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Low-Cost
Solar Array Project

DOE/JPL-1012-42
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Progress Report 14

for the Period August 1979 to December 1979

and Proceedings of the 14th Project Integration Meeting

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period August through November, 1979. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering, and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of the visual materials presented at, the Project Integration Meeting held December 5-6, 1979.

PROGRESS REPORT

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PROCEEDINGS OF THE 14TH PROJECT INTEGRATION MEETING

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NOMENCLATURE

A	Angstrom(s)
Ar	Argon
Al	Aluminum
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
BSF	Back-surface field
B-T	Bias/temperature
B-T-H	Bias/temperature/humidity
Ca	Calcium
CFP	Continuous-flow pyrolizer
CLF	Continuous liquid feed
Co	Cobalt
Cr	Chromium
Cu	Copper
CVD	Chemical vapor deposition
CZ	Czochralski (classical silicon crystal growth method)
DCF	Discounted cash flow
DLTS	Deep-level transient spectroscopy
DOE	Department of Energy
DS/RMS	Directionally solidified/refined metallurgical silicon
EB	Electron beam
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EPR	Ethylene propylene rubber
EPSDU	Experimental Process System Development Unit
ESB	Electrostatic bonding
EVA	Ethylene vinyl acetate

FAST	Fixed Abrasive Slicing Technique
Fe	Iron
FPUP	Federal Photovoltaics Utilization Program
GRC	Glass-reinforced concrete
H	Hydrogen
HCl	Hydrochloric acid
HEM	Heat exchanger method (silicon crystal ingot growth method)
HF	Hydrofluoric acid
HNO_3	Nitric acid
ID	Inner diameter
ILC	Intermediate Load Center
IPEG	Interim Price Estimation Guidelines
IPEG 2	Improved Price Estimation Guidelines
I_{sc}	Short-circuit current
I-V	Current-voltage
K	Potassium
LAPSS	Large-area pulsed solar simulator
LAR	Low-angle ribbon (silicon growth method)
LAS	Large-Area Silicon Sheet Task
LCP	Lifetime cost and performance
LSA	Low-Cost Solar Array
MBS	Multiblade sawing
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MWS	Multiwire sawing
Na	Sodium
NDE	Nondestructive evaluation

Nb	Niobium
NOCT	Nominal operating cell temperature
O	Oxygen
OTC	Optional test conditions
P	Phosphorus
P	Individual module output power
PA&I	Project Analysis and Integration Area
P_{avg}	Module rated power at SOC, V_{no}
PDU	Process Development Unit
P/FR	Problem/failure report
PIM	Project Integration Meeting
PMMA	Polymethylmethacrylate
P_{max}	Maximum power
PnBA	Poly-n-butyl acrylate
$POCl_3$	Phosphorus oxychloride
PP&E	Production Process and Equipment Area
ppba	Parts per billion atomic
ppma	Parts per million atomic
PRDA	Program Research and Development Announcement
PV	Photovoltaic
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RTR	Ribbon-to-ribbon (silicon crystal growth method)
S	Sulfur
SAMICS	Solar Array Manufacturing Industry Costing Standards

SAMIS	Solar Array Manufacturing Industry Simulation
SCIM	Silicon coating by inverted meniscus
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute
SERI	Solar Energy Research Institute
Si	Silicon
$SiCl_4$	Silicon tetrachloride
SiF_4	Silicon tetrafluoride
$SiHCl_3$	Trichlorosilane
SOC	Silicon on ceramic (crystal growth method)
SOC	Standard Operating Conditions (module performance)
SOLMET	Solar-meteorological
SPG	Silicon particle growth
SSMS	Spark-source mass spectrometry
STC	Standard Test Conditions (cell performance)
Ta	Tantalum
TD&A Lead Center	Photovoltaics Program Technology Development and Applications Lead Center
Ti	Titanium
UV	Ultraviolet radiation
V	Vanadium
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage
W	Tungsten
Xe	Xenon
Zn	Zinc
$ZnCl_2$	Zinc chloride

PROGRESS REPORT

Project Summary

Flat-plate photovoltaic module design and manufacturing technologies have been significantly improved after five years of active cooperation by module manufacturers and JPL/LSA personnel. The four LSA module block buys have provided the stage for a rapid evaluation of module design technologies, module testing (exploratory and qualification), field development and monitoring, and module problem/failure analyses.

Lessons learned were summarized during a plenary session of the 14th Project Integration Meeting with specific design approaches, rationale and recommendations presented in subsequent sessions. Recommendations were made for module design objectives and approaches in the areas of mechanical and electrical configuration, fault tolerance and environmental endurance. Project experience with respect to environmental reliability and durability was described. Progress by the manufacturers in improving production yields by reduction in workmanship defects was described on the basis of Quality Assurance inspection records.

Block IV module manufacturers displayed their brand-new prototype modules and gave presentations on design features and rationale. Numerous design and production technology innovations based upon both LSA and private R&D activities have been incorporated, resulting in improvements in module price, performance, and reliability. A key point stressed was the need for continuing field-data acquisition, array-performance evaluation, and corrective design action for problem/failures experienced.

The Battelle polysilicon Process Development Unit, consisting of the four critical components (full-size) for their 50 MT/yr EPSDU, has started operation.

Hamco has repeatedly grown 105 kg of silicon ingots from a single crucible by periodic melt replenishment. Crystal systems has cast nearly single-crystal ingots using upgraded metallurgical silicon with their heat-exchanger method (HEM). Impurities segregated at the top and sides.

Average wafer-cutting speeds of Crystal Systems multi-wire saw are about 40% higher than required for meeting 1986 goals. Siltec has cut 250-μm-thick wafers with kerfs of 200 μm-thick using their rotating-ingot ID slicing technique.

Mobil Tyco has grown 7.5 cm-wide edge-defined film-fed growth (EFG) ribbons at 5.0 cm/min. Westinghouse has exceeded their throughput goal (27 cm^2/min) with their dendritic-web growth. Five-hour growth has been achieved with melt replenishment. Honeywell has grown 200 μm-thick silicon films at 12 cm/min pull rates with their silicon-coating-by-inverted-meniscus (SCIM) unit. Energy Materials Corp. has grown horizontal ribbons (1.5 cm wide) at rates up to 60 cm/min (average 20 to 30 cm/min).

Several 1986 candidate encapsulation systems are now undergoing intensive evaluation of module life, fabrication, and performance. The major unknown for the lowest-cost systems is the 20-year-life requirement. The encapsulation materials now being incorporated into the newest designs should permit 20-year-life module designs in the $2 to $5/W price range. An encapsulation materials status summary is included in this report.

Some highlights in production processing are: spray-on junction technique is successful; nickel is a barrier to copper migration; copper sinters well using a lead frit; thick-film metal systems have been successfully doped with AlSi and AlGe eutectics; induction soldering of ribbon contacts to cell have been successful.

Tony Carey presented HUD's Urban Development Action Grant Problem and its potential for monies to help build plants in areas of high unemployment.

A JPL lead team assured the present and near-term availability of polysilicon, single-crystal ingots and wafers and needs for same. Between 1981 and 1983 there will be a strong sellers' market for polysilicon with a shortage developing in the latter part of that period. This shortage will not be relieved until the new polysilicon production plants are operating (1985 to 1986). Ingot and wafer demand and supply will balance. Lead time for new manufacturing hardware is less than a year.

A summary of the Federal Photovoltaic Utilization Program status was presented.

Prof. A. Weinstein of Carnegie-Mellon University presented a capsule summary of the product liability situation from a manufacturer's viewpoint: safety considerations must be integrated into the design and manufacture of photovoltaic systems as we strive for performance and cost optimization.

Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

PLANNING AND INTEGRATION

The Technical Readiness 1982 document was published October 31 as JPL Document 5101-114.

The SERI PVPO/JPL LSA interface has been established for evaluating the transition of technologies between the various stages of technical development. SAMICS information has been forwarded to SERI on one technology and plans have been formulated for analysis of another candidate material.

In the effort to develop project planning aids, the theory has been developed for combining the cumulative distribution functions for parameters of parallel technology development efforts. An HP-97 calculator program was written for testing the theory. It revealed some problems with the approach used, but an alternative approach has been devised and has apparently overcome the previous difficulties.

ARRAY TECHNOLOGY COST ANALYSIS

The review of the updated Price Allocation Guidelines has been completed. The new guidelines are apportioned by sheet-material type accounting for specific sheet properties such as efficiency and silicon utilization.

The Project Analysis and Integration Area is participating in the evaluation of the Near-Term-Cost-Reduction contracts. Using contractor supplied data plus JPL estimates, SAMIS runs have been completed for five of the contracts. Most runs to date show reasonably good agreement with predicted cost data; however, the technical success of some contracts remains to be seen.

The development of the Improved Price Estimation Guidelines (IPEG2) was completed and presented at the Fourteenth Project Integration Meeting and is shown in the Proceedings (Section III of this document). IPEG2 will permit more flexibility in price estimation and should be in closer agreement with SAMIS results.

ECONOMICS AND INDUSTRIALIZATION

A number of studies were conducted to examine the long-term relationship of the LSA Project and industry and to examine the effects of PV market elasticity on the obsolescence of technology.

TECHNOLOGY DEVELOPMENT AREA SILICON MATERIAL TASK

INTRODUCTION

The objective of the Silicon Material Task is to establish by 1986 an installed plant capability of producing silicon (Si) suitable for solar cells at a rate equivalent to 500 MWp of solar arrays per year and at a price of less than $14/kg (1980 $). The program formulated to meet this objective provides for development of processes for producing either semiconductor-grade Si or a less pure but utilizable (i.e., a solar-cell-grade) Si material.

TECHNICAL GOALS, ORGANIZATION AND COORDINATION

Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about $65/kg. A drastic reduction in price of material is necessary to meet the economic objectives of the LSA Project. Efforts are currently under way to develop processes that will meet Task objectives and produce semiconductor-grade Si. Another way of meeting this requirement is to devise a process to produce Si material that is less pure than semiconductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSA is dependent on optimization trade-offs, which concomitantly treat the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si. This structure has been presented in detail in previous LSA Progress Reports. Besides the process development mentioned above, the program includes economic analyses of silicon-producing processes and supporting efforts, both contracted and in-house at JPL, to respond to problem-solving needs.

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

Four processes for producing Si equal to or approaching semiconductor-grade silicon in composition or performance are under development by Battelle Columbus Laboratories, Energy Materials Corporation, Hemlock Semiconductor Corporation, and Union Carbide Corporation. Progress in these four efforts is described below.

Battelle Columbus Laboratories (BCL) is conducting a Process Development Unit (PDU) program for the experimental investigation of four major items of process equipment for a projected 50 MT/yr

Experimental Process System Development Unit (EPSDU). The BCL process is based on the reduction of silicon tetrachloride by zinc; the four items are a zinc feed system, a fluidized bed reactor, a reactor effluent condenser, and a zinc chloride electrolysis cell. Completion of fabrication and assembly of the PDU had been scheduled for October 1, 1979, but now is expected in late January 1980, having been set back by numerous procurement delays and fabrication errors.

The only major item yet to be installed is the zinc feed system. In this period a succession of failures was experienced with it, but remedies have been applied to the known problems, and the system is being assembled.

Energy Materials Corporation, under a near-term cost-reduction contract, is developing and demonstrating a Si melt-replenishment system for continuous Czochralski (Cz) crystal growth. The system consists of a novel reactor for Si production and melting at a rate of 0.5 kg/h by hydrogen reduction of trichlorosilane, and a delivery system to transfer the molten Si to a Cz crystal puller.

The design, fabrication, and installation of a prototype system neared completion. This particular activity is lagging three months behind schedule, primarily because of problems in procurement of the reactor vessel and enclosure.

The Union Carbide Corporation is developing a process based on producing silane and pyrolyzing it in either a free-space reactor or a fluidized bed reactor. In this period, contract negotiations were completed for the Experimental Process System Development Unit (EPSDU) program to be completed in December 1982. The EPSDU will have a capacity of 100 MT of Si per year.

The preliminary piping and instrumentation diagrams were completed, as well as all the layout drawings required to prepare the detailed EPSDU cost estimate. Preparation of requests for purchase was initiated and equipment long-lead items are being identified. Four proposals for Si powder melting and consolidation R&D work by a subcontract were evaluated, and a recommendation was made regarding a subcontractor. Negotiations are under way between this subcontractor and Union Carbide.

A technical workshop on fluidized-bed Si production and free-space reactor technologies, attended by the Oregon State University consultants and personnel from Union Carbide and JPL, was held at Corvallis, Oregon. The major result of the workshop is the assessment that fluidized bed reactors are feasible devices for production of Si from silane.

Installation of the free-space reactor process development unit neared completion. Work on modeling the free-space reactor as an axisymmetric confined jet started. Tests continued in capacitive heating and particle separation in a fluidized bed. The bed was heated to 500°C with a Si-coated electrode for 23 hours. During these tests a minimal amount of sintering was observed. Particle separation tests conducted with a wide range of particle sizes revealed that large particles can be separated using a boot. More tests are required, however, to optimize the boot design.

A contract was started on October 2, 1979, with Hemlock Semiconductor Corporation for a 15-month R&D effort on a process for making Si by a modification of the Siemens process. The process is based on the use of dichlorosilane and/or mixtures of dichlorosilane and trichlorosilane. Reactor tests were made with trichlorosilane and dichlorosilane to shake down the system and to characterize the reactor. An analysis of reactor parameters was initiated to permit definition of requirements for intermediate-size and EPSDU-size reactors. Three PDU designs were considered for redistribution of trichlorosilane to dichlorosilane. A mixed-feed (trichlorosilane-dichlorosilane) system was chosen as the most cost-effective approach to meeting program requirements, and detailed design with equipment specification was initiated. A preliminary mass balance for the PDU was completed using vent gas composition obtained from experimental reactor runs.

Development of Processes for Producing Solar-Cell-Grade Silicon

SRI International: An 18-cm-dia reactor made of Inconel (erroneously reported in Progress Report No. 13 as having a diameter of 15 cm) capable of making 1-kg batches of Si, as compared to the 0.5-kg capacity of the previous 13-cm-dia Pyrex reactor, was put into operation. Sodium reaction was relatively complete even when reactants were added at a rate equivalent to 0.5 kg of Si/h. Analyses of Si obtained by melt separation of the product from the sodium/silicon tetrafluoride reaction are presented below in the Proceedings of the 14th Project Integration Meeting.

An economic analysis performed by the contractor indicates a product price of $11.93/kg Si (1980$ 25% ROI), assuming that only 80% of the melted Si is acceptable as solar-grade, and that the balance of the silicon and the by-product sodium fluoride are sold for credit.

Westinghouse: Assembly and installation of the process demonstration system and shakedown of the reactant subsystems (sodium and silicon tetrachloride) were completed. Arc heater/reactor tests without reactants were conducted over ranges of arc-heater power and gas flow. Based on the results, a modification was made to the arc heaters to obtain higher gas enthalpy and thereby establish more favorable conditions for the Si condensation process. Another test was conducted without reactants, and then on December 8 a test with reactants was made. The test was terminated early because a thermocouple in the burnoff stack indicated a low burner temperature, apparently erroneously, but 31 min of operation at 100% reactant flows were obtained. Partial disassembly of the system after the test revealed that the only damage sustained appears to be the loss of a portion of the sodium spray nozzle. Earlier tests with the nozzle had indicated that only moderate degradation of the spray characteristics should result from this damage.

A skull of reaction product, appearing to be a mixture of sodium chloride and finely divided Si, covered the inside surfaces of the reactor and cyclone separator. Some small pieces of material having the typical silvery luster of Si were found. The collector was filled with reaction product appearing to be a mixture of sodium chloride and finely divided silicon. A number of samples were taken from various regions in the apparatus and are being analyzed.

Impurity Studies

Aerospace Corporation: This effort, the purpose of which was to assess the applicability of the photon catalysis technique for metal impurity analysis in silicon, was concluded in this period. In this technique, metal atoms from a vaporized sample are excited by active nitrogen, and the atomic emission spectrum is analyzed to give the metal vapor pressure. In the program, direct evidence was obtained that when a silicon sample is evaporated into a stream of active nitrogen, the composition of the vapor is representative of the sample composition. The experimental results also suggest that the excitation process occurs independently for each species present in the vapor, and that the technique is sensitive to silicon impurities at the ppm level. The high signal-to-noise level obtained in the work portends well for achieving the goal of 10-ppb sensitivity by further development of the technique.

C.T. Sah Associates: Thermal-capture and emission-rate measurements were made using the voltage-stimulated capacitance (VSCAP) transients for titanium, zinc, and gold. These measurements are used to make a more accurate assessment of the effects of these elements on Si solar-cell performance.

Solarex Corporation: Twenty-two experimental lots (containing intentionally incorporated impurities) of solar cells were fabricated and measured. Two additional lots were fabricated but are not yet completely electrically characterized. The experimental test cells appear to be clustered into two distinct resistivity ranges, one around 0.2 Ω-cm and the second around 3 to 4 Ω-cm. As is to be expected, the lower-resistivity-range cells generally give higher voltages and lower currents than the higher-resistivity cells.

Where performance degradation occurs due to the incorporated impurities, the current parameter is usually much more drastically affected than the voltage parameter, although both can be severely degraded by titanium. All seven titanium-containing lots thus far tested were severely degraded in maximum power output, even when titanium was present in combination with copper.

Through analysis of the control and monitor cells it has been determined that there are no observable effects that might be attributed to cross-contamination. Also several lots of experimental cells with similar levels of incorporated manganese yielded similar degradations, indicating reasonable consistency. It should be noted that a significant number of cell lots have exhibited marked lifting of grid line metallization that might compound subsequent analysis.

Westinghouse R&D Center: The objective of this program is to define the effects of impurities, various thermochemical processes, and impurity-process interactions on the performance of terrestrial Si solar cells. The results of the study form a basis for Si producers, wafer manufacturers, and cell fabricators to develop appropriate cost-benefit relationships for the use of less pure, less costly solar-grade Si. The Phase III technical effort was completed November 30, 1979.

As part of the assessment of impurity effects for Czochralski (Cz) growth and for silicon web growth (a ribbon crystal production process), the effective distribution coefficients were measured for a variety of potentially harmful impurities. Spark-source mass spectroscopy was used to determine C_s, the Si crystal impurity content, while atomic absorption was used to obtain C_ℓ, the impurity concentration in the liquid from which the crystal grew.

Gettering of titanium-based silicon wafers (4 Ω-cm) improves cell performance by 1% to 2% (absolute) for the highest temperatures and longest times. $HC\ell$ is somewhat more effective than $POC\ell_3$, and $HC\ell$ produces essentially identical results for molybdenum (Mo) or iron (Fe). The performance improvement is due to a reduction in impurity trap center density which for titanium, and probably the other impurities, is not uniform but varies with distance from the wafer surface. For example, it has been shown by deep-level spectroscopy that a concentration gradient, or profile, forms in titanium-doped silicon wafers during 1100°C gettering treatments. At this temperature the titanium-depleted region extends from the surface to more than 2 mils deep in the wafer; at 850°C, the cell fabrication temperature, the profile extended only about 12 μm. In contrast, molybdenum-doped wafers exhibit abrupt profiles; after 1100° treatment the molybdenum concentration returns to the bulk value within 6 μm of the surface. This probably explains the rather small response of cell performance to gettering in molybdenum-doped Si.

Gettering of low-resistivity (0.2 Ω-cm) Si produces some improvement of the performance of titanium- and molybdenum-doped cells. However, the cells made on the gettered low-resistivity material exhibit considerable performance variation that tends to negate the benefits due to gettering itself. This behavior, especially evident when Mo-doped material is treated in $POC\ell_3$, is due to excessive junction currents in the device. These results are ascribed to precipitate formation near the high-field region of the cell during the high-temperature treatment.

A cell performance-impurity effects model, verified for both n- and p-base cells, is now available to project the efficiency of devices made of Si contaminated with various kinds and amounts of impurities.

Supporting Studies

A contract was initiated with AeroChem Research Laboratories on October 3, 1979, to investigate processes involved in the production of solar-cell-grade Si from silicon halides and alkali metals. The specific objectives of the contract are: 1) to determine the reaction kinetics, extent of reaction, and rates of heat release for a range of operating conditions in a jet-stirred reactor, 2) determine the suitability of various reactor materials for a range of operating conditions of jet-stirred reactor, 3) to determine the Si collection efficiency and purity of Si product for impaction collection devices, and 4) prepare preliminary engineering and economic analysis of a Si production process using the jet-stirred reactor.

Since the beginning of the contract, the jet-stirred rector test facility has been made operational and some experiments have been run. AeroChem has provided JPL a small sample of Si product for impurity measurements.

The contract with AeroChem for developing a model and computer code for description of Si production processes employing silicon hydrides or halides expired on October 20, 1979. The draft final report was written.

As a result of executing the contract, AeroChem developed two computer programs, CHEMPART and GENMIX, to simulate the Si production process in an arc-heater reaction. The overall reaction of the process is reduction of silicon tetrachloride by sodium in a hydrogen-argon plasma. The computer code CHEMPART simulates the reaction between sodium and silicon tetrachloride, nucleation of silicon, and growth of Si nuclei in the core of the reactor. The computer code GENMIX calculates the rates of heat and mass transfer to the reactor walls from the core of the reactor. Thus GENMIX calculates the transfer and hence condensation of Si vapor and droplets to the reactor wall as a function of reactor length.

Using these two reactor codes, AeroChem simulated the arc-heater process of Westinghouse for Si production for two different enthalpy conditions. The lower enthalpy conditions (0.3 to 0.4 MW of arc-heater power) resulted in the formation of Si droplets in the core of the reactor, thus reducing the collection efficiency for Si condensation on the reactor wall. The higher enthalpy condition (1.8 MW of arc-heater power) resulted in high gas velocities (100 m/s) in the reactor, limiting the collection efficiency of Si condensation to 20% in 8 m of reactor length.

It is, therefore, apparent that the optimal conditions for the operation of the arc-heater reactor lie somewhere between the two power levels. AeroChem is supplying the complete details of the computer codes and their usage in a supplement to the final report. The computer codes CHEMPART and GENMIX can therefore be used by JPL or Westinghouse.

Lamar University: Analyses of process system properties of chemical materials important in the production of Si were continued. Primary activities were initiated for physical, transport, and thermodynamic property data of Si.

Process design results for BCL process--Case A (two deposition reactors and six electrolysis cells) were presented previously. During this reporting period, major chemical engineering efforts were initiated on preliminary process design of the BCL process--Case B (one deposition reactor and two electrolysis cells). Chemical engineering design results are reported for Case B including raw materials, utilities, major process equipment, and production labor requirements for a Si plant of 1,000 MT/yr capacity.

For economic analysis, major efforts centered on cost sensitivity analysis for the BCL process--Case A for producing Si. Cost-sensitivity results are presented for the influence of primary cost parameters. For both 1975 and 1980 time periods, the results indicate that the cost-parameter influence on product cost is: plant investment (most), raw materials (intermediate), utilities (intermediate) and labor (least). For profitability, the results indicate a sales price of $14/kg (1980 $), at a 7.5% DCF rate of return on investment after taxes. These results suggest good potential of the BCL process for meeting the LSA cost goal of $14/kg (1980 $).

Massachusetts Institute of Technology: A contract review was conducted by JPL at the contractor's site on October 26, 1979. It was found that all the contractual activities were on schedule; technical results to date indicated that significant improvement in terms of lowering the operating temperature or pressure could be achieved for the hydrogenation of silicon tetrachloride and metallurgical-grade Si in the Union Carbide contract.

Extensive experiments were carried out on the hydrogenation of silicon tetrachloride to trichlorosilane. Reaction kinetic data were collected as functions of reactor temperatures, pressures, and hydrogen-to-silicon tetrachloride molar ratios. As expected, the reaction rate increases rapidly with increasing reactor temperatures. At higher hydrogen-to-silicon tetrachloride ratio, the conversion of trichlorosilane per pass increases. The effect of reactor pressure on the rate of the hydrogenation reaction was also obtained. The rate of approaching equilibrium at higher reaction pressure (500 psig) is somewhat slower than those at lower reactor pressure (300 psig).

JPL In-house Studies: Silane pyrolysis experiments with high throughput rate were conducted in the continous-flow pyrolyzer system at reactor temperatures of 600 to 700°C. Si product appears to be of a different texture, higher bulk density, and larger particle size in comparison with the Si particle product obtained in previous CFP experiments. Further experiments are under way to investigate the effectiveness of the current direction.

The 2-in.-dia stainless-steel fluidized-bed reactor was run for 51 minutes with 10% silane in the feed and with gas velocity 10 times minimum fluidization velocity. No agglomeration occurred and the conversion was greater than 95%. The deposition rate was about 2.6 g/min. The Si growth layer appeared to be dense and 15 to 25 μm thick.

The apparatus for conducting Si CVD experiments has become fully operational. Several experiments were made in a 1-in.-dia reactor to study critical concentration phenomena and homogeneous kinetics of silane pyroysis. A special substrate for heterogeneous pyrolysis of silane was designed and fabricated.

Fifteen contracts now in progress are listed in Table 1.

Table 1. Silicon Material Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SEMICONDUCTOR-GRADE SILICON PROCESSES	
Battelle Columbus Laboratories Columbus OH JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized bed reactor
Energy Materials Corporation Harvard MA JPL Contract No. 955269	Gaseous melt replenishment system
Hemlock Semiconductor Corporation Hemlock MI JPL Contract No. 955533	Modified Siemens process using SiH_2Cl_2
Union Carbide Corporation Tonawanda NY JPL Contract No. 954334	Silane/Si process
SOLAR-CELL-GRADE SILICON PROCESSES	
SRI International Menlo Park CA JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corporation Trafford PA JPL Contract No. 954589	Reduction of $SiCl_4$ by Na in arc-heater reactor
IMPURITY STUDIES	
Aerospace Corporation El Segundo CA JPL Contract No. 955201	Impurity concentration measurements by analytical photon catalysis
Lawrence Livermore Lab Livermore CA NASA Defense Purchase Request No. WO-8626	Impurity concentration measurements by neutron activation analysis

Table 1. Silicon Material Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
IMPURITY STUDIES	
Sah, C.T., Associates Urbana IL JPL Contract No. 954685	Effects of impurities on solar cell performance
Solarex Corporation Rockville MD JPL Contract No. 955307	Effects of impurities on solar cell performance
Westinghouse R&D Center Pittsburgh PA JPL Contract No. 954331	Definition of purity requirements
SUPPORTING STUDIES	
AeroChem Research Labs Princeton NJ JPL Contract No. 954777	Investigation of silicon halide/alkali metal flames
AeroChem Research Labs Princeton, NJ JPL Contract No. 954862	Development of model and computer code for description of silicon production processes employing silicon hydrides or halides
Lamar University Beaumont TX JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge MA JPL Contract No. 955382	Hydrochlorination of metallurgical-grade silicon

LARGE-AREA SILICON SHEET TASK

INTRODUCTION

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 low-cost, high-efficiency solar photovoltaic energy conversion. To meet the objective of the LSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each of producing large areas of crystallized silicon. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

Technical Goals: Current solar-cell technology is based on the use of silicon wafers obtained by slicing large Czochralski (Cz) or float-zone ingots (up to 12.5 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline silicon wafers is tailored to the needs of large-volume semiconductor products (i.e., integrated circuits plus discrete power and control devices other than solar cells). The small market offered by present solar-cell users does not justify the development of high-volume silicon production techniques that would result in low-cost electrical energy.

Growth of silicon crystalline 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), web-dendritic growth (WEB), low-angle ribbon growth (LAR), vacuum die-casting growth, etc., are possible candidates for the growing of solar cell material. The growing of large ingots requiring very little manpower and machinery would also appear plausible. It appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

Research and development on ribbon, sheet, and ingot growth plus multiple-blade, multiple-wire, and inner-diameter (ID) blade cutting, initiated in 1975-76 is in progress.

ORGANIZATION AND COORDINATION

When the LSA 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 now funded. After a period of accelerated development, these methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from 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 production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

Large-Area Silicon Sheet Contracts

Research and development contracts awarded for growing silicon crystalline material for solar-cell production are shown in Table 2. Preferred growth methods for further development during FY 79-80 have been selected.

Table 2. Large-Area Silicon Sheet Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SHAPED RIBBON TECHNOLOGY	
Arco Solar, Inc. Chatsworth CA JPL Contract No. 955325	Vacuum die casting
Energy Materials Corporation Harvard MA JPL Contract No. 955378	Low-angle Si sheet
Mobil Tyco Solar Energy Waltham MA JPL Contract No. 954355	Edge-defined film-fed growth (EFG)
Westinghouse Research Pittsburgh PA JPL Contract No. 954654	Dendritic web process
SUPPORTED FILM TECHNOLOGY	
Honeywell Corporation Bloomington MN JPL Contract No. 954356	Silicon-on-ceramic substrate
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem MA JPL Contract No. 954373	Heat exchanger method (HEM) cast ingot, and multiwire fixed abrasive slicing

Table 2. Large-Area Silicon Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
INGOT TECHNOLOGY	
Hamco Corporation Rochester NY JPL Contract No. 954888	Advanced Cz growth
Silicon Technology Corporation Oakland NJ JPL Contract No. 955131	ID wafering
Siltec Corporation Menlo Park CA JPL Contract No. 955282	ID wafering
Siltec Corporation Menlo Park CA JPL Contract No. 954886	Advanced Cz growth
DIE AND CONTAINER MATERIALS STUDIES	
University of Missouri Rolla Columbia MO JPL Contract No. 955415	Partial pressures of reactant gases
MATERIAL EVALUATION	
Applied Solar Energy Corp. (Formerly Optical Coating Laboratory) City of Industry CA JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca NY JPL Contract No. 954852	Characterization--Si properties
Charles Evans and Associates San Mateo, CA JPL Contract No. LK-694028	Technique for impurity and surface analysis
Spectrolab Sylmar CA JPL Contract No. 955055	Cell fabrication and evaluation

Table 2. Large-Area Silicon Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
	MATERIAL EVALUATION
UCLA Los Angeles CA JPL Contract No. 954902	Material evaluation
Materials Research, Inc. Centerville UT JPL Contract No. 957977	Quantitative analysis of defects and impurity evaluation technique

TECHNICAL BACKGROUND

Shaped-Ribbon Technology: Vacuum Die Casting Method--ArcoSolar. This technique to produce a shaped-ribbon material involves lowering a die into a crucible of molten silicon under vacuum. The liquid silicon is forced by argon or some other inert gas into the die where it remains until it has cooled and is then removed from the die. Single-crystal growth may be achieved by slowly solidifying the material from the apex of the die downward. SRI International has been subcontracted by Arco Solar to investigate various die materials. Phase I of the Project is a feasibility study requiring the demonstration of 25 cm^2/min throughput rate. The material must be capable of making 12% efficient 2 x 2 cm solar cells at AM1. Phase II is the scale-up phase requiring 7.9 m^2/h throughput rate on 12% efficient material.

Shaped-Ribbon Technology: Low-Angle Ribbon (LAR) Growth Process--Energy Materials Corporation. The LAR method involves growing ribbon material in an almost horizontal direction rather than the usual vertical direction. The advantage is that the heat of fusion is radiated from a larger area and the material can solidify much faster. This Project is doing a feasibility study requiring a demonstration of the technique.

Shaped-Ribbon Technology: EFG Method--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 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 7.5 cm/min and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterication of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

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

Supported-Film Technology: Honeywell. The purpose of this program is to investigate the technical and economic feasibility of producing solar-cell-quality sheet silicon by coating inexpensive ceramic substrates with a thin layer of polycrystalline silicon. The coating methods to be developed are directed toward a minimum-cost process for producing solar cells with a terrestrial conversion efficiency of 12% or greater. By applying a graphite coating to one face of a ceramic substrate, molten silicon can be caused to wet only that graphite-coated face and produce uniform thin layers of large-grain polycrystalline silicon; thus only a minimal quantity of silicon is consumed.

Ingot Technology: Heat Exchanger Method (HEM)--Crystal Systems. The Schmid-Vicchnicki technique (heat exchanger method) has been 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 might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchange ingot casting method can be applied to the growth of large shaped silicon crystals (>8-in.-cube dimensions) in a form suitable for the eventual 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.

Ingot Technology: Advanced Cz--Siltec and Hamco. In the advanced Cz contracts, efforts are geared toward developing equipment and a process in order to achieve the cost goals and demonstrate the feasibility of continuous Cz solar-grade crystal production.

Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Hamco will demonstrate the growth of 100 kg of single-crystal material using only one crucible by periodic melt replenishment.

Ingot Technology: Fixed Abrasive Sawing Technique (FAST) --Crystal Systems; Inner Diameter (ID) Sawing--Silicon Technology and Siltec. Today most silicon is sliced into wafers with an inside-diameter saw, one wafer at a time being cut from the crystal. Advanced efforts in this area are continuing. The multiwire slicing operation employs reciprocating blade head motion with a fixed workpiece. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheet, which is impregnated with diamond as an abrasive.

Die and Container Materials Studies--University of Missouri Rolla (UMR). In the crystal-growing processes a refractory crucible is required to hold the molten silicon, while in the ribbon processes an additional refractory shaping die is needed. UMR is investigating the effects of partial atmospheric pressures on the reaction at the contact interface between the molten silicon and fused silica.

Material Evaluation--Applied Solar Energy Corp. (ASEC), Spectrolab, UCLA, Materials Research, Inc., Cornell University and Charles Evans and Associates. 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 therefore is logical and essential that the various forms of low-cost silicon sheet be impartially evaluated in solar-cell manufacturing environments with well-established techniques and standards. Two solar-cell manufacturers, ASEC and Spectrolab, have been retained to satisfy this need.

A small ongoing effort is being supported at UCLA to provide evaluation of silicon sheet by device fabrication and electrical characterization.

Materials Research, Inc. (MRI), is currently under an expanded effort to survey techniques best capable of providing impurity characterization with desired spatial and chemical impurity resolution. This assessment program will be an extension of the current MRI sheet-defect structure assessment effort permitting a correlation of impurity distributions with defect structures.

Charles Evans and Associates and Cornell University are doing silicon sheet impurity analysis and structure characterization, respectively.

SUMMARY OF PROGRESS

Shaped-Ribbon Technology: Arco Solar (Vacuum Casting). SRI, subcontractor to Arco Solar, has selected coated graphite as their die material. The fused-salt liquid-barrier coating consists of a sodium silicate-sodium fluoride mixture and is used to prevent any silicon-graphite reaction. Using these dies, several silicon discs are being cast for solar cell fabrication at Arco Solar. Energy Materials (Low-Angle Ribbon): During the current feasibility study, EMC has grown ribbons up to 34 cm in length at rates up to 85 cm/min. Mobil Tyco (EFG): Mobil Tyco has reduced operation of the 10-cm growth cartridges to routine operation with 65 m of material having been grown during this period in the multiple machine and in the fully instrumented machine. The multiple machine has been operated in single-cartridge mode with melt replenishment. It is now being prepared for the three-cartridge multiple demonstration of 10-cm material by the end of the year. Studies of material quality and purity have continued, but only minor improvements have been made with efficiencies on a routine basis running from 9% to 10% AM1. Non-routine studies have produced 11% to 12% cells. Westinghouse (WEB): A 5-hour run using continuous melt replenishment has been demonstrated. The material quality from this run has been shown to be equal to or better than runs without melt replenishment.

Supported Film Technology: Honeywell (SOC). Honeywell has modified the skim coater to improve substrate manipulation and to avoid slipping of the substrates on the transport mechanism. Variations in the angle of skimming indicate little effect of this variation over a range of approximately 5° to 25°. Evaluation of the quality of skim-coated material has been hampered by the lack of large slotted substrates. These have been ordered and shipped, but have not yet been evaluated. Performance of diodes of skim-coated material has been 8% to 9%, which is considered encouraging since no special purification efforts were made during the setup for these runs.

Ingot Technology: Crystal Systems (HEM). Several large ingots, over 10 kg in mass, have been grown. The largest ingot cast to date was 16.3 kg, with dimensions 21 x 21 x 16 cm and no crucible attachment. Several ingots have been cast using upgraded metallurgical-grade silicon as the starting material. Nearly single-crystal ingots were produced, indicating that HEM may be a viable process for using low-purity material directly. Crystal Systems (FAST): Emphasis during this period has been on wire development, especially on the in-house impregnated wires. Several wire packs have been produced and are currently being tested. Hamco (Cz): Two 100-kg ingots were grown from 100% chunk polysilicon feedstock material at a throughput rate greater than 1.0 kg/h. Wafers taken at a random sampling from the first to the last ingot of the runs have consistently produced 15% to 16% efficient solar cells at AM1. Silicon Technology (ID Wafering): 10-cm ingots have been sliced using crystal rotation and automated recovery to transport and load sliced wafers into a cassette. Kerf thickness of 9 mils has been achieved. Slicing speeds of up to 1 in./min using rotation have been demonstrated with minimal edge chipping. Siltec (Cz): Two 150-kg demonstration runs are scheduled for the end of February, 1980. The program is running behind schedule. Siltec (ID Wafering): Runs producing slices 100 mm in diameter, 250 μm thick, and 200 μm kerfs have been demonstrated. Cutting feed rates were in the range of 12 to 13 mm/min. The test runs were performed with 12-in. blades and 76 μm core thicknesses.

Die and Container Materials: University of Missouri Rolla (UMR). Investigations of the effect of partial pressures of oxygen on devitrification of silica in contact with molten silicon have been completed. The results indicate a trend toward a greater degree of devitrification at lower oxygen partial pressures. Measurements of the effects of oxygen partial pressure upon silicon ribbon were conducted at Mobil Tyco.

Material Evaluation: Applied Solar Energy. Figure 1 summarizes the average efficiencies of various silicon-sheet materials processed by ASEC. Cornell University: No impurity precipitates were found in EFG material that was investigated using the transmission electron microscope (TEM). The electron-beam-induced current (EBIC) studies showed that the twin boundaries contain both electrically active and inactive sections. Grain-boundary passivation using hydrogen was only partially successful. The spatial distribution of dopants and impurities were studied with the SIMS technique. Undoped ribbons indicated an undetectable level of molybdenum, aluminum and boron while doped ribbons indicated a boron content of $2x10^{17}/cm^3$. Spectrolab: Table 3 summarizes the results obtained for various sheet materials. UCLA: The development of a new technique to measure minority carrier diffusions lengths has continued during this period. Materials Research, Inc.: Several hundred cm^2 of various silicon-sheet materials have been quantitatively characterized for a variety of structural defects.

Procurement Status: Add-on contracts are being negotiated for the following contractors: Energy Materials Corp., Crystal Systems, Honeywell, Materials Research, and Mobil Tyco Solar Energy Corp. UCLA: A four month, no-cost extension has been granted. Varian: The final report has been received by JPL.

JPL In-House Activities: Laboratory facilities for cell processing are nearly complete. The only required items lacking are a vacuum pump for the yellow room and a recirculating water supply for the vacuum evaporators. Baseline cell processing has begun and 13% AMO cells (28°C) have been fabricated (2 x 2 cm). Problems with AR coating are being investigated. HEM cast material is being processed. Initial oxide growth studies indicate this material yields poor cell efficiencies.

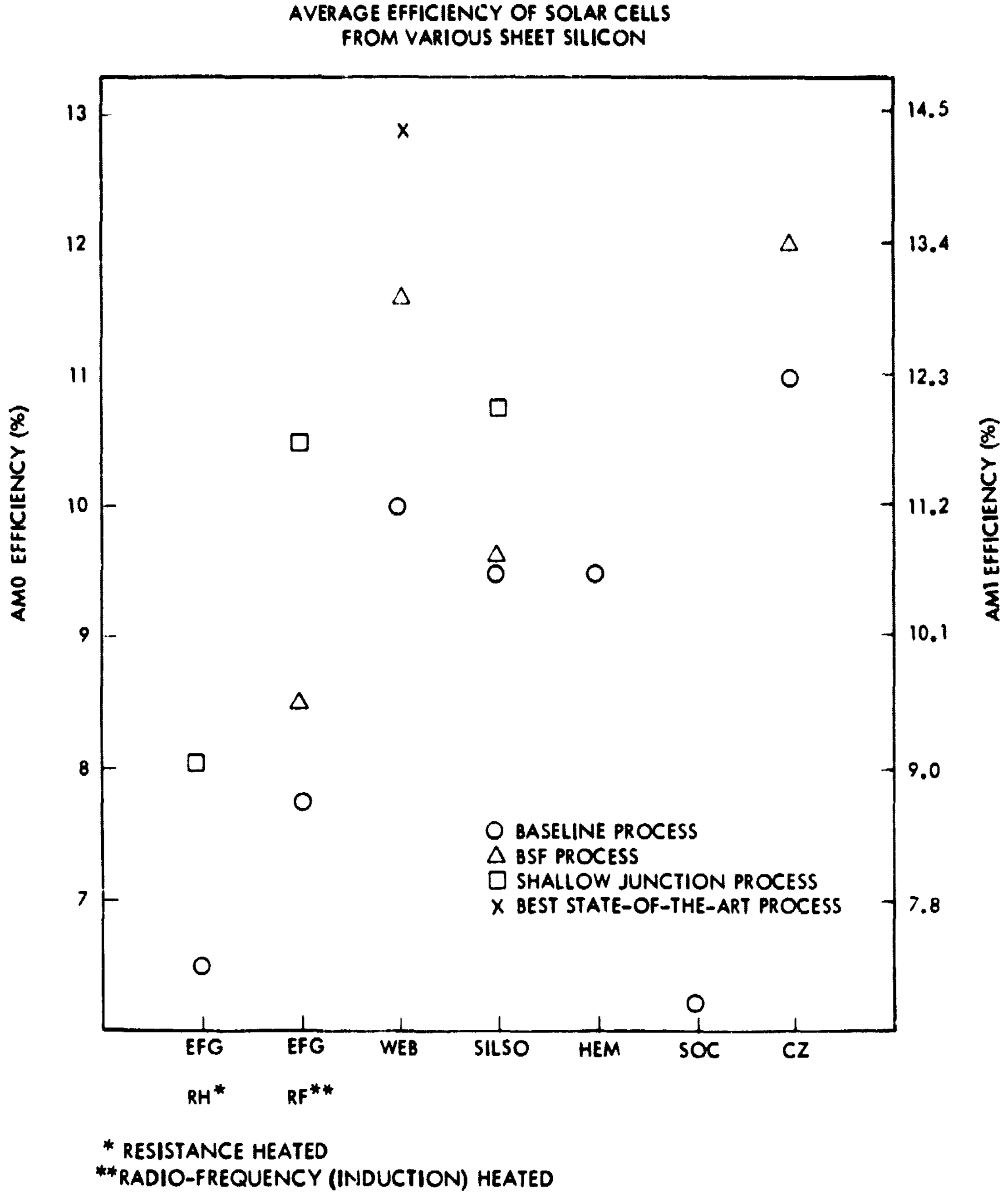


Figure 1. Applied Solar Energy's Material Evaluation

Table 3: Spectrolab's Material Evaluation

I-V DATA FOR HIGHEST EFFICIENCY
CELLS IN EACH MATERIAL

MATERIAL	S/N	I_{sc} MA	V_{oc} MV	P_{max} MW	FF	%	REMARKS
RTR	5	95	559	39.1	.74	7.2	Baseline, RTR-2
EFG(RH)	D	116	537	45.5	.73	8.4	Baseline, 184-36
EFG(RF)	46	125	567	53.0	.75	9.8	Baseline
WACKER	4	134	554	57.3	.77	10.6	Baseline
HEM	43	137	573	60.8	.77	11.2	Textured, X-tal #857
Web	2	149	584	65.3	.75	12.0	BSF, strip Re 25-23
Hamco	3T21A	150	583	67.3	.77	12.4	Textured, Top, X-tal #3
Control	3	158	607	73.5	.77	13.6	T & BSF, run WO-1

ENCAPSULATION TASK

INTRODUCTION

The objective of the Encapsulation Task is to develop and qualify one or more solar array module encapsulation systems that have demonstrated high reliabilities and 20-year lifetime expectancies in terrestrial environments, and are compatible with the low-cost objectives of the project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem has been the development of high-transparency materials on the sunlit side that also meet the LSA Project low-cost and 20-year life objectives. In addition, technical problems have occurred at interfaces between elements of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections.

The encapsulation system also serves other functions in addition to providing the essential environmental protection: e.g., structural integrity, electrical resistance to high voltage, and dissipation of thermal energy.

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. These efforts can be divided into two technical areas:

(1) Materials and Processes Development--This effort includes all of the work necessary to develop, demonstrate, and qualify one of more encapsulation systems to meet the LSA Project cost and performance 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 analyses and testing to develop optimized module designs.

(2) Life Prediction and Material Degradation--This work is directed toward the attainment of the LSA Project 20-year minimum life requirement for modules in the 1986 time frame. It includes the development of a life prediction methodology applicable to terrestrial photovoltaic modules and validation by application of the methodology to a specific photovoltaic demonstration site. Material degradation studies are being conducted to determine failure modes and mechanisms. This effort supports both the materials and processes development work and the life-prediction methodology development.

SUMMARY OF PROGRESS

Materials and Process Development

A baseline ethylene/propylene rubber (EPR) pottant was developed by Springborn Laboratories. EPR is an alternative to EVA, also requiring vacuum lamination. The cost of EPR at a production level of 10 million pounds per year is approximately $1.09 per pound or $0.10 per square foot for a 20-mil-thick sheet versus $0.95 and $0.095 for EVA. EPR is considered ready and is now available for industrial evaluation.

Dow Corning developed a family of low-cost silicone/acrylic films incorporating a flexible UV screening agent. The techniques and details of producing these films are being transferred to Springborn Laboratories for continued development and subsequent production scale-up.

Dr. Edwin P. Plueddemann of Dow Corning has developed a "self-priming" coupling agent for EVA that is incorporated directly in the EVA formulation. He is developing a similar coupling agent (primer) for EPR. Dr. Plueddemann's first annual report on chemical bonding technology has been published (Reference 1).

Fifteen full-size (4x8 ft) glass-fiber-reinforced concrete (GRC) substrate panels were manufactured by MBAssociates using semi-automated equipment and procedures. One of these was tested and passed JPL static loading requirements. The other 14 were delivered to JPL. Two of these (one covered with encapsulated cells) were displayed at the JPL 14th Project Integration Meeting (PIM). The estimated cost to produce such panels with encapsulated cells including total field installation cost (but not including the cost of cells and interconnects), at a rate of 15 mW/yr is $6/ft^2.

Abrasion resistance and transmission tests have been completed on two types of anti-reflection coatings for soda-lime glass at Motorola: acid etching and etched silicate coatings. Acid etching produces AR coatings on glass with 99% transmission but with marginal abrasion resistance. Glass samples produced by the etched silicate coating method show lower transmissions, approximately 96%, but have excellent abrasion resistance. Cost effectiveness of the two competing methods is being evaluated.

Spire has completed semi-automation of the electrostatic bonding (ESB) process to the point where production of 6 x 6-inch, 4- and 6-cell minimodules, with cells electrostatically bonded to Type 7070 glass, is routine. Yield is approximately 90%. Future work will be concentrated on the development of mesh contacts and the development of low-temperature electrostatic bonding using interdigitated back contact cells.

Contracts with Illinois Tool Works, to develop ion plating methods, and with Spectrolab, to design and optimize one or more encapsulation systems, have been initiated.

Life Prediction and Material Degradation

Mini-modules (12 x 16 in.) incorporating six different encapsulation designs were received from two manufacturers. Samples of the six designs are being assembled for placing in outdoor exposure at three Southern California sites: Point Vicente, Goldstone, and JPL. Outdoor weathering racks have been installed at JPL and installations are being completed at the other two sites. Samples of the designs are being subjected to the JPL qualification tests (temperature cycling and high humidity exposure). In addition, NOCT is being determined for each design. All designs are encapsulated with ethylene/vinyl acetate (EVA) pottant, with various combinations of superstrate, substrate, film/foil/film back covers, Mylar back covers, and Korad acrylic film front covers. Electrical output will be determined as a function of site, time of weathering, and soiling over a period of approximately two years.

Rockwell Science Center installed two corrosion monitors at the Mead, Nebraska site. One is covered with Sylgard 184 encapsulant while the other is unprotected. Their comparison will show the protective behavior of the encapsulant. An improved corrosion model was developed and will be applied to the Solarex and Sensor Technology modules at the site.

Construction has begun on a laboratory test simulator for the Mead NB site to control atmosphere (including corrosive gases), temperature, moisture, and insolation. The simulator will be used to simulate or accelerate Mead climate conditions to complement field data from modules previously deployed with special corrosion monitors.

The first phase of a modeling effort to demonstrate the feasibility of a finite element approach to predicting stress distributions in solar cell modules has been successfully completed and reported (Reference 2). The second phase to develop an automated input program was begun. An interactive graphic program, Unitstruc II, written by Control Data Company, was chosen and various sample problems are being run to develop techniques.

The Battelle final report on the development of an accelerated test design for predicting service life of the array at Mead has been published (Reference 3).

A report has been released describing a UV reactor that was designed and constructed at JPL (Reference 4).

References

1. Edwin P. Plueddemann, "Chemical Bonding Technology for Terrestrial Solar Cell Modules," LSA Project Report No. 5101-132, September 1, 1979.

2. JPL IOM 3545:79:211, C. P. Kuo to Cliff Coulbert, "Report of Thermomechanical Modeling of Solar Cell Modules," September 20, 1979.

3. G. B. Gaines et al, "Development of an Accelerated Test Design for Predicting the Service Life of the Solar Array at Mead, Nebraska," Report No. DOE/JPL-954328-79/13, June 7, 1979.

4. E. Laue and A. Gupta, "Reactor for Simulation and Acceleration of Solar Ultraviolet Damage," DOE/JPL 1012/31. LSA Project Report 5101-135, JPL Publication 79-92, September 21, 1979.

PRODUCTION PROCESS & EQUIPMENT AREA

AREA OBJECTIVES

As can be seen by Figures 2, 3, and 4, the first two major categories of objectives of the PP&E Area are being successfully completed.

It is appropriate to point out that Phase I, Process Assessment, although completed in its major effort, is not a closed subject. Due to the nature of the industry, it is entirely possible that processes will be developed in the near future that will replace those selected. This is also true of Phase II, Part 1. Both of these areas are considered dynamic and subject to being reopened on an if-needed basis.

Phase III has been started by outlining the requirements of the proposal. Some of those requirements are stated in the Documentation section of the Summary of Progress.

SUMMARY OF PROGRESS

Some of the contracts listed in Table 4 were scheduled to have ended within this reporting period but for a variety of reasons have been extended. In some cases this was caused by logistical problems in some funding and, in at least one, additional work was required. In all cases, except those in which additional work was requested, the extensions were on a no-cost basis.

Process Sequence Development

Westinghouse has completed fabrication of panels made using dendritic web cells. These have been submitted to NASA Lewis for preliminary electrical testing. They will then be sent to JPL for test verification and environmental testing.

At Westinghouse the use of an arc-spray technique for forming aluminum back-surface fields has proven as successful as has evaporating, sputtering or screen printing of the aluminum. This is potentially more cost-effective than the others and will be costed out in the final form of the required SAMIS data.

SAMIS costing-sensitivity analysis by Westinghouse has given the following results:

(1) For $\$10 \times 10^6 \pm 10\%$ capital expenditure, each $\$10^6$ of capital adds \$0.03/Wp to the selling price.

(2) In the 70% to 90% yield range, each 10% increase in yield decreases the selling price by \$0.07/Wp.

(3) When web width is decreased from 5.0 cm to 2.5 cm, the selling price is increased by \$0.07/Wp (assuming equal yields and efficiencies).

(4) In the range of 10 to 15% panel efficiency, for each 1% increase in efficiency the selling price is decreased by \$0.06/Wp (assuming equal yields).

Table 4. Production Process and Equipment Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Applied Solar Energy Corp. City of Industry CA	954830	Slicing
Applied Solar Energy Corp. City of Industry CA	955118	Ion implanter investigation
Applied Solar Energy Corp. City of Industry CA	955217	High-efficiency solar module
Applied Solar Energy Corp. City of Industry CA	955244	Low-cost contacts
Applied Solar Energy Corp. City of Industry CA	955423	Laboratory services
Arco Solar, Inc. Chatsworth CA	955278	Automated solar-panel assembly
Bernd Ross Associates San Diego CA	955164	Thick-film solar cell contact
Kinetic Coatings Inc. Burlington MA	955079	Ion implantation
Kulicke & Soffa Ind Morsham PA	955287	Automated solar module assembly
MBAssociates San Ramon CA	954882	Phase II, process development
Motorola, Inc. Phoenix AZ	954847	Phase II, process development
Motorola, Inc. Phoenix AZ	955324	Etch-resistant wax patterns

Table 4. Production Process and Equipment Contractors (Continued)

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Motorola, Inc. Phoenix AZ	955328	Thin substrate
Photowatt International, Inc. Chatsworth CA	954865	Phase II, production process
Photowatt International, Inc. Chatsworth CA	955265	Polysilicon solar cell
Photowatt International, Inc. Chatsworth CA	955266	Si wafer-surface texturing
RCA Princeton NJ	954868	Phase II, process development
RCA Princeton NJ	955342	Megasonic cleaning
Sol/Los, Inc. Los Angeles CA	955318	Metallization
Solarex Corp Rockville MD	954822	High-density panels
Solarex Corp Rockville MD	954854	Phase II, process development
Spectrolab, Inc. Sylmar CA	954853	Phase II, process development
Spectrolab, Inc. Sylmar CA	955298	High-resolution contact development
Spire Corp Bedford MA	954786	Ion implanter
TBA Los Angeles CA	955519	Development of technical manuals & mathematical manuals
Texas Instruments Dallas TX	954881	Cell development--tandem junction cell
Univ. of Pennsylvania Philadelphia PA	954796	Automated array
Westinghouse Research Pittsburgh PA	954873	Phase II, process development

Figure 2. Production Process and Equipment Area Phase Schedule

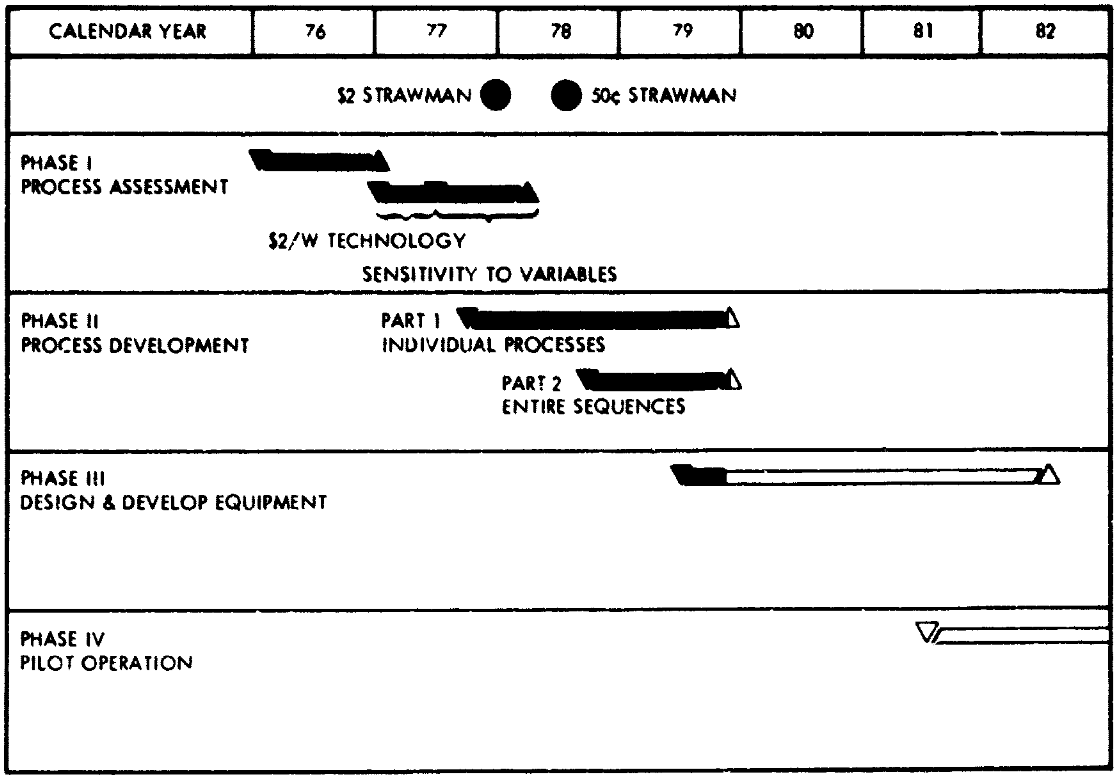


Figure 3. Production Process and Equipment Area Major Milestones

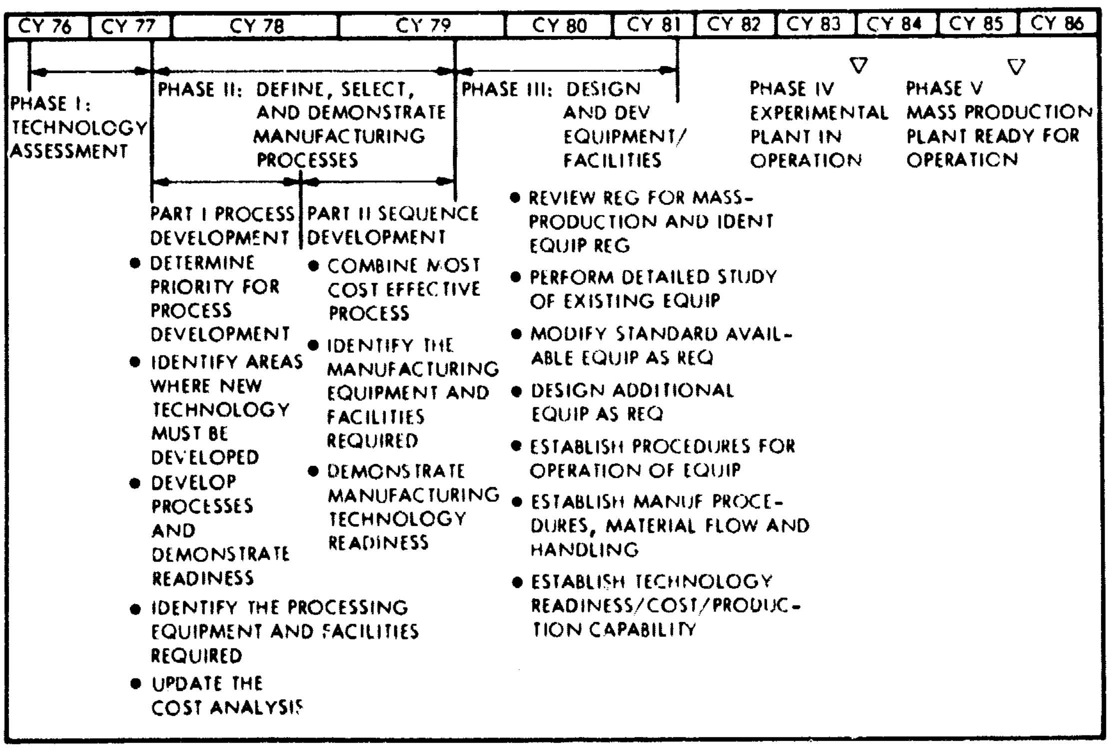
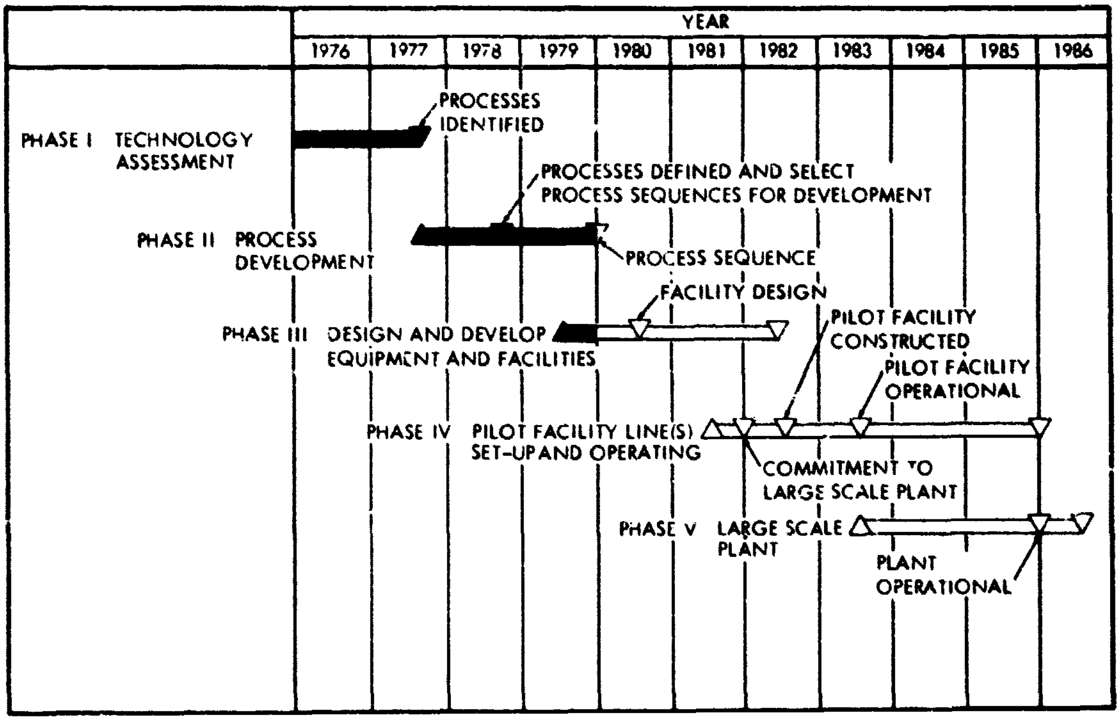


Figure 4. Production Process and Equipment Schedule



RCA has received a partial shipment of dendritic web material from Westinghouse. They are outlining a process sequence which will include their screen printed metallization.

Surface Preparation

Photowatt International reports a uniform 38% output enhancement using spray-on titanium isopropoxide as developed by RCA under another PP&E contract. This is in line with the results reported by RCA on non-texture-etched cells.

The enhancement of texture-etched cells is 8%. Previous reports have reported problems in this area when an investigation was made by Photowatt and Spectrolab together. The change has been due to an intermediate step of spray-on, or dip in, n-butyl acetate.

Photowatt International has submitted the SAMICS Format A's covering the four surface-texturing processes to the formal review board. Work is being completed on the draft final report.

Motorola has investigated Apiezon W, Multiwax and glycol phthalate waxes with methylene chloride, mineral spirits and acetone as solvents for formulation of inks. The only conclusion reached so far is that methylene chloride is the best solvent; mineral spirits left too many residuals and acetone was too volatile.

Spectrolab has continued their investigation of plasma etching on front surfaces. They have found that inclusion of small amounts of oxygen in the Freon 14 enhances its ability to remove diffusion oxides. There is still surface pitting with Freon 14, however. By substituting sulfur hexafluoride the pitting is greatly reduced or eliminated.

The effects of the etching gas used when a small amount of the surface layer is removed are markedly different.

When Freon 14 is used the increase in short circuit current is in the 9% range. Spectral analysis shows this to be a fairly uniform enhancement over the major portion of the range. When sulfur hexafluoride is the etchant gas, however, the predominant response is in the shorter wavelengths and is still in the 9% range.

One possible explanation of this is in the pitting found with the Freon. If the pits are acting the same as textured surfaces it would be expected that this would be true over the entire range since all wavelengths would be similarly treated. The effect from sulfur hexafluoride etching, which takes four times as long but does not produce the pits, is the same as that which could be expected from removal of the dead band.

When tests were run using Freon 23 to remove the diffusion oxide, two problems occurred: the plasma did not completely remove the oxide, and the removal that did occur was not uniform. Fair uniformity occurred in an area about 2 in. in dia at the center. After that there was a sharp fall-off. This is difficult to explain since Freon 23 is standardly used for this purpose. Further evaluations will be made.

Junction Formation

Photowatt International, Inc. has tested the first sprayed-on metallic-aluminum back-surface field cells. On base material in the 3 to 8 Ω-cm range, the V_{OC} is clustered around 580 mV. When 10 to 15 Ω-cm material is used the V_{OC} climbs to between 605 and 610 mV. The previously authorized aluminum spray-on modification to the existing machine has been designed and is currently being fabricated by Advanced Concepts.

Concurrent with the spraying of aluminum, an experiment to verify the reduction of bowing on printed back-surface fields by use of the Spectrolab gridded pattern was conducted. The experiment confirmed that bow was reduced on 4-in. wafers from 0.015 in. average to 0.004 in. average. It was noted, however, that the wafers that had a sprayed-on BSF had no bow. This is being investigated.

Photowatt International, Inc. has produced highly uniform cells using Borofilm to produce back-surface fields. The concentration used was 5×10^{20}. Over a 50-cell lot the V_{OC} was 60 mV $\pm$2mV. The average curve fill factor was 0.76.

In companion experiment, the back-surface field was screened on using the Spectrolab formulation for aluminum paste. There was an inconsistency in V_{oc} with readings from 570 to 620 mV.

Work has been completed on the Spire contract for pulsed-electron-beam annealing. A final report is being drafted. The cells and the analytical data have been shipped to JPL for analysis.

Metallization

Motorola has successfully plated nickel directly onto silicon electrolytically without an intermediate electroless palladium step. In addition, they have plated a layer of copper over the nickel and heat-soaked the entire system at 300°C for 30 min with no ill effects.

This technique has been used to fabricate several solar cells utilizing Motorola's silicon nitride AR-coating/masking method to define the metallization pattern. The cells produced were comparable in performance to those made with the standard electroless palladium metallization method, which indicates that the nickel does provide an adequate barrier against copper migration into the silicon.

The spray-on copper metallization being done by Photowatt International, Inc., in cooperation with Advanced Concepts, has been accomplished. Although they have been fabricated, the cells have not yet been evaluated.

Applied Solar Energy Corporation has ascertained that nickel is the most practical, most cost-effective barrier to copper migration.

ASEC has constructed a test matrix to test this premise. The basic chromium/palladium/copper plating system will have nickel inserted just before the copper. The cells produced will be soaked at various temperatures and then tested for all parameters.

They are also continuing to develop and test the print-on mask using HB Printing Plating Resist. Promising results have been produced repeatedly, using a 200-mesh screen. Copper lines of less than 0.005 in. width have been produced using HB mask.

Sol/Los, in conjunction with Dr. Goldman, an assistant to Dr. Wolf of the University of Pennsylvania, determined that silver metallization would cost $0.40/W on a megawatt production basis whereas the molybdenum system would cost approximately $0.015/W.

Sol/Los has delivered five ounces of their molybdenum/tin ink formulation and one ounce of their powder (without the binder) to JPL. The plans are to use the screenable ink to produce cells and verify the reported mechanical and electrical properties. Part of the powder will be used in analytical studies and a part of it will be delivered to the Ferro Corporation for studies to see if there is any incompatability between it and their Midfilm technique. Testing will occur after the previously reported sheet-resistance problem has been straightened out.

The mechanical and electrical tests scheduled for this period by Sol/Los have been completed. Mechanical contact of the ink to silicon is reported as being equal to the best nickel contact and superior to screened silver. Electrical tests indicate consistently low levels of junction leakage and contact resistance.

The entire system was demonstrated to JPL during this report period.

