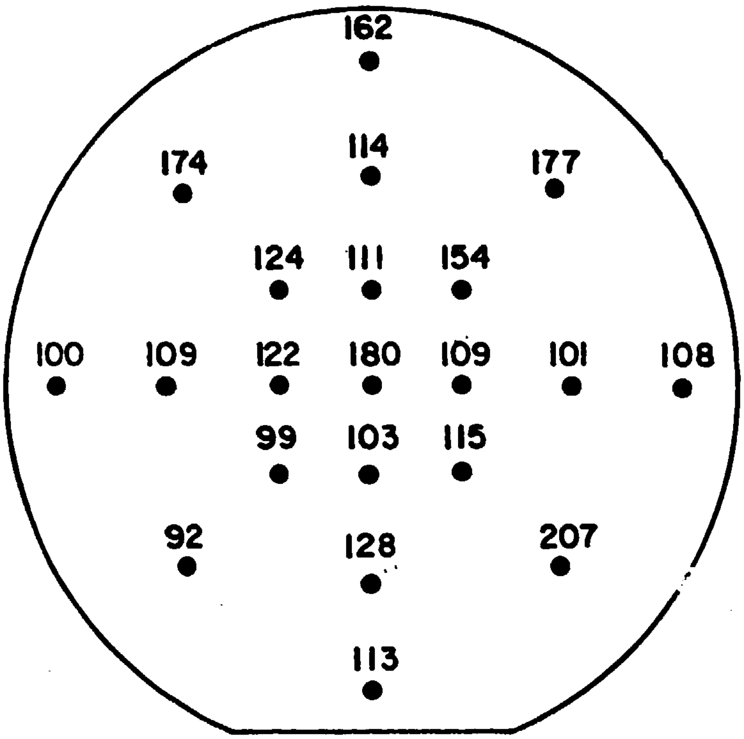
Junction Processor-PEBA Cells

LOT NUMBER: 4031
CONTRACT No: 10073
ORIGINATOR: S. Bunker
SURFACE: Pol
COMMENT: PEBA
CELL AREA: 4.0 cm^2
ILLUMINATION: AMO

RESISTIVITY: 10.0 ohm-cm
AR COATING: None
MATERIAL: CZ
THICKNESS: 18 mils
DATE: 11/01/81
RATED VOLT: 0.400 V
TEMPERATURE: 25^0C

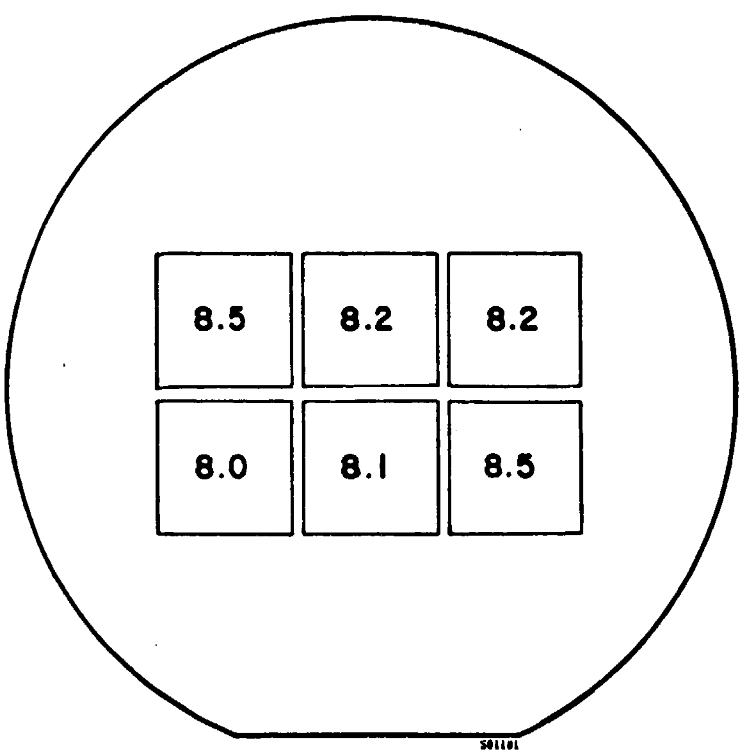
Cell	V oc (V)	Jsc mA/cm^2	FF (%)	Eff. (AMO) (%)
71	0.540	29.4	71.9	8.45
72	0.540	29.3	69.8	8.15
73	0.535	29.0	71.6	8.20
74	0.540	29.1	68.9	8.01
75	0.540	29.1	69.3	8.05
76	0.543	29.1	72.8	8.50
91	0.545	28.5	71.9	8.25
94	0.553	28.2	73.8	8.50
ave.	0.552	29.1	71.3	8.26
sdv.	0.005	0.3	1.7	0.20


QUANTUM EFFICIENCY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
JUNCTION PROCESSOR
PEBA
LOT 4031
STANDARD PROCESS
300
400
600
800
1000
Wavelength in nanometers

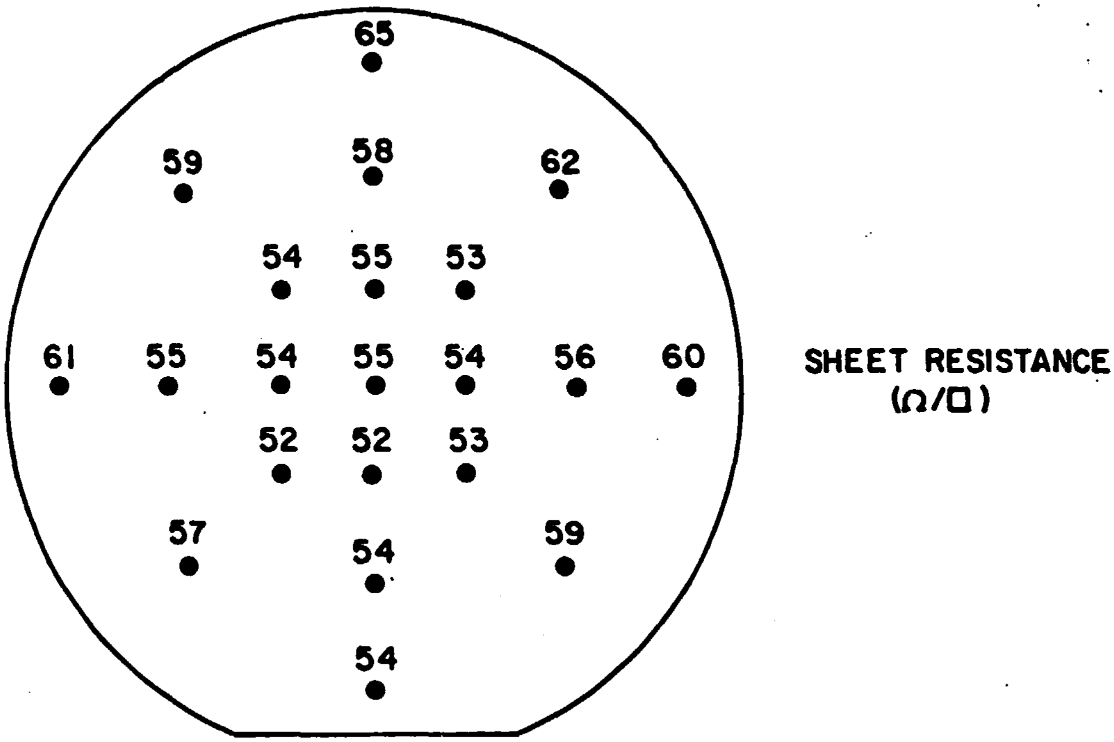


SHEET RESISTANCE
(Ω/□)

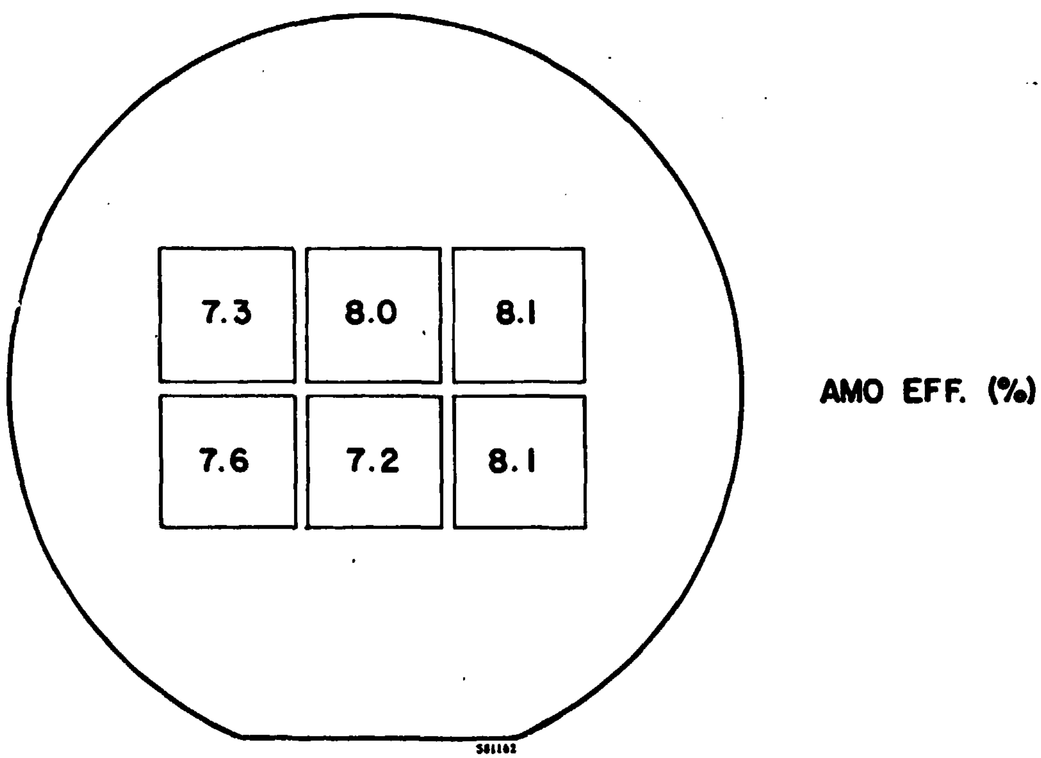
WAFER No. 7



AMO EFF. (%)


65
59
58
62
54
55
53
61
55
54
55
54
56
60
52
52
53
57
54
59
54
SHEET RESISTANCE
(Ω/□)

WAFER No. 10


7.3
8.0
8.1
7.6
7.2
8.1
AMO EFF. (%)

Test Conclusions

- Pulser is complete except for minor modifications
- Uniform anneals produced, but further improvements likely
- Pulser charging rate shown
- Transport has operated for a complete cassette
- All of above have been demonstrated individually but not yet simultaneously

Ion Implanter, Task 3

GOAL: PHOSPHORUS ION IMPLANTATION OF WAFERS AT A RATE COMPATIBLE WITH SPI-PULSE 7000

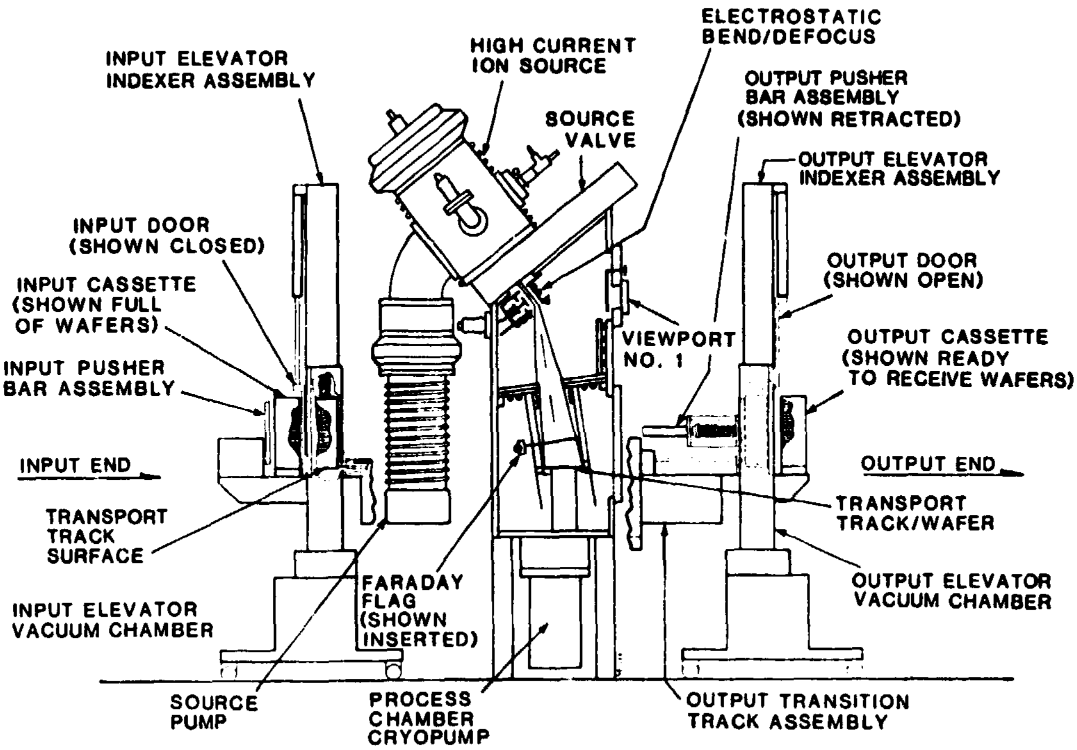
APPROACH: NON-MASS ANALYZED, 10 keV IMPLANT, ELECTROSTATICALLY BENT BEAM ONTO WALKING BEAM TRANSPORT

STATUS:

1) EXPERIMENTAL TEST IMPLANTATION CHAMBER OPERATIONAL
2) ION SOURCE DESIGN IN PROGRESS
3) TEST DESIGN FOR PARTIAL BEAM BENDER BEING EVALUATED

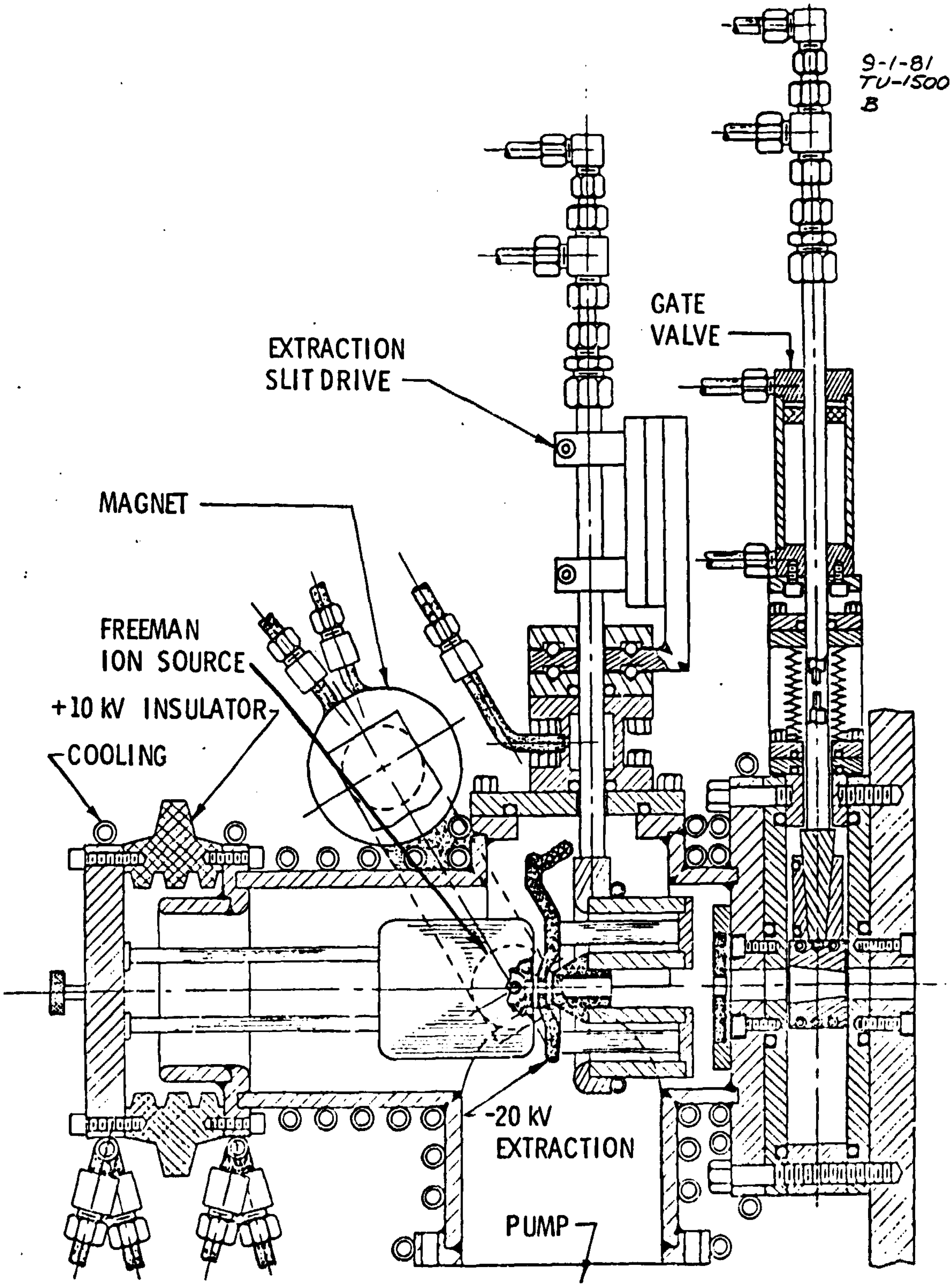
Solar Cell High-Throughput Ion Implanter (Task 3)

- IMPLANT RATE: 3 seconds/wafer, WALKING BEAM TRANSPORT
- IMPLANT IONS/DOSE: P_1^+, P_2^+, etc. @ 2.5×10^{15} ions/cm^2
- ION CURRENT: 10-15 ma^2
- ION ENERGY - 5-10 keV
- DIAGNOSTICS - BEAM CURRENT
  BEAM CENTERING
  TRANSVERSE UNIFORMITY
- WAFER HEATING - LESS THAN 150^{0}C RISE FOR WAFERS ON CARRIERS

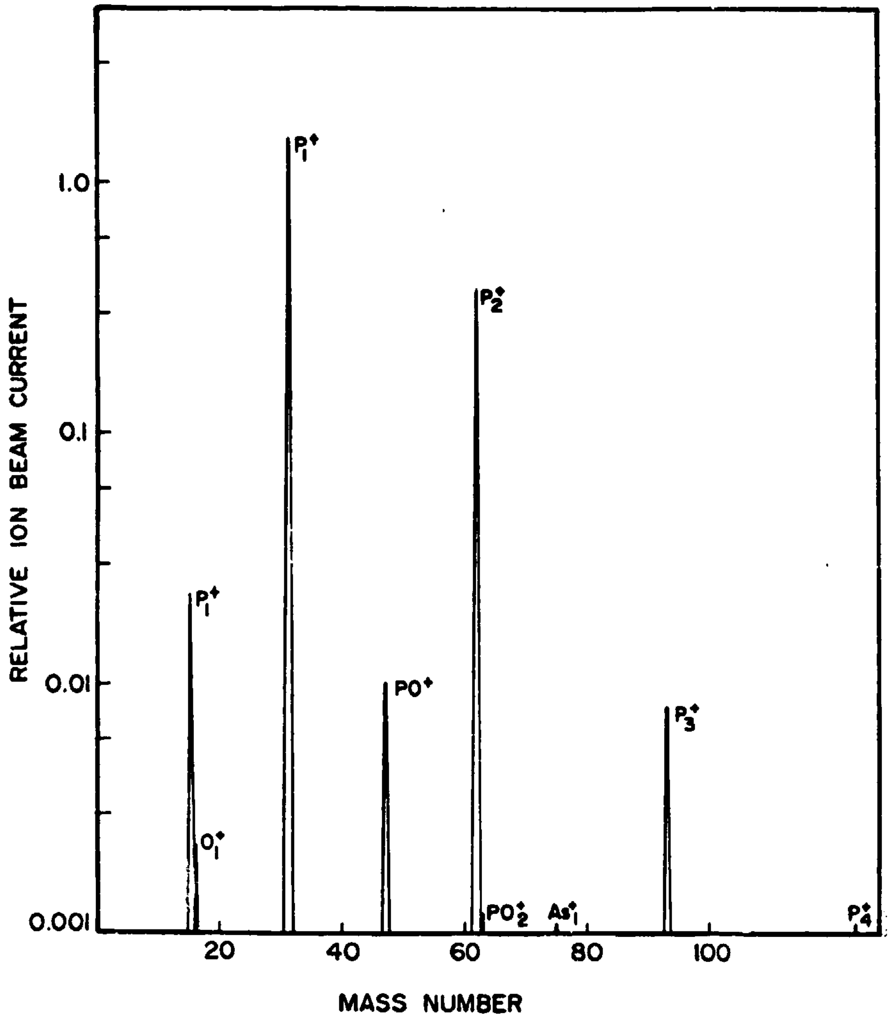


HIGH THROUGHPUT ION IMPLANTATION SYSTEM
(CENTRAL SECTION ROTATED 90° FOR CLARITY)

NMA Ion Source Concept



Ions Produced by Commercial-Grade Solid Phosphorus



Experimental Ion Implanter Facility

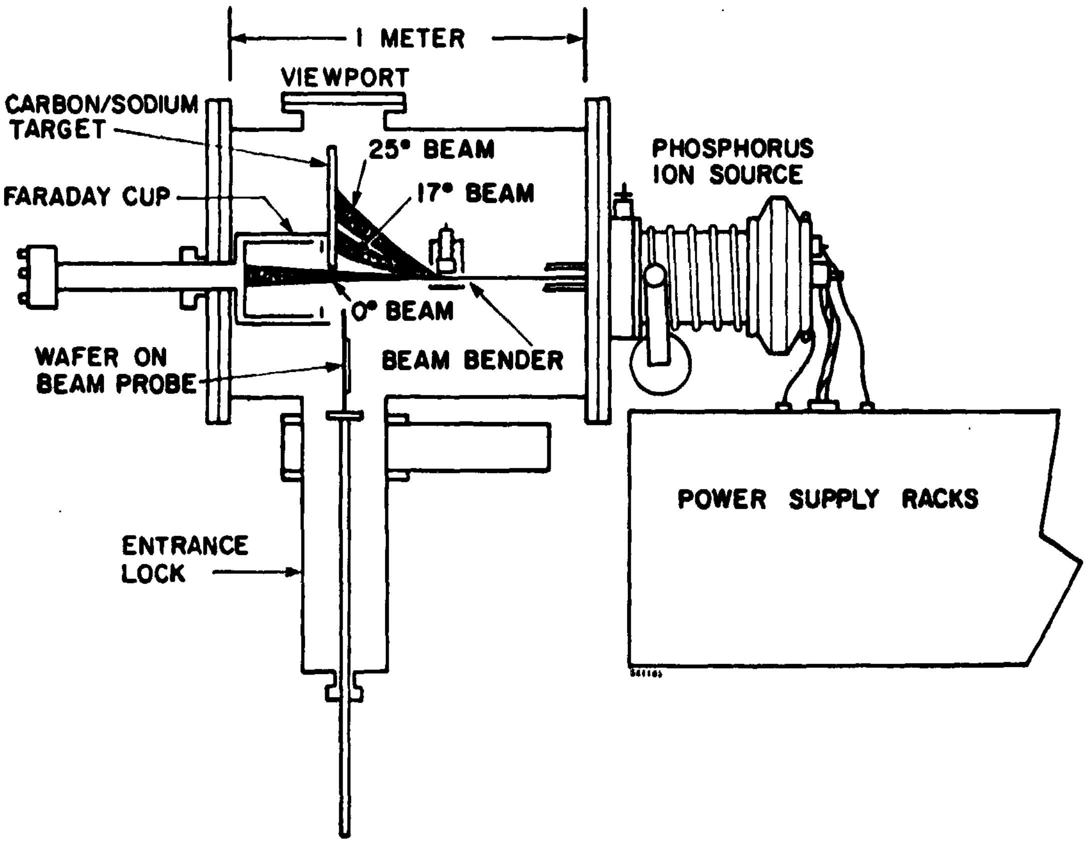
PURPOSE

1) Test concepts to be used for N.M.A. implanter
2) Establish engineering data for high intensity beam

EQUIPMENT

1) Commercial ion source with low voltage and high current modifications.
2) Electrostatic beam bender
3) Beam diagnostics and probe for holding wafer for implant

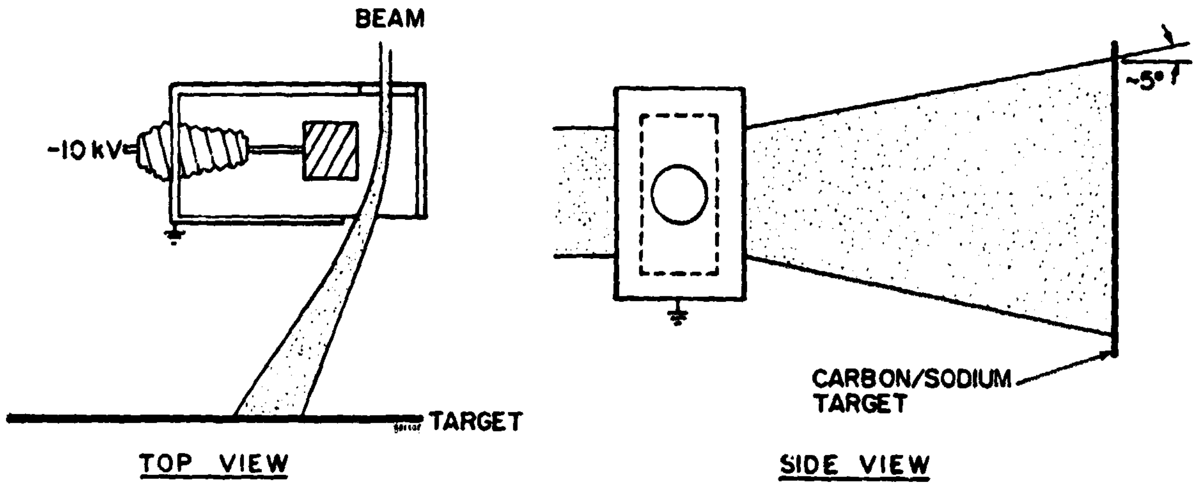
NMA Test Implant Chamber



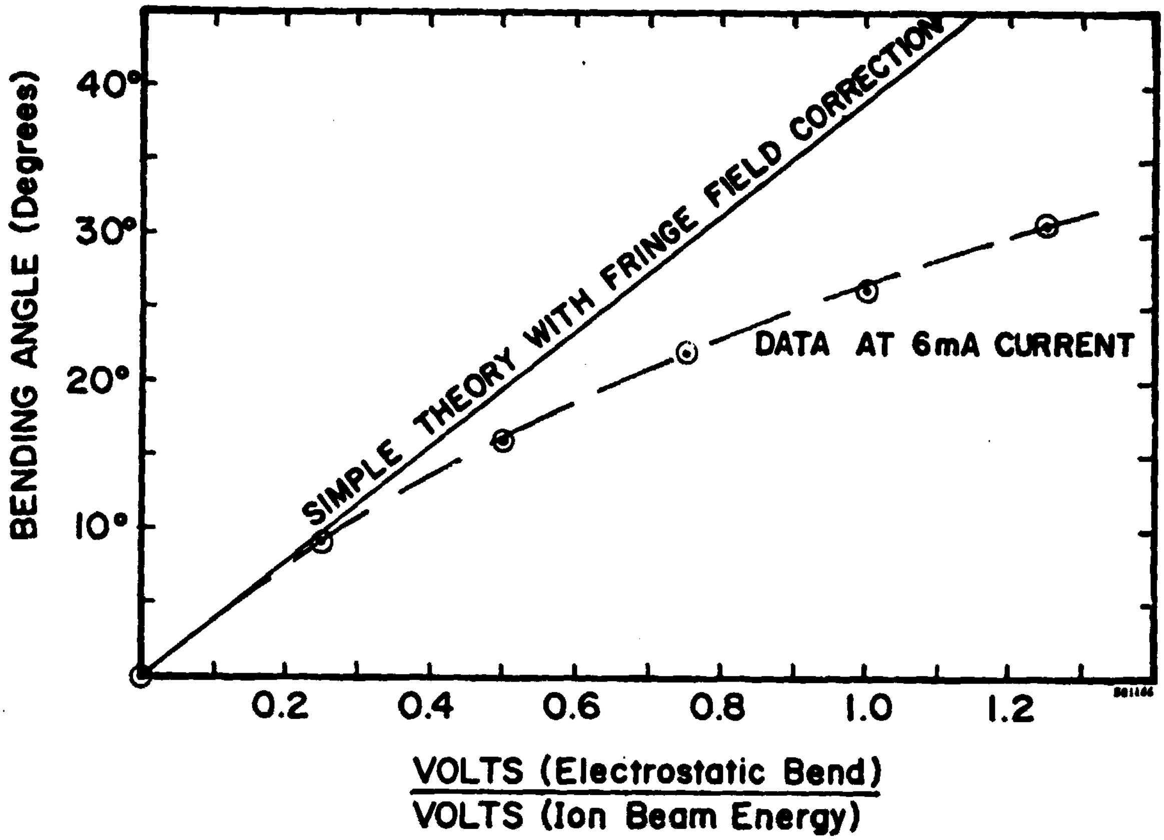
Tests Completed in NMA Experimental Facility

- o ELECTROSTATIC BEAM BENDING
  1) Beam divergence angles
  2) Bending angle at high currents
- o PHOSPHORUS BEAM FROM ELEMENTAL PHOSPHORUS
  1) Source parameters
  2) Source purity
- o SAMPLE N.M.A. IMPLANTS
  1) Bending angles of 0^0, 17^0, 25^0

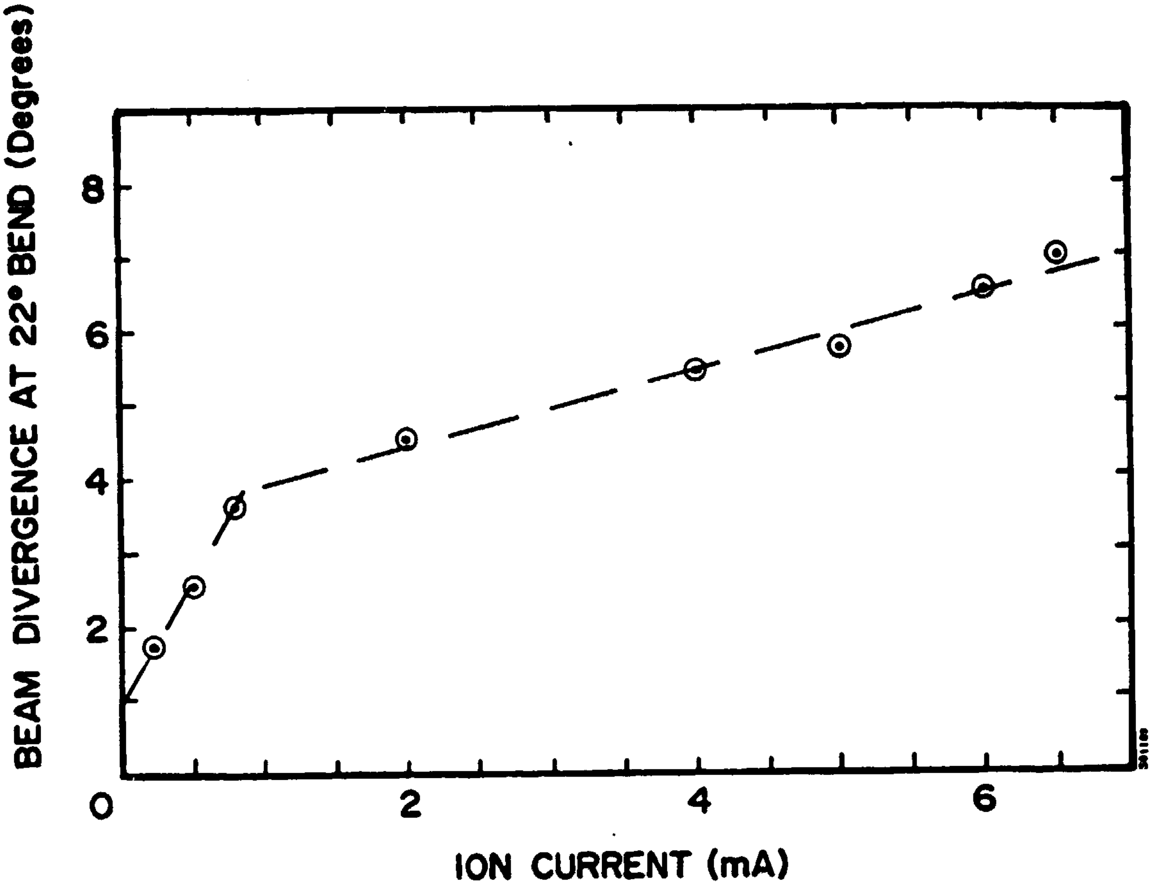
Test Model Beam Bender



Electrostatic Beam Bending at High Current



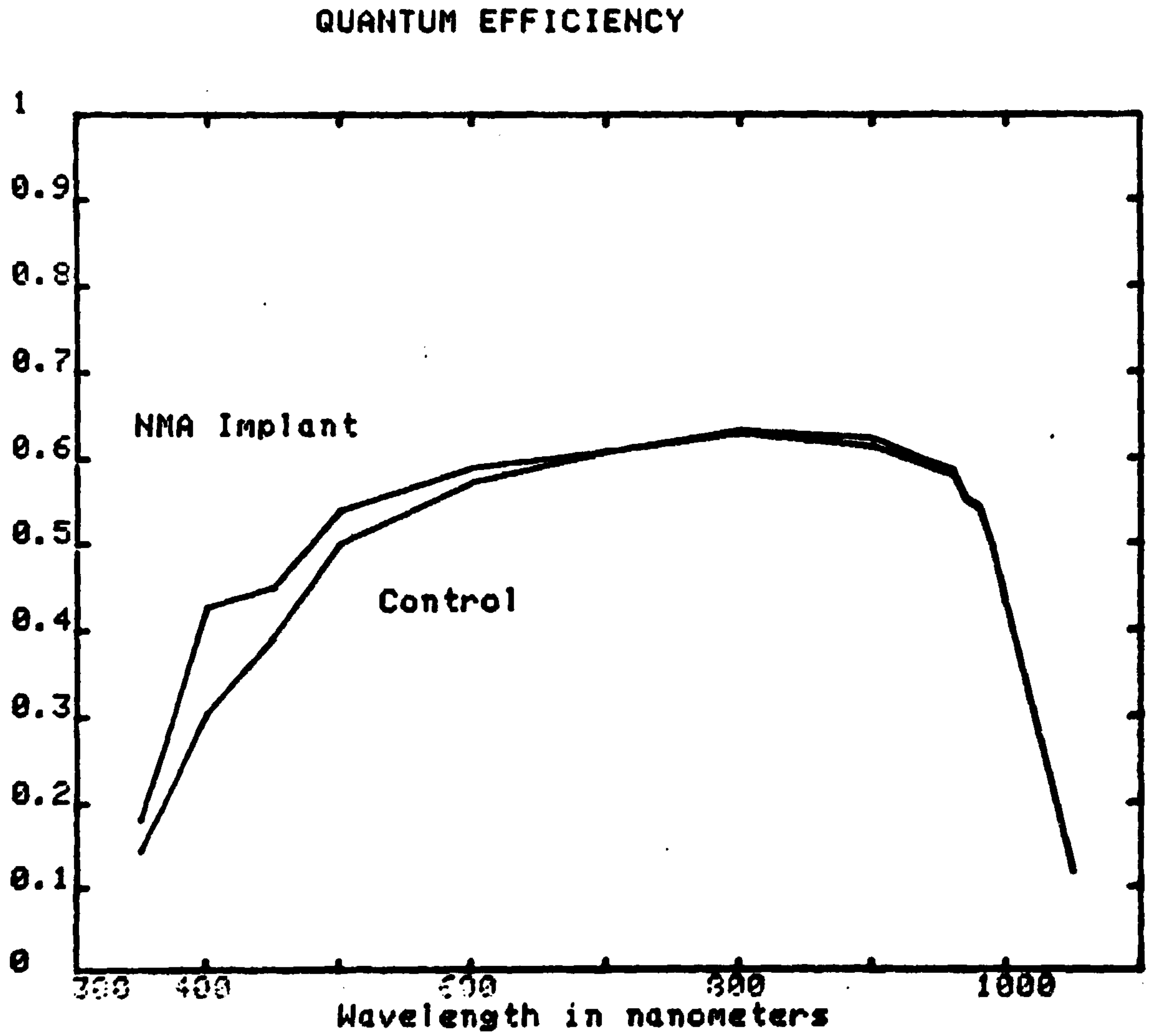
Ion Implanter Beam Spread After Bend-Defocus



NMA Implant Cells

	Lot 3969 Non Analyzed Implant	Lot 3969 Standard Implant
Voc (mV)	578 ± 1	573 ± 1
Jsc (mA/cm^2)*	28.7 ± 0.16	28.2 ± 0.08
Fill Factor (%)	75.7 ± 0.3	76.0 ± 0.2
η(AMO) (%)	9.29 ± 0.05	9.08 ± 0.04
η(AM1)+ - Extrapolated (%)	15.4 ± 0.08	15.0 ± 0.07
R_{sheet} (OHMS per square)	61.6 ± 3.1	55.4 ± 0.6
ρ (ohm-cm)	10	10

* No A.R. coating
\+ Times 1.4 for A.R. coat and times 1.18 for AM1


QUANTUM EFFICIENCY
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
NMA Implant
Control
300
400
600
800
1000
Wavelength in nanometers

Comments on Spire NMA Implants, Lot 3969

- Absolute dose varied by a factor of 10 for the nine wafers implanted with 10 keV phosphorus

- Dose variation within each wafer was also up to a factor of ten. (Spire's test facility is designed for beam transport studies rather than uniform implants.)

- Angle of incident beam for implant varied between 0^{o} and 35^{o}

- Efficiency of individual cells ranged between 9.21% and 9.37%. Efficiency of control cells ranged between 9.03% and 9.15%.

- Conclusion: There is little sensitivity to implant dose or angle observed in this test lot.

Tests to Be Performed in NMA Experimental Facility

o HIGH CURRENT SOURCE MODIFICATION

1) Test to 15 ma

o ELECTROSTATIC BEAM BENDER

1) Complete test matrix at high currents
2) Modifications for steering

o SAMPLE N.M.A. IMPLANTS

1) Perform with improved, more uniform beam

NON-MASS-ANALYZED ION IMPLANTS

JET PROPULSION LABORATORY

D.J. Fitzgerald

Current Objectives

- DETERMINE EFFECTS OF PRETREATMENT OF MATERIAL
- EVALUATE COMBINE N-M-A JUNCTIONS AND BSF
- TEST REQUIREMENT FOR CLEANING BEFORE ANNEAL STEP

Effect of Pretreatment

	Voc (mV)	Isc (mA/cm^2)	F.F. (%)	η(AM1) (%)	η^*(AM1) @ FF = 75 (%)
BASELINE[1]	593	31.8	78.6	14.9	(14.2)
NO PROCESS[2]	558	29.4	72.0	11.8	(12.3)
GETTERED[2,3]	556	29.9	71.0	11.8	(12.5)
HEAT CYCLE[2,4]	556	29.7	72.0	12.0	(12.5)

(1) $POCl_3$ DIFFUSED (ASEC)
(2) N-M-A IMPLANT, P @ 6 x 10^{15} ATOMS/CM^2, 15 KEV, 10^{o}
(3) $POCl_3$ DIFFUSED, ETCH BOTH SIDES (ASEC)
(4) HEAT CYCLE (DIFFUSION LIKE), ETCH BOTH SIDES (ASEC)

Effect of N-M-A Junction* and BSF**

	BSF	Voc (mV)	Isc (mA/cm²)	F.F. (%)	η(AM1) (%)	η*(AM2)@ FF = 75 (%)	
NO PROCESS	NO	558	29.4	72.0	11.8	(12.3)	
	YES	565	30.6	73.0	12.7	(13.0)	+.7%
GETTERED	NO	556	29.9	71.0	11.8	(12.5)	
	YES	561	30.6	71.3	12.2	(12.8)	+.3%
HEAT CYCLE	NO	556	29.7	72.0	12.0	(12.2)	
	YES	567	30.7	75.0	13.1	(13.1)	+.9%

* P - $6x10^{15}$ ATOMS/CM^2 @ 15 KEV, 10°

** BF_3 - $1x10^{16}$ ATOMS/CM^2 @ 20 KEV, 10°

Effect of Cleaning* Before Anneal Step**

	CLEANED	Voc (mV)	Isc (mA/cm²)	F.F. (%)	η(AM1) (%)	η(AM1)@ FF=75 (%)	
NO PROCESS	NO	560	29.6	71.5	11.8	(12.4)	
	YES	556	29.4	72.2	11.8	(12.3)	-.1%
GETTERED	NO	560	29.4	74.0	12.2	(12.4)	
	YES	556	29.9	70.4	11.7	(12.5)	+.1%
HEAT CYCLE	NO	557	29.5	71.0	11.6	(12.3)	
	YES	556	29.9	73.0	12.2	(12.5)	+.2%

* ORGANIC SOLVENT, $H_2SO_4 + H_2O$, 5 MIN. , 20°C

** NO BSF, N-M-A ION IMPLANTED, $6x10^{15}$ ATOM/CM^2 @

Conclusions

- MATERIAL PRETREATMENT (GETTERING) HAS SLIGHT BENEFIT
- N-M-A JUNCTION HAD LOWER Voc
- N-M-A BSF SHOWED SMALL INCREASE IN Voc

Problem Areas

- MINORITY LIFETIME FACTOR OF 2 LOWER THAN BASELINE CELLS
- POSSIBLE IRON CONTAMINATION FROM MASK/ION SOURCE

ALL-METAL THICK-FILM METALLIZATION

BERND ROSS ASSOCIATES

Bernd Ross

Progress

A COPPER PASTE WITH A SHARPLY REDUCED SILVER FLUORIDE ADDITION GAVE ADHERENT CONTACTS.

REPRODUCIBLE RESULTS HAVE BEEN ACHIEVED WITH ABOVE PASTES WITH A NEW FIRING SCHEDULE.

COST PROJECTIONS HAVE BEEN MADE FOR SILVER FLUORIDE - AND CARBON FLUORIDE-COPPER ELECTRODE PASTES.

CHEMICAL REACTIONS AND PHYSICAL PROCESSES HAVE BEEN FURTHER ANALYZED.

A SOLAR CELL EXPERIMENT IS IN PROGRESS.

Copper Paste Experiments

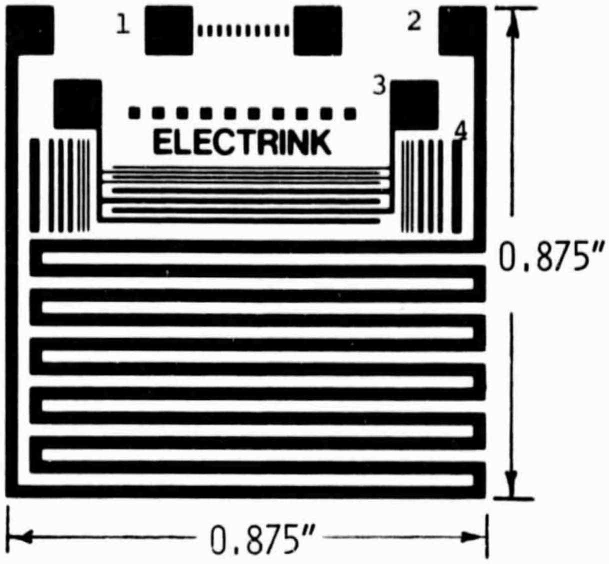
ANALYSIS OF POSSIBLE REACTIONS OF SILVER FLUORIDE WITH OTHER PASTE COMPONENTS LEAD TO THE IDENTIFICATION OF SPOILER REACTIONS (DURING FIRING)

$$Cu + 2AgF \rightarrow CuF_2 + 2Ag + 29.9 \text{ Kcal/mole}$$
$$Pb + 2AgF \rightarrow PbF_2 + 2Ag + 61.5 \text{ Kcal/Mole}$$
$$CuO + 2AgF \rightarrow CuF_2 + 2Ag + \tfrac{1}{2}O_2 - 7.2 \text{ Kcal/Mole}$$
$$PbO + 2AgF \rightarrow PbF_2 + 2Ag + \tfrac{1}{2}O_2 + 9.3 \text{ Kcal/Mole}$$

REMOVAL OF THE FRIT METAL, LEAD, IS DETRIMENTAL TO THE LIQUID PHASE SINTERING PROCESS.

PASTES WERE PREPARED WITH SILVER FLUORIDE FRACTIONS AS SMALL AS 0.7 WT%.