Sol/Los reports encountering a problem when their molybdenum/tin formulation was applied to live cells which had had an aluminum back-surface field incorporated.

After a firing cycle at 700°C was used, cells metallized on the insolated side were shorted. A speckled appearance on both sides of the wafer led them to suspect that aluminum had adhered to the surfaces and this had subsequently been diffused through the junction at 700°C. Processing of a lot of 10 with a maximum of 525°C exposure produced no shorting and the I-V curves were good. The cells were mechanically weaker, however.

Bernd Ross Associates has successfully produced a copper metallization using lead as a frit. Excellent adhesion to the silicon surface was demonstrated by the fact that approximately 20% of the metallized surface pulled a significant quantity of silicon with it when pull tests were performed.

The pull test results allayed initial concerns that soldering would leach the lead out of the copper-lead intergranular alloy that occurs at the copper particle interfaces.

After metallization, firing in hydrogen reduces the oxidized copper surface to a bright elemental one providing an easily soldered connection using tin-lead eutectic solder.

The controlled atmosphere firing furnace is operational at Bernd Ross Associates. Silver fluoride-fluxed silver inks were fired containing GeAlGa (p-type) and GeSb (n-type) additions (5%). These experiments resulted in poor surface bonding to the silicon.

A variety of nickel-based inks containing 5, 10, 20% lead or 5, 10, 20% tin was fired in nitrogen, hydrogen and 10% hydrogen/90% nitrogen. Experiments were performed up to 700°C and no sintering was evidenced. These inks also had silver fluoride added as a fluxing agent.

The RCA-developed thick-film screen-printed metallization appears to be less compatible with ion-implanted cell junctions than with diffused junctions. Average efficiencies of small cell lots was

11.7% AM1 (12% based on exposed silicon) for cells with diffused junctions, compared with 6.7% AM1 (7.3% based on exposed silicon) for cells with ion implanted junctions.

A contract has been executed with Solarex Corporation to optimize and environmentally test the product of a nickel-plating bath. The Program and Process Plan, recently submitted to JPL, appears to need only minor modifications and, as a result, work is proceeding on the initial phases.

Spectrolab has encountered a series resistance problem on their work with Ferro Corporation.

Using Ferro's patented Midfilm process, cells have been produced having silver metallization; unfortunately, voids have shown up and series resistances have been in the 300 mΩ/unit range vs the expected 100 mΩ. One possible reason is that the powder was applied at Ferro in Cleveland, OH and the firing occured at Spectrolab in Sylmar, CA; there could have been in-transit damage. To counter this problem in the future, Spectrolab is sending an engineer to Ferro for technique training.

In spite of these problems the overall yield showed >20% to be in the ≧15% efficiency category.

Non-noble metal systems of copper/tin, nickel/tin and molybdenum/tin with Thick Film Systems frit are being formulated for Phase 2 analysis.

The new infrared furnace has been installed at Spectrolab. Initial tests show that firing of the screened-silver front contacts in this furnace produced units with efficiencies of approximately 15%, which is as good as or better than those produced in a tube furnace. When the same thing was tried on aluminum paste, however, the open-circuit voltages were too low. If the drying occurred in an air-circulating oven and firing in the IR oven, the results were good. Spectrolab believes that further work must be done on the IR-drying cycle and that this technique is a viable one, once the proper cycle is evolved. The front contact screen mask has been redesigned to produce a wider ohmic bus to reduce series resistance in a modified cell at Spectrolab.

Assembly and Test

RCA has fabricated two 4 x 4 ft solar modules, and several smaller units, with the double-glass PVB laminate auto-windshield technique using an autoclave. These modules will be exposed to a standard battery of environmental tests at JPL.

Applied Solar Energy Corporation is continuing to make progress toward development of a 3-in. dia, p on nn^+ high-efficiency cell. Results of a most recent lot of development cells include: 20 wafers; 19 finished cells; 15 cells with good performance η_{max} = >15.6%, η = 15.1%, η_{low} = 14.7%.

A contract extension has been released for signatures at Applied Solar Energy Corporation. The modification provides $30,500 of added funds to cover further cell development on their 14% module contract. The completion date will be extended to April, 1980.

Module Development

During this period Texas Instruments reported a probable cost overrun of $52K to satisfy all delivery requirements on this contract for development of large-area Tandem-Junction Cells (TJC) and Tandem-Junction Modules (TJM). No fully assembled modules will be delivered unless the overrun is funded. TI has attributed the overrun to their original underestimate of material costs plus current cell-process problems (an entire production lot of 100 large-area TJCs was recently lost). A final report, describing all progress made under the contract, will be published.

RCA has completed three double-glass modules. They will be submitted to JPL for evaluation and life testing.

Advanced Equipment Design

Advanced Concepts has notified Photowatt International, Inc. that the metallic-aluminum spraying machine will be delivered in late January. The delays have been caused by their suppliers not keeping to schedule.

Cober Electronics, through a subcontract with Photowatt International, Inc., has made considerable progress on the hardware associated with their microwave process. A horn has been developed and is functional. It has been applied to continuous energy only. A tentative design of a full-scale system has been completed as has a design for a cylindrical wave-guide that has the potential for more uniform wave delivery.

In another phase of the effort, work is being performed on an interference fringe technique of depth-of-penetration control of pulsed microwaves. A variable power supply and the material required for the balance of the system have all been ordered. This is to be a prototype of the final system.

Cober Electronics has reported that heating with microwaves appears to be uniform across the surface of the 3-in. wafer. The shape of the horn has been established and they are now working on a power/frequency matrix to produce the required skin effect. Samples of sprayed-on dopant and printed aluminum have been sent to them for testing.

A low-temperature (900°C) version of the microwave system for alloying and sintering of metallization has been constructed by Cober Electronics. The penetration depth and uniformity are good at 2.45 GHz. Further testing is now being done.

A computer simulation of a cooling jacket arrangement for one side of the wafer holder shows this system to be feasible. This remains to be proven in actual tests, however.

MBAssociates reports that they are nearing completion on their cell-preparation station. All component parts have been purchased or manufactured and tested. One of the components, the solder paste dispenser, has been found to give very uniform results over a wide range of dispensing rates.

Bonding methods for the robot end effectors are being investigated. Good solder bonds have been obtained with resistance-heated electrodes. These require precision placement, however; therefore, investigation is being made into induction-type heating electrodes. These are showing promise.

During early October an internal design review was completed at ARCO Solar's Albuquerque Laboratory. Significant progress has been made on the design of the automated soldering machine. Detail layouts have been completed on the conveyer/transport system that presents wafers to the soldering station. The ribbon-feed mechanism and ultrasonic cleaning equipment have been ordered.

ARCO Solar, Chatsworth, committed to delivery of several thousand final-configuration production cells by 19 October. These are being used for final machine development work at Albuquerque Laboratory. The cell back is an interim design but the contact/interconnect point geometry will be the same as the final one.

The target date for delivery of the completed soldering machine to ARCO in Camarillo has slipped to 18 January 1980. A contract modification that will insure contract completion without additional JPL funds being required and without future scope deletions is in process.

Albuquerque Laboratory of ARCO Solar has successfully completed several minidesign demonstration tests relating to the automated soldering machine. These included: (a) cell cassette unloading; (b) cell alignment; and (c) interconnect ribbon guiding. Norbell, Daytona Beach, Florida, has been selected to supply the ribbon supply and cut-off mechanism.

ARCO Solar, Chatsworth, is continuing soldering development. Twenty cell/interconnect samples were fabricated using the RF induction coil/roller contact method. All samples showed peel strength in the range of 300 to 350 grams.

The full RCA megasonic system is now functional and is being optimized. Preliminary tests indicate that a mechanism is needed for deflecting the wafers while they are progressing through the drying tunnel to promote the removal of water drops from the slots in the carriers. A pair of deflectors was installed and found effective.

Cleaning and drying wafers in 3/16 in. spaced carriers at a speed of 12 cm/min have been tested successfully in ambient conditions with an equivalent rate of 1100 wafers/h. To achieve the projected 2500 wafers/h rate would require either a second drying module or halving the spacing between wafers and increasing the speed to 14/cm/min. Quartz carriers with 3/32 in. spacing are to be delivered soon.

Fluoroware Corporation is now offering these units (in various configurations) for sale to the industry.

Another contract with RCA has been extended for three months to the end of March, 1980. This was done at no additional cost to permit further development of their mass module/interconnect soldering technique using IR lamps. In addition, they will attempt to develop a plasma-etch technique for junction (edge) cleaning.

Module fabrication has been reduced from 20 to 10 because of the lack of availability of silicon sheet materials from a supplier.

Kulicke & Soffa Industries has completed both the theta orientation and flux application station and the vacuum pick-up and lance assembly. The string conveyer and the first interconnect station are in final stages of completion.

Kulicke & Soffa reports having been contacted by two companies with inquiries about the potential procurement of sub-systems developed on their contract. The areas of interest are the vacuum pickup lance subsystem and the tabbing (interconnection) section. Work on the balance of the system and integration of the subsystems continues without serious problems; the previously reported problem with induction-heating soldering combined with the cell-supply problem have caused a delay in the scheduled progress, however. This has resulted in an approved request for a no-charge, three-month extension of the contract. The supplier is Applied Solar Energy Corporation.

Documentation

Theodore Barry and Associates have received the corrections to the handbook draft. A review was conducted with the JPL Technical Manager and the proper corrections will be made.

A new contract for continued consultation is in the mail to the University of Pennsylvania.

Westinghouse has submitted their first-draft final report on their process-sequence development contract.

Phase III general conditions have been outlined:

- Technical readiness to be demonstrated by the end of FY82
- Entire process sequences to be automated (if cost effective)
- Proposers are to select starting silicon sheet material of their choice and use values in SAMIS cost account catalogue (or derive in extensive detail if not in catalogue)
- More than one contract award may be requested
- Cost-sharing proposals are appropriate.

Miscellaneous

The draft form of the final report from Applied Solar Energy Corporation on their efforts to produce cast silicon has been submitted. The report's final conclusions include the statement that casting silicon sheet appears to be feasible in spite of the fact that functional solar cells have not been produced using this material. It further states that more work must be done on the mold materials and on improvement of the casting equipment.

Spectrolab has run comparisons among cells made from three different sources of silicon. Wacker material produced cells that were consistantly 20% higher in short-circuit and power-point currents when compared with cells produced from Texas Instruments material. When Smiel material was used, the cells were about 10% better than TI's.

Spectrolab has made an analysis of diffusion lengths vs short-circuit current. For diffusion lengths of less than 60 μm there appears to be a marked reduction in I_{sc}.

As a result of this investigation, they attempted to incorporate a diffusion-length requirement in their procurement specification. They found, however, that vendors will not accept such a specification for resistivities less than 15Ω-cm.

Motorola has concluded that cells of 0.004 and 0.008 in. thickness can be processed under the same conditions as the 0.013-inch cells.

ENGINEERING AREA

INTRODUCTION

During this reporting period work has been focused on array design and engineering, reliability and durability requirement development and standards. Detailed status of the engineering area contracts (listed in Table 5) was reported in the 14th PIM handout.

SUMMARY OF PROGRESS

Array Design and Engineering

Series/parallel analysis for multi-cell failures in intermediate load applications, which was initiated during the last reporting period, continued. Progress was made on development of a diffuse spectrum model to be incorporated in the spectral analysis computer program. These efforts were directed toward preparation of an in-depth presentation for the 14th IEEE PV Specialists Conference. In conjunction with these presentations, the results of the series/parallel investigations were distilled into preliminary guidelines applicable to circuit design of modules and array subsystems for presentation at the 14th PIM.

Work was initiated on development of test methods and devices to measure the performance of the foundations, structures and panel frames for low-cost utility application array structures. The design and fabrication of a full-scale prototype (8 x 16 ft) array panel structure was completed. The panel successfully withstood a 50 PSF uniform pressure loading test. The panel was displayed at the 14th PIM. Kaiser Steel Co. provided mass-production cost estimates for this panel structure and an alternative version based on this concept but using potentially cheaper-to-produce sections. A quarter-scale model of the panel, including foundations, also was fabricated.

Work was begun on the flat-plate PV thermal-collector design task. During this period activities were concentrated on investigating optimal temperatures of PV/T collectors for heat-pump applications and on the effect of cover glass on PV/T-collector performance.

Reliability and Durability

The IR camera recently acquired by the Engineering Area was successfully used to map the hot-spot problem at Mt. Laguna; it provided useful data on numbers of hot cells and their temperatures. Field mapping and controlled laboratory experiments are being continued to understand further the hot-spot heating problem and to aid in the development of a new module qualification test to eliminate the problem in future module designs.

Engineering Area personnel actively participated in the evaluation and analysis of module design/performance for the

Mt. Laguna array installation and for the planned PRDA 38 applications. Support included series/parallel analyses of module/array circuitry, performance degradation prediction, cracked-cell probability studies, I-V curve translation and analysis, and design of performance degradation exploratory tests.

In the area of module testing, planning for a long-duration module temperature soak test was initiated. The purpose of this effort is to develop low-cost testing methods for detecting module design deficiencies and degradation mechanisms that may not be revealed during current qualification testing. An outdoor "hotbox" concept is being pursued.

Work continued on the Phase II module-soiling investigations. Efforts centered on comparing the differences between the relative normal hemispherical transmittance (RNHT) and the integrated hemispherical transmittance (measured at Battelle Pacific Northwest Laboratories). The values measured at Battelle show, in most cases, a greater loss in hemispherical transmittance than expected. Also during this reporting period, material samples from four of the seven outdoor exposure sites were returned to the materials laboratory for transmittance measurements. The task report documenting the Phase I soiling ivestigations is in final review.

A fracture mechanics, cell testing and analysis program for determination of cell crack strength characteristics has been initiated with several of the module manufacturers. A series of detailed fracture mechanics tests is planned and a large quantity of samples have been received. The samples include specimens in varying stages of completion (from wafer to completed cell) taken off the production line at selected points in the cell-processing cycle. Tests will be conducted using a modified version of the four-point flexure jig which has been described previously.

Array Standards

Interactions with consensus standards organizations continued during the rewriting period with participation in ASTM and IEEE meetings. During the September ASTM solar subcommittee meetings at Lake Tahoe, Engineering Area personnel presented recent work examining the appropriateness of the Air Mass 1.5 reference spectrum and reference temperature and intensity levels. The preliminary results indicate that the AM1.5 spectrum may overpredict the annual energy production of flat-plate arrays by 10% or so. This is caused by the fact that the diffuse component of insolation contributes heavily to flat-plate-array output and is much bluer (less efficient at generating cell output) than the reference spectrum. Work has been initiated at both JPL and DSET better to characterize the diffuse radiation spectrum to understand the problem. A contract was negotiated with DSET Labs to perform periodic (monthly) complete spectral measurements of the natural sunlight over a two-year period for purposes of supporting the photovoltaic performance measurement standards effort.

The Array Subsystem Task Group, which is led by Engineering Area personnel, held its sixth meeting at Sandia in conjunction with the concentrator PIM, and its seventh meeting at JPL in conjunction with the LSA 14th PIM. Performance criteria and test methods have been drafted for the following attributes: electrical, mechanical, structural, safety, durability and reliability, installation, operation, and maintenance. A package of all completed documentation is being prepared for submittal to SERI as part of the January 1980 Interim Performance Criteria Release.

Table 5. Engineering Area Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Bechtel National Columbus OH	954698	Curved-glass module and electrical isolation
Boeing Co. Seattle WA	954833	Wind loading study on module/array structures
Burt Hill Association 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 testing of modules
DSET Laboratories, Inc. Phoenix AZ	713137	Spectral Radiometric Measurements and Standards
Motorola, Inc. Phoenix AZ	955367	Study of termination design requirements
T and E Enterprises Los Angeles CA	713135	Integrated Low-cost Array Concepts Study
Underwriters Lab Melville NY	955392	Solar array and module safety requuirements

OPERATIONS AREA
LARGE-SCALE PRODUCTION TASK

Block III Production

During this reporting period the contracts with Sensor Technology, Inc., were modified to allow a change in the design of the Block III module that would provide both an improved module and an improved delivery rate. In four months, August through November, Sensor Tech shipped 4.7 kW, 4.1 kW during the last two months. The Sensor Tech contract is now 81% completed.

The contract with Solarex for high-density modules is again being modified to enable Solarex to deliver a glass-faced high-density module. Completion of this contract is expected during the next reporting period.

Block IV Design and Qualification

All preliminary design reviews have been completed and each contractor has completed a prototype module of the proposed design. These were displayed at the 14th Project Integration Meeting. Motorola has delivered mdoules to JPL for the qualification test program, but the other contractors are two to three months behind the initial schedule. The delays are the result of unanticipated design problems, internal conflicts for facilities, and optimistic scheduling. JPL has received cells from all contractors and has mounted them in prescribed fixtures, calibrated the cells and returned them to the contractors for use in measuring the power output of the modules.

At this writing, the RFQ for the production part of this block is ready for issuance.

MODULE TEST AND EVALUATION

Environmental Testing

Four sets of Block III modules were subjected to environmental qualification tests during the reporting period, with generally satisfactory results. Humidity-heat and humidity-freezing exploratory tests were completed on sample Block III modules. Degradation from these tests was more severe than for the standard environmental test sequence, and the degradation more closely resembled that induced by field exposure. A comparison of results is given in Table 5.

Table 6. Block III Environmental Testing: Qualification vs Exploratory Tests

VENDORS	NO. MDLS. TESTED	QUALIFICATION TESTS			EXPLORATORY TESTS		
		TEST	NO. MDLS. AFFECTED	RESULTS	TEST	NO. MDLS. AFFECTED	RESULTS
R		T~	4	Air bubbles	HR	1	4% el. degrad.
R cells	4	T~	4	Air bubbles decreased	HH	1	5% el. degrad., milky discoloration near edge seal
					HF	3	Air bubbles
		T~	3	Encap leak	MI-10K	1	Open at all cycles over 730
R M cells	4	H~	2	Bubbles	HR	4	Discolored metallization
			1	Bubbles decreased	HF	3	Bubbles
U	5	T~	5	End channels shrinking, lifting	MI-10K	4	Rails cracked at mounting holes
			1	El. degrad. 4%	HH	5	Frame seal delam.
		H~	1	Cell crack	HF	5	End channels shrinking, bends broken
						3	Further frame seal delam.
V	8	H~	8	Term corrosion	HH	8	Term corrosion, yellow discoloration
					HF	4	Encap. delam. over cells
Y	4	T~, H~	4	Satisfactory	HH	4	J-box hardware corrosion
Z	3	T~	3	Satisfactory	MI-10K	1	Delam. intercons, encap wrinkling & splitting
		H~	3	Intercon delam.	HH	1	8% El. degrad., 3 cell cracks
			3	Frame seal delam.		2	Delam. at cell edges
			2	1 cell crack		1	Yellow discoloration, 2 cell cracks
					HF	3	Frame seal delam., el. degrad. of 21%, 9%, 15%, resp.
						2	One cell crack
						1	2 cell cracks, encap split

T~ --- Temperature Cycling
H~ --- Humidity Cycling
MI --- Mechanical Integrity
HR --- Heat - Rain
HH --- Humidity - Heat
HF --- Humidity - Freeze

Three developmental module types and two commercial module types were tested. None of these designs was able to pass the tests; severe physical and/or electrical degradation was observed for all types. Cracked cells were a common cause of degradation. Two previously unobserved problems occurred on a glass-PVB laminated design: wrinkling of an aluminum-foil back-side vapor barrier during temperature cycling, and cracking of cells behind an intact glass superstrate during a 0.75 in.-dia hailstone impact test. Another of the developmental module designs tested incorporated cadium sulfide cells. This exploratory test series was intended mainly to develop test techniques for this cell type, since the modules used were rejects from an experimental production run. As expected, pulsed solar simulators cannot be used to measure the output of such modules because of the relatively slow response time of the cells.

A nominal operating cell temperature test on a late-arrival PRDA-38 concentrator assembly was aborted because of moisture accumulation within the enclosure. The linear compound parabolic collector enclosure apparently gathered moisture by diurnal "breathing" and condensation.

In view of the cell fractures observed at Mount Laguna (see Failure Analysis below), two PRDA-38 manufacturer modules were subjected to an exploratory humidity-freeze test. Two Block III modules from the same manufacturer were included in the test for comparison. No electrical degradation was observed on any of the modules. Physical degradation was minor, but the PRDA-38 modules weathered the test better than the Block III modules. A more complete test series is planned, using new modules of each type.

Block III testing has been reported in document 5101-134, "Environmental Testing of Block III Solar Cell Modules, Part 1: Qualification Testing of Standard Production Modules".

Performance Measurements

Calibration and delivery of the Block IV reference cells has been completed with the exception of the ARCO cells. The ARCO cells will be completed after delivery of a new set of 2 x 2 cm solar cells for reference cell fabrication. The new LAPSS facility is nearing completion and is expected to be operating by the end of the year.

A review of field test data from the Pasadena site indicates that the data is statistically very good, exhibiting standard deviations in the 1% range. A problem area has been observed, however, in that the field data indicate a short-circuit degradation of 3% to 8% that is not supported by indoor LAPSS measurements. Investigation into the cause of this anamolous behavior is continuing.

Field Tests

The principal activity this period was preparation of the annual report. In this process a thorough review of data from the over 600 modules at the 16 sites was made. Evaluation indicates that the modules are enduring well both electrically and physically, and most important, there is nothing to suggest that the 20-year lifetime goal cannot be reached. The results from the JPL site to date show that electrical degradation is not a slowly increasing phenomenon, as first believed; it occurs abruptly as the result of an event such as a cell cracking. Therefore, a change in the testing strategy is being introduced. Instead of placing emphasis on determining degradation rates and failure statistics, the emphasis is being shifted to investigating and isolating degradation mechanisms. A complete summary of the data and a presentation of future plans is included in the annual report.

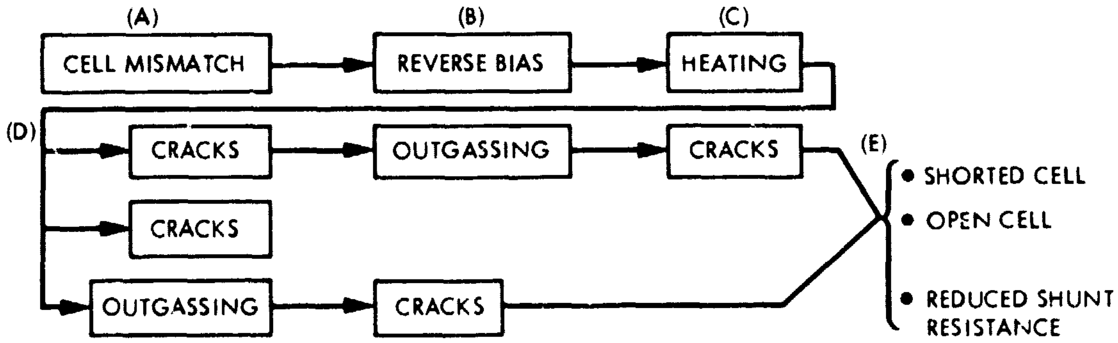
At the request of the TD&A Lead Center, an on-site survey of a PV array powering a water-well pump was made. The facility is located near Sweetwater AZ and is operated by the Indian Health Service. Results of the array assessment have been forwarded to the Lead Center.

The on-site survey of the LeRC-installed endurance test sites has been completed. Results are given in the Annual Field Test Report. Continuation of testing at these sites is being recommended.

Failure Analysis

The major activity during this reporting period was an investigation of the cause of numerous cell fractures on one module type at the Mount Laguna Air Force Radar Tracking Station, and additional evaluation of the PRDA-38 glass/silicone/Mylar encapsulated module from the same manufacturer.

The analysis accomplished in the laboratory and at the array site of the Block III modules leads to a failure model as shown in the life-cycle diagram:



The trigger appears to be cell mismatch in short-circuit characteristics, which leads to reverse bias and subsequent heating because of the high shunt resistance inherent in the cells. Such mismatch can arise from manufacturing, handling, shadowing, or induced environmental effects.

The use of bypass diodes can reduce the amount of power that can be dissipated in a back-biased cell. A series of laboratory tests were performed for the above module type in which short-circuit current (2.0 amps) was dissipated at varying voltages across a single back-biased cell. Figure 5 shows the result of these tests. Note that cell cracking occurred at 14 volts reverse bias, well within the nominal rating for this 40-cell module. A second bypass diode (i.e., one diode per 20 cells) would apparently have prevented the cracking of the cell, at least over the short term.

A similar test was performed on a 36-cell PRDA-38 type module from the same manufacturer. The results are shown in Figure 6. The temperature rise was similar to that of the Block III module, but no cell cracking was observed. This module is of different configuration from Block III, which employed a polyester substrate, prone to outgassing at elevated temperatures. The PRDA-38 module features a glass superstrate, silicone rubber encapsulant, and Mylar film back.

Additional work is in progress to investigate the mechanics of cell heating and cracking.

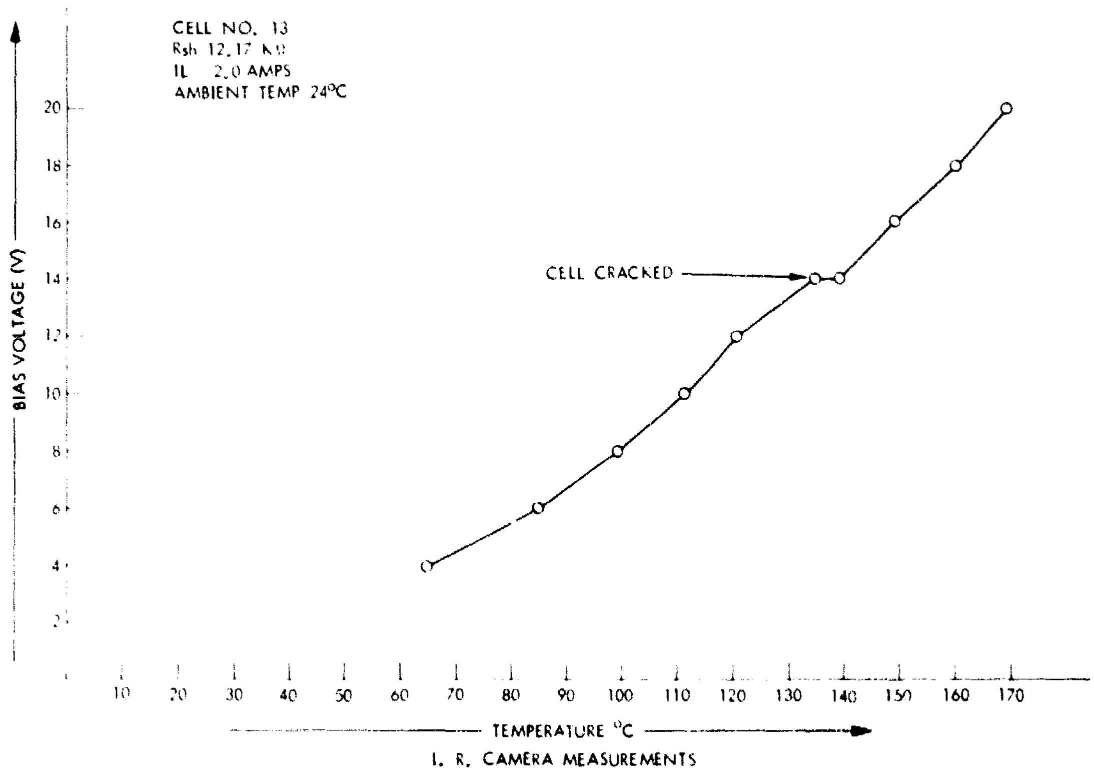


Figure 5. Block III Module 78D-1377

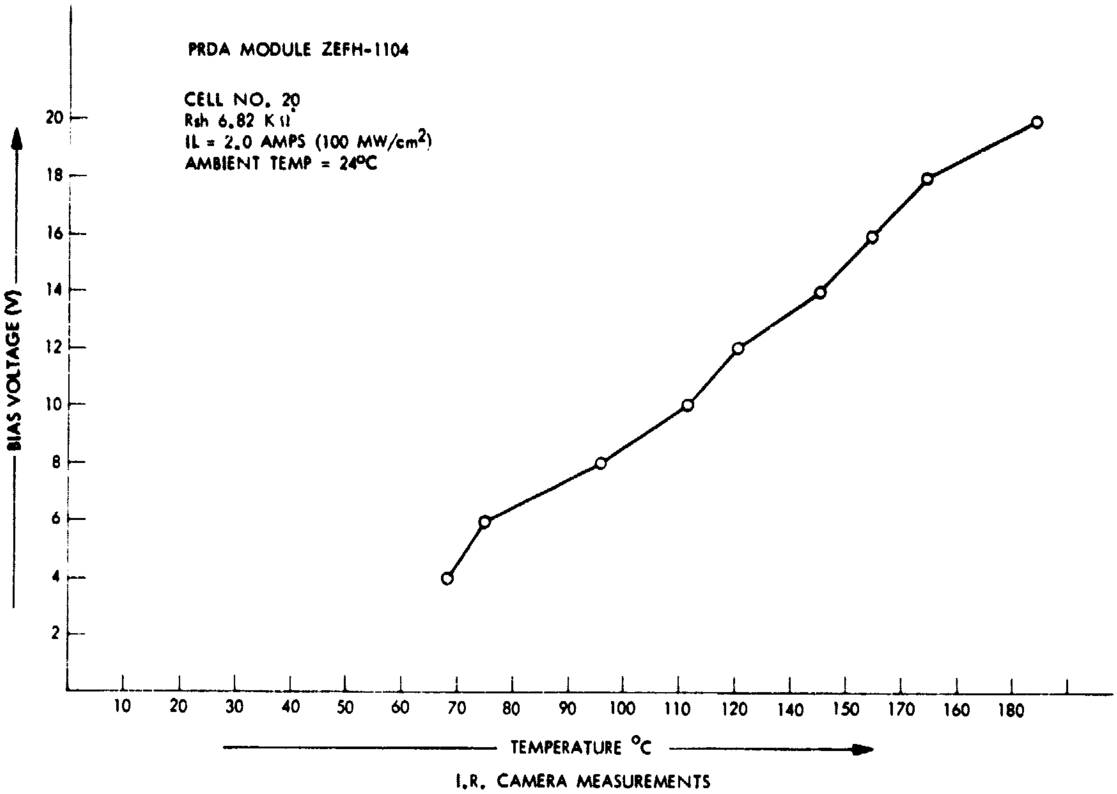


Figure 6. PRDA Module ZEFH-1104

PROCEEDINGS

of the 14th Low-Cost Solar Array Project Integration Meeting held at the California Institute of Technology on December 5 and 6, 1979

Note: In a departure from the format of previous PIM Proceedings, we are endeavoring to present the graphic material given at the meeting in a sequence that more nearly approaches the order in which the presentations themselves were actually given. Since many sessions were held simultaneously and others were split, that order can only be approximated.

AGENDA

<u>WEDNESDAY, December 5</u>

7:30	Registration		
8:30	Welcome; LSA Announcements	W. Callaghan	
8:40	DOE & PV Lead Center Announcements	L. Magid, R. Forney	
9:00	HUD Announcements	A. Carey	
9:20	Silicon Material Summary	R. Ferber	
9:40	FPUP Status	E. Smith, A. Lawson	
10:00	Introduction of Module Mfrs.	D. Runkle	
11:10	Lessons Learned That Affect Module Design	R. Ross, L. Dumas	(pp. 3-15)
12:10	Discussion		
12:15	Lunch		
1:15	Technology Sessions (simultaneous)		
	Silicon Material	R. Lutwack	(pp. 16-46)
	Large-Area Sheet	J. Liu	(pp. 47-176)
	Block IV Module Designs and Design Rationale: Presentations by Module Manufacturers	D. Runkle	(pp. 177-235)
3:45	Technology Sessions (simultaneous)		
	Silicon Material	R. Lutwack	(pp. 16-46)
	Large-Area Sheet	J. Liu	(pp. 47-176)
	Encapsulation	C. Coulbert	(pp. 236-244)
	PP&E: Copper Metallization	D. Bickler	(pp. 296-337)
	PA&I, Engineering & Operations	J. Arnett	(pp. 354-382)

THURSDAY, December 6

8:00	Technology Sessions (simultaneous)		
	Silicon Material	R. Lutwack	(pp. 16-46)
	Large-Area Sheet	J. Liu	(pp. 47-176)
	Module Design	R. Ross	(pp. 383-454)
1:30	Parallel Sessions		
	Automated Module Assembly Studies	D. Bickler	(pp. 338-351)
	Module/Cell Life Prediction and Modeling (Includes EVA Studies)	C. Coulbert	(pp. 244-247)
	Test and Applications	L. Dumas	(pp. 455-462)
3:15	Product Reliability and Liability	A. Weinstein, Carnegie Mellon U.	(pp. 463-465)
3:45	Summaries		
	LSA		
	DOE, Lead Center		
5:00	End of Meeting		

ENGINEERING AND OPERATIONS AREAS

LESSONS LEARNED THAT AFFECT MODULE DESIGN

JET PROPULSION LABORATORY

R. Ross and L. Dumas

The LSA Project has been actively interfacing with, and procuring modules from, photovoltaic manufacturers for five years. Valuable experience and design knowledge has been gained by LSA from rapid evolution of design technologies and from qualification and exploratory testing, field deployment and failure analysis of modules during this time.

A joint presentation at the Wednesday morning plenary session by Ron Ross, Engineering Area Manager, and Larry Dumas, Operations Area Manager, summarized the lessons learned that most significantly influence module design. The module design process, a closed-loop approach, was described by emphasizing from a historical perspective how design problems have been identified in successive block procurements and how appropriate design solutions were found.

In many cases work began as potential design problems were perceived earlier than actual field occurrence was observed. Recommendations were made for module design objectives and approaches in the areas of mechanical and electrical configuration, fault tolerance and environmental endurance. Project experience with environmental reliability and durability was described both from the aspect of understanding and predicting degradation mechanisms and from the results of qualification testing, and field endurance performance.

Progress by manufacturers in improving production yields by reduction in workmanship defects was described on the basis of Quality Assurance inspection records. The need to allow adequate lead time for design, development and qualification of new designs and to plan for and learn from field endurance performance, as part of the iteritive module design process, was emphasized.

The details of this overview of module design factors appear in the following graphic material.

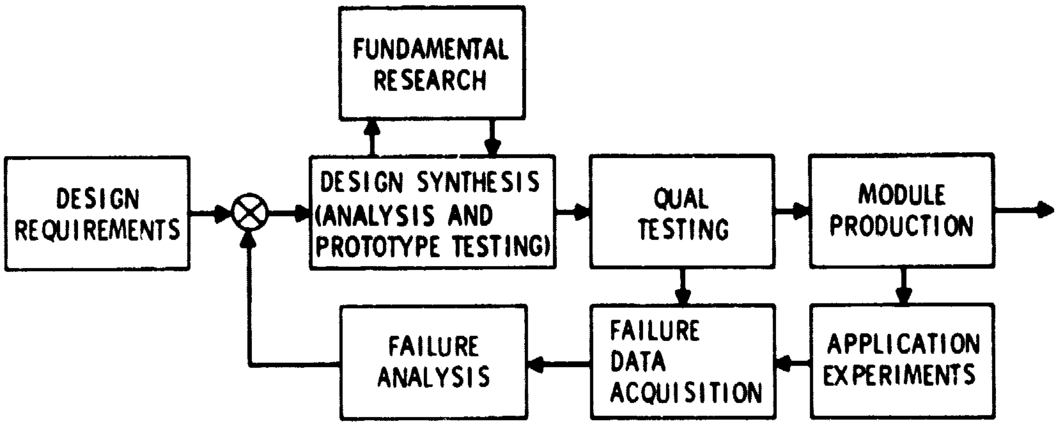
In a subsequent four-hour Module Design session (Thursday, 8:00 a.m.) LSA Engineering, Encapsulation and Quality Assurance personnel expanded these Lessons Learned to cover specific design approaches, rationale, and recommendations. Additional sessions covering other aspects of module design, fabrication, and field performance are identified in the meeting agenda. In particular the session in which individual module manufacturers described their Block IV designs will be of interest.

INTER-TECHNOLOGY SESSION

Lessons Learned in Module Engineering

- DESIGN PROCESS OVERVIEW
- MODULE HISTORICAL SUMMARY
- LESSON HIGHLIGHTS
  - MECHANICAL CONFIGURATION
    - EFFICIENCY
    - STRUCTURAL SIZING
    - THERMAL
  - ELECTRICAL CONFIGURATION
    - SAFETY
    - RELIABILITY
  - ENVIRONMENTAL ENDURANCE
    - ENGINEERING
    - ENVIRONMENTAL TEST
    - FIELD TESTS
    - APPLICATIONS
  - PRODUCTION EXPERIENCE
- RECOMMENDATIONS

Module Design Process (Closed Loop)



APPROACH

- SPECIFY REQUIREMENTS
- SYNTHESIZE DESIGNS
- SCREEN DESIGNS USING QUAL TESTS
- ACQUIRE AND FEED BACK PERFORMANCE DATA
- PERFORM FUNDAMENTAL RESEARCH AS REQUIRED
- USE FEEDBACK AND RESEARCH TO IMPROVE DESIGNS

Module Historical Overview

YEAR	PROBLEMS	SOLUTIONS
1975 (BLOCK I)	• DELAMINATION • INTERCONNECT BREAKAGE	• FIRST QUAL TESTS (HUMIDITY, TEMP. CYCLE)
1976 (BLOCK II)	• POOR INTERCHANGEABILITY • EXCESSIVE STRUCTURE • EXCESSIVE TEMPERATURES • LOW-EFFICIENCY • FIELD WIRING COMPLEXITY • VOLTAGE BREAKDOWN • WORKMANSHIP PROBLEMS • CONTINUED DELAMINATION	• STANDARD 4'x4' PANEL • 50 lb/ft^2 TEST • NOCT RESEARCH • EFFICIENCY STUDIES • CONNECTOR STUDIES • HI-POT QUAL TEST • QA INSPECTION PLAN • UV-RESEARCH • HOT-SPOT RESEARCH
1977 (BLOCK III)	• EXCESSIVE SOILING • CELL CRACKING • CONTINUED - DELAMINATION - WORKMANSHIP	• SOILING RESEARCH • SERIES-PARALLEL RESEARCH • BIAS-HUMIDITY RESEARCH • HAIL RESEARCH

YEAR	PROBLEMS	SOLUTIONS
1978	● HAIL DAMAGE ● CONTINUED - SOILING - CELL CRACKING - DELAMINATION	● HAIL QUAL TEST ● CONTINUED RESEARCH - UV - SERIES-PARALLEL - SOILING ● CELL FRACTURE MECHANICS ● INSULATION RESEARCH
1979 (BLOCK IV)	● HOT-SPOT HEATING ● CONTINUED - CELL CRACKING - DELAMINATION - SOILING - HAIL DAMAGE	● HOT-SPOT QUAL TEST ● CONTINUED RESEARCH - SERIES/PARALLEL - UV, SOILING - FRACTURE MECHANICS - INSULATION ● SAFETY RESEARCH

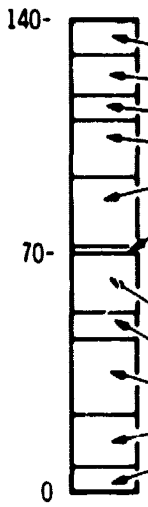
Module Lesson Highlights

- MECHANICAL CONFIGURATION
  - EFFICIENCY
  - STRUCTURAL SIZING
  - FIELD ASSEMBLY LABOR
- ELECTRICAL CONFIGURATION
  - VOLTAGE LEVEL
  - SAFETY
  - RELIABILITY
- ENVIRONMENTAL ENDURANCE
  - ENGINEERING
  - ENVIRONMENTAL TEST EXPERIENCE
  - FIELD TEST EXPERIENCE
  - APPLICATIONS EXPERIENCE
- PRODUCTION EXPERIENCE

Mechanical Configuration Lessons

- MAXIMIZE MODULE EFFICIENCY
  - ENCAPSULATED vs UNENCAPSULATED CELL EFFICIENCY
  - CELL OPERATING TEMPERATURE (10^{0}C · 6¢/WATT)
  - UNUSED BORDER AREA (LARGE MODULES HAVE LESS)
  - CELL NESTING (SHAPED CELLS)
- MINIMIZE STRUCTURE COSTS
  - ARRAY SURFACE AREA WITHOUT CELLS COSTS 60 $\$/m^2$ IN 1986 (1980$)
  - COSTS INCREASE LINEARLY WITH WIND LOADING LEVEL.
- MINIMIZE FIELD ASSEMBLY LABOR
  - INTEGRATED STRUCTURES
  - MINIMUM LABOR CABLING
  - NEED FOR BETTER ACTUAL COST DATA

Flat-Plate Array Cost Breakdown (1980 $)



	COST (¢/WATT)	
FIELD FAILURES (2% PER YEAR)	11.5	69.2
SOILING (10% LOSSES)	11.5	
FOUNDATIONS	8.0	
ARRAY STRUCTURE	16.2	
PANEL STRUCTURE	20.6	
CONNECTOR & DIODES	1.4	
MODULE ASSEMBLY	17.2	70.0
ENCAPSULATION MATERIALS	7.6	
CELL PROCESSING	22.0	
SHEET FABRICATION	15.8	
SILICON MATERIAL	7.4	
	139.2	

Electrical Configuration Lessons

- MAXIMIZE SAFETY
  - MODULE $V_{oc} \leq 30$ VOLTS @ $-20^{0}C$
  - CELL STRING ISOLATED ($2 \times V_{sys}$ + 1000 VDC)
  - EXTERIOR SURFACES GROUNDED
  - TERMINALS PROTECTED
  - MUST BE COMPATIBLE WITH OVERALL SAFETY SYSTEM
- MAXIMIZE RELIABILITY *
  - FACTORY YIELD LOSSES
  - FIELD FAILURE LOSSES
  - FIELD FAILURE RUNAWAY

---

* INSENSITIVITY TO AND CONTAINMENT OF LOW PROBABILITY CIRCUIT FAILURES.

Reliability Lessons

<u>KEY FAILURE MECHANISMS:</u>

- CRACKED CELLS (OPEN/REDUCED OUTPUT)
- OPEN INTERCONNECTS
- SHORTED CELLS
- SHADOWED CELLS

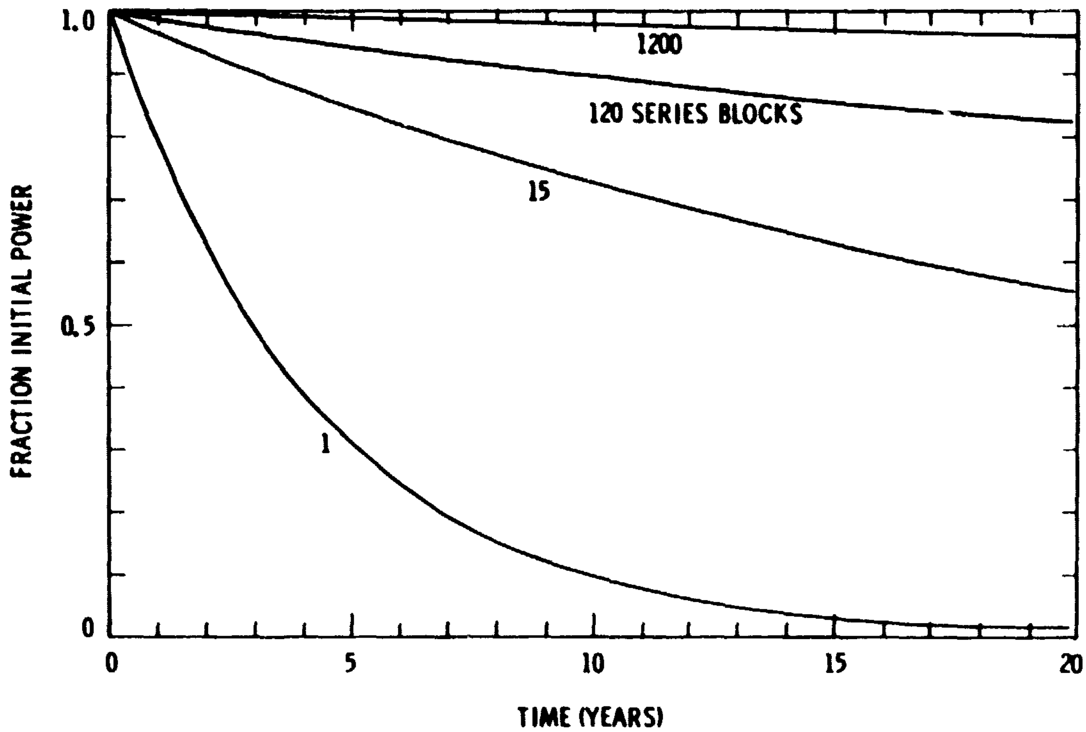
<u>LESSON:</u>

- RANDOM FAILURES AND ASSOCIATED HOT-SPOT HEATING MUST BE EXPECTED AT LEVELS OF 1 PER 100 CELLS AND MUST BE NEUTRALIZED.

<u>SOLUTIONS:</u>

- BY-PASS DIODES
- MULTIPLE CELL CONTACTS
- SERIES/PARALLELING

Array Power Degradation vs Circuit Redundancy



Environmental Endurance

DEGRADATION MODE	EFFECT PREDICTABLE	SOLUTION KNOWN
INTERCONNECT FRACTURES	●	●
UNSOLDERED INTERCONNECTS	●	●
WIRE & TERMINAL CORROSION	◐	◐
CELL METALLIZATION CORROSION	◐	◐
CRACKED CELLS	◐	●
HAIL DAMAGE	●	●
HOT-SPOT HEATING	●	●
INSULATION BREAKDOWN	○	○
ENCAPSULANT DELAMINATION	○	○
ENCAPSULANT CRACKING/BREAKDOWN	○	○
ENCAPSULANT/CELL DISCOLORATION	○	○
SOILING	●	●
STRUCTURAL FAILURE	●	●
HANDLING/SHIPPING/INST. DAMAGE	●	●

● = YES ◐ = PARTIALLY ○ = NO

DEGRADATION MODE	IMPORTANCE PAST DESIGNS	IMPORTANCE CURRENT DESIGNS
INTERCONNECT FRACTURES	●	
UNSOLDERED INTERCONNECTS	○	○
WIRE & TERMINAL CORROSION	◐	
CELL METALLIZATION CORROSION	◐	○
CRACKED CELLS	●	●
HAIL DAMAGE	●	●
HOT-SPOT HEATING	○	●
INSULATION BREAKDOWN	◐	●
ENCAPSULANT DELAMINATION	●	◐
ENCAPSULANT CRACKING/BREAKDOWN	◐	○
ENCAPSULANT/CELL DISCOLORATION	◐	
SOILING	●	●
STRUCTURAL FAILURE		○
HANDLING/SHIPPING/INST. DAMAGE	○	○

● CRITICAL AND WIDESPREAD
◐ INTERMEDIATE CONCERN OR UNCERTAIN EFFECT
○ OCCASIONAL PROBLEM

Environmental Endurance Lessons

ENGINEERING LESSONS

- ENVIRONMENTAL STRESSES AND FAILURE MECHANISMS ARE VERY COMPLEX AND APPLICATION SPECIFIC
- POOR PREDICTION CAPABILITY PLACES HIGH RELIANCE ON QUAL TESTS TOGETHER WITH REAL-TIME SYSTEM EXPERIMENTS FOR CALIBRATION.
- LARGE STATISTICAL SAMPLE SIZES (LARGE ARRAYS) ARE REQUIRED TO QUANTIFY FAILURES.
- RELIANCE ON FIELD-FAILURE DATA PLACES REQUIREMENTS ON SYSTEM EXPERIMENTS:
  - TO OBTAIN QUANTITATIVE DATA ON FAILURES
  - TO HAVE FAILURE CONTAINMENT FEATURES
  - TO HAVE FAILURE CONTINGENCY PLANS

Environmental Test Experience

- NEW DESIGNS SELDOM PASS ON FIRST TRY
- TEMPERATURE CYCLING MOST DAMAGING, FOLLOWED BY COMBINED TEMPERATURE AND HUMIDITY CYCLING
- COMMON FAILURE MODES ARE CRACKED CELLS, ENCAPSULANT DAMAGE, AND RESISTIVE SHORTS TO FRAME
- PRESENT QUAL TEST SERIES DOES NOT SCREEN FOR:
  - DIRT EFFECTS
  - UV EFFECTS
  - LONG-TERM CORROSION
  - * BACK-BIAS HEATING EFFECTS

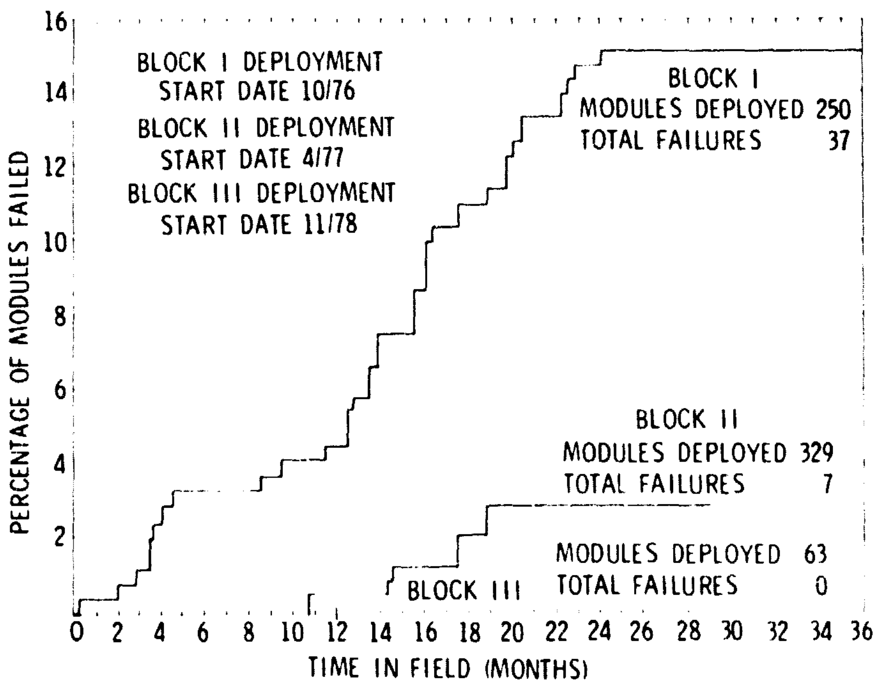
Box Score: PRDA Module Test Criteria

CRITERIA	NUMBER OF PROBLEMS				TOTAL (%)
	THERMAL	HUMIDITY	MECHANICAL	HAIL	
GROUND CONTINUITY	0	3	3	0	6 (5%)
ELECTRICAL ISOLATION	11	10	4	0	25 (22%)
POWER DEGRADATION	5	9	6	1	21 (19%)
PHYSICAL DEGRADATION	33	20	4	4	61 (54%)
TOTAL (%)	49 (43%)	42 (37%)	17 (15%)	5 (4%)	113 (≈100%)

Module Field Test Experience

- BLOCK II AND III FAILURE RATES LOW
- DIFFICULTIES IN DETECTING AND MEASURING ELECTRICAL DEGRADATION CAN LEAD TO OVERLY OPTIMISTIC CONCLUSIONS ABOUT FIELD PERFORMANCE
- MOST COMMON CAUSES OF ELECTRICAL DEGRADATION FOR RECENT DESIGNS ARE CRACKED CELLS AND SOILING
- MOST COMMON FORMS OF PHYSICAL DEGRADATION ARE CRACKED CELLS, ENCAPSULANT DELAMINATION, CORROSION, AND VARIOUS TYPES OF DISCOLORATION
- NATURE AND DEGREE OF DEGRADATION ARE GREATLY INFLUENCED BY TYPE OF ENVIRONMENTAL EXPOSURE

Failure Rates for Blocks I and II Modules At JPL & Lewis Test Sites



Status of JPL/Lewis Endurance Test Sites: Summary of Field Data

MODULES INSPECTED 180	CANAL ZONE	KEY WEST	NEW ORLEANS	CRANE	HOUGHTON	NEW LONDON	MINES PEAK	ALBUQUERQUE	DUGWAY	WASHINGTON	ALASKA	SAN NICOLAS ISL
ELECTRICAL DEGRADATION												
FAILED MODULES	1*							1				
DEGRADED MODULES	2	1	1		1			2				
PHYSICAL DEGRADATION												
CRACKED CELLS												
METALLIZATION DISCOLORED/CORRODED		•				•		•		•		
DELAMINATION					•							
FRAME/HARDWARE CORROSION		•	•	•		•			•			•
CONNECTOR DETERIORATION		•			•			•	•	•	•	
WIRING DETERIORATION												
EMBEDDED DIRT		•	•	•	•	•		•	•	•	•	•
STAND CORROSION	•	●	•	•		•			●	•	•	●

• MODERATE AMOUNT

● SUBSTANTIAL AMOUNT

* ENCAPSULANT DAMAGED BEFORE INSTALLATION

Applicati›ns Experience

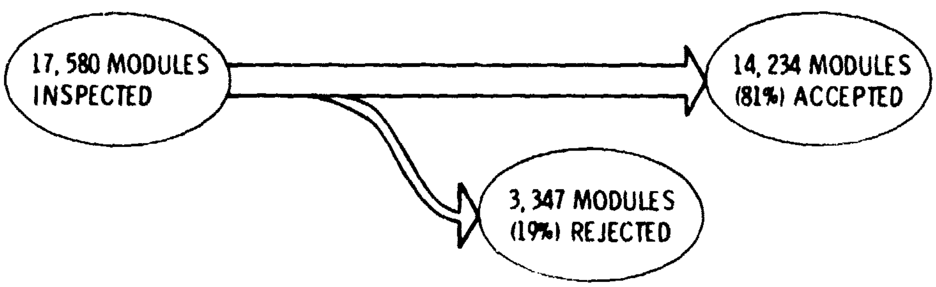
- MODULES OFTEN JUDGED O‹ THE BASIS OF SUBJECTIVE EFFECTS OF VISUAL OBSERVATIONS
    - ENCAPSULANT DELAMINATION
    - DISCOLORATION
    - CORROSION
- HANDLING, SHIPPING, INSTALLATION, AND MAINTENANCE PROBLEMS BEGINNING TO SURFACE
- OPERATIONAL INTERACTION OF SYSTEM AND MODULE ARE IMPORTANT SOURCE OF MODULE STRESS
    - NOTABLY, STRING SHORTING
- RELIABILITY A KEY CONCERN

Production Experience

- MODULE REJECTION RATES UNACCEPTABLY HIGH
    - SILICONE ENCAPSULANT DEFECTS AND CRACKED CELLS MAIN PROBLEMS
- PRODUCTION TYPICALLY LOW-VOLUME, NON-AUTOMATED, NON-EQUILIBRIUM
- ELAPSED TIME FROM CONTRACT EXECUTION TO DELIVERY OF FIRST PRODUCTION MODULES:

BLOCK I	2-5 MONTHS
BLOCK II	7-13 MONTHS
BLOCK III	2-6 MONTHS
BLOCK IV	≈ 10-12 MONTHS

Block III Inspection Summary



DEFECTS (4505)	
ENCAPSULANT	38%
CELLS	27%
MECHANICAL	17%
INTERCONNECTS	9 1/2%
DOCUMENTATION	6 1/2%
SOLDER	2%
	100%

Recommendations

- PROVIDE FOR ADEQUATE QUALIFICATION AND DEBUGGING OF NEW MODULE DESIGNS
  - TEST PROGRAM
  - TIME
- PLAN FOR AND LEARN FROM FIELD FAILURES
  - MONITORING, CONTINGENCY, MAINTENANCE PLANS
  - ACQUIRE DATA → ANALYZE PROBLEMS → IMPROVE DESIGNS
- DESIGN MODULES AND SYSTEMS FOR FAULT - TOLERANCE
- DESIGN MODULES AND SYSTEMS FOR SAFETY
- INTEGRATE SYSTEM AND SUBSYSTEM DESIGN PROCESSES

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

Presentations on silicon (Si) production processes and supporting technology were made by 11 contractors and JPL personnel.

In the area of Si production process development, Union Carbide Corp. reported that work proceeded on design of equipment and the facility for the 100-MT/yr EPSDU (Experimental Process System Development Unit) based on their silane-to-Si process. In the supporting R&D program, efforts continued on the two concepts for making Si by decomposing silane: the free-space reactor (FSR) and the fluidized-bed reactor (FBR). The FSR process development unit was installed and checked out and is ready for shakedown testing. In support of the UCC program, the Massachusetts Institute of Technology reported on their experimental and theoretical work on the conversion of metallurgical-grade silicon and silicon tetrachloride to trichlorosilane, the feedstock of the UCC process. The Battelle Columbus Laboratories (BCL) reported that their Process Development Unit (PDU), consisting of the four critical components (full-size) of BCL's 50-MT/yr EPSDU design, was brought to a state of completion that permitted operations to start. The BCL process is based on the reduction of silicon tetrachloride by zinc. The initial operations consist of coating the inside of the fluidized bed reactor with Si formed by decomposing trichlorosilane. Battelle also presented results from their experimental support program, in particular on removal of residual zinc from silicon product. SRI International reported on progress in scaling up their process, based on reducing silicon tetrafluoride by sodium, and presented information on analyses of product silicon. Energy Materials Corporation described their process for producing silicon by gaseous melt replenishment; construction and installation of the prototype system is nearing completion. Hemlock Semiconductor Corporation described a recently started program for developing a modified Siemens process for making Si, using dichlorosilane as feedstock.

In the area of silicon impurity studies, the Westinghouse R&D Center and C.T. Sah Associates reported on their studies of the effects of impurities on Si properties and solar-cell performance. Solarex Corporation described their program for determining the effects on solar-cell efficiency of impurities intentionally incorporated into the Si.

Supporting studies were described by Lamar University (preliminary process design and preliminary cost analysis of the Battelle process), AeroChem Research Laboratories (investigation of the high-temperature reactions of alkali metals and silicon halides), and JPL (studies on the fluidized bed reactor and the continuous-flow pyrolyzer).

The material presented by contractors and JPL is summarized in the following pages.

TECHNOLOGY SESSION

Ralph Lutwack, Chairman

PROCESS FEASIBILITY (TASK I): BCL PROCESS, CASE B

LAMAR UNIVERSITY

13TH PIM: BCL PROCESS - CASE A

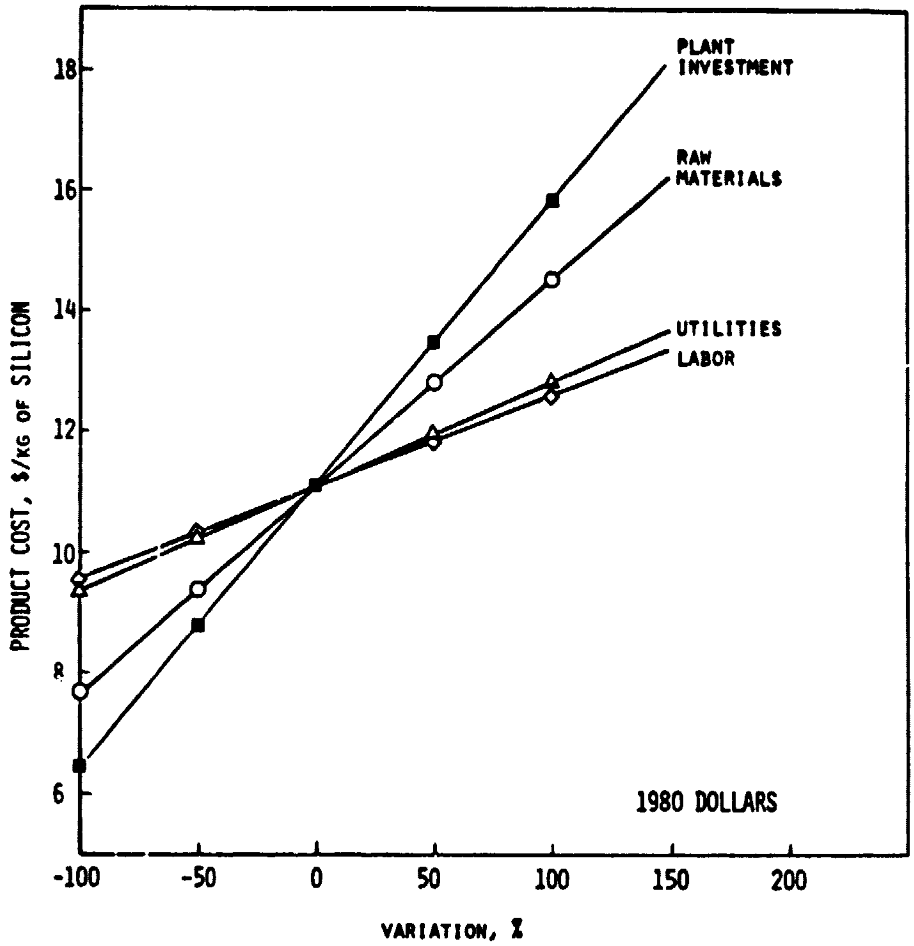
- TOTAL PRODUCT COST 12.1 $/KG (1980 DOLLARS)
- CASE A BASED ON
  - TWO DEPOSITION REACTORS
  - SIX ELECTROLYSIS CELLS

14TH PIM BCL PROCESS - CASE B

- RESULTS WILL BE REPORTED AT THIS MEETING
- CASE B BASED ON
  - ONE DEPOSITION REACTOR
  - TWO ELECTROLYSIS CELLS

Cost Sensitivity Analysis

STEP 1-7 CASE B



Summary of Cost and Profitability (1980 $)

PLANT SIZE	:	1000 MT SI/YR
PRODUCT	:	SILICON GRANULES
PLANT INVESTMENT	:	$16,500,000.
FIXED CAPITAL	:	$14,350,000.
WORKING CAPITAL	:	$ 2,150,000.
PRODUCT COST	:	$11.08/KG
PRODUCT PRICE	:	$18.72/KG (25% ROI)

CHLOROSILANE VAPOR DEPOSITION

HEMLOCK SEMICONDUCTOR CORP.

Reasons for Considering Chlorosilane Technology

- ONLY MAJOR PRODUCTION PROCESS
- PROVEN MATERIAL QUALITY
- IN-PLACE CAPACITY FORMS BASE FOR MEETING EXPANDED DEMAND
- SIGNIFICANT COST REDUCTION POSSIBLE TO MEET INTERMEDIATE AND LONG RANGE PHOTOVOLTAIC OBJECTIVES

Conclusions

SOLAR CELL REQUIREMENTS

- LOW COST DOE PHOTOVOLTAIC OBJECTIVES WILL ONLY BE MET WITH HIGH EFFICIENCY SOLAR CELLS.
- IT IS COST EFFECTIVE TO USE HIGHER COST POLYSILICON IF HIGHER CELL EFFICIENCY IS ACHIEVED.

Limitations of Existing Siemens Process

- LOW DEPOSITION RATE
- HIGH POWER CONSUMPTION
- LARGE BYPRODUCT STREAM ($SiCl_4$)

Characteristics of Low-Cost CVD Process

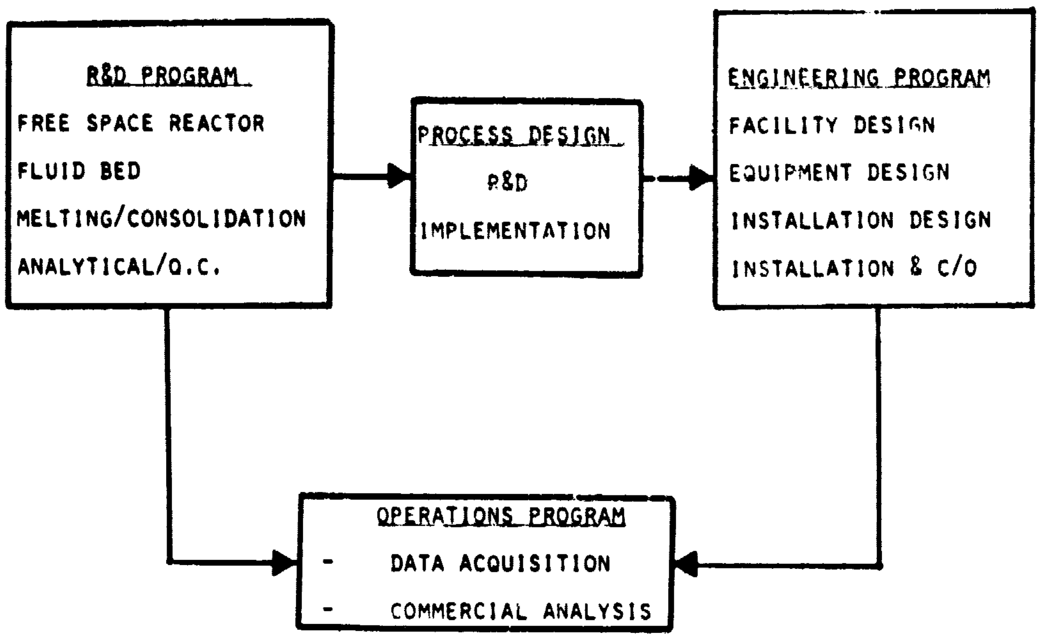
- DICHLOROSILANE FEEDSTOCK
- ADVANCED REACTOR DESIGN
- $SiCl_4$ RECYCLE

Phase I Objectives

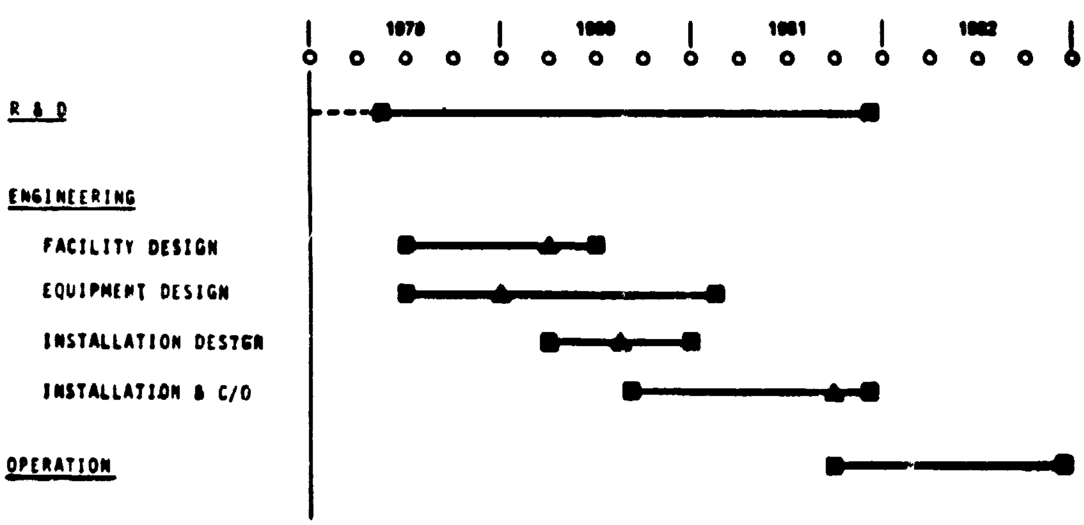
- CHARACTERIZE EXPERIMENTAL REACTOR OPERATION WITH DICHLOROSILANE FEED
- DESIGN AND CONSTRUCT INTERMEDIATE SIZE REACTOR TO DEMONSTRATE SCALE-UP
- EVALUATE TCS - DCS REDISTRIBUTION PROCESS/PRODUCT
- PRELIMINARY EPSDU DESIGN

SILANE-TO-SILICON EPSDU

UNION CARBIDE CORP.



Program Schedule



HYDROGENATION OF $SiCl_4$

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

$$3\,SiCl_4 + 2\,H_2 + Si \rightleftharpoons 4\,SiHCl_3$$

I <u>REACTION KINETICS</u>

• TEMPERATURE	400° - 550°C
• PRESSURE	TO 500 PSIG
• CONCENTRATION	H_2, $SiCl_4$
• CATALYST	COPPER
• PARTICLE SIZE	
• SURFACE AREA	
• IMPURITIES	M.G. SILICON
• FLUIDIZATION	

II <u>THEORETICAL STUDIES</u>

- REACTION MECHANISM
- ROLE OF CATALYST
- SURFACE ANALYSIS

Summary

I <u>EXPERIMENTAL RESULTS</u>

- 500 PSIG DATA GENERALLY CONFIRM PREVIOUS ESTIMATES EXTRAPOLATED FROM LOW PRESSURE DATA
- REACTION RATE INCREASES RAPIDLY WITH TEMPERATURE
- $SiHCl_3$ CONVERSION INCREASES AT HIGHER H_2: $SiCl_4$ RATIO
- $SiHCl_3$ CONVERSION INCREASES AT HIGHER REACTOR PRESSURE
- REACTION APPROACHES EQUILIBRIUM SOMEWHAT SLOWER AT HIGHER REACTOR PRESSURE
- HIGHER REACTOR TEMPERATURE AND PRESSURE GIVE MOST BENEFITS

II <u>PLANS FOR NEXT QUARTER</u>

- COLLECT EQUILIBRIUM DATA
- COMPLETE RATE MEASUREMENTS
- THEORETICAL STUDIES
- COPPER CATALYST

GASEOUS MELT REPLENISHMENT

ENERGY MATERIALS CORP.

Process Description

1. BRING THE REACTOR TO TEMPERATURE UNDER AN ARGON ATMOSPHERE.
2. MELT SILICON IN THE U-TUBE TO FORM A POSITIVE GAS SEAL.
3. INTRODUCE H_2 AND H SI CL_3 INTO THE CHAMBER TO PROVIDE OPTIMUM MASS DEPOSITION OF SILICON UNTIL THE DESIRED AMOUNT OF SILICON HAS BEEN DEPOSITED.
4. RAISE THE REACTOR TEMPERATURE TO 1450 TO MELT DOWN THE SILICON KEEPING THE U-TUBE SOLIDIFIED.
5. EQUILIBRATE THE GAS PRESSURE BETWEEN THE REACTOR AND THE DELIVERY TUBE.
6. RAISE THE TEMPERATURE OF THE U-TUBE ABOVE THE SILICON MELTING POINT. THE SILICON WILL DRAIN OUT OF THE REACTOR INTO THE CRYSTAL GROWTH CRUCIBLE.
7. THE SILICON IN THE U-TUBE WILL BE SOLIDIFIED AND THE REACTOR RETURNED TO THE INITIAL REACTION CONDITIONS.

JPL IN-HOUSE STUDIES

Objective

- TO CONDUCT JPL IN-HOUSE COMPLEMENTARY STUDIES IN SILICON PROCESSING AREAS TO SUPPORT CONTRACTUAL ACTIVITIES AND TECHNICAL MANAGEMENT IN THE DOE/LSA SILICON MATERIAL TASK

In-House Si Production Activities

- FLUIDIZED BED REACTOR AREA
  - Si FINE FORMATION EXPERIMENTS
  - FLUID BED Si DEPOSITION EXPERIMENTS
- SILANE PYROLYSIS AREA
  - CONTINUOUS FLOW PYROLYZER
  - SILANE TO MOLTEN Si INVESTIGATION
  - FUNDAMENTAL CVD AND RATE STUDIES
- REACTOR MODELING AREA
  - MODELING OF PYROLYZER OPERATION
  - MODELING OF FLUID BED Si DEPOSITION

FBR Development Needs

DETERMINE RANGES OF TEMPERATURE, FLOW AND SILANE CONCENTRATION THAT MAY CONTINUOUSLY PRODUCE DENSE GROWTH WITH ACCEPTABLE DUST PRODUCTION

Dust Production

LOW LEVELS OF DUST FOR UP TO 15%
SILANE WHEN CONVERSION IN BED
IS COMPLETE

SIGNIFICANT DUST LEVELS SEEN WHEN
CONVERSION IN BED IS INCOMPLETE

Bed Agglomeration

AGGLOMERATION OCCURS RAPIDLY AT >630 C
AND >3% SILANE FOR BUBBLING BEDS

STRONG BONDS SIMILAR TO SINTERING

POSSIBLE CAUSES

HOT SPOTS DUE TO EXOTHERMIC
REACTION CAUSE SINTERING

PRESENCE OF LIQUID PHASE AT BULK
BED TEMP. DUE TO IMPURITY EUTECTIC

Possible Solutions

HIGH FLOW RATES (>8*MFV)
MULTIPLE INJECTION
USE VERY PURE SILICON

2-in. S.S. FBR Tests

DEPOSITED SILICON AT A RATE OF 2.65 GRAMS/MIN
FOR 51 MIN AT 700C WITH 10% SILANE IN
HYDROGEN FEED AT A SUP VEL OF 8-10*MFV

DEPOSIT APPEARED DENSE, 15-25 MICRONS THICK

DUST AMOUNTED TO <0.1% OF SI PRODUCED

NO EVIDENCE OF BED AGGLOMERATION

IN-HOUSE LSA PROGRAM
CONTINUOUS-FLOW PYROLYZER, SECOND GENERATION: CFP-II

Purposes

- PARAMETRIC STUDIES, e.g., EFFECTS OF T, P, C AND V ON SILICON PARTICLE SIZE AND BULK DENSITY
- REACTOR MATERIAL STUDIES
- REACTOR PURITY STUDIES
- REACTOR CLOGGING STUDIES
- IN GENERAL, COOPERATION WITH AND TECHNICAL SUPPORT FOR THE UC EPSDU

Experimental Runs in Development of CFP-II

						GAS PHASE SILICON PRODUCT			
RUN NUMBER	RUN TIME min	AVE TEMP °C	PRESSURE psig	RATE OF Si PROD lb/hr	SEED	% YIELD	BULK DENSITY g/cc	DIAM μm	PRODUCT COLOR
1	10	640	0-2	0.04	YES	100	<0.05	<0.1	GRAYISH BROWN
2	26	670	0-2	0.15	YES	100	<0.05	<0.1	GRAYISH BROWN
3	3.6 6.0	650	0-2	1.6 2.5	YES	~65	~0.27	—	DULL BLACK
4	7.3	640	0-2	2.6	NO	~45	~0.24	~0.35	DULL BLACK
5	1.0	840	0-2	2.3	YES	100	~0.06	~0.1	YELLOWISH BROWN
6	8.2	800	0-2	4.73	YES	100	—	~0.2	RED-BROWN
7		600	50	3.94	NO				
8		600	100	7.88	NO				

EFFECTS OF IMPURITIES ON CELL PERFORMANCE

C. T. SAH

THIS PROGRAM IS CONDUCTED FOR A STUDY OF THE EFFECTS OF IMPURITIES ON THE PROPERTIES OF SILICON MATERIAL AND PERFORMANCE OF SILICON SOLAR CELL. IT INCLUDES THEORETICAL AND EXPERIMENTAL STUDIES TO DETERMINE THE EFFECTS OF IMPURITIES ON THE PROPERTIES OF SILICON DOPED WITH SPECIFIC IMPURITY ELEMENTS AS WELL AS THE EFFECTS OF THESE IMPURITIES ON THE IMPURITY RELATED ENERGY LEVELS, ON THE CONCENTRATION OF THESE ENERGY LEVELS, AND ON THE RECOMBINATION PROPERTIES OF ELECTRONS AND HOLES AT THESE ENERGY LEVELS.

A MATHEMATICAL MODEL IS DEVELOPED TO PREDICT THE EFFECTS OF IMPURITIES ON SOLAR CELL PERFORMANCE. NUMERICAL SOLUTIONS ARE OBTAINED FROM THE SIX COUPLED NONLINEAR SHOCKLEY EQUATIONS ON A HIGH SPEED COMPUTER USING THE EQUIVALENT-CIRCUIT-MODEL METHOD OF SOLUTION.

THEORETICAL AND NUMERICAL ANALYSES ARE PERFORMED ON THE EFFECTS OF SPECIFIC IMPURITIES AND FABRICATION PROCESSES ON THE PROPERTIES OF SILICON MATERIALS AND SILICON SOLAR CELL PERFORMANCE USING EXPERIMENTAL DATA.

IN THIS PRESENTATION, A SUMMARY OF THE FINDINGS WILL BE DISCUSSED. THE PHYSICS OF THE MATHEMATICAL MODEL WILL FIRST BE REVIEWED. RESULTS OF THE EFFECT OF SEVERAL IMPURITY RELATED RECOMBINATION LEVELS ON SILICON SOLAR CELL PERFORMANCE WILL BE PRESENTED.

Computation Procedure

1. SYNTHESIZE THE 6 SHOCKLEY EQUATIONS INTO 2 TRANSMISSION LINE EQUIVALENT CIRCUITS.
   - D.C. STEADY-STATE EQUIVALENT CIRCUIT
   - SMALL-SIGNAL ERROR CORRECTION EQUIVALENT CIRCUIT
2. IMPOSE BOUNDARY CONDITIONS
   - PUT IN APPRORIATE VALUES OF RECOMBINATION CONDUCTANCES FOR INTERFACE RECOMBINATION AT THE FRONT AND BACK SURFACES
3. INPUT PARAMETERS
   - AM1 SOLAR SPECTRAL DENSITY TABEL
   - MOBILITIES VS IMPURITY CONCENTRATION
   - RECOMBINATION PARAMETERS: c_n, c_p, e_n, e_p, E_T
   - INTRISINC CARRIER CONCENTRATION: $n_i(T, N_{DD}, N_{AA})$
   - DIFFUSION PROFILE: $N_{DD}(x)$, $N_{AA}(x)$
   - DEVICE THICKNESS
   - DEVICE TEMPERATURE
4. COMPUTER MODEL SELECTION
   - 4 REGIONS (EMITTER, JUNCTION SPACE CHARGE, QUASI-NEUTRAL BASE, BACK SURFACE FIELD.)
   - Δx VARIATIONS IN EACH REGION.
5. NUMERICAL ITERATION FOR ILLUMINATED I-V
   - BEGINS AT 0 VOLTS AND DARK
   - INCREASES LIGHT INTENSITY TO AM1
   - INCREASES APPLIED VOLTAGE TO V_{OC} OR $J > 0$.
6. COMPUTE J_{MAX}, V_{MAX}, P_{MAX}, EFF, FF, V_{OC}
   - USE POLYNOMIAL FIT TO I-V

Computation Results

(High-Efficiency Cells)

1. HEAVY DOPING EFFECTS

   IN DIFFUSED EMITTER AND BACK SURFACE FIELD LAYERS FOR HIGH BASE RESISTIVITY CELLS.

   - INTERBAND AUGER RECOMBINATION.
   - ENHANCED SOLUBILITY OF RECOMBINATION CENTER.
   - NONIDEAL DIFFUSION PROFILES.

2. STEADY-STATE LIFETIMES

   - POSITION DEPEDNECES
   - CARRIER DENSITY DEPDENCES
     - FORWARD VOLTAGE DEPENDENCE
     - ILLUMINATION LEVEL DEPENDENCE
   - RECOMBINATION LEVEL DENSITY DEPENDENCE
     - ELECTRON LIFETIME ≠ HOLE LIFETIME

       (2 STEADY-STATE LIFETIMES)

3. INTERFACE RECOMBINATION

   - BACK SURFACE - SHIELDED BY BACK SURFACE FIELD
   - FRONT SURFACE - IMPORTANCE DIMINISHED BY BULK EMITTER RECOMBINATION

CONCLUSION

BASE RECOMBINATION AT IMPURITY OR DEFECT RECOMBINATION CENTERS DOMINATES SOLAR CELL PERFORMANCE.

(Impurity-Doped Cells)

1. TITANIUM DOPED CELLS
   - P+/N/N+ CELL BETTER THAN N+/P/P+ CELL.
   - FOR EFF(AM1) > 16%

	(P+/N/N+)	(N+/P/P+)
N_{TT} <	$6x10^{12}$ Ti/cm^3	$4x10^{11}$ Ti/cm^3

V_{OC} = 576 mV

J_{SC} = 30.2 mA/cm^2

FF = 0.822

N_{DD} = $5x10^{15}$ P/cm^3

L = 250 μm

X_E = 0.25 μm

τ_n = τ_p = 6.5 μs

2. ZINC DOPED CELLS
   - N+/P/P+ CELL BETTER THAN P+/N/N+ CELL.
   - FOR EFF(AM1) > 16%

N_{TT} < $8x10^{12}$ Zn/cm^3 (N+/P/P+)

N_{TT} < $2x10^{12}$ Zn/cm^3 (P+/N/N+)

CHEMICAL PROCESS EVALUATION

BATTELLE'S COLUMBUS LABORATORIES

OBJECTIVE - \$14/KG (1980 DOLLARS;
\$10/KG 1975 DOLLARS) SILICON FOR
PHOTOVOLTAIC APPLICATION

CURRENT PHASE - ZINC REDUCTION OF SILICON
TETRACHLORIDE IN A FLUIDIZED BED TO
PRODUCE SILICON GRANULES

Experimental Operation of the PDU

- DEMONSTRATE OPERABILITY
  - NOMINAL OPERATING CONDITIONS
- REACTOR OPERATION VARIABLES
  - REACTANT COMPOSITION
  - REACTANT THROUGHPUT
  - PRODUCT PARTICLE SIZE
- CONDENSER OPERATION
  - HEAT TRANSFER
- ELECTROLYTIC CELL OPERATION
  - ZINC PRODUCT PURITY
  - CURRENT EFFICIENCY
  - POWER EFFICIENCY
  - CONVERSION OF SUSPENDED SILICON
- ZINC VAPORIZER OPERATION
  - LEVEL CONTROL SYSTEM
  - VAPORIZATION RATE CONTROL
  - ALTERNATIVE HEAT SOURCE
- PRODUCT QUALITY
- ENERGY CONSUMPTION

Experimental Support Program

- RESIDUAL ZINC REMOVAL
- REACTOR LINER OPTIMIZATION
- ALTERNATIVE ZINC VAPORIZER DESIGNS

Residual Zinc Distribution

(Preliminary Electron Microbe Results, Scans of Only Five Particles Total from Miniplant Runs 93, 95, 97, and 98)

- Zinc Highly Segregated
- Peaks as high as 2.4a/o (24000ppm) above ± 400ppm background. (Neutron activation = 1480ppm (Run 97), 1520ppm (Run 98) for average analysis)
- Correlation with deposition band sequence questionable
- Some multiple peaks of up to 20-30μm net width (~thickness of deposition band)
- Suggests occluded zinc mist as origin
- If so, correctable with no need for post-deposition heat treatment to remove zinc
- Further study planned

Si PROCESS BASED ON REDUCTION OF SiF_4 by Na

SRI INTERNATIONAL

Impurity Analysis, ppm, Sample 30-4

Elements	Emis. Spec.	Spark Source Mass Spec.	Plasma Emis. Spec.	LLL/JPL Plasma Emis. Spec.	LLL/JPL Neut. Act.	Elements
Ti	<12	3.	--	0.72	--	Ti
V	<25	0.1	<0.1	<0.03	--	V
Cr	< 7	21	4.5	--	1.26	Cr
Mn	< 8	<0.1	0.5	0.22	--	Mn
Fe	<20	15	8.5	4±0.7	2.65	Fe
Co	< 7	4	4.0	--	2.0	Co
Ni	< 9	17	10	4.9±0.2	3.11	Ni
Cu	< 4	2	<0.1	0.3	< 4	Cu
Zn	--	0.2	1.5	0.36	<0.01	Zn
B	<30	10.	10.	--	--	B
P	<4500	0.8	5.	<0.79	-- <0.1*	P
As	--	0.2	--	--	0.52	As
Al	< 5	1	8.	<0.5	--	Al
Zr	<35	0.7		--	0.17	Zr
Mo	<35	≤0.3	3.5	0.36±0.1	0.65	Mo
Ag	5	<0.3		--	<0.003	Ag
Cd		<0.3	8.5	<0.013	--	Cd
Pb	<50	<0.3	10	<0.12	--	Pb
Se		<0.3		<0.49	--	Se
Na	<200	<740		312±12	310	Na
K		0.1		< 1.2	--	K
Ca	< 7	1.0	1.0	1±0.6	--	Ca
Mg		1.0	0.1	2±0.3	--	Mg
Ba	<10	<0.3		--	--	Ba
Li				<0.007	--	Li
Sr				<0.045	--	Sr
S		0.3				S
F		0.8				F

*Balazs Wet Chem.

Impurity Analysis, ppm, Sample 30-7

Elements	Emis. Spec.	Spark Source Mass Spec.	Plasma Emis. Spec.	LLL/JPL Plasma Emis. Spec.	LLL/JPL Neut. Act.		Elements
Ti	<12	0.6	--	3.4	--		Ti
V	<25	<0.1	0.6	<0.05	--		V
Cr	< 7	8	--	--	5		Cr
Mn	< 8	<0.1	3.6	1.2	--		Mn
Fe	<20	15	--	21.4±1.4	23		Fe
Co	--	0.9	0.1	--	0.02		Co
Ni	< 8	4	--	9.6±0.3	<11		Ni
Cu	< 4	2	3.6	1.5±0.1	<4.8		Cu
Zn	--	0.2	1.4	0.8±0.1	<0.02		Zn
B	<30	9	8.8	--	--		B
P	<4500	0.8	3.0	<1.5	--	<0.1*	P
As	--	<0.1	0.3	--	0.94		As
Al	--	<0.1	--	1.5±0.9	--		Al
Zr	<35	<0.3	--	--	<0.24		Zr
Mo	<35	0.2	6.7	1.7±0.2	1.6±0.1		Mo
Ag	< 5	<0.3	--	--	0.015		Ag
Cd	--	<0.3	0.04	0.37±0.03	--		Cd
Pb	--	<0.3	0.4	<0.23	--		Pb
Se	--	<0.3	--	<0.93	--		Se
Na	<1100	<740	876	542±21	540		Na
K	--	<0.1	3	<2.3	--		K
Ca	< 7	<0.1	3.	3.7±1.2	--		Ca
Mg	< 6	0.5	6.	1.9±0.5	--		Mg
Ba	<10	<0.3	--	--	--		Ba
Li	--	--	--	<0.013	--		Li
Sr	--	--	--	<0.08	--		Sr
S	--	<0.3	--	--	--		S
F	--	0.3	--	--	--		F

*Balazs Wet Chem.

COMBUSTION PROCESS

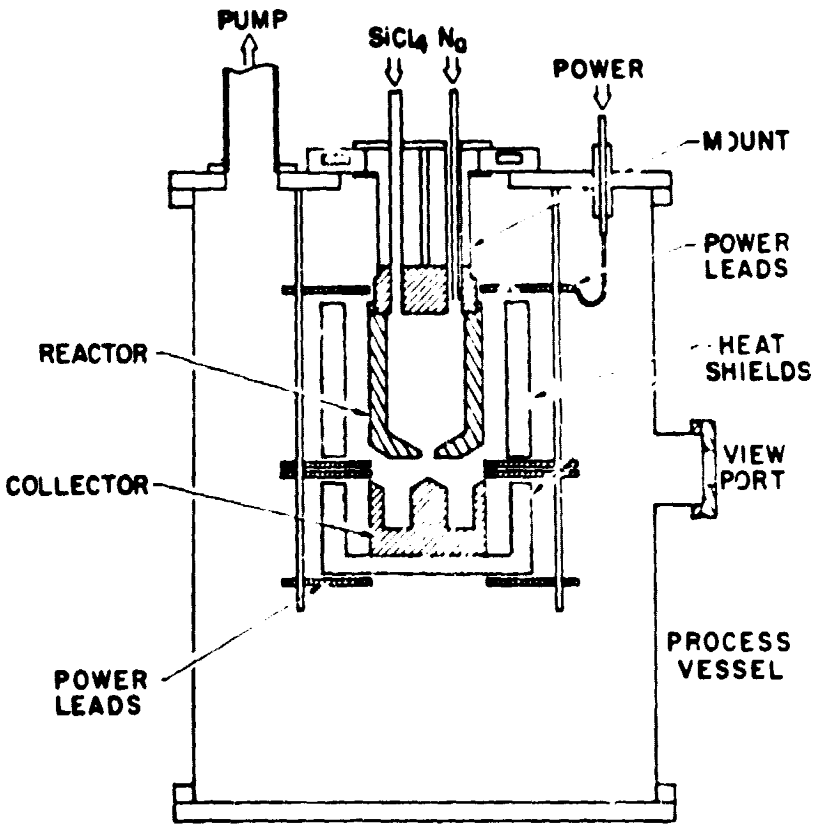
AEROCHEM RESEARCH LABORATORIES

Objectives

DETERMINE THE FEASIBILITY OF USING HIGH TEMPERATURE REACTIONS OF ALKALI METALS AND SILICON HALIDES TO PRODUCE SOLAR-GRADE SILICON

1. MEASURE HEAT RELEASE/REACTION RATE PARAMETERS.
2. EVALUATE PRODUCT SEPARATION AND COLLECTION PROCESSES.
3. DETERMINE EFFECTS OF REACTANTS AND/OR PRODUCTS ON MATERIALS OF CONSTRUCTION.

Process Vessel



Status

EFFORT TO PRODUCE 0.2-0.5 KG SAMPLES. RUNS OF 0.5- 1 HR.

PROBLEMS WITH REACTANT INLET AND REACTOR CLOGGING DUE TO INSUFFICIENT START-UP TEMPERATURES.

LARGER POWER SUPPLIES ARE BEING INSTALLED.

VERY SMALL SAMPLES OF FUSED SILICON HAVE BEEN PRODUCED.

Plans

PRODUCE 0.1-0.5 KG SAMPLES

CHECK:

1. SAMPLE COLLECTION EFFICIENCY
2. REACTION EFFICIENCY
3. SAMPLE PURITY

INCREASE RUN TIME--LARGER SAMPLES, CHECK RELIABILITY

C-2

EFFECTS OF IMPURITIES

WESTINGHOUSE R&D CENTER

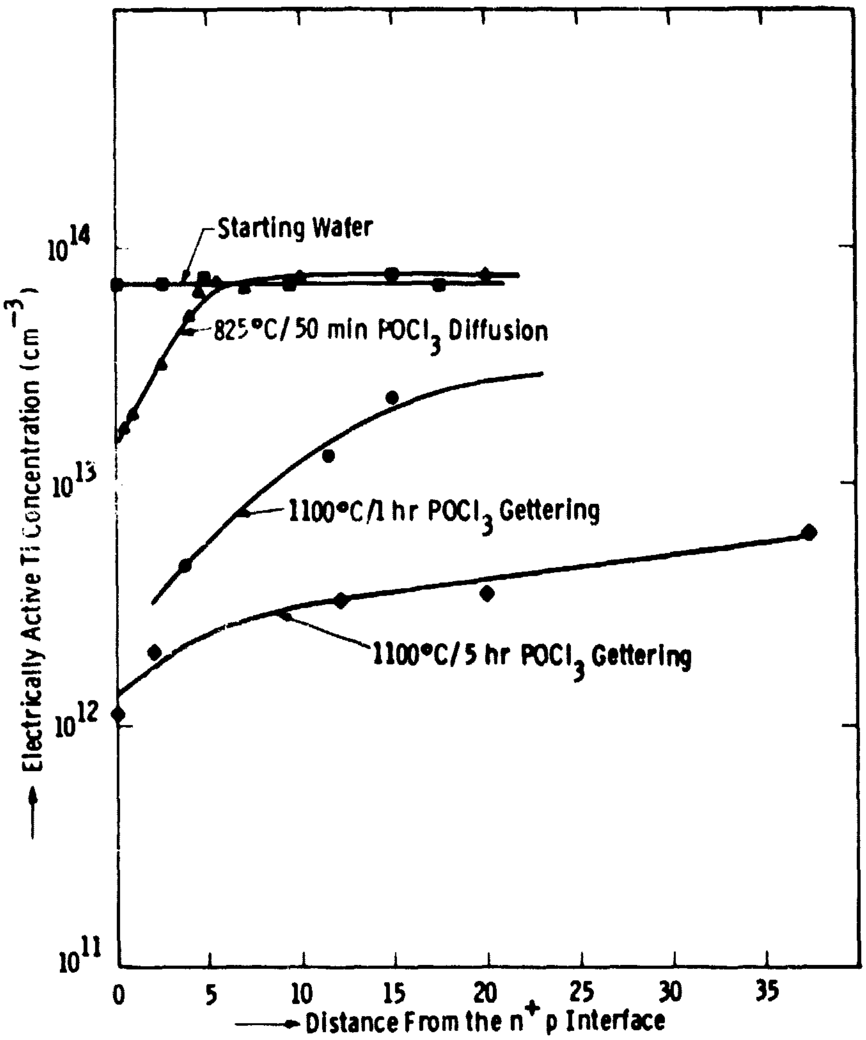
- CHARACTERIZE THE EFFECTS OF IMPURITIES ON SILICON SOLAR CELLS

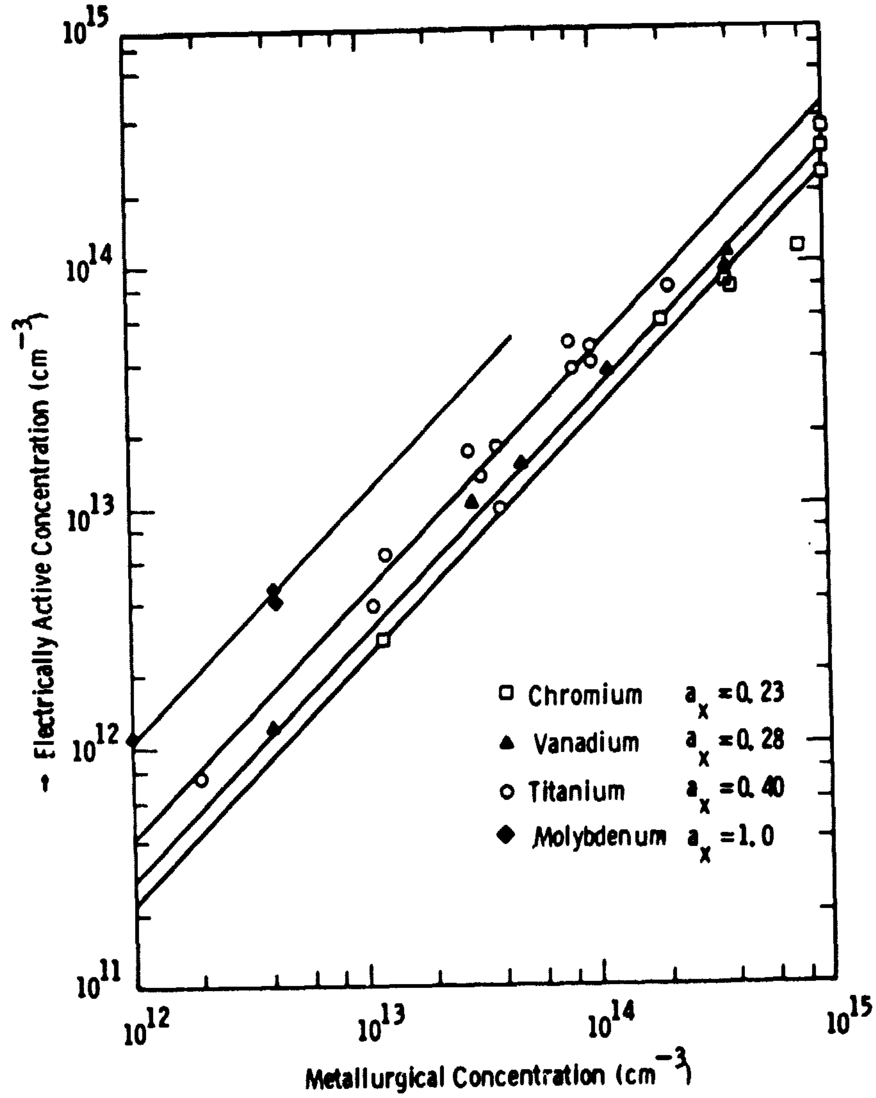
- PROVIDE A BASIS FOR EVALUATING THE COST-BENEFIT TRADE-OFFS BETWEEN SILICON PURITY, CELL FABRICATION TECHNOLOGY AND CELL PERFORMANCE.

Impurity Effects

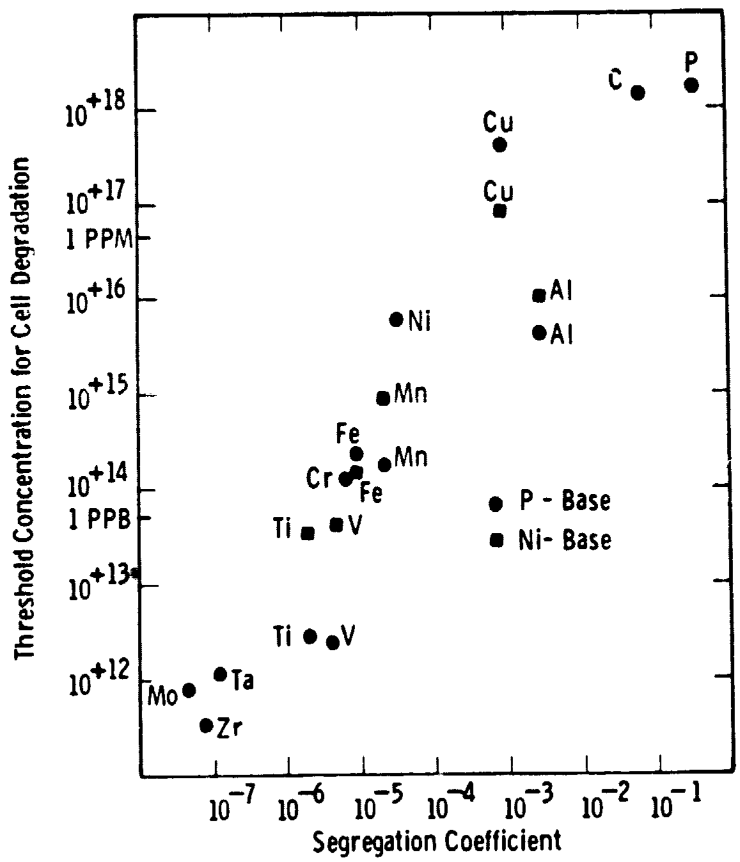
- CRYSTAL GROWTH
  - CONSTITUTIONAL SUPER-COOLING AND CRYSTAL BREAKDOWN
  - GRAIN BOUNDARY DECORATION
  - NON-UNIFORM IMPURITY DISTRIBUTION
- RESISTIVITY
  - COMPENSATION
  - NON-UNIFORMITY
  - IMPURITY-DOPANT COMPLEXING
- LIFETIME/DIFFUSION LENGTH
  - ELECTRICALLY ACTIVE RECOMBINATION CENTERS
- JUNCTION RELATED
  - PRECIPITATES/CLUSTERS
    - SHUNTING/EXCESS CURRENTS
- IMPURITY-IMPURITY
  - SYNERGY/ANTISYNERGY
- SURFACE AND BOUNDARY RELATED
  - PILE-UP
  - PASSIVATION/DEPASSIVATION
  - CONTACT DEGRADATION
- PROCESS RELATED
  - GETTERING
  - REDISTRIBUTION
- TIME DEPENDENT
  - AGING/PERMANENCE

$POCl_3$ Gettering of Ti-Contaminated Silicon





10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
Electrically Active Concentration (cm^{-3})
□ Chromium $a_x = 0.23$
▲ Vanadium $a_x = 0.28$
○ Titanium $a_x = 0.40$
◆ Molybdenum $a_x = 1.0$
10^{12}
10^{13}
10^{14}
10^{15}
Metallurgical Concentration (cm^{-3})



Web Grown From Battelle Silicon

Polysilicon Characteristics	Battelle Lot 33645-38-97 (Supplied by JPL) Pretreated 6 hrs at 1290°C in Argon to Emit Zn
Web Growth Behavior	Same as Observed for Semiconductor Grade Silicon
Solar Cell Characteristics	Cell Efficiency: Uncoated Avg. 9.0 ± 0.2% (η_{AR} ~ 12.8% est.) Range Uncoated 8.6 to 9.2% (η_{AR} 12.3% to 13.2% est.)
	Test Conditions: n^+pp^+ Cell, 91.6 mW/cm^2 Illumination

SOLAREX CORP.

PURPOSE OF THE PROGRAM:

TO CONDUCT A SOLAR CELL FABRICATION AND ANALYSIS PROGRAM TO DETERMINE THE EFFECTS ON THE RESULTANT SOLAR CELL EFFICIENCY OF IMPURITIES INTENTIONALLY INCORPORATED INTO SILICON.

METHOD:

EMPLOY "FLIGHT-QUALITY" TECHNOLOGIES AND QUALITY ASSURANCE TO ASSURE THAT VARIATIONS IN CELL PERFORMANCE ARE DUE TO THE IMPURITIES INCORPORATED IN THE SILICON.

SAMPLES:

PROVIDED BY JPL FROM WESTINGHOUSE-DOW CORNING PROGRAM.

PROGRAM ORGANIZATION:

DESIGNED TO INSURE THAT:

- SAMPLES ARE ALWAYS POSITIVELY IDENTIFIED.
- ALL PROCESSES ARE WELL CONTROLLED AND DOCUMENTED TO ASSURE THAT THE RESULTS ARE NOT PROCESS DEPENDENT.
- THERE IS NO CROSS-CONTAMINATION FROM LOT TO LOT.
- FINISHED CELLS ARE SUBJECTED TO SUFFICIENT MEASUREMENTS AND ANALYSIS SO THAT THE MECHANISMS OF IMPURITY EFFECTS ON CELL BEHAVIOR CAN BE IDENTIFIED.

CONTROL SILICON:

VERIFICATION CELLS - DONE BEFORE STARTING TEST PROGRAM TO SERVE AS A TRAINING TOOL FOR THE PROCESS SEQUENCE AND TO SERVE AS A DATA BASE.

CONTROL CELLS - PROCESSED WITH THE TEST CELL SILICON TO ASSURE THAT THE RESULTS ARE NOT PROCESS DEPENDENT.

MONITOR CELLS - PROCESSED AFTER CLEANING OF EQUIPMENT TO ASSURE THAT ALL IMPURITIES ARE REMOVED FROM THE EQUIPMENT AND WILL NOT CONTAMINATE SUBSEQUENT LOTS.

Verification Lot Summary (6 Lots)

I_{SC}	=	150.4 mA	
V_{OC}	=	595.0 mV	
P_{MAX}	=	69.8 mW	
I_{MP}	=	140.6 mA	
V_{MP}	=	498.2 mV	
I_{SC} BLUE	=	38.8 mA	CORNING #9788
I_{SC} RED	=	84.0 mA	CORNING #2408
FILL FACTOR	=	78.3%	
EFFICIENCY	=	12.9%	AM0 AT 25° C
	≈	15%	AM1 AT 25° C

Impurity Content vs Performance

EXPERIMENTAL LOT #	IMPURITY	CONCENTRATION 10^{15} ATOMS/CC	P/P_0	I_{SC}/I_{SCO}	V_{OC}/V_{OOC}	FF
1	C	200-400	0.87	0.95	0.96	74
2	CA	?	0.93	0.96	0.97	78
3	CR	0.5	0.85	0.89	1.03	72
4	CU	2.0	0.92	0.92	1.02	76
5	MN	0.63	0.83	0.89	0.94	76
6	MN	1.0	0.77	0.87	0.92	75
7	MN	0.66	0.83	0.88	0.94	78
8	P	28	0.95	0.95	1.00	78
9	CR-MN	0.5/0.3	0.58	0.72	0.87	73
10	MN	0.7	0.87	0.90	1.02	74
11	MN	0.63	0.86	0.92	0.95	77
12	MO	0.00092	0.81	0.88	0.92	79
13	CU/TI	1.0/0.033	0.53	0.62	0.87	76
14	TI	0.11	0.38	0.55	0.80	66
15	TI	0.167	0.31	0.44	0.90	60
16	TA	<0.0008	0.79	0.90	0.95	72
17	CR/TI	1.0/0.011	0.60	0.69	0.87	78
18	TI	0.033	0.56	0.65	0.87	76
19	CR/MN/TI	0.4/0.5/0.0033	0.73	0.82	0.91	77

LOTS E-3, 4, & 10 ARE 0.2 TO 0.25 Ω-CM.

REMAINDER BETWEEN 3.0 & 6.0 Ω-CM.

CONTROL SILICON 1.0 TO 3.0 Ω-CM.

Materials Effects

SINGLE DOPANTS

1. CARBON - BLUE CURRENT NORMAL
   200-400 VOLTAGE NORMAL
   RED OR BULK CURRENT MAJOR DEGRADATION
   SOME EVIDENCE OF SHUNTING
2. CALCIUM - BLUE CURRENT NORMAL
   ? VOLTAGE NORMAL
   RED OR BULK CURRENT MAJOR DEGRADATION
   FILL FACTOR NORMAL
3. CHROME - BLUE CURRENT SLIGHTLY LOWER
   0.5 VOLTAGE NORMAL
   RED OR BULK CURRENT NORMAL
   SHUNTING MAJOR DEGRADATION
4. COPPER - AFTER EFFECTS OF RESISTIVITY AND
   2.0 PROCESSING ARE FACTORED OUT, THERE
   IS NO STATISTICAL DIFFERENCE BETWEEN
   THIS LOT AND THE CONTROLS. (REQUIRES
   RUNS ON 0.2 Ω-CM CONTROL SI TO
   VERIFY.)
5. MANGANESE

SUMMARY OF MN RUNS

LOT #	10^{15} ATOMS/CC	P/PO	$\frac{I_{SC}}{I_0}$	$\frac{V_{OC}}{V_{OOC}}$	NOTES
5	0.63	0.83	0.89	0.94	
6	1.0	0.77	0.87	0.92	POLYCRYSTALLINE
7	0.66	0.83	0.88	0.94	
10	0.7	0.87	0.90	1.02	LOWER RESISTIVITY
11	0.63	0.86	0.92	0.95	SLOW GROWTH

BLUE CURRENT NORMAL
VOLTAGE NORMAL
RED OR BULK CURRENT MAJOR DEGRADATION
MANY CELLS EXHIBIT NORMAL FILL FACTORS
SOME CELLS IN EACH LOT EXHIBIT SHUNTING
POLYCRYSTALLINE CELLS EXHIBIT MUCH MORE
SEVERE SHUNTING PROBLEM.

8. PHOSPHOROUS - MINOR DEGRADATION IN POWER
28 LOSS DUE TO DECREASE IN BLUE CURRENT
ALL OTHER COMPONENTS NORMAL

12. MOLYBDENUM - VOLTAGE SOMEWHAT REDUCED
0.00092 BLUE CURRENT NORMAL
FILL FACTOR NORMAL
RED OR BULK CURRENT MAJOR DEGRADATION

14. TITANIUM

SUMMARY OF TI RUNS

LOT #	CONCENTRATION 10^{15} ATOMS/CC	P/P_0	$\frac{I_{SC}}{I_0}$	$\frac{V_{OC}}{V_{OOC}}$	NOTES
14	0.11	0.38	0.55	0.8	(3-6 Ω-CM)
15	0.167	0.31	0.44	0.9	(0.2 Ω-CM)
18	0.033	0.56	0.65	0.87	(4-6 Ω-CM)

LARGE CONCENTRATIONS OF TI (14 & 15) CAUSE DEGRADATION OF ALL COMPONENTS INCLUDING SEVERE SHUNTING.

SMALL CONCENTRATIONS OF TI (18) CAUSE MAJOR DEGRADATION OF BULK CURRENT, MINOR DEGRADATION OF BLUE CURRENT BUT NO SHUNTING.

16. TANTALUM - VOLTAGE NORMAL
<0.0008 BLUE CURRENT NORMAL
RED OR BULK CURRENT MAJOR DEGRADATION
LOWER FF DUE TO SHUNTING

MULTIPLE DOPANTS

9. CR - MN - BLUE CURRENT NORMAL
0.5/0.3 VOLTAGE SOMEWHAT REDUCED
RED OR BULK CURRENT MAJOR DEGRADATION
SEVERAL CELLS SHUNTED
REMAINDER HAVE NORMAL FILLS

APPEAR TO BE SYNERGISTIC EFFECT WITH MULTIPLE DOPING CAUSING MORE DEGRADATION THAN SUM OF INDIVIDUAL.

13. CU - TI - BLUE CURRENT NORMAL
1.0/0.033 FILL FACTOR NORMAL
VOLTAGE DEGRADED
RED OR BULK CURRENT MAJOR DEGRADATION

DEGRADED SLIGHTLY MORE THAN LOT E-18 WITH THE SAME AMOUNT OF Ti BUT NO COPPER.

17. CR - TI - BLUE CURRENT NORMAL
1.0/0.011 FILL FACTOR NORMAL
VOLTAGE DEGRADED
RED OR BULK CURRENT MAJOR DEGRADATION

SUFFICIENT DATA NOT AVAILABLE TO COMPARE MULTIPLE DOPANTS WITH EACH INDIVIDUAL DOPANT.

19. Cr-Mn-Ti - BLUE CURRENT NORMAL
0.4/0.5/0.0033 VOLTAGE SLIGHTLY DEGRADED
RED OR BULK CURRENT MAJOR DEGRADATION
SEVERAL CELLS SHUNTED
REMAINDER EXHIBIT NORMAL FILL

Large-Area Silicon Sheet Task

INGOT TECHNOLOGY

Crystal Systems, Inc., reported on ingots cast from upgraded metallurgical silicon using the Heat Exchanger Method (HEM). Nearly single-crystal ingots have been cast due to impurity segregation to the top of the ingot and the walls of the crucible. High-purity meltstock has produced single-crystal shaped ingots of 22 x 22 x 18 cm dimensions weighing 16.3 kg.

Hamco (Kayex Corporation) reported on repeated demonstrations of growth of 105 kg of silicon ingots from one crucible by periodic melt replenishment. A total of five 100-kg runs have been accomplished on this contract, with two of them completed in this reporting period. Efficiencies of solar cells fabricated on silicon from an earlier run ranged from 11% to 13.5% AM1. Also, impurity analyses on earlier runs are being used to determine sources of growth contamination. Under another contract for Near-Term Cost Reduction, Hamco also reported on the modification of a CG2000 Hamco Crystal Puller to demonstrate growth of up to 150 kg of 6-in.-dia single-crystal silicon from one crucible. Modification of the crystal puller is nearly complete and the microprocessor control is being tested. Three preliminary runs have been completed using the puller in the standard resistance mode.

Siltec Corporation reported on a continuous liquid-feed Czochralski approach to growing 150 kg of monocrystalline silicon ingots, 150 mm in dia, from one crucible. Fifteen runs with 12-kg charges were performed and solidification rates of 2.7 to 3.5 kg/h were achieved. Of the total material grown, 96% was monocrystalline. Manufacturing of parts and installation of the polyrod feed mechanism for continuous recharging of the meltdown chamber was completed, together with the feedback control system which uses the melt level sensor of the growth crucible as input. Short melt replenishment runs with 5 to 8 kg of continuous melt transfer were performed.

WAFERING TECHNOLOGY

Crystal Systems, Inc., reported on wire improvements for the multi-wire Fixed Abrasive Slicing Technique (FAST). Average cutting rates of 0.143 and 0.122 mm/min were attained; these rates are about 40% higher than those required to meet the 1986 goals. The performance of 45 µm diamonds used in the diamond-impregnated wires has been seen to be superior to the [illegible] µm diamonds.

Siltec Corporation performed demonstration runs of ingot cutting with ingot rotation and minimum exposed blade area in their program to develop and demonstrate enhanced ID slicing technology. Slices with 100 mm dia were produced with 250 µm thickness and kerfs of 200 µm. Applied cutting feed rates were in the range of 12 to 13 mm/min.

A characterization of the slices from the test series was performed to analyze taper, bow, thickness variation and depth of saw damage.

Silicon Technology Corporation reported results of ID sawing of 100-mm dia ingots with 9-10 mils kerf loss. Optimal programmed feeds (in./min) and rotation (rpm) vs slice thickness was detailed.

SHAPED-SHEET TECHNOLOGY

Arco Solar: Stanford Research Institute (SRI) reported on their die material research for Arco Solar. Boron nitride, low-density graphite, high- density graphite and silicon nitride were found to be unacceptable. A graphite die coated with boron nitride and sodium silicate-sodium fluoride was found to keep the silicon from wetting the coating. Preliminary casting experiments were carried out in boron nitride dies with some success. A standard process has been developed at Arco Solar for polycrystalline cells using Wacker Silso material.

Mobil-Tyco Solar Energy Corporation is developing a multiple-growth furnace to grow three 10-cm-wide edge defined film fed growth (ERG) ribbons with continuous melt replenishment. Rates of 3 to 3.8 cm/min and ribbon thicknesses of 7 to 15 mils have been achieved. Diffusion length measurements have revealed a real inhomogeneity with averages of 10 to 20 μm. High-speed growth runs have resulted in growth of 7.5-cm-wide ribbons at 5.0 cm/min with active helium gas cooling of cartridges and 4.5 cm/min without. Installation of instrumentation for automatic control of meniscus height for the 10-cm system is completed.

Westinghouse has exceeded the area throughput rate goal (27 cm^2/min) and the solar cell conversion efficiency goal (15.5%) set for their silicon web growth process. Process acceptance of solar grade (Battelle) polysilicon has been demonstrated and short-term (5 h) growth has been achieved with melt replenishment.

Energy Materials Corporation reports growth speeds of up to 60 cm/min for their horizontal-ribbon-growth method, with the rate typically being 20 to 30 cm/min. The length of the ribbon grown has been limited by the stroke of the puller to about 66 cm. The ribbons, 1.5 cm wide and 0.03 to 0.12 cm thick, are of a large-grain polycrystalline structure.

SUPPORTED-FILM TECHNOLOGY

Honeywell has grown 200-μm thick silicon films at 0.2 cm/sec with helium cooling in their silicon-coating-by-inverted-meniscus (SCIM) effort. Cell efficiencies of 9.9% on a 10 cm^2 cell and 10.04% on a 4 cm^2 cell heve been achieved. Another new SCIM coater design is complete and construction is under way.

MATERIAL CHARACTERIZATION

The University of Missouri Rolla has studied the effects of varying partial pressures of reactant gases, primarily oxygen and nitrogen, in a furnace where molten silicon is in contact with die and container materials. A new portable thoria - 7 wt% yttria polycrystalline ceramic solid electrolyte cell, designed to be used in measuring the oxygen partial pressure above silicon melts at the sheet and ribbon production facilities of other Task II contractors, has been constructed. Calibration procedures and initial results were described.

Cornell University reported on the microstructure of EFG and RTR ribbons. The EFG ribbon showed coherent twins, bundles of of microtwins and, less frequently, incoherent twins on the (112) planes and high-angle grain boundaries. RTR ribbons showed twin boundaries perpendicular to the silicon surface.

Applied Solar Energy Corporation presented data on further evaluation of EFC ribbon (RH process), dendritic web and continuous Czochralski. A cell efficiency of almost 13% (AMO) was achieved on dendritic web with best state-of-the-art cell processing. The evaluation groups are exploring the optimum process for each sheet and to identify possible areas for improvement in terms of controllable sheet properties.

Spectrolab presented data on processing of HEM, continuous Cz, EFG, RTR, Wacker Silso and dendritic web materials including overall cell conversion efficiency and relative spectral response. The program will continue to try to optimize processing for each sheet to achieve 12% AM1 efficiency at 28°C.

JPL IN-HOUSE PROGRAM

Two additional laboratories are now available for direct support of contractor activities. The Photovoltaic Materials and Device Testing Laboratory has facilities for dicing, lapping and polishing wafers and electronically testing wafers and completed solar cells. The Solar Cell Prototype Fabrication Laboratory has facilities for total processing of solar cells from unpolished wafer to finished, AR-coated cells.

TECHNOLOGY SESSION

J. Liu, Chairman

CRYSTAL CASTING – HEM

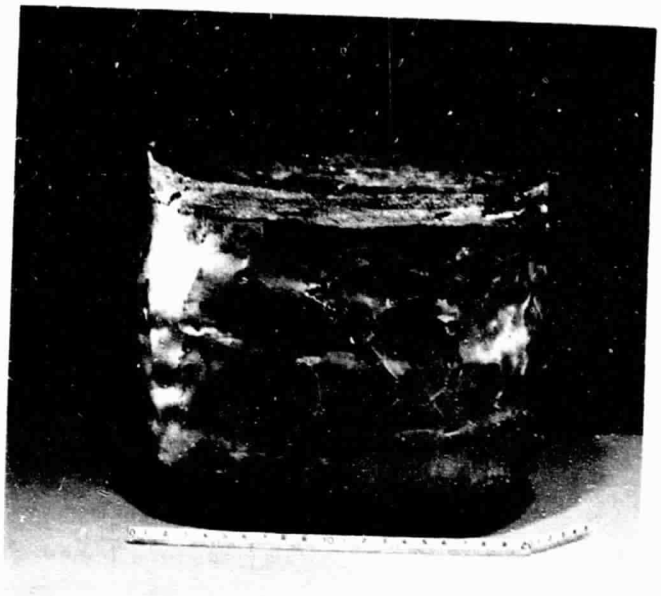
CRYSTAL SYSTEMS, INC.

C. P. Khattak and F. Schmid

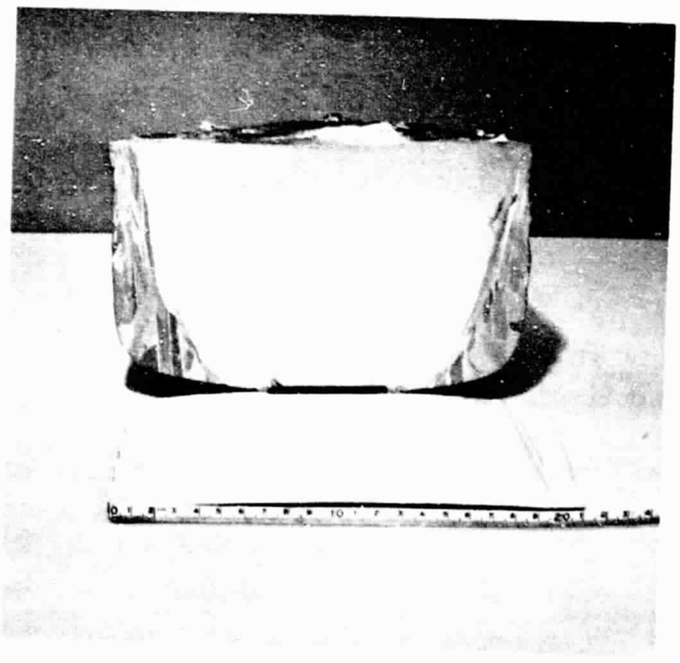
It has been demonstrated that silicon produced by the Heat Exchanger Method (HEM) is comparable to that produced by the Czochralski process for photovoltaic application. In addition, it has been shown that the process can be easily scaled up to produce large-size ingots. The projected costs of this directional solidification process is low. Significant advancements have been made to show that low-cost polycrystalline silicon can be used as a starting material with HEM for sheet production. This has been demonstrated with upgraded metallurgical silicon. Nearly single-crystal ingots were cast with a single HEM solidification using this starting material. The impurities were rejected to the last material to freeze--near the wall of the crucible. The upgraded metallurgical silicon is contaminated with silica and silicon carbide. Macroscopic precipitates, presumably SiC, did not break down the solid-liquid interface and, in some cases, caused only localized twin formation. The resistivity of the silicon produced after HEM solidification was 0.1 - 0.2 Ω-cm. With this silicon, the material cost could be reduced below the cost goal and the projected silicon shortfall would be avoided. The initial experiment with upgraded metallurgical silicon showed the entrapment of SiC particles in the silicon. In the second experiment, by using a slagging operation during solidification, the SiC particles were considerably minimized. In this experiment single crystallinity was maintained all the way to the top of the ingot and the sides of the crucible. This slagging step eliminates a polycrystalline silicon charge preparation step, thereby reducing the costs further.

In the scale-up of the process, square ingots of 22 cm x 22 cm x 18 cm weighing 16.3 kg have been solidified out of high-purity melt stock. The ingots were almost entirely single-crystalline. The crucible attachment problem has been eliminated and good reproducibility has been achieved.

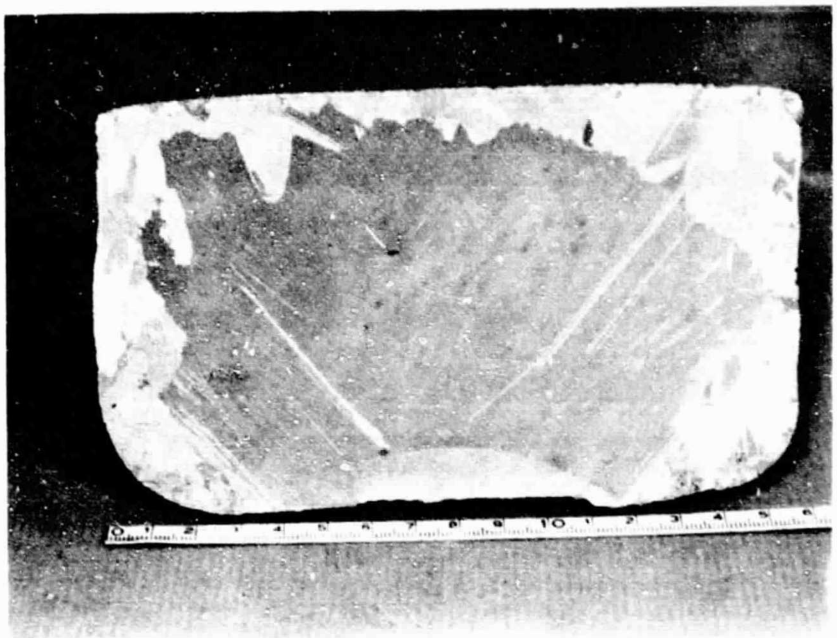
22 × 22 × 18 cm Crystal Solidified by HEM



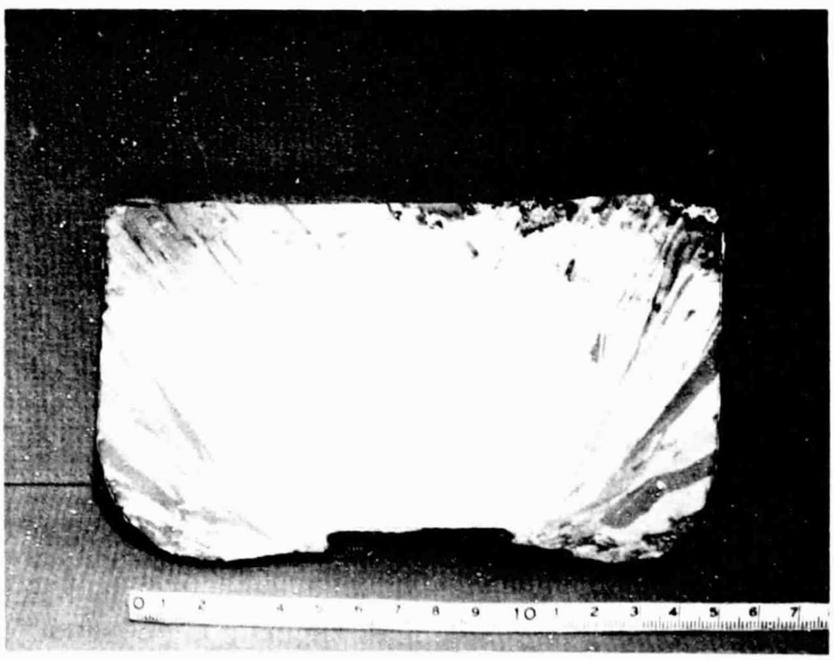
Polished and Etched Section of 22 × 22 cm Cross Section Crystal



Crystallinity of Ingots After Single Directional
Solidification by HEM Using Upgraded Metallurgical Si



(a) Without Slagging



(b) With Slagging During Solidification

MULTI-WIRE SLICING – FAST

CRYSTAL SYSTEMS, INC.

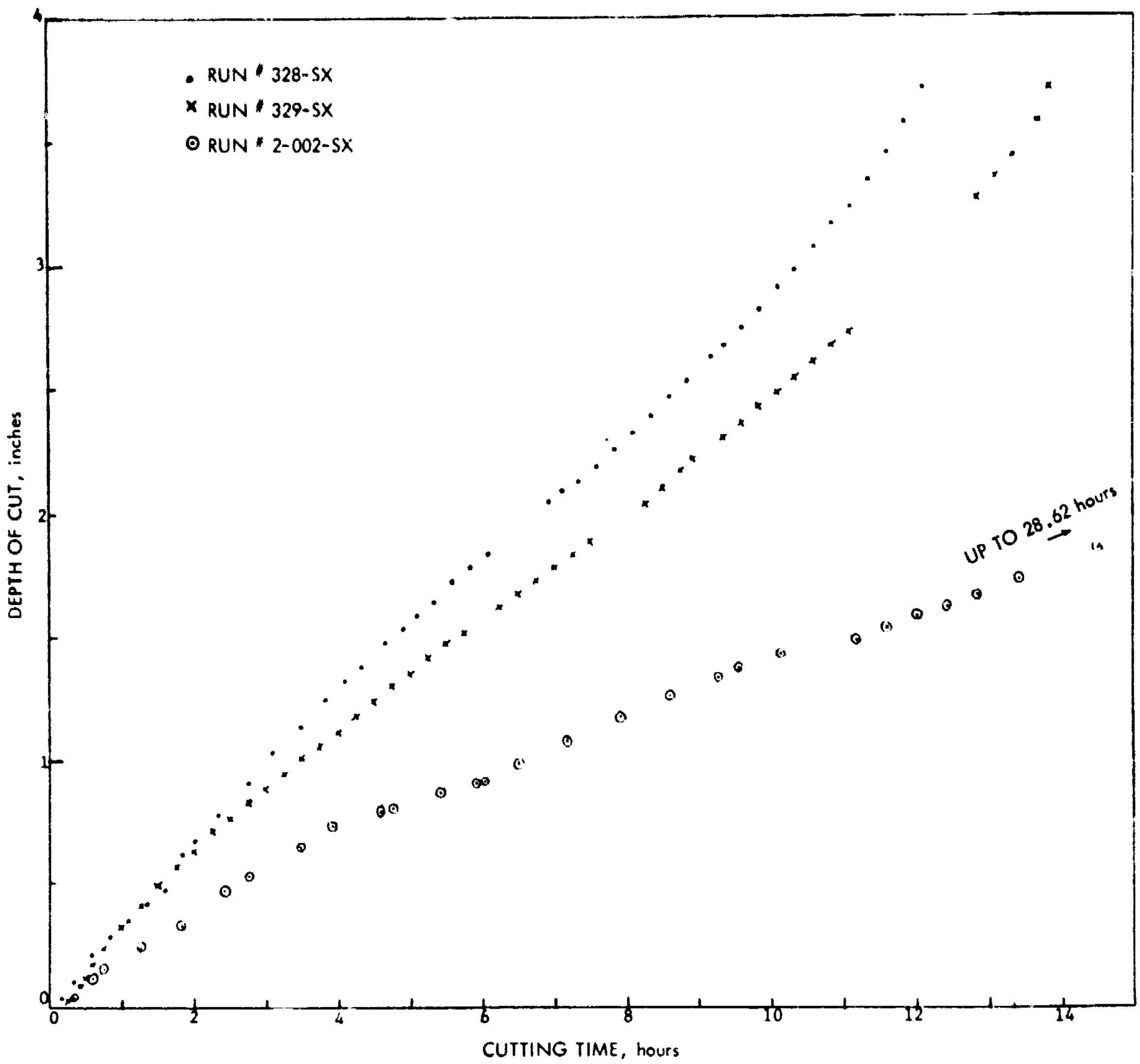
C. P. Khattak and F. Schmid

Significant developments have been made using the multi-wire Fixed Abrasive Slicing Technique (FAST).

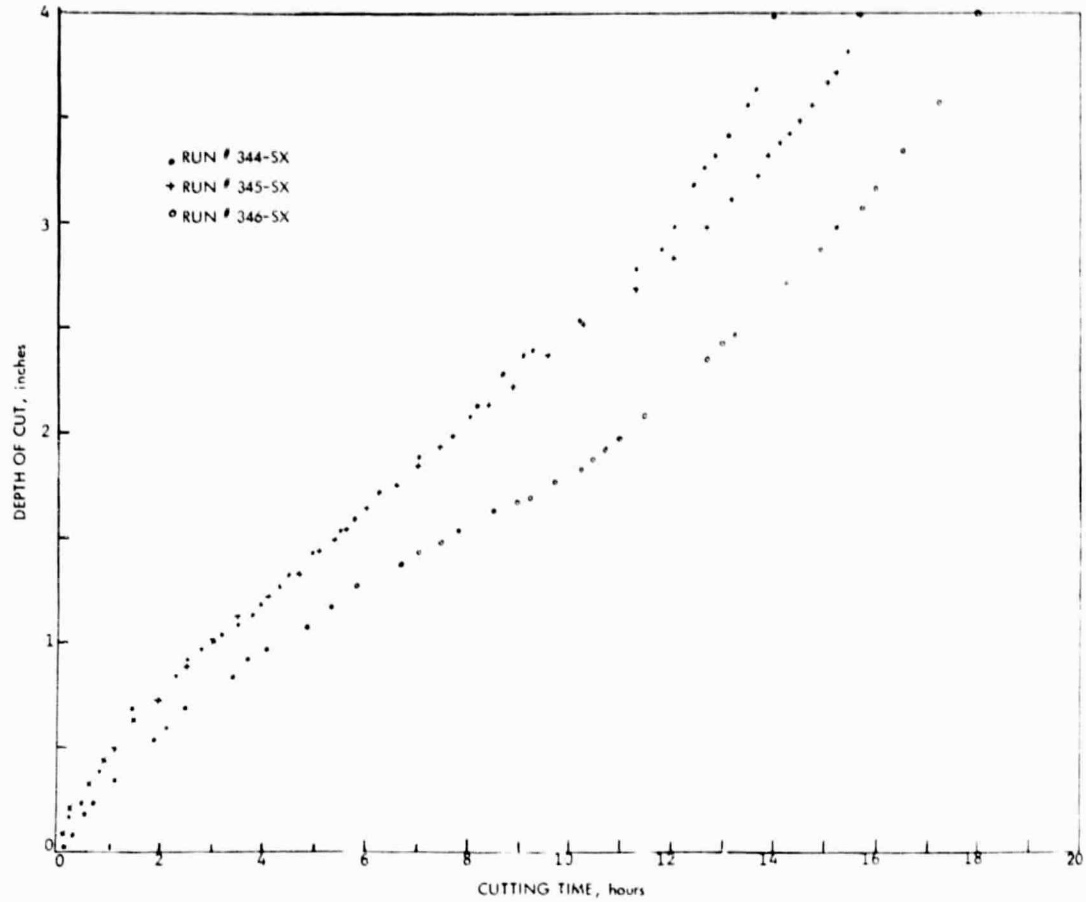
High throughput of the slicer and extended life of the wires has been demonstrated. Cutting rates of about 40% more than the projected estimates used in the economic analysis to meet 1986 goals have been achieved. This has been accomplished through the combination of higher surface speeds of the wires and improvement in the wire. Figure 1 shows a plot of the depth of cut with time for runs 328-SX and 329-SX using the same bladepack. At a surface speed of 400 ft/min, the average cutting rates for these two runs were 0.143 and 0.122 mm/min. respectively. Also shown is the data for run 2-002-SX at a surface speed of 200 ft/min. The average cutting rate was 0.059 mm/min for this run.

Figure 2 shows the slicing performance achieved during runs 344-SX, 345-SX and 346-SX. These runs were sliced with the same set of electroplated wires and the average slicing rate was 0.120, 0.105 and 0.095 mm/min. respectively. These data show that the wires can be used to slice three silicon ingots with little degradation in performance. This set of wires was electroplated using 30 μm natural diamonds. The performance of 45 μm diamonds has been seen to be superior as compared to 30 μm size, hence still longer life is expected.

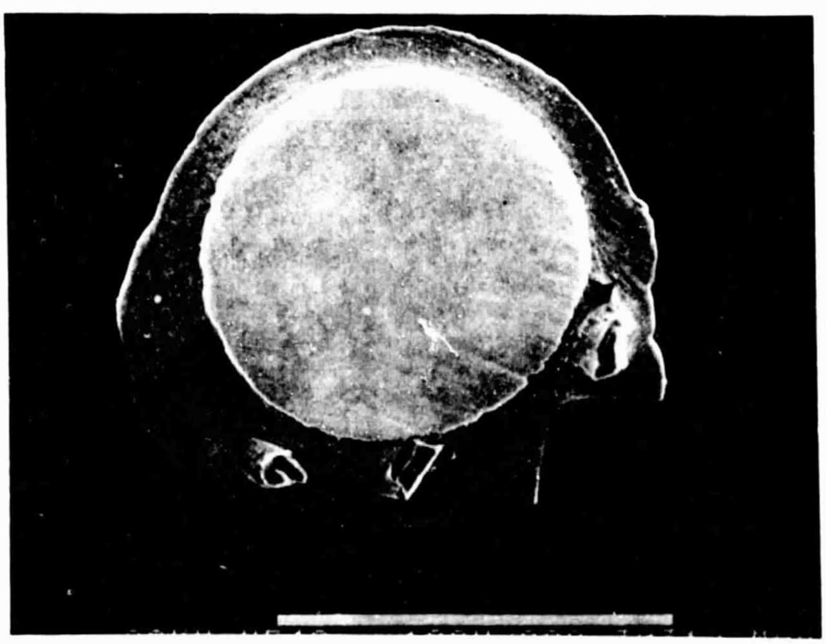
Commercially available impregnated wires used have shown poor quality control. Impregnation equipment has been fabricated to impregnate diamonds in the cutting edge only. Very high diamond concentrations with good uniformity have been achieved. Slicing tests have shown that the absence of diamonds on the top of the wires allows the wires to seat well in the grooved rollers and thereby achieve better accuracy and lower kerf.



RUN # 328-SX
RUN # 329-SX
RUN # 2-002-SX
UP TO 28.62 hours
DEPTH OF CUT, inches
CUTTING TIME, hours
0
1
2
3
4
0
2
4
6
8
10
12
14



Impregnated Wire with Diamonds in Cutting Edge Only



ADVANCED Cz CONTINUOUS GROWTH

HAMCO DIVISION OF KAYEX CORP.

Introduction

CONTINUOUS CZ INGOT GROWTH

THE APPROACH TO THIS PROJECT IS TO USE PERIODIC MELT REPLENISHMENT BETWEEN SUCCESSIVE INGOT GROWTH CYCLES USING ROD OR LUMP POLYSILICON TO GROW 100 KILOGRAMS OF SILICON CRYSTAL FROM ONE CRUCIBLE.