THESE FORMULATIONS REPRODUCIBLY PASSED TAPE TESTS.



TEST SCREEN PATTERN WITH:

1. CONTACT RESISTANCE ARRAY
2. LINE RESISTANCE PATTERN
3. ELECTRICAL RESOLUTION PATTERN
4. OPTICAL RESOLUTION PATTERN

Firing Process

THE HYDROGEN PHASE OF THE TWO STEP FIRING PROCESS TENDS TO IMPROVE SINTERING BUT REDUCE ELECTRODE ADHESION (TIME-TEMPERATURE).

THIS HAS BEEN VERIFIED BY RETURN TO SILVER ELECTRODE FIRING EXPERIMENTS.

SIEMENS INVESTIGATIONS HAVE SHOWN THAT THE DANGLING BONDS IN AMORPHOUS SILICON ONCE SATURATED WITH HYDROGEN, WERE RELUCTANT TO RELEASE IT (TO $T=1000^{\circ}K$).

A PREFERENCE OF THE DANGLING BONDS OF THE CRYSTALLINE SILICON SURFACE FOR HYDROGEN WOULD EXPLAIN THE OBSERVED CONTACT BEHAVIOR AFTER HIGH TEMPERATURE HYDROGEN TREATMENT.

A NEW FIRING PROCESS WITH HYDROGEN EXPOSURE ONLY AT TEMPERATURES BELOW $350^{\circ}C$ HAS GIVEN GOOD RESULTS.

REVISED FIRING PROCESS

AMBIENT GAS	FLOW (ℓ/m)	TEMPERATURE (°C)	TIME (MIN.)
NITROGEN	4	190	2
NITROGEN	4	450	3
NITROGEN	4	550	1
NITROGEN	4	600	4
NITROGEN	4	320	4
NITROGEN HYDROGEN	4 7	320	4
NITROGEN HYDROGEN	4 7	90	2
NITROGEN	4	30	1
NITROGEN	4	30	1

A SOLAR CELL TEST EMPLOYING ABOVE FIRING WITH 0.7% AgF - COPPER BACK ELECTRODES IS IN PROCESS.

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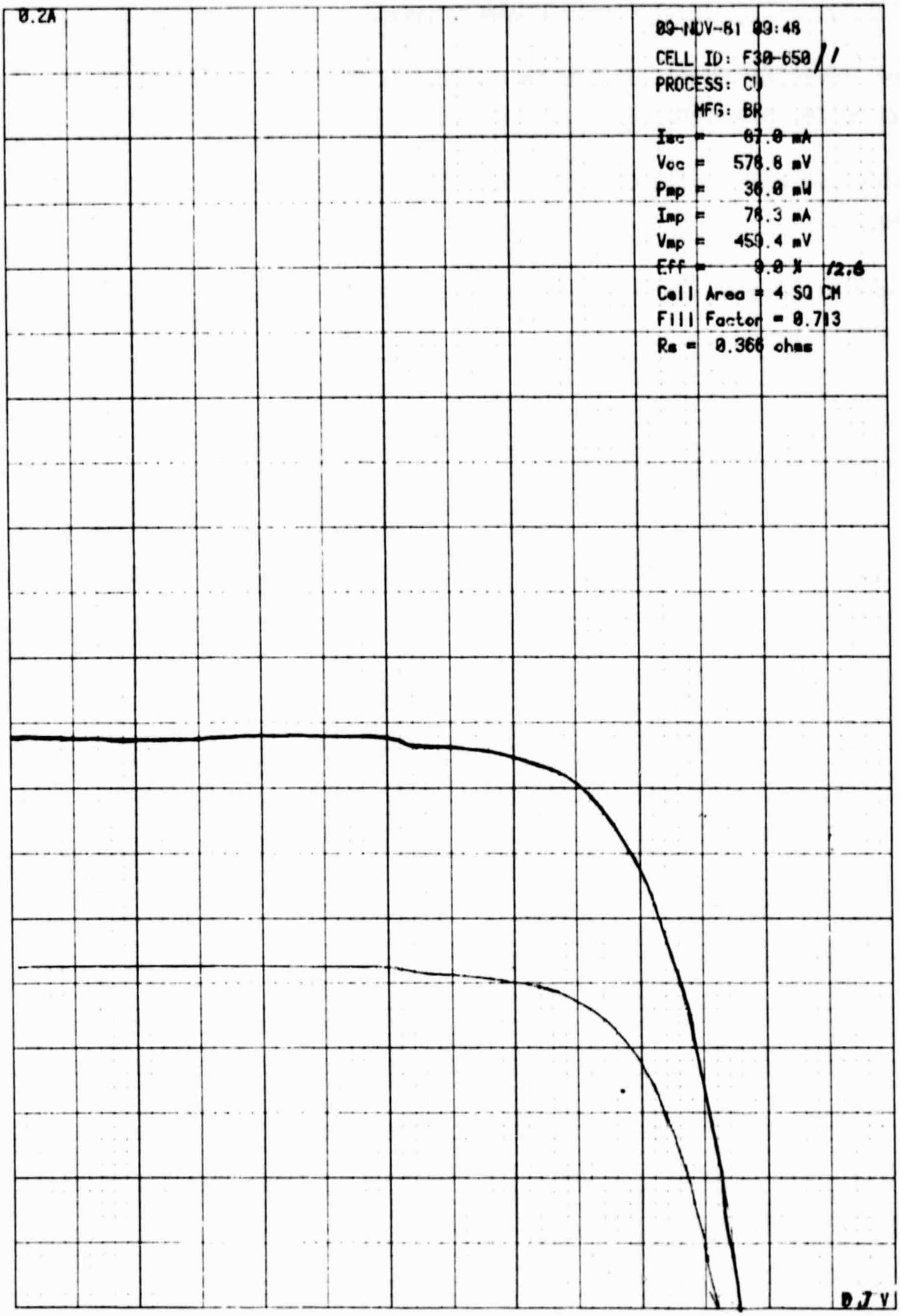

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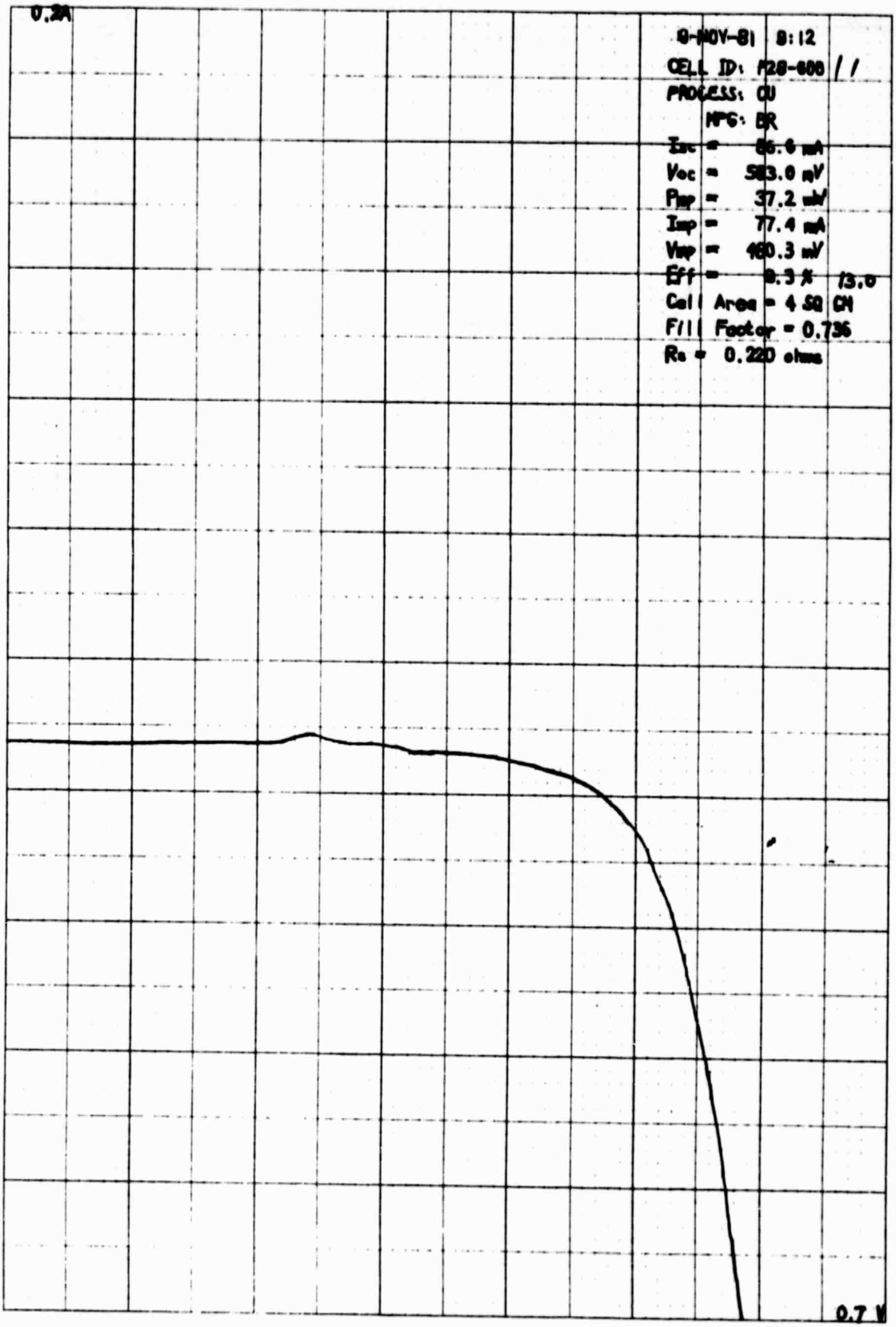
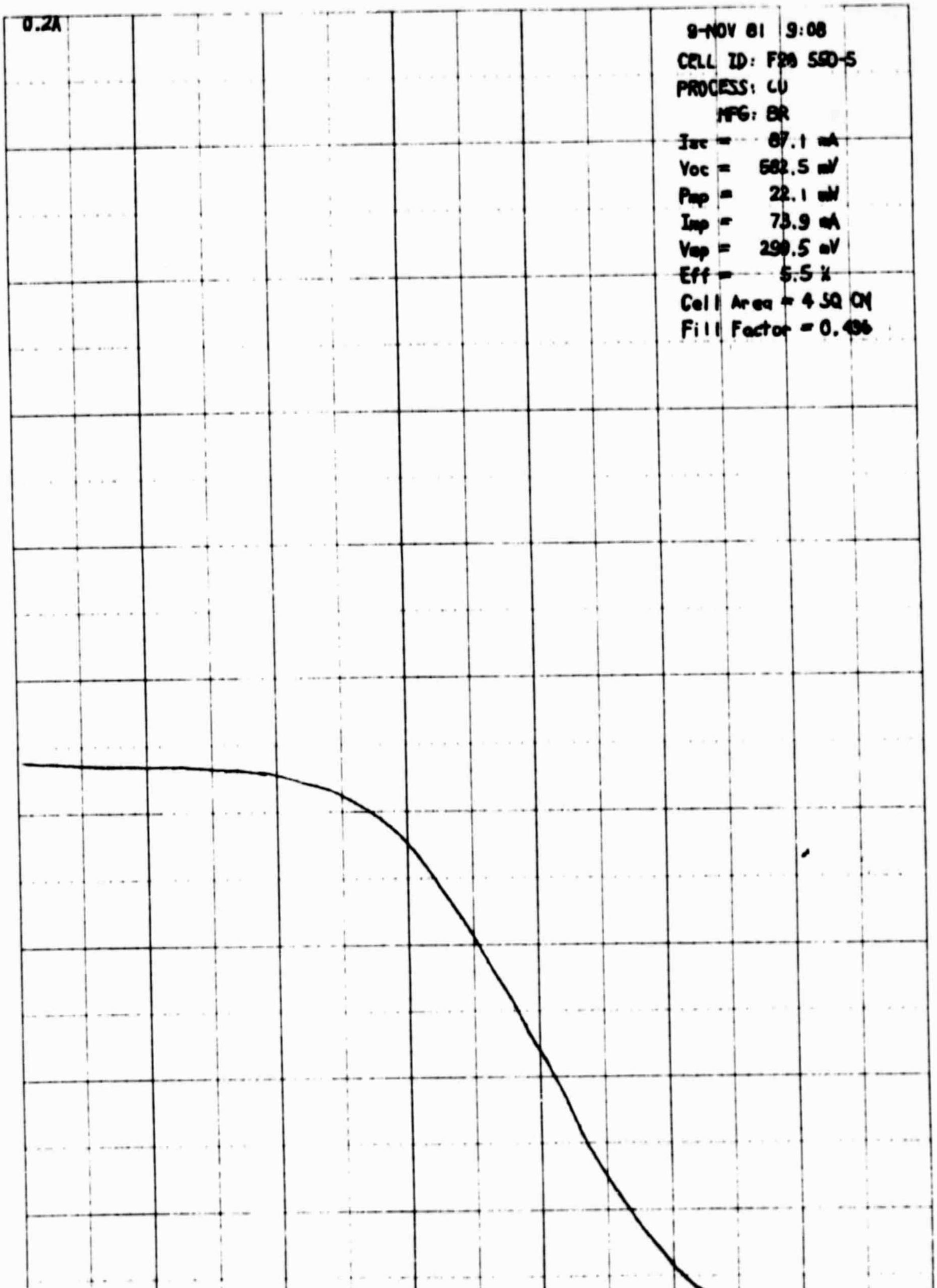
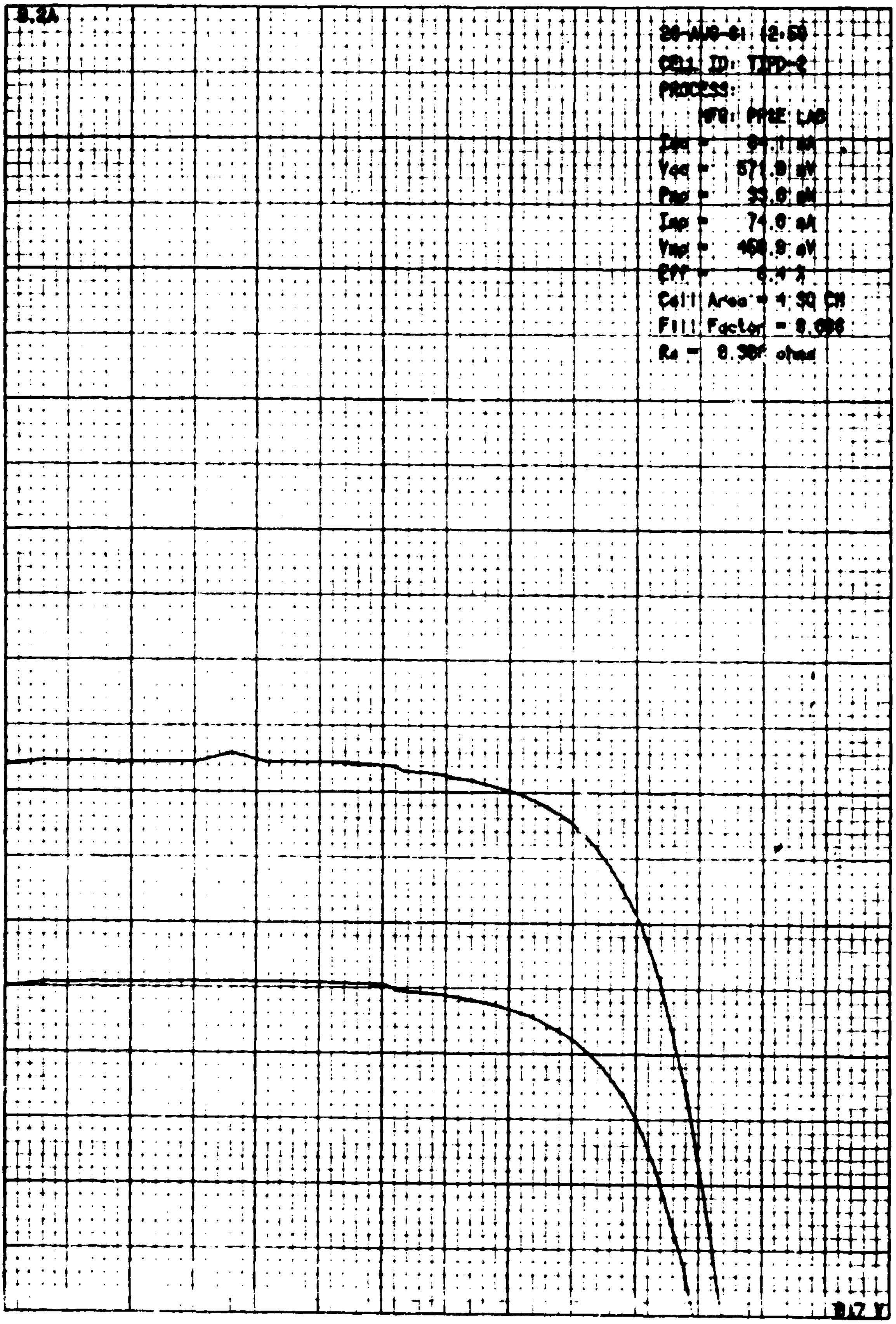



0.2A
9-NOV 81 9:08
CELL ID: F28 550-5
PROCESS: CU
MFG: BR
Isc = 87.1 mA
Voc = 582.5 mV
Pmp = 22.1 mW
Imp = 73.9 mA
Vmp = 290.5 mV
Eff = 5.5 %
Cell Area = 4 SQ CM
Fill Factor = 0.436
0.7 V


PROCESS:
Cell Area
Fill Factor
ohms
V

Costs

MATERIAL	PASTE F12 (AgF) AMOUNT(WT%)	COST $	COST %	PASTE F13 (C_XF_Y) AMOUNT(WT%)	COST $	COST %
ORGANIC SOLVENT	31.2	0.343	20.5	30.8	0.338	21.0
RESIN	4.2	0.093	5.56	2.2	0.0619	3.83
THIXOTROPIC AGENT	0.6	0.0089	0.53	0.4	0.0059	0.37
COPPER POWDER	57.1	1.142	68.29	56.9	1.138	70.44
LEAD POWDER	4.6	0.014	0.84	4.6	0.014	0.87
ALUMINUM-SILICON EUTECTIC	1.2	0.044	2.63	1.1	0.041	2.54
SILVER FLUORIDE	1.1	0.0275	1.64	-	-	-
LEAD ACETATE	-	-	-	2.3	0.0122	0.76
FLUORO CARBON	-	-	-	1.1	0.0043	0.27

	PASTE F12	PASTE F13
MATERIAL COST	$1.6724/oz	$1.6156/oz
LABOR	0.50/oz	0.50/oz
AUXILIARY MATERIALS		
PAPER WIPES	0.014/oz	0.014/oz
CLEANING SOLVENT	0.048/oz	0.048/oz
PACKAGING & GLASSWARE	0.047/oz	0.047/oz
ROLLERMILL DEPRECIATION 200,000 oz/MILL LIFE	0.04/oz	0.04/oz
TOTAL LABOR, MATERIALS, DEPRECIATION	2.3214/oz	2.2646/oz
YIELD 80%	3.77/oz 0.121/G	3.68/oz 0.118/G
COST OF HYDROGEN FIRING	0.006/CELL	0.006/CELL
COST PER 4"OD CELL (1 WATT)	$0.04449/W	$0.0440/W

Conclusions and Problems

1. BOTH SILVER FLUORIDE AND FLUOROCARBON SCREENED PASTE ELECTRODES CAN BE PRODUCED FOR APPROXIMATELY $.004 PER WATT.

2. REPRODUCIBLE RESULTS HAVE BEEN ACHIEVED WITH ADHERENT COPPER ELECTRODES CONTAINING 0.7 WT% SILVER FLUORIDE.

3. ANALOGOUS RESULTS WITH HYDROGEN BONDED AMORPHOUS SILICON SUPPORTED THE HYPOTHESIS THAT HYDROGEN REPLACES METAL-SILICON BONDS AND LED TO A MODIFIED TWO STEP FIRING PROCESS.

4. CARBON FLUORIDE-COPPER PASTES REQUIRE FURTHER MODIFICATION TO ACHIEVE REPRODUCIBLY ADHERENT ELECTRODES.

5. INITIAL RESULTS OF SOLAR CELL EXPERIMENT GAVE 13.0% AM1 EFFICIENCY.

NICKEL-COPPER PROGRAM REVIEW

PHOTOWATT INTERNATIONAL INC.

Subcontractors

- ELECTRO-SCIENCE LABORATORY
  - NICKEL PASTE FORMULATIONS
- VANGUARD PACIFIC
  - BRUSH COPPER PLATING

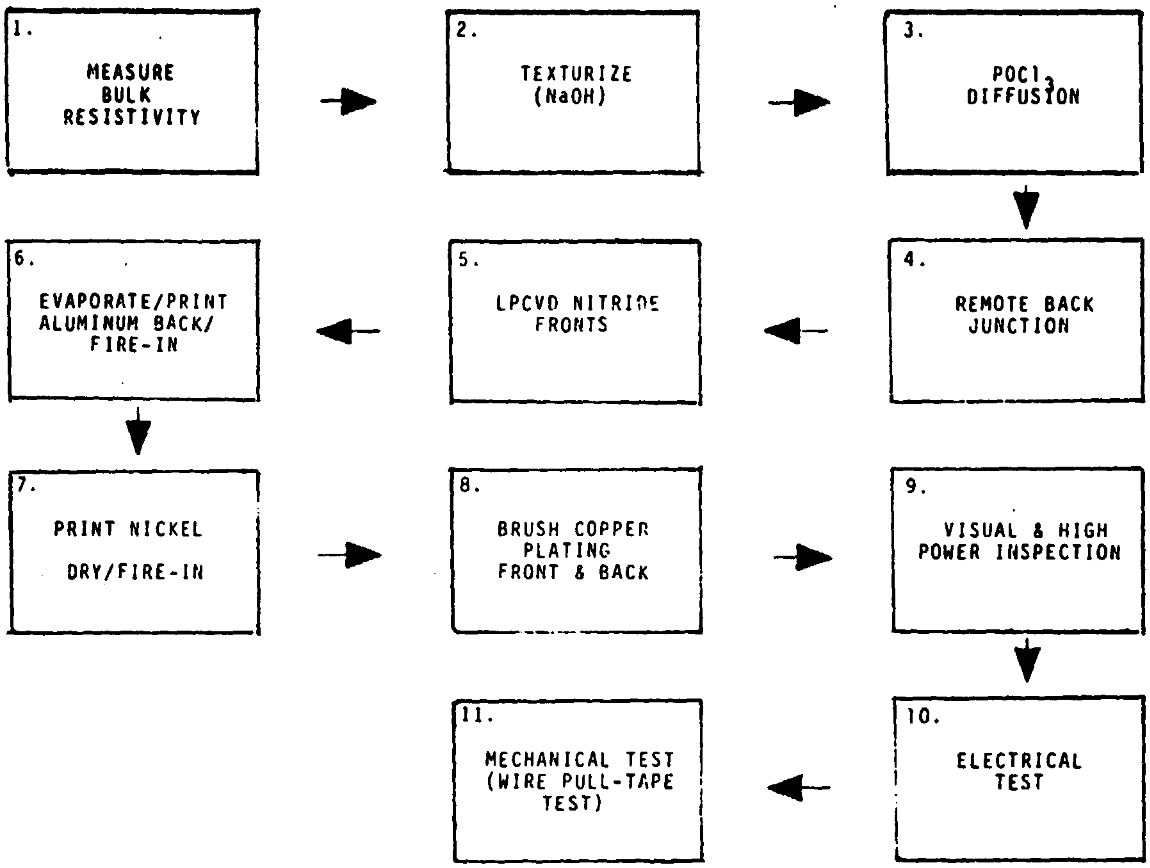
Contract Objective

DEMONSTRATE AN ENVIRONMENTALLY STABLE, THICK FILM NICKEL/BRUSH COPPER PLATED METAL SYSTEM THAT IS CAPABLE OF GREATER THAN 10% EFFICIENCY

Approach

- UTILIZE A BASE METAL SYSTEM TO MINIMIZE THE IMPACT OF METAL COST:
  - CONTACT: NICKEL THK FILM
  - BARRIER: NICKEL THK FILM
  - CONDUCTION: PLATED COPPER
- UTILIZE SILICON NITRIDE (A/R) "FIRE-THROUGH" APPROACH TO MINIMIZE COPPER DIFFUSION
  - UNDER METAL PATTERN
  - AT RANDOM Cu DEPOSITION SITES
- ENHANCE OHMIC CONTACT OF NICKEL WITH SMALL AMOUNTS OF AgF
- UTILIZE BRUSH Cu PLATING TECHNIQUES TO IMPROVE CONTROL AND UNIFORMITY

Outline of Process Sequence



MAJOR PROBLEMS	CORRECTIVE ACTIONS
• EXCESSIVE SERIES RES.:	
• CONTACT RESISTANCE	• MODIFY FIRE CYCLE/AgF CONTENT
• PHYS. DISCONTINUITIES - Ni	• MODIFY DRY/FIRE CYCLE/PASTE
• HIGHLY POROUS Cu	• REDUCED Cu PLATING TEMP/VOLTAGE
• LOW SHUNT RES.:	
• Cu PLATED AROUND EDGE	• REDUCED Cu PLATING TEMP/VOLTAGE & TIME
• NICKEL CONTACT ADHESION SEVERELY REDUCED DURING PLATING	• MODIFIED FRIT COMPOSITION • UTILIZED NEUTRAL Cu BATH • REDUCED PLATING TEMP/VOLTAGE
• Cu ADHESION TO Ni THK FILM	• REVERSED ELECTRODE POLARITY BEFORE INITIATION OF Cu PLATING TO INCREASE Cu DEPOSITION SITE DENSITY

Electrical Test Results

NI PASTE CELL	FIRE TEMP(C)	FIRE TIME(MIN)	ISC(mA/cm^2)	Voc(VOLTS)	F.F.	EFF(%)
1-C	625	10	23	0.55	0.31	3.64 *
2-C	650	10	25	0.56	0.39	4.90 *
3-C	700	5	25	0.54	0.40	5.35 *
1-D	625	10	18	0.45	0.26	2.14 *
2-D	650	10	25	0.57	0.62	8.78 *
3-D	700	5	25	0.58	0.63	9.27 *
1-E	625	10	24	0.56	0.36	2.39 *
2-E	650	10	25	0.56	0.48	6.40 *
3-E	700	5	24	0.57	0.65	8.99 *
4-E	700	5	25	0.588	0.58	8.39 **
1-AA	625	10	28	0.585	.71	11.5 **
2-AA	650	10	28	0.585	.688	11.3 **
3-AA	700	3	27	0.585	.715	11.1 **
3-AA	700	5	24	0.585	.706	9.9 **
3-AA	700	10	28	0.59	.68	11.3 **

* ALKALINE COPPER PLATING HIGH TIP TEMP.
**CENTRAL COPPER PLATIN LOW TIP TEMP.

Mechanical Test Results

CELL #/ Ni PASTE TYPE	FIRE CYCLE		Ni PASTE/Cu		Al PASTE/ Cu PLATE
	TEMP(C)	TIME(MINS)	FRONT SHEAR PULL STRENGTH (GRAMS)	90° PEEL STRENGTH (GRAMS)	BACK SHEAR PULL STRENGTH (GRAMS)
1-C	625	10	980	100	900
2-C	650	10	330	25	900
3-C	700	5	170	17	900
1-D	625	10	290	25	900
2-D	650	10	190	20	900
3-D	700	5	260	24	900
1-E	625	10	685	75	800
2-E	650	10	1000	120	900
3-E	700	5	600	65	900

Plans

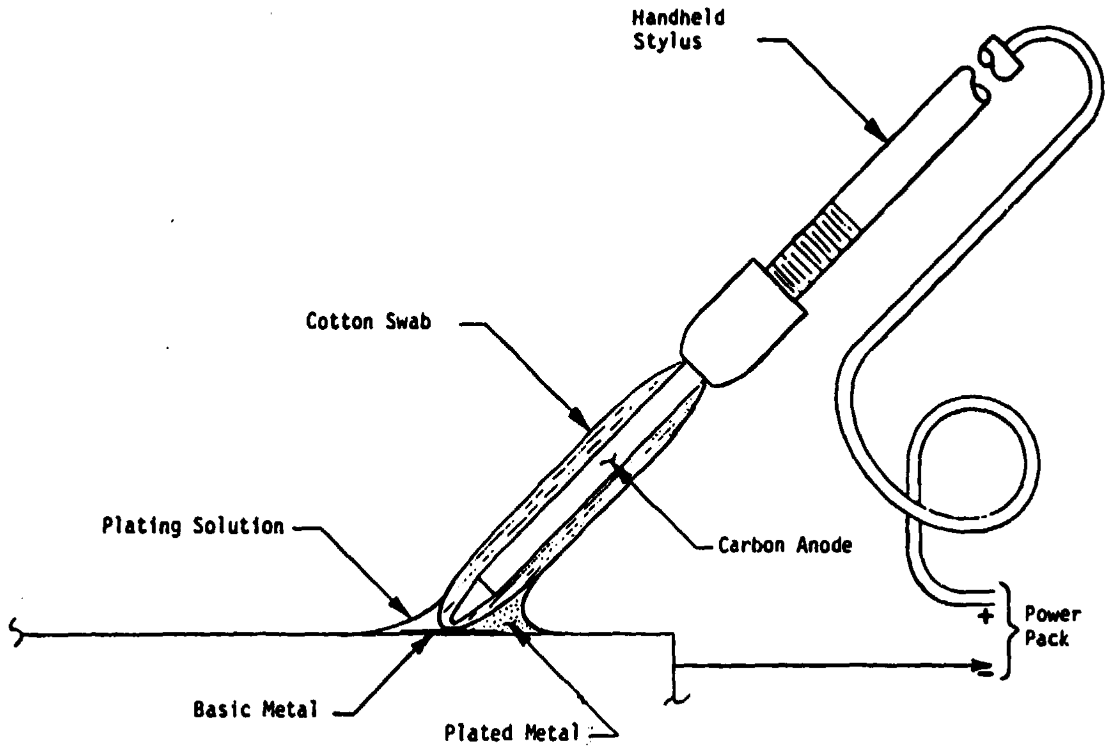
- NICKEL PASTES:
  - OPTIMIZE FRIT CONTENT
  - OPTIMIZE AgF CONTENT
  - ADDRESS PASTE RHEOLOGY
  - EVALUATE HIGH TEMP FRITS

- THK FILM DRY/FIRE CYCLE
  - EVALUATE EFFECTS ON LINE DISCONTINUITIES/NON-HOMOGENEITY
  - OPTIMIZE FIRE CYCLES FOR SELECTED PASTES

- EVALUATE EFFECTS OF AgF ON CONTACT RESISTANCE

- INITIATE LIFE TESTING

Brush or Selective Plating Operation



ENGINEERING SCIENCES AREA
MODULE PERFORMANCE & FAILURE ANALYSIS AREA
ANALYSIS & INTEGRATION AREA

JOINT TECHNOLOGY SESSION R.G. Ross and L.D. Runkle, Chairmen

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

L.D. Runkle, FSA Module Performance and Failure Analysis Area manager, presented a brief status report on the Module Development Task. Two of the 10 modules developed under Block IV contracts have not completed the environmental test requirements, and modules for field deployment have been received from only two of the nine contractors. The Block V design contracts are in place; preliminary indications show a trend to more cells, larger cells, larger modules, more efficient cells, higher packing factors, EVA as a pottant, and silicon in forms other than Cz.

J. S. Griffith (JPL) reviewed experience in testing modules procured on the open market by The Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) for the Residential Experiment Stations. Many of the same deficiencies in module processing and design were seen in this group of modules as in the JPL block procurements. It appears that all the lessons learned in the block procurements had not yet been assimilated by the time the RES orders were placed.

D. H. Otth (JPL) presented data from recent exploratory residential roof-fire tests conducted on integral and direct-mounted modules at Underwriters Laboratories (UL). Initial results show EVA and PVB encapsulants to be highly flammable, and glass superstrate modules using these encapsulants will drop flaming material into the space below. They do not appear to be fire-ratable under UL test specifications.

J. S. Griffith (JPL) reported on the outcome of the first series of tests of modules to determine susceptibility to hot-spot heating. These tests, which are a part of the Block V test requirements, were found to be useful and accurate. Modules with high-shunt-resistance cells without diode protection are risky.

S. Forman of MIT-LL updated experience at the Northeast and Southwest Residential Experiment Stations and at other applications experiments installed by MIT-LL. A composite figure of 470 failed modules out of over 11,000 installed, or 4.3%, provides an indication of durability to be expected. Installations were made between May 1977 and January 1980.

P. K. Henry, manager of the Analysis and Integration (A&I) Area, presented a description of a system of models developed separately by A&I, the Engineering Sciences Area and the PV Program Technology Development and Applications Lead Center. The models, linked by A&I, describe the electrical and economic performance of residential PV systems over their lifetimes, including the effects of cell failures, module replacement, array orientation, utility rate and tax structures. The system net present value, break-even prices and levelized energy costs can be calculated from the models and a break-even price example was given.

G. Royal of the AIA Research Corporation reported on the status of its integrated photovoltaic array development. Development of the leading candidate concept was discussed by Burt Hill Kosar Rittelmann Associates. That concept consists of a nominal 2-kWp, 199-V_{no} subarray. Modules in the subarray are adhesively bonded to pre-wired wooden parlins that are mechanically fastened to the roof. Fabrication of the partial roof section prototype displayed at the 19th PIM was discussed by NAHB Research Foundation.

N. F. Shepard of the General Electric Co. reported on the results of GE's integrated residential photovoltaic array design study. The optimized concept consists of overlapping, glass-superstrate shingle modules mechanically fastened to interlocking sections of roll-formed metal substructure. A full-scale partial roof section was displayed at the 19th PIM.

A. Levins of Underwriters Laboratories, Inc. (UL), reported on array safety systems in terms of summarizing the proposed article on photovoltaic solar systems that is to be considered for incorporation in the 1984 edition of the National Electrical Code. He also discussed the use of ground-fault detectors, bypass diodes and arc detectors as components of an array safety system.

C. C. Gonzalez presented initial results of the photovoltaic-array and power-conditioner interface requirement studies. These studies have concentrated on several aspects of array-conditioner operation including (1) selection of power-conditioner operational mode and parameters; (2) selection of power-conditioner maximum power, current, and voltage limits, and (3) determination of the effects of array degradation and site location in selection of the power-conditioner operational mode and parameters. Plots of some results for Albuquerque, New Mexico, were presented, as were some by parameter values for four other sites of the 26 continental U.S. sites considered. Ranges of values over the 26 sites were presented.

N. F. Shepard of GE reported on the integration of bypass diodes in PV modules. The general conclusion is that diode chips encapsulated within the module laminate offer many interface advantages.

Recent developments in the interconnect fatigue investigation were presented by G. R. Mon (JPL). Topics included (1) a review of the interconnect failure prediction algorithm, (2) a discussion of interconnect thermal-cycle life testing, with a demonstration of how the failure prediction curves can be used to determine an unambiguous maximum test-failure level (to qualify modules for 20-year service at a specified maximum field failure level) and (3) a comparison of test results and performance characteristics of clad-metal interconnects and copper interconnects.

Laser scanning technology has so matured that it now has the potential of being used to evaluate performance characteristics of solar cells quantitatively from output module-response data. A. Shumka (JPL) demonstrated how this can be accomplished by first interpreting the solar-cell laser-scanner

(SCLS) data in terms of a simplified physical model for a solar cell and then applying a theoretical model for measuring one of the basic cell parameters (shunt resistance) from the SCLS data.

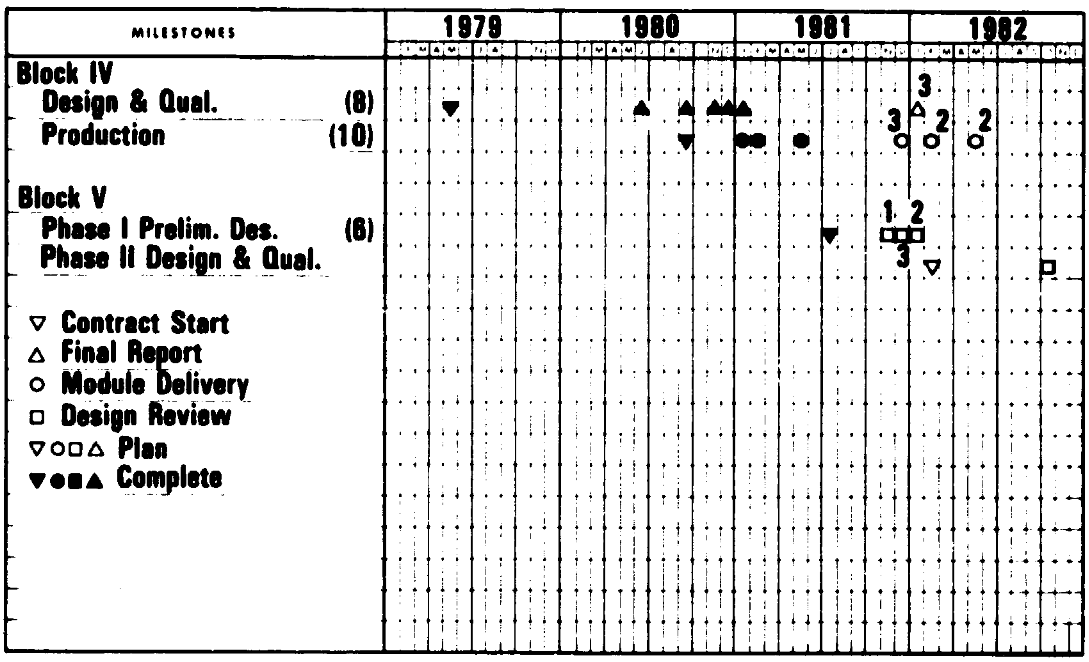
G. R. Mon (JPL) presented pre-aging breakdown measurements with Mylar and Tedlar films that resulted from tests made with newly constructed voltage-breakdown and insulation-aging equipment. The test program goal is to characterize statistically the voltage-breakdown behavior of PV electrical-insulation systems.

MODULE DEVELOPMENT

JET PROPULSION LABORATORY

L.D. Runkle

Schedule



Block V Participants

ARCO Solar, Inc.

General Electric Co.

Mobil Tyco Solar Energy Corp.

RCA Corp.

Solarex Corp.

Spire Corp.

Block V Modules

Power:	**46 to 164 watts**
Nominal Voltage:	**5 to 17 volts**
Projected Cell Efficiency:	**9% to 15%**
Cell Size:	**Up to 14 cm Dia & 10 x 15 cm**
Number of Cells:	**34 to 352**
Packing Factor:	**0.72 to 0.95**
Cell Material:	**Cz, Semi, HEM, EFG**
Pottant:	**EVA**
Front Surface:	**Tempered Glass**
Diodes:	**1 to 4**
Frame:	**None to Steel Pan**

Test Program Commercial Modules

Letter of Interest   Aug. 14, 1981

Test to Block V Requirements

Nine Responses

Five Orders Placed, Two on Hold

RESULTS OF QUALIFICATION TESTING OF MIT-LL RESIDENTIAL EXPERIMENT STATION PV MODULES

JET PROPULSION LABORATORY

J.S. Griffith

Contents

- BACKGROUND OF MIT/LL RES PROGRAM
- TYPE OF TESTS USED
- DESCRIPTION OF MODULES AND TEST RESULTS
- CONCLUSIONS

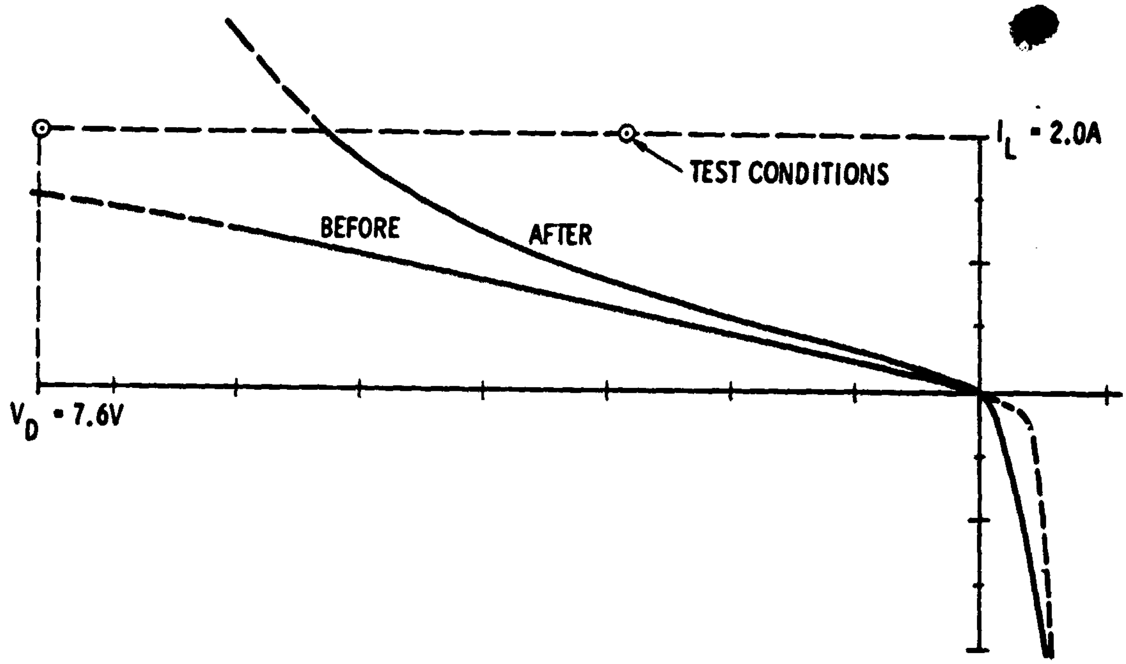
Background of MIT-LL RES Program

- MIT/LL RES PROTOTYPES
- LOCATIONS – NORTHEAST, SOUTHWEST U.S.
- TESTS, SCHEDULES

Types of Tests

- BLOCK IV TESTS, EXCEPT:
  - TWO MODULES ONLY
  - NO NOCT MEASUREMENTS
  - BLOCK IV THERMAL COEFFICIENTS USED
  - NO TEST FRAMES USED
- BLOCK V HOT SPOT TEST
  - TEST FOR SUSCEPTIBILITY OF CELLS TO REVERSE BIAS AND OVERHEATING

Degradation of Cell 3 of FG Module From Hot-Spot Test



MIT-LL RES: Results of Qualification Tests

VENDOR CODE	AU	BU	CM	DM
MODULE DESCRIPTION (MATERIALS LISTED FROM TOP TO BOTTOM)	GLASS, PVB/CELL, PVB, WHITE TEDLAR, PVB, TEDLAR/STEEL/TEDLAR ALUM. FRAME WITH HOT MELT BUTYL	2 MIL TEDLAR, EVA/CELL/EVA, TEDLAR COATED GALV. STEEL PAN	GLASS, PVB/CELL/PVB, WHITE TEDLAR, 2 LARGE PVC J-BOX, SQUARE CELLS.	SAME AS CM. ROUND CELLS
TEST RESULTS				
CRACKED CELLS		● ○ □	○	
ELECT. DEGRAD.	◇		○	
EDGE DELAMIN.		○		
BLISTERS, DELAM. OF BACK SURFACE			○	
HIPOT TEST	△	▽		
OTHER*	◇[1]		●[2]	●[3] ⦶[4]

● TEMP. CYCLING
○ HUMIDITY
⦶ WIND SIMULATION
△▽ INITIAL, FINAL HIPOT
□ HAIL
◇ HOTSPOT

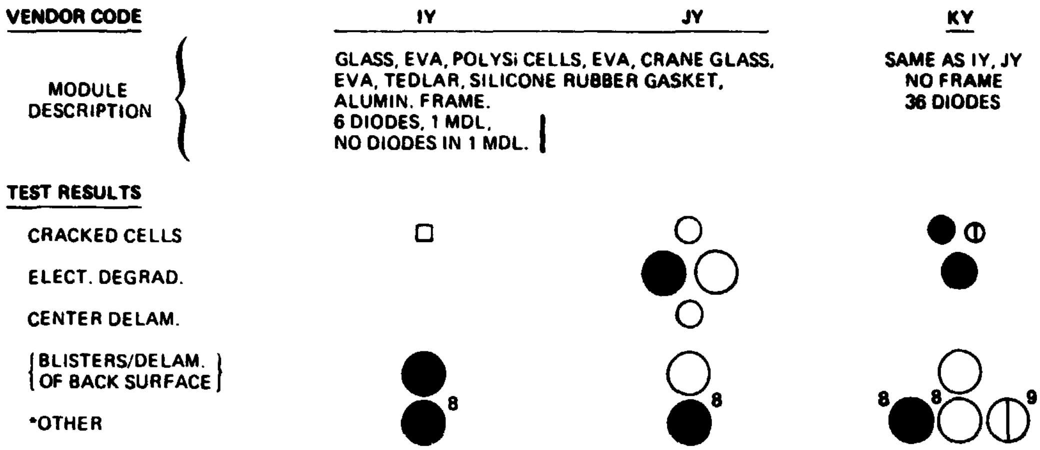
*OTHER PROBLEMS

1. TEDLAR WRINKLED, BUBBLES, DISCOLORATION (HOTSPOT, HI POT ONLY)
2. J-BOXES WARPED, BONDING BROKEN
3. J-BOX WARPED, ENCAP BUBBLES
4. UNSTABLE POWER OUTPUT

VENDOR CODE	EG	FG	GR	HR
MODULE DESCRIPTION	GLASS, CELLS BONDED WITH CLEAR SILICONE, WHITE SILICONE ENCAP., WEATHERIZED CARDBOARD BACK. FLEX. PORTION: POLYESTER SCRIM REINFORCED RUBBER OVER POLY-ETHYLENE FOAM CORE		GLASS, PVB/CELLS/PVB, TEDLAR/ALUM/TEDLAR, STAINLESS FRAME.	SAME AS GR
TEST RESULTS				
CRACKED CELLS				⦶
ELECT. DEGRAD.	● ○	◇[6]		
EDGE DELAMIN.				
CENTER DELAM.			●	●
BLISTERS/DELAM. OF BACK SURFACE				○
*OTHER	●[5]		○[7]	

*OTHER PROBLEMS:

5. DUMMY SHINGLES SCRIM/RUBBER SHRINKS & DELAMINATES, INTERCONNECT DISCOLORATION.
6. ELECTRICAL DEGRADATION, BUBBLES, ENCAP DISCOLORATION.
7. 5 CORNER FRAME WELDS BROKEN



*OTHER PROBLEMS:

8. AIR BUBBLES AT EDGE OF LAMINATE, SOME CELLS TOUCHING AFTER TEST
9. RUBBER EDGE SEAL SEPARATING

Conclusions

- MODULE PERFORMANCE FROM TESTS WAS POOR. IMPROVEMENTS ARE NEEDED.
  - LOW PRODUCTION OF NEW MODULES
  - PROCESSING PROBLEMS
- BLOCK IV QUALIFICATION TESTING OF SIMILAR MODULES
  - 8 OUT OF 10 PROTOTYPE MODULES HAVE QUALIFIED
  - BASIC DESIGNS ARE GENERALLY GOOD
  - HOWEVER, TWO PRODUCTION TYPES OF THE 8 HAVE HAD PROBLEMS IN TEST
- ADEQUATE TEST TIME SHOULD BE ALLOWED BEFORE PRODUCTION FOR TEST COMPLETION AND PROCESSING IMPROVEMENTS

RESIDENTIAL MODULE FIRE TESTING

JET PROPULSION LABORATORY

D.H. Otth

Objectives

Development of Module and Array Safety Requirements That Address the Unique Safety Issues of Roof-Mounted Residential Arrays

- **Identify and Develop Applicable Requirements**
- **Assess PV Technology's Ability to Meet Requirements**
- **Recommend Modified Requirements and Technology Improvements**

Applicable Fire Requirements

- **Flammability of Module From External and Internal Sources**
  - **External Sources – UL 790 Burning Brand Test (A, B, & C)**
  - **Internal Sources – Under Study By UL**
- **Effect of Module or Array on Flammability or Flame propagation of the Roof System**
  - **UL 790 Spread of Flame Test (A, B & C)**

UL-JPL Exploratory Fire Tests

OBJECTIVE

Assessment of Various Module Technologies and Mechanism of Fire Penetration

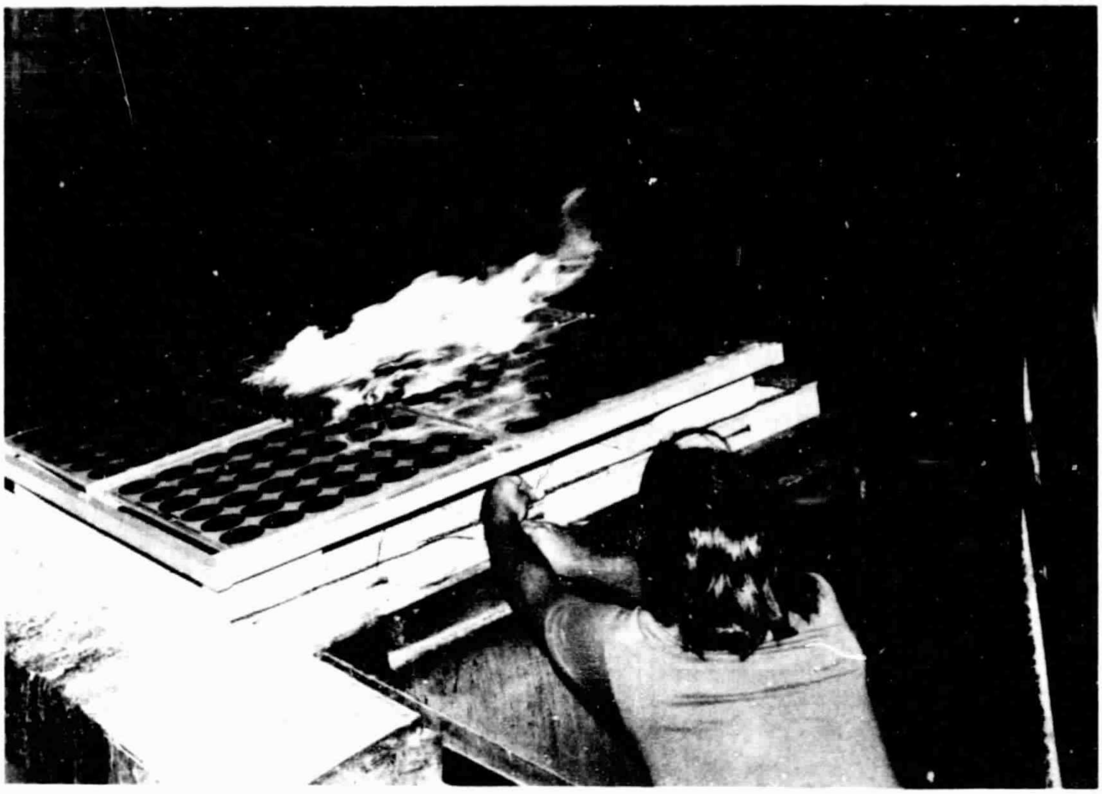
- **Different Mounting Types (Standoff, Direct, Integral)**
- **Different Encapsulation Systems (EVA, Silicone, etc.)**

CONFIGURATIONS TESTED

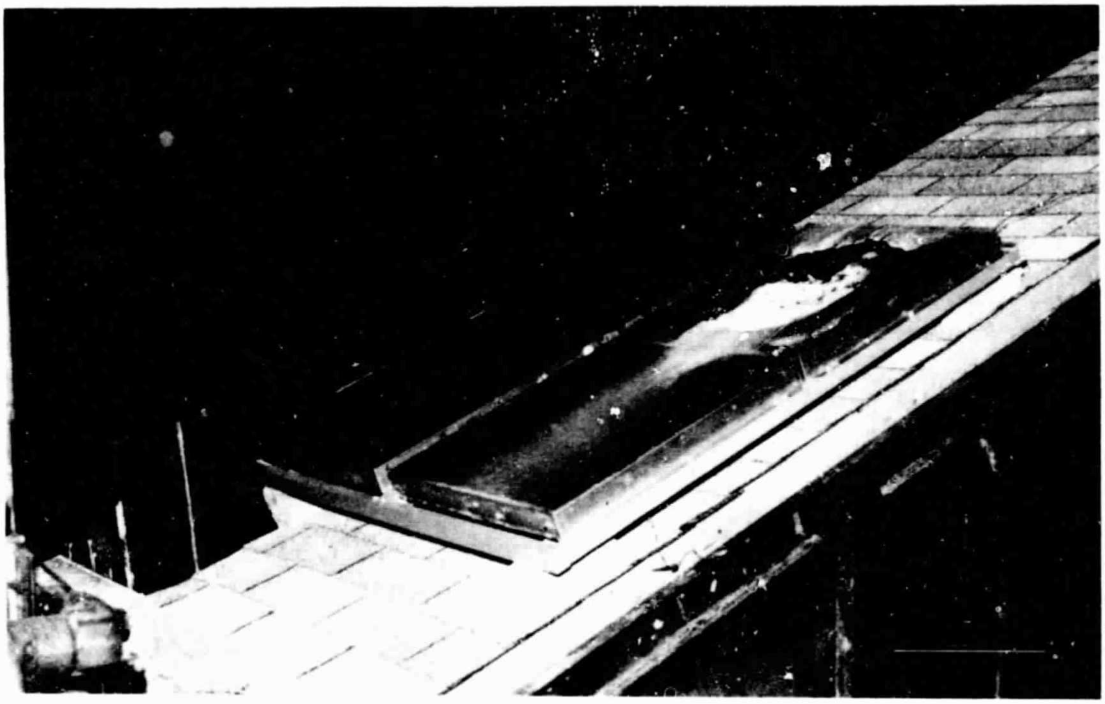
Mounting Scheme	Burning Brand*	Spread of Flame*
Standoff		
• RTV/Fiberglas (Blk III)	A	--
• Glass/RTV (Gel)/SS Pan (Blk III)	A	A
Direct		
• Glass/Silicone/Pan-L-Board (GE Shingle)	A	A
Integral		
• Glass/EVA/Tedlar (Blk IV)	B	--

*A, B = Test Level

Burning-Brand Test at UL

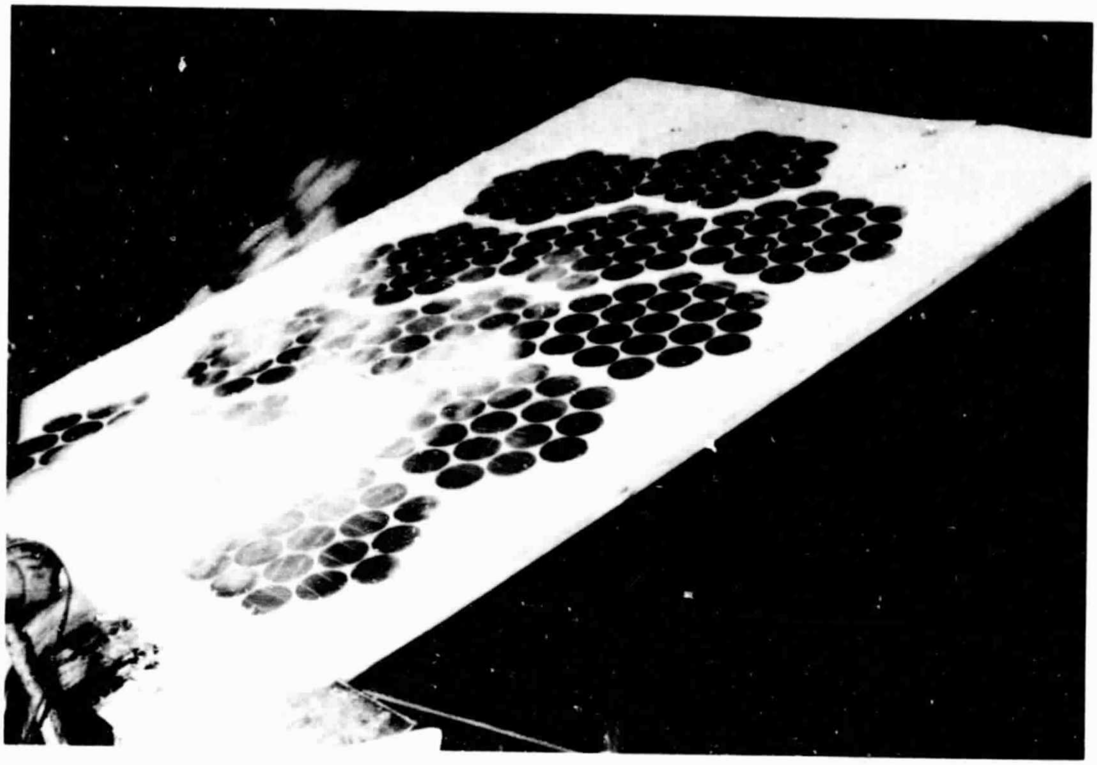


Post-Burning-Brand Test

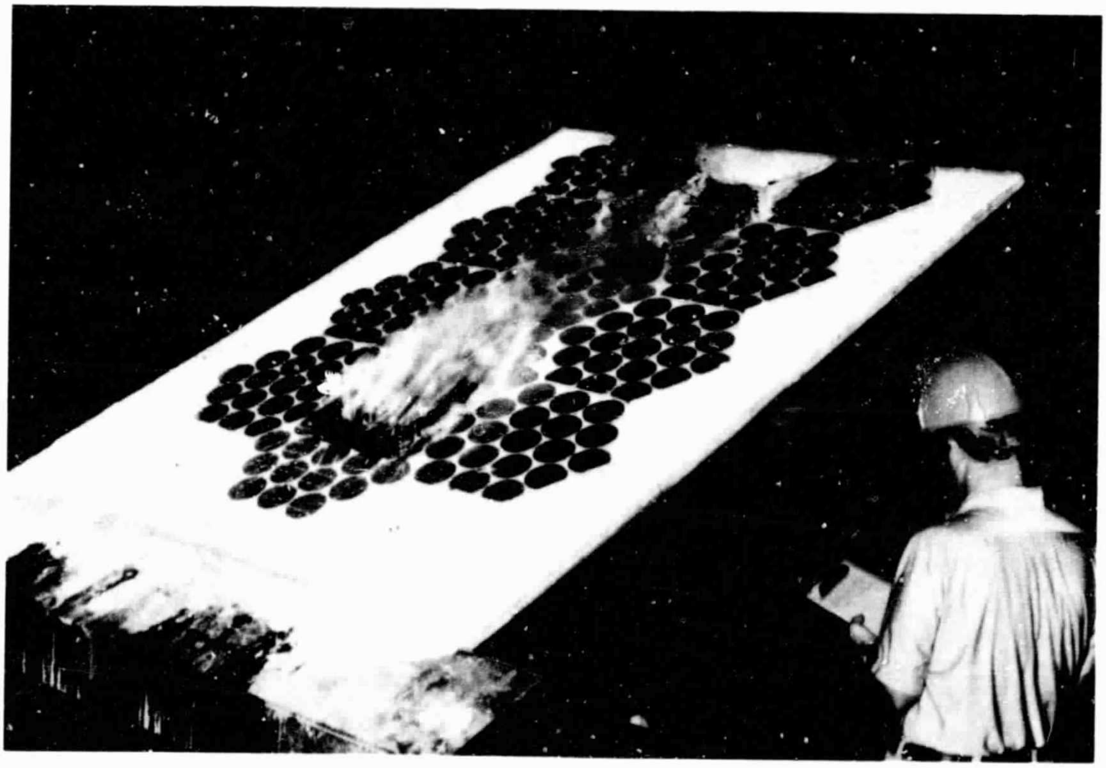


Stand-Off Mounting Scheme Subject
To Spread-of-Flame Test

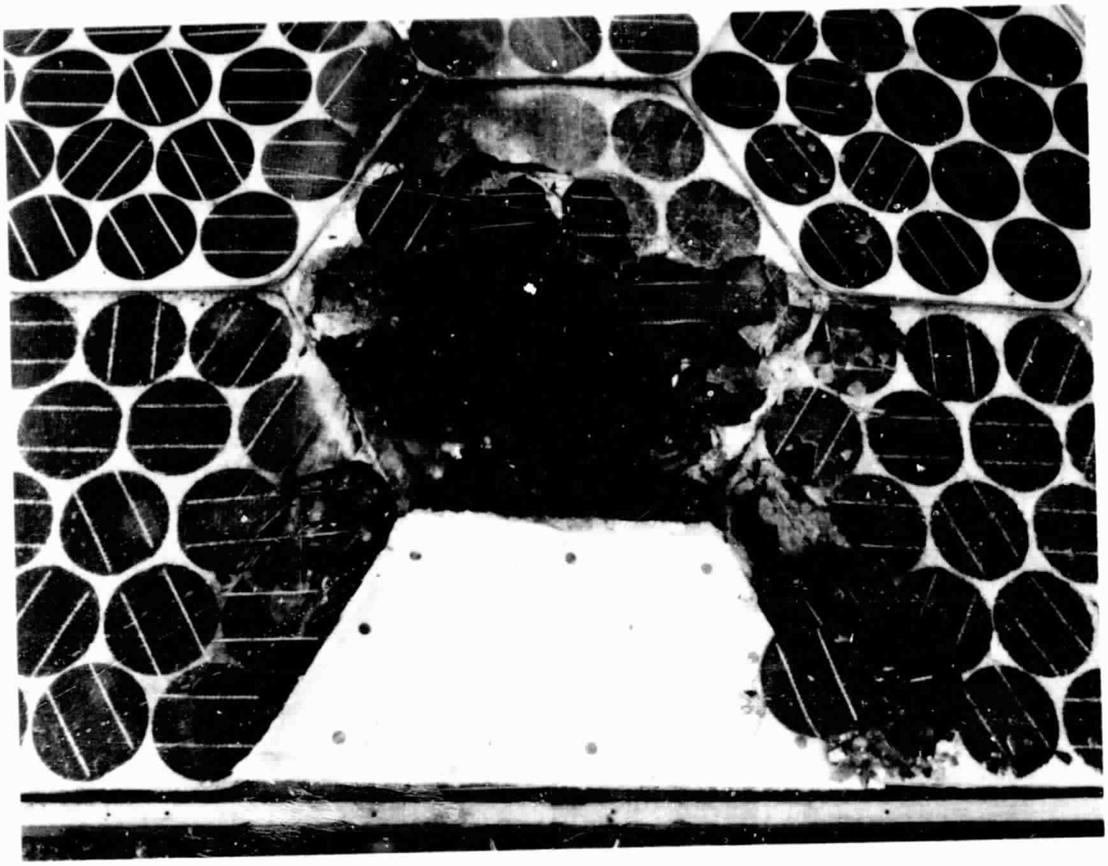
Spread-of-Flame Test on Shingle Modules



Burning-Brand Test on Shingle Module

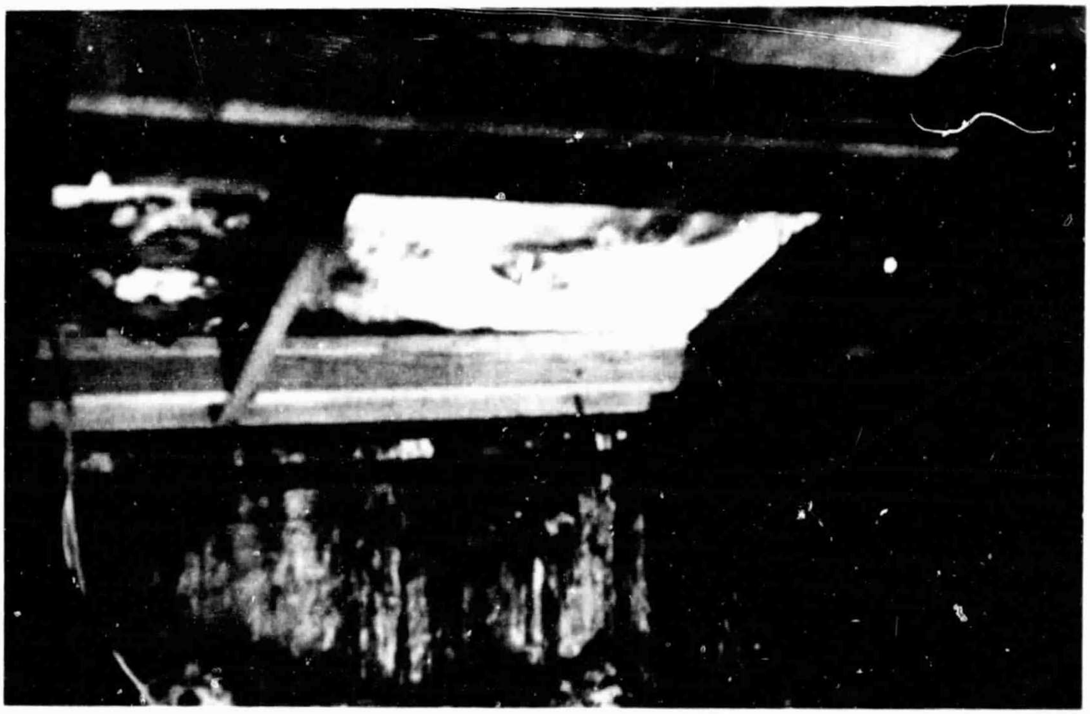


Post-Burning-Brand Test on Shingle Module



Integral-Mounted EVA-Encapsulated Module
Viewed From Attic at Start of Burning-Brand Test

Heat From Burning Brand Breaks Glass Cover;
Flame Propagates Through Module and Back Cover



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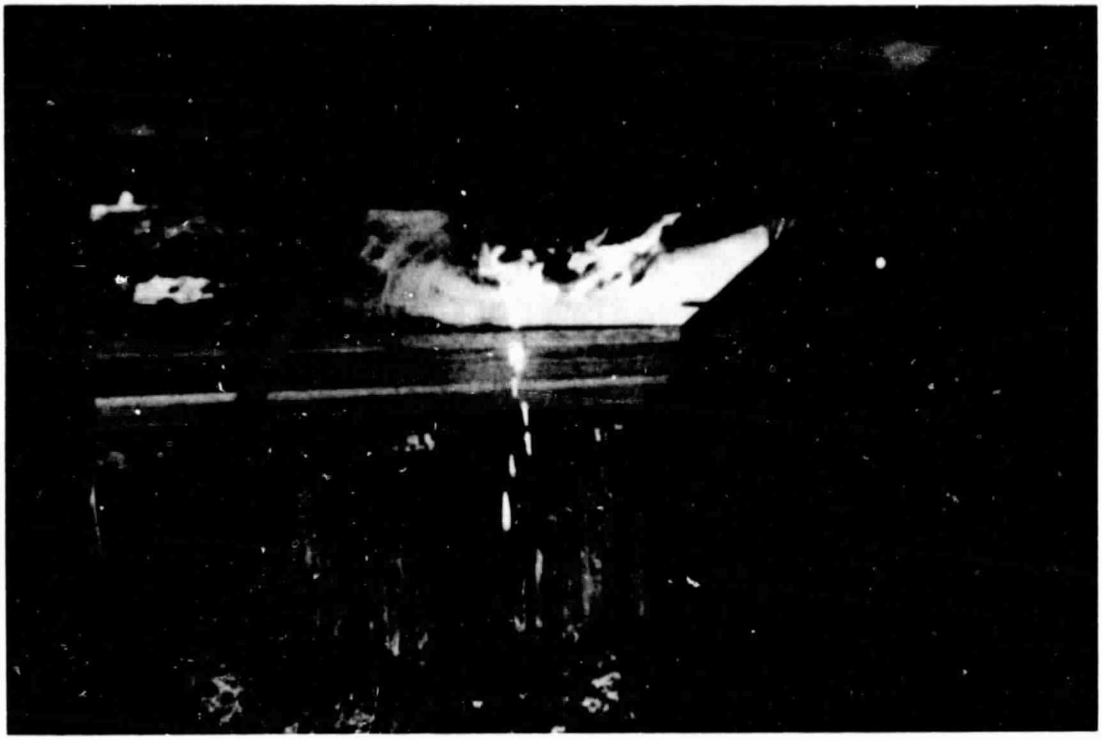
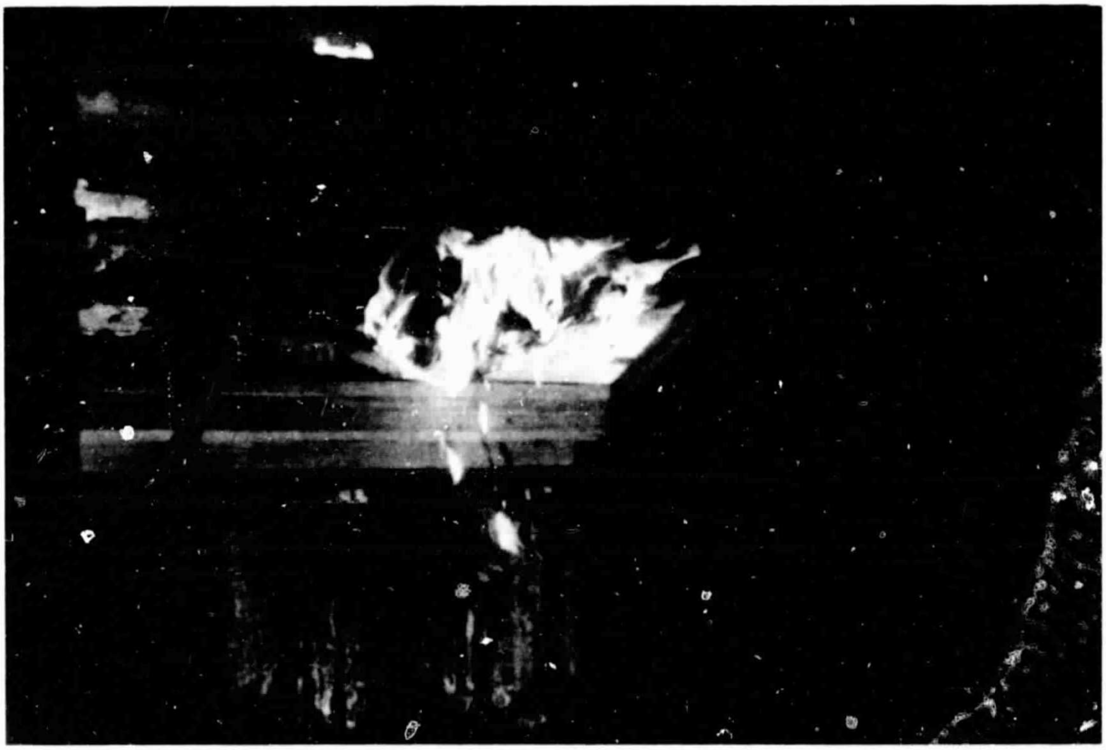
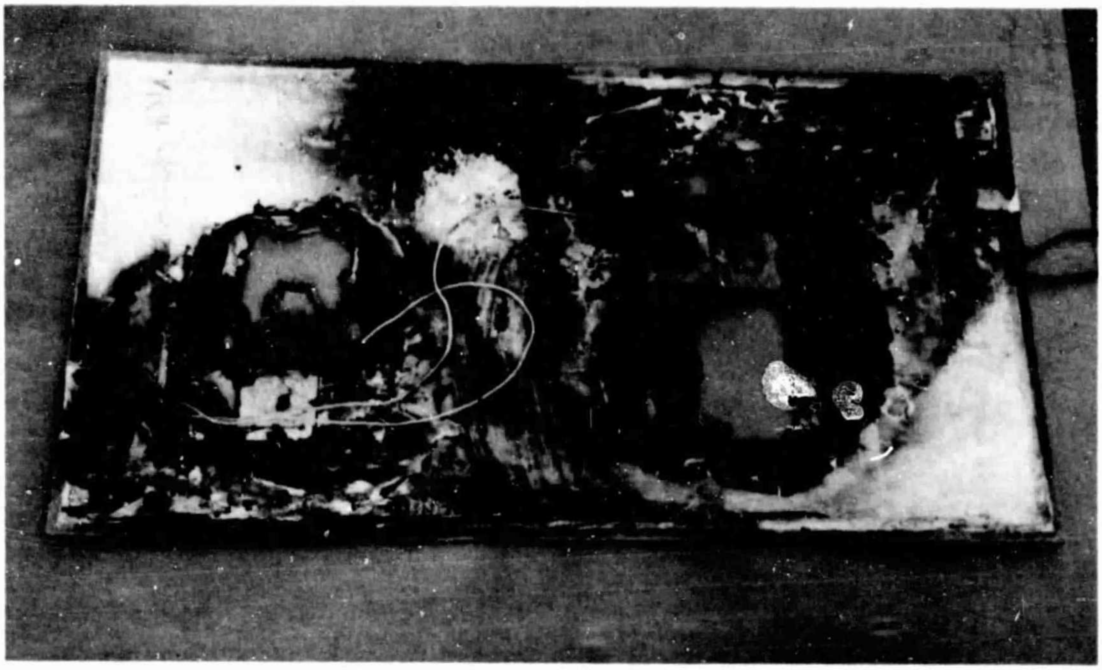
Flaming Material Falls Into Area Below



Flame Engulfs a Third of Module Within 5 Minutes



Post-Test Detail From Two Different Burning-Brand Tests



Conclusions

ARRAY SAFETY

- **Direct-Mount Arrays Appear to Have No Adverse Effects on Roof System**
- **Standoff Arrays Create a Flame Tunnel That Intensifies Flame Propagation – Initial Test Results Show That This Degrades Existing Roof System**
- **Glass-Superstrate, EVA-Film-Back Modules Lead to Flaming Material Falling Into Space Below**

MODULE SAFETY

- **RTV, RTV (Gel), Silicone Encapsulants Are Inherently Resistant to Flaming**
- **EVA Encapsulants-Tedlar Backs Are Highly Flammable; Modules Using These Materials With Tempered Glass Covers Do Not Appear to Be Fire-Ratable**

EARLY RESULTS OF THE BLOCK V HOT-SPOT TEST

JET PROPULSION LABORATORY

J.S. Griffith

Contents

- THE CELL HOT SPOT PROBLEM
- THE NEW HOT SPOT TEST – A BLOCK V TEST REQUIREMENT
- TEST RESULTS TO DATE

The Problem

CRACKED, SHADOWED, OR UNBALANCED CELLS RESULT IN REVERSE BIAS (VOLTAGE)

REVERSE BIAS CAUSES ENERGY TO BE ABSORBED BY THE CELL

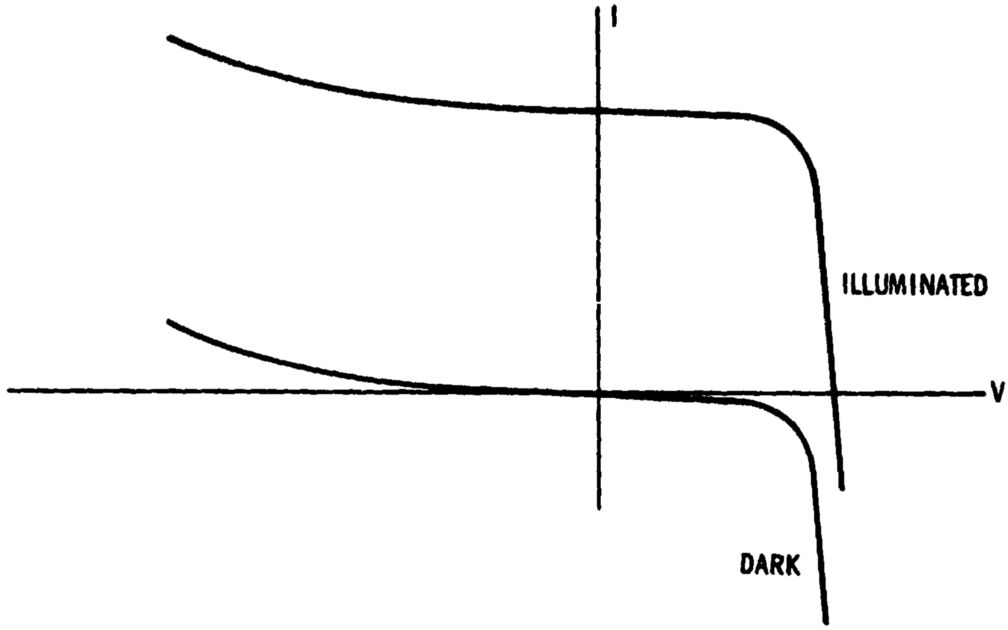
THIS RESULTS IN:

- OVERHEATING
- CELL CRACKING
- SPLITTING, BULGING OF ENCAPSULANT
- SHORTING OF CELL JUNCTION, POWER DEGRADATION
- MELTING OF SOLDER

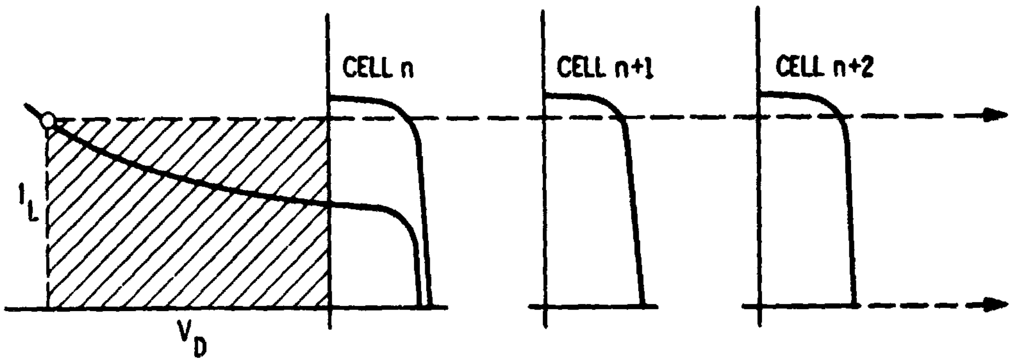
THE MOUNT LAGUNA SOLAR ARRAY

- MODULES HAD HIGH SHUNT RESISTANCE CELLS
- HAD LONG, FLAT I-V CHARACTERISTIC IN REVERSE QUADRANT
- NO INTERNAL DIODES
- RESULT: MANY MODULES DEGRADED

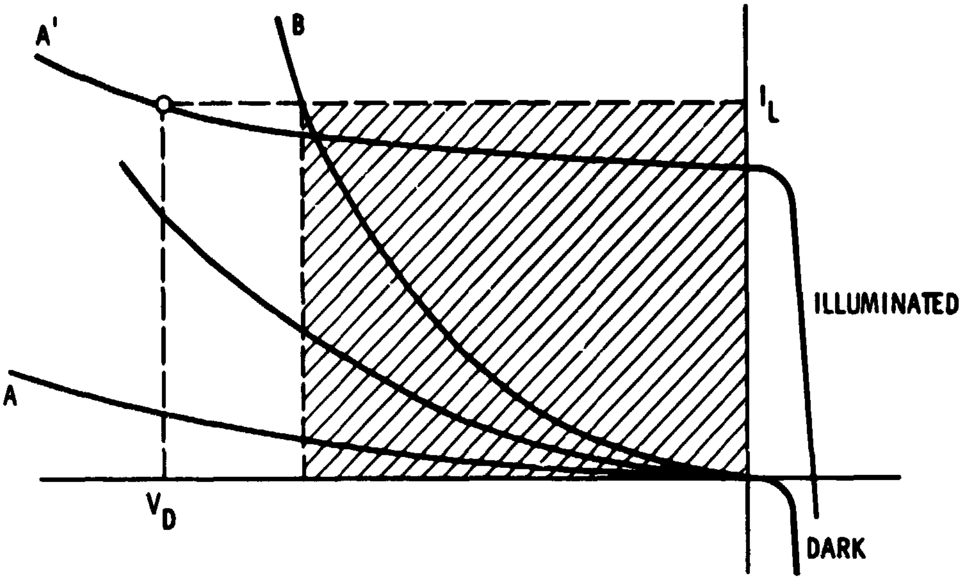
PV Cell Voltage-Current Characteristic Curves



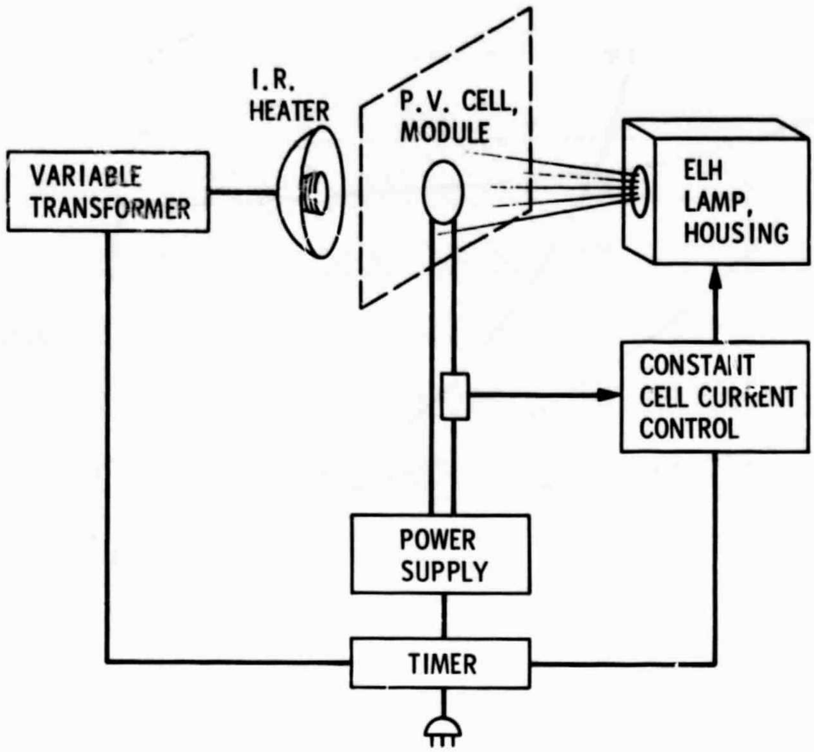
PV Cells in a Series String

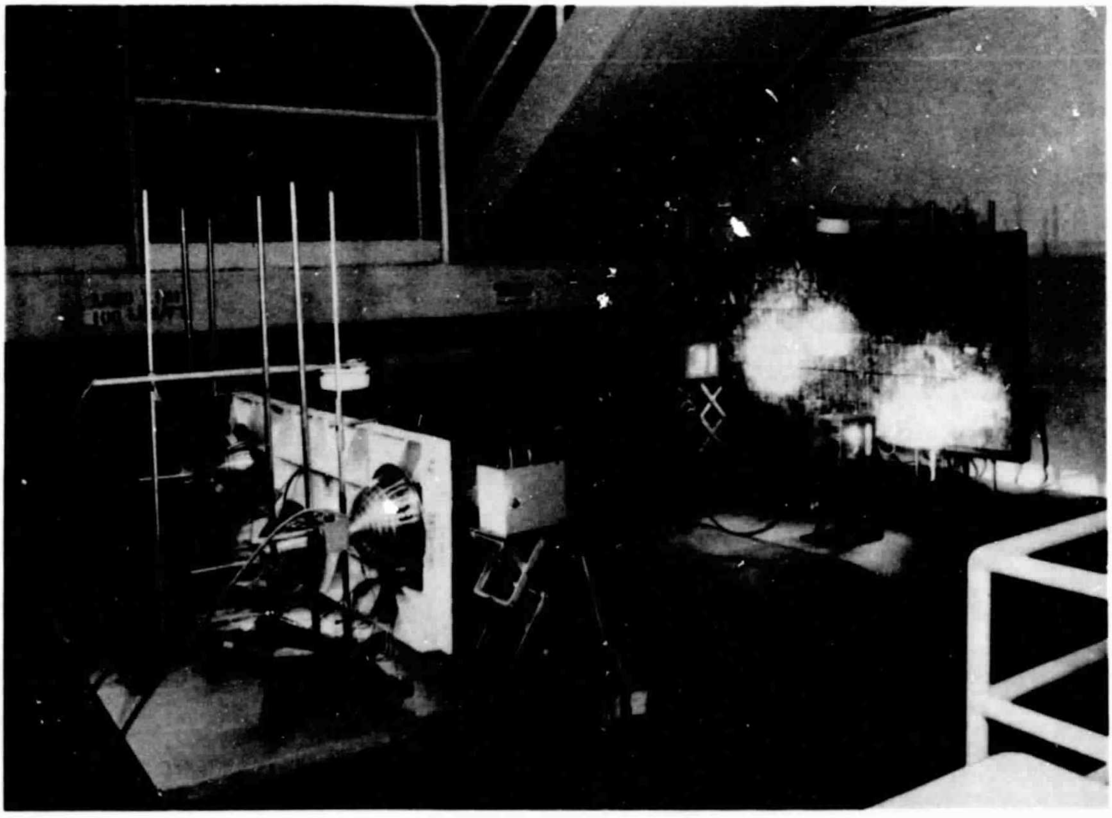


Hot-Spot Test Conditions



Test Setup





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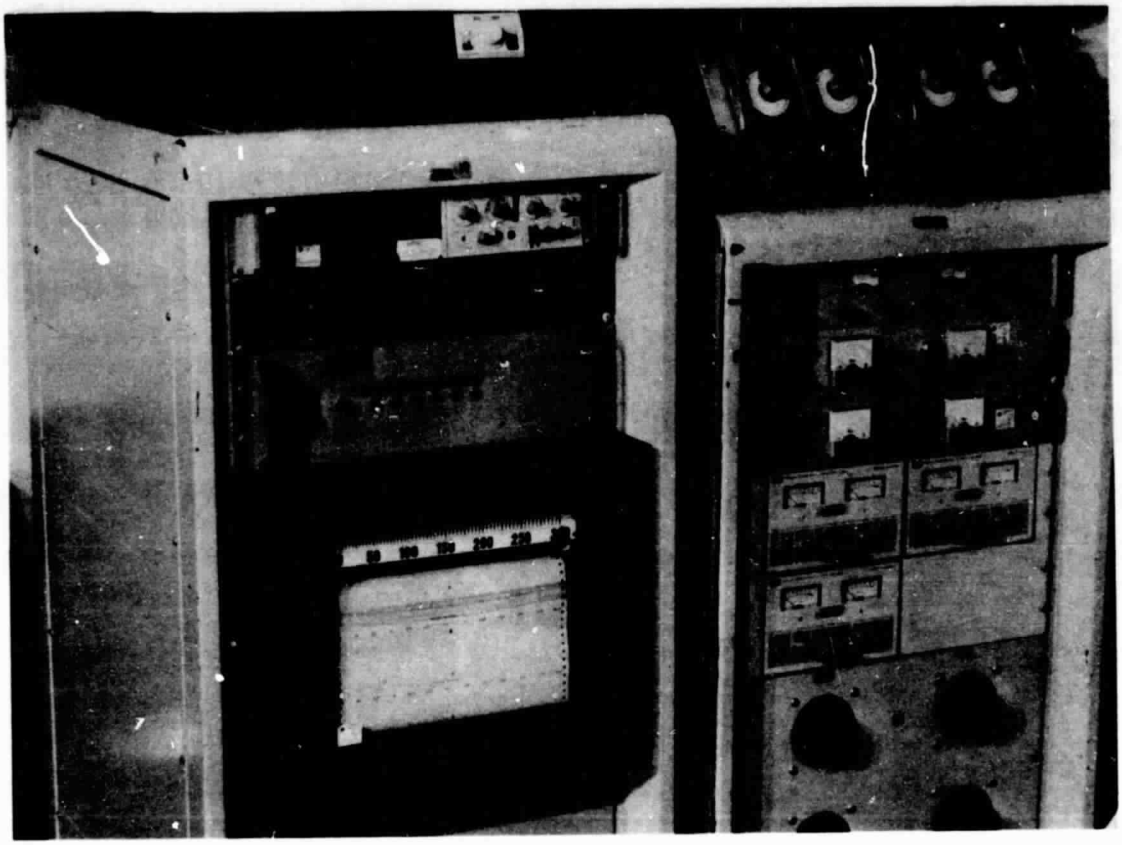
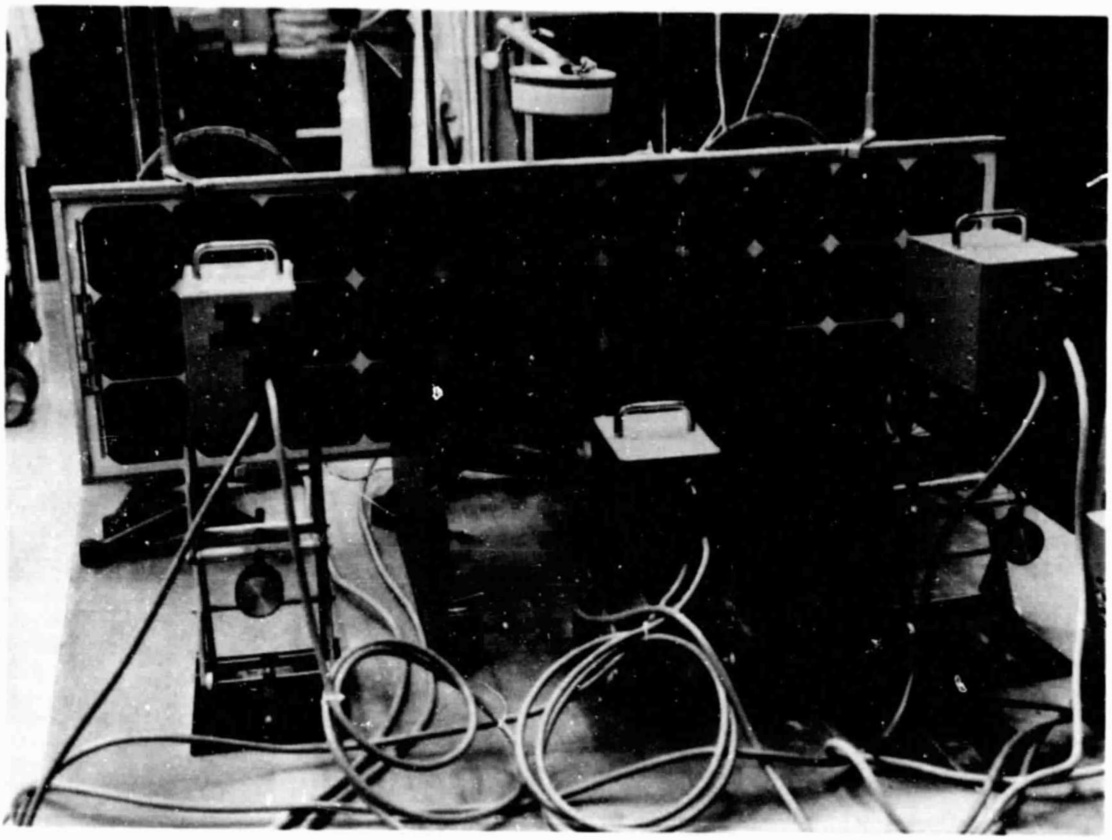
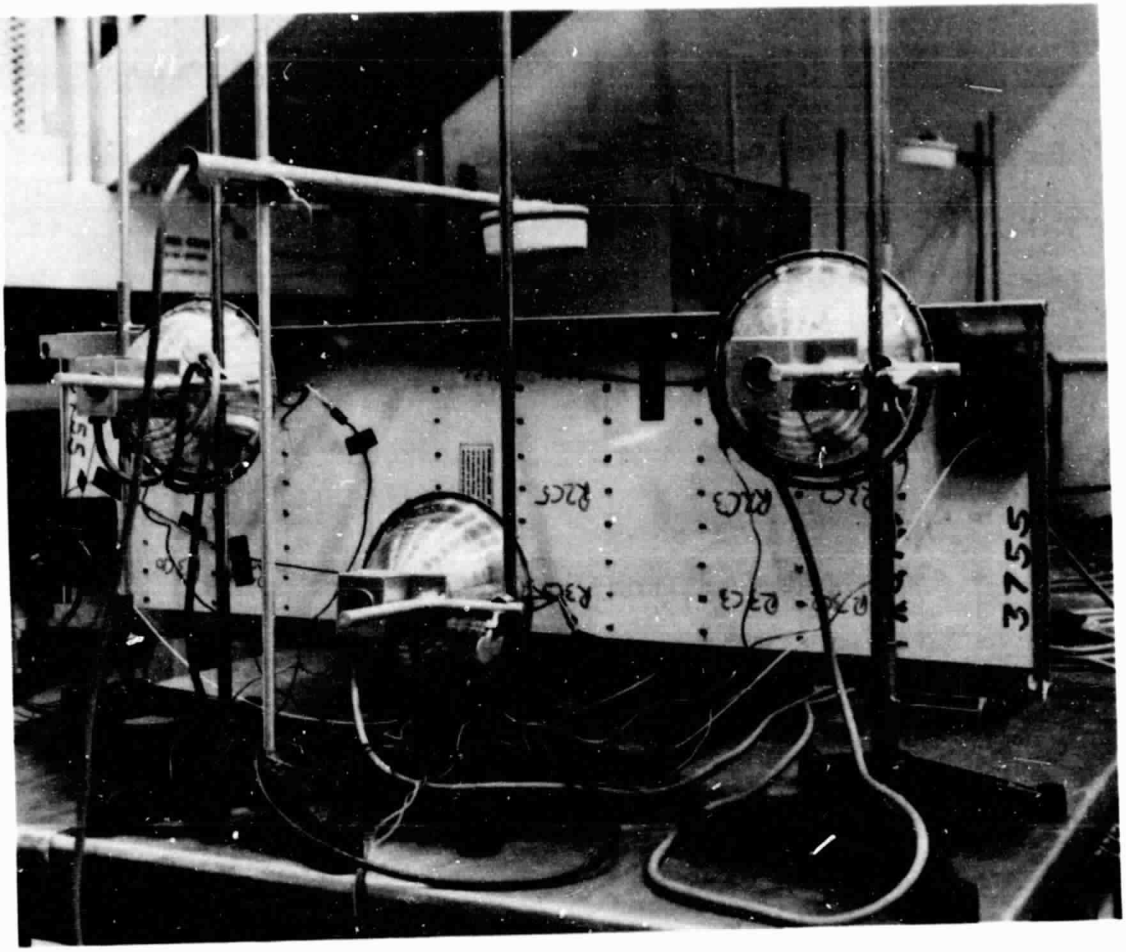
Consoles