Status of Continuous Cz Ingot Growth

GOAL	STATUS
1. GROW 100 KG FROM ONE CRUCIBLE.	COMPLETE
2. ACHIEVE 14% SOLAR CELL EFFICIENCY (AM-1).	ACHIEVED
3. REPLENISH MELT USING ROD OR LUMP.	DEMONSTRATED
4. MAINTAIN HIGH QUALITY CRYSTAL GROWTH THROUGHOUT RUN.	DEMONSTRATED
5. PERFORM SIX 100 KG RUNS.	FOUR COMPLETED
6. REDUCE PROCEDURES FOR CONTINUOUS CZ GROWTH TO ROUTINE TECHNOLOGY.	ONGOING (PROCESS SPECIFICATION BEING WRITTEN)
7. IMPROVE ADD-ON COST.	GOALS CAN BE ACHIEVED OR POSSIBLY SURPASSED BY GROWING FEWER CRYSTALS.

RUN NO. 55 AND NO. 2* REPRESENT THE THIRD AND FOURTH 100 KG CONTINUOUS RUNS OF THE SIX REQUIRED UNDER THE PROJECT EXTENSION. RUN NO. 55 WAS PERFORMED ON THE ORIGINAL CRYSTAL GROWER BUILT FOR THE 954888 PROJECT, WHILE RUN NO. 2* WAS PERFORMED ON A NEW CRYSTAL GROWER TO BE USED FOR THE "TSONGAS" PROJECT (CONTRACT NO. 955270). RUN NO. 55 WAS PERFORMED USING A 35.5 CM (14 INCH) CRUCIBLE AND HOT ZONE, WHILE RUN NO. 2* WAS PERFORMED USING A 30.5 CM (12 INCH) CRUCIBLE AND HOT ZONE.

THE CRYSTAL DIAMETER VARIED FROM 12.7 CM TO 16.0 CM DURING RUN NO. 55 DUE TO AN EARLY PROBLEM WITH THE DIAMETER CONTROL, WHICH WAS CORRECTED AFTER THE THIRD CRYSTAL WAS GROWN. 100.6 KG WAS GROWN FROM A TOTAL MELT OF 106.1 KG, YIELDING 75.1 KG OF MONO CRYSTALLINE INGOT. 10 INGOTS WERE GROWN. DURING THE GROWING OF THE EIGHTH CRYSTAL, A PIN HOLE WATER LEAK DEVELOPED IN A VIEWPORT WELD. THIS PROBLEM WAS READILY VISIBLE DURING THE FOLLOWING RECHARGE CYCLE. FROM THAT POINT ON, IT WAS IMPOSSIBLE TO GROW HIGH QUALITY CRYSTALS. THIS CONDITION DECREASED THE YIELD OF HIGH QUALITY CRYSTAL FROM 92.5% AFTER THE EIGHTH CRYSTAL WAS GROWN TO 74.6% WHEN THE RUN WAS COMPLETED FOLLOWING THE TENTH CRYSTAL.

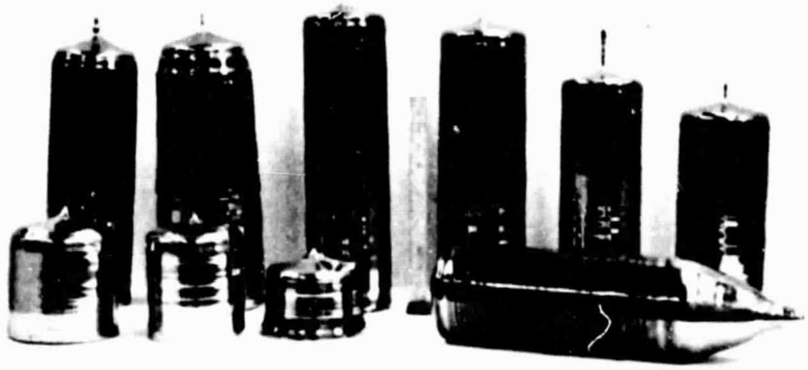
RUN NO. 2* WAS PERFORMED ON NEW STANDARD CRYSTAL GROWER THAT WILL BE USED IN CONJUNCTION WITH THE 955270 PROJECT. A PRESENTATION RELATING TO THAT PROJECT WILL BE GIVEN BY MR. ROBERTS FOLLOWING MY PRESENTATION. THIS GROWER WAS DELIVERED AND SET UP WITH A 12 INCH HOT ZONE. THE FIRST CRYSTAL WE GREW IN THIS GROWER WAS VERY SUCCESSFUL AND RESULTED IN A PREVIOUSLY UNSCHEDULED CONTINUOUS RUN BEING ATTEMPTED WITH THIS NEW GROWER.

AT THE REQUEST OF THE JPL MONITOR, WE ATTEMPTED A CONTINUOUS RUN ON THIS MACHINE WITH THE RESULTS SHOWN IN THE VIEWGRAPH. EVEN THOUGH THE FIRST ONE-CRYSTAL RUN PERFORMED IN THIS GROWER WAS VERY SUCCESSFUL, WE WERE PLAGUED WITH SEVERAL MECHANICAL PROBLEMS DURING THE CONTINUOUS RUN, WHICH RESULTED IN NINE CRYSTALS BEING GROWN OVER AN EXCEPTIONALLY LONG TIME PERIOD OF 108 HOURS. THIS RESULTED IN A DISAPPOINTING THROUGHPUT OF 0.93 KG/HR AND A CORRESPONDINGLY LOW YIELD OF HIGH QUALITY CRYSTAL (63.7%). HOWEVER, WE WERE ABLE TO GROW 100.3 KG OF INGOT FROM 104.5 KG TOTAL MELT.

THE NUMBER OF CRYSTALS GROWN DURING THESE TWO RUNS WAS GREATER THAN PLANNED. THEREFORE, THE RUN TIME WAS ALSO LONGER THAN PLANNED, RESULTING IN LOW THROUGHPUTS.

Run No. 2

Run No. 55



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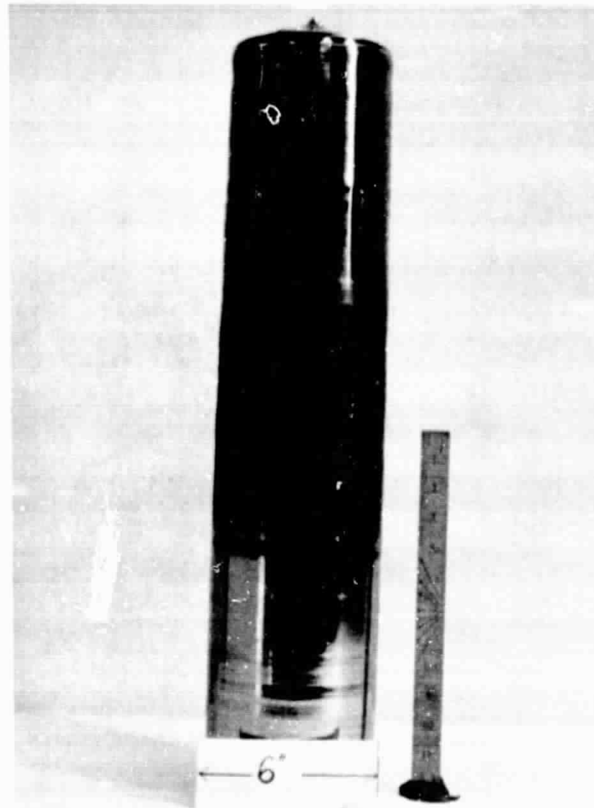
Summary of Run No. 55 and Run No. 2*

	NO. 55	NO. 2*
CRYSTAL INGOT DIAMETER	12.7 - 16.0 CM	12.7 CM
INITIAL MELT CHARGE	30 KG	18 KG
CRUCIBLE DIAMETER	35.5 CM (14 IN)	30.5 CM (12 IN)
TOTAL SILICON MELTED	106.1 KG	104.5 KG
TOTAL INGOT PULLED	100.6 KG	100.3 KG
PULLED YIELD	94.8%	[illegible]%
TOTAL MONO CRYSTAL	75.1 KG (74.6%)	64.9 KG ([illegible])
NUMBER OF INGOTS	10	9
THROUGHPUT	1.11 KG/HR	0.[illegible] KG/HR
TOTAL RUN TIME	91 HOURS	1[illegible]3 HOURS
RECHARGE MATERIAL	100% [illegible]	[illegible]

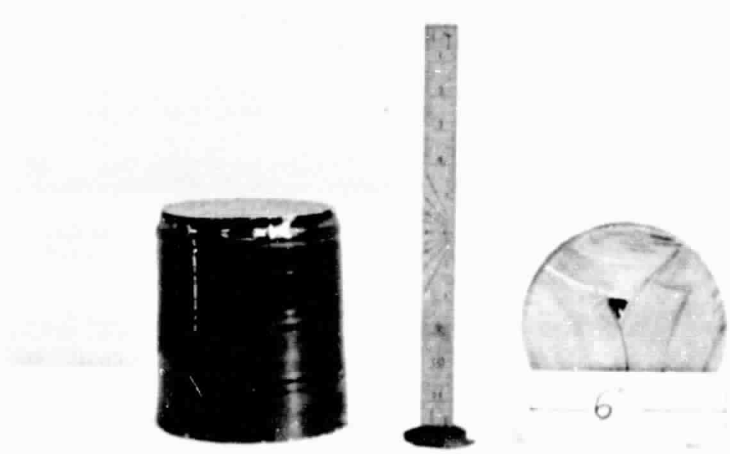
SEVERAL INDIVIDUAL PROCESS RUNS WERE ATTEMPTED BETWEEN RUN NO. 49 - THE 108 KG CONTINUOUS RUN - AND THE NEXT CONTINUOUS RUN (RUN NO. 55). TWO OF THESE RUNS RESULTED IN 15 CM (5.9 INCH DIAMETER) CRYSTALS BEING GROWN. THIS SLIDE SHOWS THE CRYSTAL GROWN DURING RUN NO. 51. THIS CRYSTAL IS TWENTY FIVE (25) INCHES LONG AND WEIGHS 25.9 KG. THE TIME NECESSARY TO GROW THIS CRYSTAL WAS 15-1/2 HOURS FROM POWER ON TO POWER OFF. IF FOUR HIGH QUALITY CRYSTALS LIKE THIS COULD BE GROWN, WE WOULD SURPASS OUR GOALS FOR CZ 2. IF YOU ADD 3 HOURS TO RECHARGE AFTER EACH GROWTH CYCLE, THE THROUGHPUT WOULD BE 1.4 KG/HR.

Run No. 51



This slide shows the second crystal grown during Run No. 55. It has been cut and the slab is 6 inches in diameter. This crystal was grown when we were having problems with diameter control. However, it does show that high quality crystals can be grown at this diameter.

Crystal No. 2, Run No. 55



During the last nine months, much emphasis has been placed on solving the problem of structure loss during continuous recharge runs.

Impurity analysis of crystal ingots, virgin feed stock poly silicon, residual melt and crucibles has been stressed.

Based upon preliminary impurity analysis results and data compiled from continuous runs, it is felt that the ability to maintain a leak-free furnace system is vital to the production of a large percentage of high quality crystal. An air leak or microscopic water vapor contamination due to weld degradation appears to drastically reduce the capability to grow high quality crystal. It is also felt that volatile contaminants within the furnace system may cause the loss of high quality crystal structure.

This viewgraph shows a chart of impurity analysis results for Run No. 47 and Run No. 49. Only the elements felt to be significant to this discussion are listed here.

This preliminary data tends to indicate that impurity concentrations are much higher in the crucible than in the grown crystal ingots or the residual melt. The chart shows impurity concentrations in the crucible from 6 to 4 x 10^3 times greater than in the last ingot grown.

However, it is possible that some impurities might be introduced into the melt when recharging new silicon.

Impurities

(Concentration in PPM weight)

Sample #	Sodium	Magnesium	Calcium	Potassium	Fluorine	Chlorine
47-1 Top	7	0.3	0.1	0.1	0.1	0.7
47-3 Bottom	0.8	0.3	0.1	0.1	0.1	0.5
47 Residual Melt	1	0.3	0.1	0.1	0.1	0.6
47-Crucible	66	6	33*	35	20	29
49-1 Top	0.4		0.1	0.1		0.3
49-5 Top	4		0.1	0.2		
49-9 Top	7	0.5	0.1	0.6	0.1	0.3
49-9 Bottom	1	0.5	0.1	[illegible]	0.1	0.7
49-Crucible	41	7	410	80	11	41

The next viewgraph lists typical impurity concentrations of fused quartz crucibles - as supplied by the crucible manufacturers. Comparisons of impurity concentrations of this chart with the test results of the previous viewgraph indicate the high impurity concentrations were not present in the crucibles before the run was started.

Published test results show that alkalies and halides increase the rate of devitrification of silica glass. Therefore, it is felt that this type of furnace contamination will increase the rate of crucible devitrification during continuous runs. It is also felt that devitrification of the crucible may be the main cause of structure loss during continuous crystal growth. Microscopic silica particles from the crucible may migrate to the growth interface, causing structure loss.

Crucible Impurities

Impurity	Amersil	Quartz Products	General Electric	Corning
Al	12	20	28	5
B	<1	NR	<1	0.5
Ca	4	3	3	1
Cu	<1	NR	<1	0.05
Fe	3	1	4	5
Li	1	1	0.5	NR
Mg	1	1	1	0.1
K	2	3	3	0.1
Na	3	1	3	2
Ti	<1	2	2	10
Cr	NR	NR	3	NR
Zn	NR	NR	2	NR
Mn	NR	NR	2	NR

NR: Not Reported

Maximum Impurities in Fused Quartz (vitreous SiO_2) crucibles provided by vendors. Expressed as parts per million by weight.

THIS SLIDE SHOWS DEVITRIFICATION OF THE CRUCIBLE USED FOR RUN No. 49. THE INNER SURFACE OF THE CRUCIBLE, WHICH IS IN CONTACT WITH THE MELT, IS COMPLETELY COVERED WITH A THICK LAYER OF CRYSTALLIZED SILICA GLASS. SOME OF THIS LAYER HAS BEEN BROKEN AWAY ON THE RIGHT TO REVEAL THE GLASSY STATE UNDERNEATH THE LAYER.

THE DEGREE OF DEVITRIFICATION CAN BE SEEN FROM THE CUTAWAY PORTION SHOWN ON THE LEFT. THE GREATEST DEGREE OF DEVITRIFICATION NORMALLY OCCURS ON THE OUTSIDE SURFACE OF THE CRUCIBLE.

Run No. 49

THIS NEXT SLIDE SHOWS DEVITRIFICATION OF THE CRUCIBLE USED FOR RUN No. 47. THE DEGREE OF DEVITRIFICATION IS MUCH LESS THAN THE CRUCIBLE USED DURING RUN No. 49. OUR RESULTS SHOW THAT, ALTHOUGH BOTH RUNS PRODUCED A HIGH PERCENTAGE OF SINGLE CRYSTAL, THE PERCENTAGE OF ZERO DISLOCATION MATERIAL PRODUCED DURING RUN No. 47 WAS MORE THAN DOUBLE THE AMOUNT PRODUCED DURING RUN No. 49.

Run No. 47

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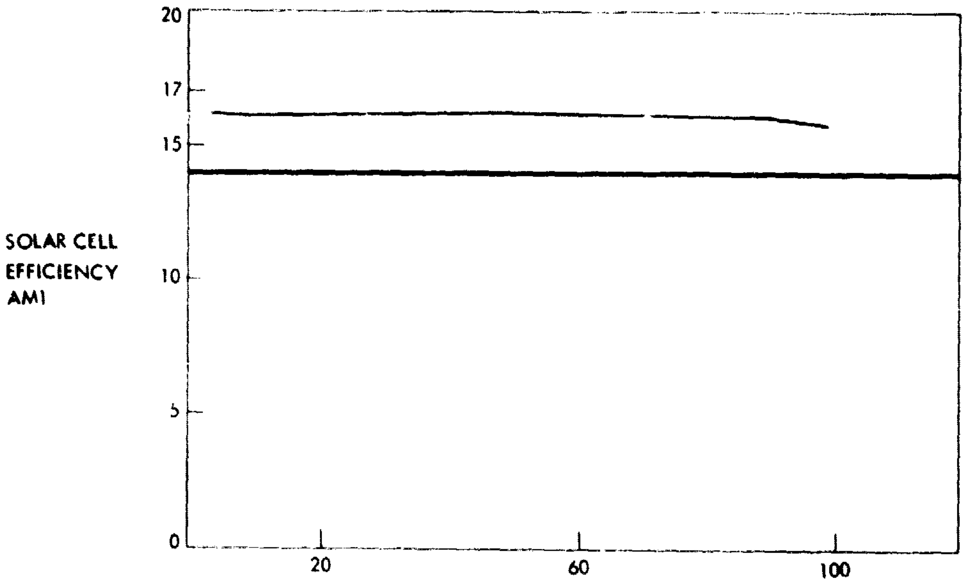
The solar cell efficiency data from Run No. 49 has been received and tabulated on the graph shown.



NOTES: RESIST. 1.8 - 2.7 ohm-cm
EFF. OF 4 CONTROL CELLS 16.0 - 16.7%
AVG. EFF. 16.35%

Four cells from each wafer were fabricated and tested. The top line represents the average of the four cells. The range of results for each wafer is indicated by each vertical line.

The cells from the top of the first crystal, taken after approximately four (4) kg had been grown, had an average efficiency of 16.3%. The cells from the bottom of the first crystal at the 10 kg mark averaged 16.1%. The cells from the sixth crystal grown at the 50 kg mark yielded an average efficiency of 16.2%. The last crystal grown yielded average efficiencies of 16.1% at the top (90 kg) and 15.8% towards the bottom after 100 kg had been grown.

The heavy dark line represents the 14% project goal.

As you can see, efficiency results have exceeded the 14% AM1 goal of this project on all cells tested. Moreover, there does not appear to be any significant decrease in efficiency throughout the run.

Four control cells yielded efficiencies from 16.0% to 16.7%, which is similar to the samples tested.

THIS VIEWGRAPH PRESENTS AN UPDATED PROJECTION OF THE TIME CYCLES AND ADD-ON COSTS FOR THE CZ-2 PROCESS WHEN FOUR 25 KG INGOTS ARE GROWN FROM A 35.5 CM DIAMETER CRUCIBLE.

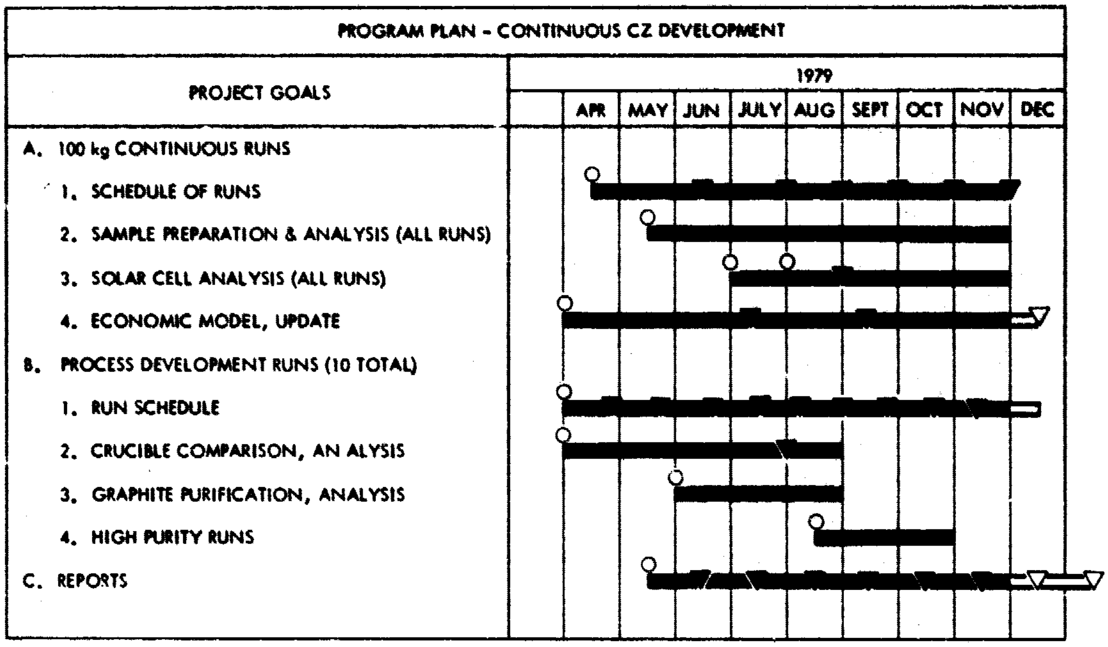
THIS UPDATED PROJECTION WAS FORMULATED USING DATA FROM RUN NO. 49 AND RUN NO. 55. BASED ON THE ACTUAL RUN DATA, WE HAVE DECREASED THE INITIAL MELT DOWN TIME FOR 30 KG FROM 4 HOURS TO 2 HOURS. WE HAVE INCREASED THE AMOUNT OF TIME NEEDED FOR GROWING PREPARATION TO TAKE INTO ACCOUNT THE POSSIBILITY OF STRUCTURE LOSS DURING CROWN GROWTH OR THE ROUNDING OVER PROCEDURE. THEREFORE, THE STEPS INVOLVING GROWTH PREPARATION CAN SIGNIFICANTLY IMPROVE THE TOTAL RUN TIME WHEN FAVORABLE RESULTS ARE ACHIEVED IN THIS AREA. INGOT GROWTH TIME REMAINS THE SAME AS EARLIER PROJECTIONS BASED ON A GROWTH RATE OF 10 CM/HR. FINALLY, THE RECHARGE CYCLE TIME HAS BEEN DECREASED FROM 22% OF THE RUN TIME AS PREVIOUSLY PROJECTED TO 16%, DUE TO IMPROVEMENTS BROUGHT ABOUT BY THE LUMP RECHARGING METHOD.

THE RESULTANT ADD-ON COST FOR THIS UPDATED PROJECTION IN 1980 DOLLARS IS $23.25 PER KILOGRAM. THIS ADD-ON COST IS SLIGHTLY LESS THAN THE PREVIOUSLY PROJECTED ADD-ON COST OF $23.76 PER KILOGRAM.

Cost Update for Cz No. 2

OPERATION	UPDATED PROJECTION (HR)	
MELT DOWN	2	(3.6%)
GROWING PREPARATION		
1) STABILIZE TEMPERATURE	14.6	(26.1%)
2) GROWING SEED	(4 INGOTS)	
3) CROWN GROWTH		
4) MELT BACKS		
INGOT GROWING	30.4	(54.3%)
(STRAIGHT SECTION)	(10 CM/HR)	
RECHARGE CYCLE (LUMP ONLY)	9.0	(16.1%)
1) REMOVAL OF CRYSTAL	(3 TIMES)	
2) LOAD HOPPER		
3) HOT FILL		
4) MELT DOWN		
TOTAL TIME	56.0	
ADD-ON COST CZ (1980 DOLLARS/KG)	$23.25	

CZ NO. 2: 14" CRUCIBLE
100 KG
15.3 CM DIAMETER
10 CM/HR



Summary and Conclusions

1. 100 kilograms of silicon crystals can be grown from one crucible with acceptable yields.
2. At least 5.9 inch diameter crystals can be grown in the crystal grower used for this project.
3. 100 kilograms of silicon crystals has been grown from one crucible using a standard production grower and continuous run techniques.
4. Crucible devitrification may be the primary cause of structure loss during continuous crystal growth.
5. Accelerated crucible devitrification can be caused by the combined effect of contamination and high temperatures.
6. Cost objectives - as projected - can be realized by decreasing the number of crystals grown during a 100 kg continuous run.
7. Solar cell efficiencies do not appear to deteriorate through the 100 kg continuous run.

LOW-COST CONTINUOUS-GROWTH TECHNOLOGY

HAMCO DIVISION OF KAYEX CORP.

Program Introduction

THE PROGRAM REQUIRES PROCESS IMPROVEMENT CONCEPTS AIMED AT:

1. LOWERING THE COSTS OF THE MELT-DOWN AND GROWTH PROCESSES. (FASTER MELT-DOWN AND INCREASED GROWTH RATE).
2. REDUCING LABOR COSTS AND IMPROVING YIELDS BY PROCESS AUTOMATION. (1 PRODUCTION OPERATOR PER 6 GROWERS).

A COMBINATION OF THE ABOVE WILL REDUCE THE CONTINUOUS CZ ADD-ON COSTS TO:

LOW COST CZ (ROD FEED)	=	\$15.36/KG *
LOW COST CZ (POLY CHUNK FEED)	=	\$14.95/KG

BOTH IN 1980 \$

* APPROXIMATELY 27.2% / 29.1% COST REDUCTION COMPARED TO "COLD FILL" PROCESS.

Cz Growth Methods

CONDITIONS	LOW COST CZ (ROD FEED)	LOW COST CZ (POLY LUMP FEED)
CRUCIBLE SIZE (INCHES)	14" x 11-1/2"	14" x 11-1/2"
CRYSTAL DIAMETER (CMS)	15.25	15.25
GROWTH RATE (CM/HR)	15.0	15.0
TOTAL POLY MELTED (KG)	160	160
TOTAL CRYSTAL PULLED (KG)	150	150
PULLED YIELD (%)	93.75	93.75
YIELD AFTER CG (%)	85.0	85.0
NO. CRYSTALS/CRUCIBLE	5	5
CYCLE TIME (HRS)	59.8	59.1
THROUGHPUT (KG/HR)	2.25	2.28

	LOW COST CZ (ROD FEED)	LOW COST CZ (POLY LUMP FEED)
IPEG PRICE:		
C1 EQPT = \$0.49/YR - \$EQPT	\$ 107,310	\$ 102,410
C2 SQFT = \$97/YR - \$SQFT	9,700	9,700
C3 DLAB = \$2.1/YR - \$DLAB	22,245	22,245
C4 MATS = \$1.3/YR - \$MATS	101,037	101,818
C5 UTIL = \$1.3/YR - \$UTIL	19,533	19,811
	\$ 259,825	\$ 255,984
QUAN. (TOTAL CHARGE x % YIELD) (KG)	16,918	17,122
THRUPUT	2.25	2.28
ADD-ON COST (\$/KG OR \$/M²)		
(ASSUME 1 KG = 1 M²)	\$ 15.36 (1980)	\$ 14.95 (1980)

SAMICS/IPEG Input Data and Cost Calculation

CONDITIONS (PER CYCLE)	LOW COST CZ (ROD FEED)	LOW COST CZ (POLY LUMP FEED)
TOTAL SI MELTED (KG)	160	160
CRYSTAL WEIGHT	30	30
NO. OF CRYSTALS/CRUCIBLE	5	5
DIAMETER OF CRYSTAL (CM)	15.25	15.25
GROWTH RATE (CM/HR)	15.0	15.0
CYCLE TIME (HRS)	59.8	59.1
CRUCIBLE SIZE	14" x 11-1/2"	14" x 11-1/2"
% YIELD (TOTAL IN SPEC. CG GROUND)	85%	85%
THRU-PUT (KG/HR)	2.25	2.28
INPUT DATA (1980 \$)		
CAPITAL EQUIPMENT COST (EQPT)	219,000	209,000
MANUFACTURING FLOOR SPACE (SQFT)	100	100
ANNUAL DIRECT LABOR SALARIES		
PROD. OPERATOR (0.65 PERSONS/YR)	8,100	8,100
ELECT. TECH. (0.3 PERSONS/YR)	1,425	1,425
INSPECTOR (0.1 PERSONS/YR)	1,068	1,068
TOTAL DLAB =	10,593	10,593

	LOW COST CZ (ROD FEED)	LOW COST CZ (POLY LUMP FEED)
DIRECT USED MATERIALS & SUPPLIES:		
85% USAGE PER YEAR		
CYCLES/YR HRS/CYCLE	124.4/59.8	125.9/59.1
POLY-KG/YR (CHARGED)	19,904	20,144
SEED ($5.82)	$ 722	$ 733
DOPANT (NOT COSTED)		
ARGON (100 FT^3/CYCLE-HR @ 0.02/FT^3)	$ 14,878	$ 14,881
CRUCIBLES (14" = $291)	36,084	36,666
MISCELLANEOUS (INCLUDING GRAPHITE: $3.5/CYCLE-HR)	26,037	26,042
MATERIALS TOTAL (MATS)	$ 77,721	$ 78,322
UTILITIES (PROCESS):		
ELECTRICITY (65KW x 0.035/KW)(CYCLE TIME-3 HRS) (# CYCLES)	$ 16,075	$ 16,354
COOLING WATER (65KW)($0.0074)(CYCLE TIME-2 HRS) (# CYCLES)	3,458	3,457
UTILITIES TOTAL (UTIL)	$ 19,533	$ 19,811

Overall Process Program

PROGRAM	PROGRAM GOAL
1. ACCELERATED MELT	(A) DECREASE CRUCIBLE DEVITRIFICATION
	(B) ACHIEVE FASTER MELT-BACK RATES, I.E. UP TO 40 KG/HR
2. ACCELERATED GROWTH	INCREASE GROWTH RATE TO 15 CM/HR FOR 15.25 CM DIAMETER CRYSTAL GROWTH
3. COLD CRUCIBLE	(A) MAINTAIN MELT PURITY LEVEL INTO CRUCIBLE
	(B) PREVENT CRUCIBLE DEVITRIFICATION
4. MICROPROCESSOR CONTROL	(A) REDUCE LABOR COSTS
	(B) IMPROVE YIELD

Program Discussion

GOALS:

1. DEMONSTRATION OF THE GROWTH OF 150 KG OF 6" DIAMETER SINGLE CRYSTAL SILICON FROM ONE CRUCIBLE.
2. MODIFICATION OF A CG 2000 HAMCO CRYSTAL PULLER TO ALLOW PERIODIC MELT REPLENISHMENT OF EITHER 5" DIAMETER POLYSILICON RODS OR POLYCRYSTALLINE SILICON CHUNK.
3. DEMONSTRATION OF A MELT RATE OF 25 KG TO 40 KG/HR.
4. DEMONSTRATION OF A GROWTH RATE OF 15+ CM/HR, UTILIZING A HEAT SINK.
5. INSTALL A MICROPROCESSOR CONTROL SYSTEM TO REDUCE COSTS AND TO IMPROVE YIELDS.

GENERAL:

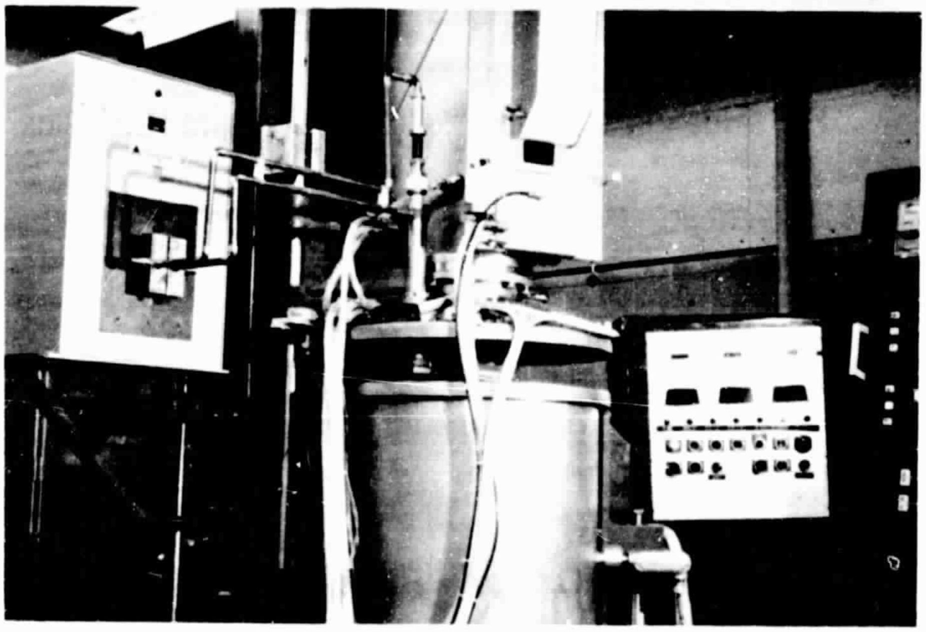
AN IMPORTANT CONSIDERATION ASSOCIATED WITH GROWTH OF > 100 KG OF SILICON FROM ONE QUARTZ CRUCIBLE IS THAT OF CRUCIBLE DEVITRIFICATION.
DEVITRIFICATION IS KNOWN TO TAKE PLACE DURING CONVENTIONAL "TOP LOADING" MELTING PROCEDURES WHEN TEMPERATURES APPROXIMATELY 200° C ABOVE THE MELTING POINT OF SILICON ARE REQUIRED TO MELT THE RECHARGED POLYSILICON.
ALSO, MAINTENANCE OF CRYSTAL STRUCTURE CAN BE A PROBLEM WHEN DEVITRIFICATION OCCURS.
BY SUBSTITUTING CONVENTIONAL MELTING OF "TOP LOADED" COLD SILICON WITH AN RF INDUCTION HEATED WORK COIL, POLY RODS CAN BE MELTED DIRECTLY INTO A CRUCIBLE OR

POLY CHUNKS CAN BE MELTED USING A "COLD CRUCIBLE" PREMELTER. DEVITRIFICATION WILL THEN BE MINIMIZED.
ALSO, THE USE OF HIGH PURITY GRAPHITE IS CONSIDERED ESSENTIAL IN REDUCING DEVITRIFICATION OF THE OUTER CRUCIBLE WALL.

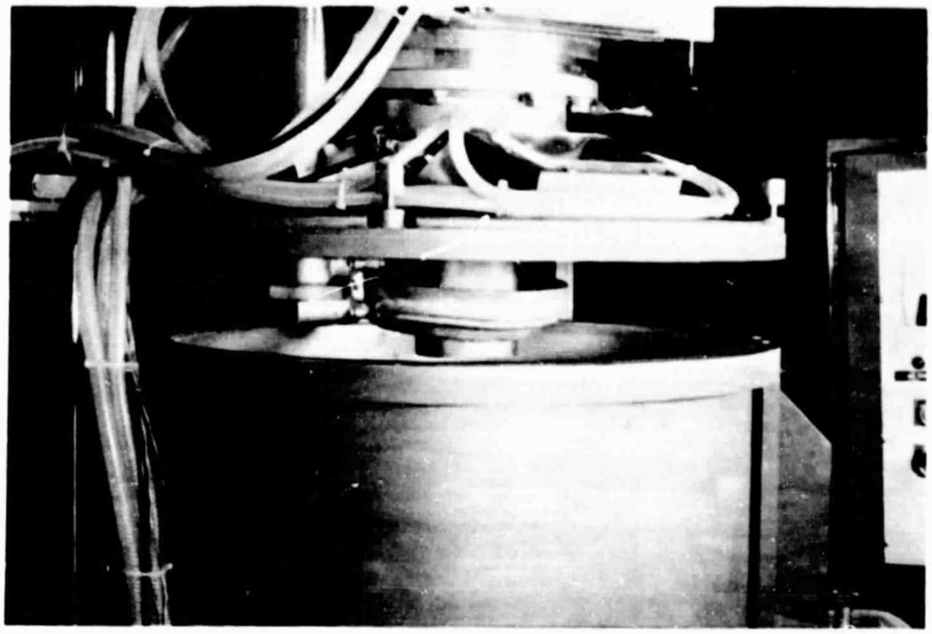
Equipment Status for Accelerated Melt and Growth Programs

GOAL	STATUS
1. CG2000 RC Crystal Puller Installation & Commissioning	Complete
2. R.F. Generator Installation	Complete
3. R.F. Remote Station Installation for Accelerated Melt Program	Complete
4. Installation of R.F. Feed-Thru & Work Coil	Complete
5. R.F. Generator Commissioning	Ongoing (Commenced 12/3/79)
6. Sub-Contract Delivery of Poly Rod Recharge Mechanism	Ongoing
7. Delivery of Purified Graphite Piece-Parts	Complete

CG2000 RC Puller



RF Work Coil Assembly



R.F. Heating Generator, Coil Design and Heat Sink

A 50 KW OUTPUT THYRISTOR CONTROLLED R.F. GENERATOR OPERATING AT A FREQUENCY OF 450 K HZ HAS BEEN PURCHASED. SYSTEM INCORPORATES TWO REMOTE STATIONS, I.E., ONE STATION FEEDS A LOW VOLTAGE, SINGLE TURN WORK COIL FABRICATED FROM MACHINED COPPER. THIS COIL WILL BE USED AS THE HEAT SINK IN THE ACCELERATED GROWTH PROGRAM AND USED TO MELT THE 5" POLYSILICON FEEDSTOCK FOR THE ACCELERATED MELT PROGRAM.
THE SECOND REMOTE STATION FEEDS A HIGH VOLTAGE MULTI-TURN COIL FOR THE SILICON COLD CRUCIBLE PREMELTER SYSTEM.

CG2000 RC Crystal Puller Run Summary

TOTAL OF 3 CRYSTAL GROWTH RUNS HAVE BEEN COMPLETED UTILIZING THE PULLER IN STANDARD RESISTANCE MODE.
7 KG CHARGED TO CHECK-OUT MECHANICAL/ELECTRONIC FUNCTIONS.

RUN 1 18 KG CHARGED - 28.4 INCHES OF 4-INCH Z.D. QUALITY MATERIAL PULLED = 16.7 KG.
A GROWTH RATE OF UP TO 4.9 INCHES/HR OBTAINED.
GROWN YIELD = 92.8%.

RUN 2 GROWN AS PART OF JPL CONTRACT #954888 AT THE REQUEST OF TECHNICAL PROJECT MONITOR.

Summary of Run No. 2*

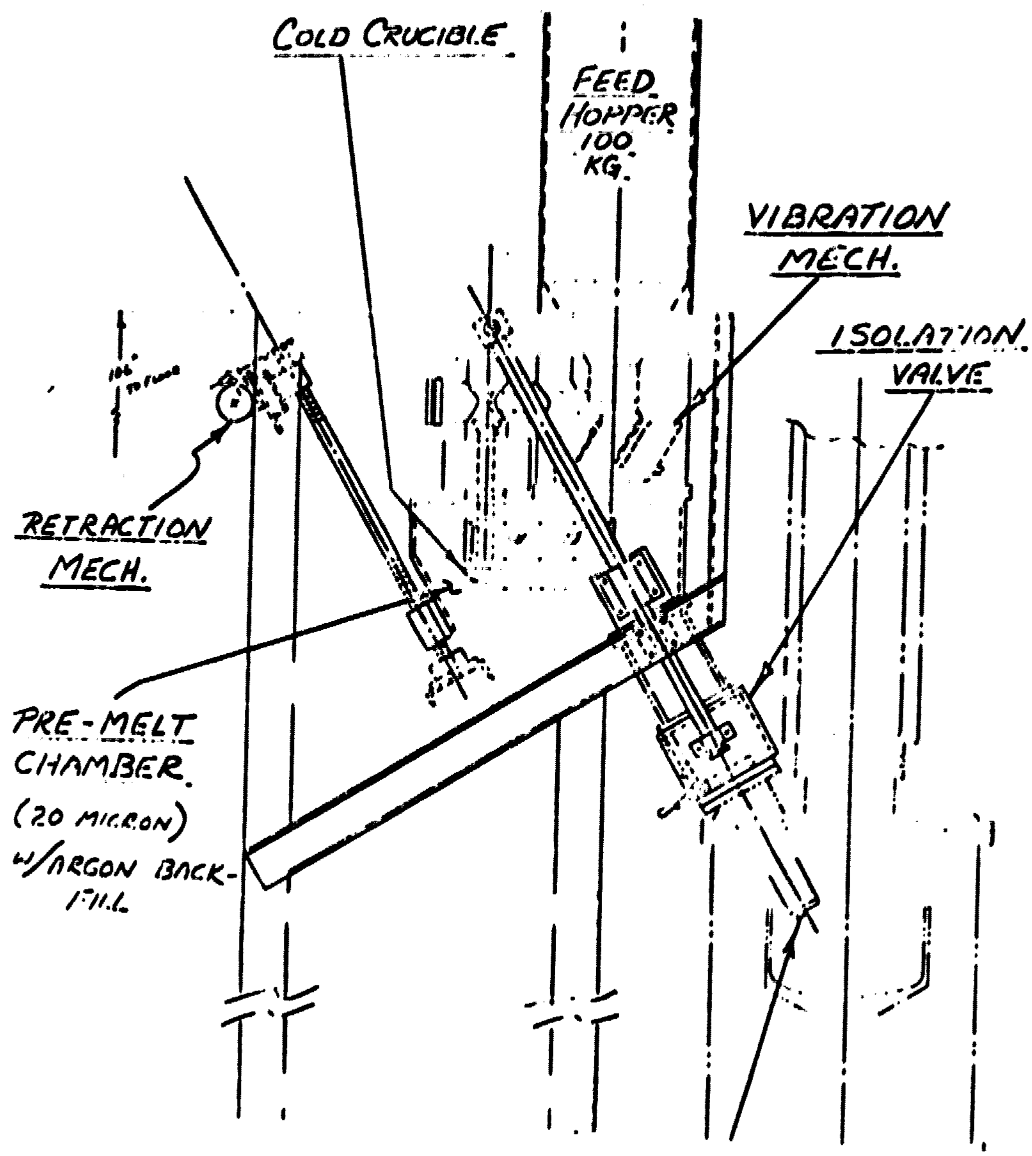
*This run was completed using 12" piece-parts as part of Contract #954888.

Crystal Ingot Diameter	12.7 cm
Initial Melt Charge	18 kg
Crucible Diameter	30.5 cm
Total Wt. of Silicon Melted	104.5 kg
Total Ingot Pulled	100.3 kg
Pulled Yield	96%
Total Mono Crystal	63.9 kg (63.7%)
Number of Ingots	9
Throughput	0.93 kg/hr*
Total Run Time	108 hrs
Recharge Material	100% Lump

Cold-Crucible Silicon Premelter Program

Goal	Status	Completion Date
1. Design of Cold Crucible	90% Complete	12/7/79
2. Sub-Contractor Design Discussions	Ongoing	12/14/79
3. Cold Crucible Boat/Coil Delivery	Ongoing	1/25/80
4. Cold Crucible/Melt Transfer and Ancillary Feed-Thru Design	Ongoing	2/29/80
5. Furnace Cover Modification/Crucible Interface	Ongoing	4/25/80
6. Melting/Growing Experiments	Ongoing	5/5/80

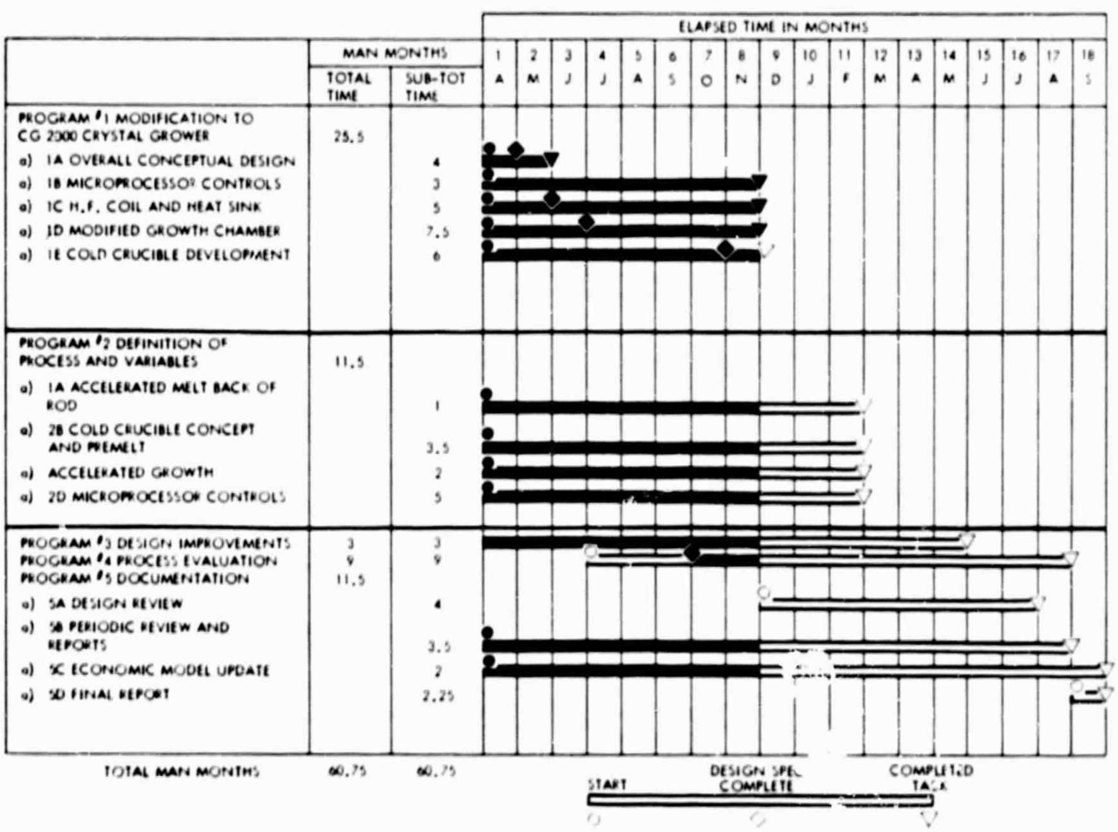
Schematic of a Cold Crucible With Hopper Mechanism



Microprocessor Control Program Status

GOAL	STATUS	COMPLETION DATE
1. SOFTWARE PROGRAMMING	COMPLETE	
2. DATA STORAGE	85% COMPLETE	12/7/79
3. MICROPROCESSOR INTERFACE DRAWINGS	COMPLETE	
4. INTERFACE OF MICROPROCESSOR WIRING TO CRYSTAL PULLER	APPROX. 50% COMPLETE	12/14/79
5. INITIAL RUN UTILIZING MICROPROCESSOR CONTROL	ONGOING	12/17/79
6. DE-BUG/TEST CONTROL SEQUENCES	ONGOING	1/18/80

Program Plan, Low-Cost Cz Crystal Growth



CONTINUOUS LIQUID FEED Cz GROWTH

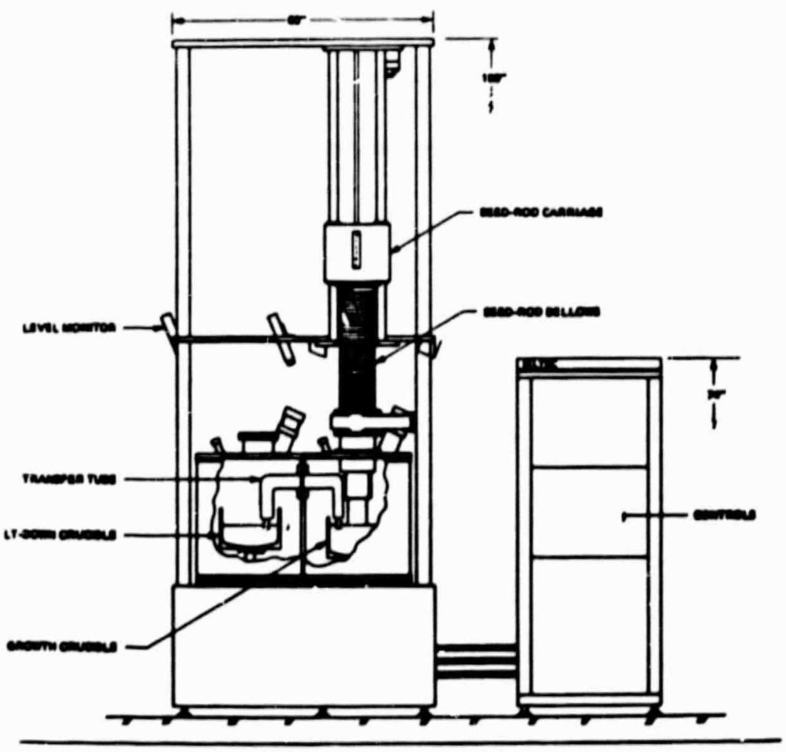
SILTEC CORP.

Program Plan

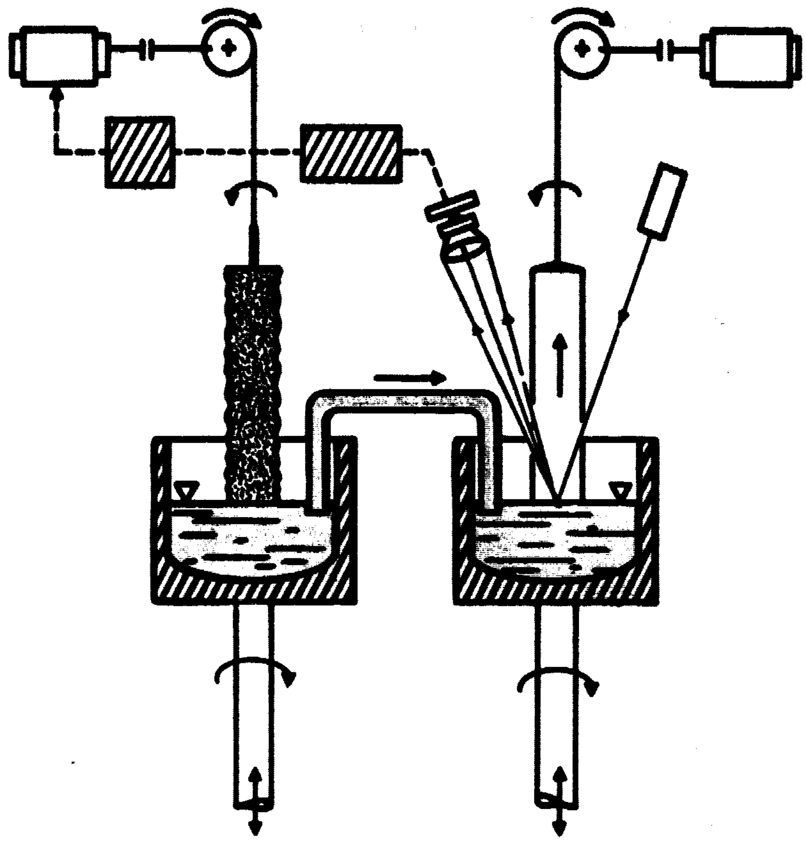
TASK DESCRIPTION	PERFORMANCE SCHEDULE								
	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN
(1) Modify the liquid feed (CLF) furnace									
(A) Overall design									
(B) Reduced pressure operation 10 to 30 Torr									
(C) Poly rod feed mechanism with feedback control system									
(D) Extend crystal lift mechanism to 60 inches above gate valve									
(2) Transfer tube system									
(A) Design and development									
(B) Fabrication									
(3) Develop particle feed system									
(A) Overall design (mechanical and electronic)									
(B) Fabrication									
(4) Growth demonstrations									
(A) Growth of one crystal 25 kg. from one set-up with melt transfer									
(B) Growth of four crystals 25 kg. mass each from one set-up with melt transfer									
(C) Growth of one crystal 50 kg. mass from one set-up with melt transfer									
(D) Growth of three crystals 50 kg. mass each from one set-up with melt transfer									
(5) Economic analysis									
(6) Provide representative samples						▲	▲	▲	▲
(7) Support design and performance reviews			▲	▲					
(8) Provide support personnel									
(A) Project integration meetings, DOE sponsored meetings and annual workshop				▲				▲	
(B) Performance review meetings									
(9) Provide documentation	▲	▲	▲	▲	▲	▲	▲	▲	▲
(10) Procure parts, material and services (as required)									

Milestone Legend △ Due Date △——△ Start-Finish

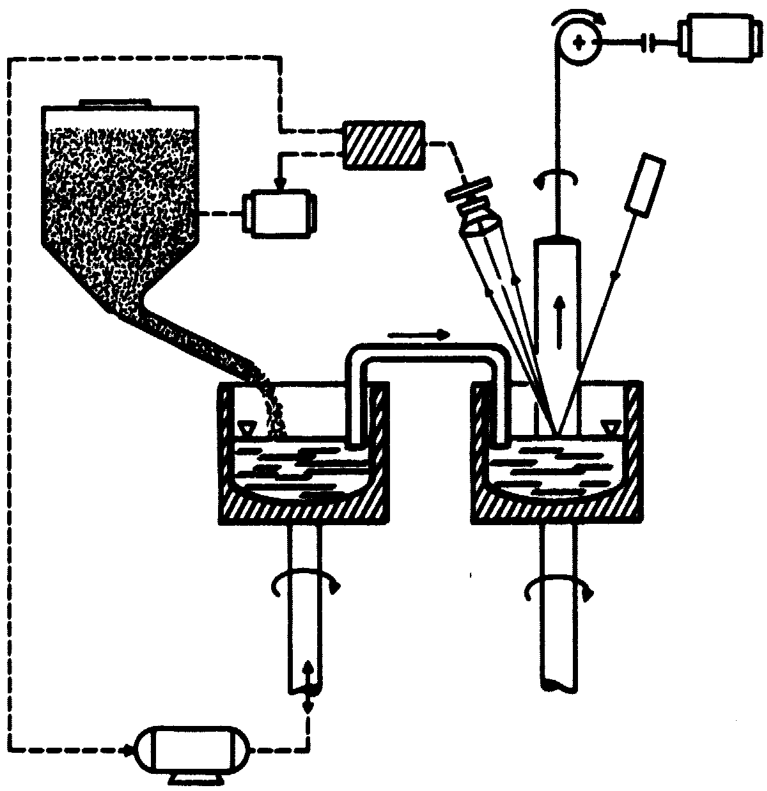
CLF Furnace



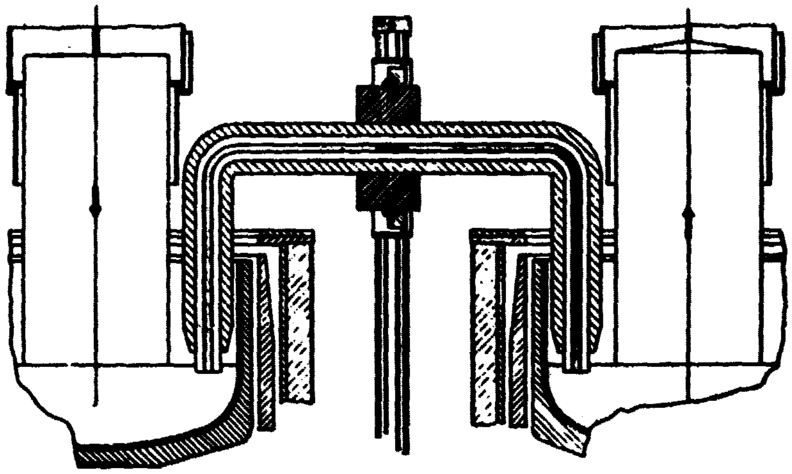
Polyrod Feeding Mechanism for CLF Furnace



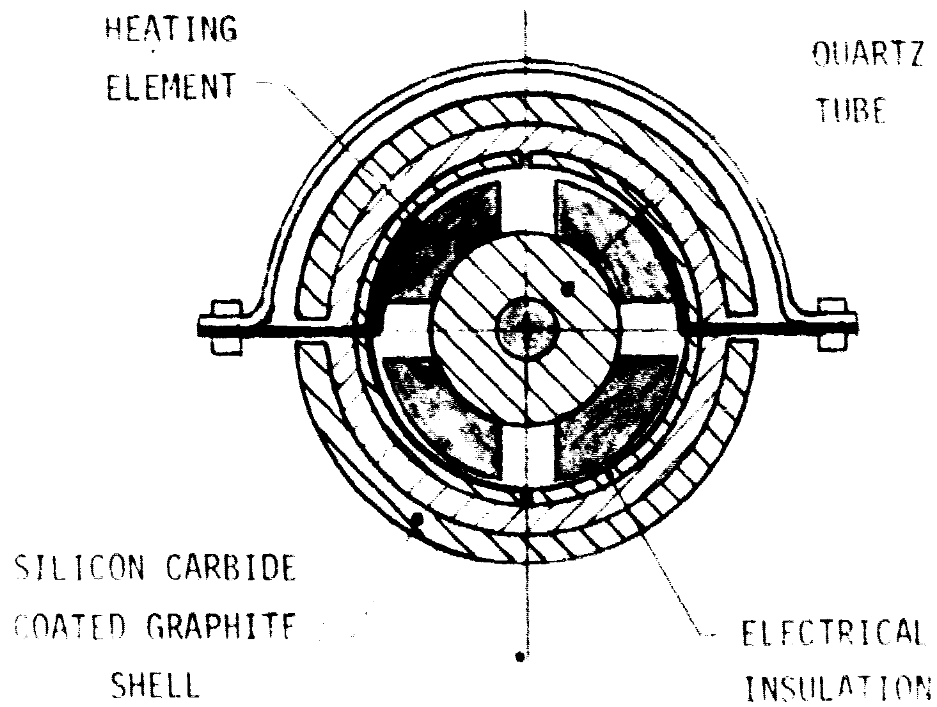
Particle Feed Mechanism for CLF Furnace



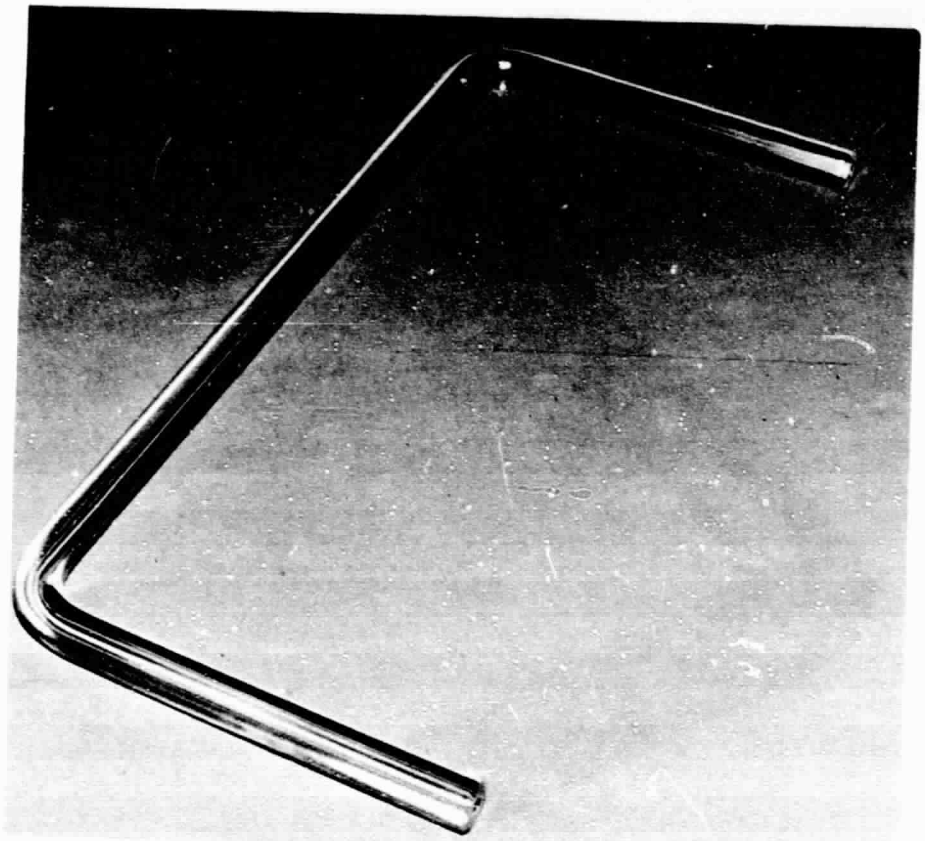
Simultaneous Polyrod Feed and Crystal Growth



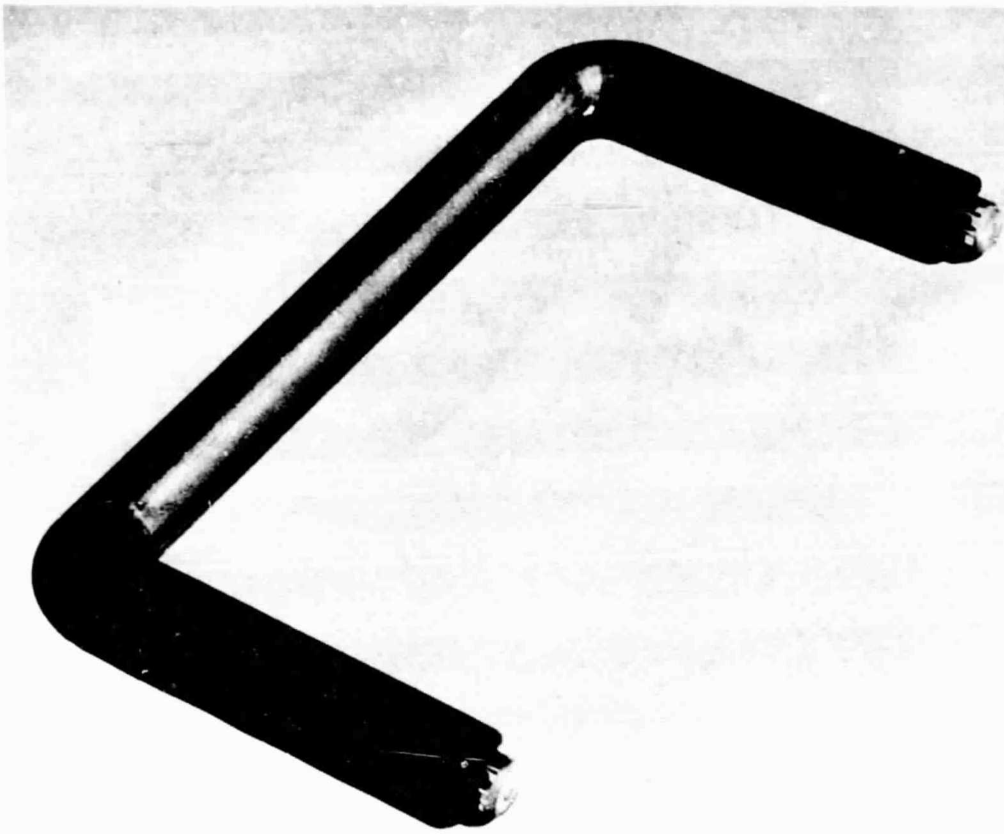
Rigid Graphite Heater



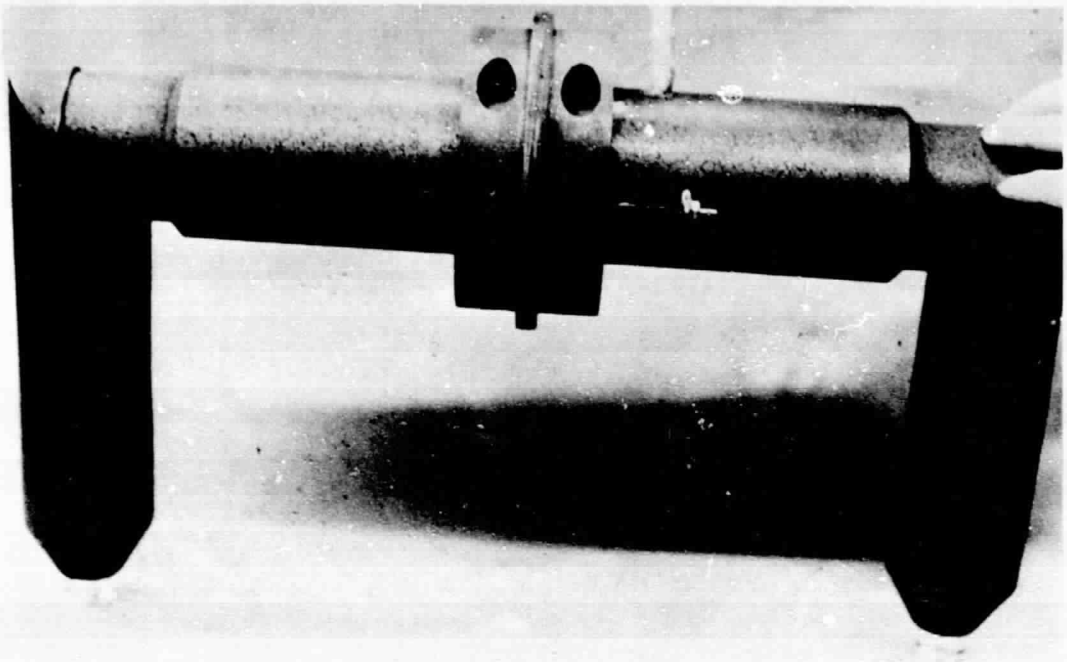
Quartz Transfer Tube



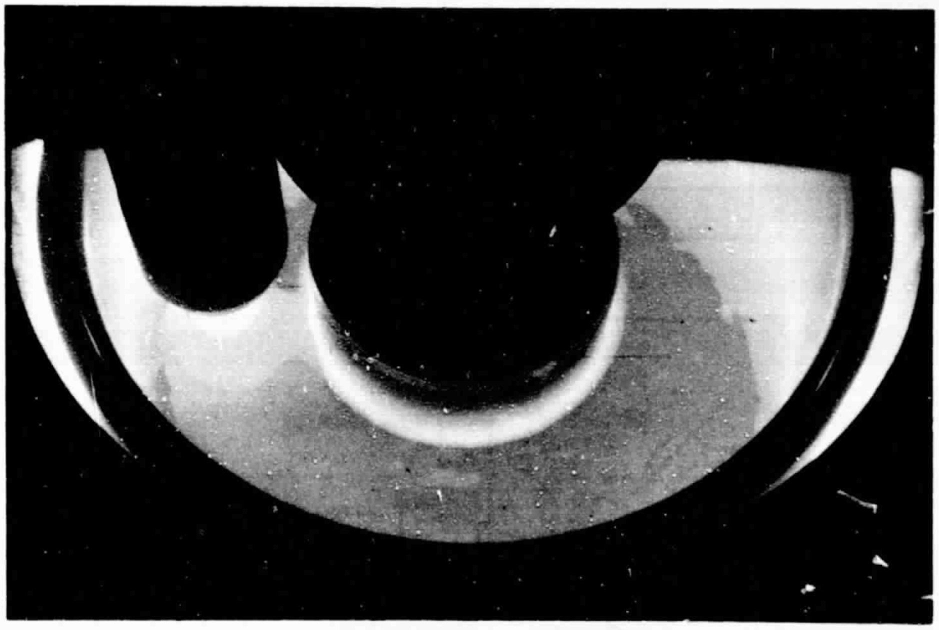
Transfer Tube Heating Element



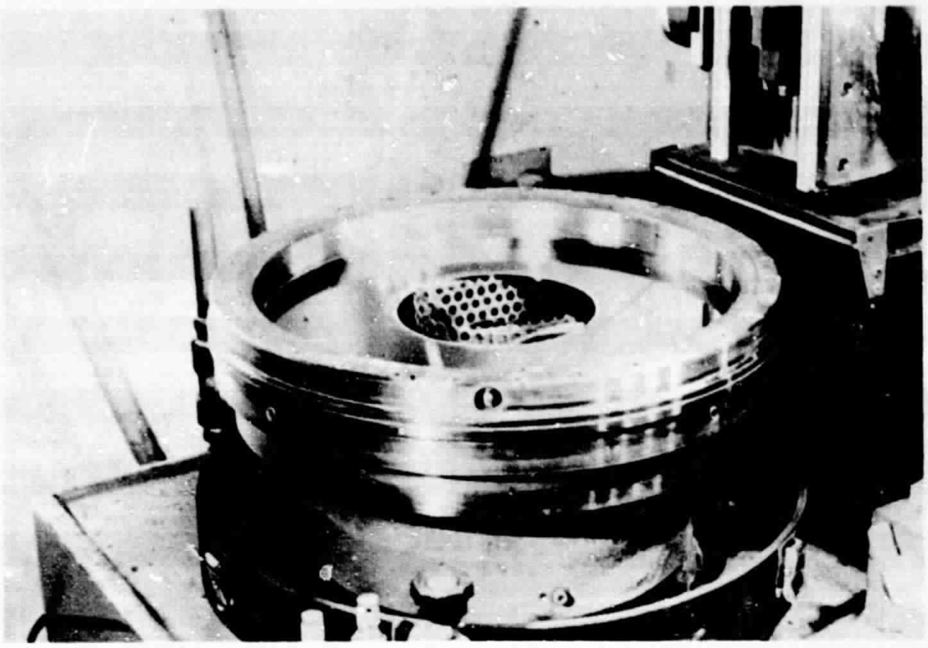
Transfer Tube Graphite Jacket



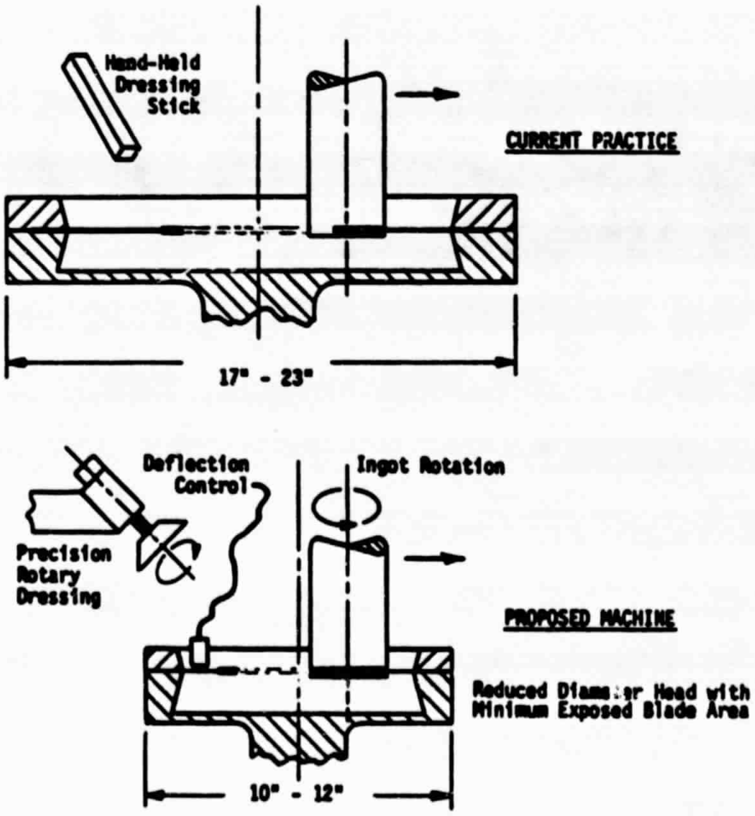
CLF Furnace in Operation



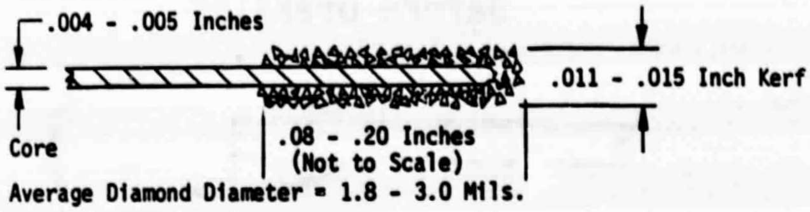
Saw With Cover Off Showing Heat With 15" Dia Blade in Place