Lamps in Place in Front of Modules



Back of Modules and the Heaters



Procedure

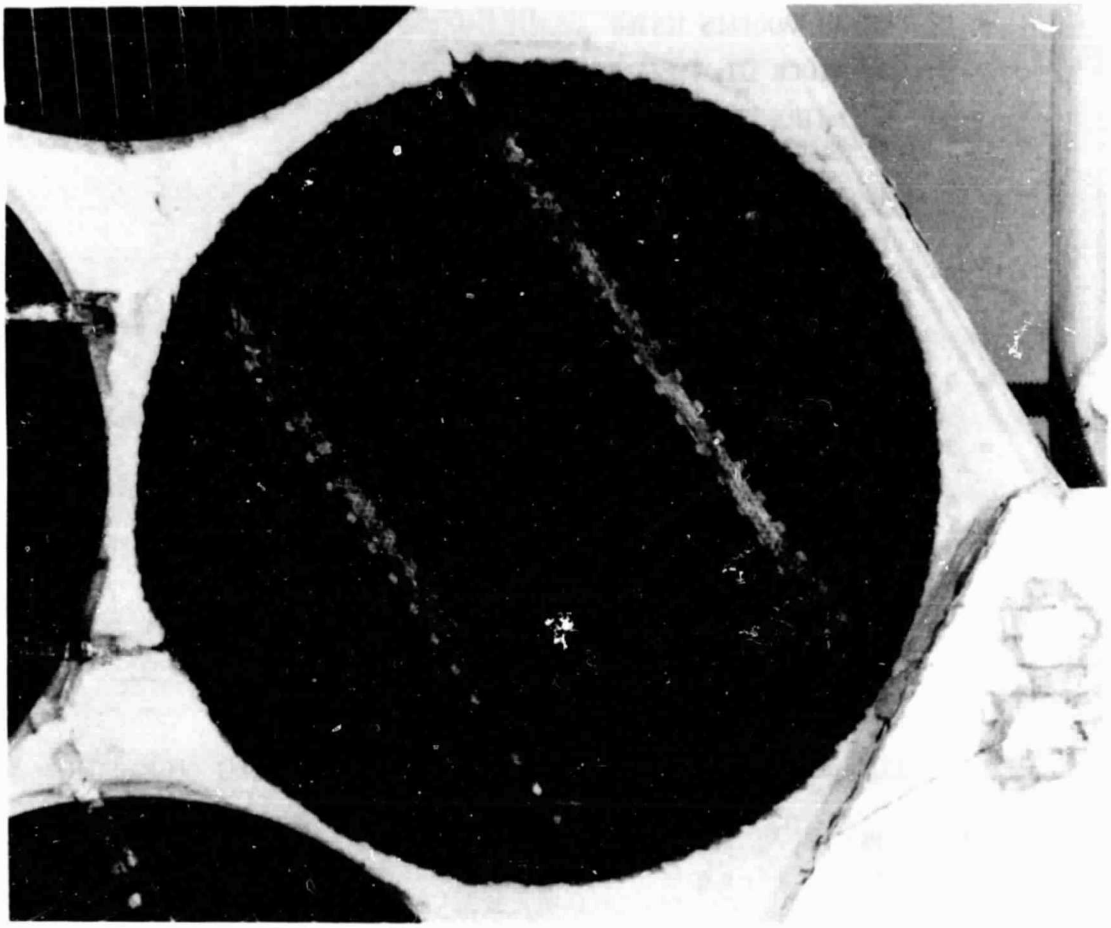
- DETERMINE TEST PARAMETERS-NOCT, TEST CURRENT AND VOLTAGE
- CONNECT WIRE TAPS TO TEN OR MORE CELLS IN THE MODULE
  - DISCONNECT CROSS TIES
  - PROBLEM: GLASS/GLASS MODULES
- MEASURE REVERSE QUADRANT DARK I-V CHARACTERISTICS
- SELECT THREE CELLS FOR TEST
  - AN A TYPE(VOLTAGE LIMITED)-HIGH SHUNT RESISTANCE, FLAT I-V CURVE IN REVERSE QUADRANT
  - A B TYPE(CURRENT LIMITED)
  - AN INTERMEDIATE TYPE
- INSTALL THERMOCOUPLES
- FLASH MODULE AND CELLS IN LAPSS
- SET UP BENCH TEST FOR 1 OR 2 MODULES (3 OR 6 CELLS)
  - ADJUST HEATERS TO NOCT
  - SET CURRENTS AND VOLTAGES
  - USE ELH LAMP, AS NECESSARY
- INSPECT VISUALLY AT 25, 50, 75, AND 100 CYCLES
- FLASH AGAIN IN LAPSS AFTER 100 CYCLES
- RUN MARGIN TESTS, IF DESIRED
  - 126, 159, AND 200% OF NOMINAL POWER

Description of Modules Tested and Results

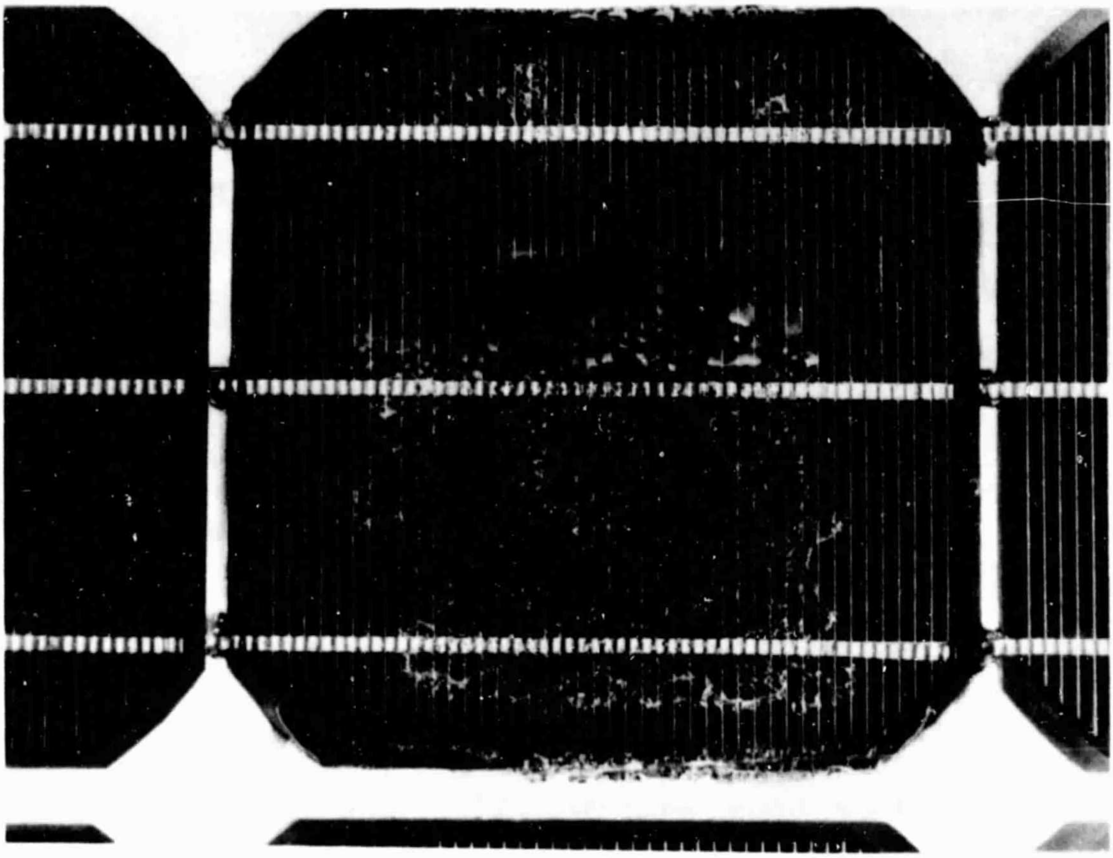
- 15 TYPES OF MODULES TESTED
  - 2 BLOCK III, TYPES Z AND Y
  - 5 MIT/LL RES
  - 3 BLOCK IV
  - 4 WORLD BANK
  - 1 PRDA 38
  - 9 OTHER TYPES NOT TESTED DUE TO SIMILARITIES WITH 15 ABOVE
- 9 OF 15 TYPES SHOWED NO CHANGE
- 3 HAD MINOR DISCOLORATION NEAR TEST CELLS
- 3 HAD MORE SERIOUS DEGRADATION
  - "MT. LAGUNA TYPE" SHOWED CRACKED AND RAISED CELLS, DELAMINATION, SPLIT ENCAPSULANT, BACKSIDE DISCOLORATION
  - 2 OTHERS HAD BUBBLES, ENCAP DISCOLORATION, DEGRADED CELLS

	TEST VOLTS	TEST CURRENT	CELL TYPE	MAX TEMP, °C	CELL DEGRADATION, %
MT. LAGUNA TYPE	18	2.0	A	156	-
	18	2.0	A	148	-
	18	2.0	A	155	-
WORLD BANK U TYPE	14.3	2.1	A	140	~40%
	14.3	2.1 → 2.4	A → B	150	
	7.3	2.4	B	100	
MIT/LL RES G TYPE	4.3	2.0	B	110	-
	4.2	2.0	B	102	~40%
	7.6 → 2.8	2.0	A → B	119	~70%

G-Type Cell After Hot-Spot Test



R-Type Cell After 59% Hot-Spot Overtest



Conclusions

- NEW HOT SPOT TEST IS USEFUL AND ACCURATE
- GLASS/GLASS MODULES MUST HAVE CELL LEADS ATTACHED BEFORE LAMINATION
- 80% OF THE MODULES TESTED HAD LITTLE OR NO PROBLEMS
- A-TYPE CELLS WITHOUT GOOD DIODE PROTECTION ARE CLEARLY AT RISK
- HOWEVER, IN ONE CASE B-TYPE CELLS AT ONLY 4.2 VOLTS DEGRADED

MIT-LL RESIDENTIAL AND FIELD TEST RESULTS

MASSUCHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

MIT-LL Experimental PV Test Sites

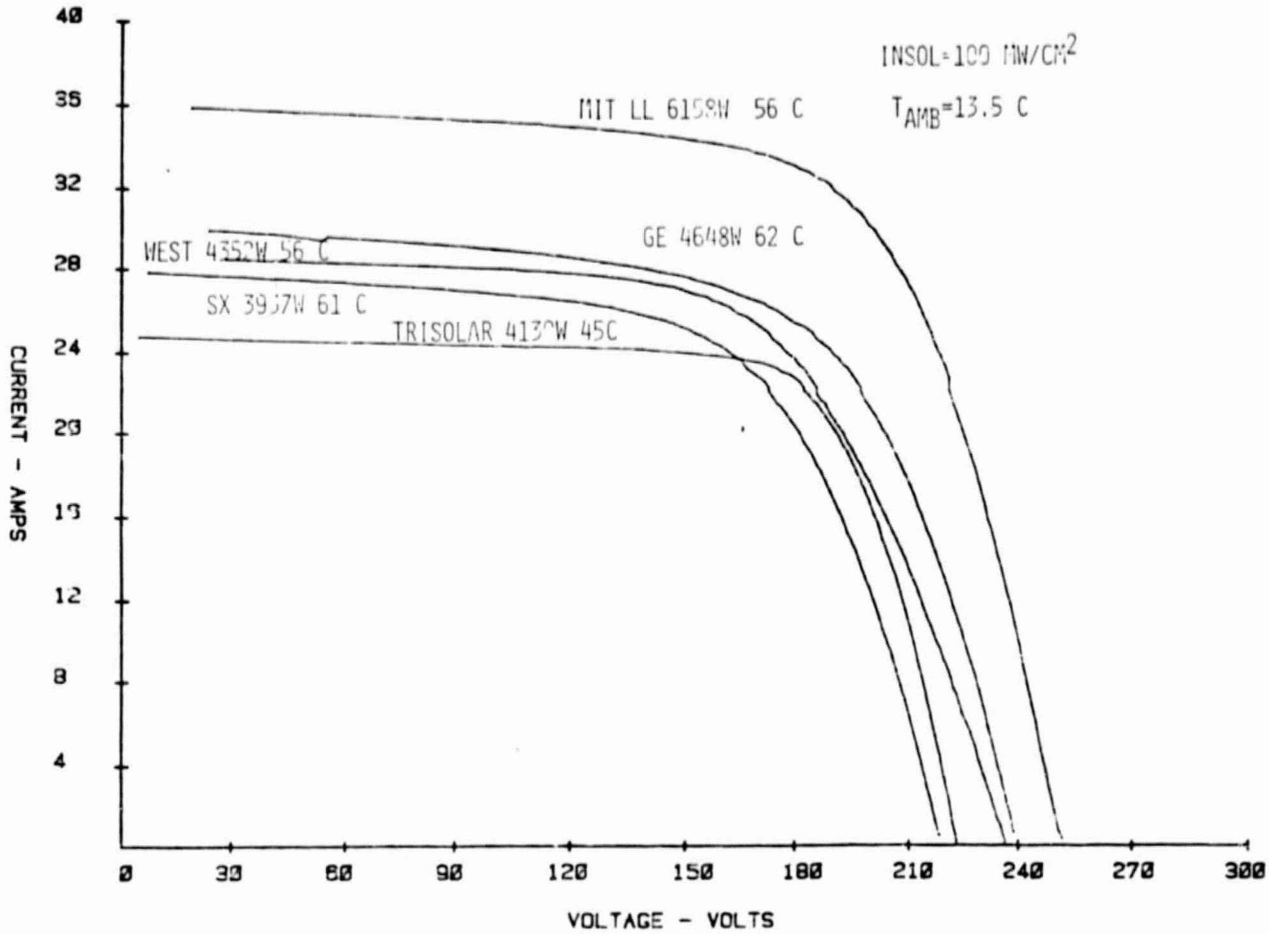
APPLICATION EXPERIMENTS	RATED POWER
NATURAL BRIDGES NATIONAL MONUMENT, UTAH	100 KW
MEAD, NEBRASKA	25
SYSTEMS TEST FACILITY, MASSACHUSETTS	25
AM RADIO STATION, OHIO	15
ROOFTOP TEST FACILITY, MASSACHUSETTS	10
UNIVERSITY OF TEXAS, ARLINGTON	7.5
MUSEUM OF SCIENCE AND INDUSTRY, CHICAGO	1.5
RESIDENTIAL EXPERIMENTS	2-9 KW
NORTHEAST RESIDENTIAL TEST STATION, MASSACHUSETTS	
--5 PROTOTYPES, 1 LIVED IN RESIDENCE	
SOUTHWEST RESIDENTIAL TEST STATION, NEW MEXICO	
--8 PROTOTYPES	
INNOVATIVE PV APPLICATIONS FOR RESIDENCES	
--ARIZONA, FLORIDA, HAWAII (3)	

Northeast Residential Test Station (RES) at Concord MA

SITE OPERATOR: MIT LL

PRIME CONTRACTOR	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
TRISOLAR	36 ASEC INTEGRAL	1 BRANCH CIRCUIT 2 IN PARALLEL x 18 IN SERIES	4.4 KW
GENERAL ELECTRIC	375 GE SHINGLE	1 BRANCH CIRCUIT 15 IN PARALLEL x 25 IN SERIES	6.5 KW
SOLAREX	80 SX STANDOFF	6 BRANCH CIRCUITS 13 IN SERIES x 6 IN PARALLEL	4.7 KW
WESTINGHOUSE	160 ARCO INTEGRAL	1 BRANCH CIRCUIT 12 IN PARALLEL x 13 IN SERIES	5.1 KW
MIT LL	112 SX STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	7.3 KW
CARLISLE	126 SX STANDOFF	9 BRANCH CIRCUITS 14 IN SERIES x 9 IN PARALLEL	7.8 KW

NE RES Array I-V Curves



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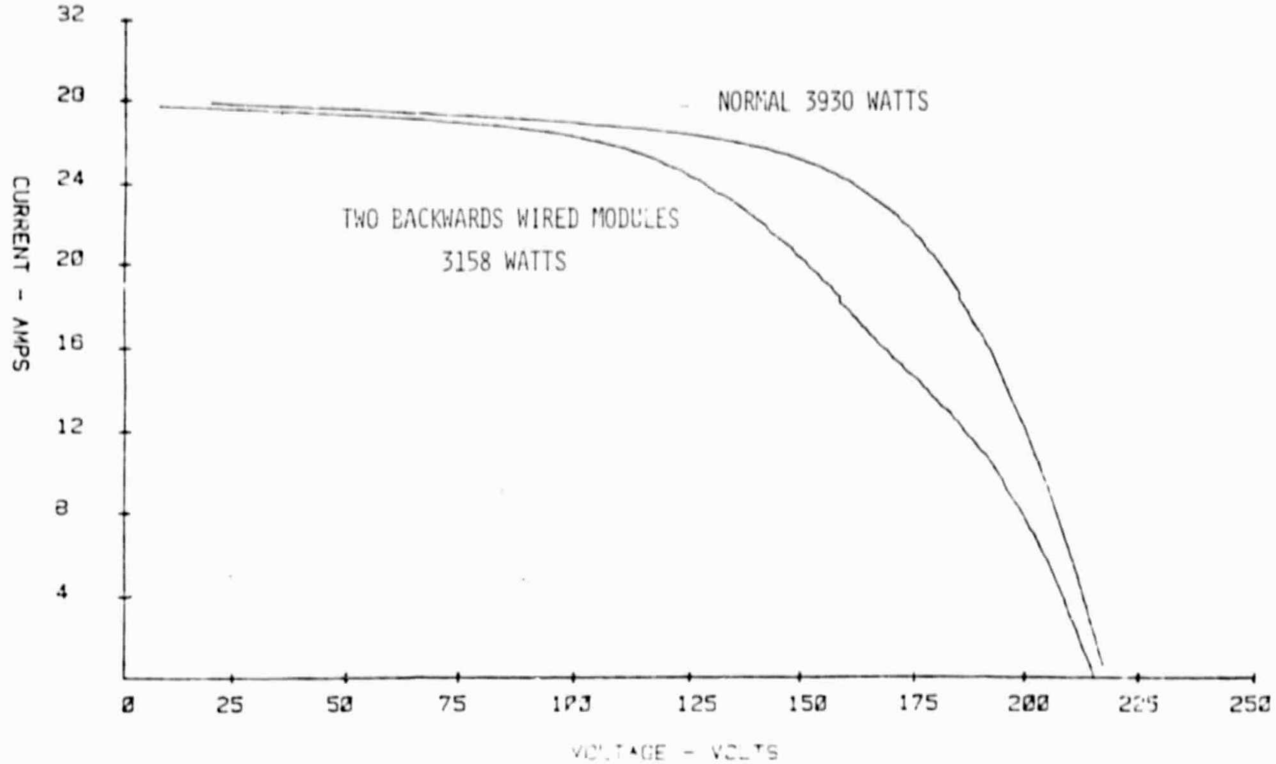
Comparison of Solarex Curves



MIT-LL Prototype NE RES: Module Problems

- SINCE TURN-ON, 7 MODULES HAVE BEEN REMOVED WITH EXCESSIVE LEAKAGE CURRENT.
  - -- PRIOR TO INSTALLATION, THE MEASURED MODULE LEAKAGE CURRENT AT 1500 VOLTS DC WAS LESS THAN 0.1 MICROAMPS.
  - -- AFTER INSTALLATION, BRANCH CIRCUIT LEAKAGE CURRENTS OF AS MUCH AS 400 MICROAMPS AT THE SYSTEM OPEN CIRCUIT VOLTAGE (260-280 VOLTS) WERE MEASURED.
  - -- PROBLEM IS CAUSED BY MOISTURE PENETRATION INTO VOIDS IN EVA ENCAPSULANT AND SUBSEQUENT CONDUCTIVE PATHS BETWEEN CELLS BUSBARS AND METAL FRAME.

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Carlisle--ISEE

PROBLEMS

- 5 MODULES WITH EXCESSIVE LEAKAGE CURRENT HAVE BEEN LOCATED AND REMOVED.
- LEAKAGE CURRENTS AS HIGH AS 2000 MICROAMPS AT THE SYSTEM VOLTAGE HAVE BEEN MEASURED.
- PROBLEM IS THE SAME AS AT MIT LL PROTOTYPE AT NERES.

SW RES at Las Cruces NM

SITE OPERATOR: NMSEI

PRIME CONTRACTOR	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
BDM	117 MOT STANDOFF	9 BRANCH CIRCUITS 13 IN SERIES x 9 IN PARALLEL	4.4 KW
TEA	112 MOT RACK MOUNT	8 BRANCH CIRCUITS 14 IN SERIES x 6 IN PARALLEL	4.2
SOLAREX	80 SX STANDOFF	6 BRANCH CIRCUITS 13 IN SERIES x 6 IN PARALLEL	4.5
TRISOLAR	44 ASEC INTEGRAL	2 IN PARALLEL BY 22 IN SERIES	5.2
AMTU	144 ARCO STANDOFF	12 BRANCH CIRCUITS 12 IN SERIES x 12 IN PARALLEL	4.9
ARCO	130 ARCO BATTEN-SEAM	5 BRANCH CIRCUITS 26 IN SERIES x 5 IN PARALLEL	7.4
GE	375 GE SHINGLE	15 IN PARALLEL BY 25 IN SERIES	6.7
WESTINGHOUSE	160 ARCO INTEGRAL	12 IN PARALLEL BY 13 IN SERIES	5.5

Innovative PV Applications for Residences

SITE	# OF MODULES	ARRAY CIRCUITRY	RATED POWER 25°C
JOHN LONG HOUSE-PHOENIX	120 ARCO BATTEN-SEAM	5 BRANCH CIRCUITS 24 IN SERIES x 5 IN PARALLEL	7.5 KW
FLORIDA SOLAR ENERGY CENTER	152 ARCO STANDOFF	12 BRANCH CIRCUITS 14 IN SERIES x 12 IN PARALLEL	5.0 KW
HAWAII NEI			
PEARL CITY	112 ARCO STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	4 KW
KALIHI	56 ARCO STANDOFF	4 BRANCH CIRCUITS 14 IN SERIES x 4 IN PARALLEL	2 KW
MOLOKAI	112 ARCO STANDOFF	8 BRANCH CIRCUITS 14 IN SERIES x 8 IN PARALLEL	4 KW

PV Module Failures at MIT-LL Test Sites: Data to 10/81

MFG START	NEE (7/77)	RES STF (11/78)	ROOF STF (5/77)	UTA (8/78)	CHIC (7/77)	WBNO (8/79)	NBNM (1/80)	TOTALS
A(I)	-	-	15/945	-	0/288	-	-	15/1233
A(II)	-	-	-	-	-	-	0/720**	0/720
B(II)	-	-	5/64	65/240	-	-	-	70/304
C(II)	97/1512	15/700	0/36	-	-	-	-	112/2248
C(III)	-	8/288	-	7/640*	-	-	-	15/928
D(II)	64/728	-	-	-	-	-	-	64/728
D(III)	-	17/192	2/74	-	-	120/800	-	139/1066
E(III)	-	-	-	-	-	-	2/1740	2/1740
F(III)	-	-	-	-	-	-	53/2064	53/2064
	7.2%	3.7%	2.0%	27% 1.1%	0%	15%	1.21%	470/11031 4.26%

* ARRAY START DATE 4/80

** 52 MODULES HAVE BEEN FOUND WITH CRACKED GLASS COVER SHEETS

Principal Causes of Module Failures

1. CELLS CRACKED DUE TO WEATHERING OR INTERNAL MODULE STRESSES.

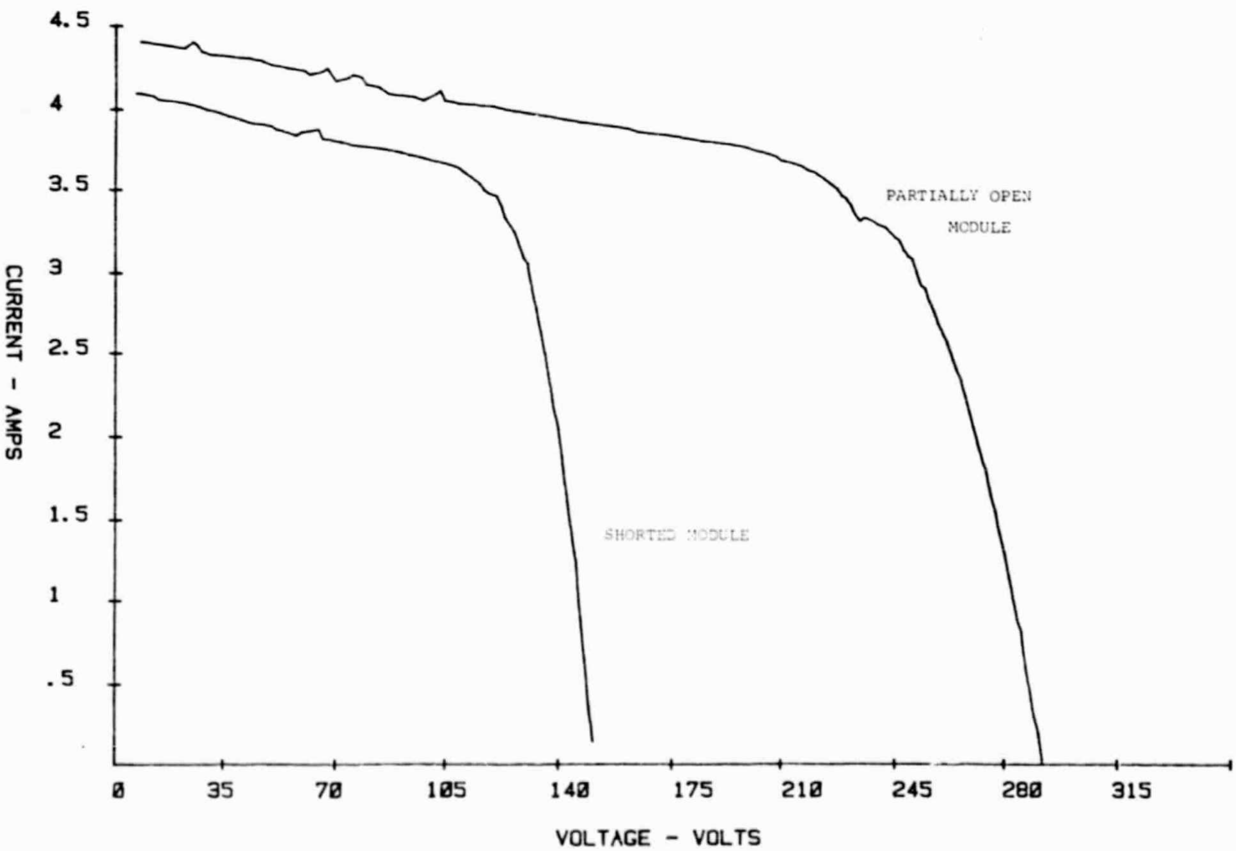
2. FAILED SOLDER JOINTS.

3. INTERCONNECTS NOT SOLDERED TO REAR SIDES OF CELLS AT ASSEMBLY.

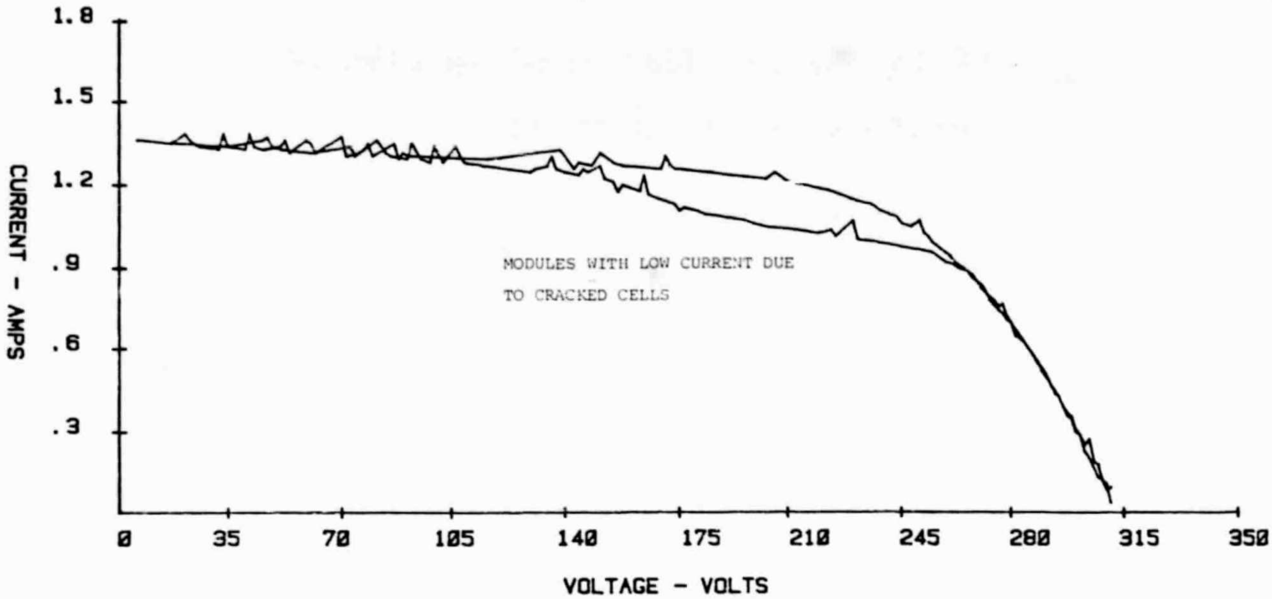
4. CELL STRING SHORTED TO SUBSTRATE.

5. BROKEN OR SPLIT INTERCONNECTS.

Natural Bridges Arrays 131A and 131B



Natural Bridges Subarrays 141A1 and 141A4



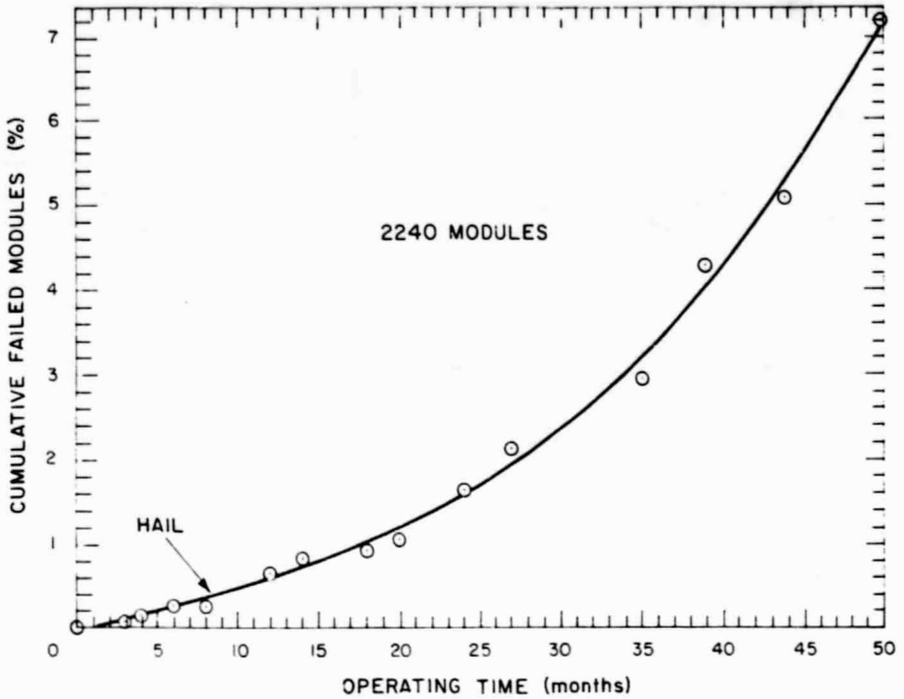
Module Failures at Mead Test Site

FRONT ROW = 728 MODULES
BACK ROW = 1512 MODULES

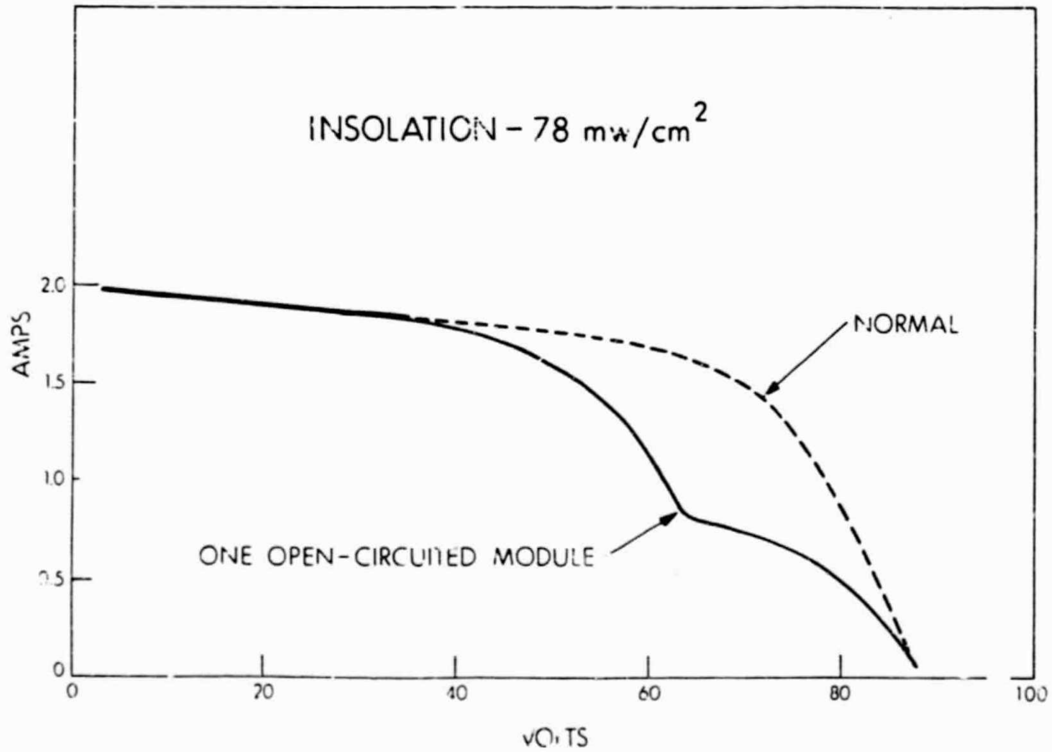
STARTING DATE = JULY 1977

	NUMBER OF FAILURES FOUND	
DATE OF SEARCH	FRONT ROW	BACK ROW
OCTOBER 1977	0	1
NOVEMBER 1977	1	1
FEBRUARY 1978	0	3
MARCH 1978	0	0
JULY 1978	6	3
SEPTEMBER 1978	3	1
FEBRUARY 1979	2	0
MARCH 1979	1	2
JULY 1979	6	7
OCTOBER 1979	1	10
JULY 1980	11	7
OCTOBER 1980	4	26
MARCH 1981	4	13
SEPTEMBER 1981	25	23
TOTALS	64	97

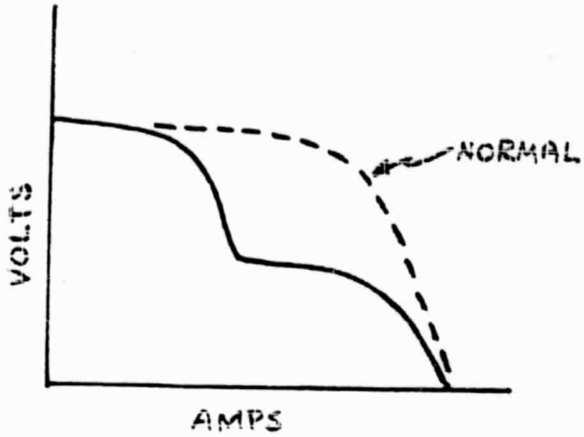
In-Service Performance Record for Nebraska PV Modules



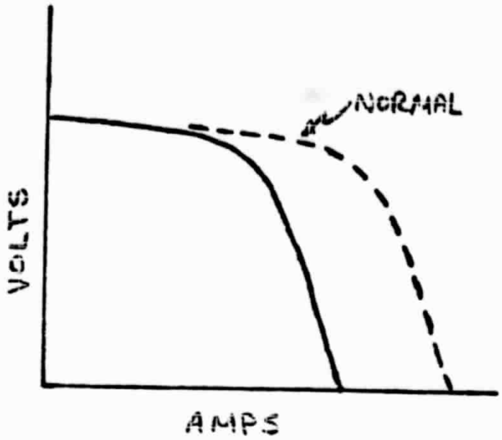
WBNO 5/14/80: Branch Circuit No. 7



WBNO I-V Curves for Branch Circuits With Two Open-Circuited Modules



BOTH FAILURES IN SAME HALF OF CIRCUIT



ONE FAILURE IN EACH HALF OF CIRCUIT

Model D Modules With Broken Interconnects

SITE	TOTAL NO. OF MODULES	TOTAL NO. OF FAILURES	FAILURES WITH BROKEN INTERCONNECTS	TIME
NEB (D-II)	728	64 (8.8%)	7	4 YRS
OHIO (D-III)	800	120 (15%)	115	2 YRS
MASS (D-III)	266	19 (7.1%)	19	3 YRS

Soil Accumulation Study at MIT, Cambridge MA

MODULE TYPE	SAMPLE SIZE	PERIOD OF EXPOSURE	PERCENT POWER LOSS
BLOCK I PLAIN GLASS	2	3 YRS.	2.8%
BLOCK II RTV	2	3 YRS.	23.8%
BLOCK II SYLGARD	2	3 YRS.	30.2%
BLOCK II HARD COAT	2	3 YRS.	8.8%
BLOCK III PLAIN GLASS	2	2 YRS. 9 MOS.	8.2%*
BLOCK III STIPPLED GLASS	2	2 YRS. 9 MOS.	0%
BLOCK III RTV	4	2 YRS. 9 MOS.	25.9%
BLOCK III SYLGARD	2	2 YRS. 9 MOS.	24.9%

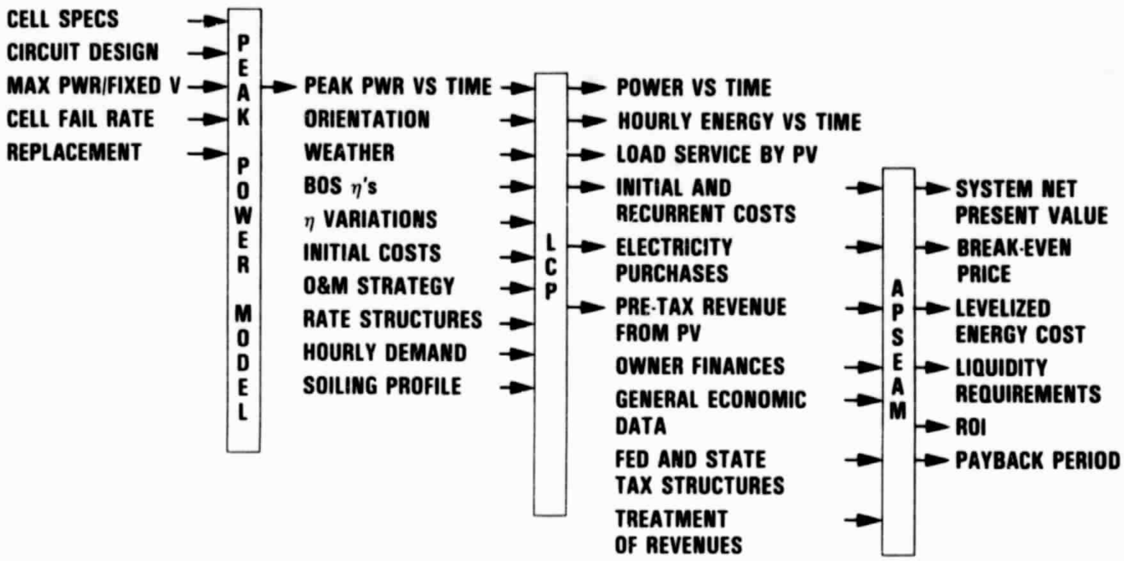
*NOTE: SEEPAGE OF RTV GEL ONTO GLASS CAUSED INCREASE IN DIRT ADHERENCE

MODULE RELIABILITY AND PV HOMEOWNER ECONOMICS

JET PROPULSION LABORATORY

P.K. Henry

PV Array Design Economic Evaluation Methodology
System Performance and Economic Models



LCP: Lifetime Cost and Performance
APSEAM: Alternative Power System Economic Analysis Model

INTEGRATED RESIDENTIAL PV ARRAY DEVELOPMENT

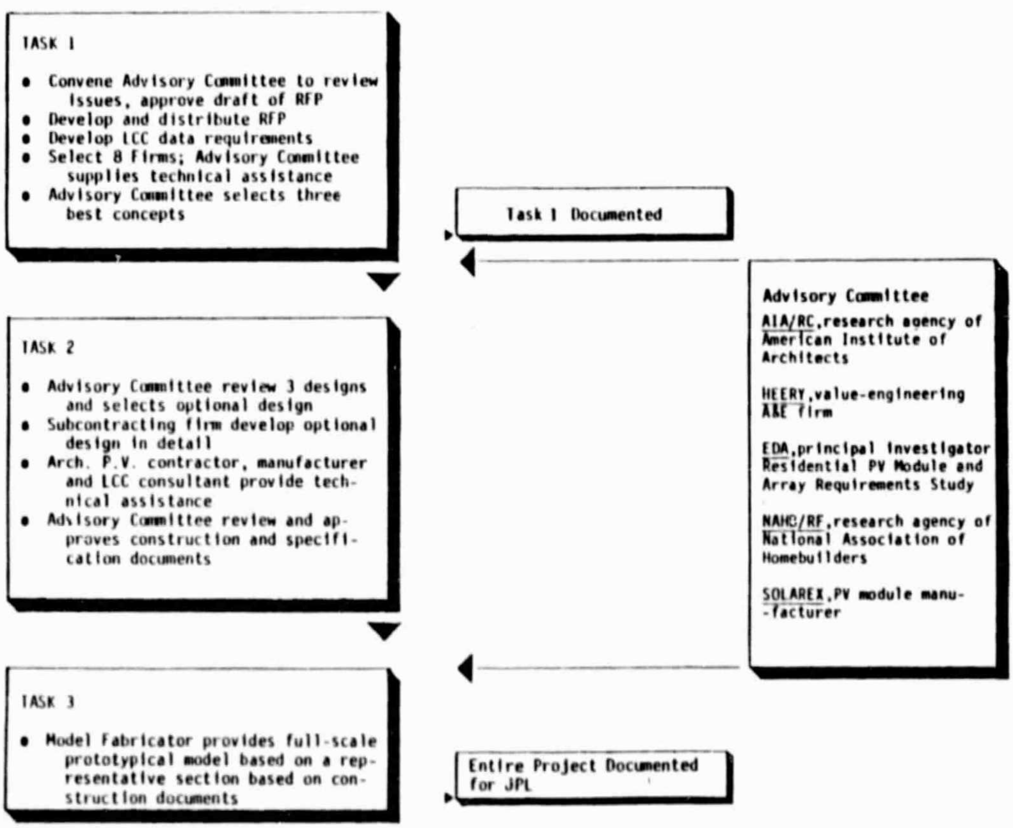
AIA RESEARCH CORP.

George Royal

Objectives

- DEVELOP INTEGRATED ROOF-MOUNTED RESIDENTIAL ARRAY FOR EARLIEST AND LARGEST MARKET PENETRATION.
- OPTIMIZE ARRAY FOR LEAST LIFE CYCLE ENERGY COST ASSUMING ANNUAL PRODUCTION RATE OF 10,000, 50,000, AND 500,000 M2.
- FOLLOW INTEGRATED SYSTEMS APPROACH CONSIDERING DETAILED ELECTRICAL, MECHANICAL, AND ENVIRONMENTAL REQUIREMENTS.
- OPTIMIZE FOR REGIONAL VARIABLES SUCH AS CODES, CONSTRUCTION PRACTICES, AND LOCAL COSTS.
- PREPARE DOCUMENTATION OF FINAL DESIGN SUFFICIENT FOR THIRD-PARTY FABRICATION.
- FABRICATE PROTOTYPE OF DESIGN TO IDENTIFY ADDITIONAL ROOF/ARRAY INTERFACE CONCERNS.

Tasks



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Design Concept Evaluation Criteria

MARKET PENETRATION

- SATISFY THE LARGEST MIDDLE-INCOME MASS MARKET
- SERVE A VARIETY OF HOUSING SIZES, TYPES AND ROOF SHAPES
- SELECTION BY BOTH LARGE AND SMALL VOLUME BUILDERS
- FLEXIBILITY IN INSTALLATION TIMING
- WITHIN THE TYPICAL PRODUCT DELIVERY AND SERVICE CHAIN OF THE HOMEBUILDING INDUSTRY

FABRICATION

- MIXTURE OF FACTORY AND FIELD LABOR FOR ARRAY ASSEMBLY
- REQUIREMENTS FOR COMPONENT INVENTORY
- MINIMIZE THE COST FOR SHIPPING AND HANDLING WITH ACCEPTABLE DURABILITY

DESIGN AND SPECIFICATION

- DESIGN ENGINEERING CAPABILITY NORMALLY EMPLOYED BY THE BUILDER OR CONTRACTOR
- MINIMIZE FIELD INSPECTION AND APPROVAL REQUIREMENTS OF LOCAL BUILDING AND ZONING CODES, THE NATIONAL ELECTRICAL CODE (NEC), FIRE CODES AND INSURANCE WARRANTS
- USE OF EQUIVALENT MATERIALS AND PRODUCTS IN STANDARD CONSTRUCTION PRACTICE
- FLEXIBILITY IN LABOR AND SCHEDULE COORDINATION THAT MEETS STANDARD PRACTICE CONDITIONS
- DOCUMENTATION FOLLOW STANDARD PRACTICE

INSTALLATION

- LITTLE IMPACT ON THE NORMAL STRUCTURAL AND ENVIRONMENTAL EXPOSURE OF THE BUILDING
- COMPATIBLE WITH STANDARD CONSTRUCTION PRACTICES, TOOLS AND EQUIPMENT
- MINIMIZE FIELD APPROVAL OF ELECTRICAL CONNECTIONS, FIELD CABLING AND GROUNDING
- MINIMIZE SAFETY RISK DURING INSTALLATION
- OPTIMIZE HANDLING AND INSTALLATION DURABILITY
- OPTIMIZE MECHANICAL ATTACHMENT AND ELECTRICAL CONNECTION REQUIREMENTS

OPERATION

- AN ACCEPTABLE OUTPUT RANGE FOR SIZE AND TEMPERATURE CONDITIONS
- ARRAY OUTPUT MUST SATISFY BALANCE OF SYSTEM INTERFACE REQUIREMENTS
- MINIMIZE GROUNDING CONCERNS AND REQUIREMENTS
- ADDRESS APPROPRIATE POWER AND DIMENSIONAL MODULARITY CONCERNS
- LIFETIME RELIABILITY AND DURABILITY CONDITIONS AT AN ACCEPTABLE COST

MAINTENANCE

- MINIMIZE THE REQUIREMENTS FOR IDENTIFICATION, REMOVAL AND REPLACEMENT OF FAILED PARTS
- NOT INTERFERE WITH NORMAL BUILDING MAINTENANCE AND REPAIR
- MINIMIZE ADDED LIFE SAFETY AND BUILDING RISKS

Phase 1 Ground Rules

CELL AND ENCAPSULATION PROCESSING BEYOND SCOPE OF STUDY

ENCAPSULATED CELL EFFICIENCY OF 135 W_p/m^2 AT 100 mW/cm^2, AM 1.5, 28°C.

GLASS ENCAPSULATED MODULE COST OF $0.70/$W_p$ IN $1980

EXCESSIVE HOT-SPOT HEATING PREVENTED

V_{oc} LESS THAN 30 Vdc AT -20°C FOR MODULES/PANELS WITH EXPOSED TERMINALS

ARRAY IS PV-ONLY,AIR-COOLED, FLAT-PLATE, SOUTH-FACING WITH FIXED TILT

ARRAY DESIGN LIFE IS 20 YEARS

ONE MODULE REPLACEMENT EVERY FOUR YEARS

ARRAY OUTPUT BETWEEN 4-10 kW_p

USE OF REGIONAL CODE LOADS

ARRAY DESIGN AND INSTALLATION WITHIN STANDARD BUILDING PRACTICES

INITIAL COSTS ONLY CONSIDERED IN PHASE 1

LIFE CYCLE COSTS WITH 6% DISCOUNT RATE CONSIDERED IN PHASE 2

DESIGN TEAM SPECIFIES MARKET AND DISTRIBUTION ASSUMPTIONS FOR EARLIEST AND LARGEST PENETRATION

TECHNOLOGY PROVEN NOT LATER THAN 1982

Summary of Design Concepts

MOUNTING TYPE	DESCRIPTION	SAMPLE N = 16	OUTPUT Wp	AREA M^2	TOTAL $/Wp	HARDWARE $/Wp	WIRING $/Wp	CREDITS $/Wp
INTEGRAL	EIGHTEEN (18) UNFRAMED PANELS/MODULES ARE PRESSURE FITTED IN A "T" SHAPED NEOPRENE GASKET GRID AND SEALED BY A ZIPLOCKING STRIP. THE GASKET GRID IS PRESSURE FITTED INTO AN ALUMINUM CHANNEL EXTRUSION GRID THAT IS SCREWED DIRECTLY TO THE RAFTERS.	1	4455	41.43	1.31	0.50	0.03	0.13
	TEN (10) FRAMED PANELS EACH MADE FROM TWO EXTRUDED ALUMINUM CARRIAGE PIECES JOINED BY LATERAL ANGLES ARE BOLTED TO THE RAFTERS. EACH OF THE NINE (9) MODULES PRESSURE FITTED IN A PANEL OVERLAPS THE LOWER ONE AND IS HELD IN PLACE BY A LAP BAR.	2	9760	76.2	1.41	0.70	0.13	0.30
	EIGHTY (80) FRAMELESS MODULES ARE SEALED USING A SILICONE ADHESIVE TO A PREFABRICATED GRID OF RIGID TAPE AND SHEET METAL BOLTED TO THE RAFTERS.	3	9990	78.1	1.07	0.23	0.04	0.11
	FORTY (40) GASKETED MODULES ARE SEALED IN A SET OF PREWIRED MOUNTING CHANNELS NAILED ALONG THE LENGTH OF THE RAFTERS.	4	9990	78.1	1.11	0.27	0.04	0.11
	TWENTY-FOUR (24) UNFRAMED MODULES ARE PRESSURE FITTED BETWEEN A SERIES OF EXTRUDED ALUMINUM BATTEN STRIPS AND PLYWOOD SUPPORT STRIPS MOUNTED DIRECTLY TO THE RAFTERS. WATERPROOF SEAL IS PROVIDED BY BUTYL GLAZING TAPE AT THE TOP AND SIDES OF THE MODULES.	5	4200	50.5	1.10	0.40	0.06	0.17

Estimates of Field Application

ELEMENT	ANNUAL PRODUCTION (M^2)		
	10000	50000	500000
Cells (@ 0.01 M^2)	1,000,000	5,000,000	50,000,000
Peak Power Output (MWp)	1.229	6.143	61.431
Max Power Output (MWp)	0.921	4.605	46.050
Houses at Nom. 4 KWp	193	965	9650
Houses at Nom. 8 KWp	96	482	4825

Innovative Design Features

MODULE DESIGN

- MODULE AREA GREATER THAN $1M^2$
- SQUARE OR RECTANGULAR CELLS
- REDUNDANT PROTECTION FOR MODULE

  OPEN-CIRCUIT VOLTAGES OVER 30 Vdc at -20°C
- MINIMIZED GROUNDING
- LOW SOILING COVER MATERIAL
- SERIES/PARALLELING AND DIODE PROTECTED RELIABILITY

WIRING

- WIRING HARNESS ELIMINATION
- PRE-WIRED MOUNTING HARDWARE
- MINIMIZED WIRE SIZE AND INSULATION
- SERIES/PARALLELING RELIABILITY FOR MODULE MISMATCH AND SYSTEM INTERFACE

INSTALLATION

- HARDWARE APPLICABLE TO SEVERAL MOUNTING TYPES
- MINIMIZED INDIVIDUAL MODULE/PANEL ALIGNMENT
- MECHANICAL FASTENING REPLACEMENT
- PRE-CUT MATERIALS
- MINIMIZED CONSTRUCTION-TRADE LIMITS
- LIMIT MODULE/PANEL ROWS TO MINIMIZE MOUNTING FRAME COMPLEXITY

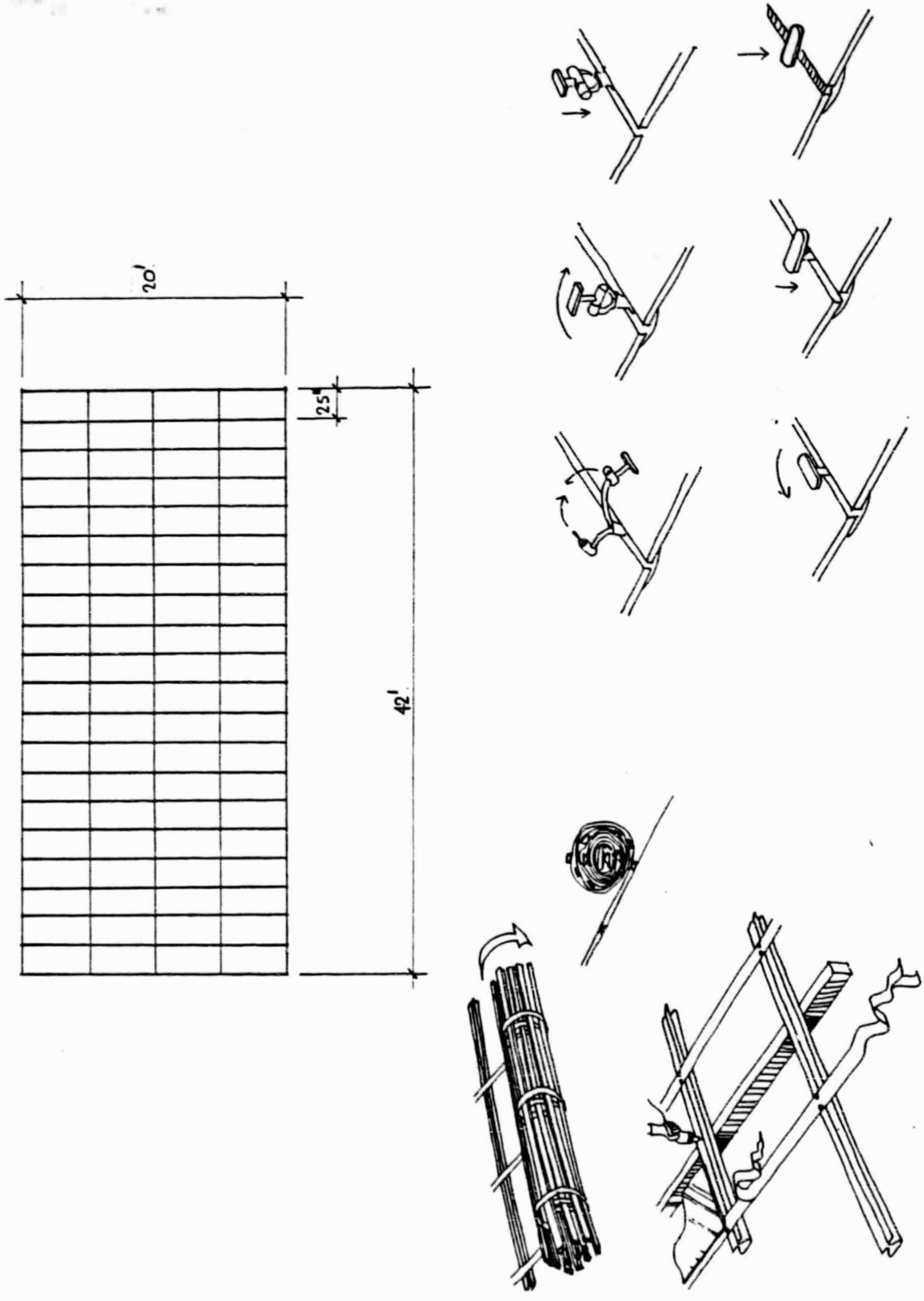
Concept Selection

CONCEPT TEAM	PROOF-OF-CONCEPT STAGE	MOUNTING SYSTEM	ARRAY SIZES	MODULE SIZES	INNOVATIVE FEATURES
TOTAL ENVIRONMENTAL ACTION (TEA)	OFF-THE SHELF	INTEGRAL	4455 4608	4 FT X 8 FT 2 FT X 4 FT	LABOR/MATERIAL TRANSFER FROM CURRENT TECHNOLOGY BASE
BURT HILL KOSAR RITTELMANN ASSOCIATES (BHKRA)	PILOT	INTEGRAL DIRECT	9990 5038	2 FT X 5 FT 2 FT X 4 FT	DUAL MOUNTING APPLICATION MINIMUM MODULE ALIGNMENT
ONE DESIGN INC (ODI)	PROTOTYPE	STANDOFF	5158 5227	4 FT X 4 FT 2 FT X 4 FT	WIRING HARNESS ELIMINATION

Selected Concepts Cost Summary

COST ELEMENT	AVG. SYSTEM COST ($/$W_p$)			DESIGN CONCEPT COST ($/$W_p$, 1980)					
	INTEGRAL	DIRECT	STAND-OFF	NO. 1		NO. 7		NO. 9	
				PHASE 1	PHASE 2	PHASE 1	PHASE 2	PHASE 1	PHASE 2
Array Installation Total	0.40	0.23	0.44	0.45	0.52	0.23	0.25	0.30	0.29
Sealants	0.03	0.02	0.00		0.04	0.04	0.03	0.01	
Flashing	0.04	0.03	0.00	0.04	0.04	0.03	0.03		
Mounting HDWR/Glazing Gaskets	0.20	0.09	0.26	0.16	0.17	0.07	0.06	0.13	0.14
Field Assembly	0.13	0.09	0.17	0.26	0.27	0.09	0.11	0.16	0.16
Shop Assembly	0.00	0.01	0.00			0.02	0.01		
Roof Work	0.02		0.16	0.05	0.05				
Wiring Total	0.06	0.05	0.11	0.03	0.06	0.04	0.08	0.01	0.01
Harnesses	•				0.02		0.05		
Connectors					0.03		0.03		0.01
Busbar(s)					0.01		0.00		0.00
Modules	0.89	0.91	0.98	0.91	0.91	0.91	0.93	0.91	0.91
Standard Roof Credit	6.17	0.05	0.06	0.13	0.16	0.05	0.07		
Net Installed Cost with Modules	1.21	1.24	1.63	1.31	1.14	1.13	1.18	1.22	1.21
without Modules	0.32	0.33	0.65	0.40	0.47	0.22	0.26	0.31	0.30
Replacement Total ($/Module)					95.00		45.52		103.26
Minor Upkeep ($/Yr.)					17.00		75		30.00

BHKRA Design Concept



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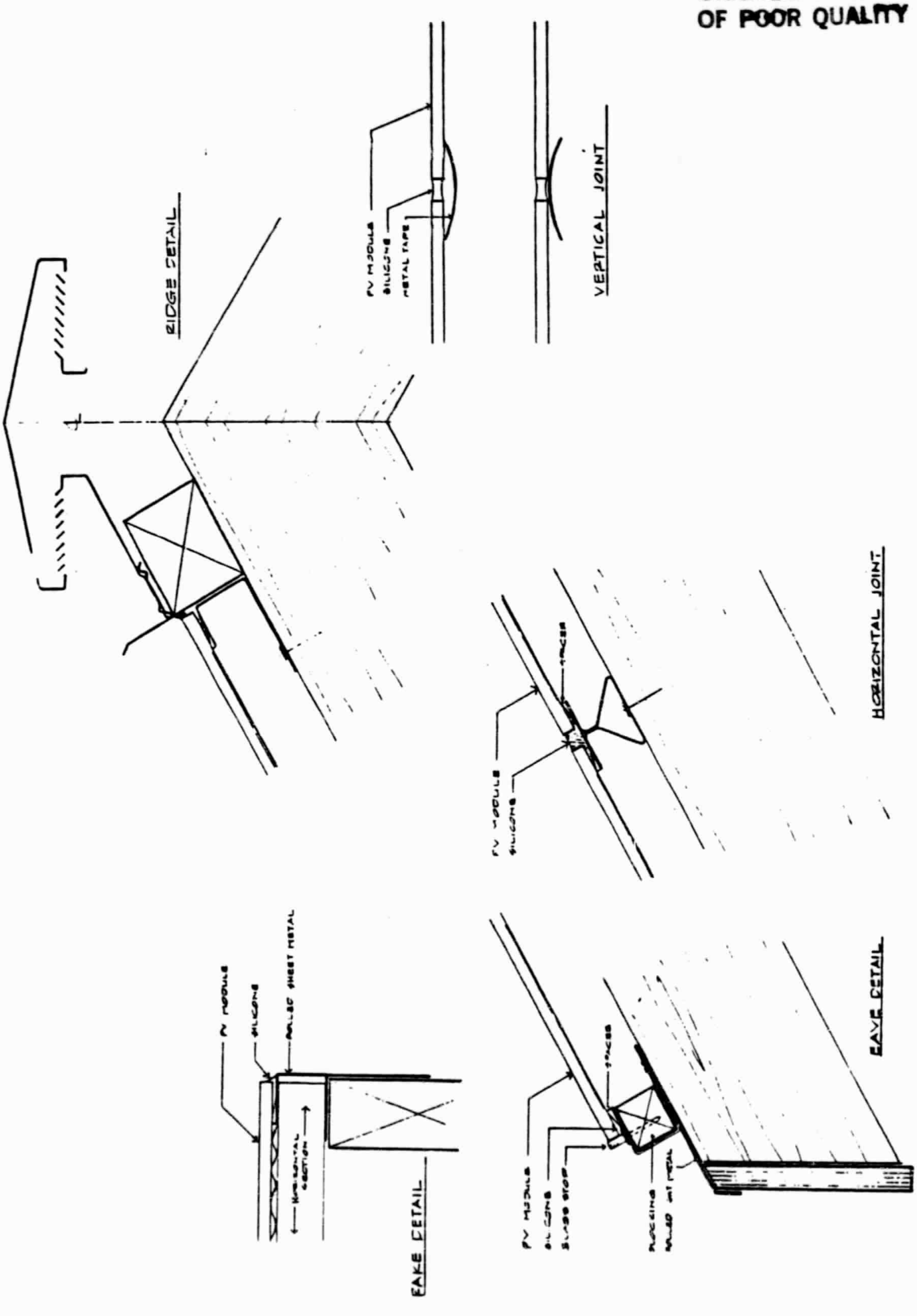

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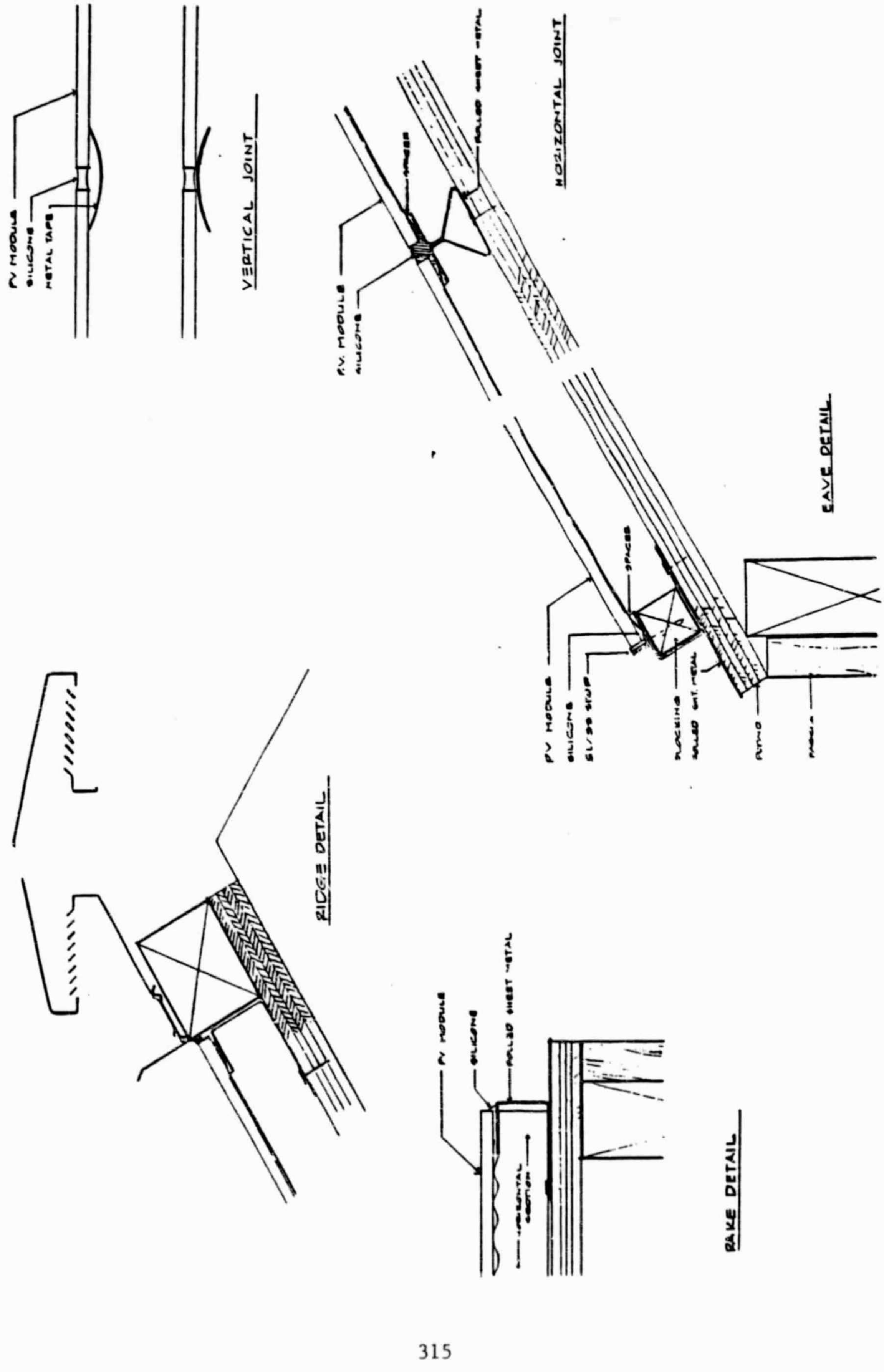

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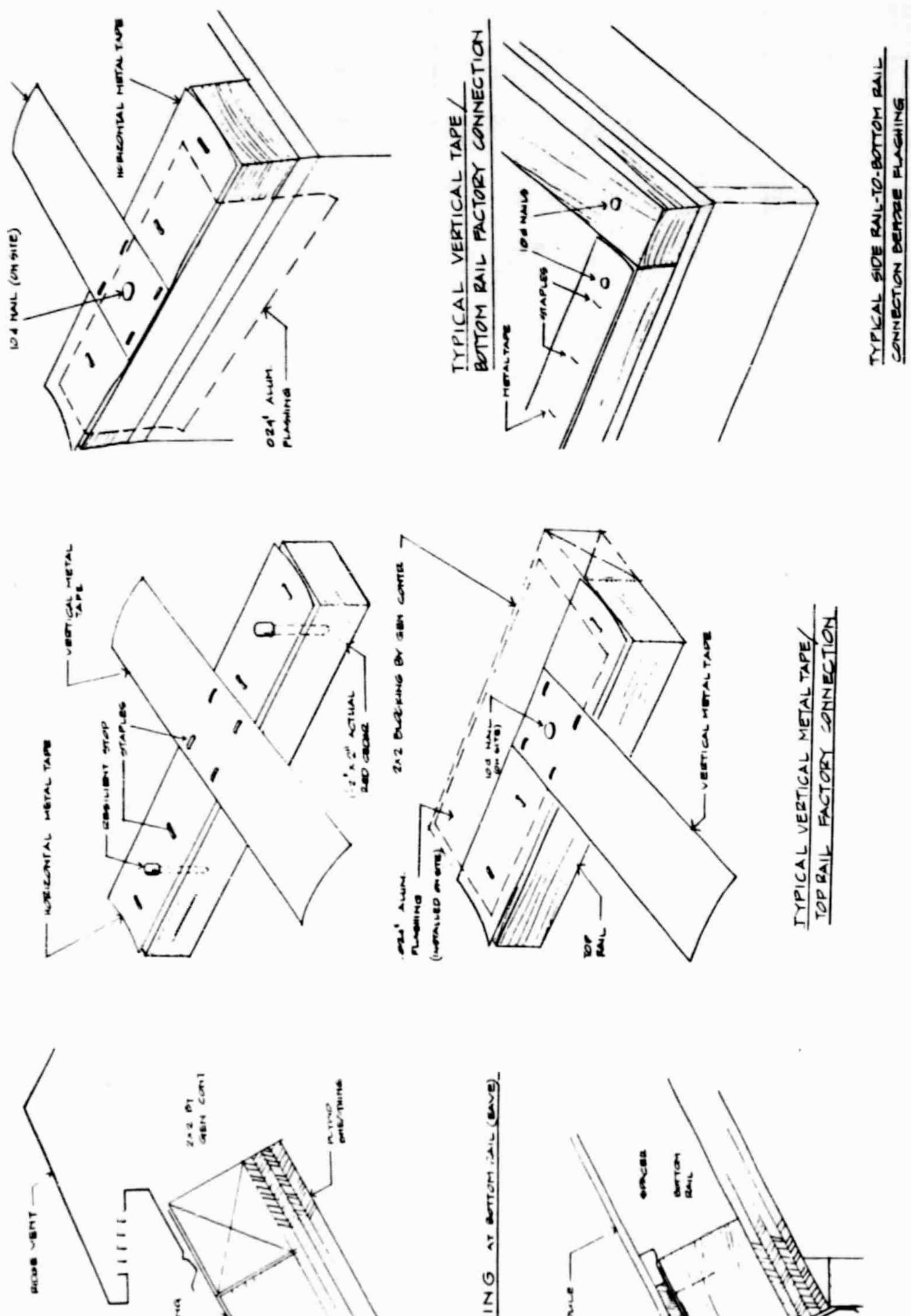
Design Concept Optimization



ENGINEERING SCIENCES/MODULE PERFORMANCE AND FAILURE ANALYSIS/ANALYSIS AND INTEGRATION AREAS

DESCRIPTION	COST($)	REMARKS
Cost per Replacement Action*	$45.52	Module Replacement
NOCT Efficiency		
Array Wiring Efficiency		
Gross Array/Cell Packing Efficiency		
Minor Upkeep Costs*	$75.00	Cleaning

Array Size (M^2)	=	55.49 m^2
Panel Size (M^2)	=	1.294 m^2
Module Size (M^2)	=	1.294 m^2
Cells/Module	=	120 Cells
Cells/Branch Circuit Substring	=	30

COST COMPONENT*

	COST($)	COST ($/$M^2$)	% OF TOTAL COSTS
Wiring	$ 133.78	$ 2.41	3.2%
Array/Panel Support Device(s)	N/A		
Array Assembly	246.55	4.44	5.9%
Array Installation	288.84	5.21	6.9%
Mounting Gaskets	N/A		
Sealants	120.00	2.18	2.9%
Roof Bracing	N/A		
Flashing	36.22	0.66	0.9%
Rack Structures	N/A		
Module/Panel Mfg. Costs (from JPL)	3,910.20	70.47	93.0%
Special Hardware	N/A		
Other	N/A		
a.			
b.			
Net Installed Cost	$4,735.59	$85.37	
Roofing Credit*	528.00	9.59	12.7%
Total Installed Cost	$4,207.59	$75.78	

5 KW PV ARRAY INSTALLATION MAN-HOURS

TASK	GLAZIER	GLAZIER	LABORER	LABORER	TOTAL
COORDINATION & SET-UP	1/4	1/4	3/4	3/4	2
ROOF CHECK	1/4	1/4			1/2
SET #1 SIDE RAIL	1/4	1/4			1/2
PREPARE MODULES & FRAME			1/4	1/4	1/2
HOIST #1 BUNDLE & ROLL OUT	1/4	1/4	1/4	1/4	1
SQUARE, TACK, SHIM, NAIL	1/2	1/2	1/4	1/4	1-1/2
SET #2 SIDE RAIL	1/4	1/4			1/2
PREPARE #2 BUNDLE			1/4	1/4	1/2
HOIST #2 BUNDLE & ROLL OUT	1/4	1/4	1/4	1/4	1
SQUARE, TACK, SHIM, NAIL	1/4	1/4	1/4	1/4	1
PREPARE FLASHING			1/2	1/2	1
INSTALL FLASHING	1/2	1/2			1
SUBTOTAL	2-3/4	2-3/4	2-3/4	2-3/4	11
INSTALL 1ST ROW	3/4	3/4	3/4	3/4	3
BREAK FOR LUNCH	1/2	1/2	1/2	1/2	2
INSTALL 2ND ROW	1/2	1/2	1/2	1/2	3
INSTALL 3RD ROW	1/2	1/2	1/2	1/2	2
INSTALL 4TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 5TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 6TH ROW	1/2	1/2	1/2	1/2	2
INSTALL 7TH ROW	1/2	1/2	1/2	1/4	1-3/4
INSTALL 8TH ROW	1	1	3/4		2-3/4
CLEAN UP			1/4	1-1/4	1-1/2
SUBTOTAL	4-3/4	4-3/4	4-3/4	4-3/4	19
TOTAL	8	8	8	8	32

PRICING SHEET For Scheme No. BHKRA-3

Cost Component: COST PER REPLACEMENT ACTION

Date: April 29, 1981
Array Designer: Burt Hill Kosar Rittelmann Associates

COST/CREDIT ITEM	QUANTITY	MAT'L UNIT COST	MAT'L COST	LABOR UNIT COST	LABOR COST	TOTAL INSTALLED COST	REMARKS
Set-Up	0.75 Hrs.			$19.92	$14.94	$14.94	
Cut Out Module	0.25 Hrs.			10.99	2.75	2.75	
Remove Module	0.25 Hrs.			19.92	4.98	4.98	
Prepare Module	0.25 Hrs.			8.93	2.23	2.23	
Place Module	0.25 Hrs.			19.92	4.98	4.98	
Sealant	1 Tube	$7.00	$7.00	10.99	2.00	9.00	
Clean-Up	0.33 Hrs.			19.92	6.64	6.64	
TOTAL						$45.52	
TOTAL COST/M^2						$52.93	Per Square Meter of Module

Cost Component: MINOR UPKEEP COSTS

Date: April 29, 1981
Array Designer: Burt Hill Kosar Rittelmann Associates

COST/CREDIT ITEM	QUANTITY	MAT'L UNIT COST	MAT'L COST	LABOR UNIT COST	LABOR COST	TOTAL INSTALLED COST	REMARKS
Cleaning	1					$75.00	
TOTAL						$75.00	
TOTAL COST/M^2						$ 1.36	

Design Tradeoffs

MODULE HANDLING SIZE REQUIREMENTS

HANDLING BY 1 OR 2 PERSONS
- ANTHROPOMETRIC LIMITS FOR LIFT AND TORQUE

CONFIGURATIONS BETWEEN 1 FT^2 AND 40 FT^2

GLASS ENCAPSULATION SYSTEMS
- EDGE TOLERANCE

MODULE SUPPORT SIZE REQUIREMENTS

MODEL CODE SERVICE LOADS

SUPPORT OPTIONS
- SIMPLE 4-SIDE
- UNIFORM

GLASS THICKNESS

MODULE CIRCUIT SIZE REQUIREMENTS

MODULARITY
- REFERENCE CELL CHARACTERISTICS
- CIRCUITS PER MODULE

SAFETY
- 30 Vdc OPEN CIRCUIT VOLTAGE AT -20°C

RELIABILITY
- HOT SPOT HEATING

ARRAY ALIGNMENT

MAJOR ISSUES INCLUDE:
- ARRAY LOCATION ON ROOF WITH RESPECT TO ROOF PENETRATION
- ROOF SIZE
- RIDGE TO EAVE DISTANCE
- ESTABLISHMENT OF ANY NECESSARY DATUM
- CUMULATIVE PLACEMENT ERROR
- TOLERANCES

METHODS:
- BLOCK/BRACKET
- STRIP/CHANNEL
- GRID/MESH

ARRAY ATTACHMENT

MAJOR CONCERNS INCLUDE:
- LOCATION OF WEATHERABLE SURFACE (i.e., either standard roof surface or module surface)
- SUPPORT CONDITIONS
- LOADING CONDITIONS
- RELIABILITY OF FASTENING METHODS

METHODS:
- MECHANICAL FASTENERS
- PRESSURE FITTING GASKETS
- ADHESIVES

ARRAY CONNECTION

MAJOR CONCERNS INCLUDE:
- CONNECTOR PROFILE AND LOCATION (i.e., dry or wet) OF CONNECTOR
- CONNECTOR REUSE AND ACCESSIBILITY
- SAFETY PROTECTION FROM EXPOSED CONDUCTIVE PARTS

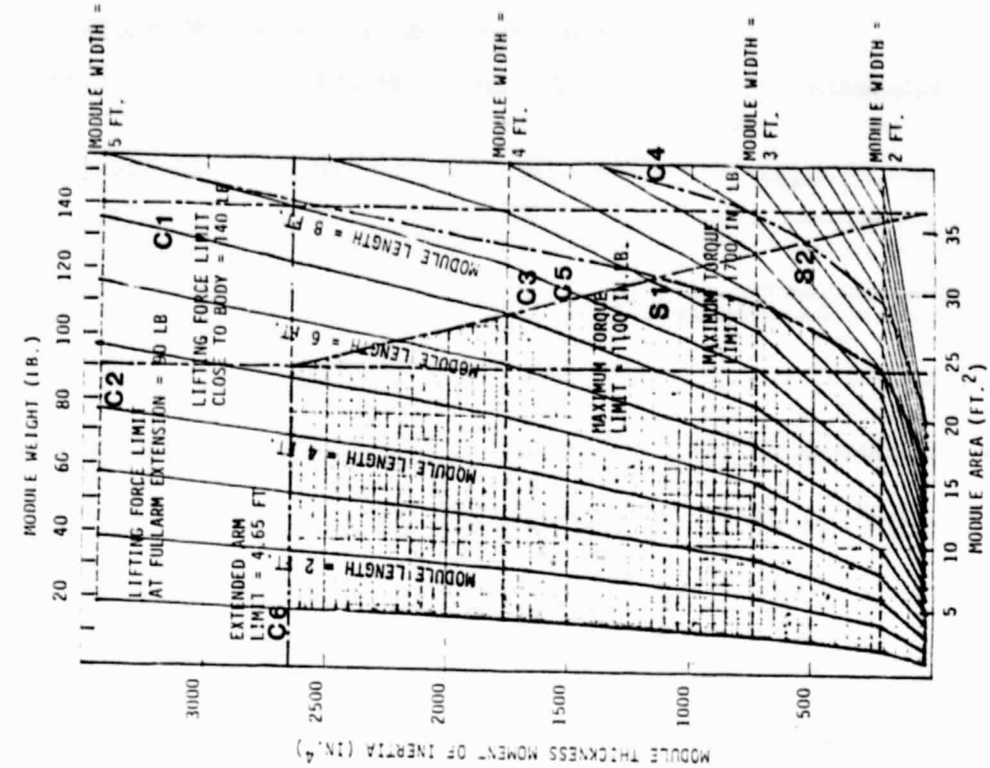
METHODS:
- JUNCTION BOXES
- QUICK CONNECT/DISCONNECT
- QUICK PERMANENT CONNECT

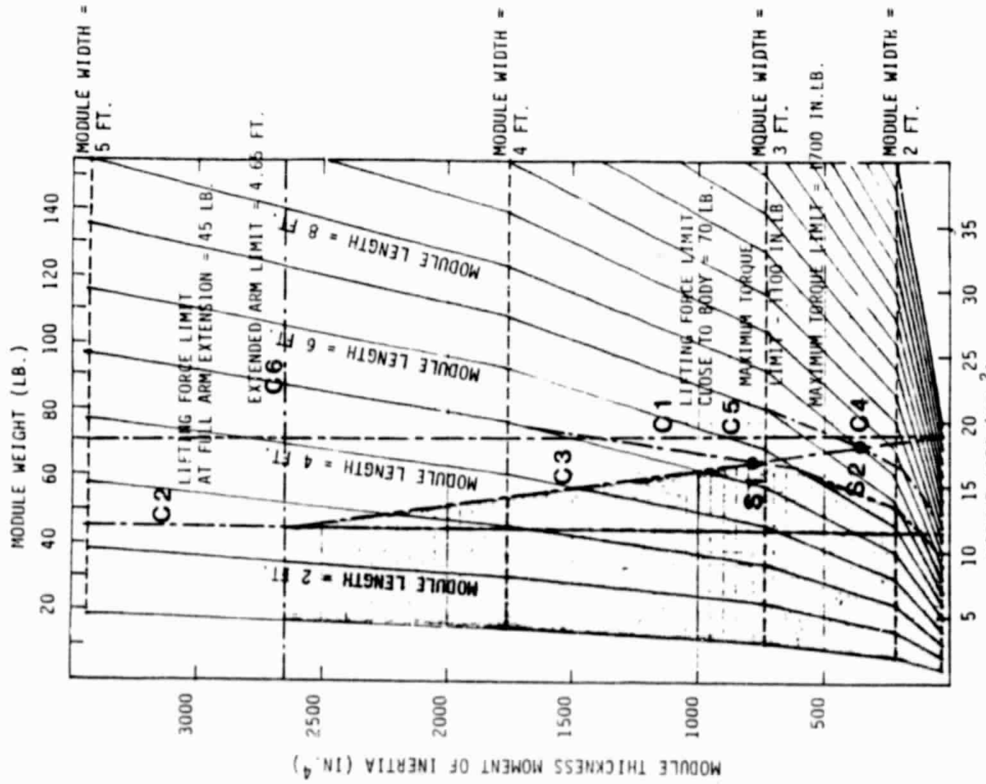
ARRAY CABLING

MAJOR ISSUES INCLUDE:
- APPROVAL AND QUALIFICATION
- FACTORY VS. FIELD REQUIREMENTS
- SAFETY PROTECTION FROM EXPOSED CONDUCTIVE PARTS

METHODS:
- SPLICE
- RIBBON
- MAT

Module Handling Limits





	Module Size:		
	2 Ft x 4 Ft	80 cm x 150 cm	80 cm x 300 cm
Cells/module	72 (6 x 12)	98 (7 x 14)	203 (7 x 19)
Modules/8 hour shift	133	98	47
Tabbing/stringing	375	500	750
Rinse machine	60	70	80
String stacker	8	10	12
Array assembly station (assemble EVA, Craneglass back cover)	12	15	18
Laminator	120	160	200
Connector installation	2	2	2
Miscellaneous equipment	50	50	50
	627	807	1,112

Module Size (m^2/mod)	Modules/Shift	M^2/yr	Modules/Yr	Cap. Equp. $	$/$M^2$
.75	133	89177	118902	627000	7.03
1.2	98	105134	87612	807000	7.68
2.4	47	100842	42018	1112000	11.03

Single Cell Characteristics

- $9.25_{cm} \times 4.75_{cm}$
- Single or Semicrystalline Silicon
- P = 0.47W, 0.8 kW/M^2 and 49°C
- $V_{oc} = 0.59$; $V_{mp} = 0.46$; $\frac{\Delta V}{\Delta T} = -0.0024$ V/°C
- $I_{sc} = 1.19$; $I_{mp} = 1.03$; $\frac{\Delta I}{\Delta T} = +0.0023$ A/°C

Module Characteristics

- 23.5625 in. x 95.5625 in.
- 87.1% Packing Density
- 48S x 6P, 6 Series Blocks, 8 Cells per Substring
- P = 137W, 0.8 kW/M^2 and 49°C
- $V_{oc} = 28.3$; $V_{mp} = 22.1$; $\frac{\Delta V}{\Delta T} = -0.115$ V/°C
- $I_{sc} = 7.1$; $I_{mp} = 6.2$; $\frac{\Delta I}{\Delta T} = +0.014$ A/°C

Branch Circuit Characteristics

- ($144\ FT^2$) 6 FT x 24 FT, 9 Modules
- 432S x 6P, 54 Series Blocks, 8 Cells per Substring
- P - 1233W, 0.8 kW/M^2 and 49^oC
- $V_{oc} = 254.7$; $V_{mp} = 198.9$; $\frac{\Delta V}{\Delta T} = -1.04\ V/^oC$
- $I_{sc} = 7.1$; $I_{mp} = 6.2$; $\frac{\Delta I}{\Delta T} = 0.01\ A/^oC$

Panel Characteristics

- ($288\ FT^2$) 12 FT x 24 FT, 18 Modules
- 2 Branch Circuits
- P = 2466W, 0.8 kW/M^2 and 49^oC
- $V_{oc} = 254.7$; $V_{mp} = 198.9$; $\frac{\Delta V}{\Delta T} = -1.04\ V/^oC$
- $I_{sc} = 14.2$; $I_{mp} = 12.4$; $\frac{\Delta I}{\Delta T} = 0.03\ A/^oC$
- Modular 2.8-4.6 MWh/YR (i.e. ≑ 2 kWp) roof mounting panels
- Glass encapsulated modules that fit within a 24 in. grid
- Module output > 30 Vdc
- Panel mechanically fastened to roof
- Module adhesively attached to panel
- BC Array voltage developed along roof slant height
- Frameless, gasketless modules
- Exposed conductive parts eliminated
- Low-cost panel material and fabrications process
- Quick connect/disconnects
- Dry wiring location

INTEGRATED RESIDENTIAL PV ARRAY DEVELOPMENT

GENERAL ELECTRIC CO.