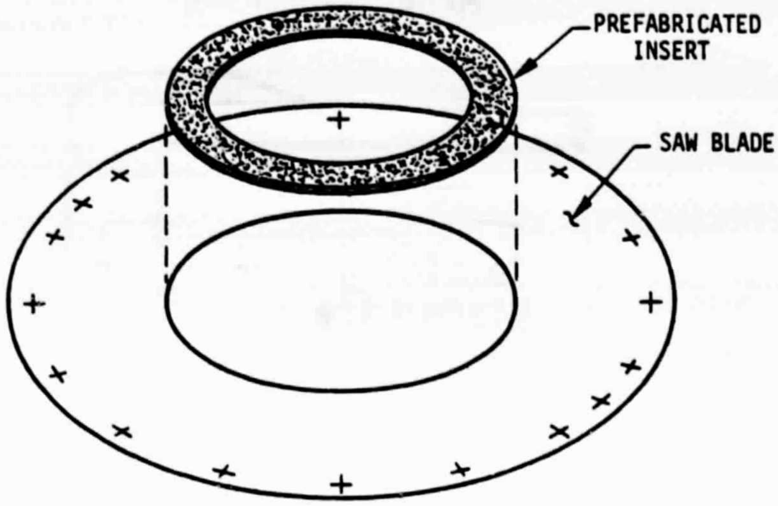
Blade Head Configuration



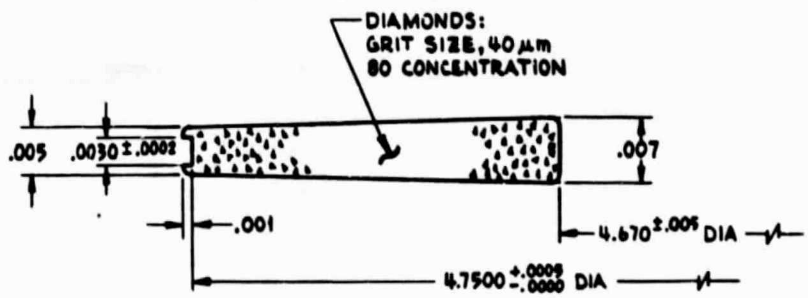
Conventional ID Blades



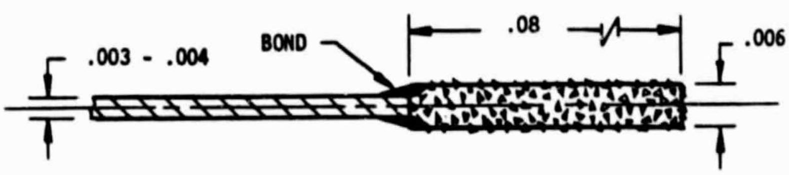
Prefabricated Insert Blade



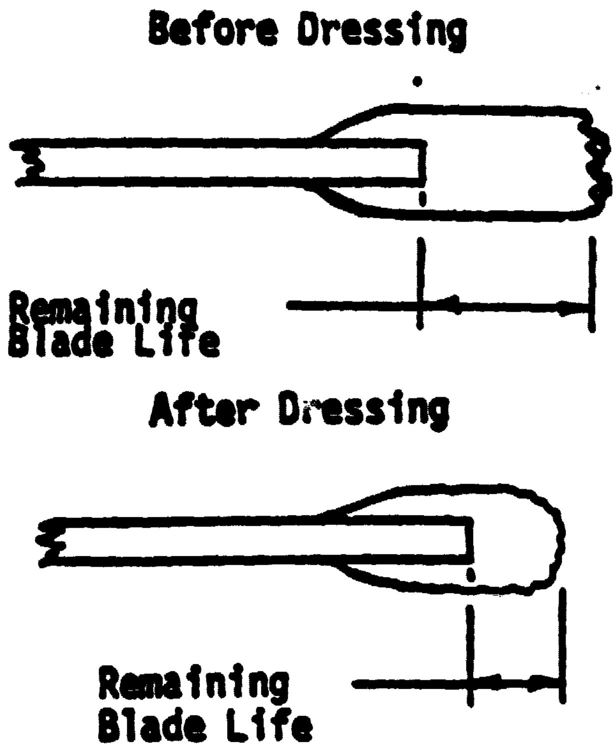
Insert, I.D. Blade Pre-Fab



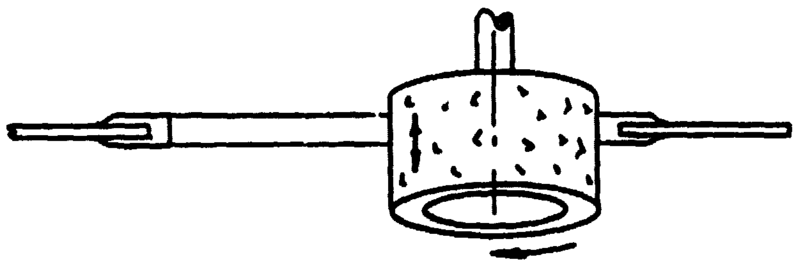
Blade Cross-Section After Bonding (Scale 50:1)

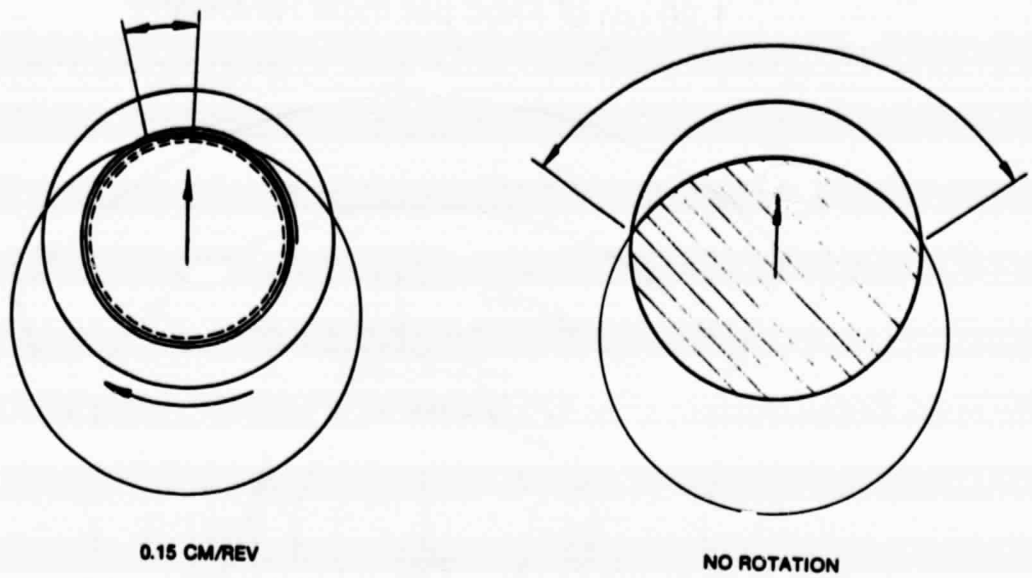


Blade Dressing

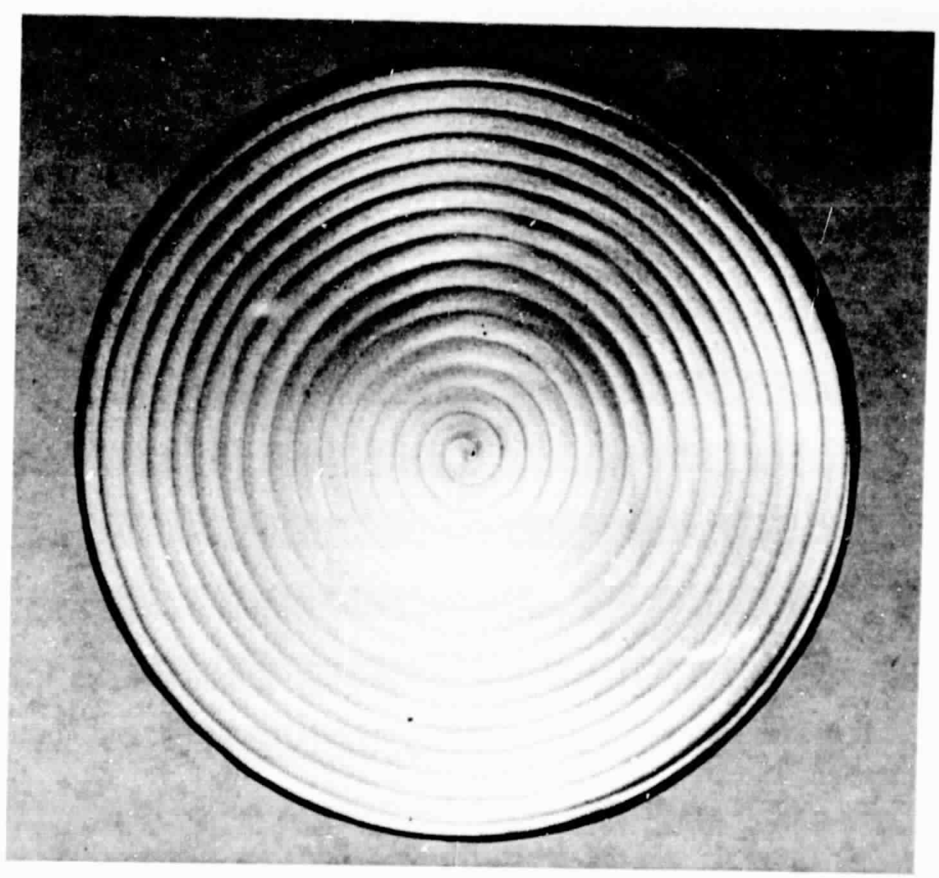


Truing Blade With Rotary Grinding

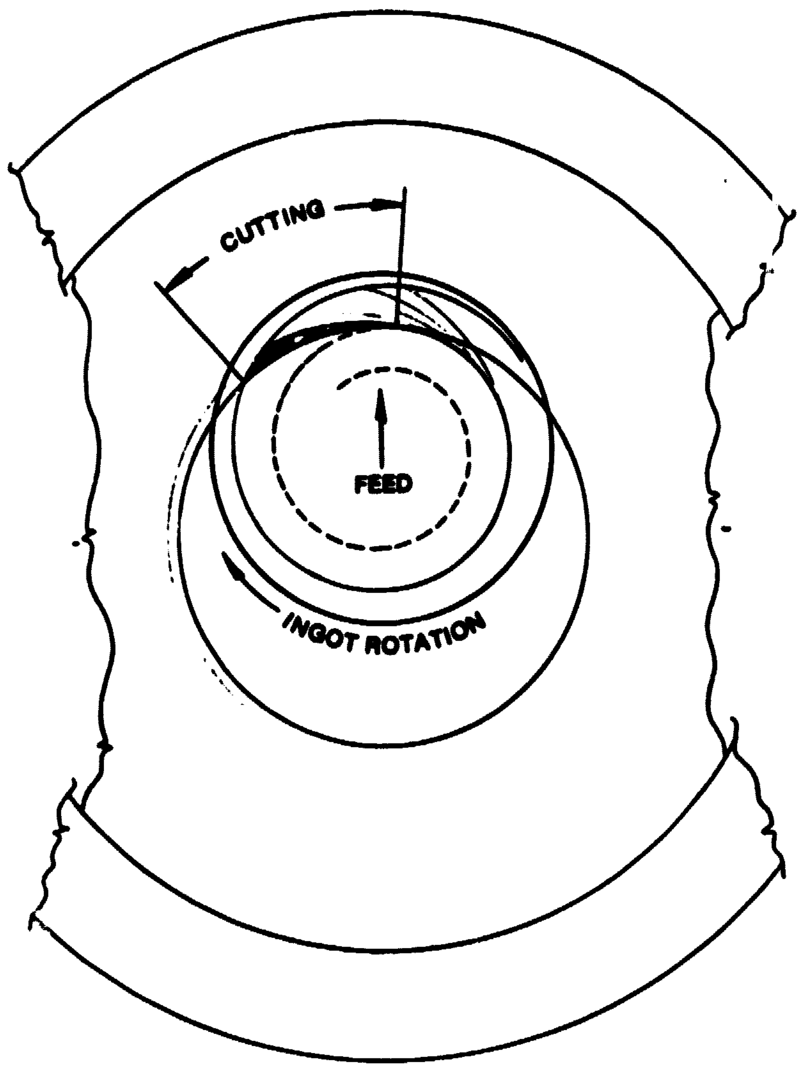




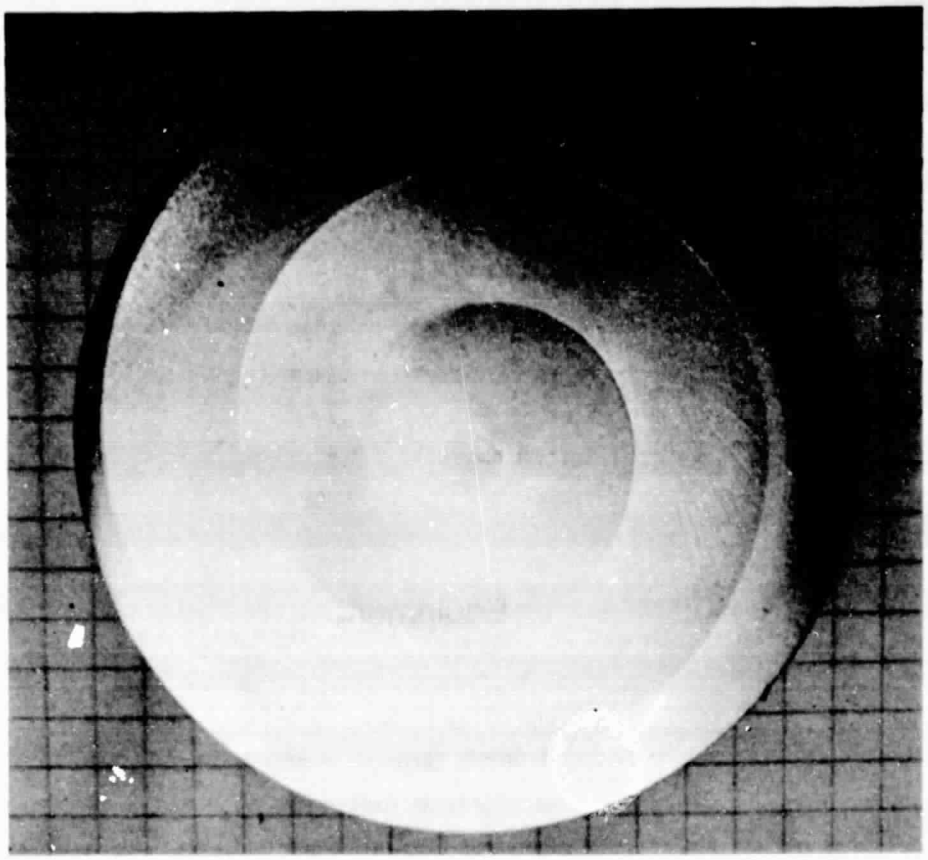
Wafer Sliced With Reduced Feed Rate



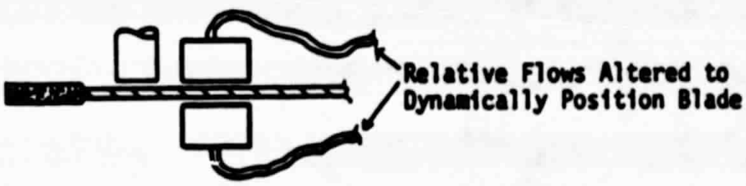
1.20 cm of Feed per Ingot Revolution



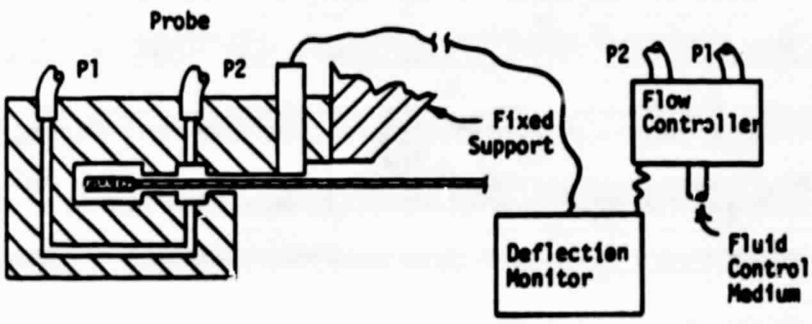
Wafer Sliced With Accelerated Feed Rate



Blade Deflection Control by Position Monitor



Closed Loop Blade Position Control System



ID SLICING

SILICON TECHNOLOGY CORP.

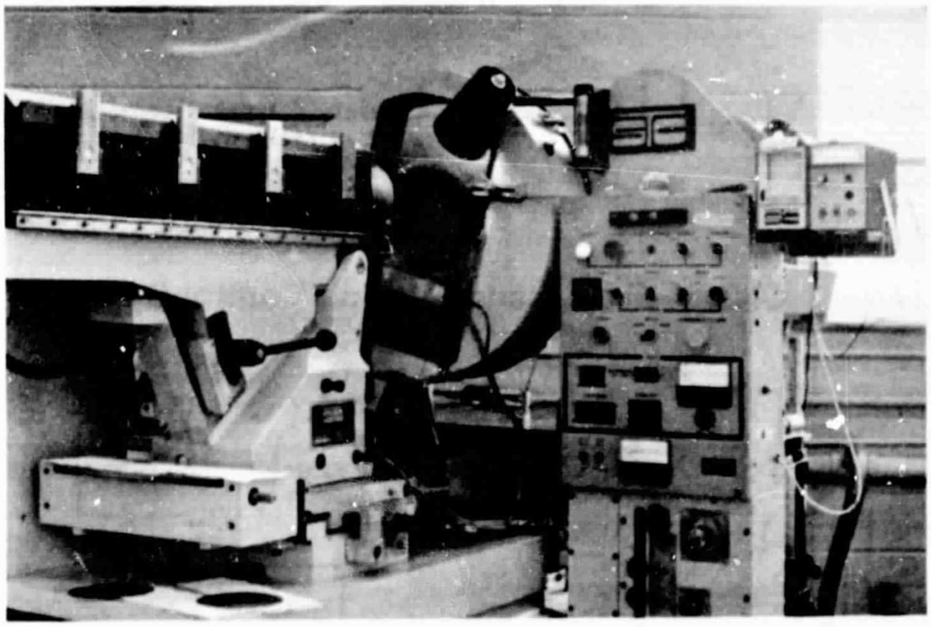
DEVELOPMENT OF METHODS OF PRODUCING LARGE AREAS OF SILICON SHEET BY THE SLICING OF SILICON INGOTS USING INSIDE DIAMETER SAWS.

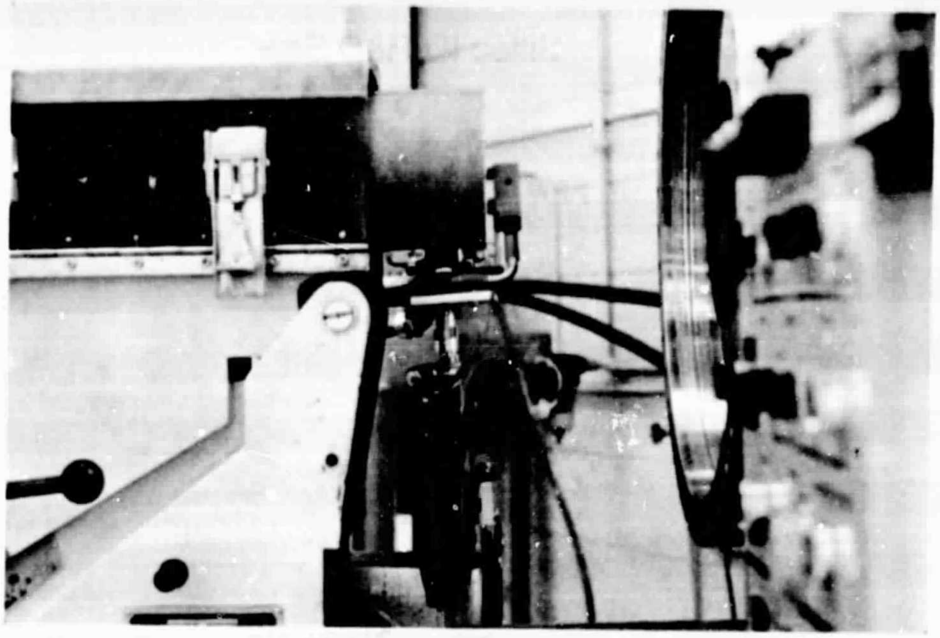
CONTRACT GOALS:

INGOT DIAMETER	10CM
WAFER THICKNESS	.24MM
KERF	.24MM
SLICING SPEED	2.5 CM/MIN.
YIELD	>90%

Equipment

- 16-INCH STC I.D. SAW
- VACUUM WAFER RECOVERY SYSTEM
- CRYSTAL ROTATING SYSTEM
- PROGRAMMABLE ELECTRIC FEED
- DYNA-TRACK BLADE MONITORING SYSTEM

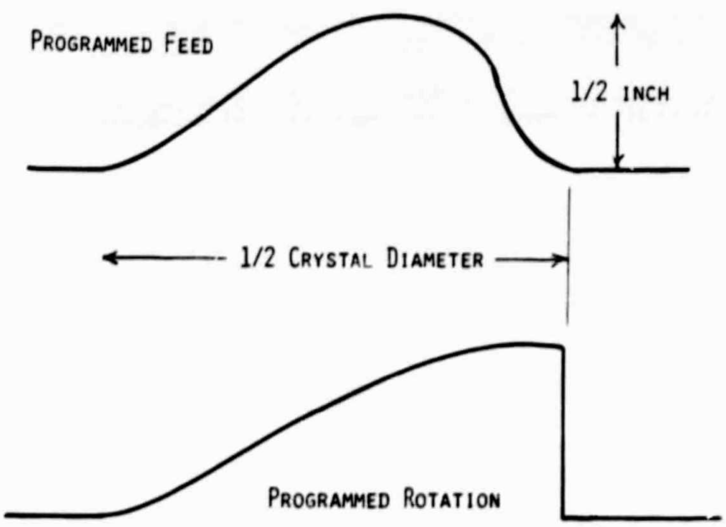




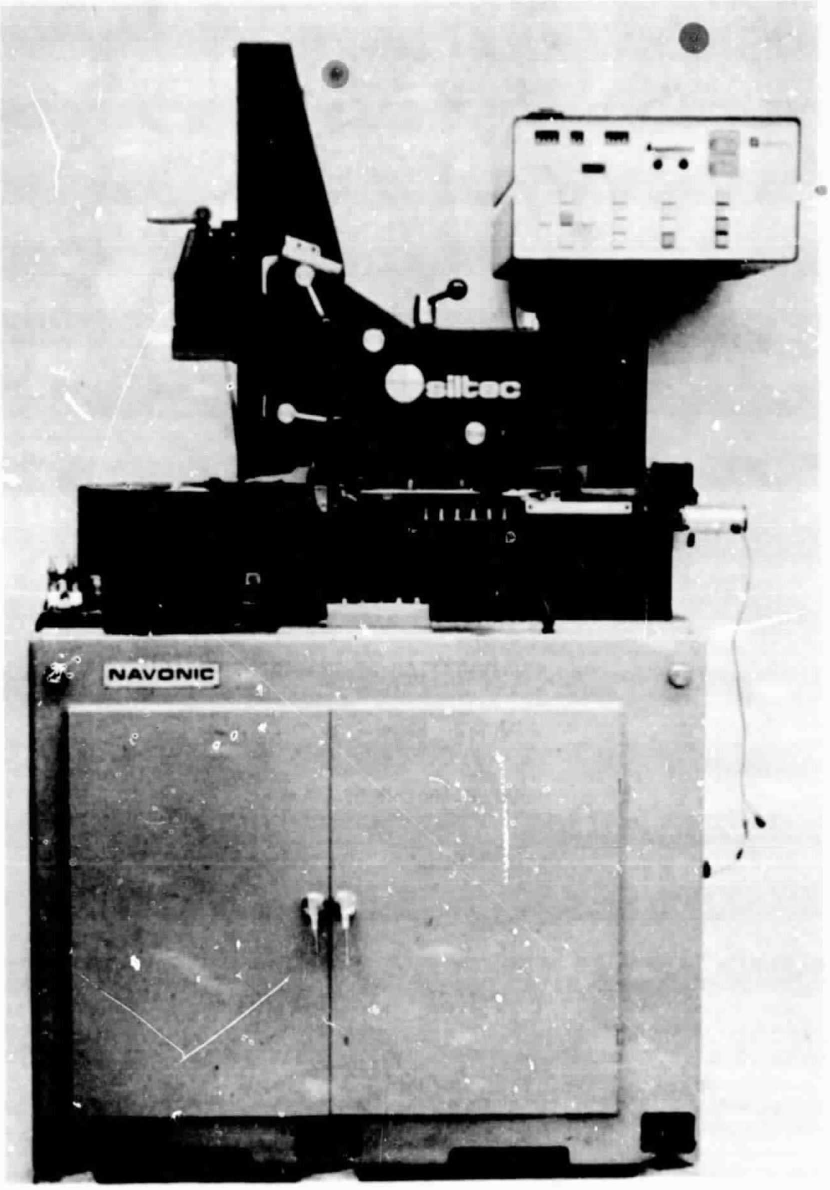
Critical Factors in Rotational Slicing

- Orientation of Crystal Axis
- Initial Feed Rate
- Wafer Thickness
- Initial Rotation Rate
- Blade Condition

Program Cam Shapes



Siltec ID R&D Saw



Slicing Tests

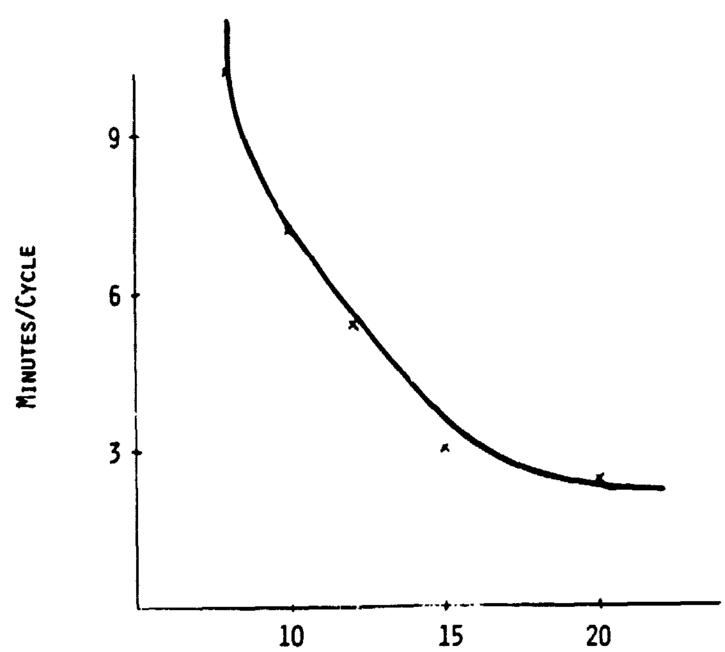
Crystal Diameter - 100mm
Kerf Loss 9 - 10 mils

Optimal Programmed Feeds and Rotations

Slice Thickness	Feeds (in/min)		Rotation
	Min.	Max.	
15 mils	.3	1.0	3-15 to 20-30 RPM
12 mils	.1	.5	5 - 30 RPM
10 mils	.07	.3-.5	7 - 20 RPM
8 mils	.05	.3	10 - 20 RPM

Rotational Slicing

Cycle Time vs Wafer Thickness



Recommended Work

NEW SAW CAPABILITIES:

1. 32-INCH BLADE CAPACITY

   3 - 10CM CRYSTALS
   2 - 15CM CRYSTALS

2. 10-INCH LINEAR STROKE - 1μM ACCURACY

3. INCREASED MASS - REDUCTION OF VIBRATION BY A FACTOR OF 10.

4. μ- PROCESSOR CONTROLS, PROGRAMMED FEED

5. UNLIMITED CRYSTAL LENGTH

6. HOLLOW SPINDLE - AUTO WAFER RECOVERY REDUCED TURBULANCE.

Blade Development

POSSIBLE NEW CORE MATERIALS

- SPECIAL 302 STAINLESS STEEL
- H11 TOOL STEEL
- BERYLIUM COPPER
- FULL WORK HARDENED 201 STAINLESS STEEL

DIAMOND MATRIX METALS

- PRESENT MATRIX - SOFT NICKEL PLATE
- NEW METALS:
  - RHODIUM
  - CHROMIUM

OBJECTIVES

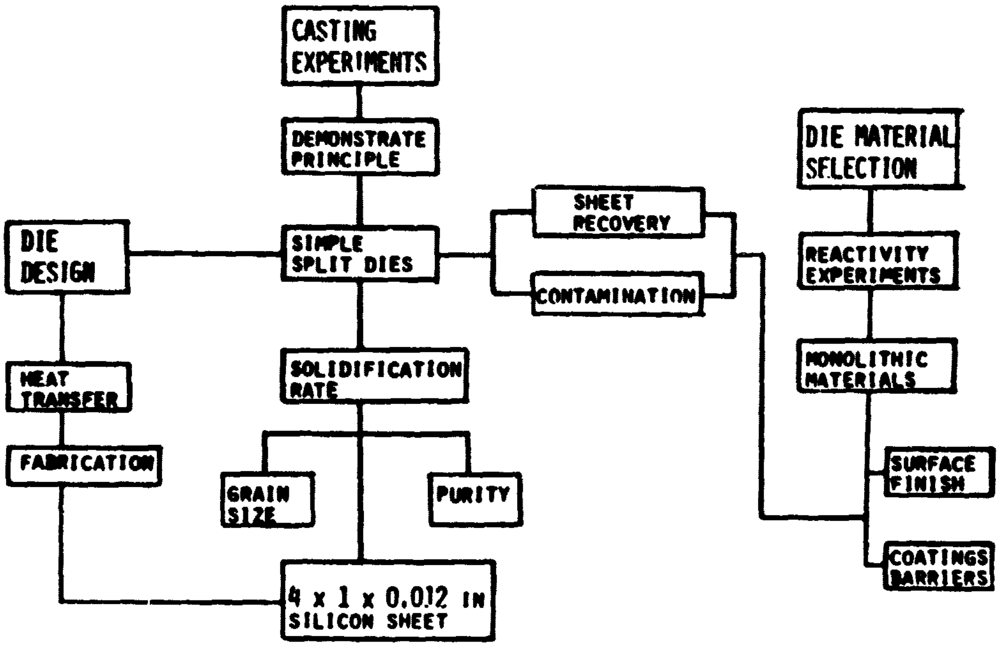
- THINNER BLADE
- LONGER LIFE
- LESS DRESSING

VACUUM DIE CASTING OF SILICON SHEET

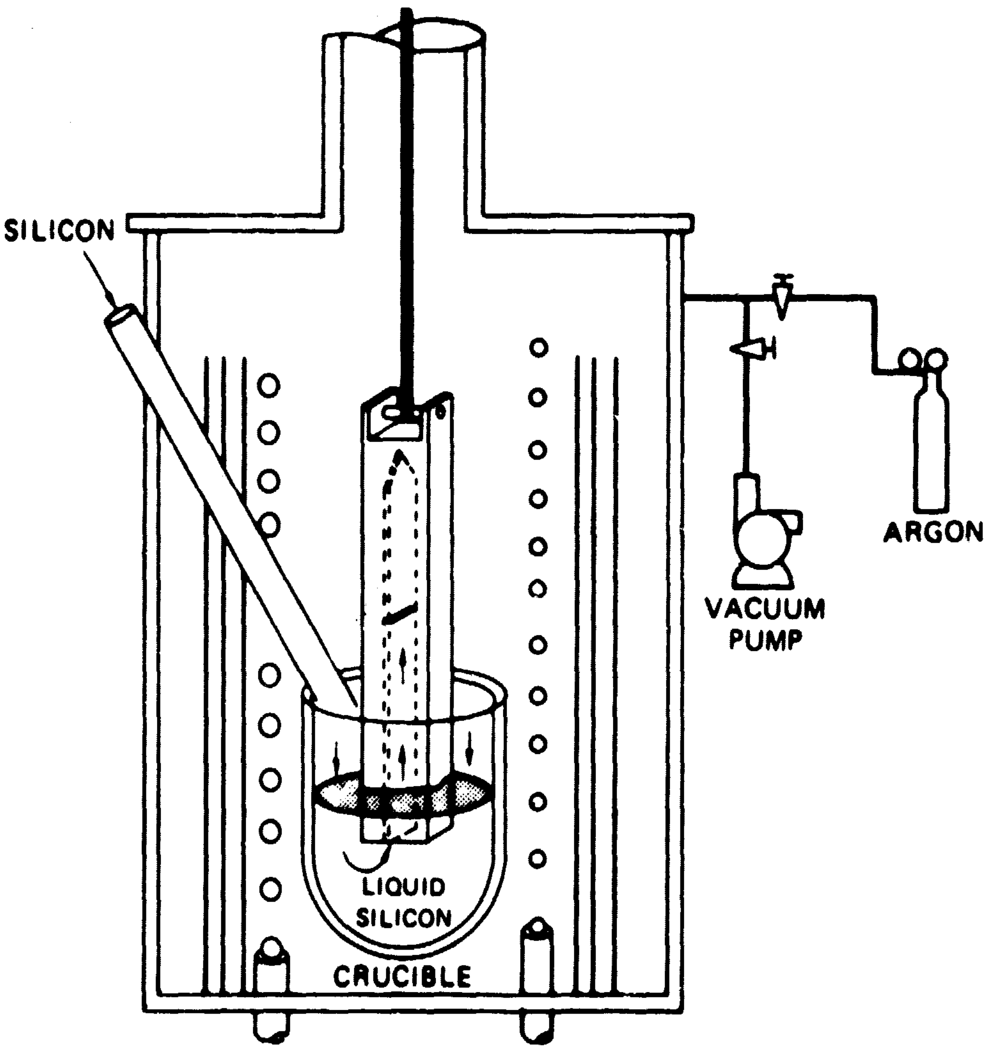
ARCO SOLAR, INC.

D. Sacoli

Basic Approach



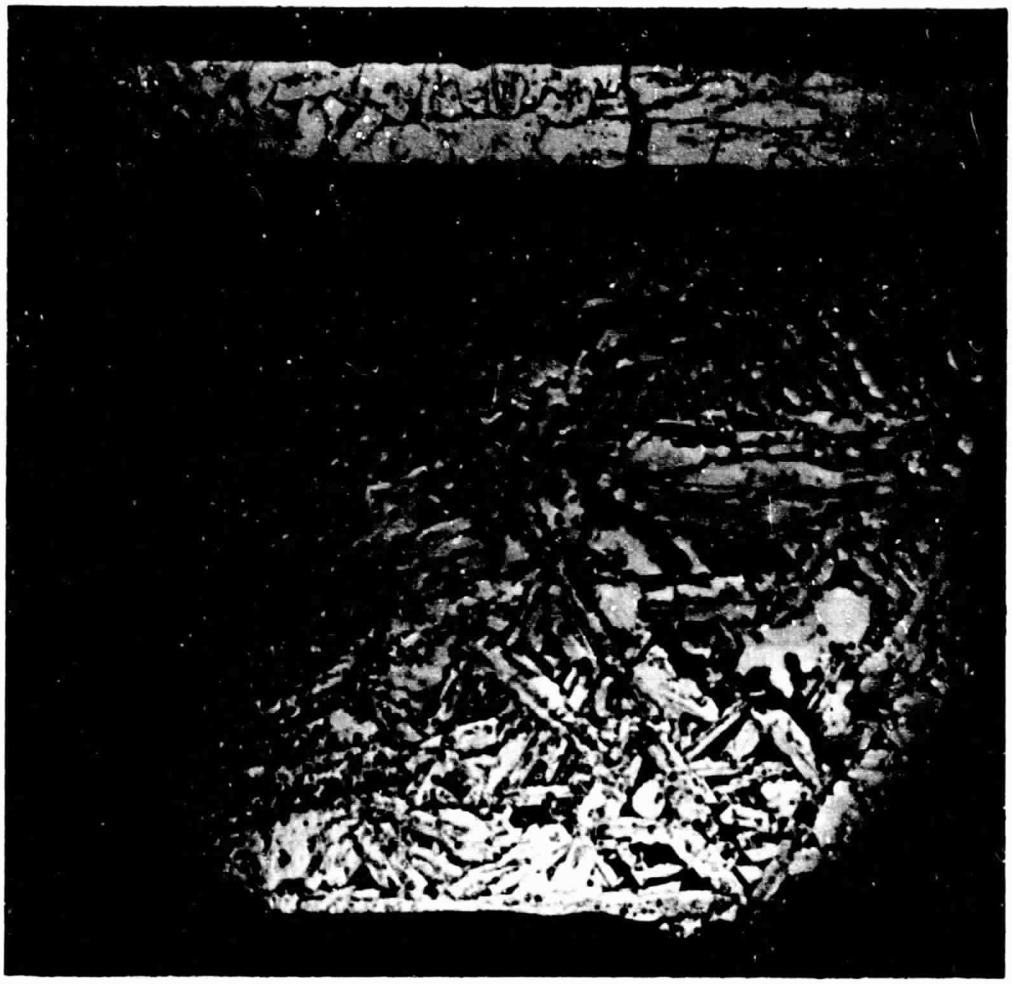
Die Casting of Liquid Silicon



Silicon Sheet Cast in BN Die

(a)

(b)



(a) Cross Section
(b) Plane Section

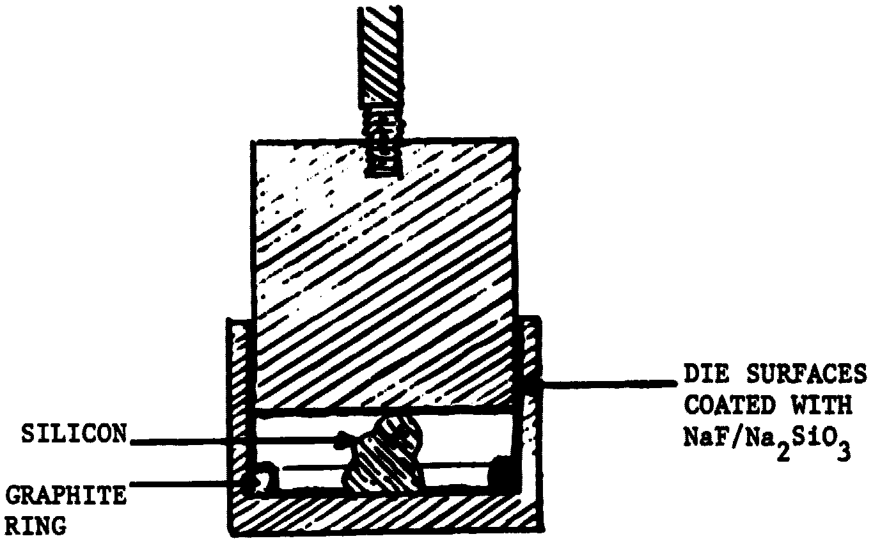
Detail of Microstructure: Silicon Sheet Cast in BN Die

(a)

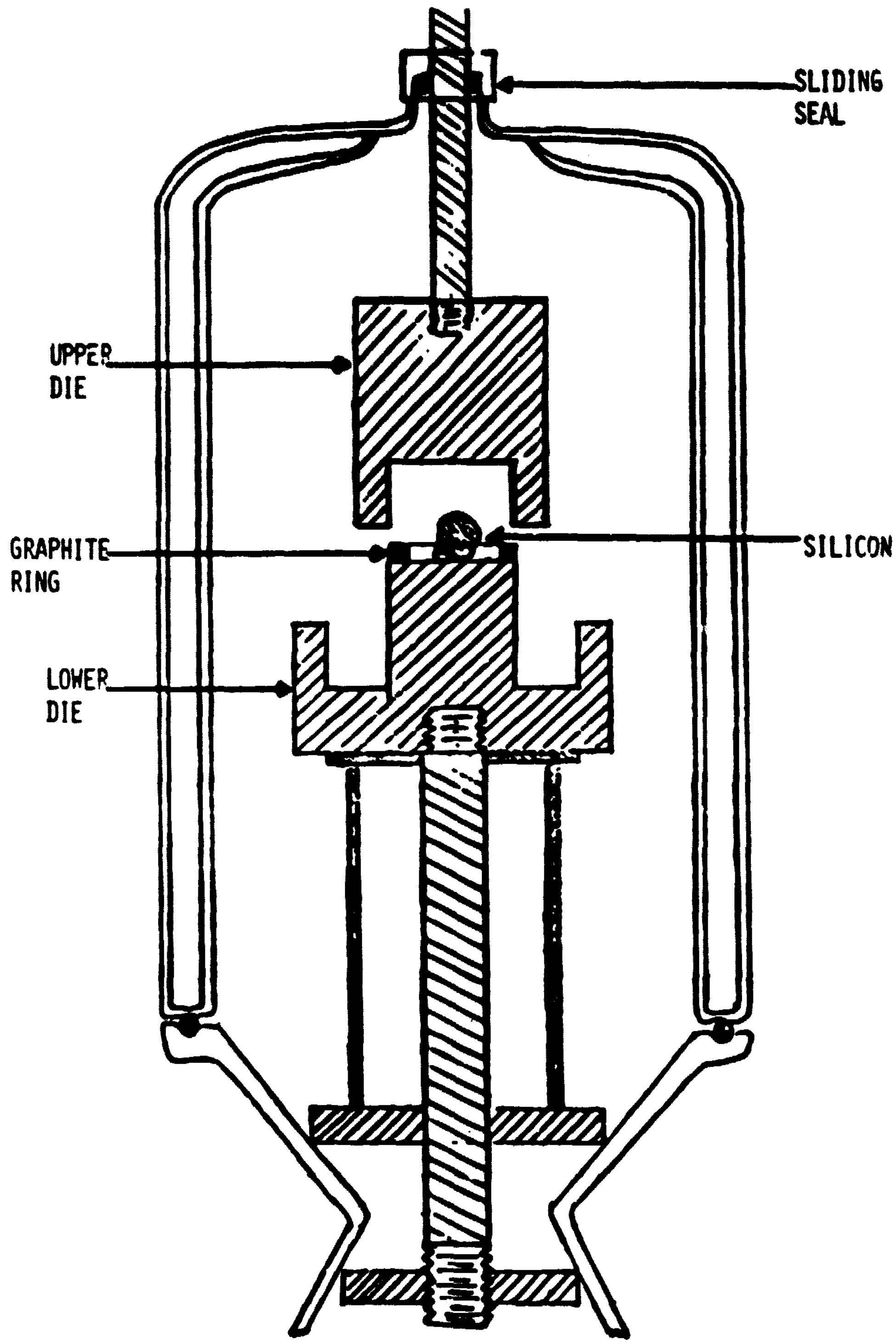
(b)

(a) Cross Section
(b) Plane Section

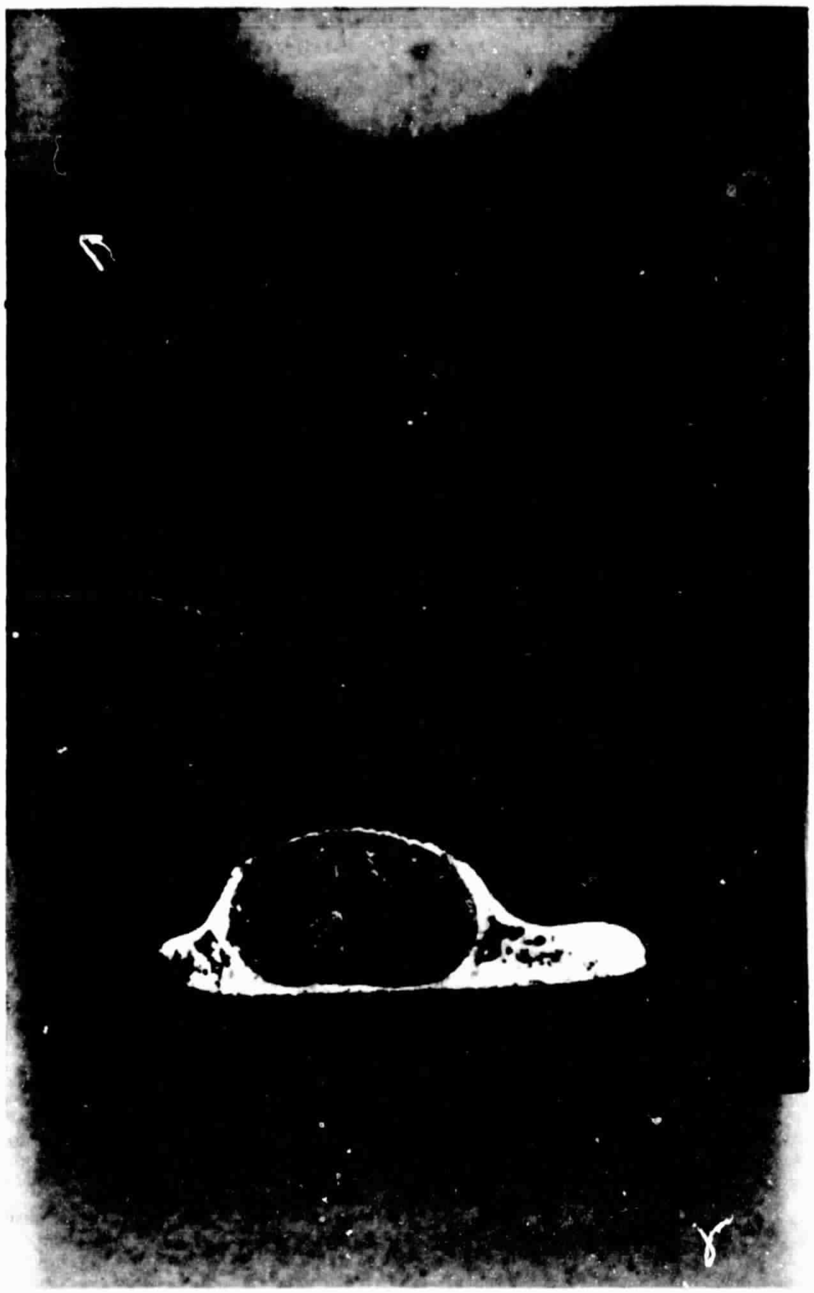
Die for Pressing Sheets from Liquid Silicon



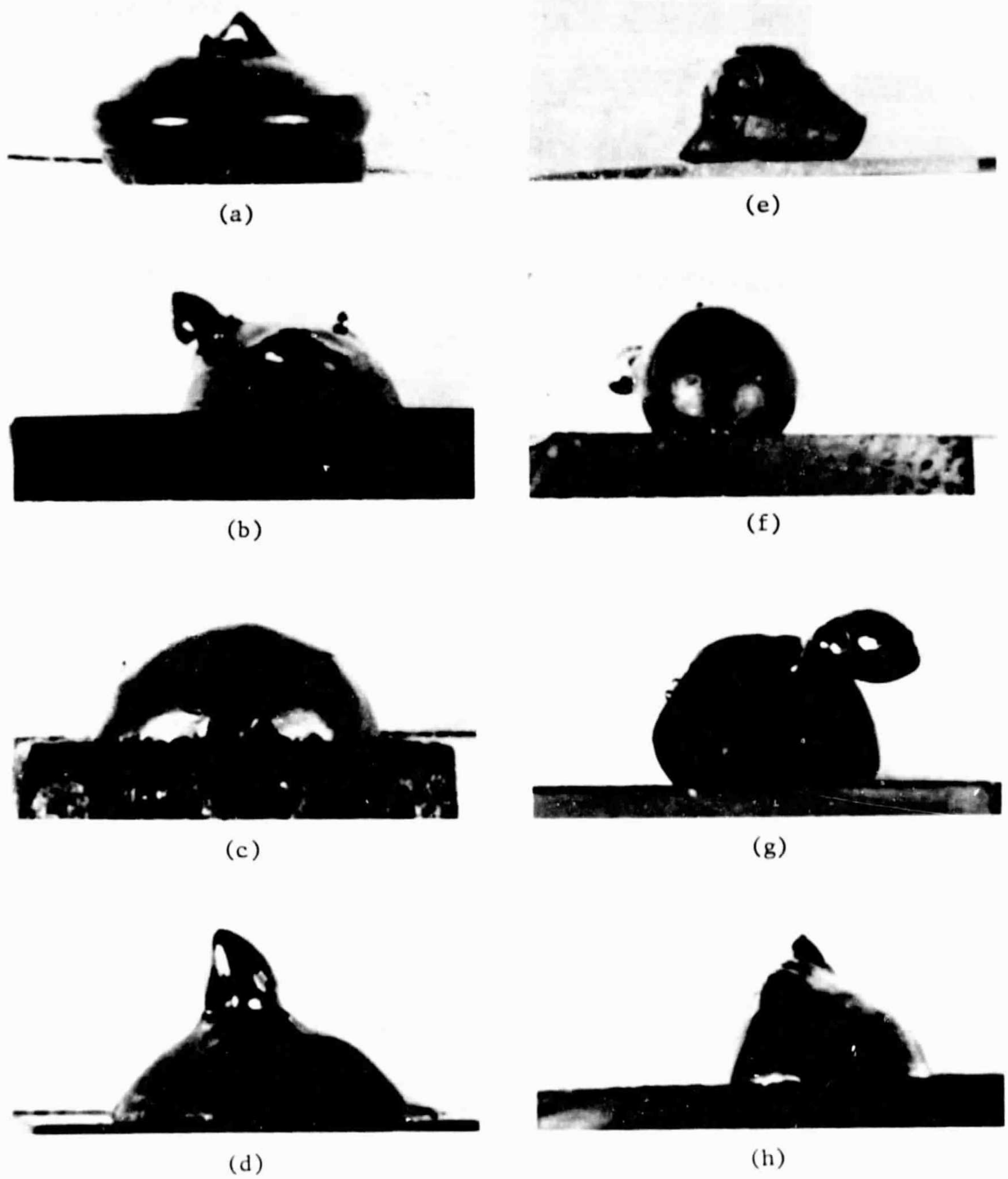
Die Arrangement for Forming Thin Sheets from Liquid Silicon



Silicon Melted in Graphite Crucible With Liquid Barrier Coating



Solidified Silicon Drops on Various Ceramics



(a) CVD Si_3N_4

(b) NC350

(c) NC312

(d) NCX34

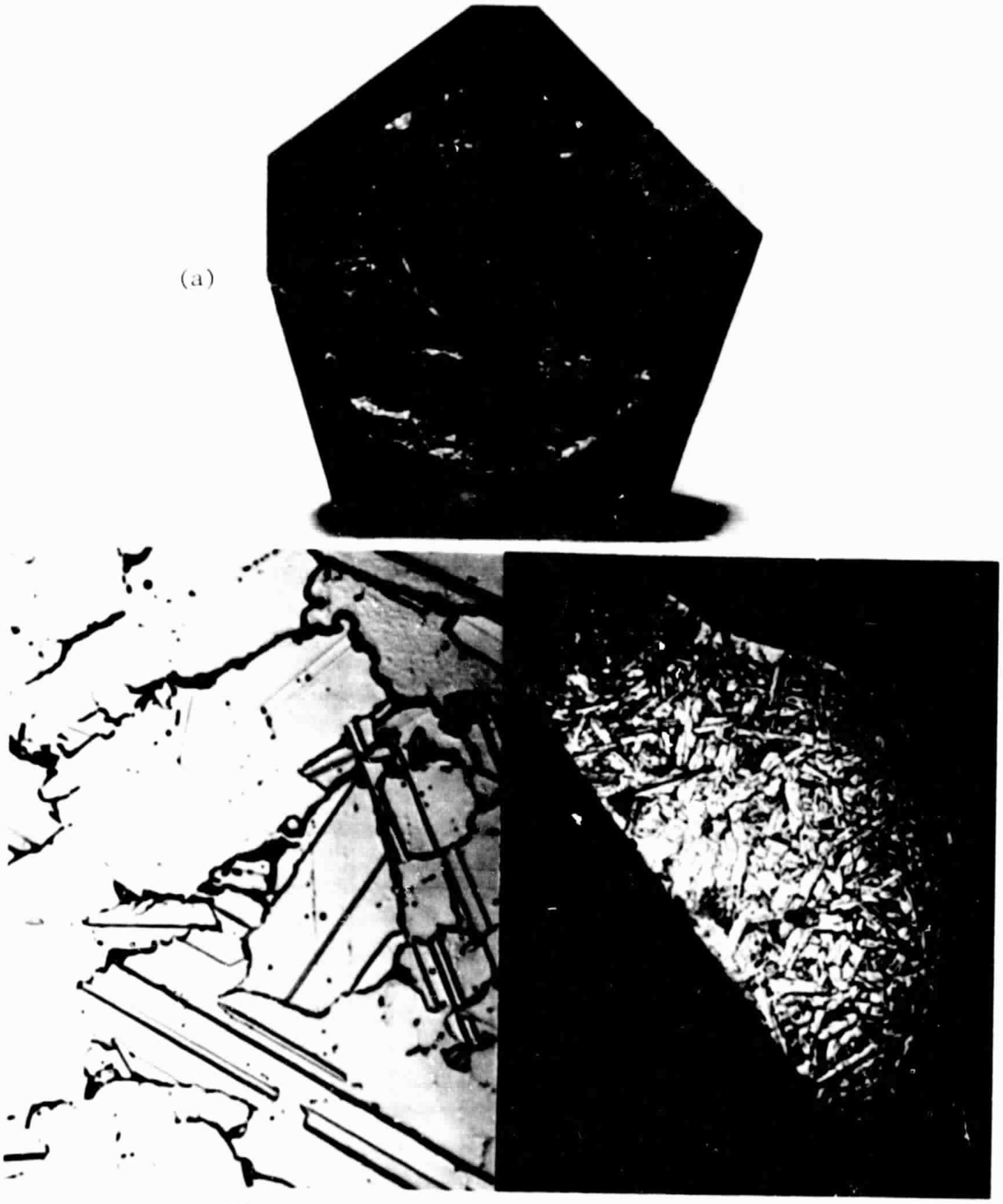
(e) CVD SiC

(f) Oxidized NC350

(g) Oxidized NC132

(h) Oxidized NCX34

Silicon Disc Pressed From a Sessile Drop



(a)

(b) (c)

(a) Disc
(b) Microstructure
(c) Microstructure

LARGE AREA Si SHEET BY EFG

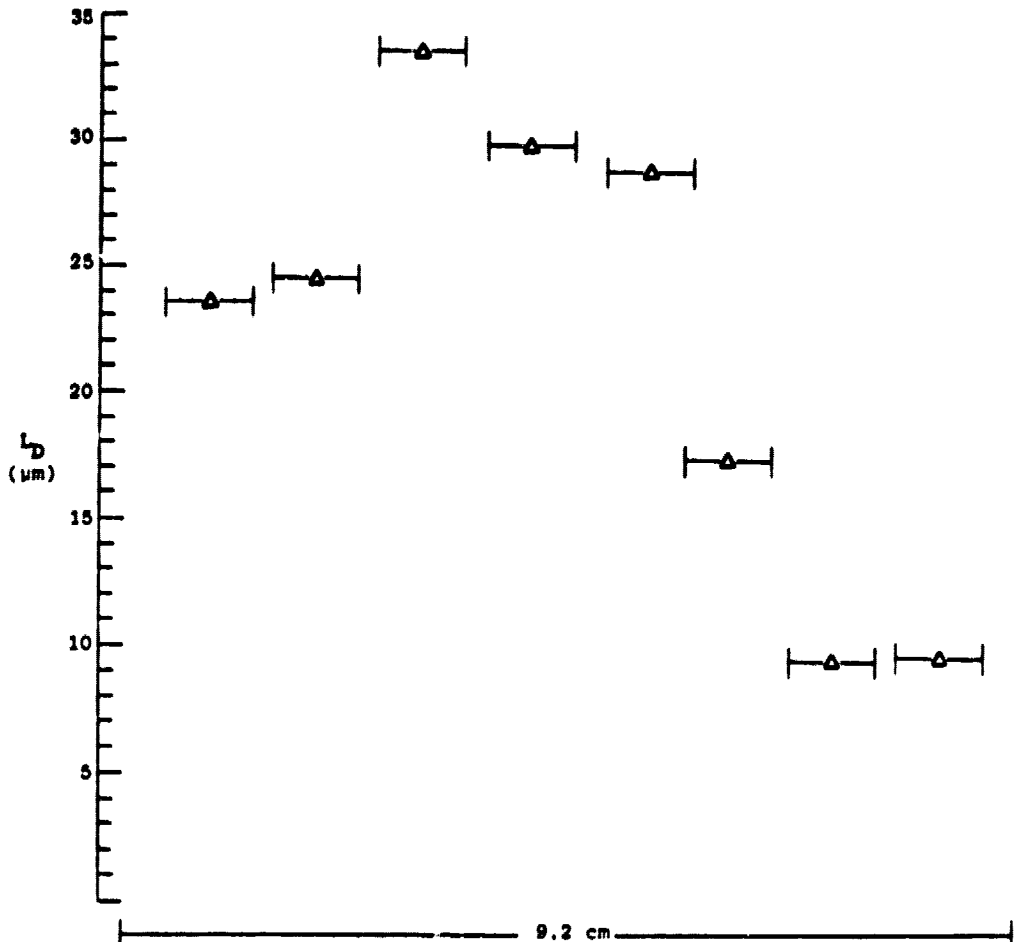
MOBIL TYCO SOLAR ENERGY CORP.

JPL Furnace 18, Separate Probes; ELH; 100 mW/cm²; 28°C

Cell No.	Area (cm^2)	I_{rv} (mA/cm^2)	V_{oc} (V)	IP (mA)	I_{sc} (mA/cm^2)	FF	P (mW/cm^2)
CZ Ref.	4.0	0.05	0.559	112	32.0	0.740	13.2
521	4.4	0.04	0.567	113	26.3	0.786	11.7
523	4.6	0.04	0.568	112	26.0	0.780	11.5
206	5.1	0.04	0.574	128	27.1	0.747	11.6
118	5.5	0.04	0.568	131	27.1	0.745	11.5
213	4.8	0.04	0.569	119	27.2	0.756	11.7

RIBBON NUMBER: 17-062
DIFFUSION NUMBER: HYBRID
DATA TAKEN BY: JDM
DATE: 12/3/79
NUMBER OF CELLS: 8
COMMENTS: CELLS FROM 4" WIDE RIBBON
ELH, 100 mW/cm², 28°C, AR COATED

CELL NO.	AREA (cm^2)	I_{sc} (mA/cm^2)	V_{oc} (V)	FF	I_{rv} (mA/cm^2)	P (mW/cm^2)
062-1	26.5	24.3	0.549	0.673	0.28	9.0
-2	25.0	24.6	0.545	0.640	0.30	8.6
-3	24.4	24.5	0.546	0.681	0.54	9.1
"FULL 4" WIDTH"	AVG.:	(24.5)	(0.547)	(0.665)	(0.37)	(8.9)
062-5	17.4	26.1	0.550	0.670	0.01	9.8
-6	13.6	25.9	0.553	0.695	0.18	9.9
-7	9.6	25.8	0.554	0.681	0.02	9.7
-8	11.6	25.7	0.553	0.668	0.21	9.5
"CENTRAL REGION"	AVG.:	(25.9)	(0.553)	(0.681)	(0.11)	(9.7)



Distribution of Minority Carrier Diffusion Length (SPV) Values Over the Width of a 10 cm EFG Ribbon (Sample No. 17-063-1).

JPL Multiple Furnace – 10-cm-Wide Ribbon

GOALS THROUGH OCTOBER 1979

- DEVELOP SINGLE CARTRIDGE GROWTH TO EQUAL 5 cm SYSTEM WITH RESPECT TO RATE, STABILITY, THICKNESS, STRESS AND FLATNESS.

PRESENT STATUS

- ALL GROWTH IS WITH CONTINUOUS MELT REPLENISHMENT.
- RATES OF 3 to 3.8 cm/min HAVE BEEN ACHIEVED.
- STABILITY DEMONSTRATED IN FULL-WIDTH GROWTH OVER TWO HOURS ON SIX OCCASIONS.
- THICKNESS RANGE: 7 to 15 MILS.
- FLATNESS AND STRESS AT ACCEPTABLE LEVELS.

GROWTH STATISTICS

- EIGHT OF 11 RUNS YIELDED FULL-WIDTH RIBBON.
- TOTAL LENGTH GROWN: 67 m (220 FT).
- PERCENT FULL WIDTH: 70%.
- AVERAGE SPV DIFFUSION LENGTH: 10 to 20 μm. VERY INHOMOGENEOUS.
- SiC PARTICLE DENSITY STILL ERRATIC. EXPERIMENTS WITH PROPER DIE DESIGN CHANGES IN PROGRESS.

GOAL FOR DECEMBER 31, 1979

- RUN THREE 10 cm CARTRIDGES CONTINUOUSLY FOR SEVERAL HOURS.

PRESENT STATUS

- ALL PARTS HAVE BEEN ORDERED, MANY RECEIVED. INSTALLATION OF TWO MORE CARTRIDGES IS IMMINENT.

JPL Furnace 17 – High-Speed and Automatic Controls

PROGRESS IN 7.5 cm WIDE GROWTH

- ACHIEVED FLAT, STRESS-FREE RIBBON GROWTH AT HIGH SPEEDS:

  (a) 5.0 cm/min WITH CARTRIDGE HELIUM.

  (b) 4.5 cm/min WITHOUT CARTRIDGE HELIUM

PROGRESS IN 10 cm WIDE GROWTH

- INSTALLATION AND TESTING OF 10 cm WIDE CARTRIDGE SYSTEM COMPLETED.

- ACHIEVED REASONABLY FLAT, STRESS-FREE, FULL-WIDTH RIBBON GROWTH AT 4.0 cm/min WITHOUT CARTRIDGE GAS.

- INITIAL EXPERIMENTS UNDER "CLEAN" CONDITIONS ENCOURAGING.

AUTOMATIC CONTROLS

- INSTALLATION OF INSTRUMENTATION FOR AUTOMATIC CONTROL OF MENISCUS HEIGHT FOR 10 cm SYSTEM IS COMPLETED. TESTS ARE IMMINENT.