N.F. Shepard

Program Work Scope

- DEVELOPMENT OF CONCEPTUAL ALTERNATIVES
  - REVIEW EXISTING DESIGN APPROACHES
  - SELECT AND OPTIMIZE THREE CONCEPTS
- OPTIMIZE DESIGN OF ONE CONCEPT
  - DETAILED DESIGN DEFINITION
  - PRODUCTION AND INSTALLATION COSTING ANALYSIS
- FABRICATE PROTOTYPE ARRAY/ROOF SECTION
  - FULL SIZE
  - FEEDBACK TO PRODUCTION DESIGN
- BY-PASS DIODE INTEGRATION

Progress

- DETAIL DESIGN OF SELECTED CONCEPT
- PRODUCTION AND INSTALLATION COST ANALYSES AT THREE ANNUAL THROUGHPUTS
- FULL-SIZE PROTOTYPE ROOF MODEL CONSTRUCTED

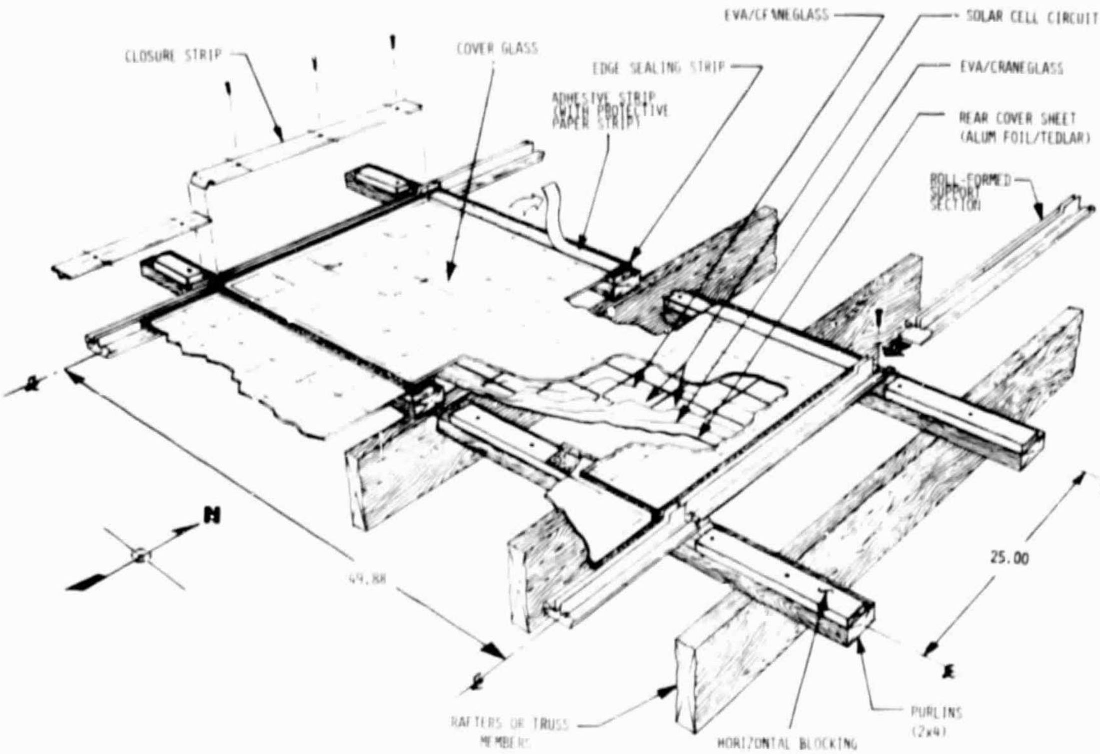
Prior Study Results

- A BASIC 2x4 FT MODULE SIZE OFFERS A REASONABLE CHOICE FOR RESIDENTIAL SYSTEMS
- PRODUCTION COSTS ARE MINIMIZED WITH A SIMPLE, FRAMELESS MODULE
- INTEGRAL MOUNT YIELDS LOWEST INSTALLATION COST
- HIGH AREAL POWER DENSITY IS REQUIRED FOR MINIMUM INSTALLED COST
- METAL SUBSTRATES LEAD TO RELIABILITY AND SAFETY PROBLEMS
- POLYMERIC OUTER COVERS HAVE QUESTIONABLE LONG-TERM WEATHERABILITY AND FIRE-RESISTANCE
- EXPOSED CONDUCTIVE ELEMENTS REQUIRE GROUNDING WITH ASSOCIATED COST

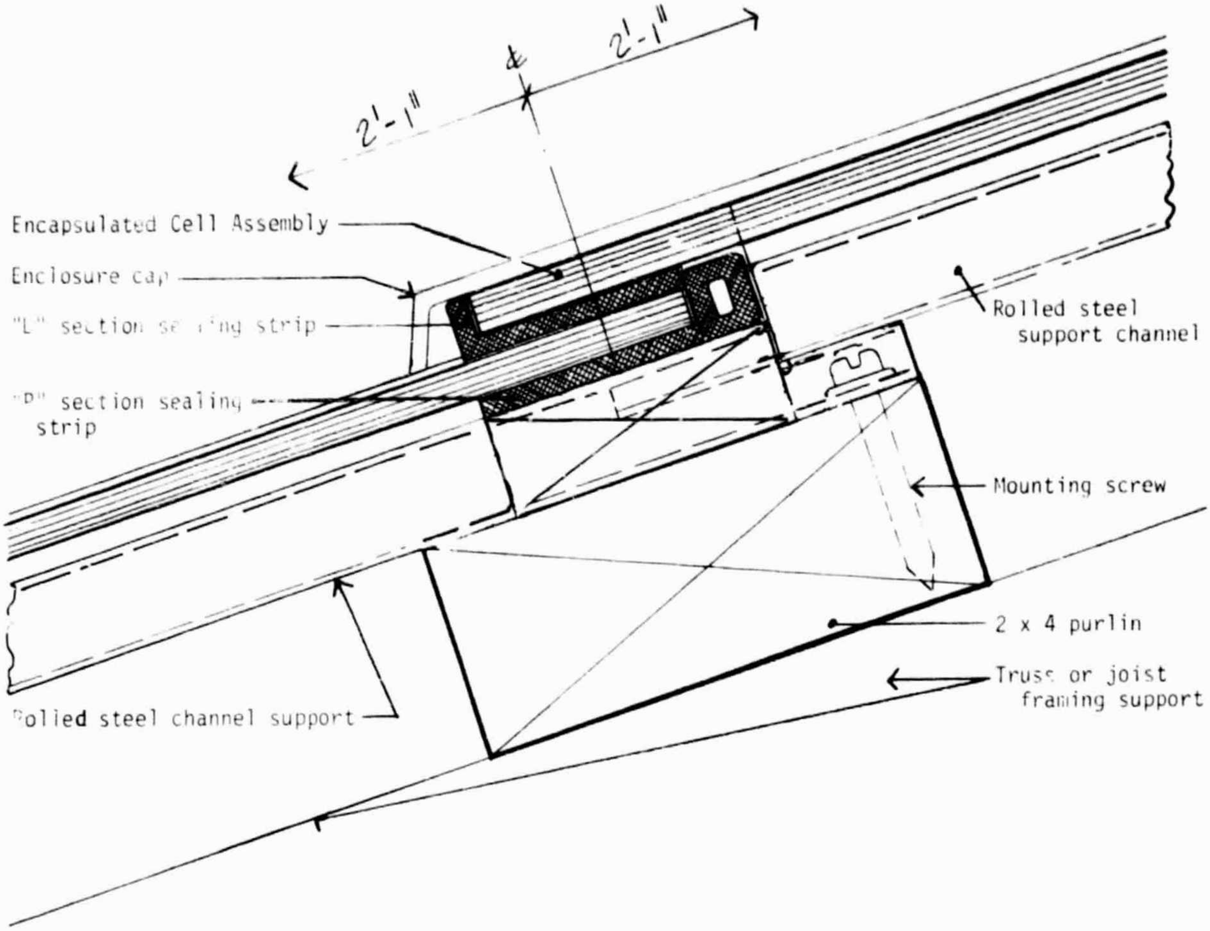
Desirable Module and Array Design Features

- UNIVERSALLY MOUNTABLE
- FUNCTIONALLY REDUNDANT WEATHER SEALS
- EASE OF MODULE REMOVAL/REPLACEMENT
- ACCOMMODATE LARGE DIFFERENTIAL LENGTH CHANGES DUE TO THERMAL AND HYGROSCOPIC EXPANSION/CONTRACTION

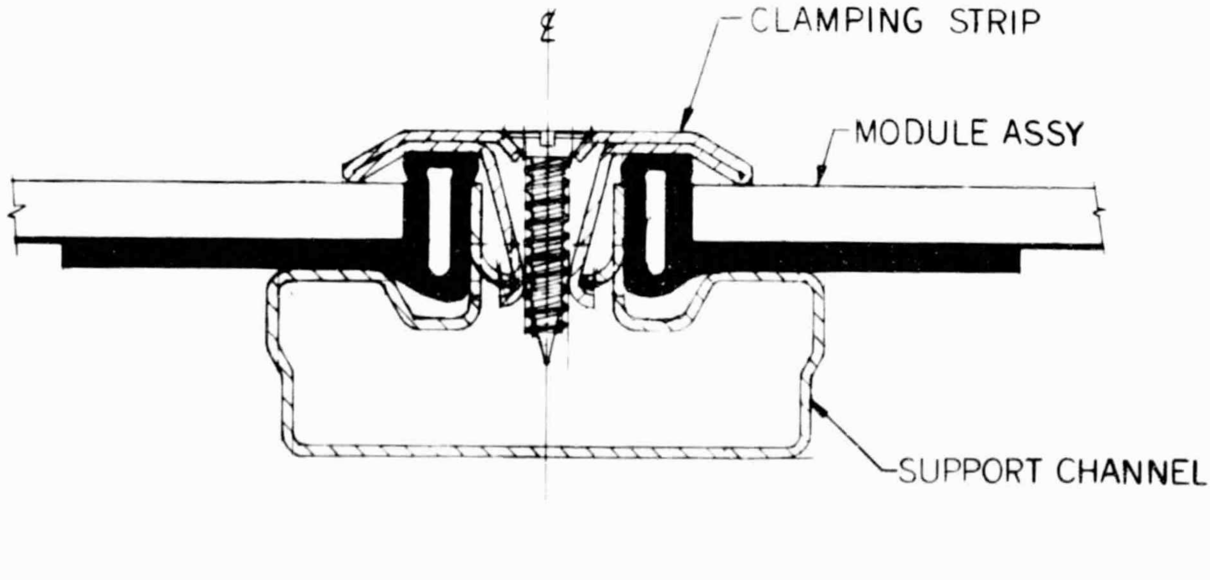
Selected Module and Array Design Concept



Overlapped Joint



Support Channel Joint



Selected Module Design and Performance Characteristics

Characteristic	Value
Solar Cell Size	100 mm square
Electrical Circuit Configuration	36 series x 2 parallel
Total Solar Cell Area per Module	0.7200 m^2
Module Area	0.8045 m^2
Module Packing Factor	0.895
Glass Superstrate	5 mm thick, Annealed Sunadex
Encapsulant	EVA
Rear Cover	Aluminum Foil/Korad Laminate
Number of By-Pass Diodes	3
Diode Type and Mounting	Chips integral with encapsulant laminate
Supporting Frame	None, rubber seal around perimeter
Module Maximum Power Output at Peak Power Conditions (100 mW/ cm^2 insolation and 25°C cell temperature)	97.2 W
Module Efficiency	12.1 percent

Summary of Production Parameters

PARAMETER	VALUE		
	LOWEST PRODUCTION RATE	MEDIAN PRODUCTION RATE	HIGHEST PRODUCTION RATE
MANPOWER (NO. OF EMPLOYEES)	13	11	39
FLOOR SPACE (FT^2)	3421	4720	36900
UTILITY SERVICES			
ELECTRICITY (KW)	23.0	31.5	340.5
AIR (CFM)	2.3	6.0	50.
WATER (GPM)	12.7	13.1	116.
EQUIPMENT COST (1980 $)	465,500	943,000	5,185,000
PROCESS YIELD (%)			
LAMINATION	98	98	98
FINAL ASSEMBLY	99.5	99.5	99.5
PLANT OPERATING HOURS PER YEAR	2376	7128	7128
ANNUAL PRODUCTION RATE (MODULES)	13,889	69,444	694,444

Direct Material Inventory

Item Description	Part Number	Quantity Required Per Module	Estimated Cost Per Module (1980 $)
Solar Cell	SVS10161	72	--
Glass Coverplate	47B258419P1	1	8.60
EVA	-	1.663 m^2	3.57
Craneglass	-	0.831 m^2	0.18
Primer	-	80 ml	0.85
Back Cover	47B258420P1	1	3.52
By-Pass Diode with Mounting Strap	-	3	4.02
Solarlok Bus Bar	-	2	0.26
Solarlok Housing	-	2	0.80
"L" Section Sealing Strip	47B258418P1	1	1.40
"P" Section Sealing Strip	47B258417P1	1	1.58
Insulator Strip	47B258425P1	3	0.15
Tin-Plated Copper Foil (75 μm thk)	-	0.09 m^2	0.41
Sealing Strip Bonding Adhesive	-	29 g	0.22
Solder	-	6 g	1.86
Protective Paper Tape	217 (3M)	0.047 m^2	0.08
		Total	27.50

Production Cost Methodology

Production Costs Are Calculated As The Sum Of (1980 $):

1. Direct Labor

$$= \frac{\text{(No. Of Employees) (Plant Operating Hours per Year) (1.25) (7.00)}}{\text{(Annual Production Rate)}}$$

2. 170 Percent Labor Overhead
3. Direct Material
4. 3 Percent Material Overhead
5. Cost of Capital Equipment

$$= \frac{\text{(Original Cost)}}{\text{(5 Yrs.) (Annual Production Rate)}}$$

6. Floor Space Rental

$$= \frac{\text{(5.50) (Floor Space Required - Ft}^2\text{)}}{\text{(Annual Production Rate)}}$$

7. Utility Services

(a) Electricity $= \dfrac{\text{(Power - kW) (Plant Oper. Hrs. per Yr.) (0.04)}}{\text{(Annual Production Rate)}}$

(b) Compressed Air Facility $= \dfrac{\text{(cfm) (20)}}{\text{(5 Yrs.) (Annual Production Rate)}}$

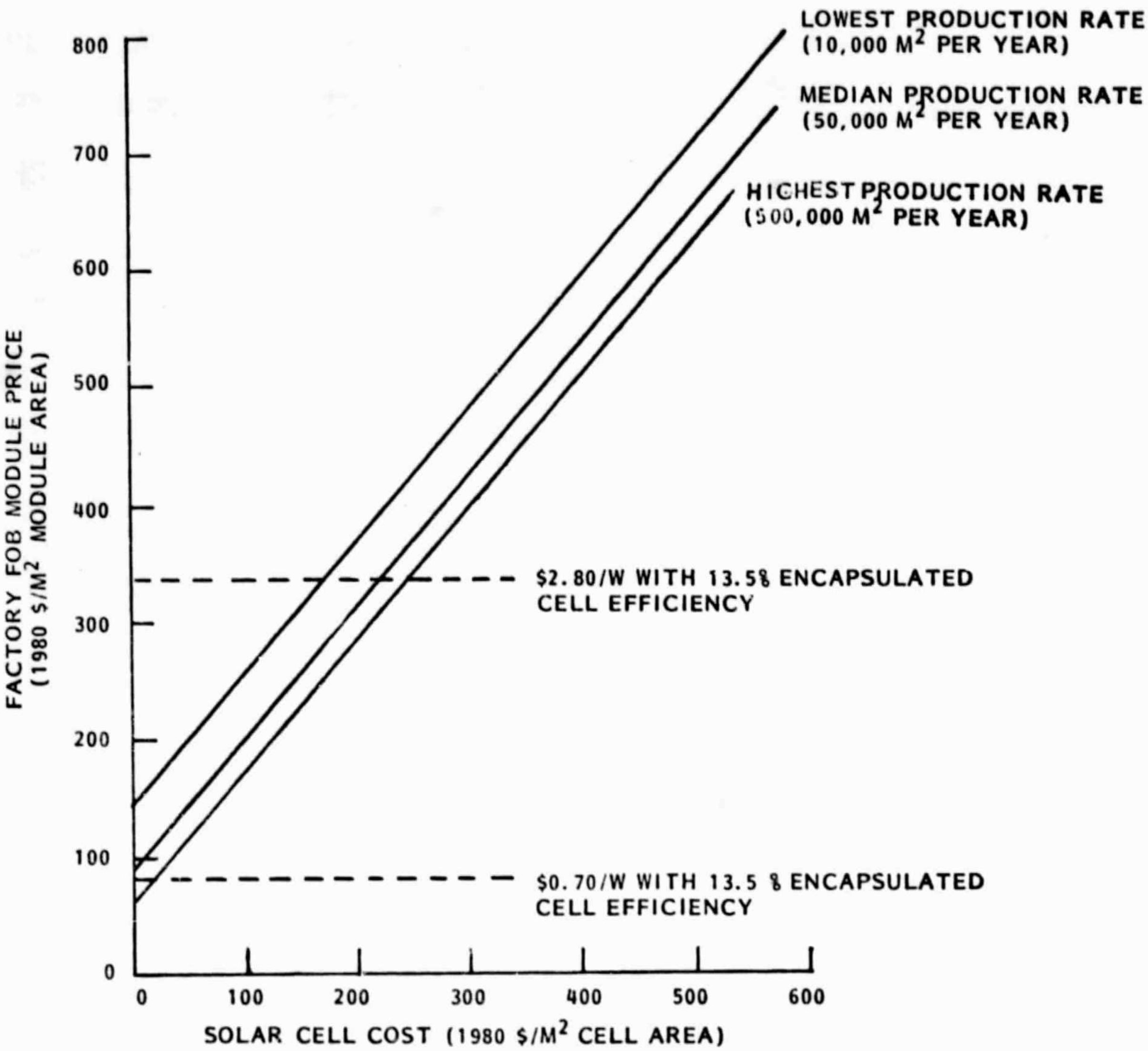
(c) Chilled Water Facility $= \dfrac{\text{(gpm) (17)}}{\text{(5 Yrs.) (Annual Production Rate)}}$

Production Cost Summary

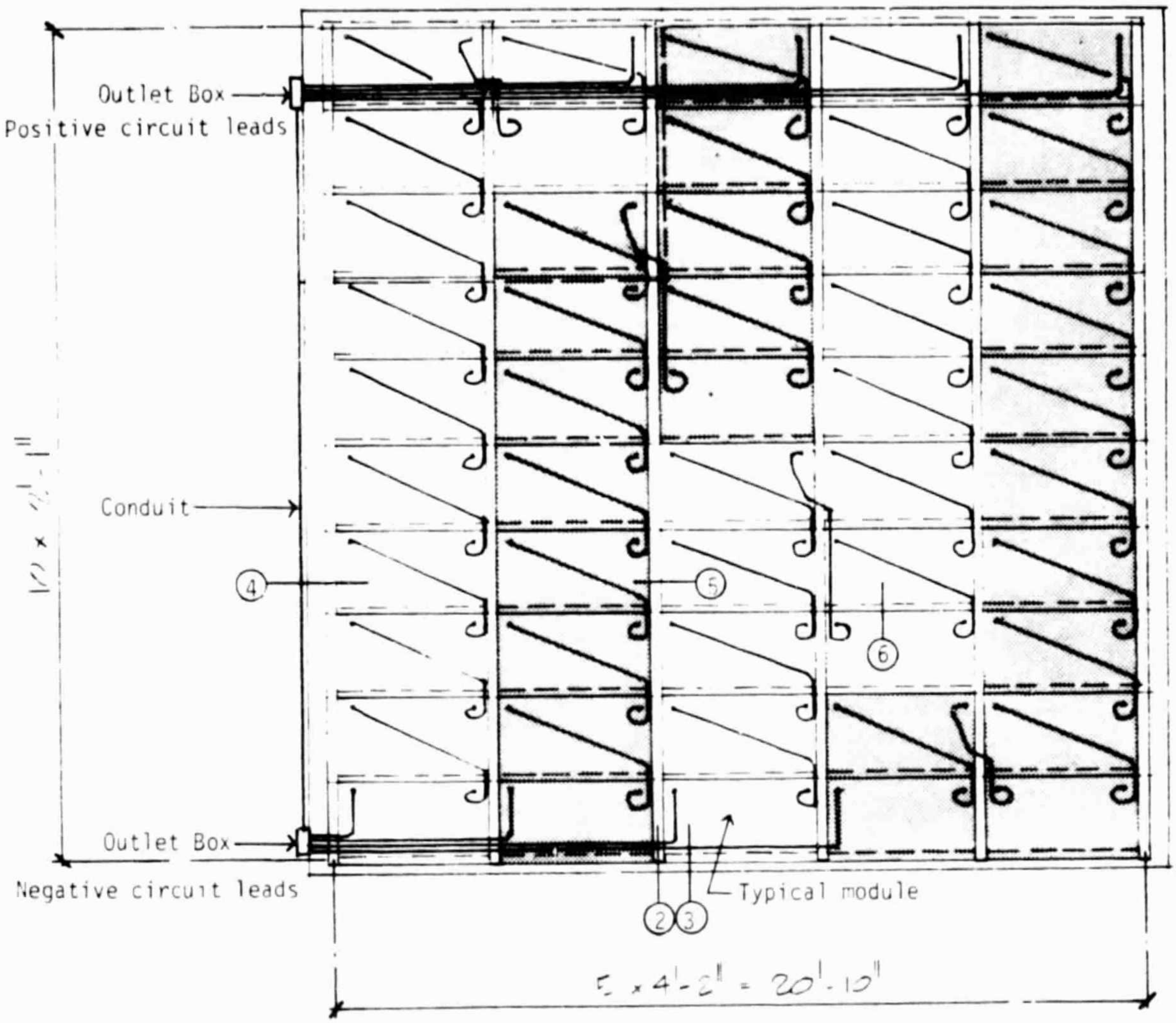
COST CATEGORY	1980 $ PER MODULE		
	LOWEST PRODUCTION RATE	MEDIAN PRODUCTION RATE	HIGHEST PRODUCTION RATE
DIRECT LABOR	19.46	9.88	3.50
LABOR OVERHEAD	33.08	16.80	5.95
COST OF CAPITAL EQUIPMENT	6.70	2.71	1.49
COST OF UTILITY SERVICES	0.16	0.13	0.14
FLOOR SPACE RENTAL	1.35	0.37	0.29
DIRECT MATERIAL *	33.74	28.12	25.31
MATERIAL OVERHEAD	1.01	0.84	0.76
SUBTOTAL	95.50	58.85	37.44
PROFIT AND WARRANTY (20%)	19.10	11.77	7.49
TOTAL FACTORY FOB PRICE	114.60	70.62	44.93

* DOES NOT INCLUDE THE COST OF SOLAR CELLS.

Module Production Cost Summary



Typical Residential Array

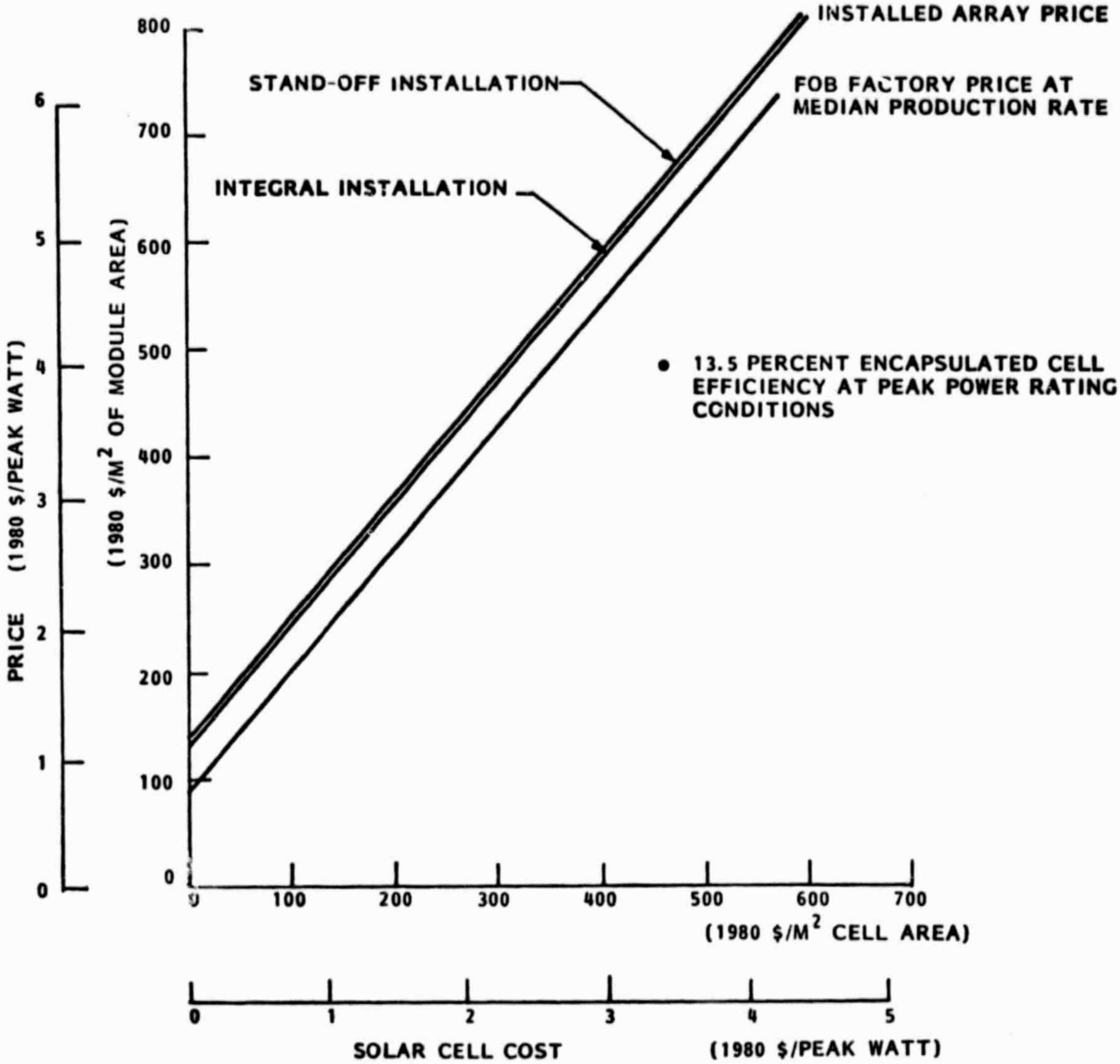


Installation Cost Estimate

INTEGRAL MOUNT

	Item Description	Quantity	Units	Unit Price (1980 $)	Total Cost (1980 $)	DIRECT	STAND-OFF
Material	Closure Strip	62	EA	1.75	109		
	Channel	70	EA	3.30	231		
	Horizontal Blocking	220	LF	0.38	84		
	Mounting Screws	2	LB	0.50	1		
	P Seal	50	LF	0.30	15		
	Double Sided Foam Tape (1/4" x 2")	24	LF	0.54	13		
	AMP Solarlok Harness						
	6' Double End	50	EA	2.50	125		
	12' Single End	5	EA	3.00	15		
	24' Single End	5	EA	4.25	21		
	CDX Plywood 3/8" Thk	2	SHT	10.00	20		
	CDX Plywood 1/2" Thk	0.5	SHT	12.50	6		
	Purlins (2 x 4 fir)	277	LF	0.24	66		
	Flashing - Black Aluminum						
	0.032" x 10" x 50'	2	RL	24.00	48		
	0.032" x 14" x 50'	0.5	RL	34.00	17		
	Eave Blocking 2" x 3"	22	LF	0.18	4		
	Conduit - 1" Dia.	20	LF	0.30	6		
	Outlet Box 4" x 4"	2	EA	2.00	4		
Labor	Set-up, Purlins, Blocking, Flashing, Plywood Substrate - 10 Hrs. Carpenter and Laborer @ $25.20/hr.				252		
	Layout, Set Supports, Lay-in Connectors, Set Panels, Set Covers, Check and Caulk - 4 Hrs. Glazier and Carpenter @ $30.80/hr.				123		
	Set Outlet Boxes, Connect Panels and Check - 2 Hrs. Electrician and Helper @ $37.00/hr.				74		
	Subtotal				1234	1429	1601
	Overhead and Profit (20%)				247	286	320
	Warranty				100	—	—
	Total Installation Cost				1581	1715	1921

Installed Array Price vs Solar Cell Cost



Installed Price Breakdown

Item	Price (1980 $/watt)	Fraction of Total Installed Price
Solar Cells	2.00	0.56
Balance of Module Assembly	1.26	0.35
Total Module FOB Factory Price	3.26	0.91
Installation Price (Integral Mount)	0.32	0.09
Total Installed Array Price	3.58	1.00

Conclusions

- LOW MATERIAL CONTENT AND SIMPLE INSTALLATION METHODS ARE THE KEYS TO MINIMUM COST
- INTEGRAL MOUNTING YIELDS THE LOWEST INSTALLATION COST
- THE FEASIBILITY OF THE SELECTED CONCEPT HAS BEEN DEMONSTRATED BY THE CONSTRUCTION OF A FULL-SIZE MODEL

ARRAY GROUNDING AND ELECTRICAL SAFETY

UNDERWRITERS LABORATORIES

A. Levins

Introduction

- **National Electrical Code**
  - **NEC Organization**
  - **AD HOC Subcommittee Membership**
  - **Solar Photovoltaic Systems: Article 690 — Proposal Summary**
- **Components for Array Safety Systems**
  - **Ground-Fault Detection**
  - **Bypass Diodes**
  - **Arc Detection**

NEC Organization

Chapter	Title	Chapter	Title
–	Introduction	5	Special Occupancies
1	General	6	Special Equipment
2	Wiring Design and Protection	7	Special Conditions
3	Wiring Methods and Materials	8	Communications Systems
4	Equipment For General Use	9	Tables and Examples

AD HOC Subcommittees

- Solar Photovoltaics 690
- Cogeneration 705
- Fiber Optics
- (Others)

NEC Correlating Committee

- Panel 1 Art. 90, 100, 110...
- Panel 2 Art. 210, 215,...9...
- Panel 3 Art. 300, 305, 690...
- (Others)

Ad Hoc Subcommittee Membership

Connector Manufacturers	2
Fuse Manufacturers	1
PV Module Manufacturers (And System Installers)	2
Utilities	1
Government Laboratories	3
Independent Laboratory	1
Contractor Association	1
Commercial Development Laboratory	1
Other	1

Also, Representatives From Independent Laboratories, Government Laboratories, Utilities, and PV Module Manufacturers Attended as Guests.

Solar PV Systems Article 690 Proposal Summary

- Scope
  - Types of Systems: Interactive or Stand-Alone; with or without storage; ac or dc
  - Technologies: Flate-Plate and Concentrator
- Definitions – Adds New Terms: PV Source Circuit; PV Output Circuit; PV Power Source
- Installation – Permits a PV System in Addition to Any Other Service(s)
- Voltage Limitations – Apply to ac and dc
  - Open-Circuit Voltage: Measurement Conditions on Component Parts Not Specified
  - Site-Dependent: More Stringent for One- and Two-Family Residences (User Contact More Likely)
  - Direct Use of Array Voltage: 150 V to Ground
  - "Shall Be Permitted Up to 600 V"

- **Grounding**
  - **Frames (Dead Metal) Grounded**
  - **Circuit Grounded But Permits a System Using Acceptable Ungrounded Equipment**
  - **No Restrictions on the Location of System Ground**
  - **Size of Equipment Grounding Conductor Specified**
- **Marking**
  - **Modules: Factory Affixed; Voltage, Current, Power**
  - **Systems: Installer Affixed; Voltage, Current**
- **Interconnection With Other Sources**
  - **Automatic Disconnect From Utility Due to Loss of Utility or Off-Normal Conditions**
  - **Ampacity of Neutral**
  - **Single Three-Phase Interconnections Not Permitted Where Imbalance is Likely**
- **Circuit Sizing, Current, Overcurrent Protection:**
  - **Recognizes That Conductor Protection May Be Achieved Without Fuses or Circuit Breakers**
  - **Considers 80% Continuous Current Ratings of Most Overcurrent Devices**
  - **Includes Protection Provisions When Circuits May Be Energized From More Than One Source**
  - **Describes Protection For Parts and Conductors From Backfeed (Utility)**
- **Disconnection Means Provided:**
  - **Between Array and All Building Wiring**
  - **To Enable Safe Replacement of Fuses**
  - **To Disable an Array**
- **Wiring Systems That Are:**
  - **Currently Accepted Within Allowed Conditions**
  - **Developed Specifically for PV Systems**

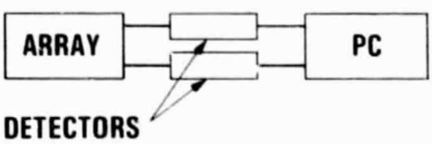
Components for Array Safety Systems

Ground-Fault Detection

- **Transformer or Transformerless Inverters**
- **Insensitive to Nuisance Tripping (dc Protection for $\approx$ 30 mA)**
- **Open Ground, Short-Circuit Array, Segment Array**
- **Installed Indoors (Protected Location)**
- **Experimental Device at MIT/LL NE RES**

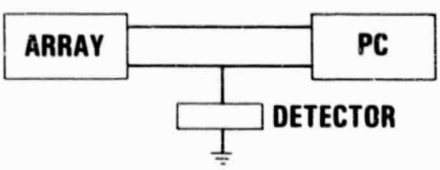
Differential

- **Transformerless Inverter**
- **Can Function With Extra Ground**
- **Permits Segmenting Array**



Direct Ground

- **Simple**
- **Load Current Does Not Pass Through Device**



Bypass Diodes (External to Modules)

- **Adaptable to Any System**
- **Multiple Functions**
  - **Allow Installation/Removal of Modules**
  - **Reduces Probability of Arcing**
  - **Minimizes Hot-Spot Heating**

Arc Detection

- **Dependent on Location Relative to Point of Arc**
  - **Attenuation of Signal Through System**
  - **Susceptible to Line Noise From PC**
- **Theoretically Susceptible to Electromagnetic Energy Sources**
- **Device Built: Functioned, But Very Dependent on Location**

Conclusions

- **NEC-Proposed Article 690**
  - **Assigned to Panel 3**
  - **Will Be Discussed in January 1982**
- **Safety System Components**
  - **Most Feasible**
    - **Ground-Fault Detector**
    - **Bypass Diodes**
  - **Difficult to Implement**
    - **Arc Detectors**

PHOTOVOLTAIC ARRAY – POWER CONDITIONER INTERFACE REQUIREMENTS STUDIES

JET PROPULSION LABORATORY

C. Gonzalez

Objective

To Determine the Power Conditioner-Array Interface Requirements:

- **Select Power Conditioner Operational Mode and Parameters**
  - **Fixed-Voltage Operation**
  - **Tracking Parameters to Obtain Maximum Array Power**

- **Select Power Conditioner Maximum Power, Current, and Voltage Limits**

- **Determine Effects of Array Degradation on Selection of Power Conditioner Operational Mode and Parameters**

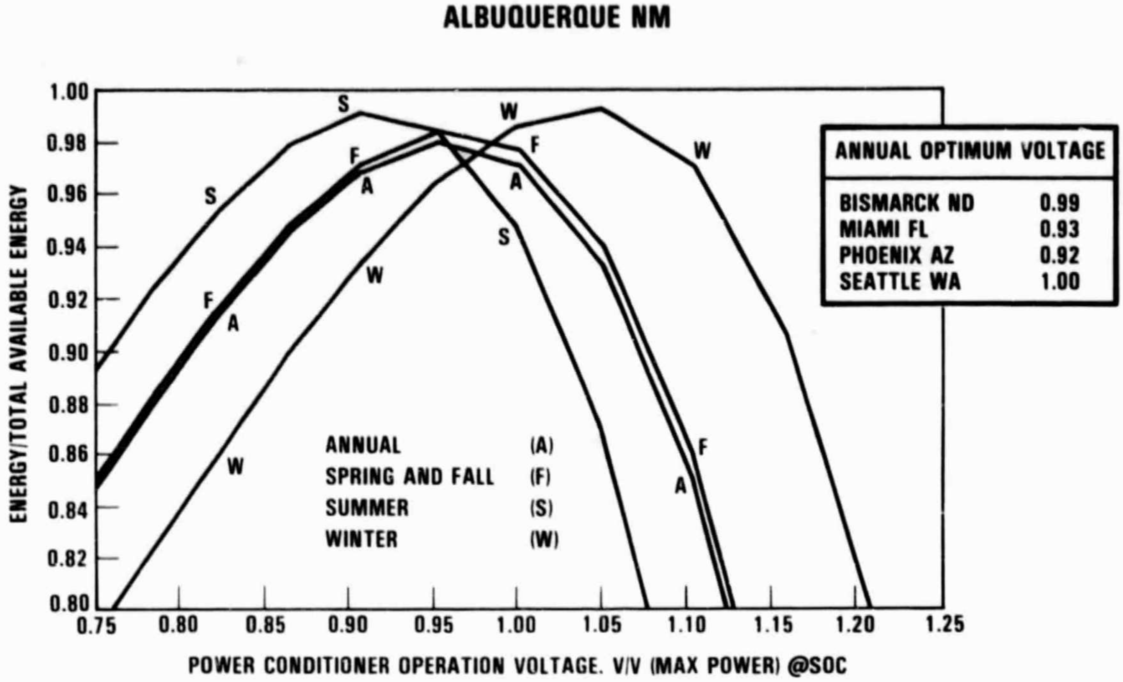
Approach

- **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)**

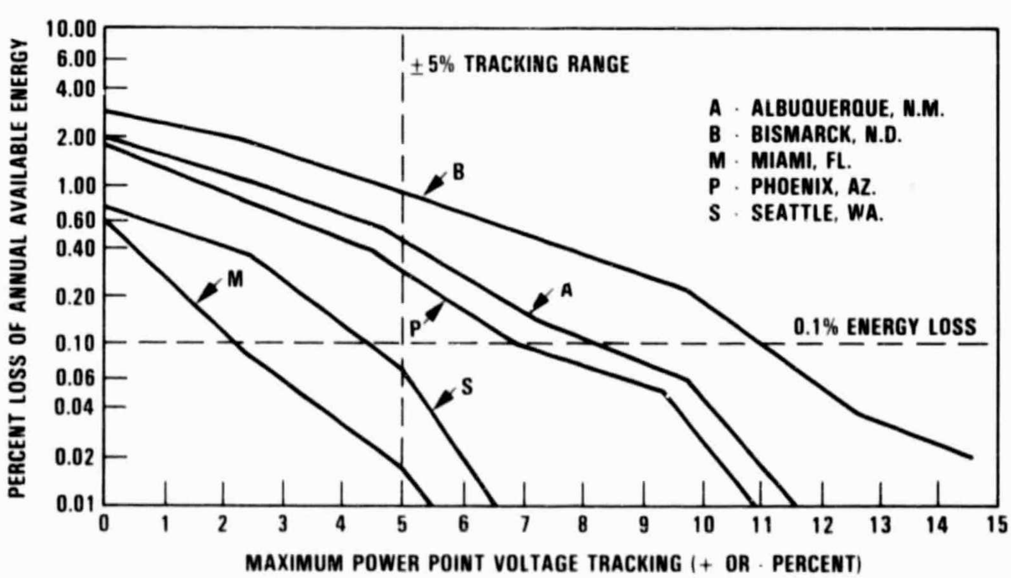
Cases Analyzed

- **Fraction of Available Energy:**
  - **For Fixed Voltage Power Conditioner, With and Without Seasonal Adjustment**
  - **Vs Power Conditioner Tracking Range**
  - **Vs Maximum Operational Power and Current Limits for Two Strategies**
    - **Rejection of All Array Power When Limits Are Exceeded**
    - **Partial Rejection of Power When Limits Are Exceeded**
- **Maximum Expected Open-Circuit Voltage**

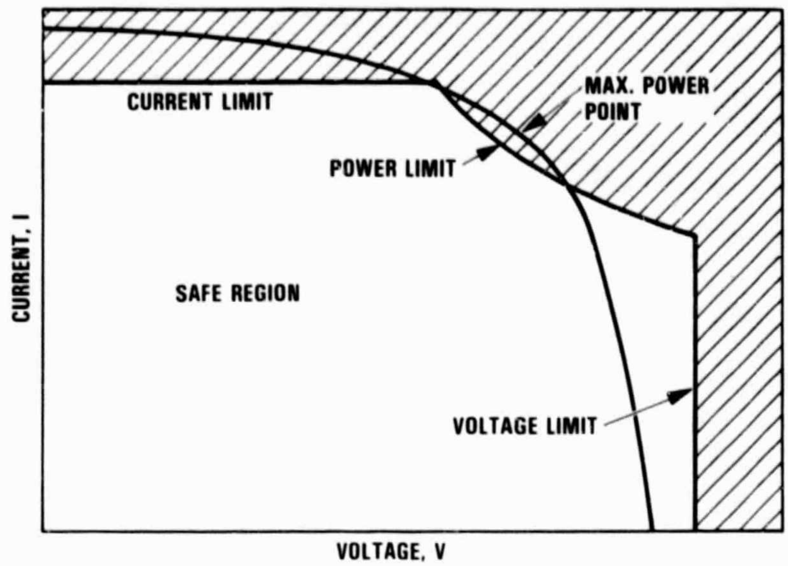
Fraction of Available Energy for Fixed-Voltage Power Conditioner



Annual Energy Losses vs Power-Conditioner Voltage Tracking Range

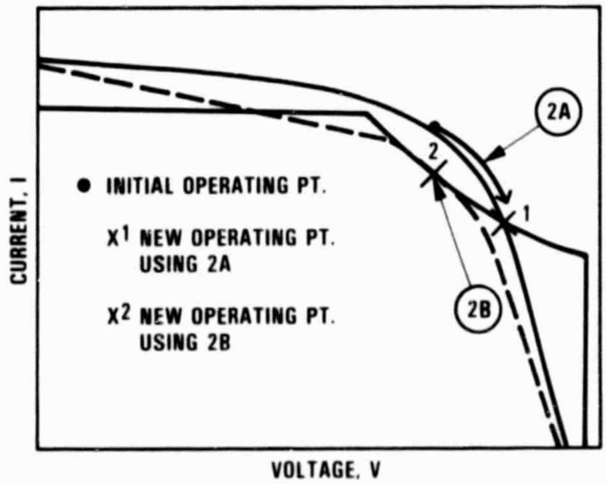


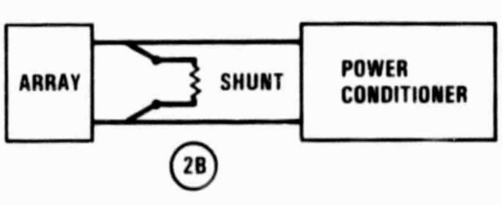
Power Conditioner Maximum Operating Limits



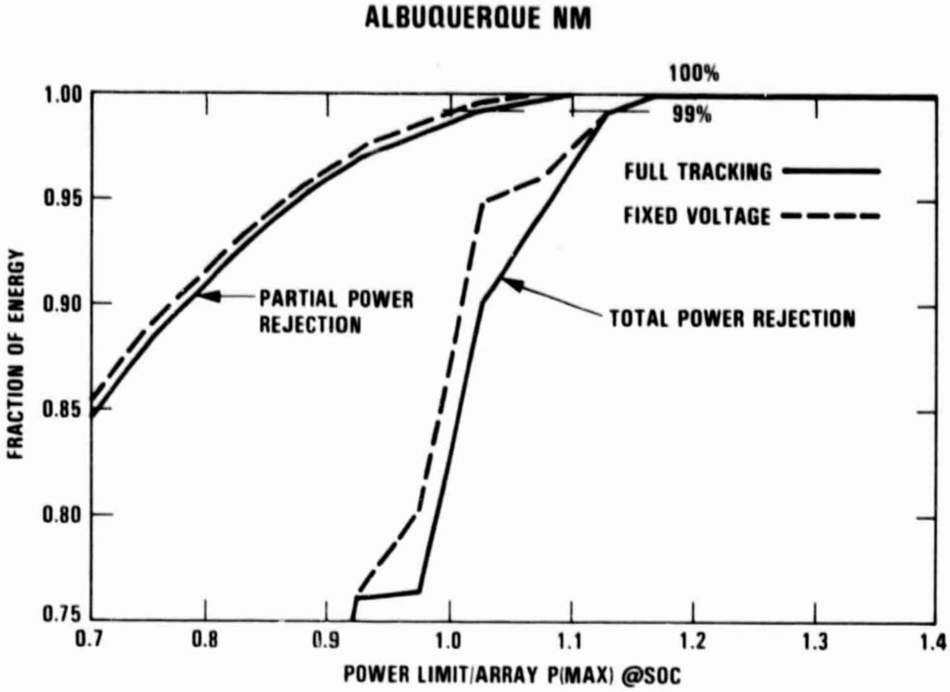
Array Power Output vs Power and Current Limits