Materials Characterization Effort

I. ROUTINE SPV DIFFUSION LENGTH MEASUREMENT

II. ROUTINE CELL EVALUATION

(i) FURNACE NO. 3A: 10 CM WIDE GROWN RIBBONS

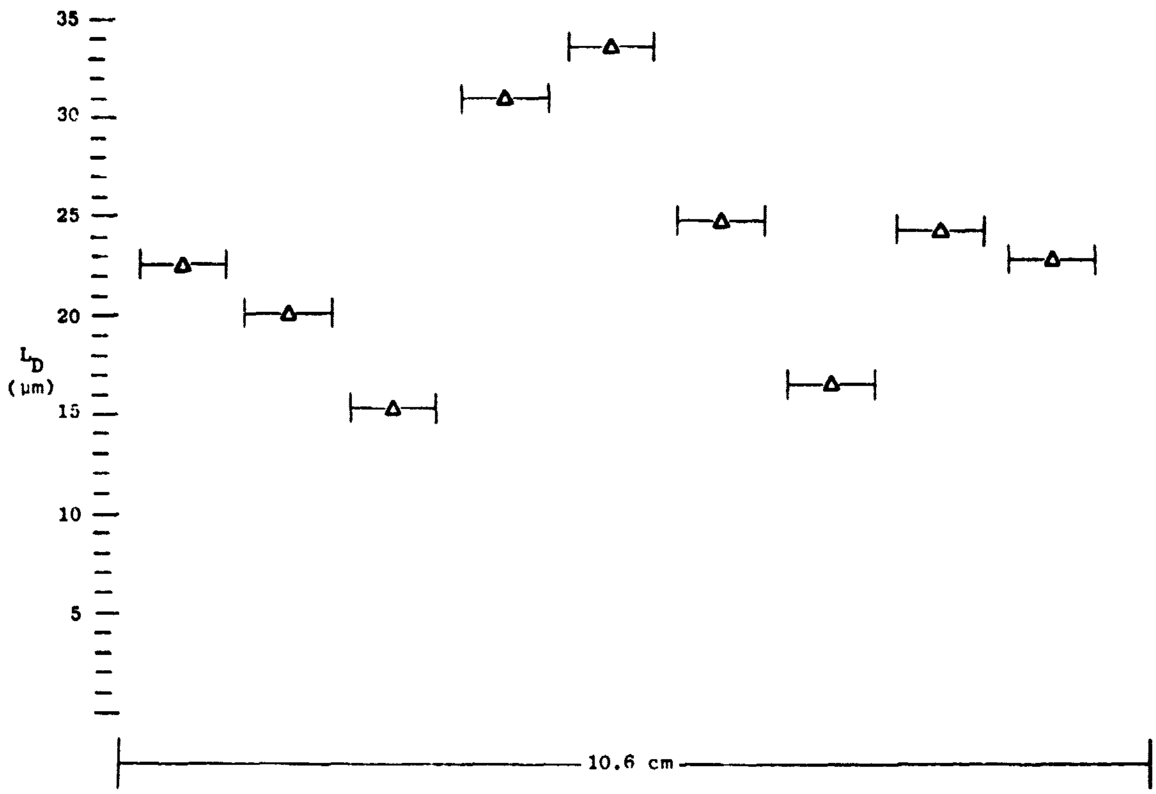
(ii) FURNACE 17: 10 CM WIDE GROWN RIBBONS

III. CELL OPTIMIZATION

(i) CELL PERFORMANCE: DIFFUSION A VS. DIFFUSION B

(ii) BULK DIFFUSION LENGTH ENHANCEMENT: DIFFUSION A VS. DIFFUSION B

(iii) 2 x 2 CM CELLS



Distribution of Minority Carrier Diffusion Length (SPV) Values Over the Width of a 10 cm EFG Ribbon (Sample No. 16-198-4B)

Solar Cell Data for Material Grown from Run 16-198. ELH Light Source at 100 mW/cm^2. 28°C. AR Coated.

10 cm wide ribbon; ~3 cm/min

Cell No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)	Notes
198-1	54.9	17.23	.530	.585	5.35	Cell Length Parallel to Ribbon Width
-2	21.8	21.34	.517	.590	6.50	
-3	18.3	24.46	.559	.721	9.86	Cell Length Perpendicular to Ribbon Width

Comparison of Solar Cell Data for Ribbons Grown from Run 16-187 and Fabricated by Two Different Diffusion Runs, A and B.

Cell No.	Diffusion Runs	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)	Notes
A-1	Run A:	16.11	.520	.694	5.82	
-2	Temperature: 1025°C	15.77	.522	.690	5.68	
-3	Time: 50 minutes	15.89	.522	.657	5.44	
-4	Source: Phosphorous-doped oxide	16.14	.528	.687	5.85	
-5		16.91	.537	.723	6.56	No AR
-6		15.82	.525	.727	6.04	
-7		15.96	.531	.727	6.16	
-8		16.17	.522	.635	5.36	
-9		15.92	.523	.701	5.84	
B-1	Run B:	11.58	.508	.735	4.33	
-2	Temperature: 900°C	11.24	.490	.679	3.74	
-3	Time: 30 minutes	11.37	.492	.667	3.73	
-4	Source: PH_3 gas	12.07	.503	.720	4.37	No AR
-5		12.68	.512	.730	4.74	
-6		11.71	.496	.716	4.16	
-7		11.67	.504	.784	4.61	

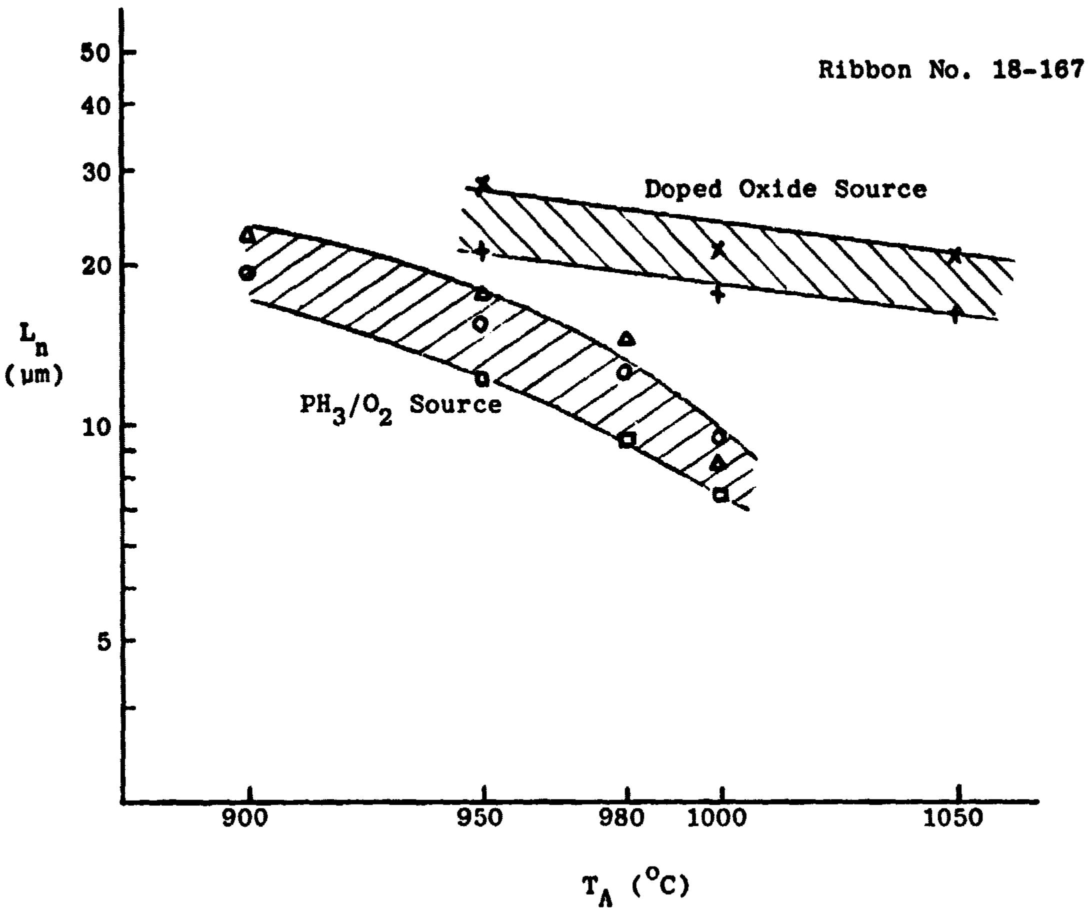
Summary of Annealing Experiment in N_2 Ambient. Furnace 18 Ribbons Grown with Graphite Crucible.

Sample No.	Annealing Condition	Position	L_D (μ)	Deviation (μ)
18-176-1C	As-grown	A1	19.6	0.9
		A2	26.7	0.8
		A3	24.1	0.8
		A4	16.6	0.8
		A5	23.7	1.0
		Average:	22.1	
	1000°C, 1 hr, N_2	B1	15.3	0.7
		B2	19.8	1.1
		B3	19.5	0.8
		B4	14.5	0.4
		B5	12.1	0.6
		Average:	16.0 (-28%)	
18-176-1J	As-grown	A1	25.3	1.8
		A2	28.9	1.2
		A3	23.7	0.7
		A4	24.3	0.7
		A5	24.9	0.9
		Average:	25.4	
	1000°C, 1 hr, N_2	B1	14.6	1.2
		B2	7.7	0.8
		B3	21.5	1.2
		B4	20.9	0.7
		B5	6.6	0.8
		Average:	14.3 (-44%)	

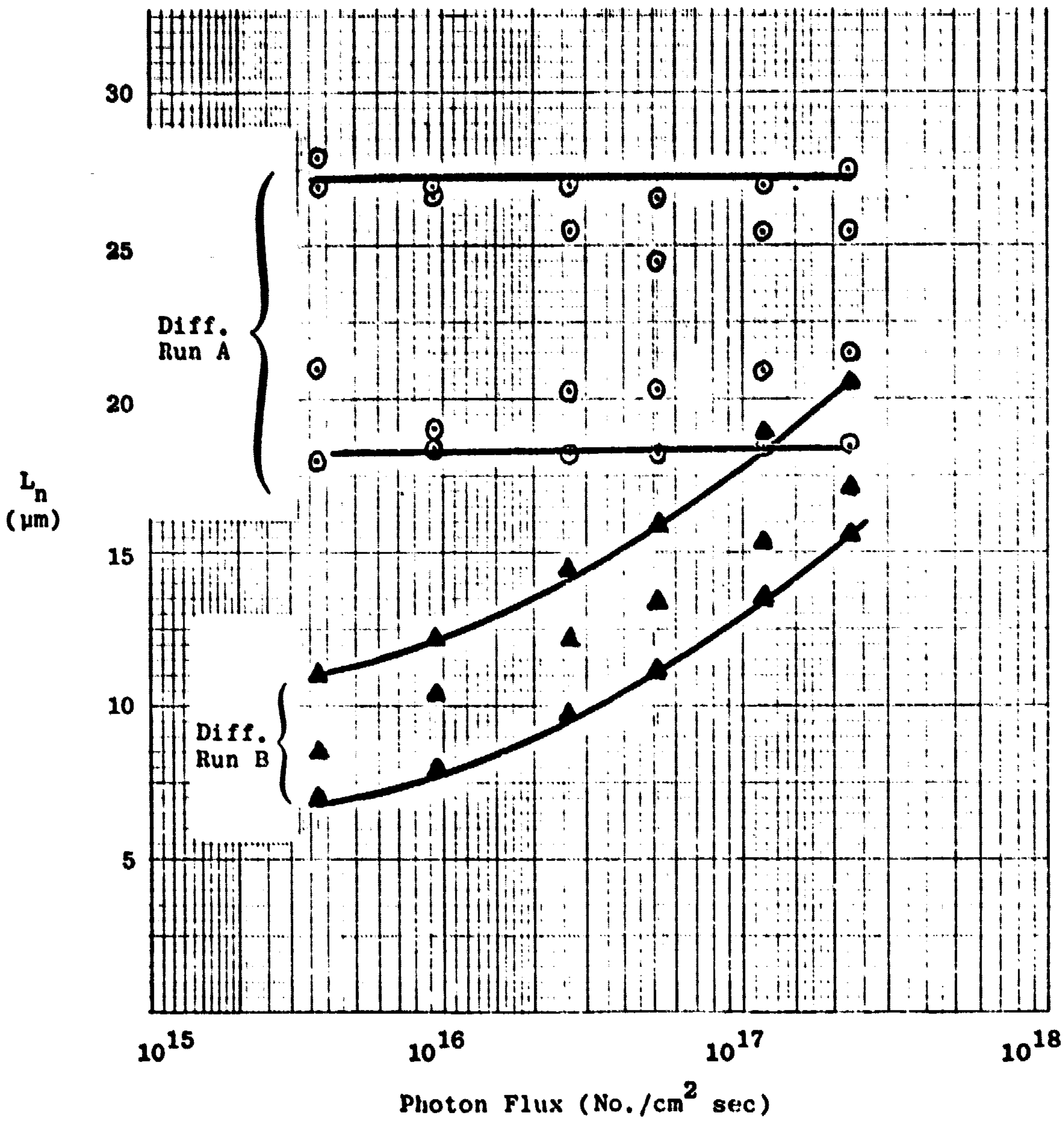
Summary of Annealing Experiment in O_2 Ambient. Furnace 18 Ribbons Grown with Graphite Crucible.

Sample No.	Annealing Condition	Position	L_D (μ)	Deviation (μ)
18-176-2H	As-grown	A1	19.2	0.5
		A2	35.5	0.9
		A3	36.5	1.1
		A4	25.9	1.3
		A5	36.6	1.3
		Average:	30.7	
	1000°C, 1 hr, O_2	B1	15.5	0.8
		B2	21.4	0.8
		B3	34.4	0.9
		B4	26.1	0.9
		B5	12.0	0.8
		Average:	21.9 (-29%)	
18-176-3H	As-grown	A1	14.5	0.5
		A2	28.1	1.2
		A3	40.8	1.0
		A4	32.4	0.9
		A5	12.4	0.4
		Average:	25.6	
	1000°C, 1 hr, O_2	B1	4.4	0.5
		B2	31.4	1.4
		B3	25.2	0.7
		B4	18.8	0.6
		B5	9.2	0.5
		Average:	10.6 (-59%)	

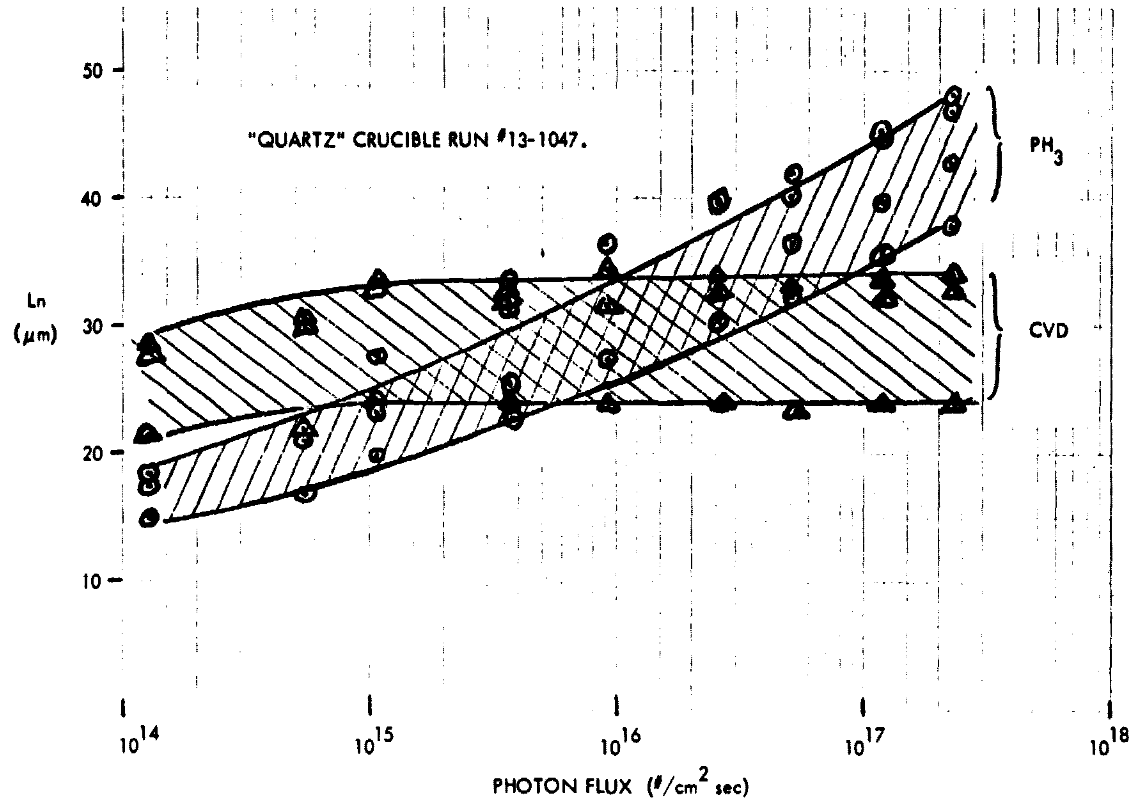
Effects of Diffusion Temperature and Conditions on the Bulk Diffusion Length of Graphite-Grown RH-EFG Ribbon.



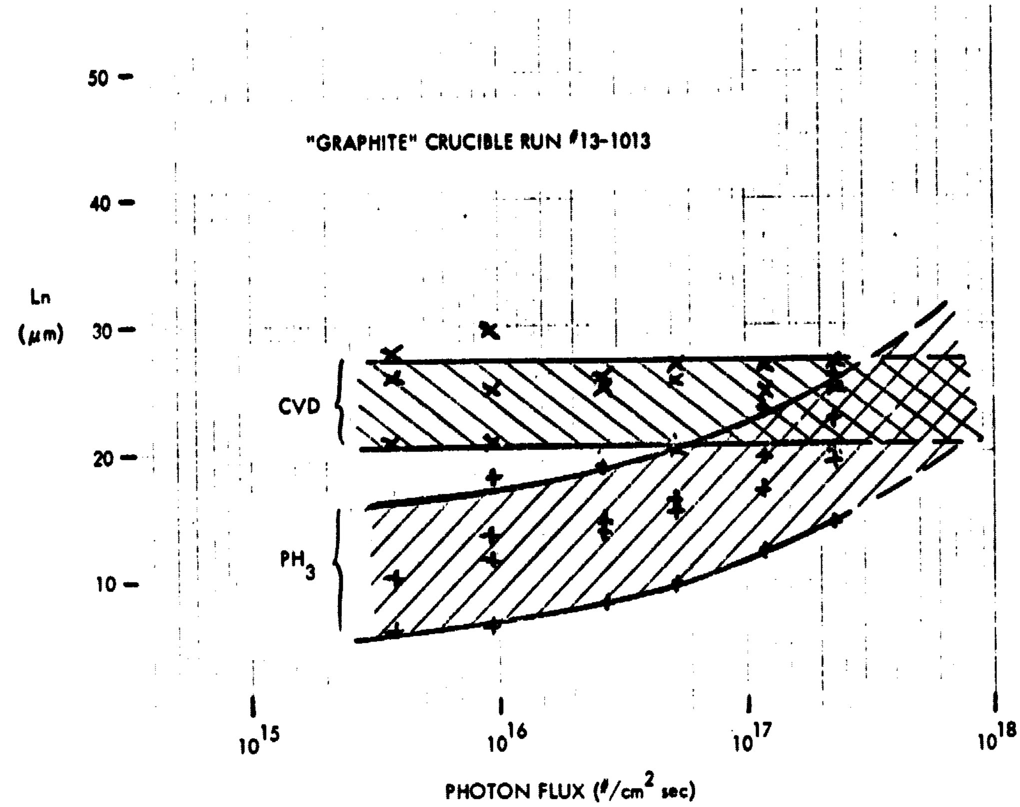
Bulk diffusion length enhancement characteristics of solar cells fabricated from two diffusion runs, A and B. The cell samples were taken from the multiple grown ribbon, No. 16-187.



Diffusion Lengths in Solar Cells as a Function of Light Intensity in 1" Wide EFG Ribbon Grown in an Induction-Heated System Using a Quartz Crucible.



Diffusion Lengths in Solar Cells as a Function of Light Intensity in 1" Wide EFG Ribbon Grown in an Induction-Heated System Using a Graphite Crucible.



SILICON WEB

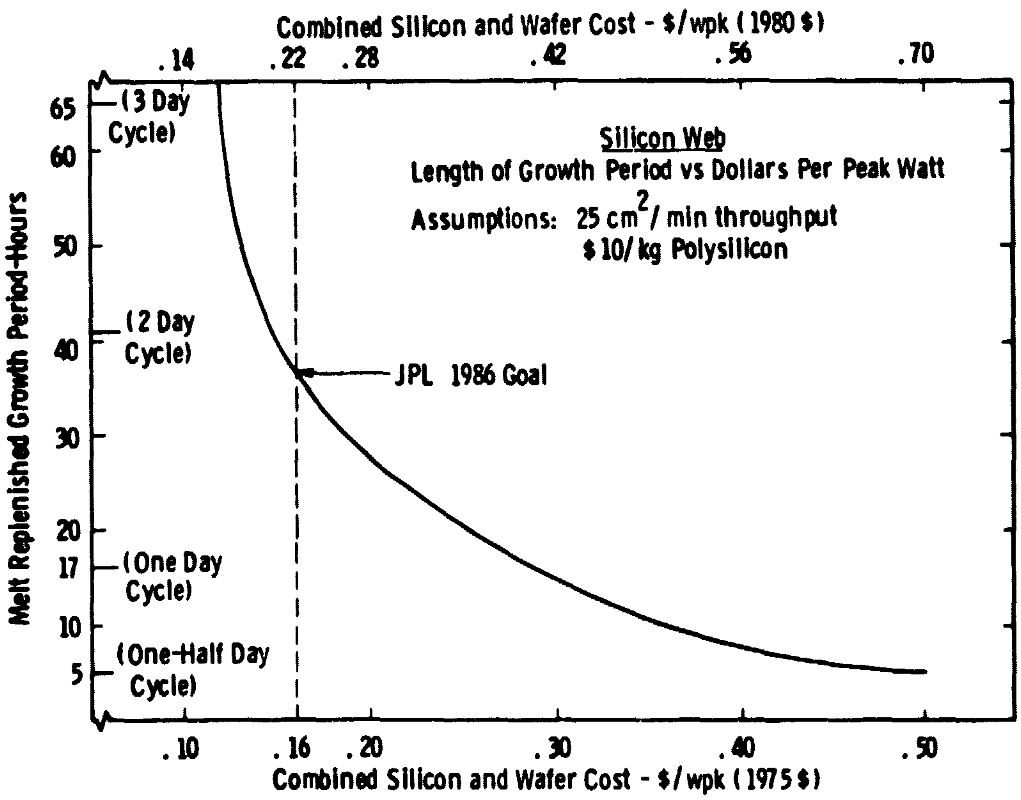
WESTINGHOUSE R&D CENTER

Technology Status:

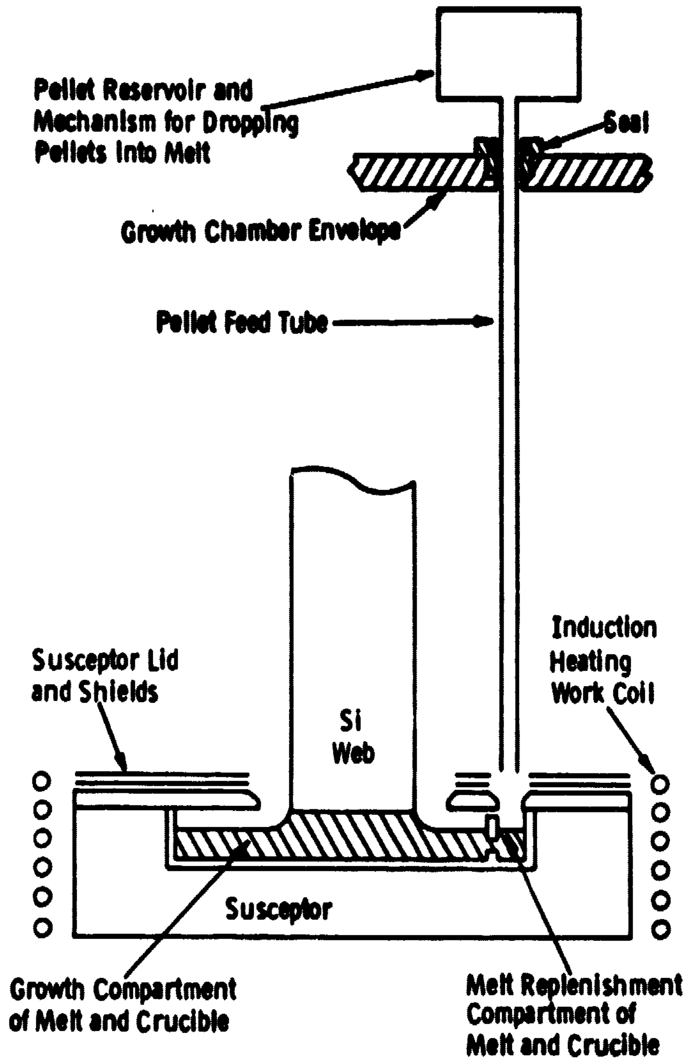
- Area Throughput Rate Goal Exceeded (27 cm^2/ min)
- Solar Cell Conversion Efficiency Goal Exceeded (15. 5 %)
- Process Acceptance of Solar Grade (Battelle) Polysilicon Demonstrated
- Melt Replenished Growth Demonstrated (5 hrs)

Development Underway:

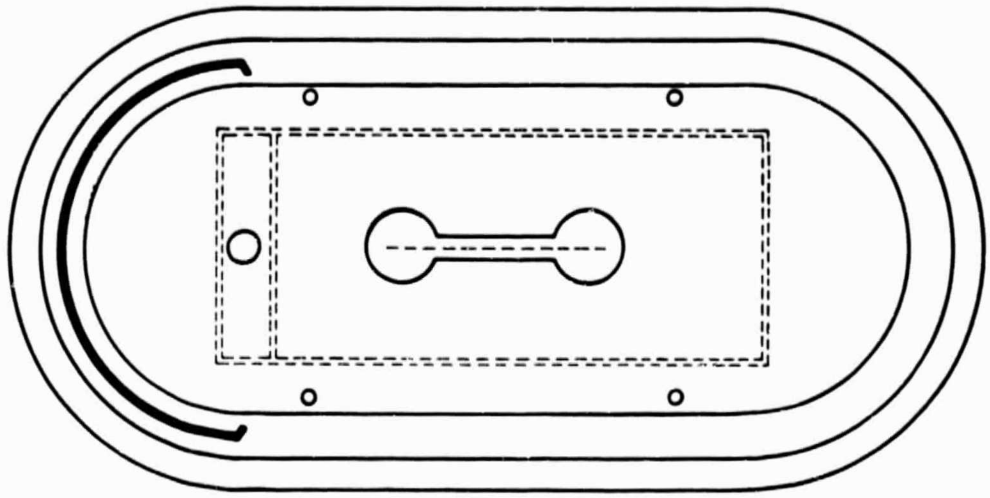
- Long Term Melt Replenishment (1 to 3 Days)



Simplified Sketch of Melt Replenishment System

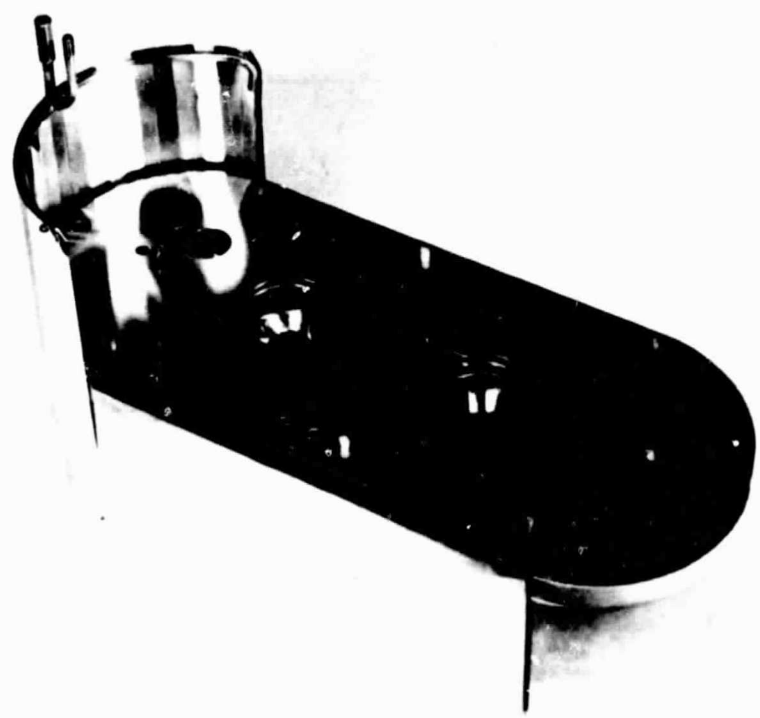


Susceptor System

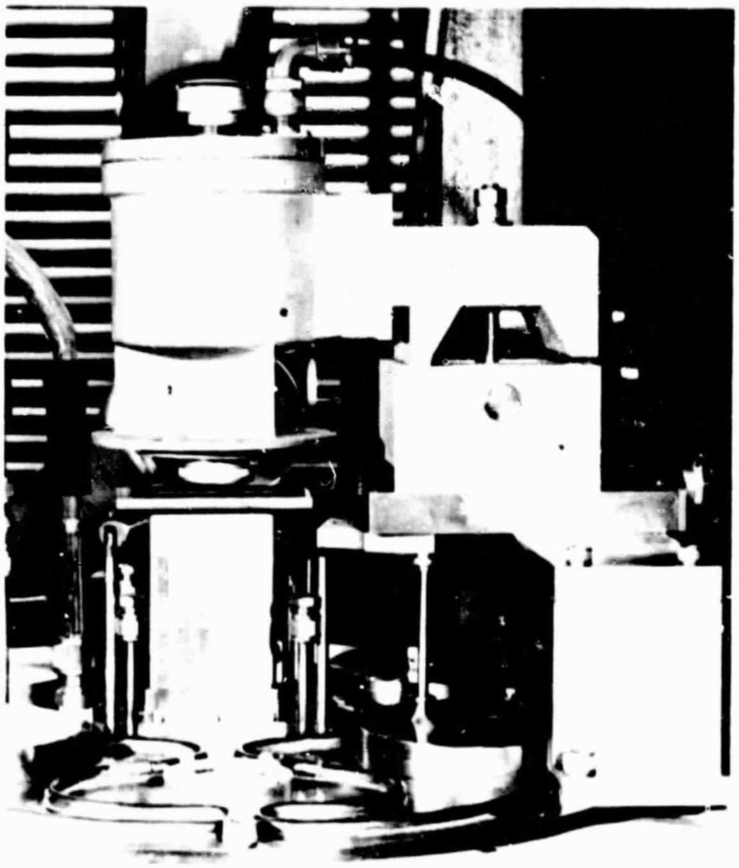


Showing Location of Vertically Adjustable Heat Shield, Melt Temperature Profile Measurement and Thermocouple Probe Holes

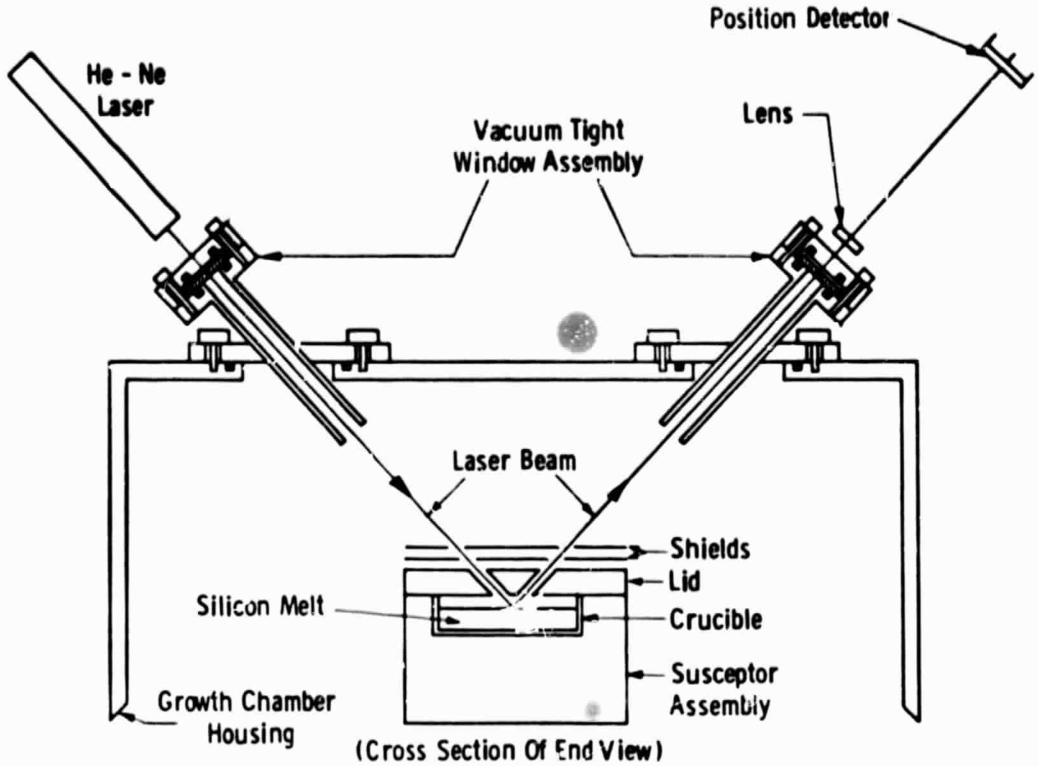
Susceptor With Adjustable Thermal Shield



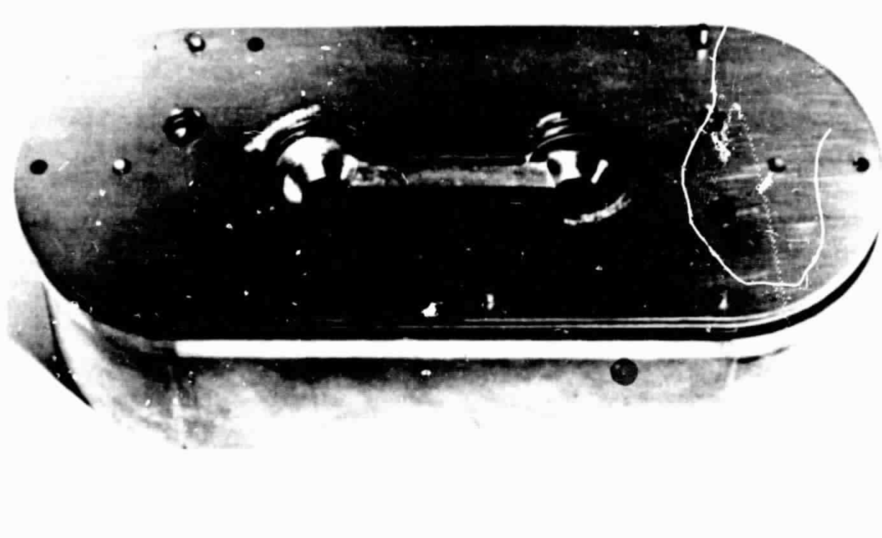
Optical Pyrometer Mounted on Web Furnace



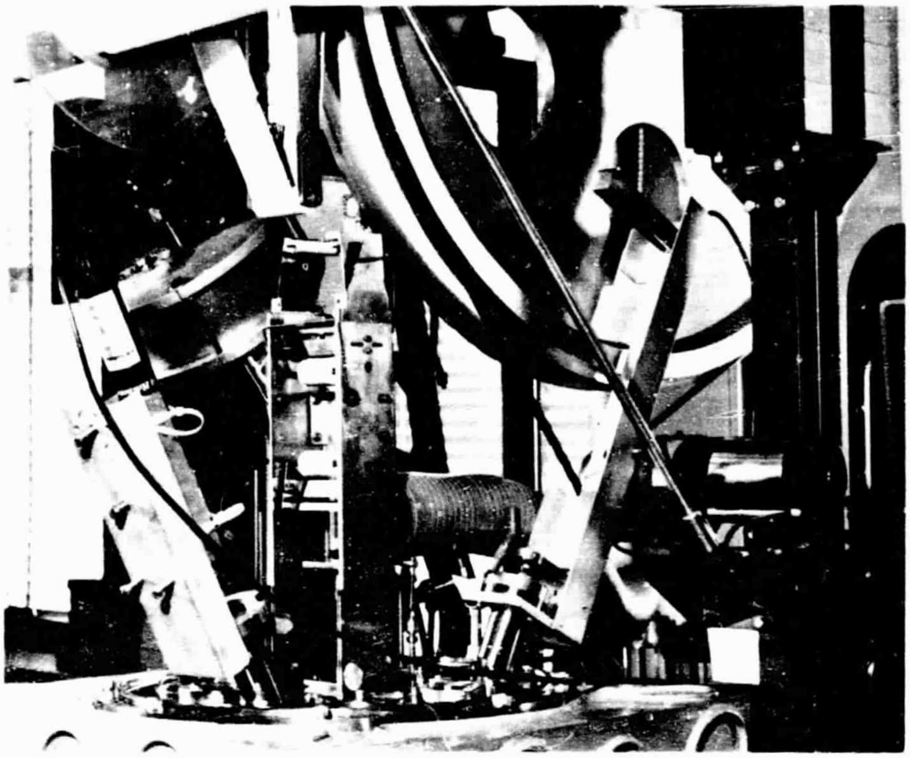
Schematic of Melt Level Sensor



Susceptor for Melt Level Sensing



Top of Web Furnace Showing Laser and Detector



SILICON WEB

Status of Hardware Modifications for Long-Term Melt Replenished Growth

Thermal Trimming

- Adjustable Shield System Built and Installed
- Characterization Near Completion

Melt Level Sensing

- Laser Sensor System Built and Installed
- Optical Alignment of Components Completed

Webqual 20: Data Summary

A = 1.039 cm^2, AM1 @ 91.6 mW/cm^2

CRYSTAL	NO. CELLS	I_{SC} mA	V_{OC} VOLT	FF	η_0 %	η_{AR} %	τ_{OCD} μsec	NOTES
RE12-3.2	4	22.18	.548	.737	9.47	13.5	11.4	STD.
RE102-2.2	4	20.18	.520	.734	8.15	11.7	3.8	
J131-2.2	4	20.98	.537	.746	8.88	12.7	6.3	
J131-3.4	4	19.40	.513	.733	7.73	11.1	2.8	
J134-2.2	4	21.70	.536	.749	9.21	13.2	6.7	
W141-1.2	4	21.90	.569	.738	9.73	13.9	6.3	
W151-1.2	4	22.18	.543	.738	9.35	13.4	8.6	FEED EXPT.
W154-1.4	4	21.58	.542	.722	8.92	12.8	7.5	FEED EXPT.
W154-2.3	4	21.35	.531	.734	8.79	12.6	5.4	FEED EXPT.

Web Grown from Battelle Silicon

Polysilicon Characteristics	Battelle Lot 33645-38-97 (Supplied by JPL) Pretreated 6 hrs at 1290°C in Argon to Emit Zn
Web Growth Behavior	Same as Observed for Semiconductor Grade Silicon
Solar Cell Characteristics	Cell Efficiency: Uncoated Avg. 9.0 ± 0.2% (η_{AR} ~ 12.8% est) Range Uncoated 8.6 to 9.2% (η_{AR} 12.3% to 13.2% est.) Test Conditions: n^+pp^+ Cell, 91.6 mW/cm^2 Illumination

Preliminary Comparison of Cells Fabricated From Silicon
Web Grown at Various Throughput Rates

Wafer Identity	Conversion Efficiency* (AM1) Uncoated	AR Coated (Est.)
CZ Baseline	8.5	12.2
Si Web @ 4 cm^2/min	9.2	13.2
Si Web @ 15 cm^2/min	8.0	11.4
Si Web @ 25 cm^2/min	9.0	12.9

*Average of Several Cells Fabricated in a Single Run

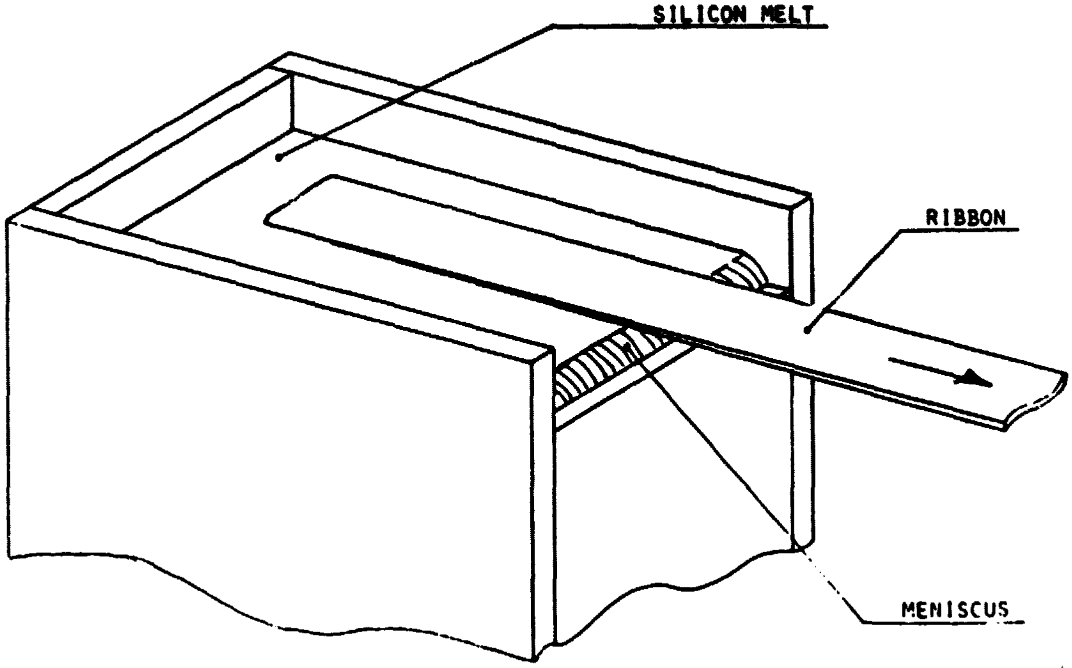
Summary

- Area Throughput Goal Exceeded
- Solar Cell Conversion Efficiency Goal Exceeded
- Solar Grade Polysilicon Acceptable
- Melt Replenished Growth Demonstrated With Good Cell Efficiency
- Preliminary Data Show Good Cell Efficiency With High Throughput Rate Web
- Hardware Modifications for Long Term Melt Replenished Growth Completed-Characterization and Operation Begun.

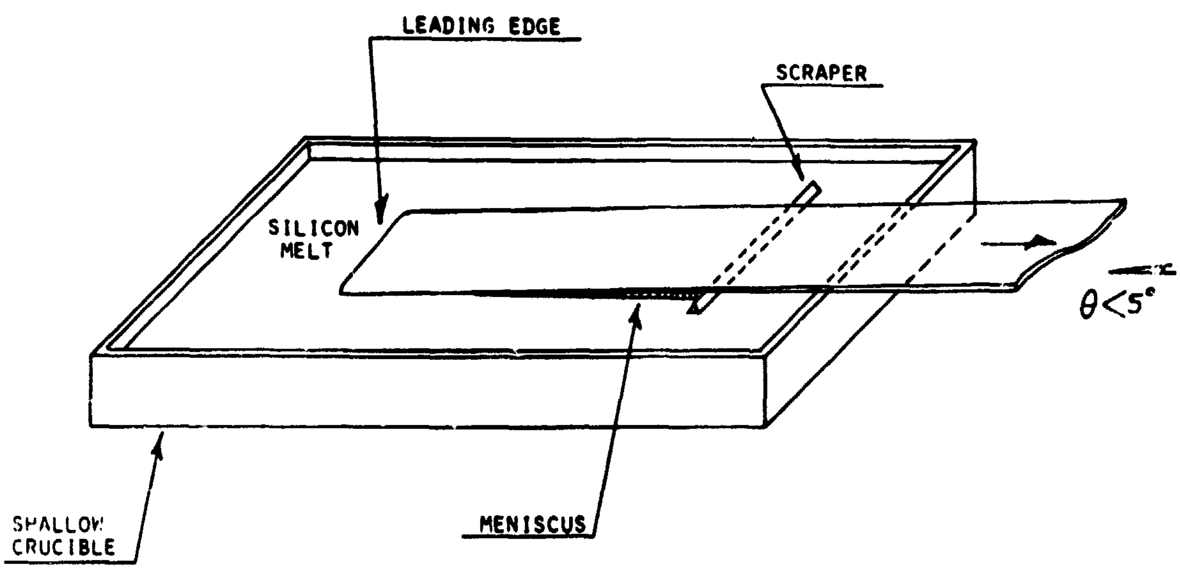
LOW-ANGLE SHEET GROWTH

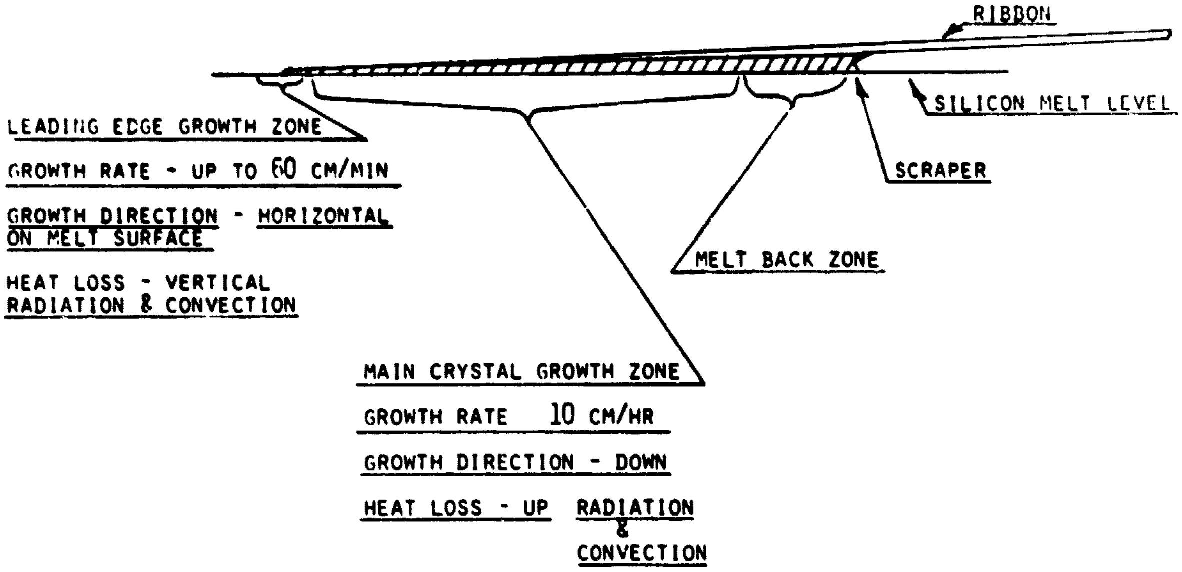
ENERGY MATERIALS CORP.

Schematic of Horizontal Ribbon Growth

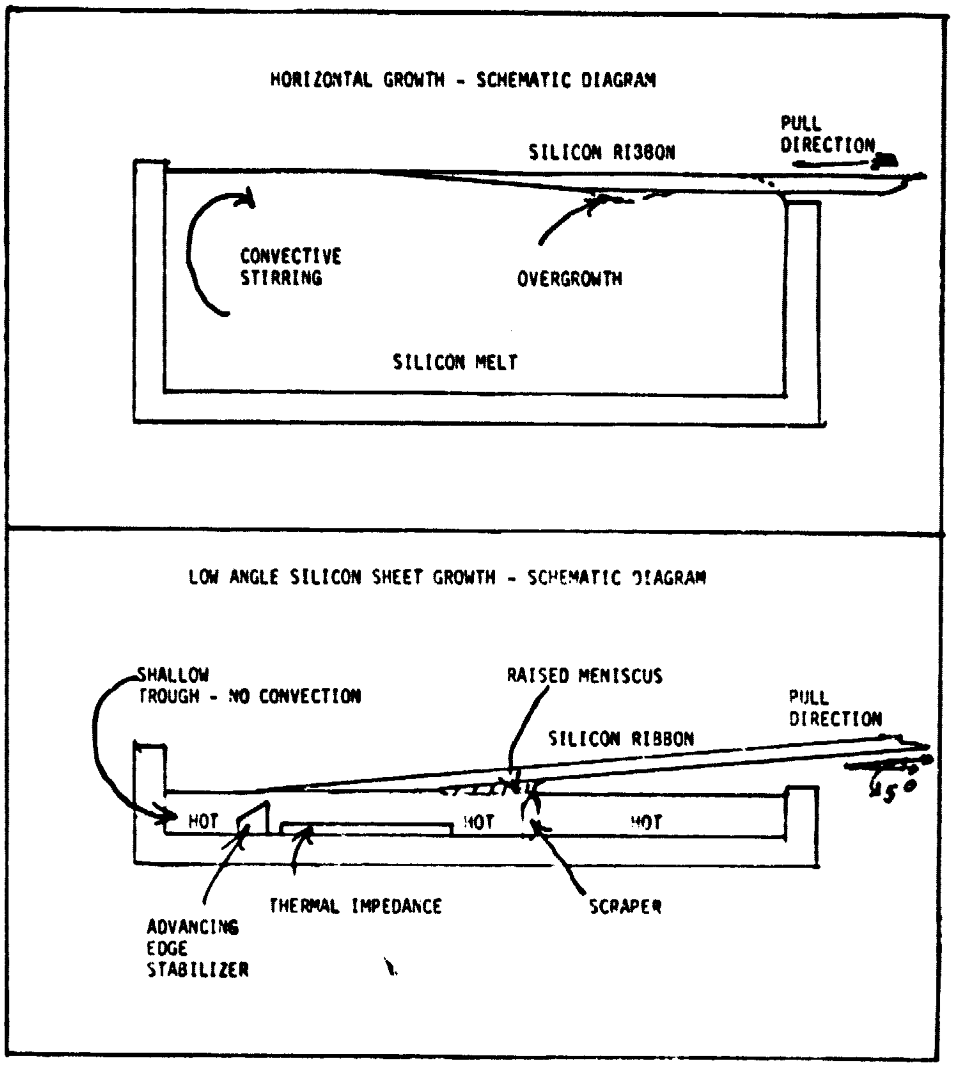


Schematic of Low-Angle Ribbon Growth




RIBBON
SILICON MELT LEVEL
SCRAPER
LEADING EDGE GROWTH ZONE
GROWTH RATE - UP TO 60 CM/MIN
GROWTH DIRECTION - HORIZONTAL ON MELT SURFACE
HEAT LOSS - VERTICAL RADIATION & CONVECTION
MELT BACK ZONE
MAIN CRYSTAL GROWTH ZONE
GROWTH RATE 10 CM/HR
GROWTH DIRECTION - DOWN
HEAT LOSS - UP RADIATION & CONVECTION

Comparison of Horizontal and Low-Angle Si Sheet Growth (Longitudinal Sections)



Results to Date

LOW ANGLE GROWTH OF SILICON RIBBON FROM FUSED SILICA TROUGHS

LENGTH	-	SEVERAL RIBBONS HAVE BEEN GROWN WHICH WERE LIMITED BY THE STROKE OF THE PULLER - ABOUT 66 CM. MAXIMUM PULLED WAS 71 CM.
GROWTH SPEED	-	TYPICALLY 20 TO 30 CM/MIN BUT SPEEDS UP TO 60 CM/MIN ARE EASILY ACHIEVED.
WIDTH	-	TYPICALLY 1.5 CM
THICKNESS	-	TYPICALLY .06 CM RANGING FROM .03 CM TO .12
QUALITY	-	THE LEADING EDGE IS PRODUCING A DENDRITIC TOP SURFACE, RESULTING IN LARGE GRAINED POLYCRYSTALLINE STRUCTURE. EFFORTS TO GROW SINGLE CRYSTAL MATERIAL ARE WAITING FOR MELT LEVEL CONTROL AND CONTINUOUS PULLING. THERE HAS BEEN NO ATTEMPT TO GROW CLEAN MATERIAL OR TO EVALUATE THE SEMICONDUCTOR CHARACTERISTICS.

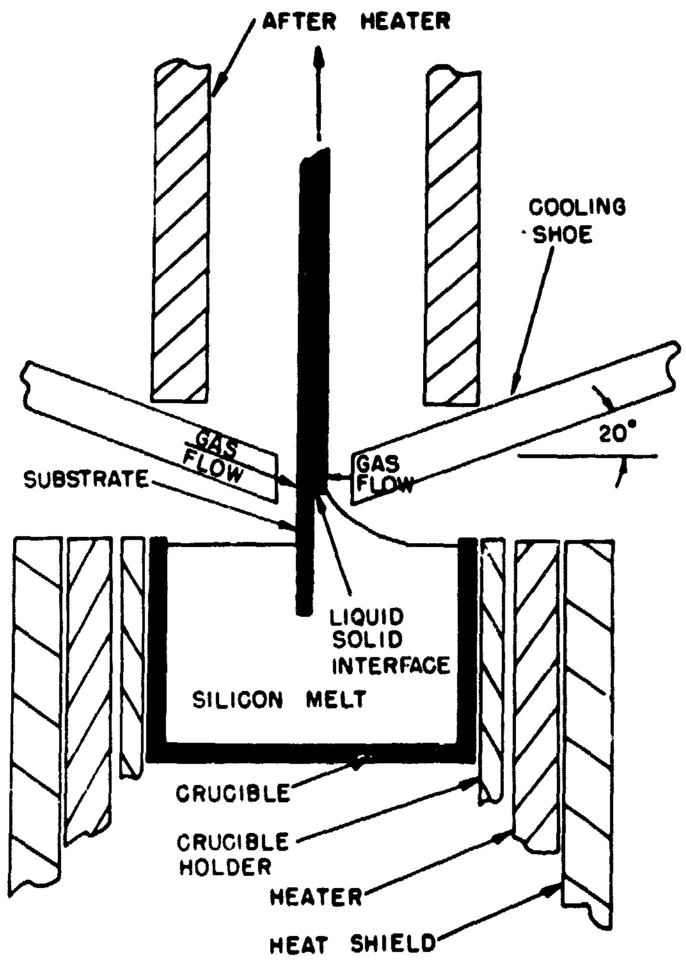
EMC 11/28/79

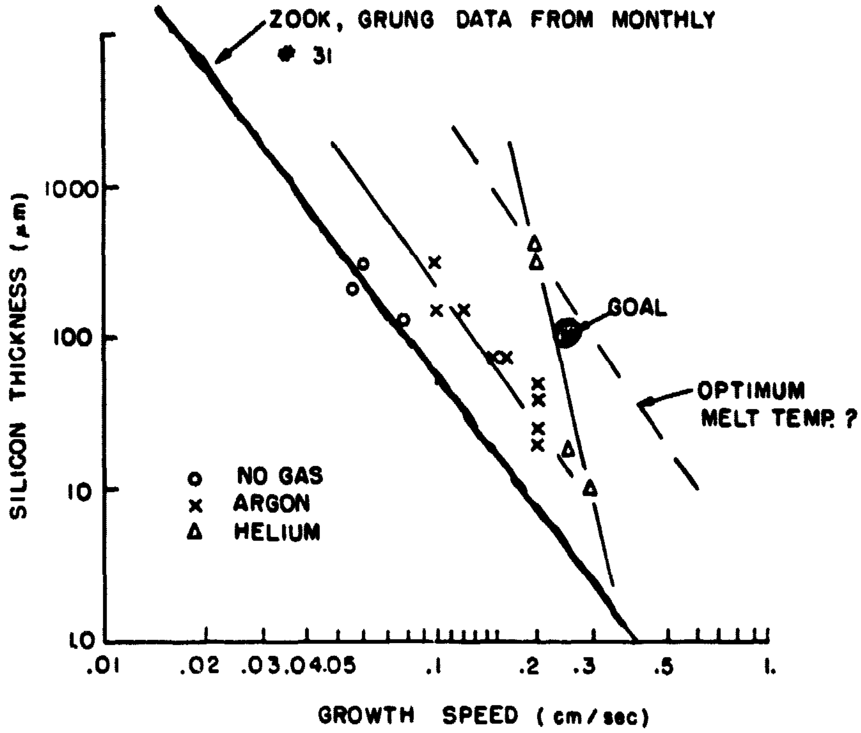
SILICON-ON-CERAMIC PROCESS

HONEYWELL CORP.

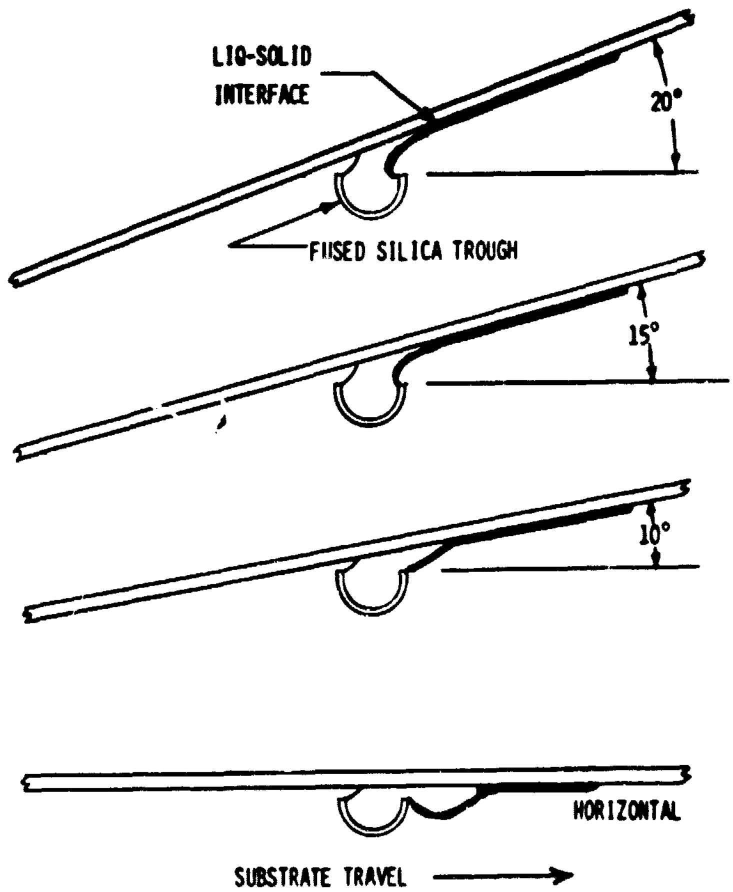
1979 Program Objectives

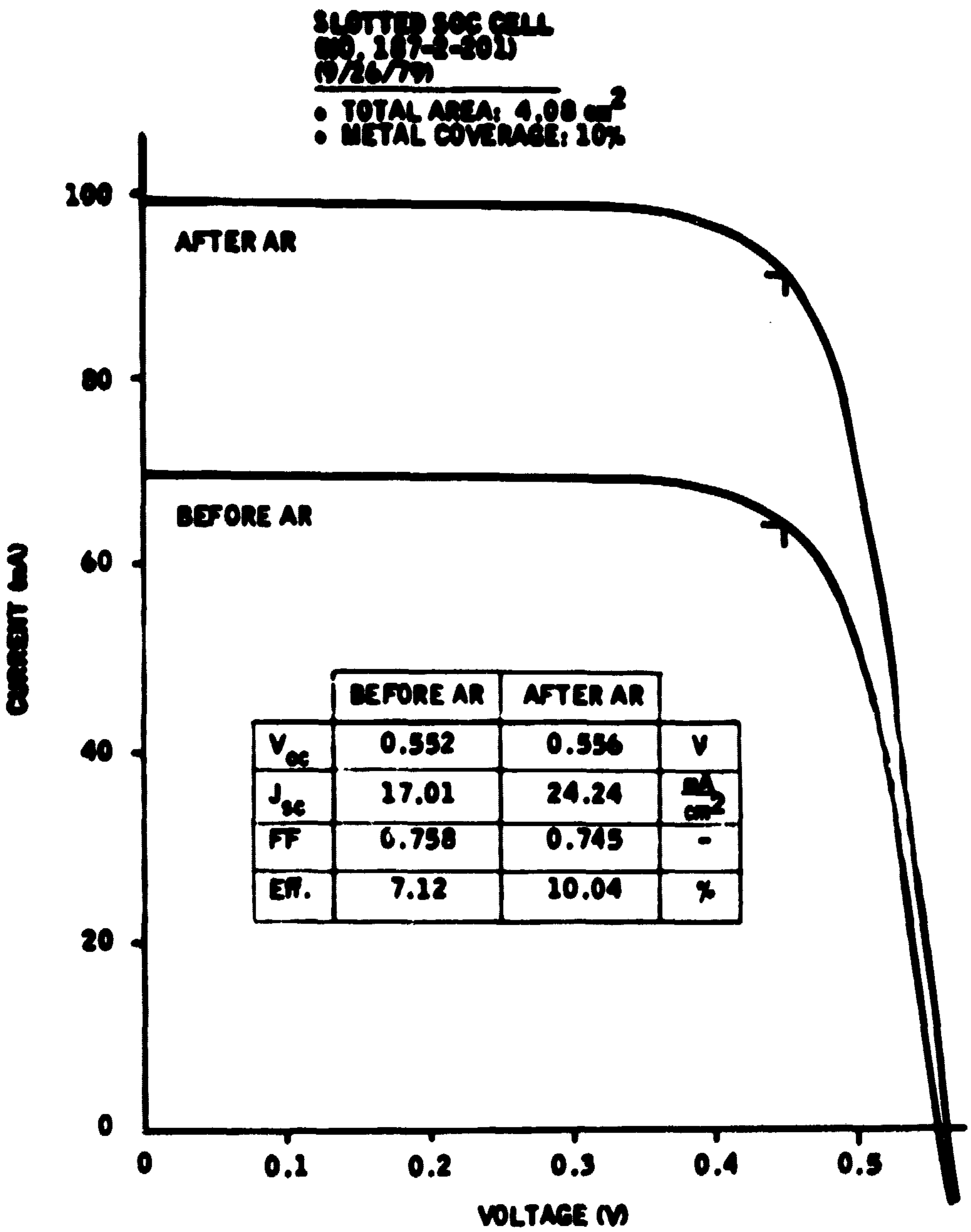
- DEMONSTRATE GROWTH SPEEDS OF 0.3 CM/SEC
  PRODUCE MATERIAL AT 0.2 CM/SEC FOR CELL FABRICATION
- DEMONSTRATE 11% CONVERSION EFFICIENCY ON 10 CM^2 CELLS
- DEMONSTRATE CONTINUOUS COATING OF LARGE-AREA SUBSTRATES
  (HONEYWELL FUNDED FROM 2/79 - 12/79)
- DETERMINE RELATIVE IMPORTANCE OF IMPURITIES VS.
  STRUCTURE ON SOC CELL PERFORMANCE.



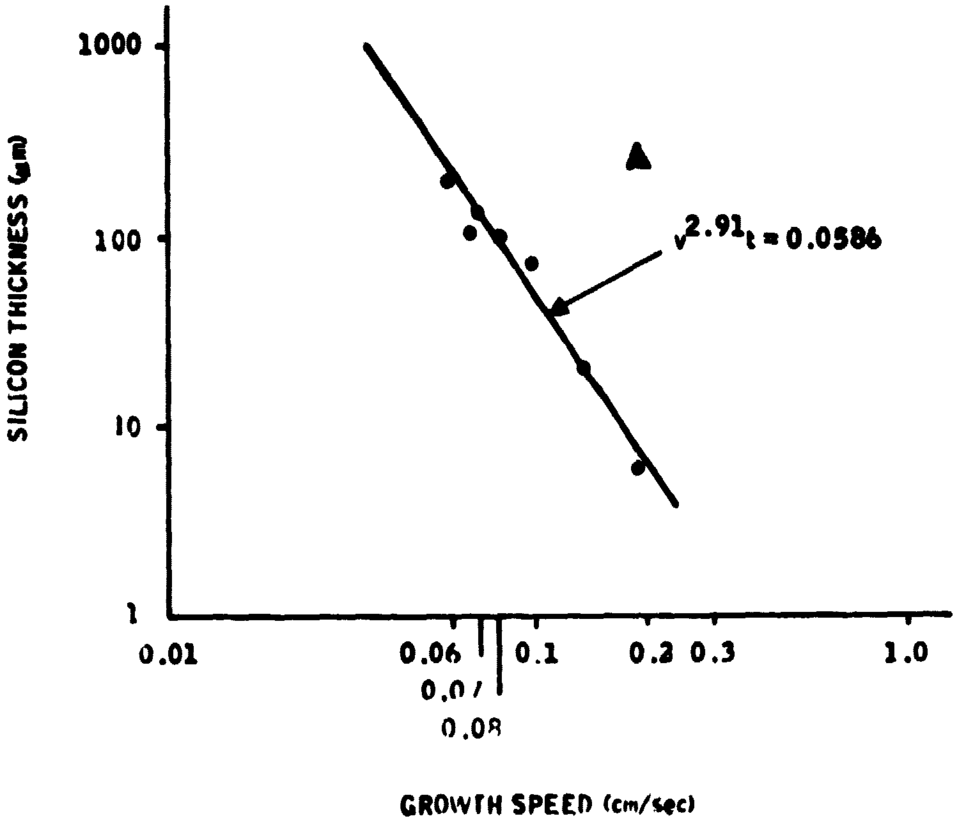


Meniscus Shape at Various Coating Angles

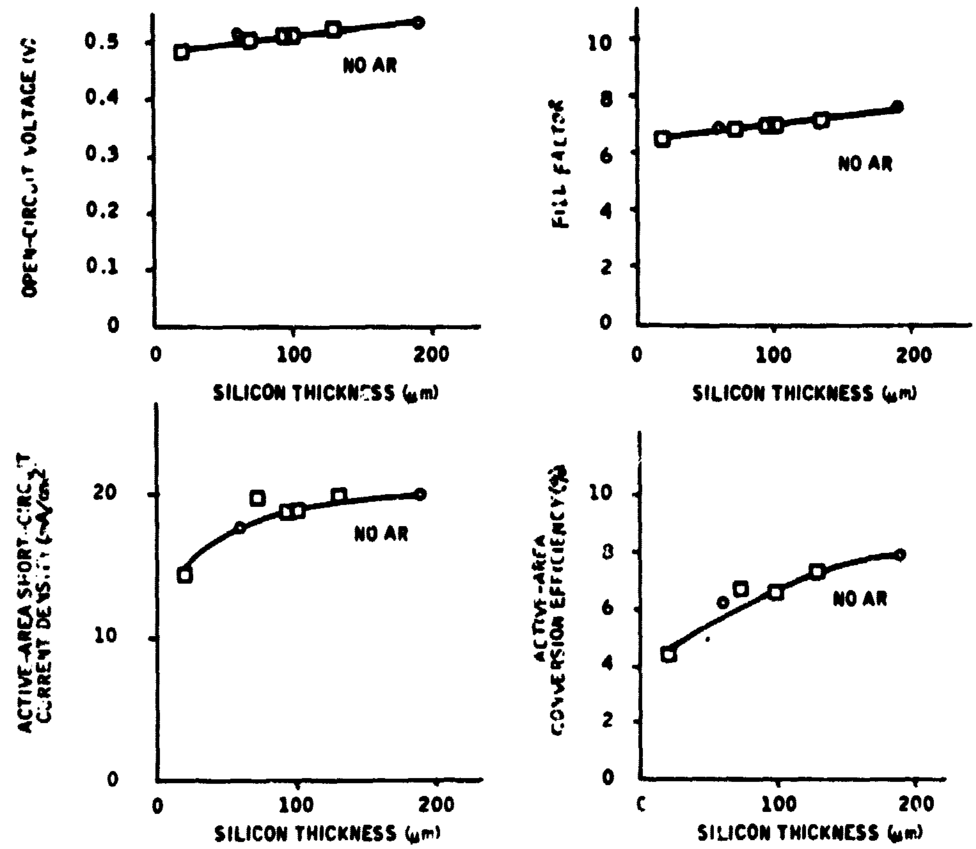




	BEFORE AR	AFTER AR	
V_{oc}	0.552	0.556	V
J_{sc}	17.01	24.24	$\frac{mA}{cm^2}$
FF	0.758	0.745	-
Eff.	7.12	10.04	%



SILICON THICKNESS (μm)
1000
100
10
1
$v^{2.91}t = 0.0586$
0.01
0.06
0.07
0.08
0.1
0.2
0.3
1.0
GROWTH SPEED (cm/sec)



OPEN-CIRCUIT VOLTAGE (V)
NO AR
SILICON THICKNESS (μm)
FILL FACTOR
NO AR
SILICON THICKNESS (μm)
ACTIVE-AREA SHORT-CIRCUIT CURRENT DENSITY (mA/cm²)
NO AR
SILICON THICKNESS (μm)
ACTIVE-AREA CONVERSION EFFICIENCY (%)
NO AR
SILICON THICKNESS (μm)

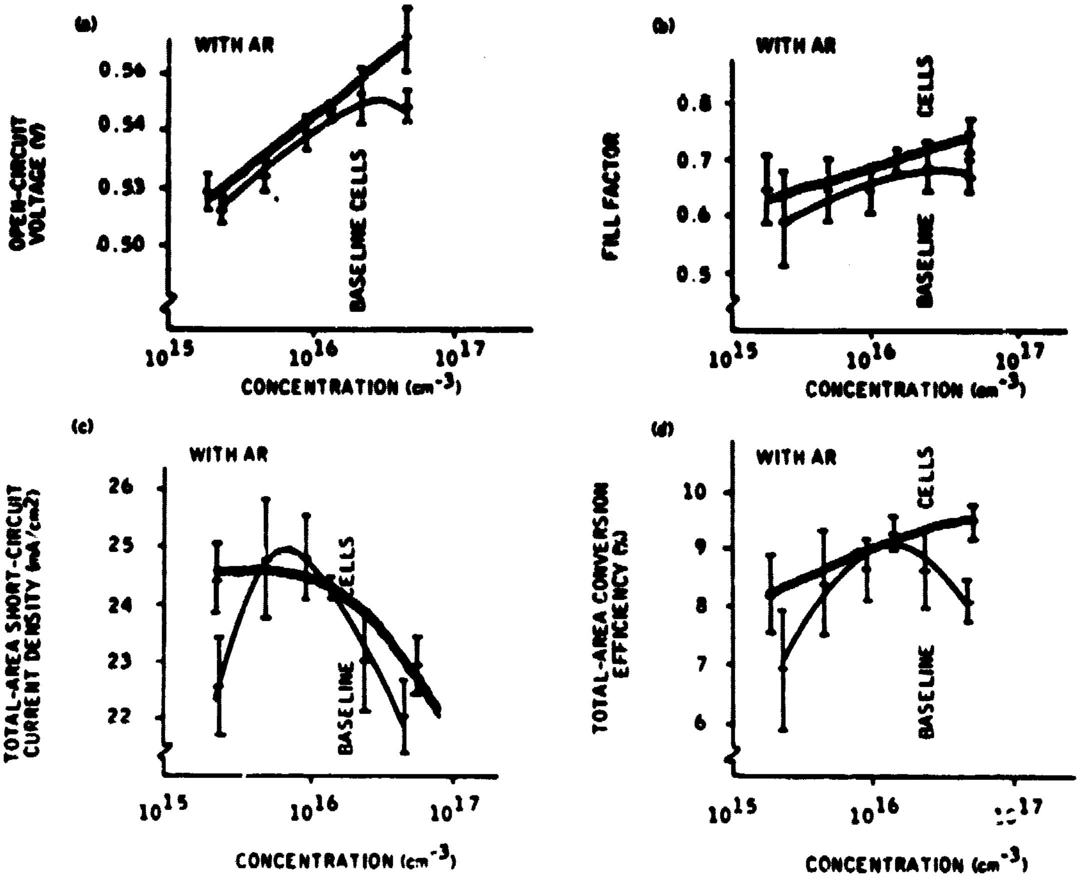
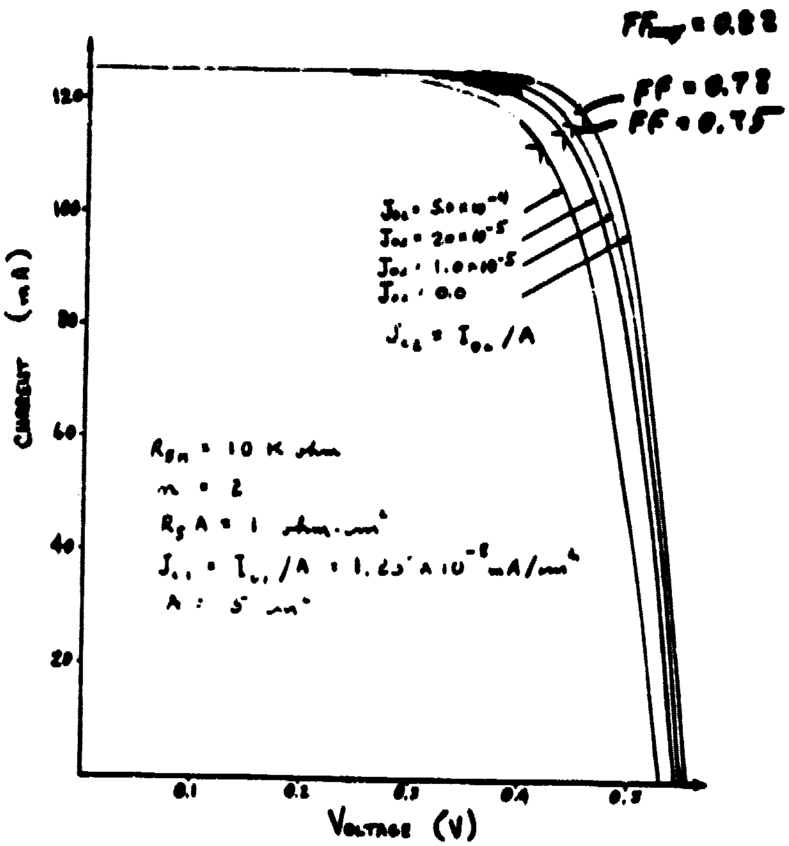
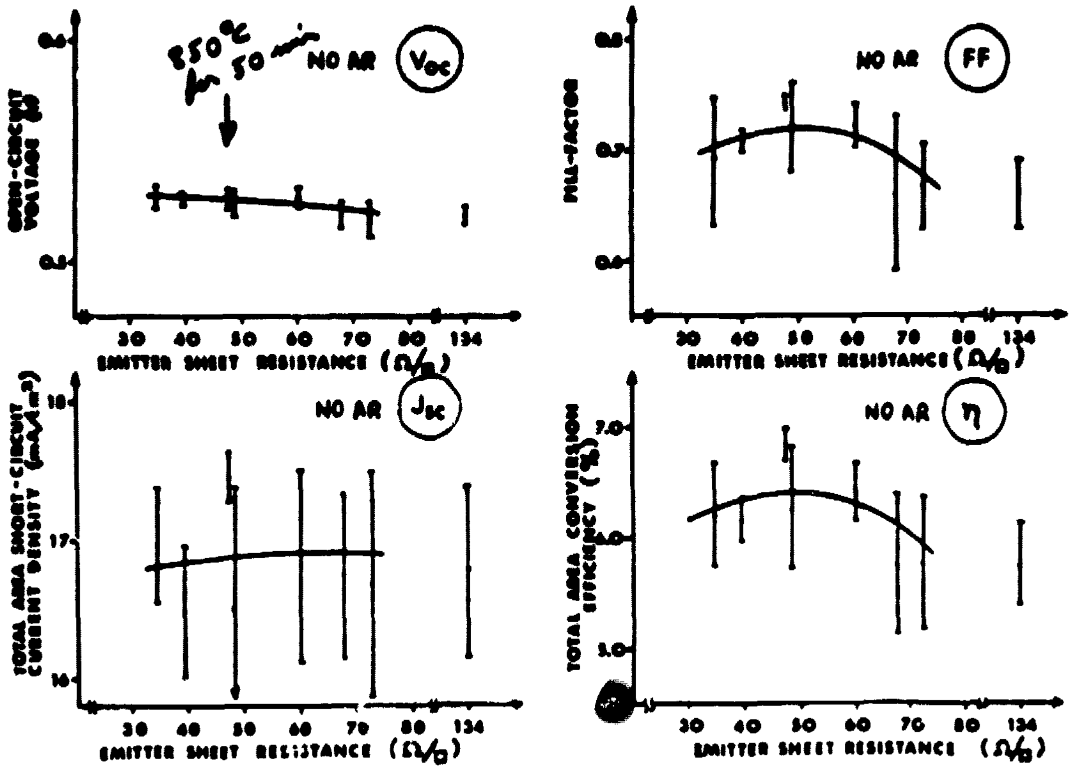
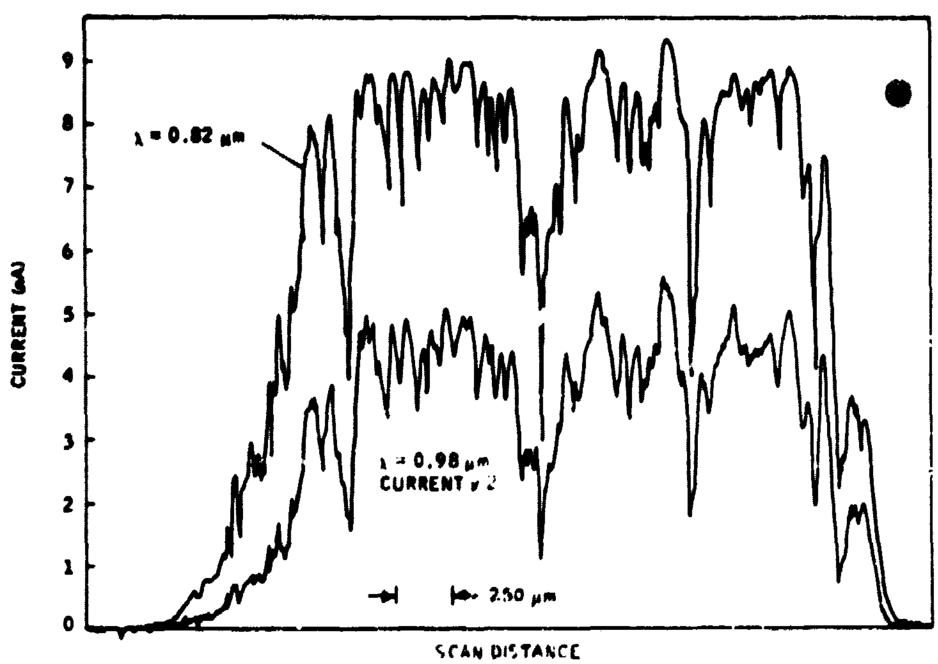


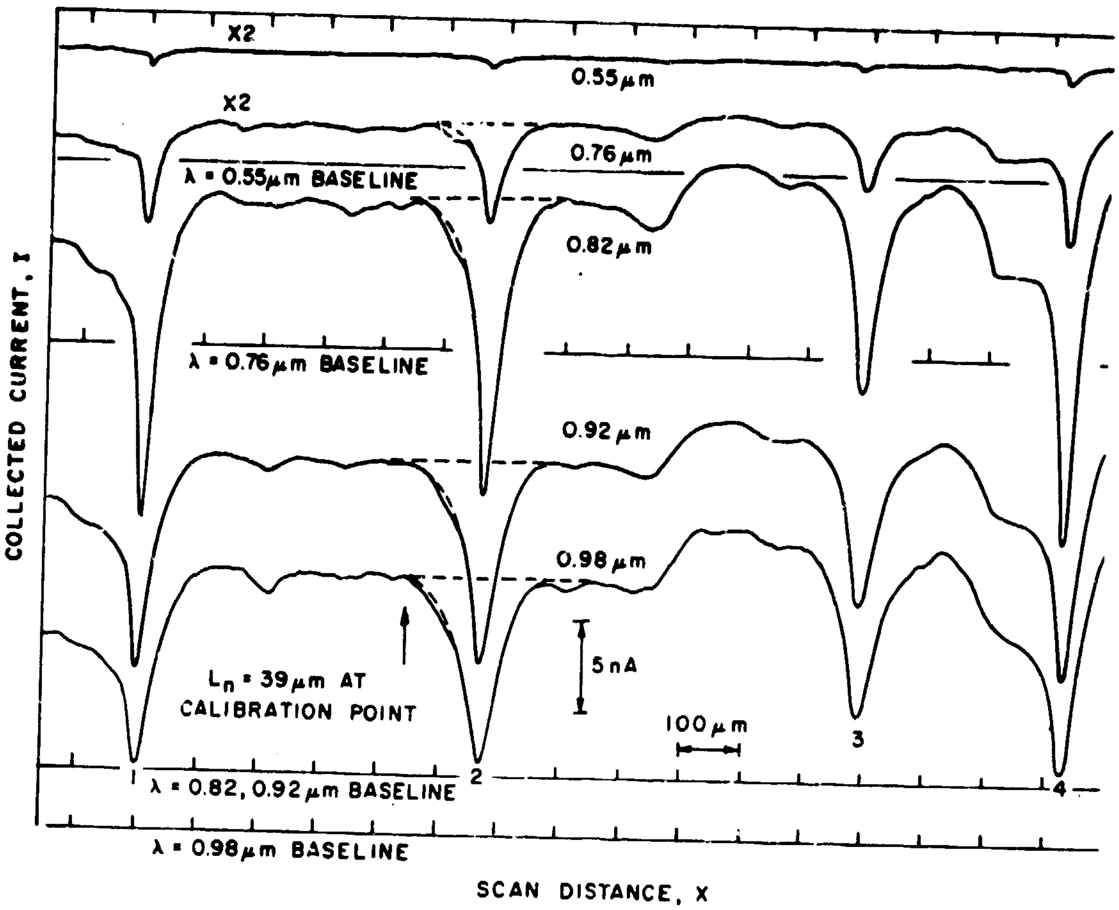
Figure 8. Performance of Slotted SOC Cells as a Function of Base Doping Concentration, for Cells with AR Coating

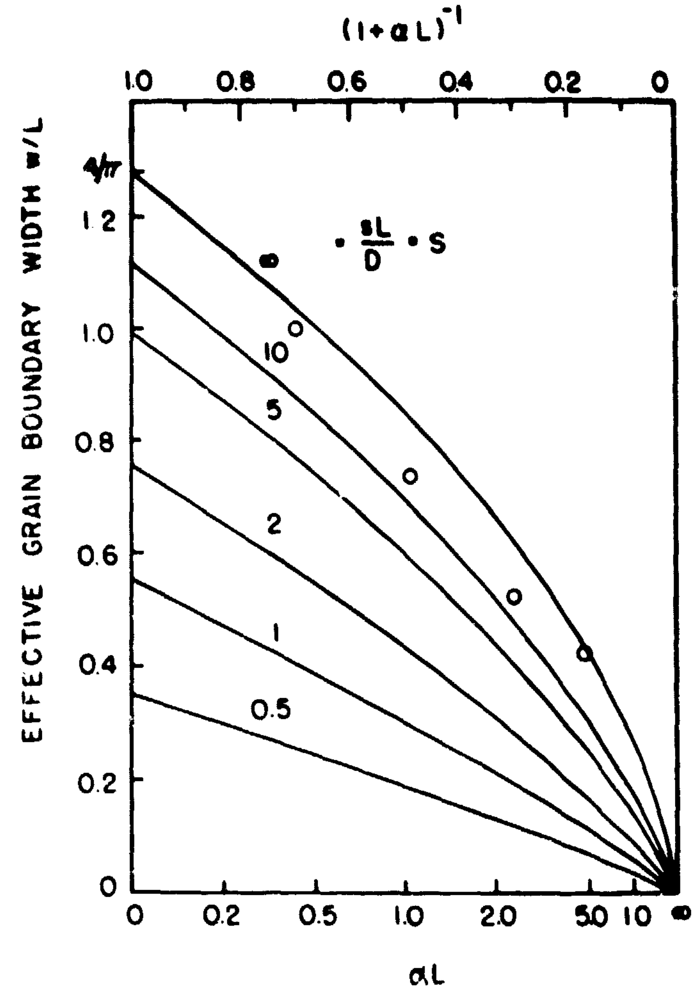
$$I = -I_{01}\left[\exp\frac{q(V-IR_s)}{kT}-1\right] - I_{02}\left[\exp\frac{q(V-IR_s)}{nkT}-1\right] - \frac{V-IR_s}{R_{sh}} + I_{sc}$$




850°C for 50 min
NO AR
Voc
OPEN-CIRCUIT VOLTAGE
FF
FILL-FACTOR
Jsc
TOTAL AREA SHORT-CIRCUIT CURRENT DENSITY
η
TOTAL AREA CONVERSION EFFICIENCY (%)
EMITTER SHEET RESISTANCE (Ω/□)
30 40 50 60 70 80 134


λ = 0.82 μm
λ = 0.98 μm
CURRENT × 2
250 μm
CURRENT (nA)
SCAN DISTANCE


X2
0.55 μm
X2
0.76 μm
λ = 0.55 μm BASELINE
0.82 μm
λ = 0.76 μm BASELINE
0.92 μm
0.98 μm
L_n = 39 μm AT
CALIBRATION POINT
5 nA
100 μm
1
2
3
4
λ = 0.82, 0.92 μm BASELINE
λ = 0.98 μm BASELINE
COLLECTED CURRENT, I
SCAN DISTANCE, X



Comparison of Diffusion Lengths Before & After Cell Fabrication

CELL NO.	BEFORE PROCESSING WITHIN GRAIN (μm)	PROCESSED (p-n JUNCTION) WITHIN GRAIN (μm)	PROCESSED (p-n JUNCTION) INTEGRATED SCAN (μm)	J_{sc} (mA/cm^2)
185-1-102	27.1			18.2
185-5-202	26.6	58.6	30.3	17.9
185-17-102	14.5	38.9	24.6	17.6
185-20-102	12.2	28.2	22.6	17.2

Summary

GOAL	STATUS
0.2-0.3 CM/SEC GROWTH SPEED	200μm THICK AT 0.2 CM/SEC WITH HELIUM COOLING
11% CELL EFFICIENCY	9.91% ON 10 cm^2 CELL 10.04% ON 4 cm^2 CELLS
CONTINUOUS COATING	SCIM PRINCIPLE DEMONSTRATED NEW COATER DESIGN COMPLETE - CONSTRUCTION UNDERWAY

QUANTITATIVE ANALYSIS OF DEFECTS IN SILICON

MATERIALS RESEARCH, INC.

During the reporting period, the Quantimet 720 Image Analyzer (QTM 720) was upgraded to enhance its capability for the automated defect analysis of silicon sheet samples. Also, during this period sixty silicon samples were analyzed using the upgraded QTM 720 System.

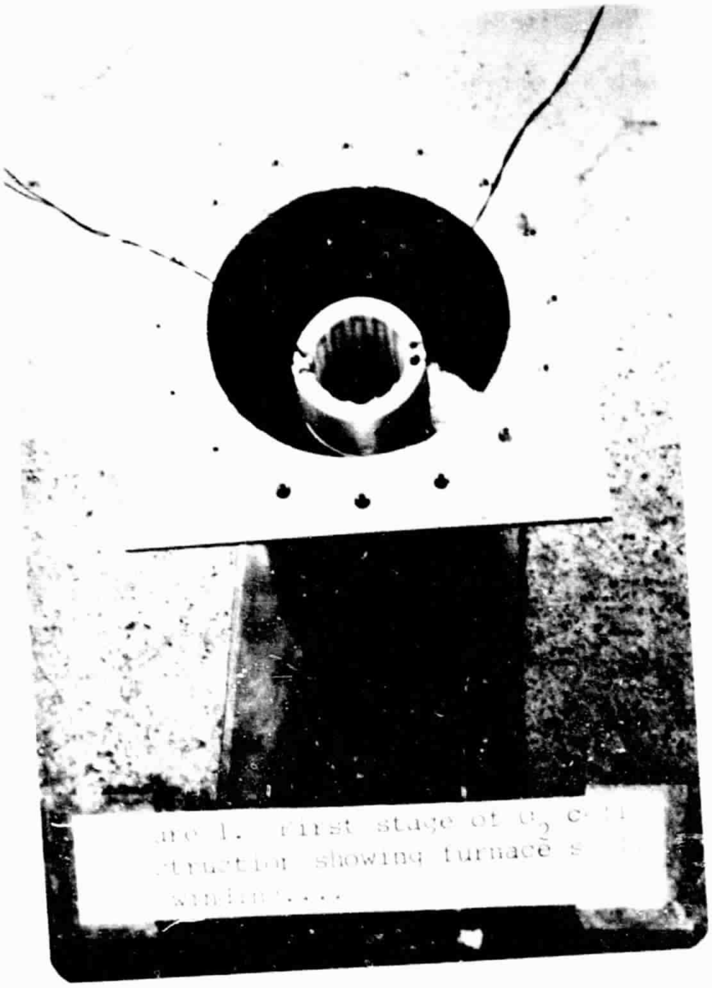
The previous QTM 720 System made use of a Hewlett-Packard Model 9810 Programmable Calculator interfaced to the system by means of a special QTM module, the Field Data Interface. The data was printed on a conventional teletype. In the present configuration, the H-P 9810 Calculator has been replaced by a PDP-11/03 Computer and the teletype replaced with a Digital Equipment Corporation Deckwriter III high speed printer. A dual floppy disk drive has also been added to the QTM 720 System. These new additions have substantially improved the data acquisition and analysis capability of the QTM, as well as increasing the speed with which the silicon samples may be analyzed.

A computer program was written for the PDP 11/03 computer to provide for software control of many of the QTM functions and automated analysis of silicon samples.

After chemical polishing and etching, sixty silicon sheet samples were analyzed for twin boundaries and dislocation pits on the upgraded QTM 720 System. Thirtytwo of these samples were manufactured by Motorola, twentyseven by Mobil-Tyco, and one by Tylan. The twin boundary and dislocation pit densities for these samples are listed as computer printouts in the technical reports: MRI - 272, - 273, and - 274. Grainboundary length measurements were made on these samples by optical microscopy technique. These data and a preliminary analysis of data are also included in the aforementioned reports. All samples have been returned to JPL for solar-cell fabrication. Conversion efficiencies will be measured on these samples and attempt will be made to correlate efficiencies with defect densities in these samples.

EFFECTS OF VARYING PARTIAL PRESSURES OF REACTANT GASES

UNIVERSITY OF MISSOURI ROLLA



…ure 2. With alumina end cap.

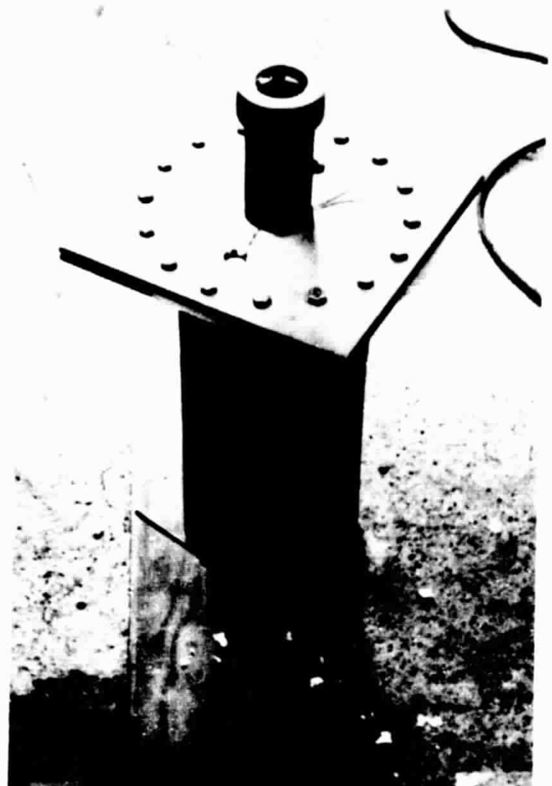


Figure 3. And end flange.

Figure 4. Copper tubing permits water flow to cool o-rings in thoria tube assembly.

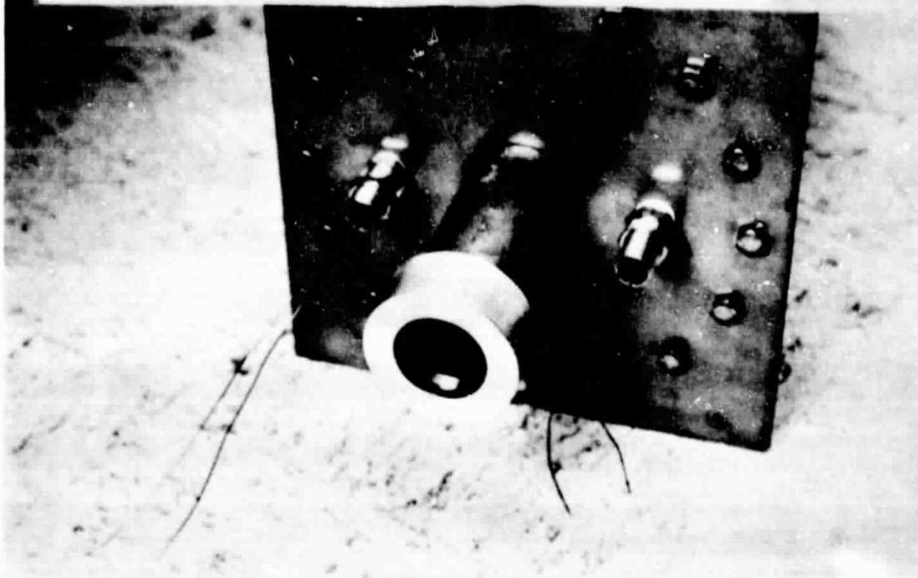


Figure 5. Furnace leads are taken through ports at end opposite thoria tube assembly.

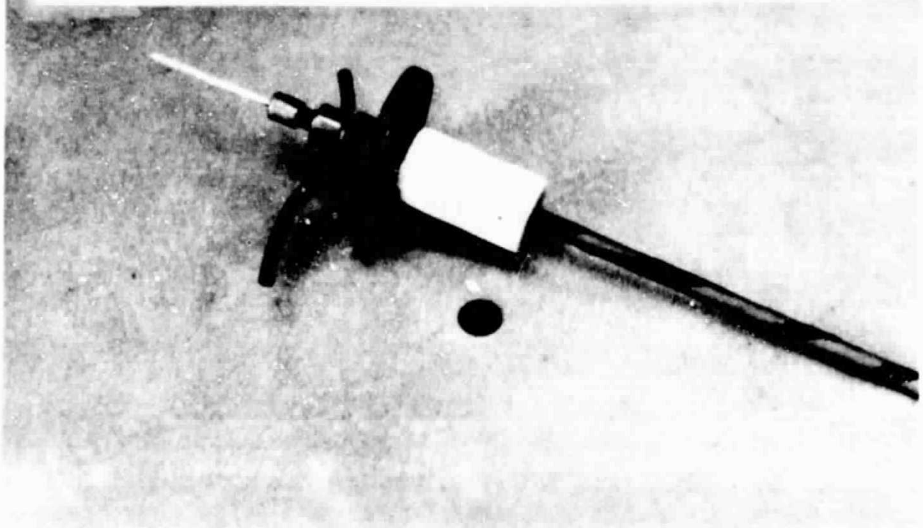


Figure 6. Thoria 7 wt% yttria tube and assembly. Note platinum wire-paste leads (painted along a helix) and alumina heat shield.

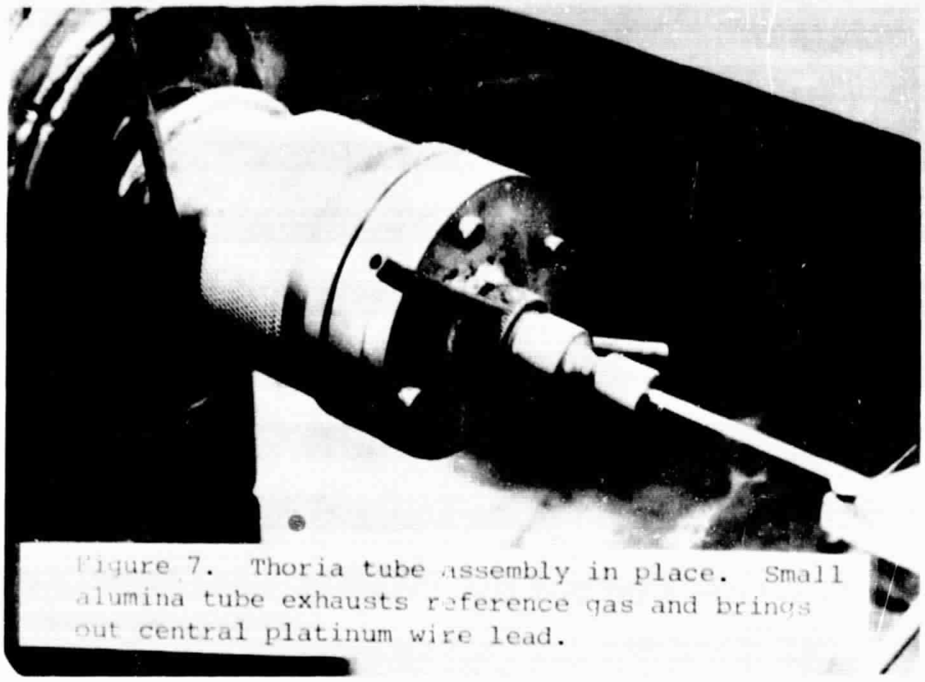


Figure 7. Thoria tube assembly in place. Small alumina tube exhausts reference gas and brings out central platinum wire lead.

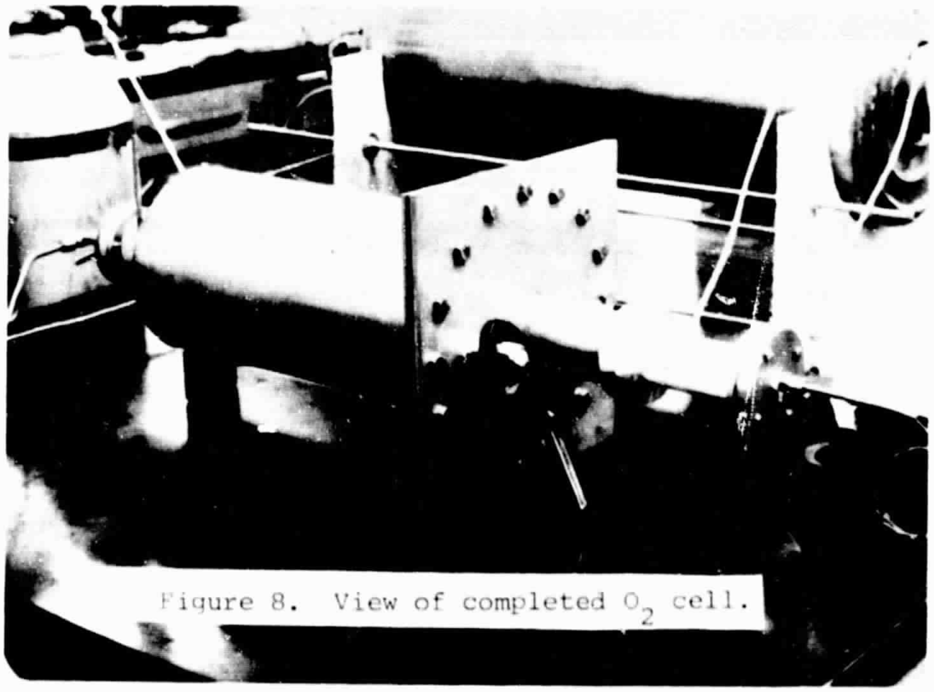


Figure 8. View of completed O_2 cell.

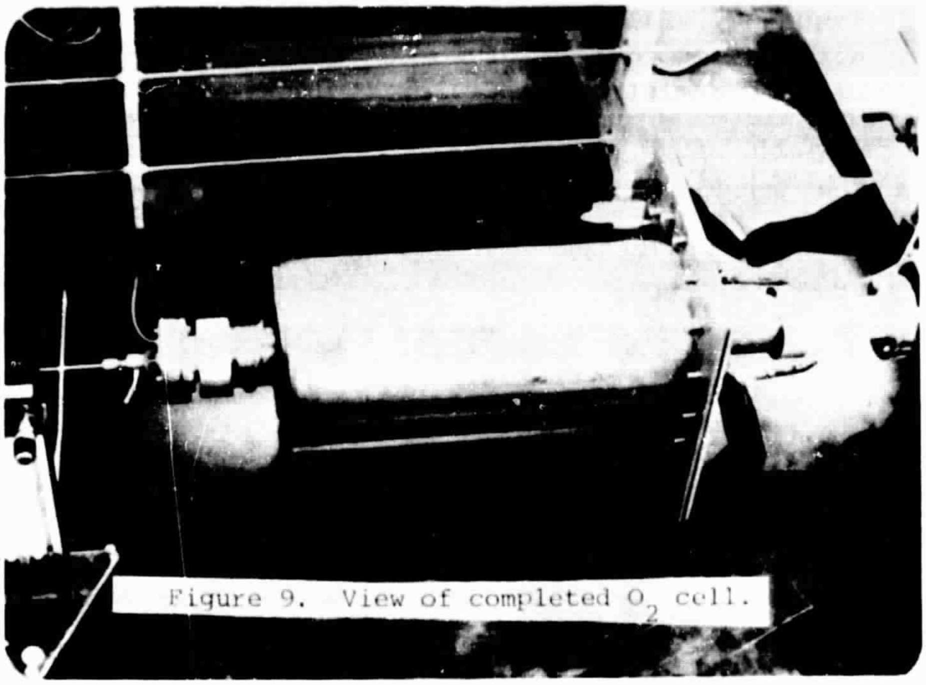


Figure 9. View of completed O_2 cell.

Figure 1. Silicon on fused silica at about 1400° in CO/CO_2 buffer at $P_{O_2} \approx 10^{-14}$ atm. Silica has already become deformed, indicative of devitrification (t=0).

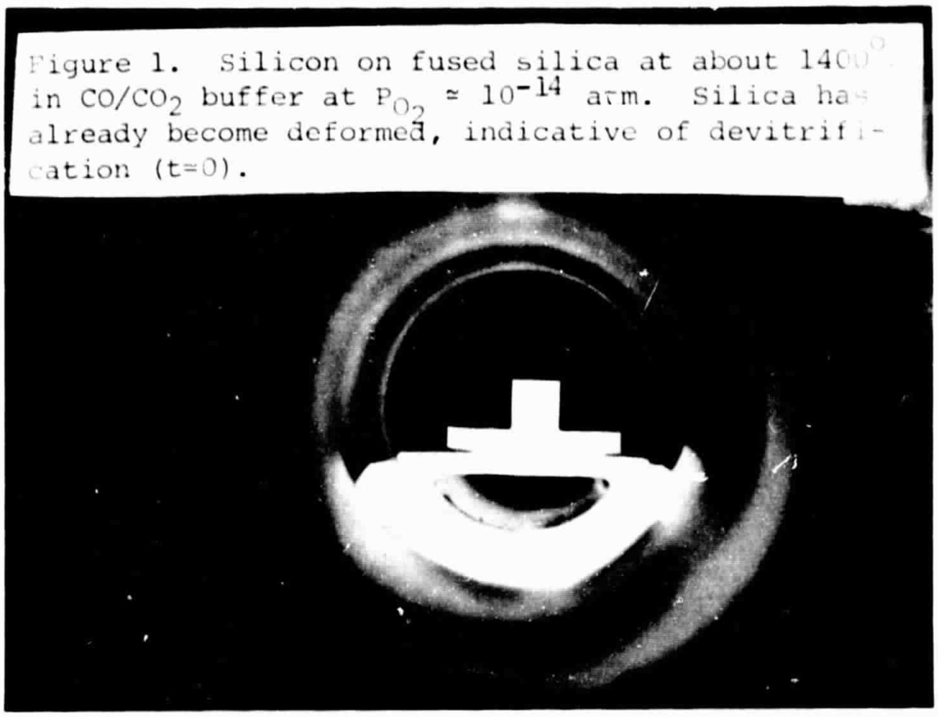


Figure 2. Silicon begins reacting (presumably with oxygen content of CO/CO_2 buffer gas) to produce a mist of particles (t=16 minutes).

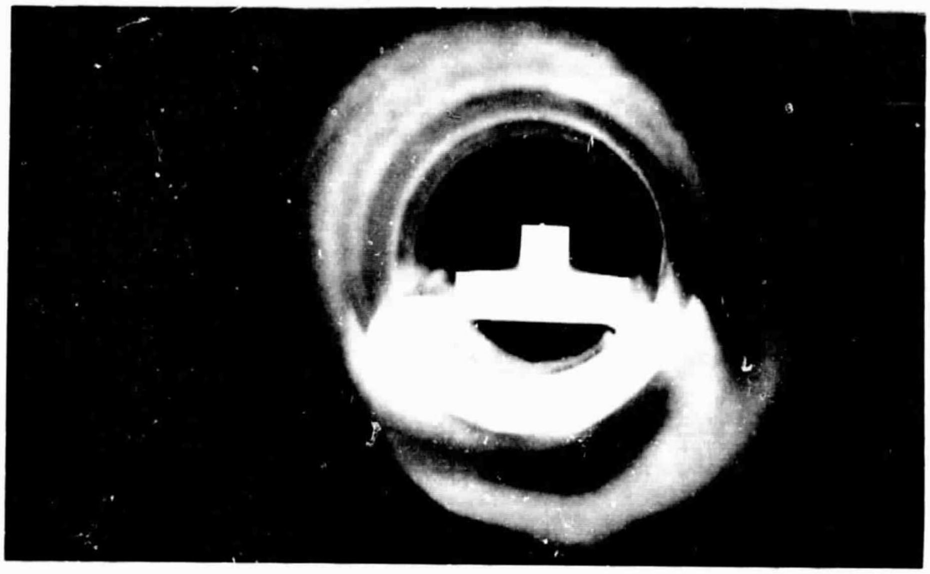


Figure 3. Silicon reaction continues. Silicon surface becomes pitted (t=22 minutes).

Figure 4. Well above silicon melting point (about 1430^{o}C). Silicon surface shows pronounced pitting and build-up of oxides has begun. Tendrils of particulates being carried in the buffer gas can be seen by the furnace wall (t=53 minutes).

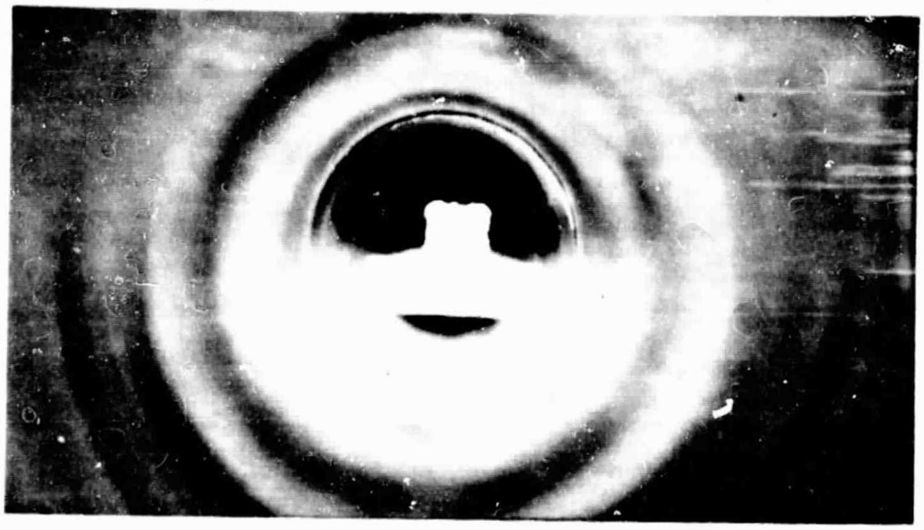


Figure 5. Much build-up of oxide on surfaces of silicon and fused silica. Particulates in gas stream still visible (t=90 minutes).

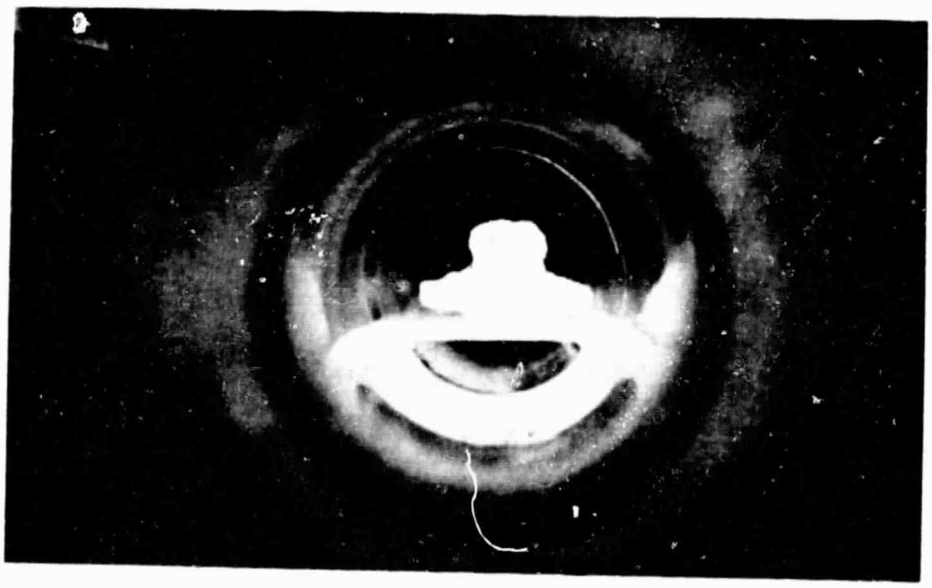


Figure 6. Silicon reaction has terminated (t=105 minutes).

Figure 7. Edge view of sample after annealing.

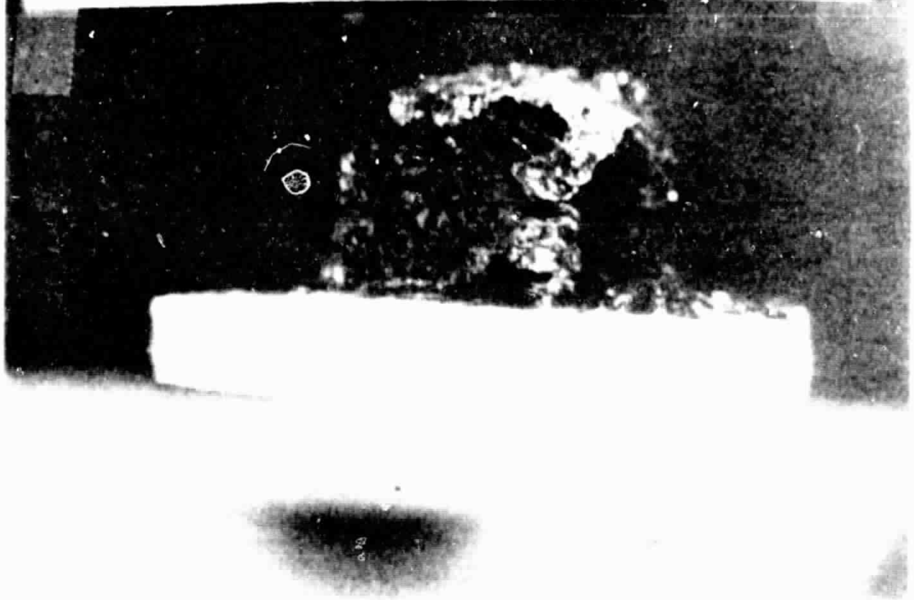


Figure 8. Top view of sample after annealing.

Figure 9. Bottom view of sample after annealing.

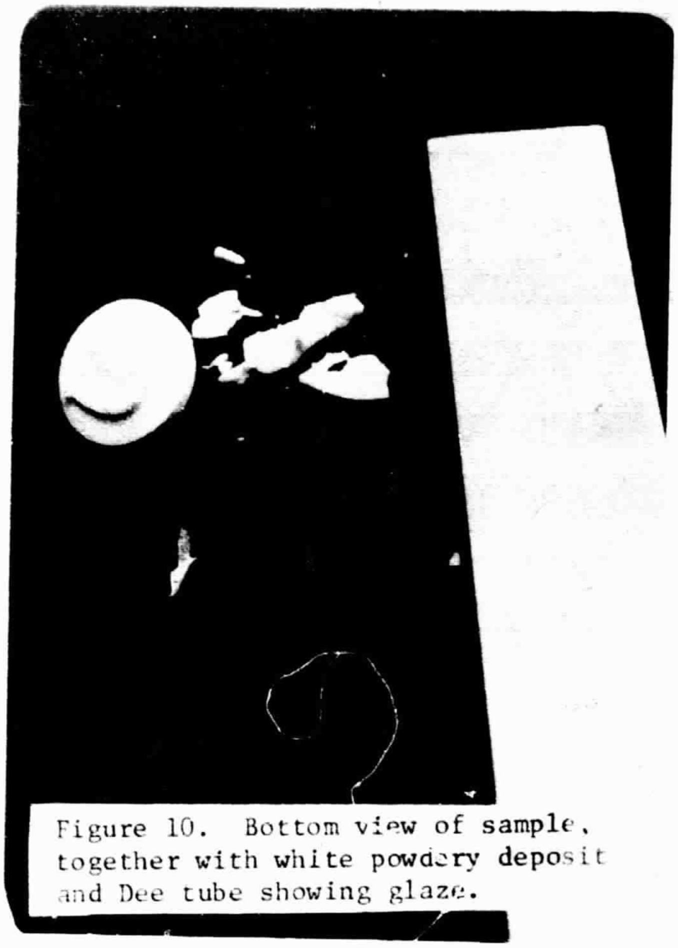


Figure 10. Bottom view of sample, together with white powdery deposit and Dee tube showing glaze.

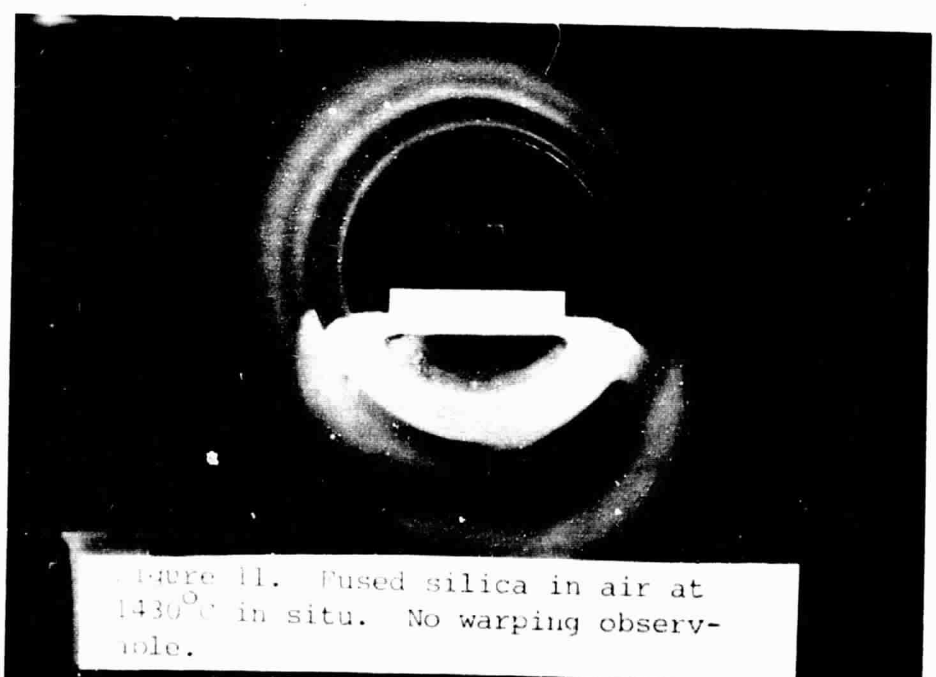


Figure 11. Fused silica in air at 1430°C in situ. No warping observable.

Figure 12. Fused silica after annealing in air at 1430°C for 1 hour. Surface devitrification only.

[illegible] 13. "Before" and "After" annealing fused [illegible] in air at 14[illegible]°C for 1 hour.

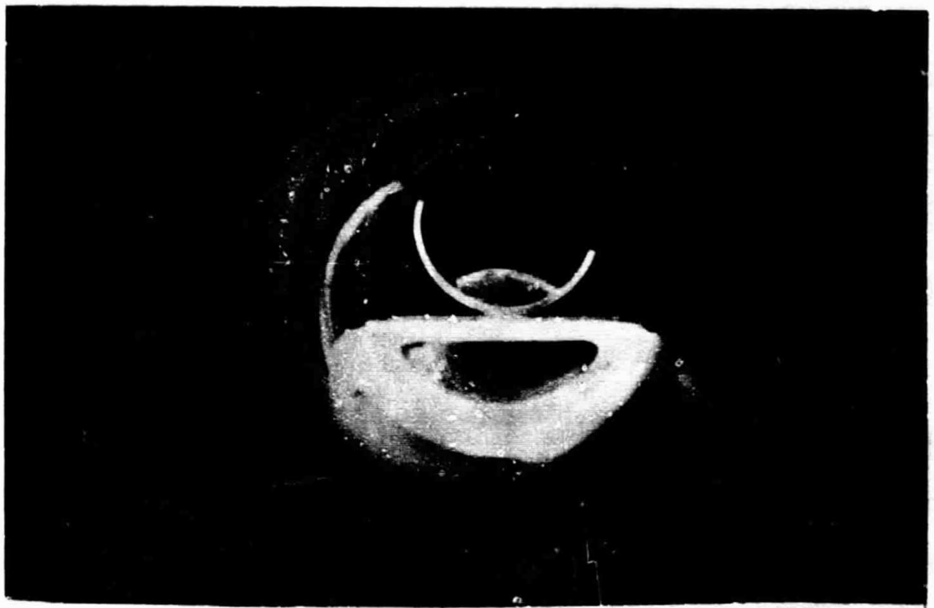


Figure 14. Fused silica in helium at 1430°C in situ. No warping observable.

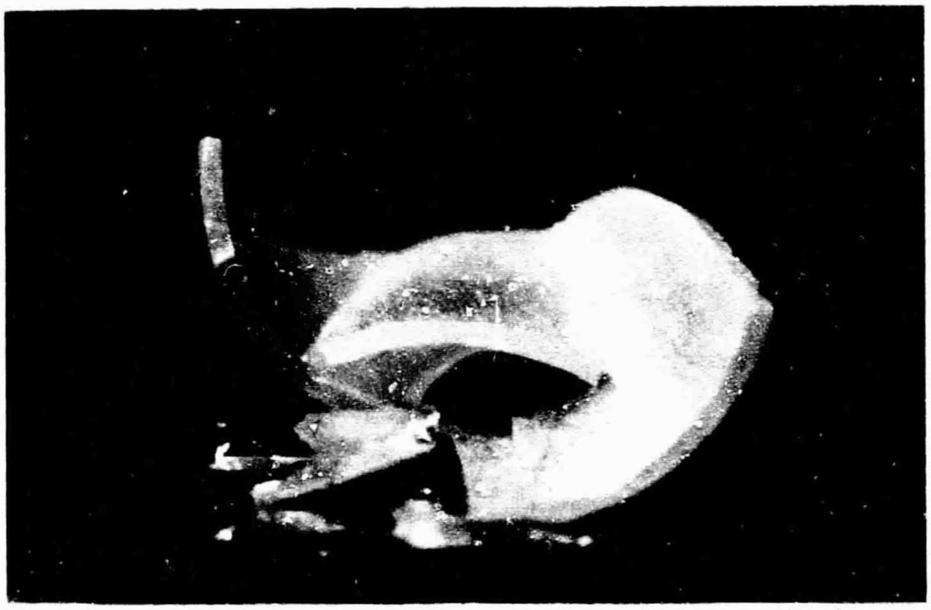


Figure 15. Fused silica after annealing in helium for one hour at 1430°C.

COMPARISON OF P_{O_2} MEASUREMENTS OVER MOLTEN SILICON BETWEEN EQUILIBRATED SESSILE DROP AND NON-EQUILIBRATED EFG RIBBON ATMOSPHERES.

Summary

I. SILICON SESSILE DROP EXPERIMENTS AT UMR ARE GENERALLY CARRIED OUT AT OXYGEN PARTIAL PRESSURES BELOW 10^{-18} ATM. (BELOW THE EQUILIBRIUM PRESSURE FOR FORMATION OF SiO_2). OXYGEN PARTIAL PRESSURE IN THE MOBIL-TYCO SILICON RIBBON PULLING FURNACE WAS MEASURED BY THE UMR OXYGEN CELL TO BE BETWEEN 10^{-6} AND 10^{-8} ATM., YET NO GROSS OXIDATION OF THE SILICON IS OBSERVED.

II. AS AN ILLUSTRATION OF WHAT OCCURS UNDER EQUILIBRIUM CONDITIONS ABOVE 10^{-18} ATM., A SILICON SESSILE DROP EXPERIMENT WAS PERFORMED AT P_{O_2} OF 1.5×10^{-12} ATM. USING A CO/CO_2 BUFFER GAS. THE EXTREME REACTION WITH THE SILICON WAS DOCUMENTED.

III. IT WAS CONCLUDED THAT THE ATMOSPHERE IN THE MOBIL-TYCO FURNACE WAS NOT IN EQUILIBRIUM WITH THE MOLTEN SILICON, AND THAT THE HIGH OXYGEN CONTENT WAS DUE TO THE HIGH AMOUNTS OF OXYGEN IN THE ARGON PURGE GAS AND TO AIR LEAKAGE INTO THE FURNACE.

IV. DEVITRIFICATION OF FUSED SILICA OBSERVED IN ALL EXPERIMENTS IN THE SESSILE DROP FURNACE INCREASED AT LOWER P_{O_2}'S. THE SLOW HEATING RATES CHARACTERISTIC OF THIS FURNACE PRECLUDE OBTAINING MEANINGFUL CONTACT ANGLE DATA ON FUSED SILICA.

EVALUATION OF LAS MATERIAL

CORNELL UNIVERSITY

D. Ast

Techniques

Structural:

1) Optical Microscopy + Etching
2) X-ray, all conventional techniques + synchrotron radiation
3) SEM
4) TEM
   a) Conventional
   b) High resolution
   c) High voltage

Chemical:

1) SIMS
2) Neutron Activation
3) STEM +
   a) X-ray analysis
   b) energy loss spectr.
4) EBIC
5) TEM
   a) Precipitates
   b) Translational shifts in grain boundaries (C?)
6) Hydrogen passivation
7) DLTS

Electrical:

1) Photovoltaic scanning
2) EBIC
3) Anodic Etching
4) DLTS

Available Fall 80: Ion back sputtering (J. Mayer)

Materials analyzed so far

EFG	Mobil Tyco
Large grain EFG	Mobil Tyco
RTR	Motorola

(In addition non JPL sponsored fundamental research on grain boundaries (see Phil. Mag. A, 40 (1979) 589)).

A) <u>EFG</u>, regular and large grain.

Predominant defects: Coherent twins
High resolution shows that optical twin boundaries consists of bundles of microtwins, some of which are only a few (say 4) (111) planes thick.

Less frequent: Incoherent twins on (112) planes
High angle grain boundaries.

No visible precipitates in either regular or large grain EFG. Incoherent twins show translations both parallel and perpendicular to boundary plane, possibly due to local incorporation of carbon. Coherent twins may be electrically unactive, partially active in sections only, or fully active. Possible reasons include: a) Termination of microtwins, b) Interactions with lattice dislocations, c) Twin boundary dislocations, d) Impurities. Passivation with atomic hydrogen tentatively indicates that most (but not all) electrical activity is impurity controlled.

B) <u>RTR</u>

Surface orientations: 110, 113, 135, 012, 001

Essentially twin boundaries perpendicular to surface. Twinned regions vary in size from long microtwins only a few (111) planes thick to large twinned areas. High density ($1...1.2 \times 10^{13}/cm^3$) small precipitates, platelet shape, habit plane generally 100 with edges parallel to 110, typical dimensions 50...100 Å. So far indications for amorphous structure (diffraction, high resolution). Tentatively: Si-nitrides, possibly associated with heavy metals. In addition, low density of nondecorated stacking faults, frequently located close to twin boundaries, of average size of ~ 1.5 µm.

PROCESS DEVELOPMENT

APPLIED SOLAR ENERGY CORP.

Since the last PIM, further evaluation has proceeded on

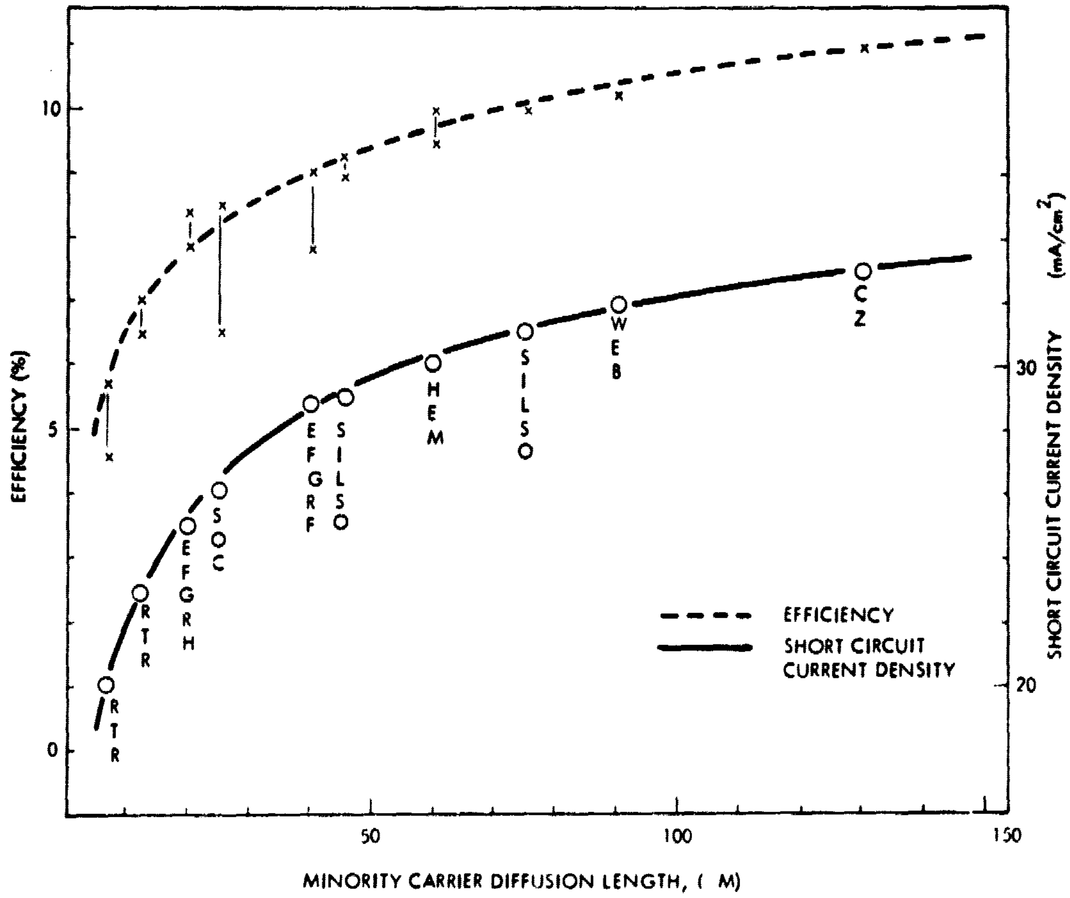
- EFG Ribbon (RH Process) - Mobil-Tyco
- Dendritic Web - Westinghouse
- Continuous Czochralski - Hamco

The photovoltaic performance after standard processing, and the other measured properties, agreed with earlier tests on these materials, and continued to show good internal consistency.

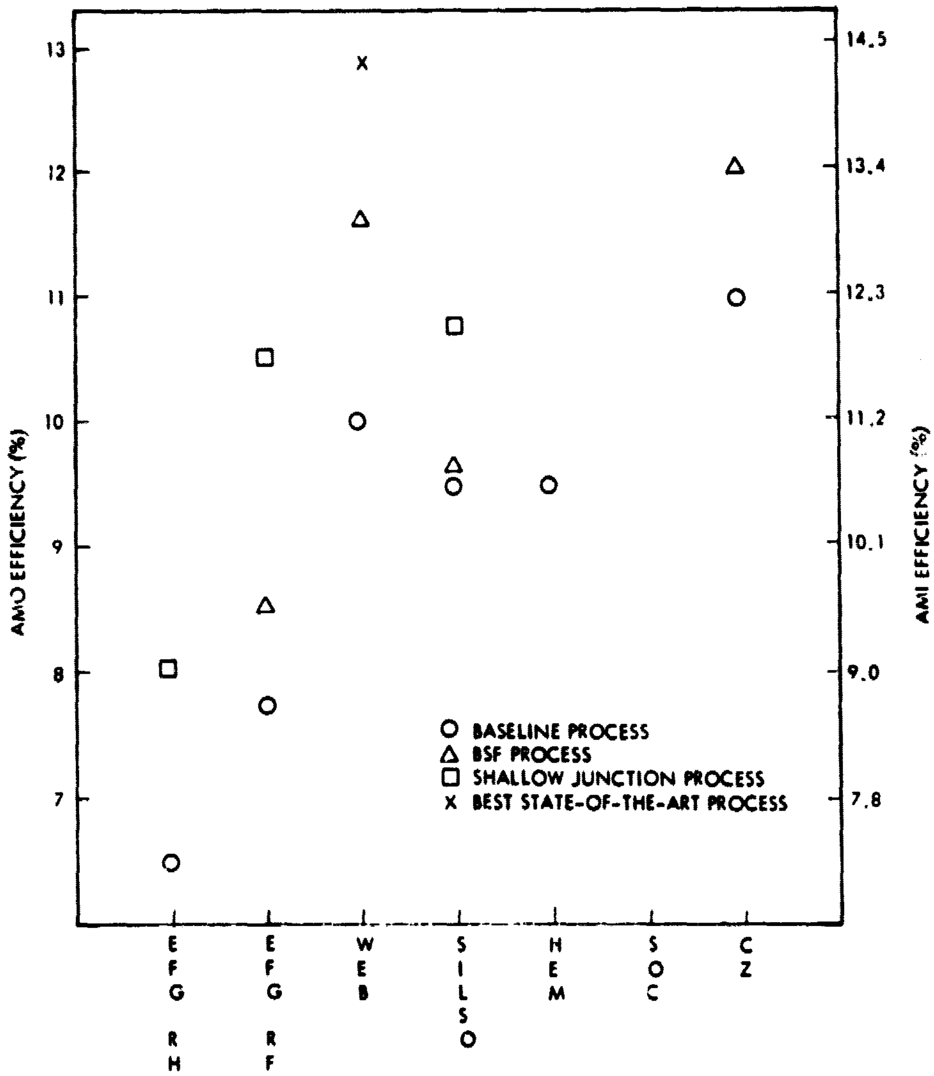
We have extended efforts to increase cell efficiency by using advanced processing with various sheet materials. Process modifications were chosen to offset material limitations identified after standard processing. The advanced processing led to significant increase in output for the ribbon-forms; from the measured properties of the continuous Czochralski slices we can predict advanced process performance approaching that of conventional Czochralski silicon.

We have begun to increase $\frac{AM1}{AM0}$ ratios for various sheets. We are also investigating unexpected problems for low resistivity (2 ohm cm) Czochralski silicon when processed with the aluminum paste BSF method. Severe shunting with decreased cell output was observed. We are studying the effects of background impurities, orientation and deposition of aluminum on the front surface, even through protective masks. Preliminary SIMS analysis showed Al penetration at the front surface,
The analysis also confirmed the Al depth profile on the back surface.

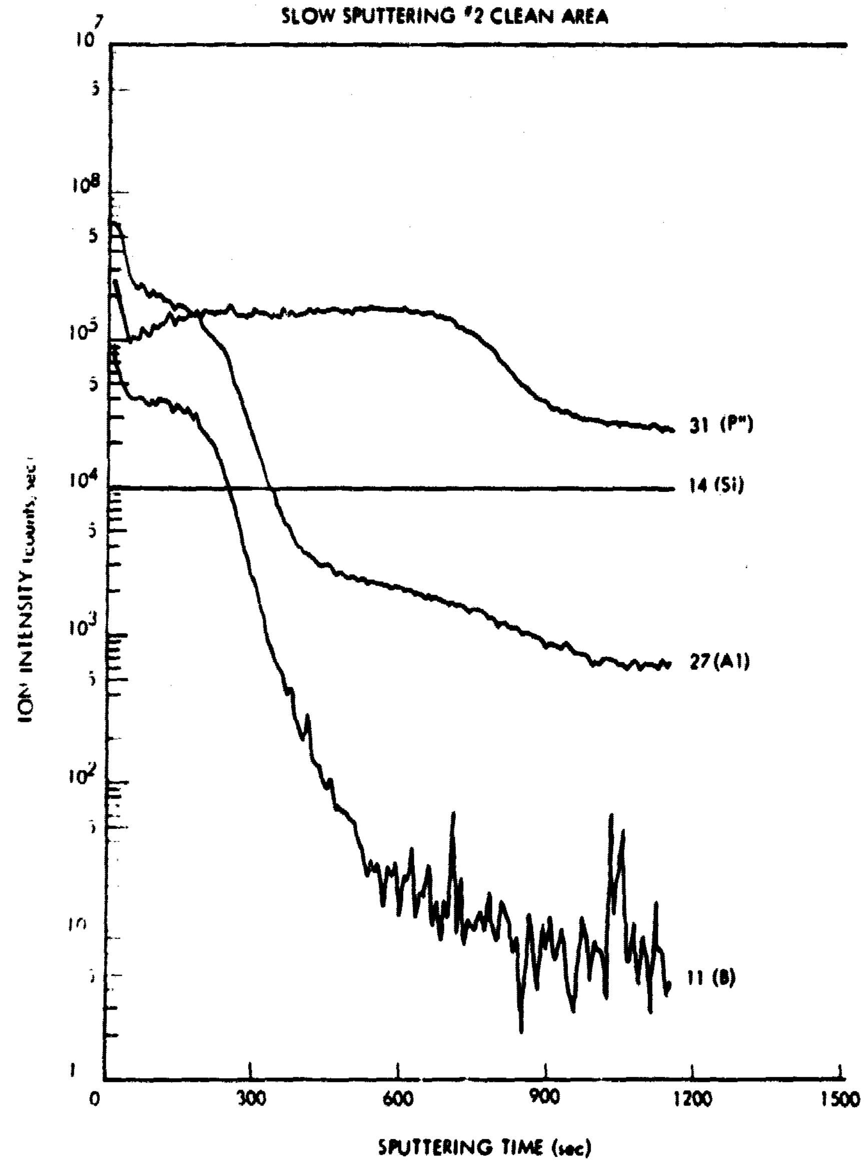
Efficiency & I_{sc} Density vs Minority Carrier Diffusion Length of Unconventional Si Sheets



Average AMO Efficiency of Cells From Various Sheet Silicon



Processed Data: Depth Profile



General Comments

Overall, the work so far has shown good correlation between standard-processed cell performance and the diffusion length, and good agreement for separate samples of various sheets. Also all the backup measurements (dark diode characteristics, spectral response, fine light spot scanning) confirmed the PV results.

The array of measurements used was chosen to verify the PV results, and to increase the confidence level of the sheet suppliers. These confidence levels are now well established, and it has been stimulating to observe first hand the technical progress achieved for all the sheet forms. The evaluation groups have tried to explore the best potential for all sheets, and to identify possible areas for improvement, in terms of controllable sheet properties.

JPL has extended the evaluation programs in two directions to reduce the dollar-per-watt ratio. Efforts are included to increase output (without equivalent cost increase), and also lower cost processes are being tested for their applicability. Understanding of the interaction of the sheet Si properties and various cell process methods is essential to combination in a mechanized operation to meet the 1982 cost goals. (This is the last PIM for the '70's, only 3 years away from the 1982 target date).