- **Algorithms Simulate Two Strategies When Limits Are Exceeded**
  - **Strategy 1: Total Rejection of All Array Power**
  - **Strategy 2: Partial Rejection of Array Power**
    - **2A: Move Off Maximum Power Point**
    - **2B: Use of Shunt to Dissipate Excess Power**





Fraction of Annual Array Energy vs Power-Conditioner Power Limit



Array Power and Current Limits Required to Obtain a Given Percentage of Available Energy

	TOTAL POWER REJECTION		PARTIAL POWER REJECTION			
SITE	99%		99%		100%	
	POWER LIMIT	CURRENT LIMIT	POWER LIMIT	CURRENT LIMIT	POWER LIMIT	CURRENT LIMIT
ALBUQUERQUE NM	1.13	1.17	1.03	1.06	1.13	1.18
BISMARCK ND	1.10	1.06	0.95	0.95	1.08	1.08
MIAMI FL	0.93	1.00	0.81	0.85	0.92	1.00
PHOENIX AZ	1.04	1.13	0.91	0.99	1.00	1.13
SEATTLE WA	0.93	0.92	0.85	0.87	0.93	0.93

Maximum Open-Circuit Voltage

- **Lower Limit**
  - **Combination of Cell Temperature and Irradiance That Gives Largest Voc**
- **Upper Limit**
  - **Lowest Annual Temperature on TMY Tape Combined With 100 mW/cm^2**

Site	Lower Limit	Upper Limit
Albuquerque NM	1.67	1.80
Bismarck ND	1.83	1.91
Miami FL	1.57	1.71
Phoenix AZ	1.59	1.74
Seattle WA	1.61	1.71

Conclusions

- **Site-to-Site Variations**
  - **Optimum Voltage: 0.92 - 1.01**
  - **Advantages of Voltage Tracking: 0.5% - 3% Gain in Annual Energy**
  - **Maximum Power and Current Limits**
    - **Variations in Upper Limits to Obtain 99% of Available Energy With the Two Strategies Are Uniform (15% Higher for Total Rejection of Power)**
  - **Maximum Open-Circuit Voltage: Upper Limit Variation about 10%**

Ongoing Work

- **Extend Analyses to Determine Impact of Changing I-V Curve (Fill Factor)**
  - **Modules With "Soft" or "Sharp" I-V Curves Compared to Nominal**
  - **Arrays With Degraded Modules**

BYPASS DIODE INTEGRATION

GENERAL ELECTRIC

N. F. Shepard

Task Work Scope

- ESTABLISH BY-PASS DIODE REQUIREMENTS FOR PHOTOVOLTAIC MODULES RANGING IN SIZE FROM 2'X4' TO 4'X8'
- DETERMINE COMMERCIALLY AVAILABLE PACKAGED AND CHIP FORM DIODES
- DEFINE PHYSICAL AND OPERATIONAL CHARACTERISTICS OF TYPICAL PACKAGED AND CHIP DIODES
- DEVELOP DIODE/HEAT SPREADER MOUNTING CONCEPTS FOR PHOTOVOLTAIC MODULES
- ANALYZE THE HEAT DISSIPATION CAPABILITY OF EACH MOUNTING CONCEPT
- EVALUATE THE FACTORS AFFECTING DIODE RELIABILITY

Diode Manufacturers Canvassed

- Alpha Industries
- American Power Devices
- Amperex Electronic
- Baytron
- Collmer Semiconductors/Fuji Electric
- Cherry Semiconductor
- Crimson Semiconductor
- Diode Transistors
- EDAL Industries
- EDI Electronic Devices
- Eaton Corp - Addington Semiconductor
- Ferranti Electric
- Fairchild Semiconductor Products
- FMC - Semiconductor Products
- GE - Electronic Component Sales
- General Instruments Discrete Semiconductors
- General Semiconductors
- GTE/Sylvania Semiconductor Products
- Hitachi America
- International Diode
- International Rectifier
- ITT Semiconductors
- Microwave Associates
- Motorola Semiconductor Products
- NAE
- NEC Electron
- PPC Products
- Parametric Industries
- RCA - Solid State
- Semicon
- Semitronics
- Solitron Devices
- Solid State Devices
- ST - Semicon
- Schauer
- Siemens - Colorado Components
- Sprague Electric
- Shigoto Far East
- Teledyne - Crystalonics
- Texas Instruments - Semiconductor Products
- Thompson CSF Components - Semiconductors
- Toshiba Semiconductors
- TRW - Power Semiconductor
- Unitrode
- Varo Semiconductor
- Westinghouse - Semiconductor

Typical Characteristics

PN JUNCTION DIODES

- MAX. JUNCTION TEMP. = 175°C (ZERO CURRENT CARRYING CAPACITY)
- REVERSE BLOCKING VOLTAGE = 50 V
- REVERSE CURRENT = 1 μA TO 10 MA
- FORWARD VOLTAGE DROP = .9 TO 1.2 V

SCHOTTKY DIODES

- MAX. JUNCTION TEMP. = 150°C (ZERO CURRENT CARRYING CAPACITY)*
- REVERSE BLOCKING VOLTAGE = 20 V
- REVERSE CURRENT = 400 μA TO 400 MA
- FORWARD VOLTAGE DROP = .5 TO .6 V

* SOME MANUFACTURERS HAVE DEVELOPED PROCESSES THAT HAVE RAISED THIS LIMIT TO 175°C

Packaged Diode Manufacturers, Forward Current = 5 to 75 Amperes

MANUFACTURER	FORWARD CURRENT RANGE (A)	SILICON PN JUNCTION	SCHOTTKY BARRIER
1. EDAL EAST HAVEN, CT	5-45	X	
2. GENERAL ELECTRIC ELECTRONIC COMPONENT SALES AUBURN, NY	5-40	X	
3. GENERAL INSTRUMENT HICKSVILLE, NY	5-25	X	X
4. NAE LYNN, MA	3-60	X	X
5. INTERNATIONAL RECTIFIER EL SEGUNDO, CA	6-60	X	X
6. MOTOROLA SEMICONDUCTOR PHOENIX, AZ	6-60	X	X
7. MICROWAVE ASSOCIATES BURLINGTON, MA	30-60		X
8. SEIMANS COLORADO COMPONENTS BROOMFIELD, CO	12-60	X	X
9. SEMICON BURLINGTON, MA	5-75	X	X
10. SOLITRON SAN DIEGO, CA (PN) RIVIERA BEACH, FL (SCHOTTKY)	5-40	X	X
11. ST - SEMICON BLOOMINGTON, IN	6-50	X	
12. TRW SEMICONDUCTOR LAWNDALE, CA	25-60		X
13. UNITRODE LEXINGTON, MA	7-60	X	X
14. VARO GARLAND, TX	5-60		X

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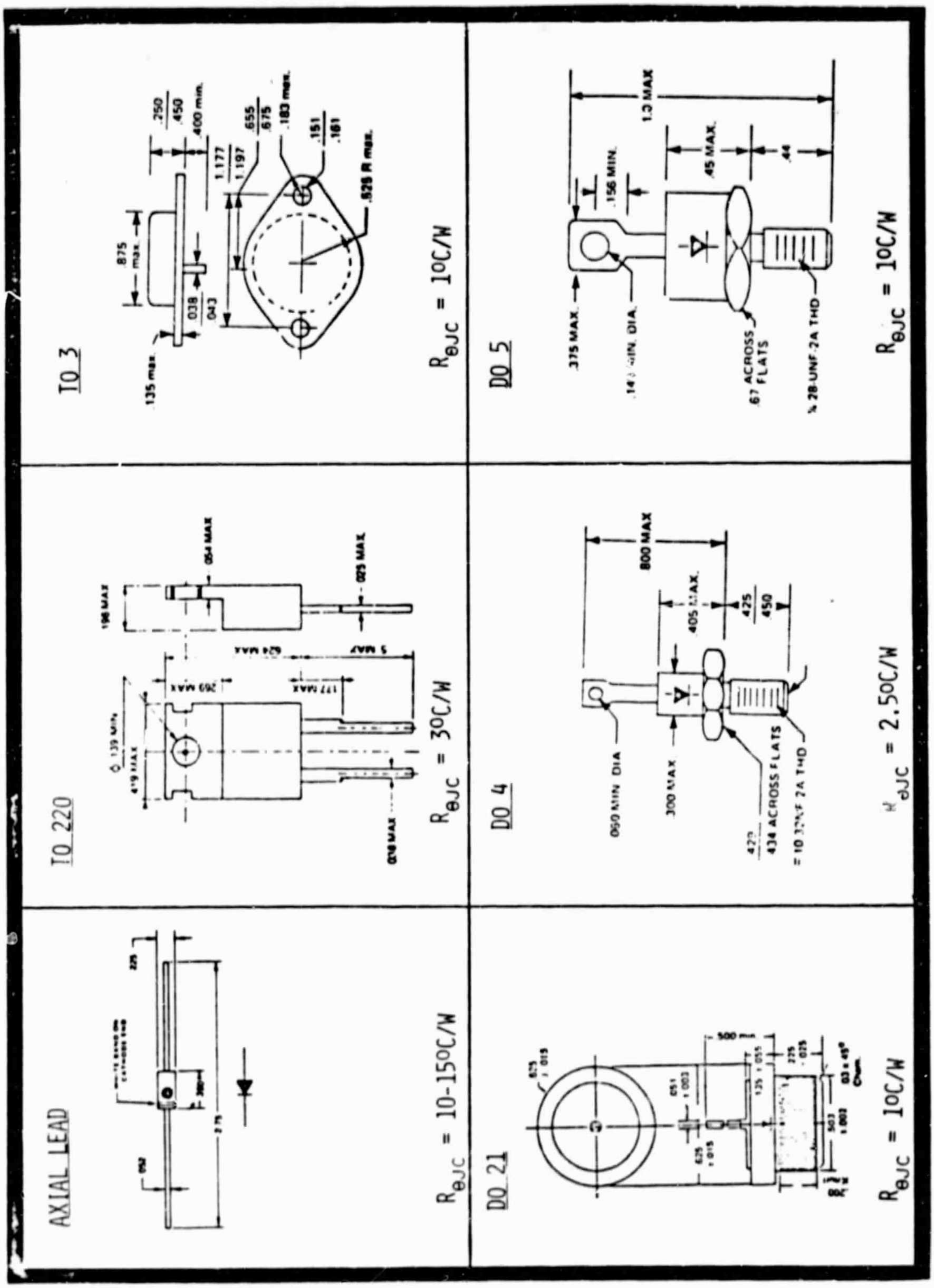
Applicable Packaged Diodes



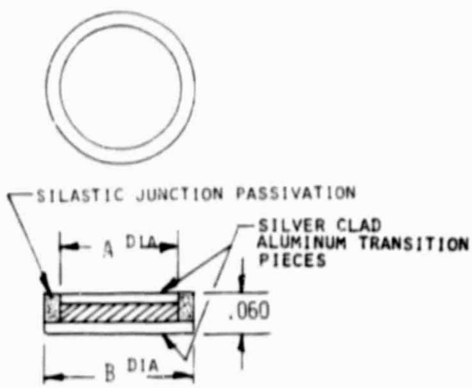
Potential Diode Chip Suppliers

COMPANY	CHIP TYPE
• UNITRODE	PN JUNCTION AND SCHOTTKY
• VARO SEMICONDUCTOR	SCHOTTKY
• INTERNATIONAL RECTIFIER	PN JUNCTION AND SCHOTTKY
• SEMICON	PN JUNCTION AND SCHOTTKY
• NAE	PN JUNCTION AND SCHOTTKY (LIMITED TYPES)
• MICROWAVE ASSOCIATES	SCHOTTKY
• GENERAL INSTRUMENTS - DISCRETE SEMICONDUCTORS	PN JUNCTION (LIMITED TYPES)
• TRW - POWER SEMICONDUCTOR	SCHOTTKY
• MOTOROLA SEMICONDUCTOR	SCHOTTKY

Silicon pn Diode Chip Characteristics

- MAX JUNCTION TEMP ($T_{J\ MAX}$) = 175°C (ZERO CURRENT CARRYING CAPACITY)
- MAX. REVERSE VOLTAGE (V_R) = 50V
- MAXIMUM REVERSE CURRENT (I_R) = 1 μA TO 10 MA
- TYPICAL FORWARD VOLTAGE DROP (I_F) = 1 TO 1.2V

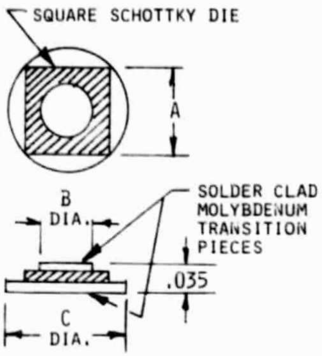
APPROXIMATE CURRENT CARRYING CAPACITY (I_F) (AMPS)	APPROXIMATE THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	CHIP DIMENSIONS (INCHES)	
		A	B
12	2.5	.120	.140
20	1.0	.140	.160
25	1.0	.200 (SQUARE)	.220
35-50	1.0	.200	.220



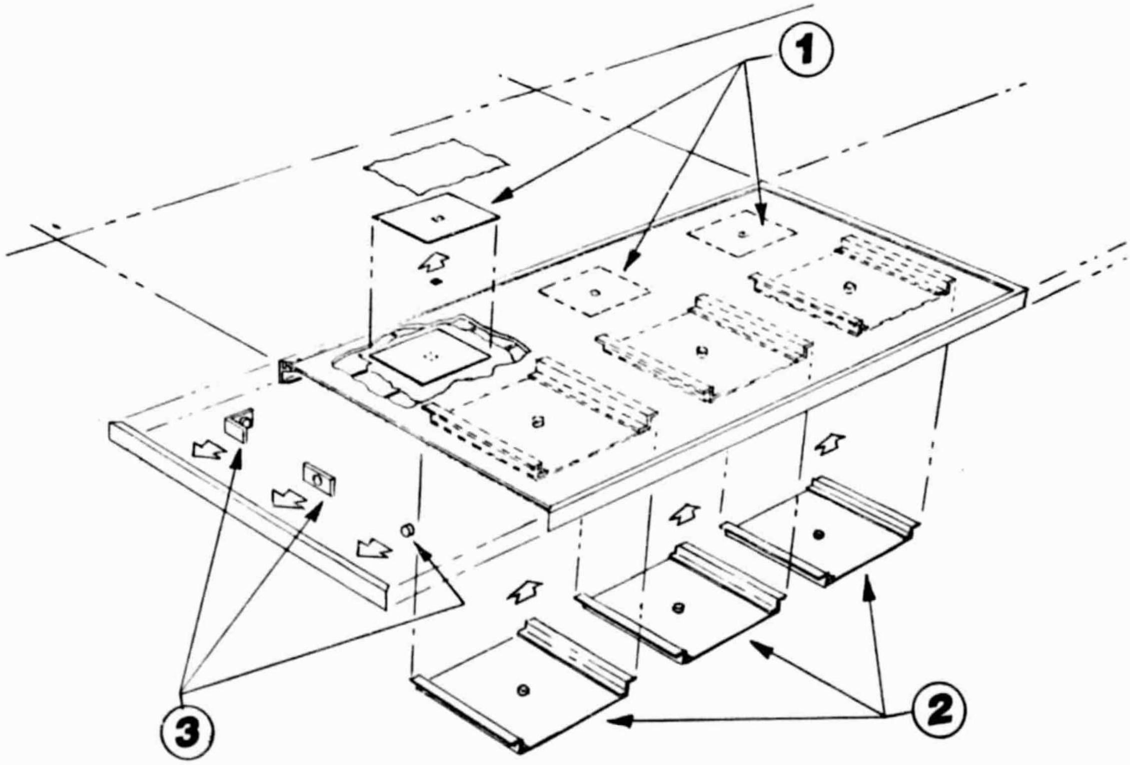
Schottky Diode Chip Characteristics

- MAX JUNCTION TEMP ($T_{J\ MAX}$) = 150°C (ZERO CURRENT CARRYING CAPACITY)
- MAX REVERSE VOLTAGE (V_R) = 20V
- MAXIMUM REVERSE CURRENT (I_R) = 400 µA TO 400 MA
- TYPICAL FORWARD VOLTAGE DROP (I_F) = 0.5 TO 0.6V

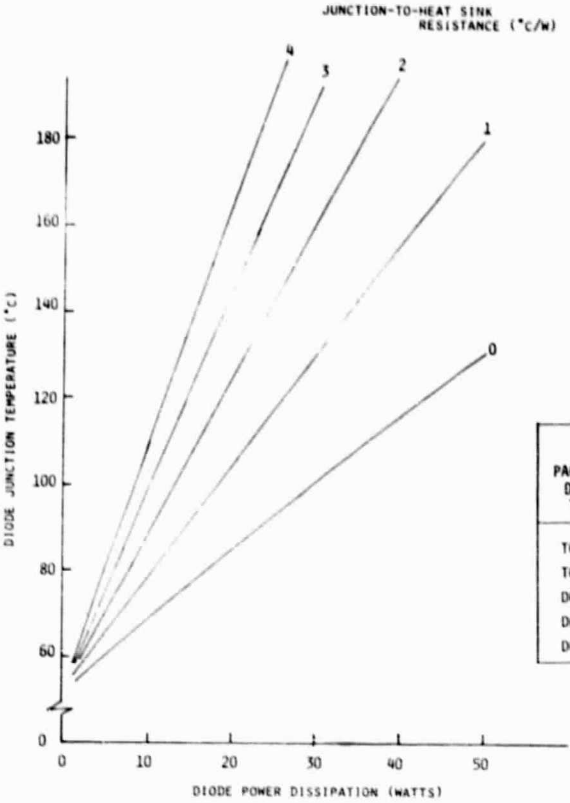
AVG. FORWARD CURRENT RATING (I_F) (AMPS)	APPROXIMATE THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	CHIP DIMENSIONS (INCHES) A	B	C
15	2.5	.125	.100	.180
30	2.0	.160	.140	.230
50	1.0	.200	.175	.250

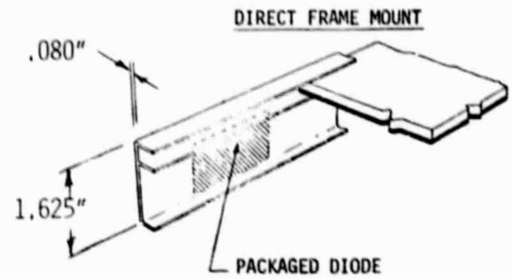


Diode Mounting Configurations



Thermal Analysis: Frame-Mounted Packaged Diode





PACKAGED DIODE TYPE	TYPICAL MAXIMUM POWER LEVEL W	ESTIMATED THERMAL RESISTANCE, °C/W		
		JUNCTION TO CASE (MFG. SPEC. DATA)	CASE TO HEAT SINK (ESTIMATED)	JUNCTION TO HEAT SINK
TO3	30	1.0	0.14	1.14
TO220	15	3.0	0.20	3.20
DO4	20	2.0	0.10	2.10
DO5	40	1.0	0.10	1.10
DO21	30	1.0	1.5	2.5

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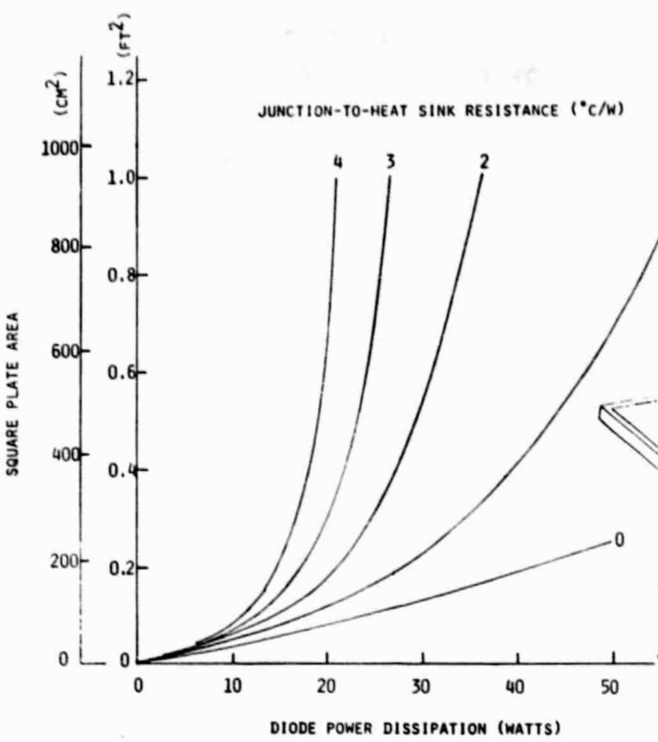
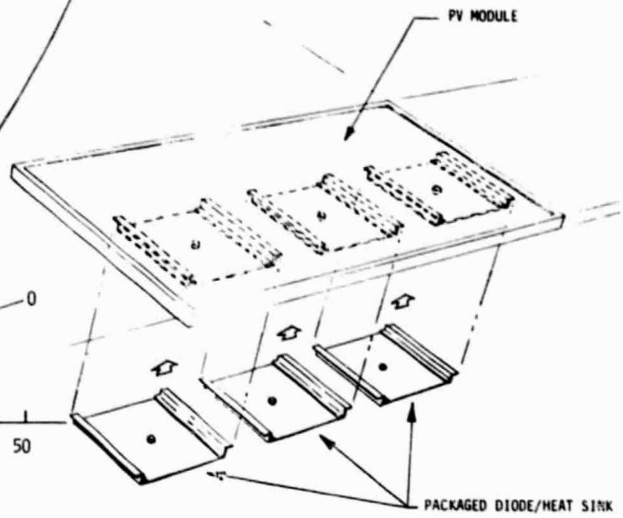
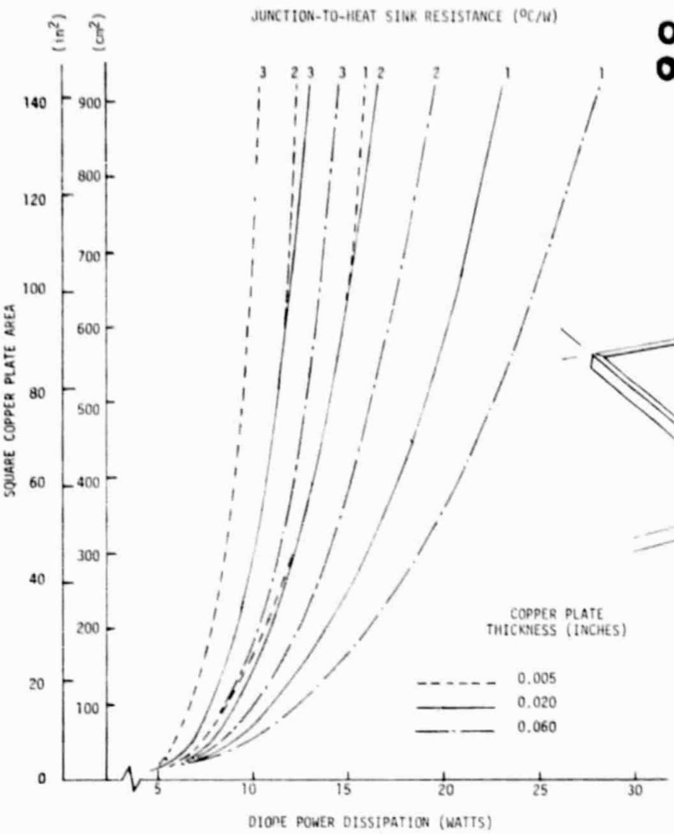
Thermal Analysis: Rear-Side-Mounted Packaged Diode

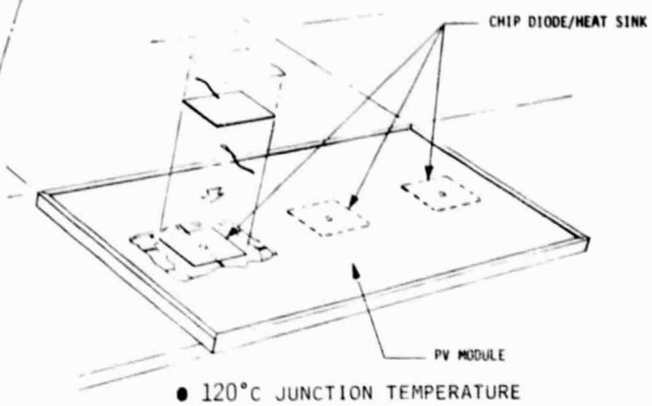


- DIODE JUNCTION TEMP = 150°C
- VALUES SHOWN APPLY FOR 0.125" COPPER OR 0.250" ALUMINUM
- HEAT SINK EMISSIVITY ϵ_S = 0.85
- SINK MOUNTED ON UNDERSIDE OF STAND-OFF MODULE-AMBIENT TEMP = 50°C



Thermal Analysis: Encapsulated Copper Plate With Diode Chip





- 120°C JUNCTION TEMPERATURE

Conclusions

- DIODE CHIPS ENCAPSULATED WITHIN THE MODULE LAMINATE OFFER MANY INTEGRATION ADVANTAGES

- SCHOTTKY DIODES ARE IDEALLY MATCHED TO BY-PASS APPLICATIONS (LOW FORWARD VOLTAGE DROP AND ADEQUATELY HIGH REVERSE BLOCKING VOLTAGE), BUT ARE PRICED HIGHER THAN PN JUNCTION DEVICES

- FURTHER WORK IS NEEDED TO DEVELOP ENCAPSULATED CHIP PACKAGING WITHIN PHOTOVOLTAIC MODULES

INTERCONNECT FATIGUE UPDATE

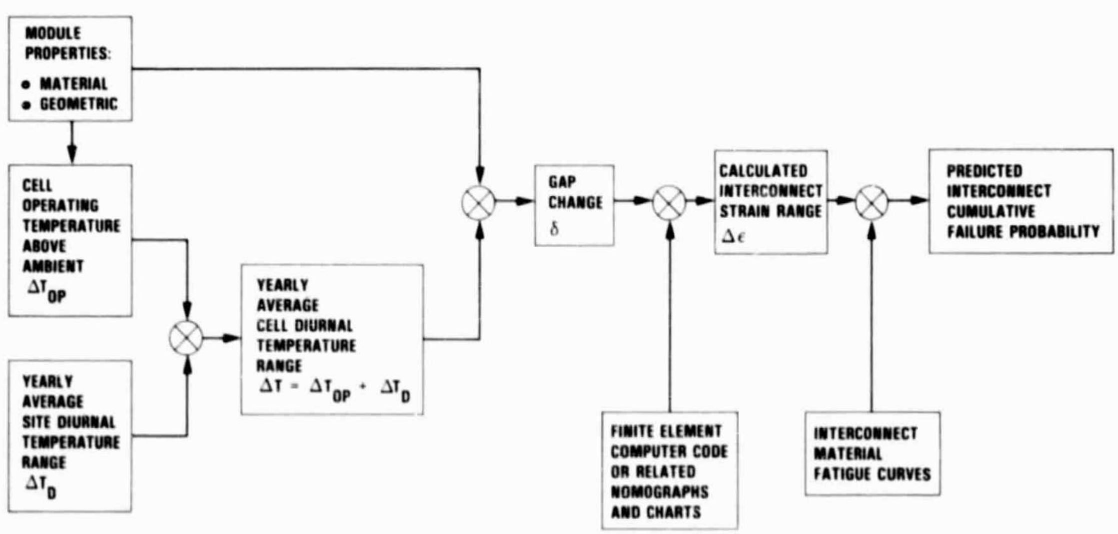
JET PROPULSION LABORATORY

G.R. Mon

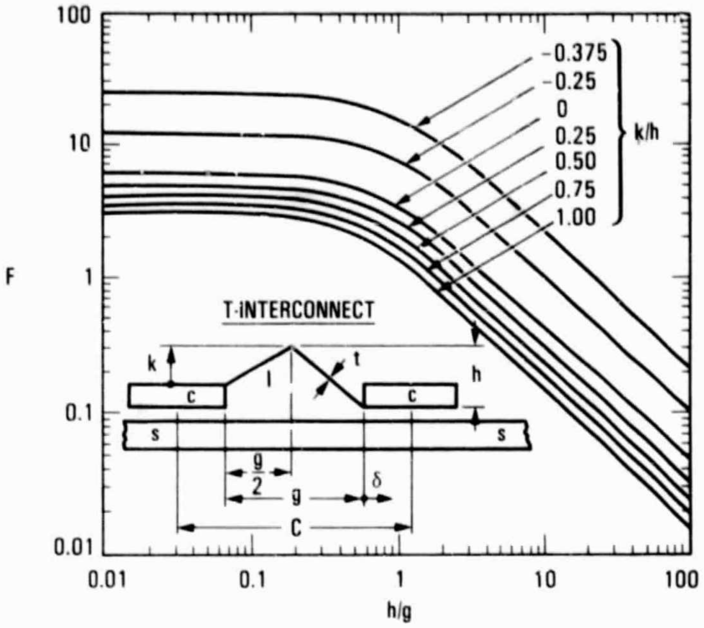
Summary

- **Overview of Interconnect Fatigue Design Problem**
  - **Interconnect Failure Prediction**
    - **Strain Computation Nomographs**
    - **Statistical Fatigue Curves**
- **Quantification of Thermal Cycling Qualification Test Results**
  - **Determination of Test Pass-Fail Threshold**
  - **Interpretation of Test Data**
- **Performance Comparison of Interconnect Materials**
  - **Experimental Fatigue Curves**
  - **Comparison of Predicted Life for Equivalent Electrical Performance**

Interconnect Failure Prediction Algorithm



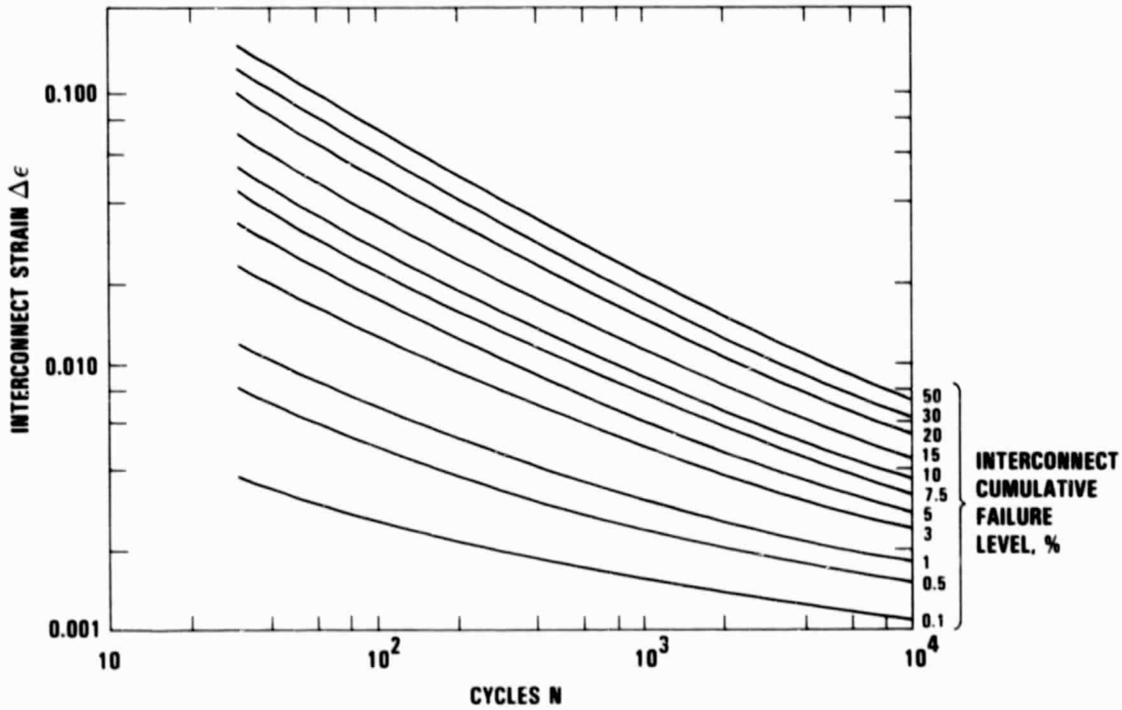
Strain Computation



- Equations
  - $\delta = \{(\alpha_s - \alpha_c)C + (\alpha_c - \alpha_i)g\}\Delta T$
  - $\Delta\epsilon = F\left(\frac{t}{h}\right)\left(\frac{\delta}{g}\right)$

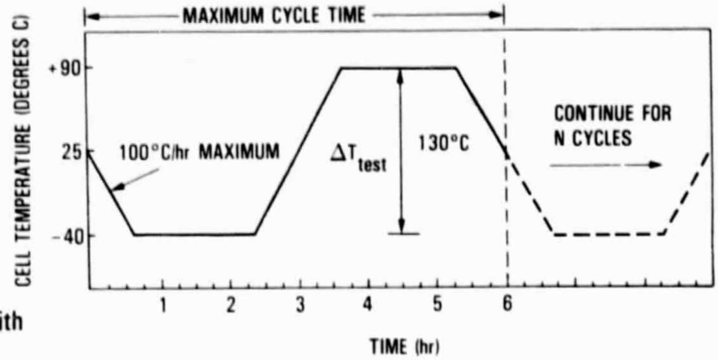
Statistical Fatigue Curves

- **Derivation**
  - **Combine Empirical Fatigue Curve With Experimental Interconnect Cumulative Failure Probability Distribution**
- **Purpose**
  - **Relate Interconnect Strain Level, Fraction (Probability) of Failed Interconnects and Cycles (Years)-to-Failure**
- **Usefulness**
  - **Array Field Life Prediction (Failure Mode: Interconnect Fatigue)**
  - **Thermal Cycling Qualification Test Design**



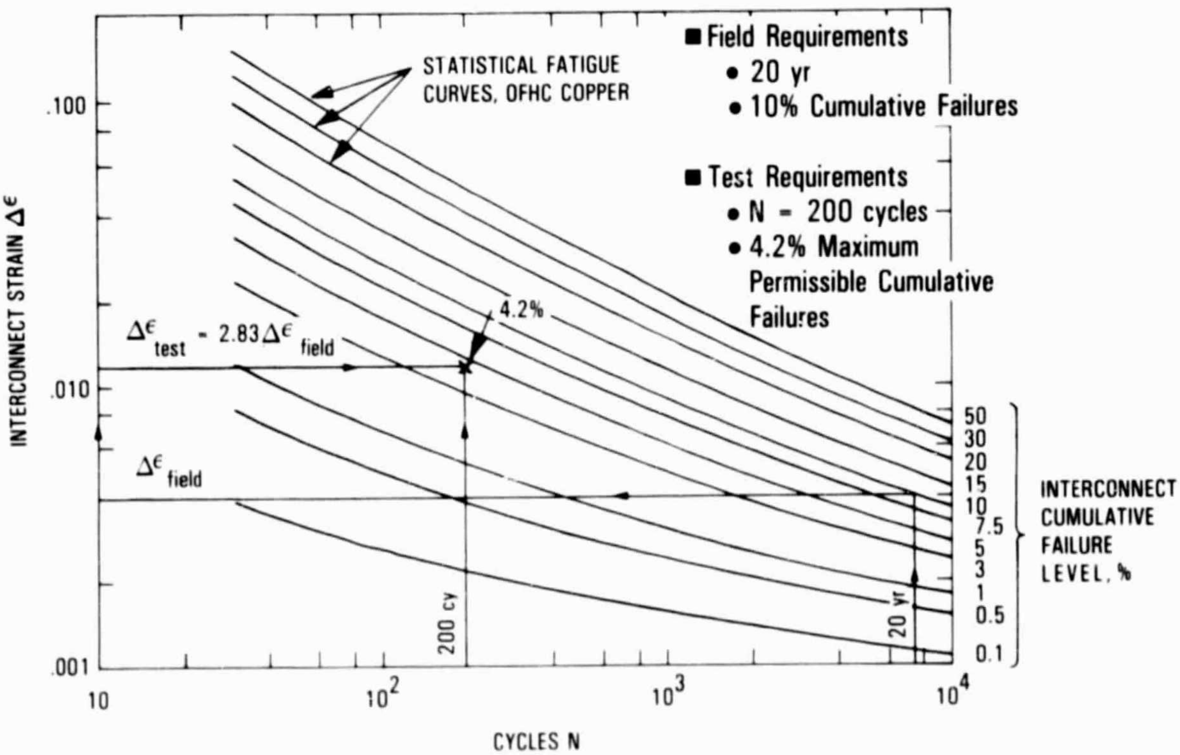
Quantification of Thermal Cycling Test Results

- Test Profile
  - Amplitude: $\Delta T_{test} = 130°C$
  - Duration: N = 200 cycles
- Test Purpose
  - To Qualify Modules for Typical Field Application ($\Delta T_{field} = 46°C$)
- Test Acceleration Factor
  - Since Interconnect Strain Varies Linearly with Temperature Change,

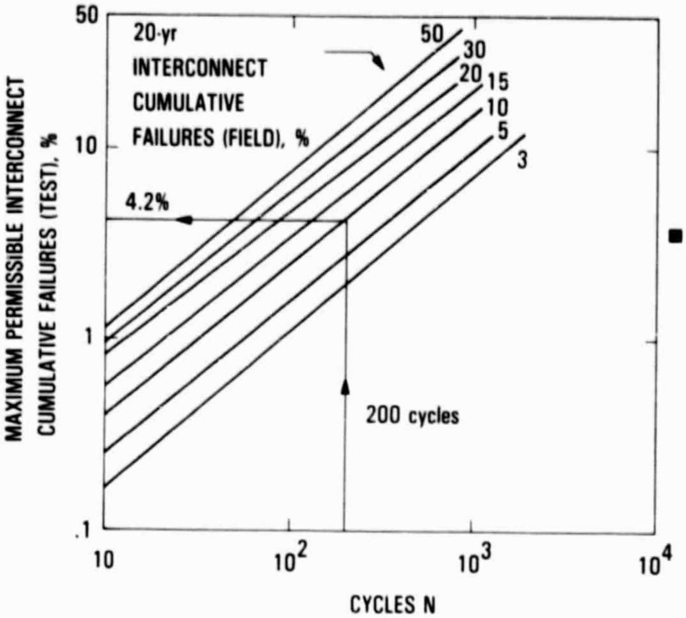


$$\frac{\Delta\epsilon_{test}}{\Delta\epsilon_{field}} = \frac{\Delta T_{test}}{\Delta T_{field}} = \frac{130}{46} = 2.83$$

Test Qualification Example



Thermal Cycling Test: Pass-Fail Criteria



- Conditions
  - OFHC Copper Interconnects
  - Field Site: $\Delta T = 46°C$
  - Test Amplitude: $\Delta T = 130°C$
  - Qualification for 20-yr Application

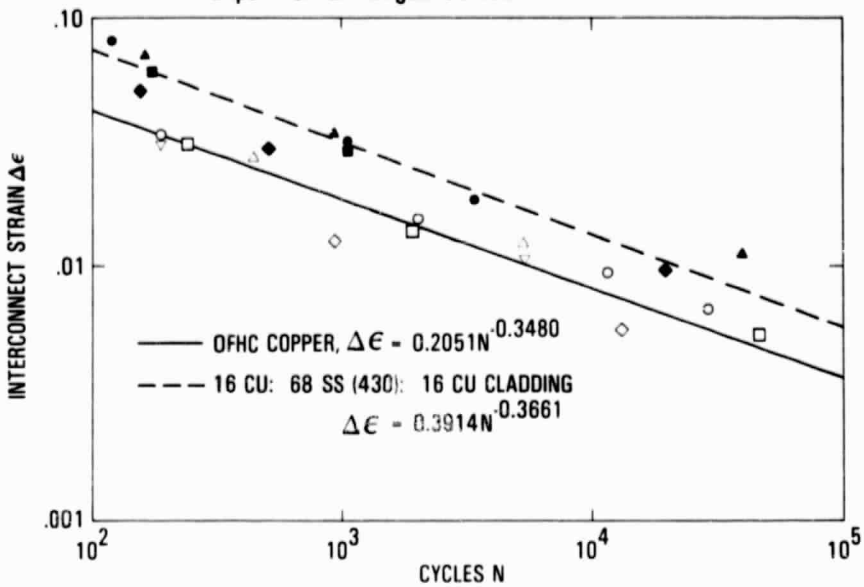
Module Qualification: 20-Year Service $\Delta T \approx 46°C$

Thermal Cycle Test Results

Type of Module	Number of Thermal Cycles (ΔT = 130°C)	Observed Interconnect Test Failure Level, %	Qualification for 10% Field Failure Level: Maximum Allowable Test Failure Level, %	Qualification for 10% Field Failure Level: Judgement	Qualification for 5% Field Failure Level: Maximum Allowable Test Failure Level, %	Qualification for 5% Field Failure Level: Judgement
Randomly Oriented Glass Fiber Substrate	297	67	5.9	Failed	3.8	Failed
	575	69	9.8	Failed	6.3	Failed
	297	36	5.9	Failed	3.8	Failed
	575	69	9.8	Failed	6.3	Failed
	297	31	5.9	Failed	3.8	Failed
Superstrate	247	0	5.6	Passed	3.2	Passed
Superstrate	446	3	8.0	Passed	5.2	Passed
Superstrate	397	0	7.3	Passed	4.7	Passed
Substrate	547	6	9.3	Passed	6.2	Marginal
	547	10	9.3	Failed	6.2	Failed
Substrate	497	0	8.7	Passed	5.6	Passed
	497	7	8.7	Passed	5.6	Failed

Comparison of Interconnect Fatigue Behavior of Two Materials

- Experimental Fatigue Curves



- Observation

  The Clad Material Is About Four Times More Fatigue-Resistant Than OFHC Copper

Comparison of Predicted Life of Two Interconnect Materials

- **Basis: Equal Plant Efficiency**
  - **Equal Interconnect Widths W (Equal Cell Power-Loss Efficiency)**
  - **Equal Interconnect Electrical Resistances R (Equal Interconnect Power-Loss Efficiency)**
  - **Identical Interconnect Configuration and Length ℓ**
- **Thickness and Strain Ratio Determination**

$$2.95 = \frac{\rho_{clad}}{\rho_{Cu}} = \frac{\left(R\frac{tw}{\ell}\right)_{clad}}{\left(R\frac{tw}{\ell}\right)_{Cu}} = \frac{t_{clad}}{t_{Cu}} = \frac{\Delta\epsilon_{clad}}{\Delta\epsilon_{Cu}}$$

- **Life Prediction**

$\Delta\epsilon_{Cu}$	$\frac{N_{Cu}}{N_{clad}}$
.005	5.6
.010	5.1
.023	4.6

- **Conclusion**
  - **Cost Optimization Notwithstanding, Copper Is Superior to This Clad Material for Application as an Interconnect**
  - **Different Cladding Ratio May Result in a Superior Material**

INTERPRETATION OF LASER SCAN DATA

JET PROPULSION LABORATORY

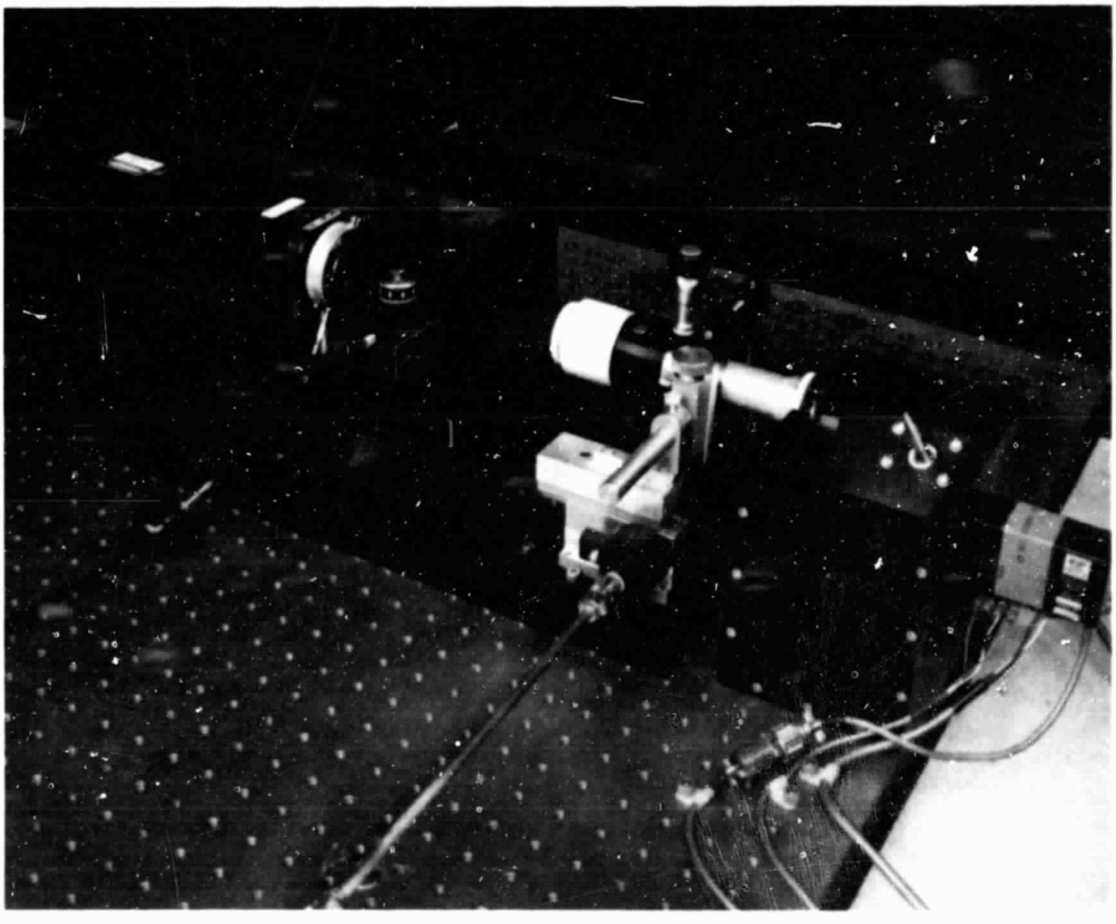
A. Shumka

Objective

1. TO INTERPRET THE SOLAR CELL LASER SCAN DATA IN TERMS OF A SIMPLIFIED PHYSICAL MODEL FOR A SOLAR CELL

2. TO PRESENT AN EASILY APPLIED THEORETICAL MODEL FOR MEASURING CELL SHUNT RESISTANCES FROM LASER SCAN DATA

Solar-Cell Laser Scanning Facility



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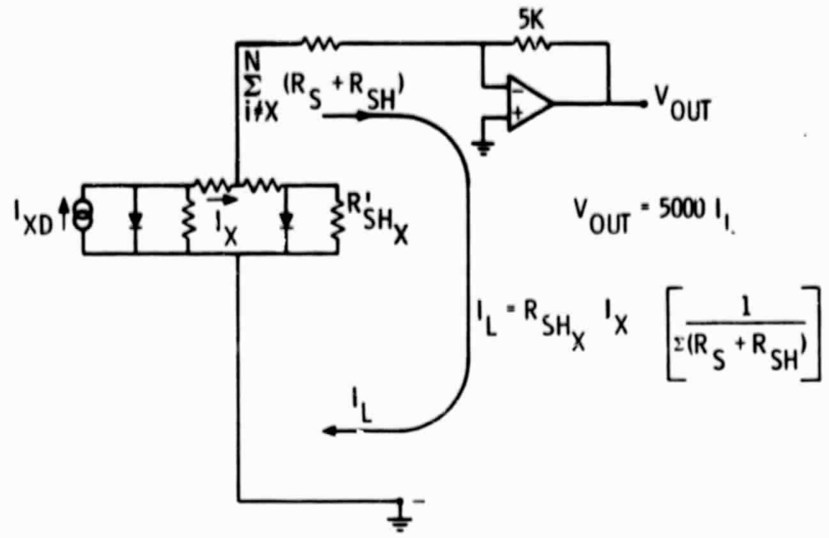
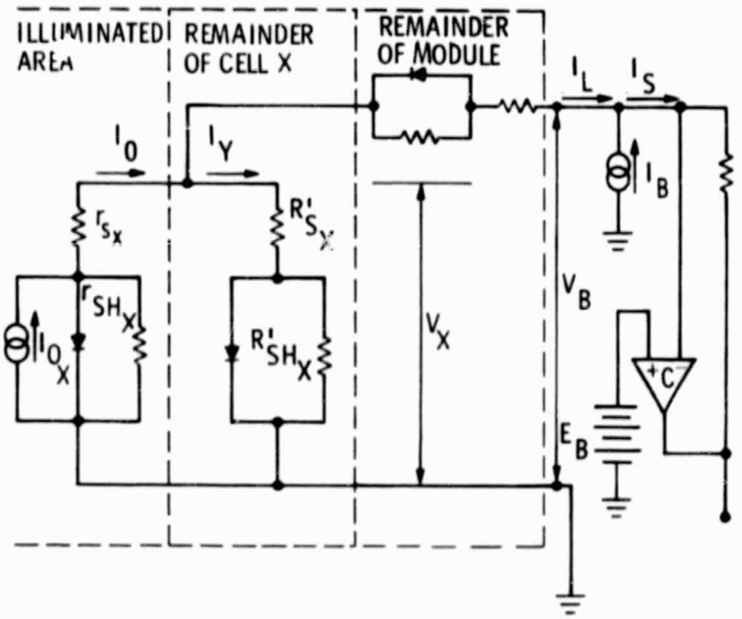
Simplified SCLS dc Equivalent Circuit for Module With N Cells



SCLS dc Equivalent Circuit for Biased Module With N Cells



Output Current, I_S, for Zero-Bias Current Condition

PARAMETERS

- MODULE CONTAINS N CELLS CONNECTED IN SERIES
- SHUNT RESISTANCE, $R_{SH'}$ IS THE SAME FOR ALL CELLS EXCEPT FOR CELL "X"
- R_{SHX} IS THE SHUNT RESISTANCE FOR CELL "X"

$$I_{SX} = \frac{R_{SHX}}{(N-1)R_{SH} + R_{SHX}} I_{SC} = \frac{R_{SHX}}{R_M} I_{SC}$$

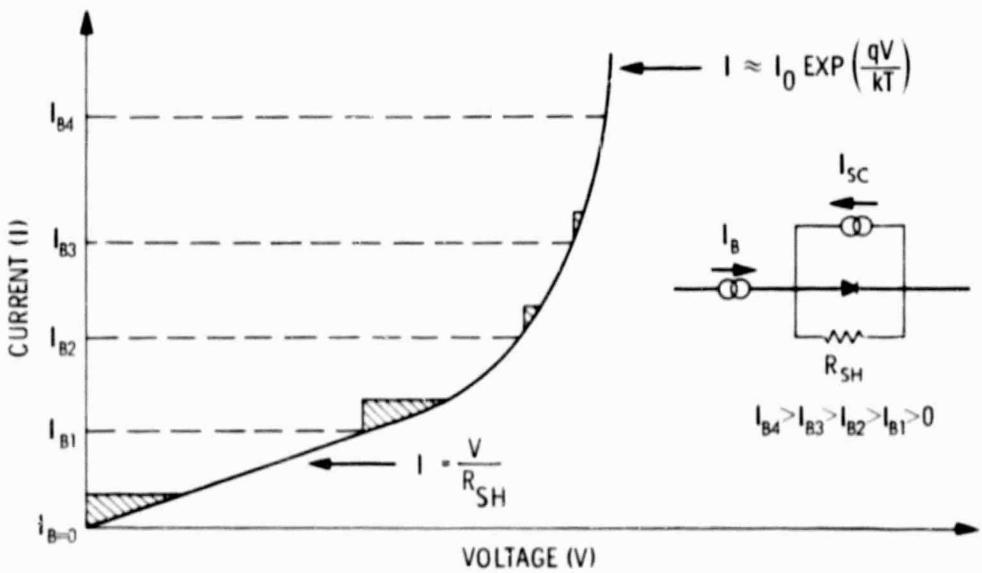
WHERE R_M IS THE DARK MODULE RESISTANCE

FOR $\quad R_{SHX} = R_{SH'} \qquad I_{SX} = \frac{1}{N} I_{SC}$

$R_{SHX} > R_{SH'} \qquad I_{SC} > I_{SX} > \frac{1}{N} I_{SC}$

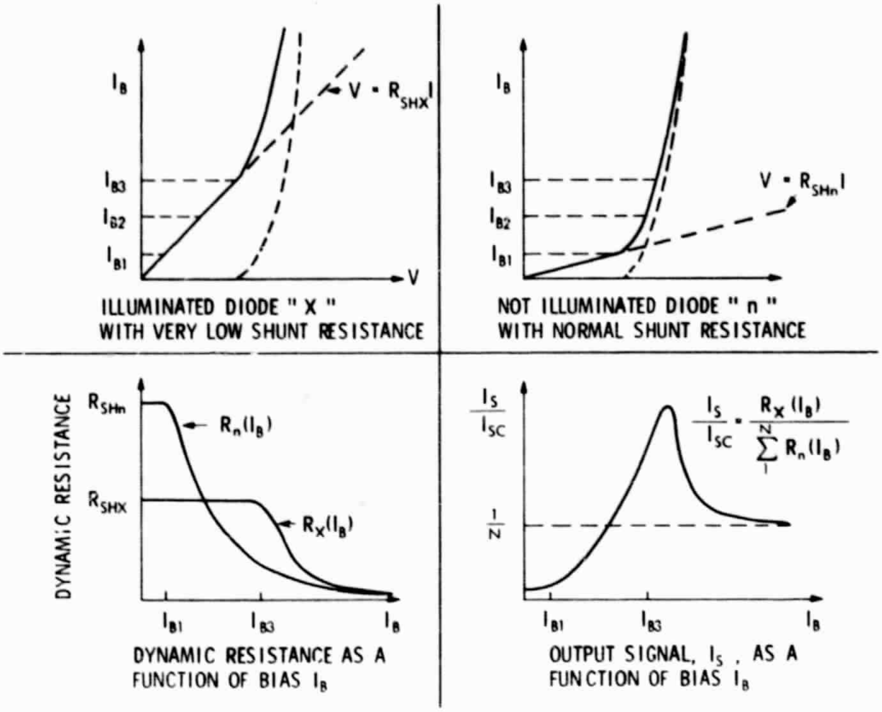
$R_{SHX} < R_{SH'} \qquad \frac{1}{N} I_{SC} > I_{SX} > 0$

Effect of Bias Current on SCLS Power Curves

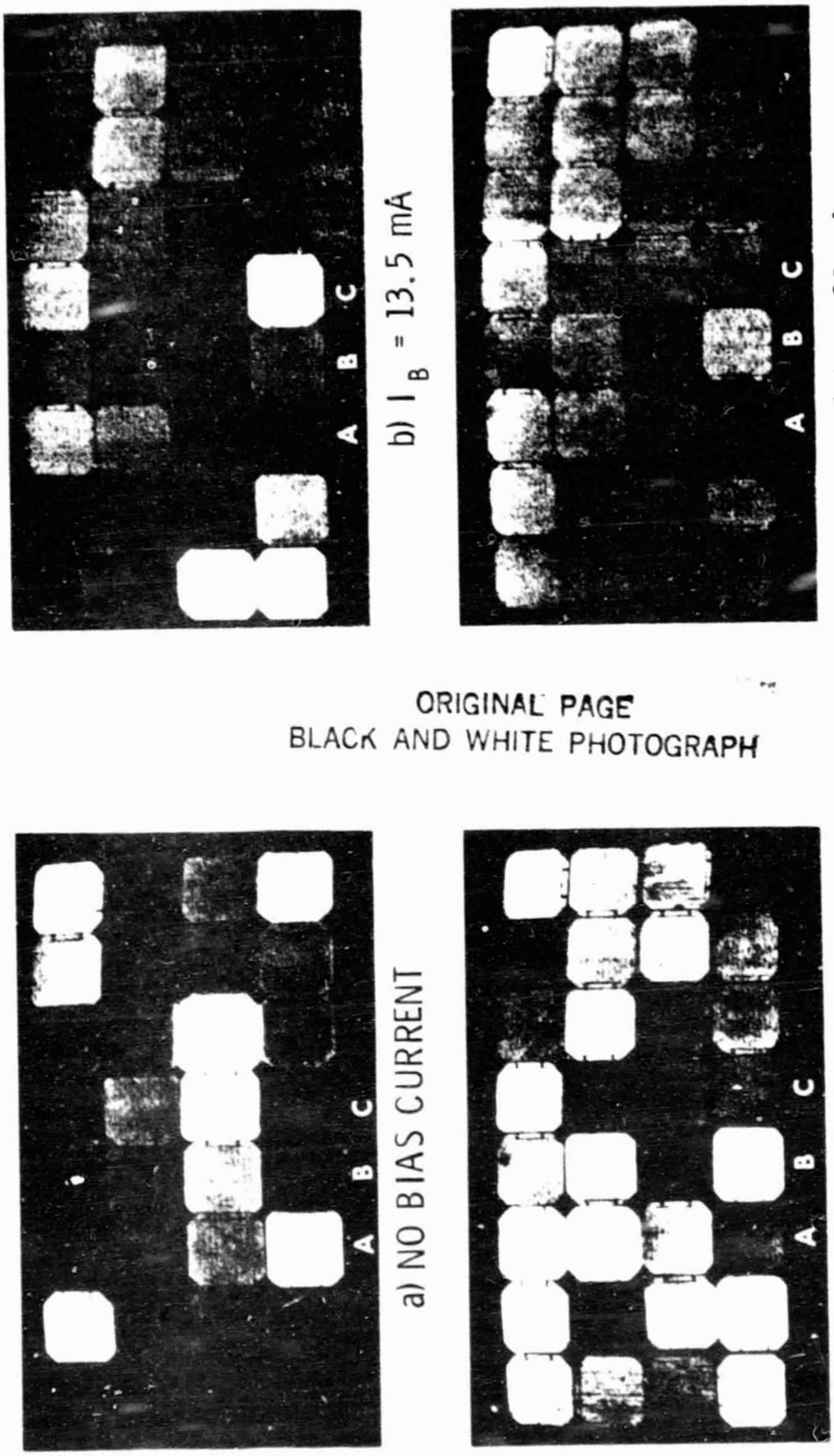


CROSS-HATCHED AREAS REPRESENT POWER CURVES FOR LASER ILLUMINATED CELL FOR DIFFERENT BIAS CURRENTS (I_B). INSET SHOWS CIRCUIT CONFIGURATION. I-- IS LASER GENERATED SHORT CIRCUIT CURRENT.

Effect of Bias Current on SCLS Module Output Current



Effect of Bias Current on SCLS Images



a) NO BIAS CURRENT

b) I_B = 13.5 mA

c) I_B = 48 mA

d) I_B = 98 mA

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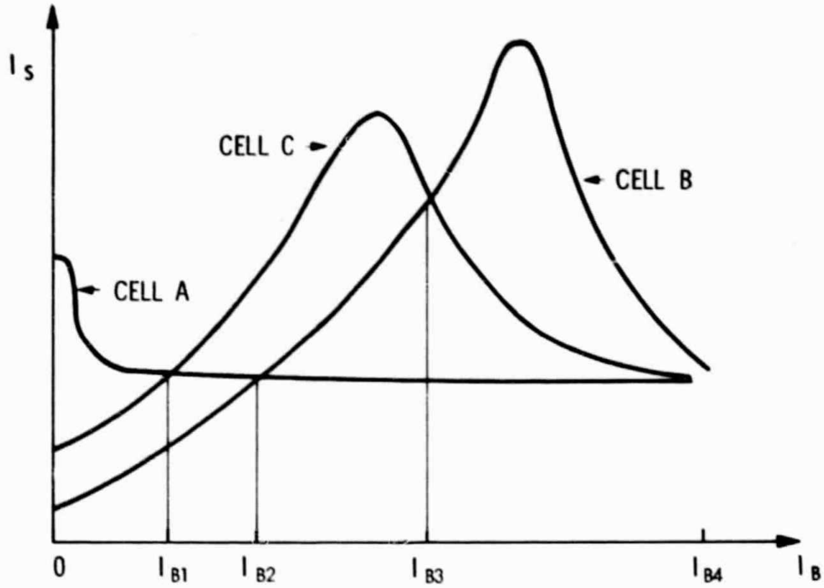
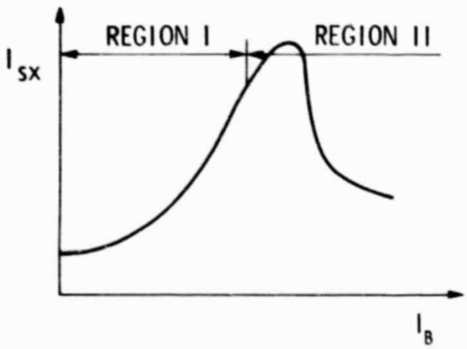
Relative Differences in Cells A, B and C Outputs as a Function of I_b



Calculation of Shunt Resistances From I_S vs I_b Data



- IN REGION I $\quad R_X = R_{SHX}$
- IN REGION II $\quad R_X = R_X(I_B) < R_{SHX}$
- ONLY DATA IN REGION I CAN BE USED TO CALCULATE R_{SHX}

IN REGION I $\quad R_{SHX} = R_M(I_B) \left. \dfrac{I_{SX}(I_B)}{I_{SC}} \right|_{I_B}$

WHERE $R_M(I_B)$ IS THE MODULE DYNAMIC RESISTANCE, AND I_{SC} IS THE SHORT CIRCUIT CURRENT

I_{SC} CAN BE MEASURED BY USING A CONTROL SAMPLE, OR FROM THE I_S vs I_B DATA BY USING THE FOLLOWING RELATIONSHIP

$$I_{SC} = \frac{1}{N} \sum_{1}^{N} I_{SN}(I_B) \Big|_{I_B}$$

Conclusions

1. THE BRIGHTNESS OF A CELL IN A LASER SCAN IMAGE IS DIRECTLY RELATED TO IT'S SHUNT RESISTANCE FOR A ZERO BIAS CONDITION

2. THE BRIGHTNESS OF A CELL WITH A LOW SHUNT RESISTANCE CAN BE GREATLY AMPLIFIED BY BIAS CURRENT

3. SHUNT RESISTANCES TO A FIRST ORDER APPROXIMATION CAN BE CALCULATED FROM A SIMPLIFIED THEORETICAL MODEL

VOLTAGE BREAKDOWN TESTING STATUS

JET PROPULSION LABORATORY

G.R. Mon

Program Goals

- **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 Least Life-Cycle Energy Cost Insulation Systems**

Approach

TEST

- **Break Down Many Unit Areas 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**

VERIFICATION

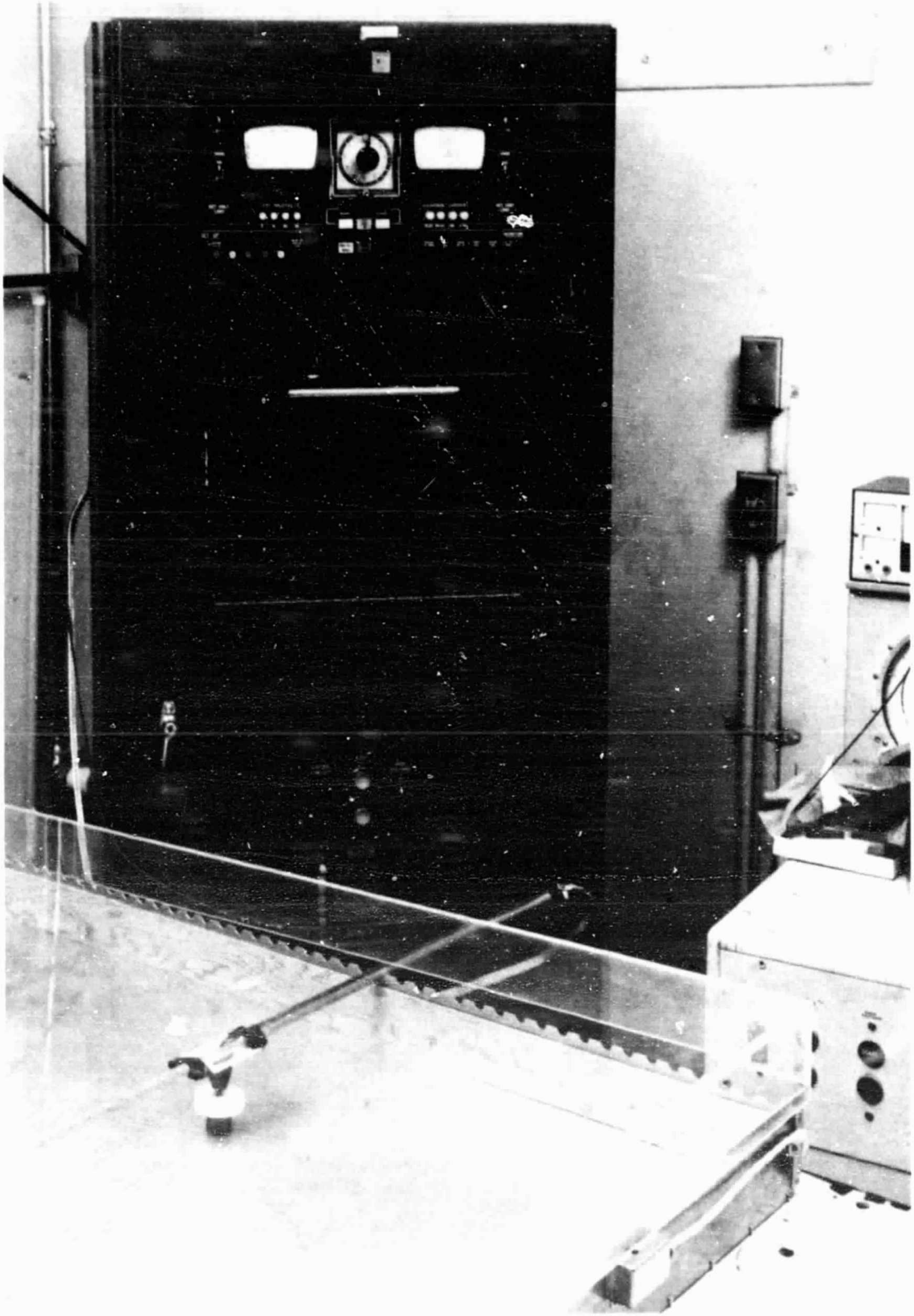
- **Age Encapsulated Single-Cell Coupons at Voltage to Characterize Insulation Breakdown of Encapsulant Under Accelerated-Test Conditions**
- **Age Minimodules at Voltage to Verify Failure Predictions of Large-Area Insulations**

Test Equipment

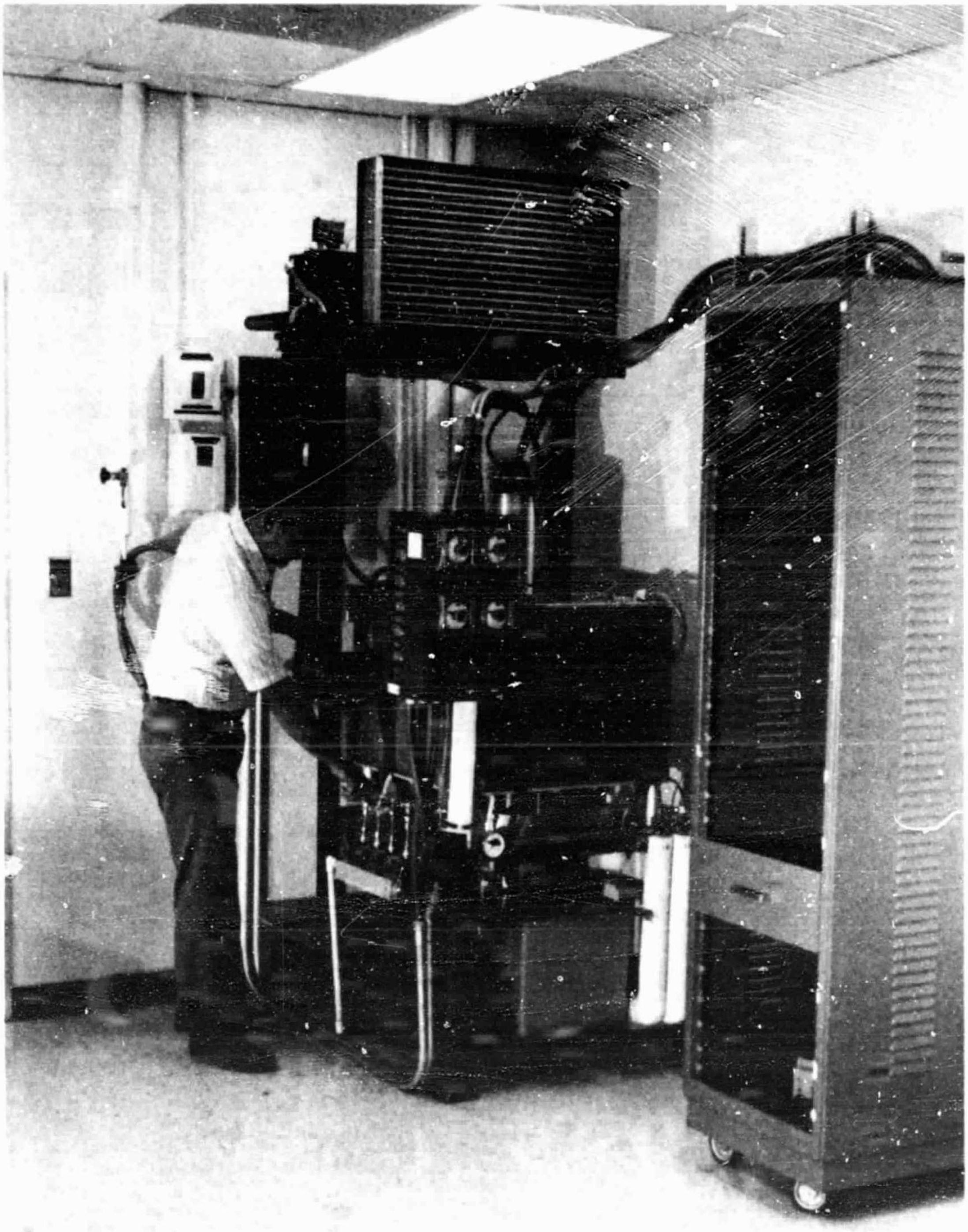
- **Voltage Breakdown Apparatus**
  - **0 to 50 kV**
  - **1 in. Diameter Electrode (Plane-to-Plane)**
  - **Can Test Up to 1100 in.^{2} of Film Material**
  - **Measures Voltage and Current at Breakdown**

- **Environmental Aging Chamber**
  - **Ultraviolet Irradiation: 0 to 10 suns**
  - **Temperature: -15°C to +175°C**
  - **Relative Humidity: Low to 100%**
  - **Voltage: 0 to 10 kV**
  - **Sample Capacity: 144 Coupons, 4 Minimodules**
  - **<u>In Situ</u> Capability to Measure**
    - **Capacitance**
    - **Loss Factor**
    - **Insulation Resistance**
    - **Partial Discharge and Pulse Frequency Distribution**

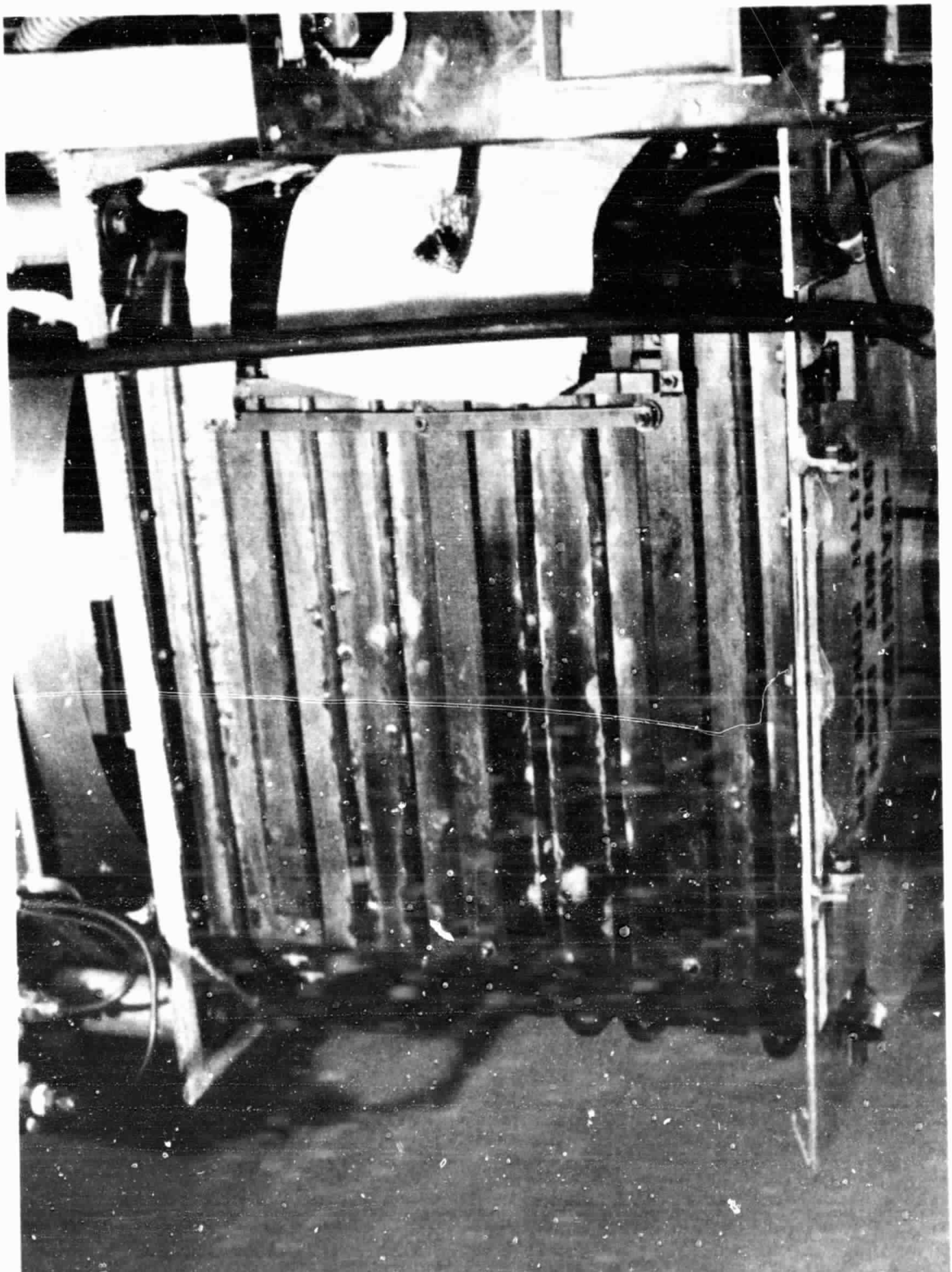
Polymer Film Voltage Breakdown Test Apparatus



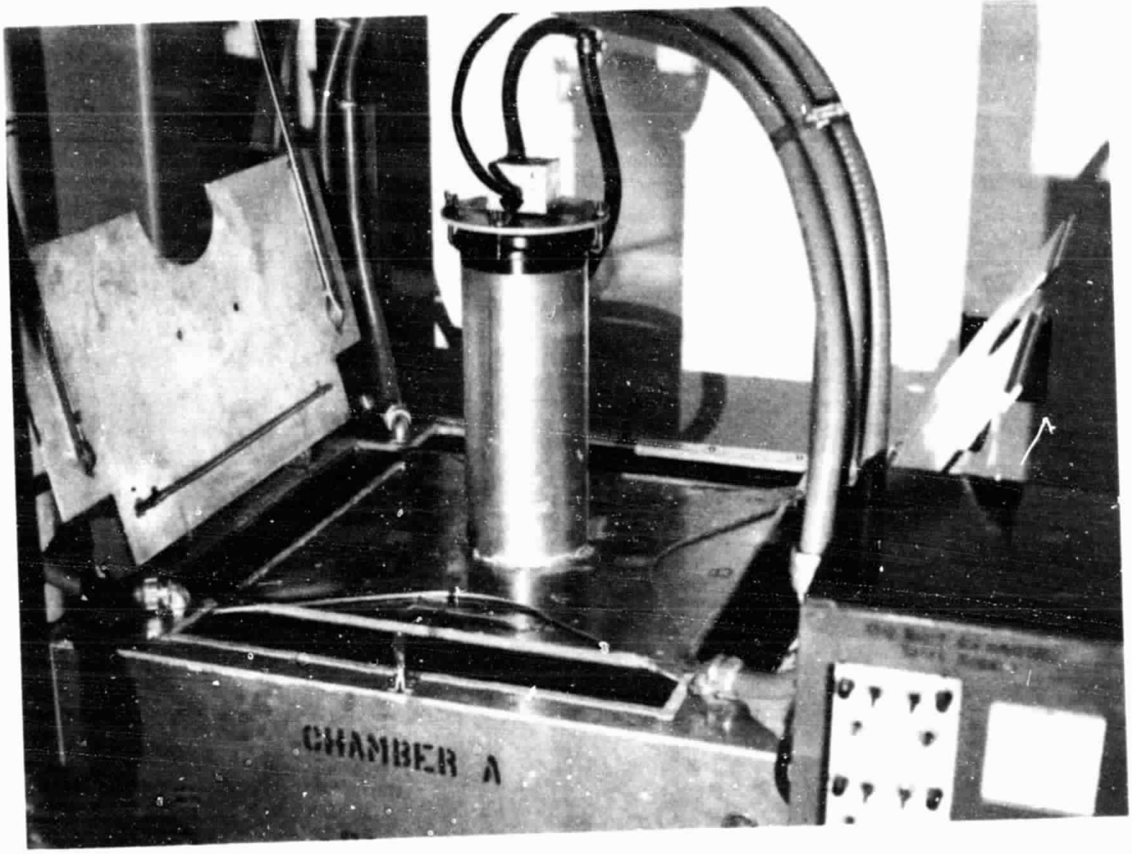
Environmental Chamber



Chamber Heating Strips and Cooling Coils



Lamp Housing and Access to Test Chamber



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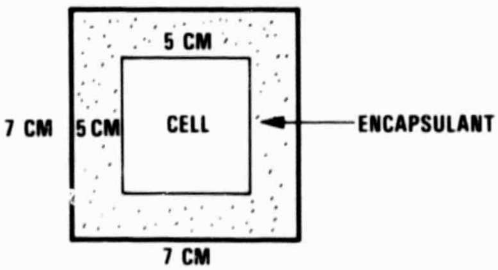
Test Specimens

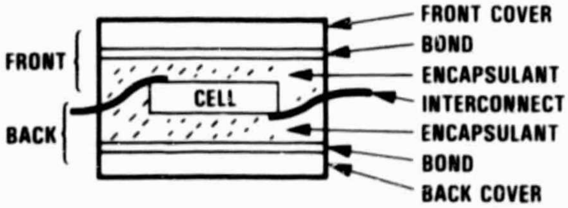
RAW MATERIALS

- Front Covers
  - Tedlar 100 BG 30 UT
  - Tedlar 200 XR - Experimental Tedlar UV Screening Film
- Pottants
  - EVA
  - EMA
- Back Covers
  - Tedlar 400 BS 30 WH
  - Tedlar 150 BL 30 WH
  - Tedlar-Foil-Tedlar
  - Scotchpar, 1 mil and 2 mils

COUPON COMPOSITES

- Configuration





- EVA Systems

Front	Back
Tedlar (Clear) 68040 Adhesive EVA	EVA Cymel Primer Scotchpar (White)
Glass A-11861-1 Primer EVA	EVA 68040 Adhesive Tedlar (White)
	EVA 68040 Adhesive Tedlar-Foil-Tedlar

- EMA SYSTEMS

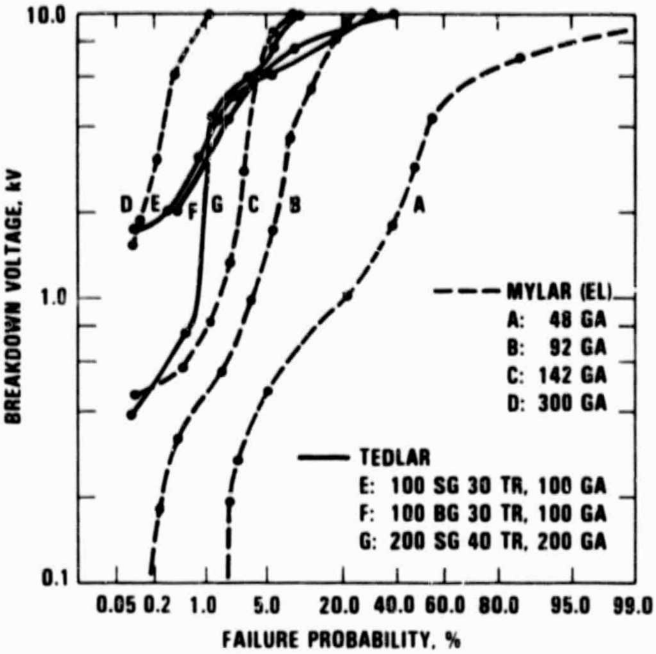
Front	Back
Glass A-11861-1 Primer EMA	EMA 68040 Adhesive Tedlar (White)

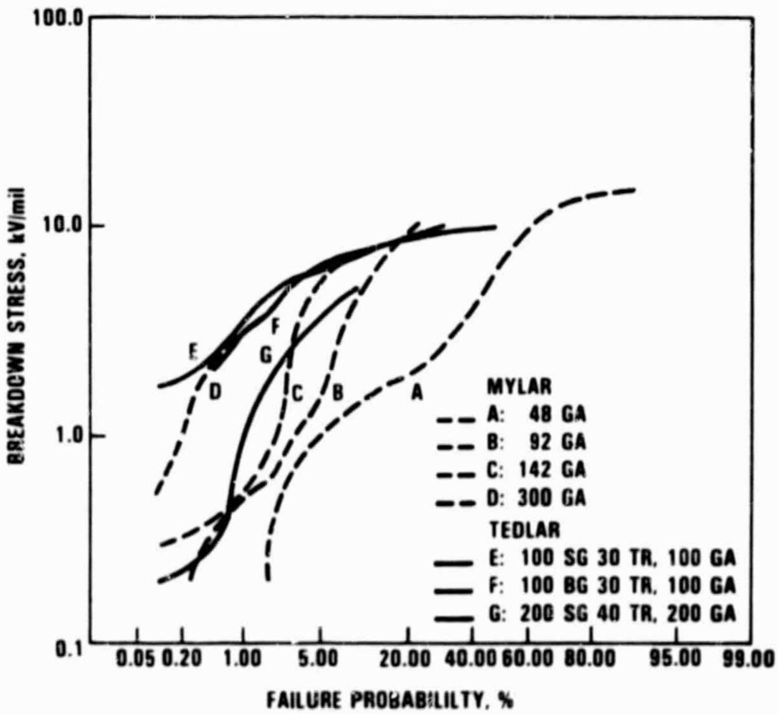
- **Block IV Minimodules**
  - **ARCO**
  - **ASEC**
  - **Motorola**
  - **Photowatt**
  - **Solarex**
  - **Solar Power**
  - **Spire**

Data Reduction and Analysis

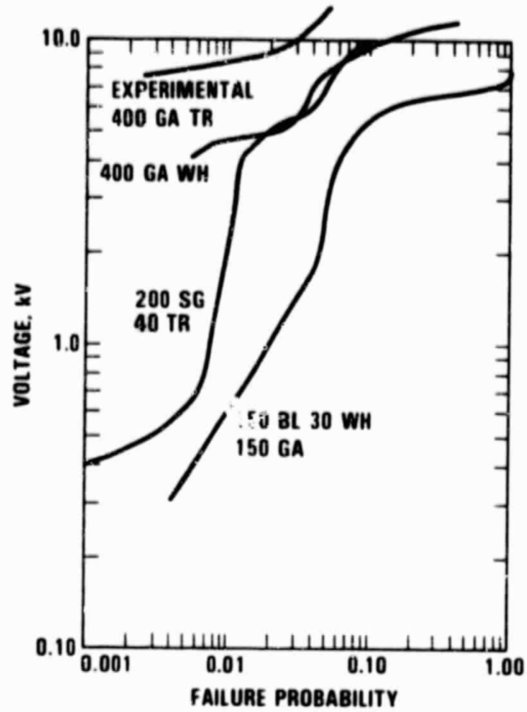
- **Data Reduction**
  - **Presentation Plots**
    - **Cumulative Failure Probability vs Breakdown Voltage**
    - **Cumulative Failure Probability vs Breakdown Stress**
    - **Flaw Density Distribution in Stress**
    - **Module Cumulative Failure Probability vs Operating Voltage**
- **Data Analysis**
  - **Performance Comparison of Materials**
  - **Observation and Investigation of Trends**
- **Data**
  - **Single- and Multi-Layer Mylar and Tedlar Insulation Systems**

Voltage Breakdown Characterization Of Single-Layer Mylar and Tedlar Films

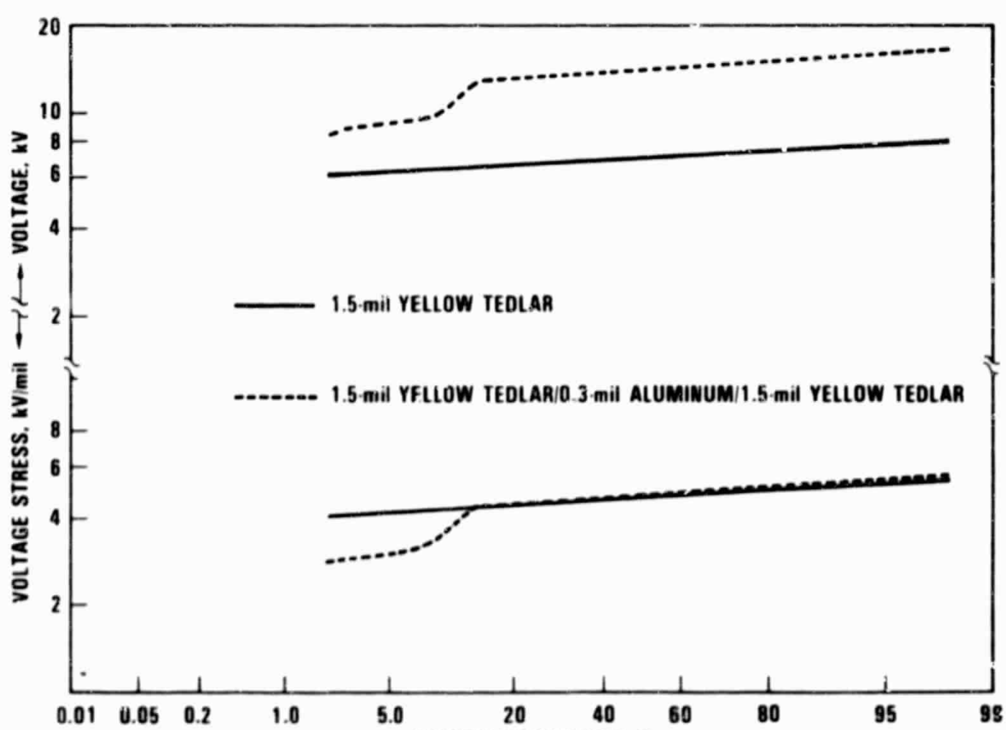




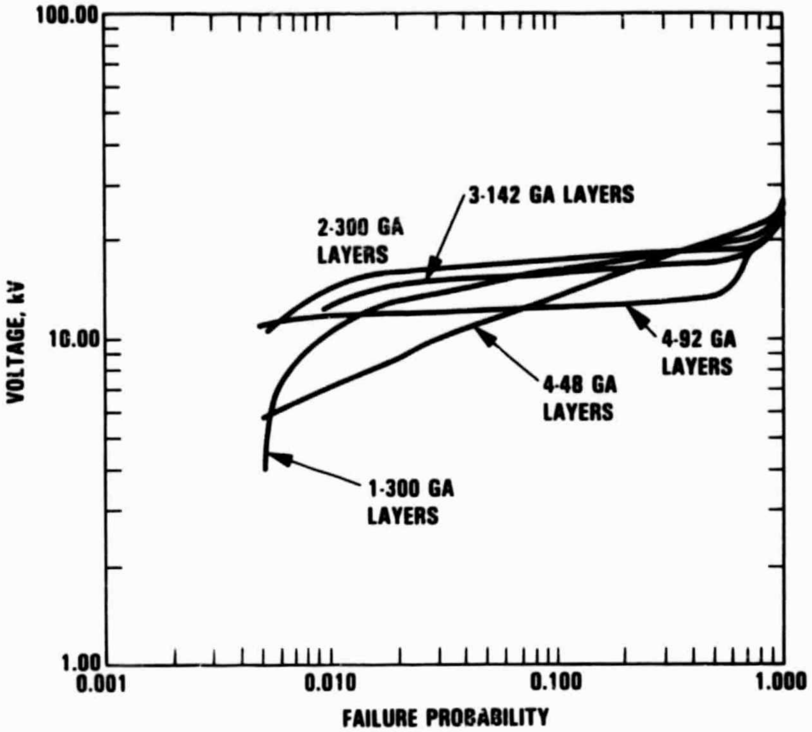
Voltage Breakdown Characterization Of Single-Layer Tedlar Systems



Voltage Breakdown Characterization Of Tedlar-Foil-Tedlar Film



Voltage Breakdown Characterization Of Multilayer Mylar Systems



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Voltage Breakdown Characterization Of Layered Polyester Systems