Thus the program appears to be moving steadily towards the goals. Recently our complacency was shaken slightly, forcing re-evaluation of several factors which we had been glossing-over, and we thought discussion of these would interest this group. We realized that the management of solar cell companies in their future planning must already begin to select the most promising sheet form(s). This selection involves the sequence of licensing, technical transfer and equipment purchase, accompanied by planning for a detailed process sequence (partly mechanized) suited to the sheet chosen. It is clear that correct selection may be critical to a company's future, because acquisition of one sheet growth and and processing equipment may not ensure easy transfer to other sheets and processes should these latter prove superior.

Therefore, groups familiar with sheet evaluation are already being challenged to consolidate their experience into definite recommendations. One obvious option is to follow the current JPL "Strawman" sequence. However, we thought this integration meeting would be appropriate to share a prejudiced list of some of the factors we found important.

1. Consistency of Performance and Properties

   For manufacturing this must be rated high. As the volume of production rises, an inconsistent process can prevent anticipated cost-reduction, and can generate large quantities of scrap. There is decreasing chance of adjusting to changing properties when operating under cost restraints. Inconsistency of ribbons can reduce advantages such as the chance of continuous processing or of regular size samples.

2. Efficiency

   For routine processing with reasonable costs, higher efficiency is preferable to reduce cost of handling, of support structures or land use, and to reduce the energy payback period. Any increase in process costs needed to increase efficiency must be carefully evaluated. Some enhancement methods (e.g. surface treatment, pulse heating, GB passivation, gettering, BSF, texturing) may not be applicable to all sheets. As the sheets become thinner, present technology requires an effective BSF to maintain efficiency.

3. Adaptability to Low Cost Processing and Methods

   a.) Squares (cast) or rectangles have ~15% advantage over round slices in arrays, for considerations like output area, land useage support, etc., and also have some process advantages from increased packing factor. However, this must be balanced against their efficiency and by the fact that the major silicon industry will continue to develop equipment suited to round slices.

b.) Mechanical strength will be most important for cell and array formation, and in testing, and in ability to accommodate low cost contact processes such as screen printing or plating. The interaction with the contact method will be particularly important, because contacts will remain a major problem for cost and reliability, the latter essential to build-up user-confidence on large scale PV applications.

c.) Improved slicing methods will be applicable to all grown and cast Si. As the costs of starting Si, and of slicing are reduced, ribbon methods lose some of their present advantage in Si useage, and must have comparable all-round properties to remain competitive.

d.) The ready availability of low cost starting Si may not mean that all sheet methods can maintain performance already achieved (depends on the growth conditions).

e.) Support substrates for ribbons may introduce handling problems, additional weight and difficulties in reducing series resistance and in providing good heat transfer.

In conclusion, we cannot present any firm conclusions, but hope we have provided some areas worth remembering. We think that present Czochralski technology can sustain any effort required for high efficiency concentrator cells. We are sure that some novel approaches will be developed in the future, although often, business decisions must be made only on available evidence.

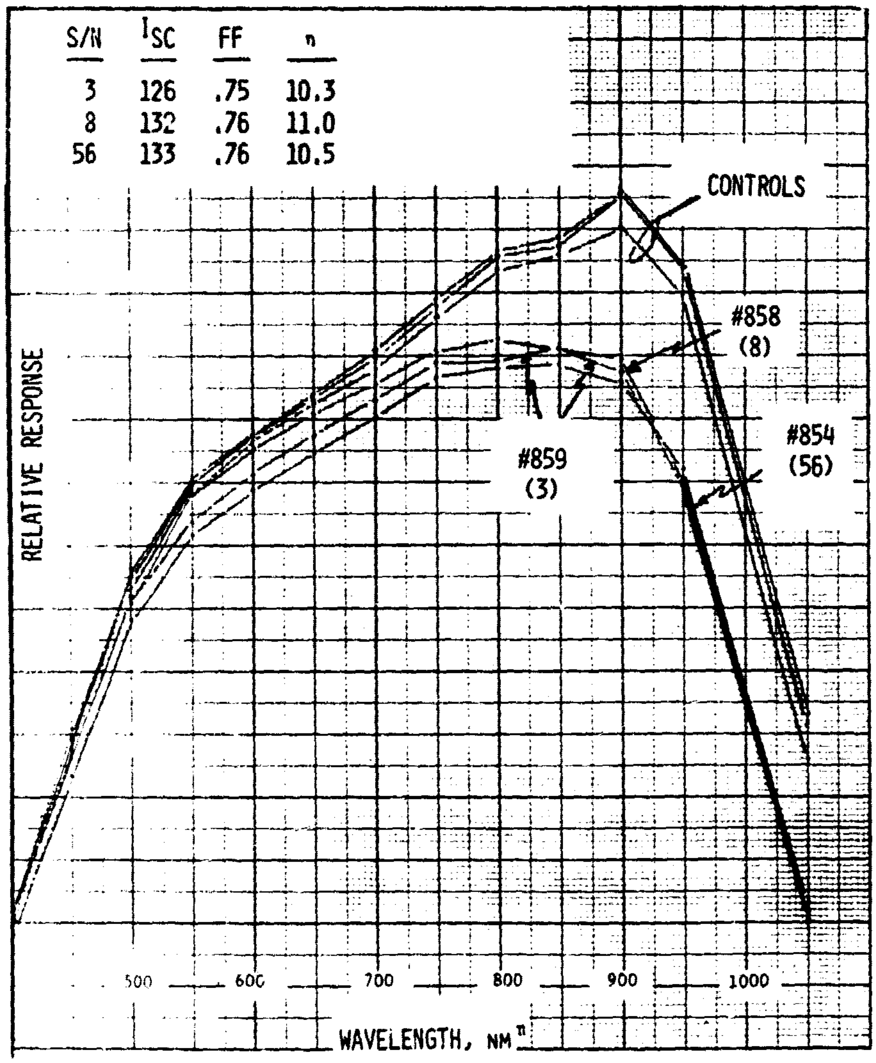
SPECTROLAB

HEM-4, Baseline, AR Film, AM0 28°C

HEM-4, BASELINE, AR FILM
AM0-28°C

Group	N	I_{sc}	V_{oc}	FF	η%	Remarks
#854 Baseline	9	133	564	.76	10.5	Max (η)
ρ = 2.6 Ω cm		134	551	.66	9.1	Average
		2.1	26.2	.10	1.6	S
		6	83	.30	5.0	Range
#858	9	132	592	.76	11.0	Max.
ρ = .7 Ω cm		129	585	.71	10.0	Average
		2.0	12.6	.09	1.4	S
		5	39	.27	4.3	Range
#859	7	126	591	.75	10.3	Max.
ρ = .7 Ω cm		127	581	.67	9.2	Average
		2.8	12.0	.07	1.1	S
		8	36	.22	3.3	Range
Controls	8	142	587	.78	12.0	Max.
ρ = 1-3 Ω cm		143	583	.74	11.4	Average
		.74	4.5	.05	.81	S
		2	13	.14	2.3	Range

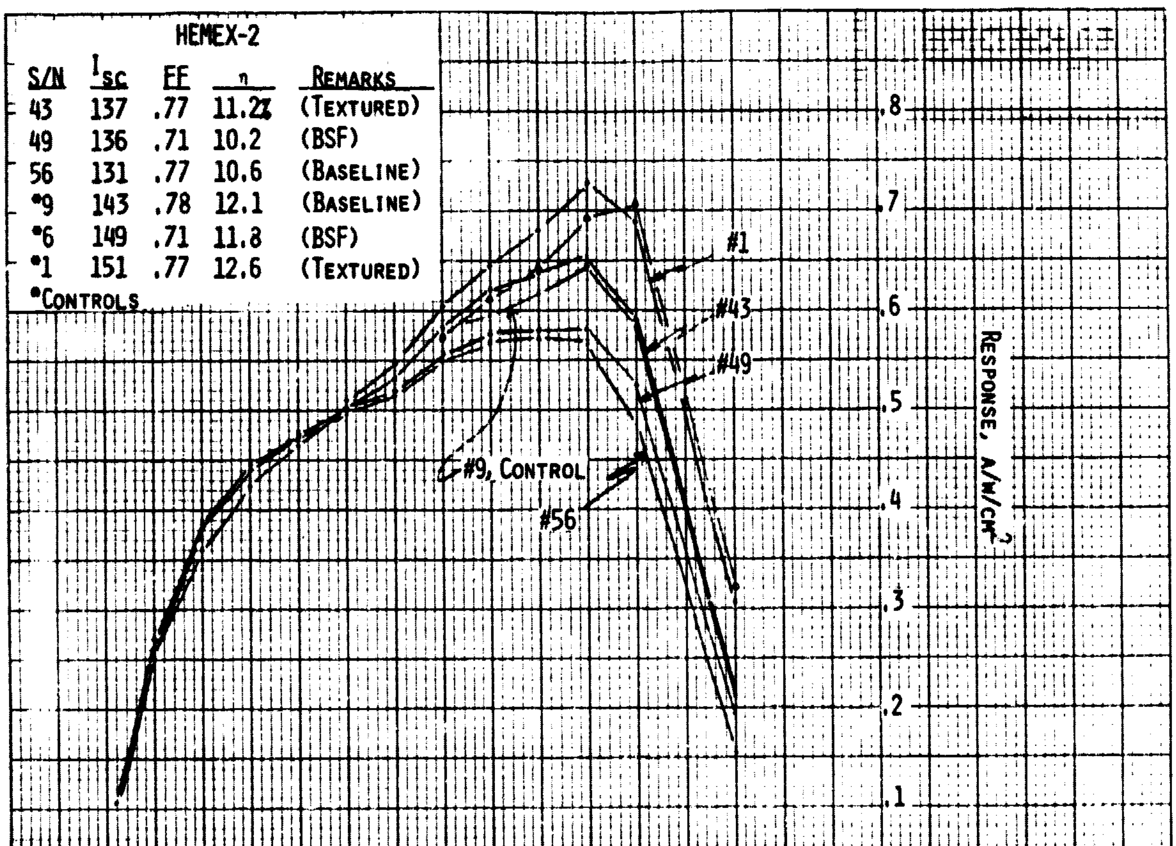
Spectral Response Data: Selected Cells, Run HEM-4



Run HEMEX-2, AR Film, AM0 28°C

S/N	I_{sc}	V_{oc}	FF	η	Remarks
52	131	592	.71	10.2	X-tal 850, BSF
53	132	593	.73	10.5	X-tal 850, BSF
51	134	585	.68	9.9	X-tal 850, textured
50	137	573	.58	8.4	X-tal 850, textured
58	131	591	.73	10.5	X-tal 850, baseline
57	129	584	.70	9.8	X-tal 850, baseline
45	137	563	.67	9.6	X-tal 857, BSF
49	136	569	.71	10.2	X-tal 857, BSF
41	134	567	.76	10.7	X-tal 857, textured
42	133	569	.76	10.6	X-tal 857, textured
43	137	573	.77	11.2	X-tal 857, textured
54	131	565	.73	9.9	X-tal 857, baseline
56	131	569	.77	10.6	X-tal 857, baseline
6	149	603	.71	11.8	Max. control, BSF
1	151	589	.77	12.6	Max. control, textured
9	143	588	.78	12.1	Max. control, baseline

Hemex-2



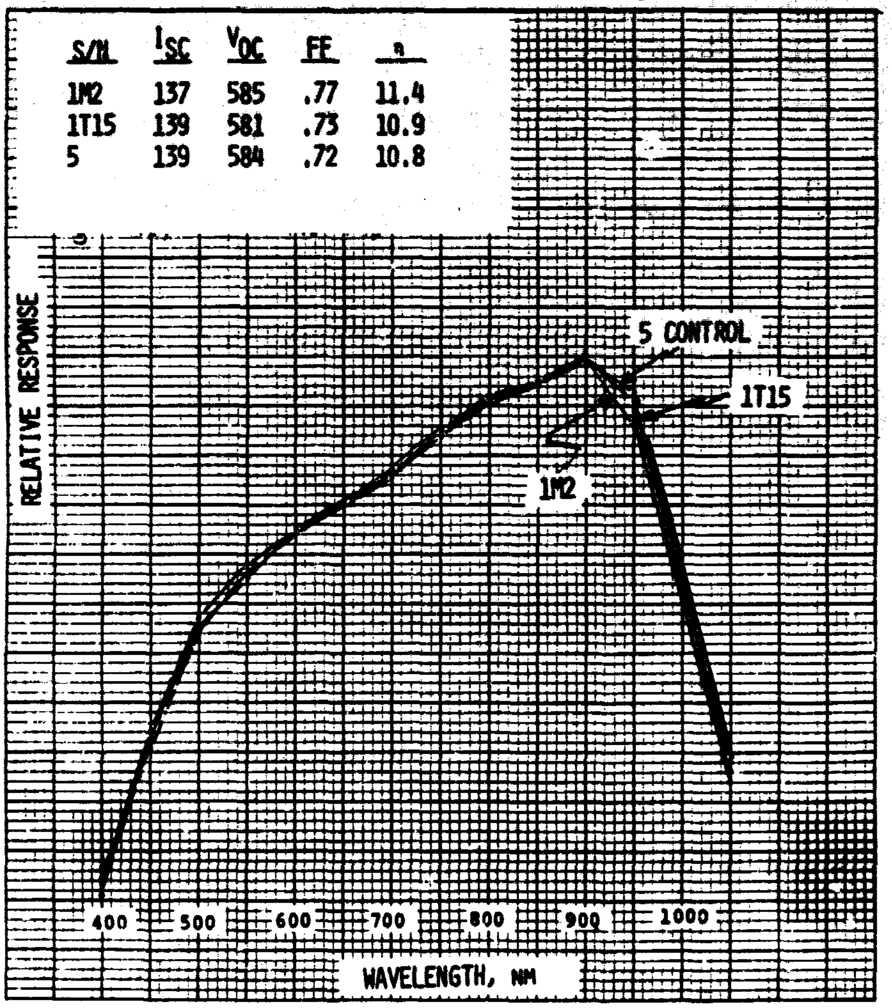
Run HAMB-2-3; Baseline Processing, AR Film, AM0 28°C

S/N*	I_{SC} (mA)	V_{OC} (mW)	P_{MAX} (mW)	FF	η%
1T12	138	582	61.1	.76	11.3
1T12A	132	581	59.5	.78	11.0
1M9	142	585	63.3	.76	11.7
1M9A	141	585	59.6	.72	11.0
2T2	136	586	62.7	.79	11.6
2M9*	116	538	46.4	.74	8.6
2M9A*	115	538	45.9	.74	8.5
3T16	139	577	60.6	.76	11.2
3T16A	136	577	59.9	.76	11.1
3B10*	103	532	41.2	.75	7.6
3B14*	110	537	43.9	.74	8.1
4T18B	139	583	62.9	.78	11.6
4T18A	139	579	58.1	.72	10.7
4B2	122	582	54.3	.76	10.0
4B2A	136	583	60.6	.76	11.2
5T11	141	585	55.1	.67	10.2
6T13	135	579	53.6	.68	9.9
6M18A*	110	524	39.7	.68	7.3
6M18*	115	533	43.5	.71	8.0
C3**	142	589	64.8	.77	12.0

*INDICATES POLYCRYSTALLINE MATERIAL

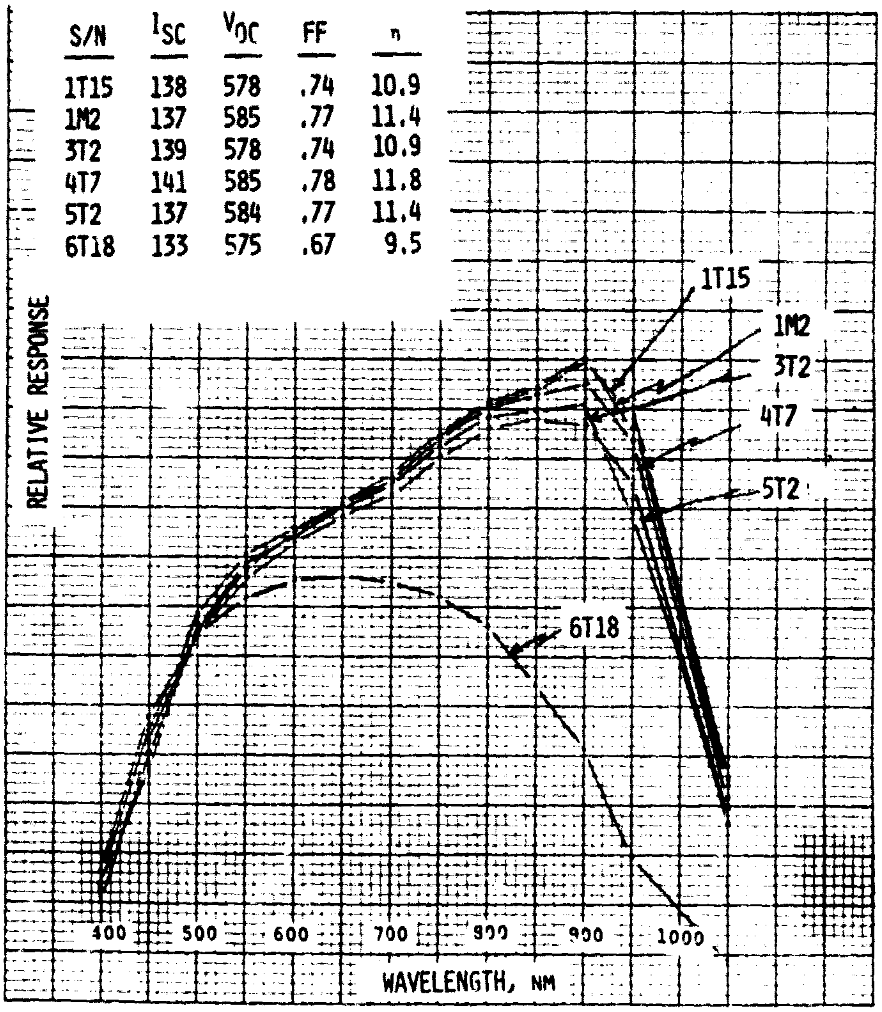
**CONTROL CELL IN RUN HAVING MAXIMUM EFFICIENCY

Spectral Response Data: Continuous-Cz Cells From Top & Middle Sections, Crystal No. 1, Run HAMB-1



Spectral Response Data: Continuous-Cz Cells From Top Sections of Crystals No. 1 Through No. 6

S/N	I_{SC}	V_{OC}	FF	η
1T15	138	578	.74	10.9
1M2	137	585	.77	11.4
3T2	139	578	.74	10.9
4T7	141	585	.78	11.8
5T2	137	584	.77	11.4
6T18	133	575	.67	9.5



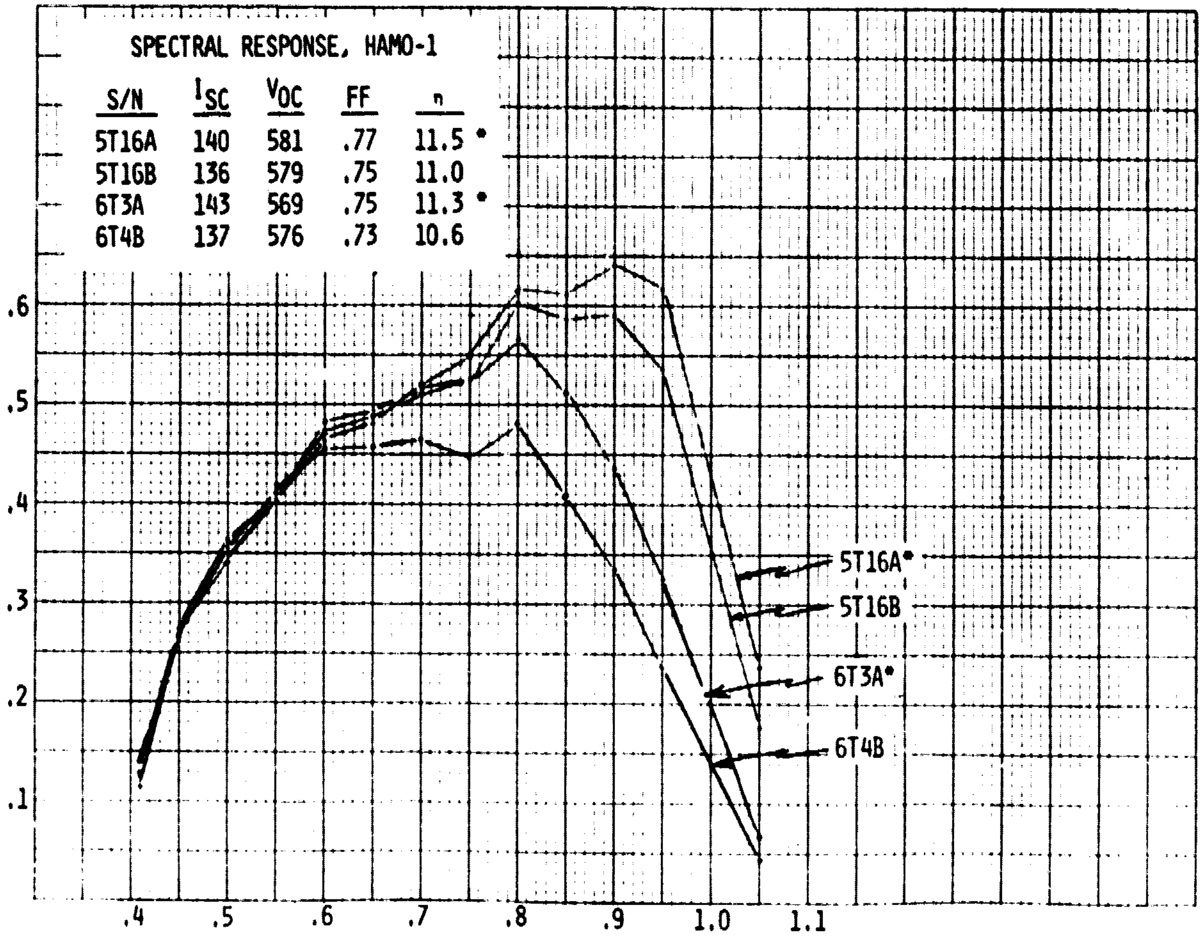
Run HAMO-1, AR Film, AM0 28°C

S/N	I_{sc}	V_{oc}	FF	η		
1T4A	142	581	.78	11.8	*	
1T4B	140	578	.72	10.8		
1M30A	140	579	.77	11.5	*	
1M30B	143	583	.78	11.9		
2T19A	135	575	.76	10.8	*	
2T19B	141	571	.65	9.7		
2M19A	111	533	.75	8.2	*	**
2B2A	114	540	.72	8.1	*	**
3T21A	150	583	.77	12.4	*	
3B25A	111	533	.67	7.3	*	**
3B26B	114	451	.48	4.6	*	**
4T2B	143	582	.78	12.0	*	
4B35A	116	558	.74	8.9	*	**
4B35B	115	563	.76	9.1		
5T16A	140	581	.77	11.5	*	
5T16B	136	579	.75	11.0		
6T3A	143	569	.75	11.3	*	
6T4B	137	576	.73	10.6		
6M10A	117	539	.75	8.7	*	**
6M10B	113	535	.76	8.5		
C2	139	584	.79	11.8	*	

* Textured

** Polycrystalline

Spectral Response, HAMO-1



Run HAMO-2, AR Film, AM0 28°C

S/N	I_{sc} mA	V_{oc} mV	FF	η%	Remarks
4T13A	137	382	.47	4.6	
4T13B	140	341	.44	3.9	BSF
1T8A	135	540	.51	6.9	
1T8B	137	580	.73	10.7	BSF
2T2B	131	598	.69	9.9	BSF
2T2A	126	578	.78	10.5	
1M23A	129	580	.78	10.7	
1M23B	145	598	.63	10.1	BSF
3T28A	135	308	.47	3.6	
3T28B	138	309	.46	3.6	BSF
6T5A	115	575	.76	9.3	
6T5B	135	591	.73	10.8	BSF
5T11A	132	570	.69	9.5	
5T11B	139	591	.67	10.2	BSF
6M21A	113	537	.75	8.4	
6M21B	108	521	.69	7.1	BSF
3B21	109	530	.70	7.4	
3B20	112	535	.70	7.7	BSF
4B16A	121	526	.53	6.2	
2B18A	108	538	.76	8.1	
C-7	136	584	.77	11.3	
C-8	139	604	.75	11.6	BSF

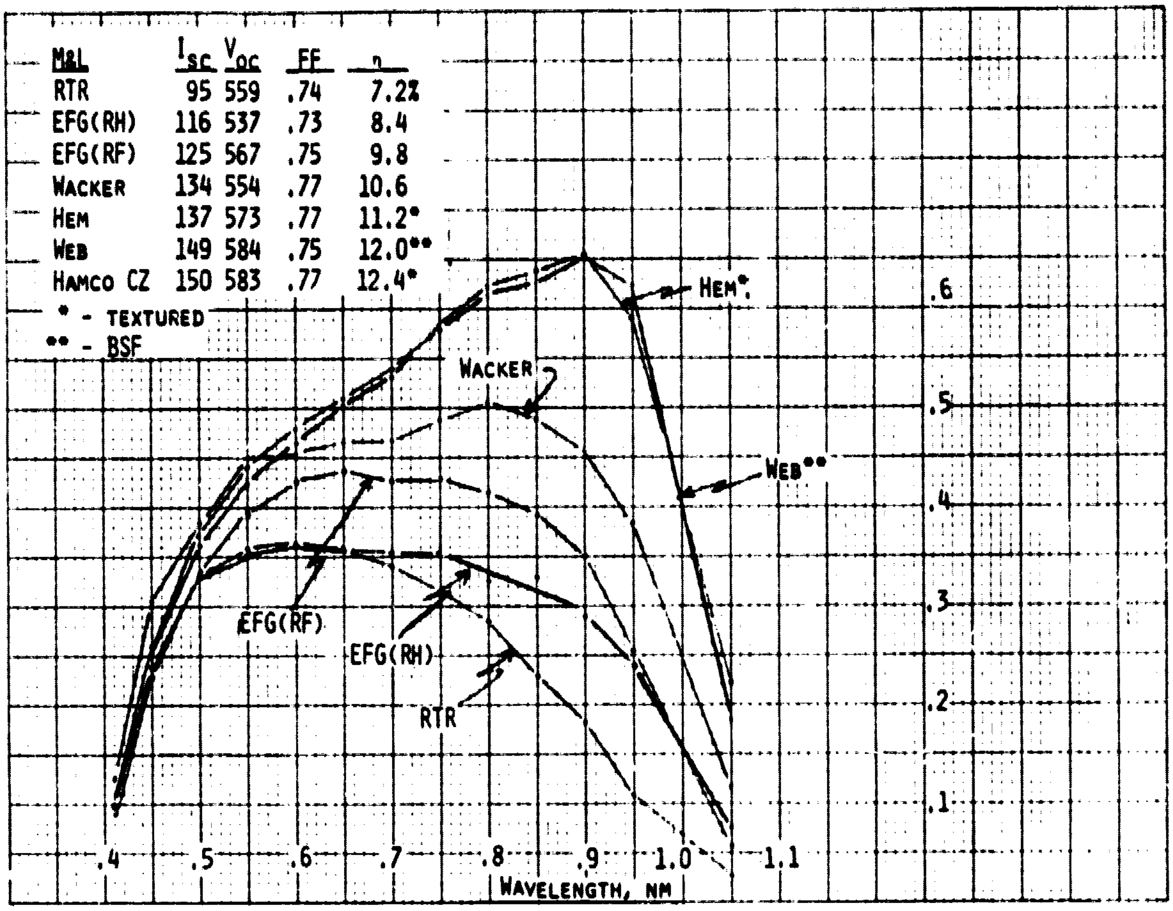
Run EFGO-1, EFG(RH), AR Film, AM0 28°C

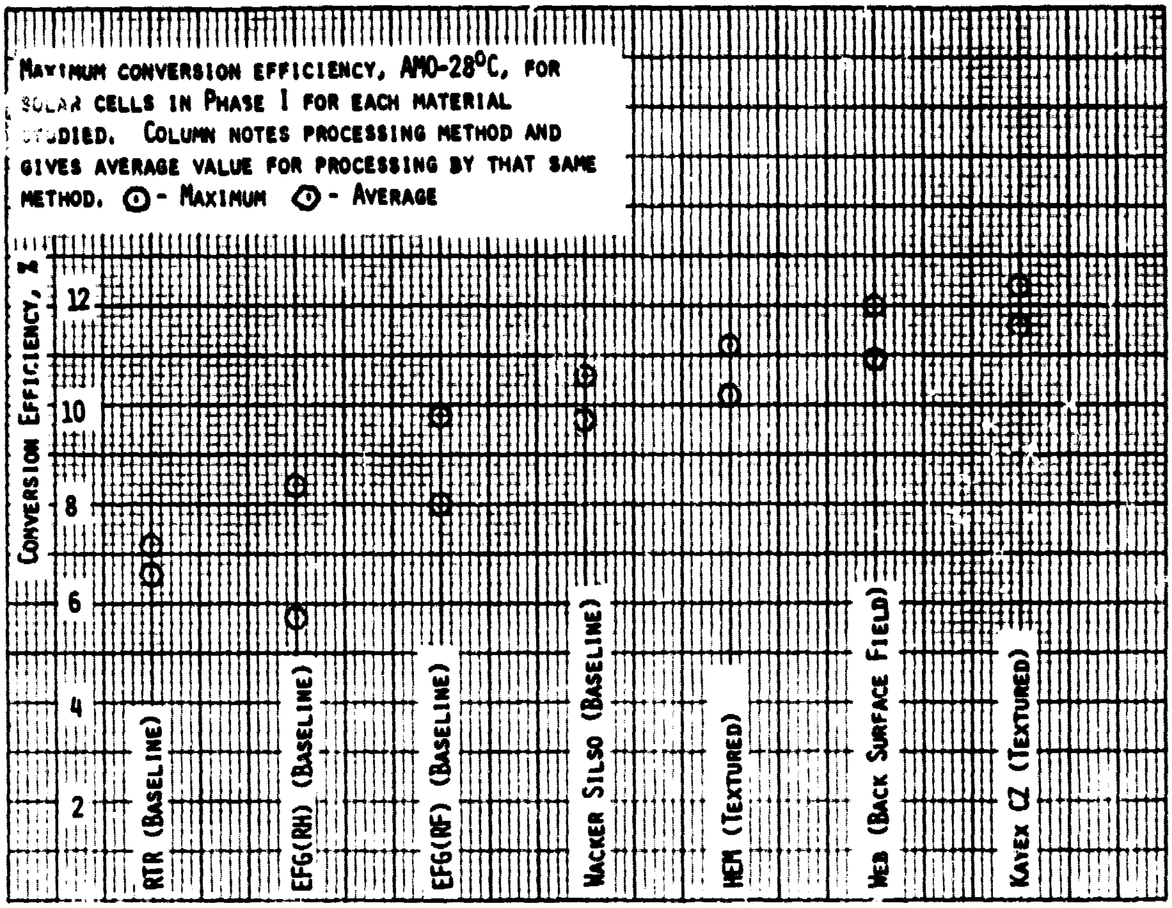
S/N	I_{SC} mA	V_{OC} mV	P_{MAX} mW	FF	η%	
#1 184-66	96	498	32.9	.688	6.1	
#2 184-275	110	514	35.1	.621	6.5	
#1 184-53	103	489	32.8	.651	6.1	
#2 184-219	106	411	17.0	.391	3.1	
#5 184-219	84	473	22.1	.557	4.1	
C-1	146	608	67.1	.756	12.4	*
C-2	145	606	62.8	.715	11.6	*
C-3	146	595	50.8	.585	9.4	*
C-4	148	607	65.9	.734	12.2	*
C-5	140	585	64.2	.784	11.9	
C-7	144	588	66.6	.787	12.3	
C-8	142	586	66.1	.795	12.2	

* Back surface field

I-V Data for Highest Efficiency Cells in Each Material

Material	S/N	I_{SC} mA	V_{OC} mV	P_{MAX} mW	FF	η%	Remarks
RTR	5	95	559	39.1	.74	7.2	Baseline, RTR-2
EFG(RH)	D	116	537	45.5	.73	8.4	Baseline, 184-36
EFG(RF)	46	125	567	53.0	.75	9.8	Baseline
Wacker	4	134	554	57.3	.77	10.6	Baseline
Hem	43	137	573	60.8	.77	11.2	Textured, X-tal #857
Web	2	149	584	65.3	.75	12.0	BSF, strip Re 25-23
Hamco	3T21A	150	583	67.3	.77	12.4	Textured, Top, X-tal #
Control	3	158	607	73.5	.77	13.6	T & BSF. Run WO-1


M&L
Isc Voc FF η
RTR 95 559 .74 7.2%
EFG(RH) 116 537 .73 8.4
EFG(RF) 125 567 .75 9.8
WACKER 134 554 .77 10.6
HEM 137 573 .77 11.2*
WEB 149 584 .75 12.0**
HAMCO CZ 150 583 .77 12.4*
* - TEXTURED
** - BSF
HEM*
WACKER
WEB**
EFG(RF)
EFG(RH)
RTR
.6
.5
.4
.3
.2
.1
.4
.5
.6
.7
.8
.9
1.0
1.1
WAVELENGTH, NM



Outline of Phase II

GOAL: 12% CONVERSION EFFICIENCY AT 28°C

CONTINUE OPTIMIZATION PROGRAM

UTILIZE LOW-COST PROCESSES

- A) REPLACE ACID ETCHES, WHERE POSSIBLE, WITH BASE ETCHES.
- B) REPLACE EVAPORATED CONTACTS WITH SCREEN-PRINTED CONTRACTS.
- C) REPLACE EVAPORATED AR COATING WITH SPRAY-ON SPIN-ON AR COATING.

CONTINUE PHASE I MEASUREMENTS + AM1 I-V ON PERCENTAGE OF CELLS.

SPECIFIC TABULATION OF BREAKAGE DURING PROCESSING AND TESTING.

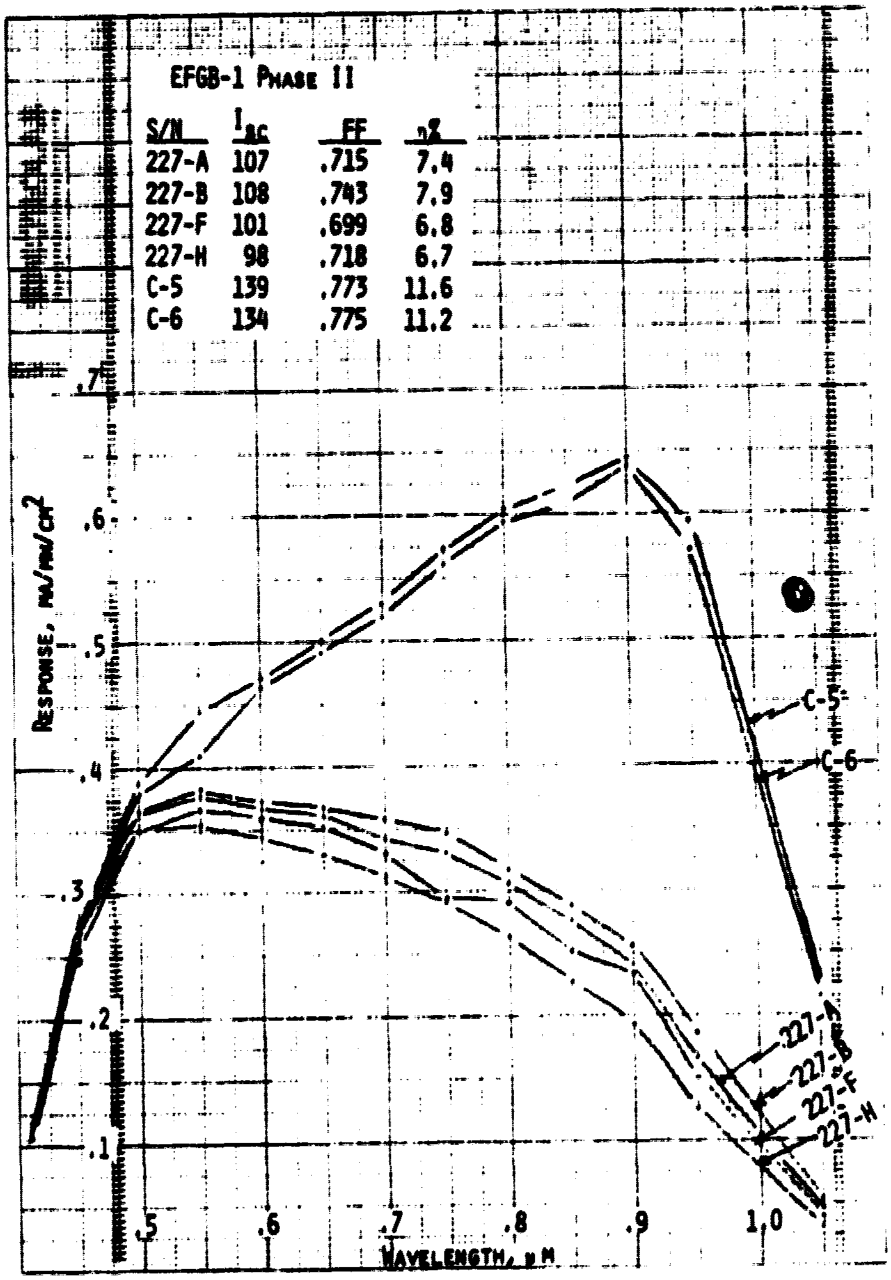
EFGB-1, EFG(RH), AR Film, Phase II, AM0 28°C

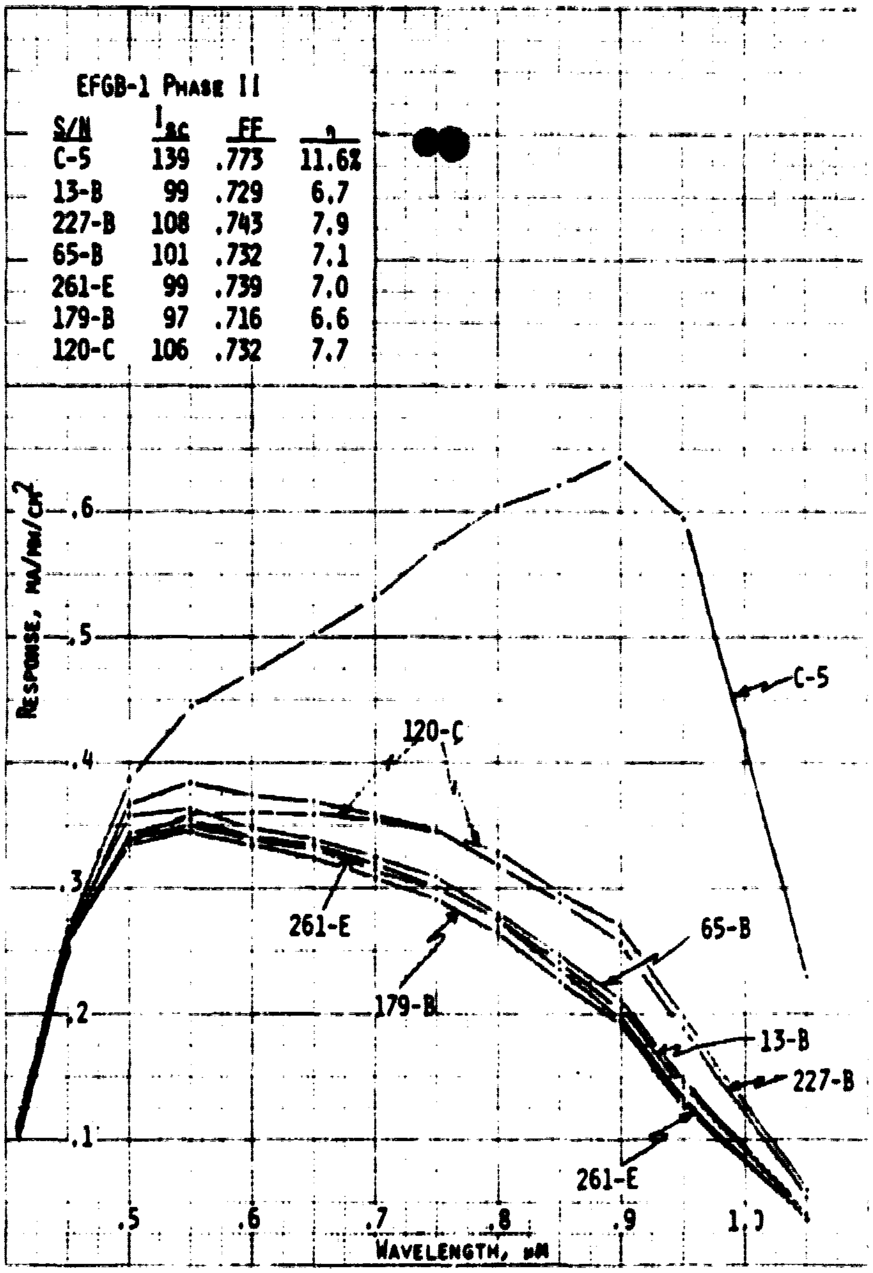
S/N	I_{sc} mA	V_{oc} mV	P_{MAX} mW	FF	η%
13-A	93	497	29.8	.645	5.5
-B	99	513	36.4	.716	6.7
-D	96	517	36.2	.729	6.7
-F	95	512	35.4	.728	6.5
65-A	97	514	36.4	.731	6.7
-B	101	520	38.4	.732	7.1
-D	99	505	34.1	.682	6.3
120-A	97	526	38.2	.748	7.1
-B	99	515	37.3	.731	6.9
-C	106	537	41.6	.732	7.7
-D	101	516	32.7	.628	6.0
-E	99	522	37.1	.718	6.9
-F	93	517	33.7	.701	6.2
-H	101	518	37.0	.707	6.8
165-C	95	518	36.0	.731	6.6
179-A	93	513	34.7	.727	6.4
-B	97	514	35.7	.716	6.6
-C	97	509	34.4	.698	5.4
-D	82	471	19.0	.492	3.5
120-G	96	521	35.2	.704	6.5
227-A	107	527	40.3	.715	7.4
-B	108	530	42.5	.743	7.9*
-C	105	527	39.9	.722	7.4
-D	108	535	41.8	.724	7.7
-E	101	525	38.7	.729	7.1
-F	101	523	36.9	.699	6.8
-G	99	515	35.9	.704	6.6
-H	98	514	36.2	.718	6.7
261-B	102	515	37.3	.709	6.9
-E	99	520	38.0	.739	7.0
-F	94	491	28.0	.607	5.2
-G	96	523	36.6	.729	6.8
-H	87	488	25.6	.603	4.7
C-5	139	582	62.5	.773	11.6**

BREAKAGE - SOME BLADE BREAKAGE BECAUSE OF WAVY SURFACE
4 RIBBON CELLS BROKEN AT V/I PROBING
2 RIBBON CELLS BROKEN AT EDGE ETCH   85% YIELD (EFG)
1 CONTROL CELL BROKEN AT EDGE ETCH   87.5% CONTROL YIELD

* MAXIMUM RIBBON CELL EFFICIENCY
** MAXIMUM CONTROL CELL EFFICIENCY

EFGB-1 Phase II



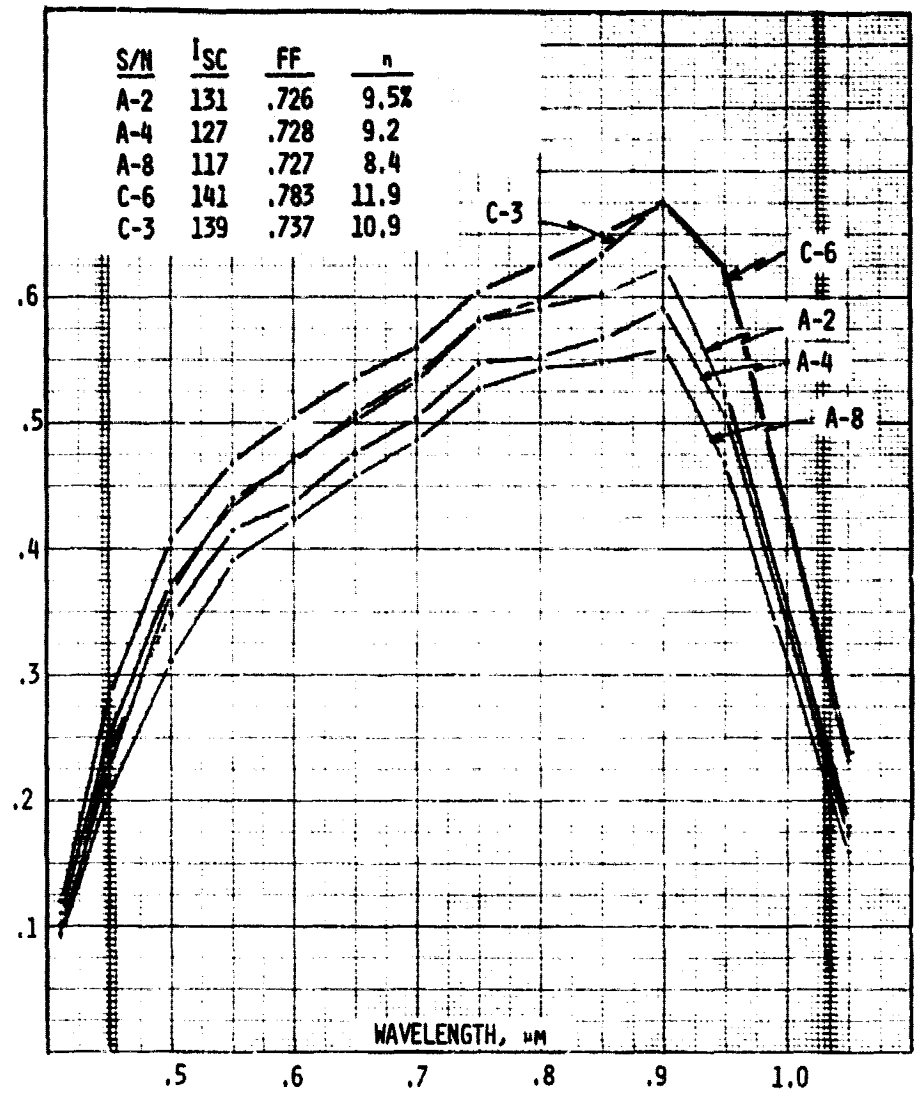

EFGB-1 Phase II
S/N I_{SC} FF η
C-5 139 .773 11.6%
13-B 99 .729 6.7
227-B 108 .743 7.9
65-B 101 .732 7.1
261-E 99 .739 7.0
179-B 97 .716 6.6
120-C 106 .732 7.7
Response, mA/mW/cm²
Wavelength, μm
C-5
120-C
261-E
179-B
65-B
13-B
227-B
261-E

WEB B-1, Baseline, AR Film, AM0 28°C

S/N	I_{SC} (mA)	V_{OC} (mV)	P_{MAX} (mW)	FF	η%	
A-2	131	542	51.5	.726	9.5	
A-4	127	539	49.8	.728	9.2	
A-7	120	539	48.2	.746	8.9	
A-6	124	536	47.8	.719	8.8	
A-8	117	536	45.6	.727	8.4	
A-9	[illegible]	537	48.4	.750	8.9	
AVG.	123	538	48.6	.733	9.0	AVG.
S	5.2	2.3	2.0	.012	.4	S
B-2			- - - SHUNTED - - -			
C-3	139	578	59.2	.737	10.9	
C-6	141	582	64.2	..783	11.9	

1 CELL, (B), BROKE WHILE LOADING INTO EVAPORATION MASKS
1 CELL, (B), BROKE DURING INK AND BAKE OPERATION
3 OF STRIP RE 161-1.7, (A), BROKEN DURING SCRIBING
6 OF STRIP J203-2.6, (B), BROKEN DURING SCRIBING
A CELLS FROM STRIP RE 161-1.7 (340 μm) 8 Ω-cm
B CELLS FROM STRIP J203-2.6 (220 μm) 11.9 Ω-cm

WEB B-1 Phase II, AM0 28°C



I-V Data for EFGO-1, Screen-Printed BSF And Contacts, AR Film, AM0 28°C, Phase II

S/N	I_{SC}	V_{OC}	P_{MAX}	FF	η	
C-1			--- SHUNTED ---			
C-2			"			
C-3			"			
C-4			"			
C-5	140	581	61.3	.753	11.3	**
C-6	137	584	59.5	.744	11.0	
C-7	141	586	62.2	.753	11.5	
15-A	86	495	18.4	.433	3.4	
15-B			--- SHUNTED ---			
15-C			"			
15-D			"			
78-A			"			
78-B	92	504	25.0	.539	4.6	
78-C	91	498	26.9	.594	5.0	*
78-D	74	444	12.6	.383	2.3	
124-A	84	467	16.5	.421	3.1	
124-B	87	488	21.3	.501	3.9	
216-A	73	479	15.5	.443	2.9	
216-B	69	432	9.5	.320	1.8	
216-C	81	483	15.3	.392	2.8	
216-D			--- SHUNTED ---			

*MAXIMUM EFFICIENCY

**BASELINE PROCESSING

BREAKAGE OCCURRED ON LARGE RIBBON SECTIONS DURING SCREEN PRINTING.

ONE CONTROL CELL WAS BROKEN DURING EDGE ETCH.

OPERATIONS AREA

Large-Scale Production Task

BLOCK IV MODULE DESIGNS AND RATIONALES

One of the parallel technology sessions on Wednesday afternoon comprised presentations by the Block IV module manufacturers on design features and rationale. These presentations were a milestone for the Project, marking the first in-depth exposition of current design practices by the Production Task contractors. In this latest step toward the simultaneous improvement of module price, performance, and reliability, the manufacturers have incorporated a number of design and production technology innovations based on their own R&D and that of other Project participants.

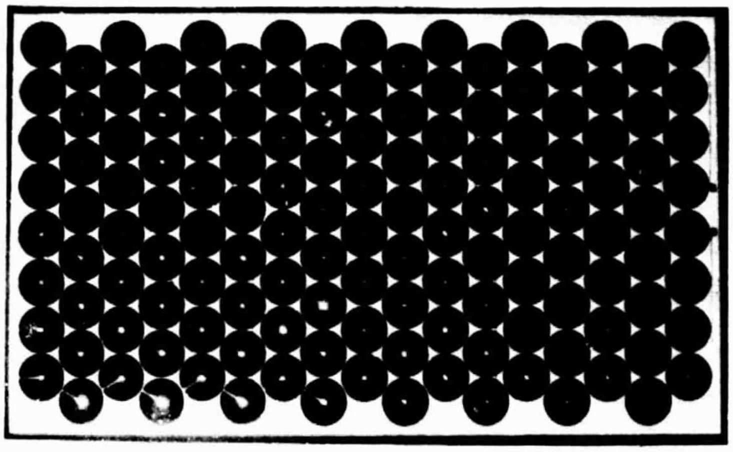
An Operations Area presentation on Test and Applications experience will be found on pp. 456-462 and a joint Project Analysis and Integration Area, Engineering Area and Operations Area presentation appears on pp. 354-382.

TECHNOLOGY SESSION

L. D. Runkle, Chairman

APPLIED SOLAR ENERGY CORP.

View of Completed Module



Agenda

1. INTRODUCTION
2. CELL DESIGN
3. ENCAPSULATION ASSEMBLY
4. FRAME EXTRUSION
5. FRAME ASSEMBLY
6. MODULE EFFICIENCY AND TECHNICAL DATA

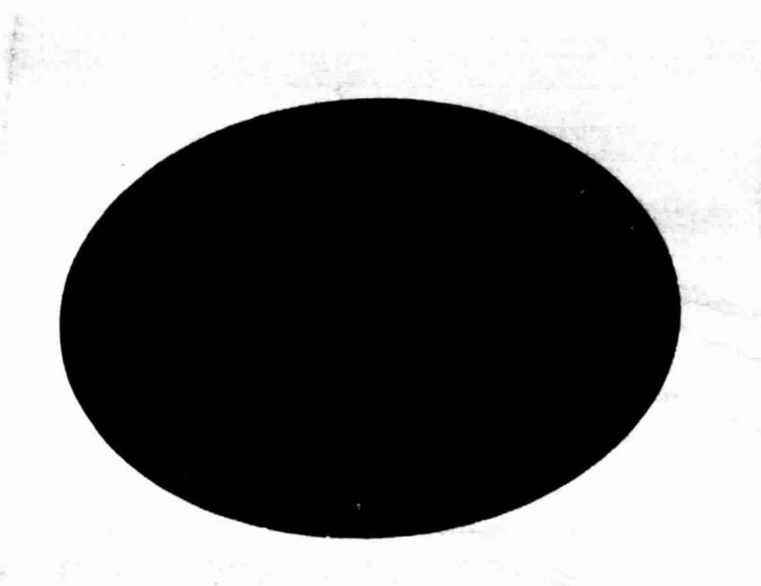
Introduction

THE OBJECTIVE OF THIS PROGRAM IS TO DESIGN, FABRICATE, ACCEPTANCE TEST, AND EVALUATE TEN (10) PRE-PRODUCTION MODULES COMPLYING WITH THE REQUIREMENTS OF JPL DOCUMENT NO. 5101-16, REVISION A, ENTITLED "BLOCK IV SOLAR CELL MODULE DESIGN AND TEST SPECIFICATION FOR INTERMEDIATE LOAD CENTER APPLICATIONS", DATED 1 NOVEMBER 1978. THE TOTAL OUTPUT OF THE TEN (10) MODULES SHALL BE IN EXCESS OF 900 WATTS OF PEAK POWER AT AM1.5 AND NOCT. IN ADDITION, ASEC IS TO PREPARE A STANDARDIZED PRICE ESTIMATE USING SAMICS FOR 10, 100, AND 1000 KILOWATTS OF SOLAR MODULES.

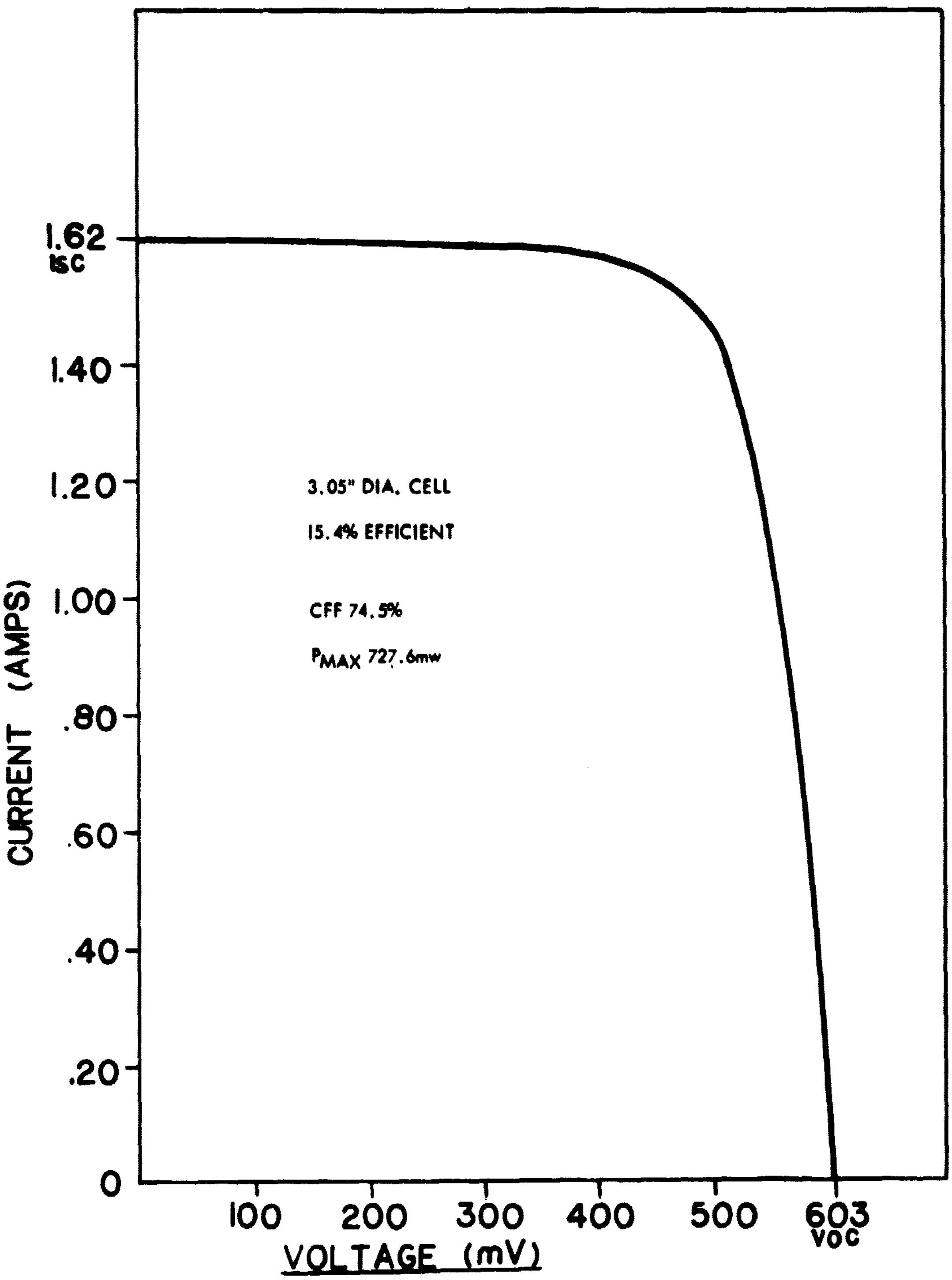
High-Efficiency Solar Cell

SIZE:	3.05 INCH DIAMETER 47.137 SQ.CM.
TYPE:	P-TYPE CZOCHRALSKI GROWN 10 OHM-CM BORON DOPED
CONTACTS:	EVAPORATED AND SINTERED TITANIUM-PALLADIUM-SILVER ALUMINUM ALLOYED BACK SURFACE FIELD
COATING:	DUAL LAYER ANTIREFLECTIVE COATING

Cell



I-V Curve



TEST CONDITIONS: AM1 28°C

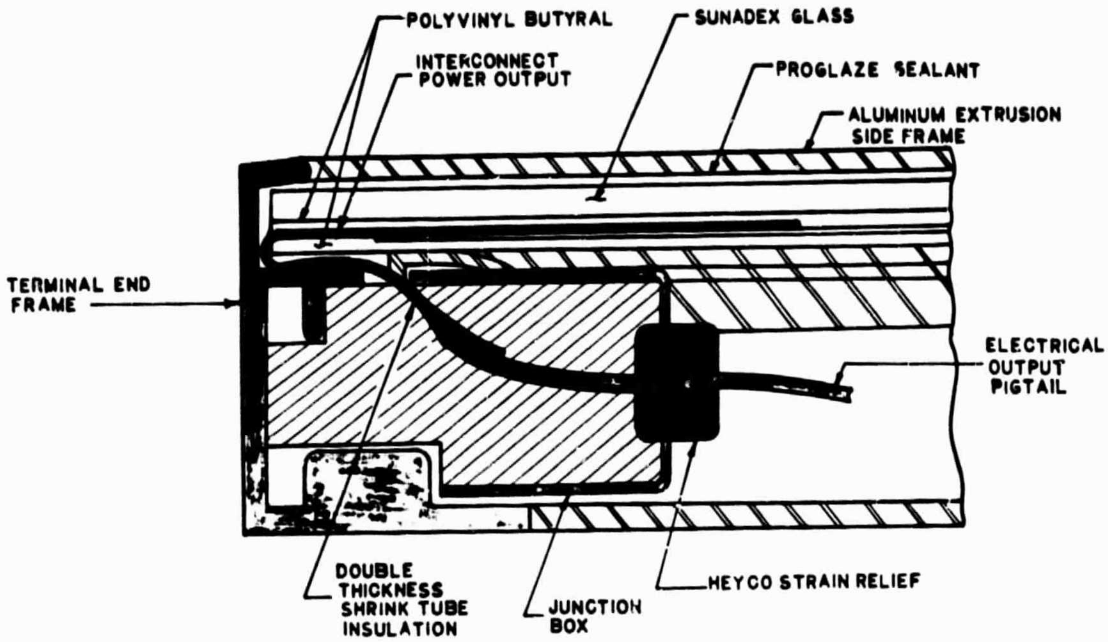
Cell Flow Chart

1. GROW INGOT
2. GRIND INGOT
3. SLICE INTO WAFERS
4. CLEAN AND CHEMICALLY POLISH WAFERS
5. DEPOSIT DIFFUSION MASK
6. DIFFUSE WAFER TO FORM JUNCTION
7. REMOVE DIFFUSION OXIDE AND MASK
8. APPLY ALUMINUM TO P-SIDE
9. ALLOY ALUMINUM TO FORM BACK SURFACE FIELD
10. CLEAN WAFERS FOR CONTACT APPLICATION
11. DEPOSIT P-CONTACT MATERIALS (AL,TI-PD-AG)
12. GENERATION OF N-CONTACT AND GRIDLINES USING PHOTORESIST TECHNIQUE
13. DEPOSIT ANTIREFLECTIVE COATING
14. SINTER CONTACTS AND AR COATING
15. INSPECT FOR MECHANICAL DEFECTS
16. TEST FOR ELECTRICAL OUTPUT

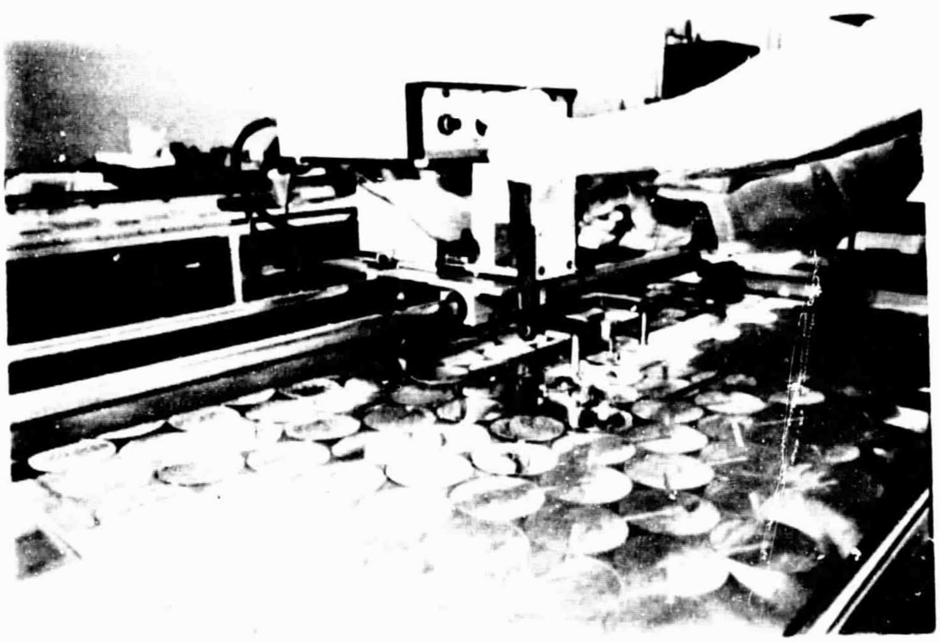
Encapsulated Assembly

- SUNADEX DEEP EMBOSSED PATTERN GLASS
- POLYVINYL BUTYRAL
- SOLDERED CELL ARRAY
- POLYVINYL BUTYRAL
- TEDLAR

Section View Through Frame and Junction Box

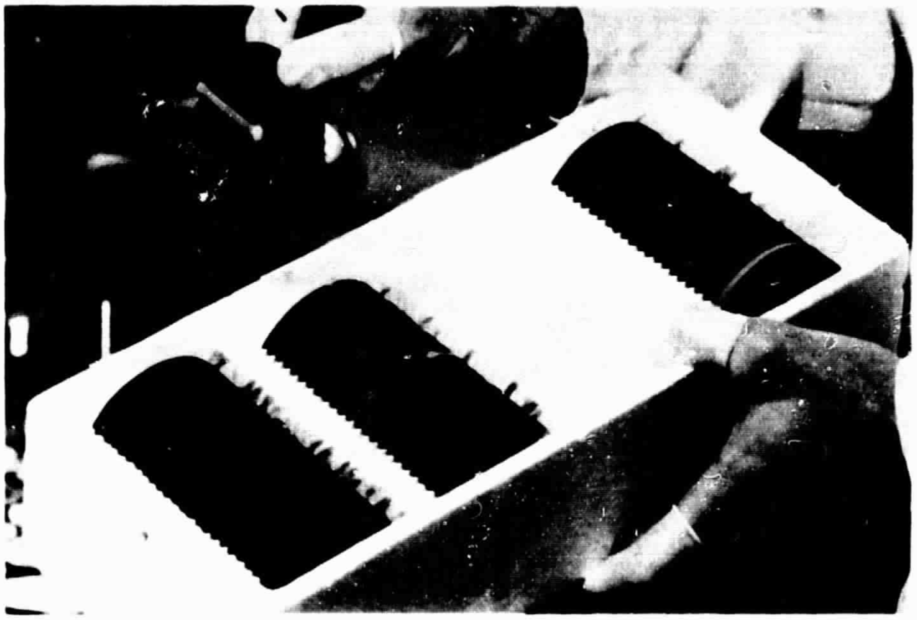


Soldering Machine



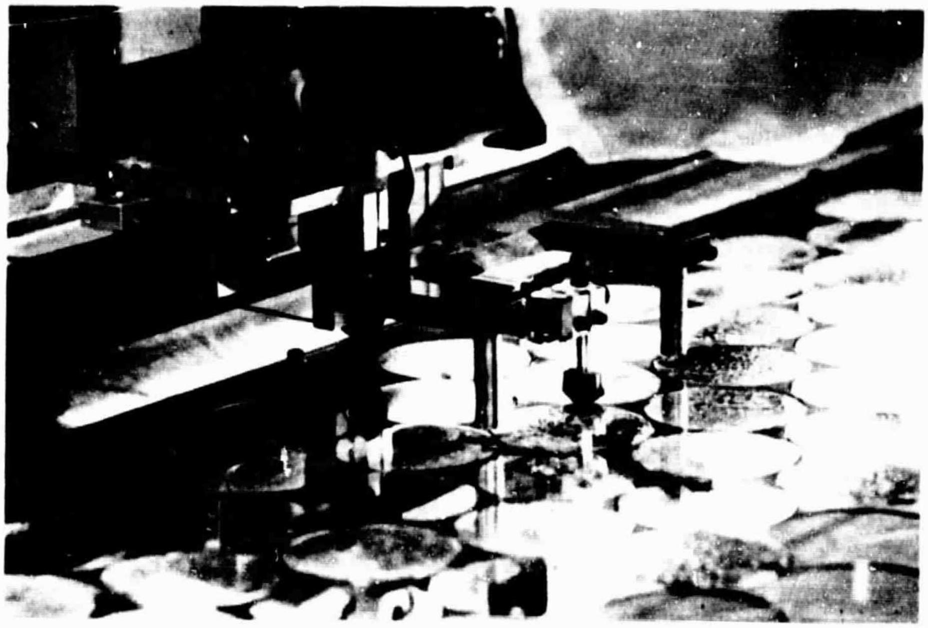
ORIGINAL PAGE IS
OF POOR QUALITY

Cells Grouped and Stored in Box



Cell Laydown

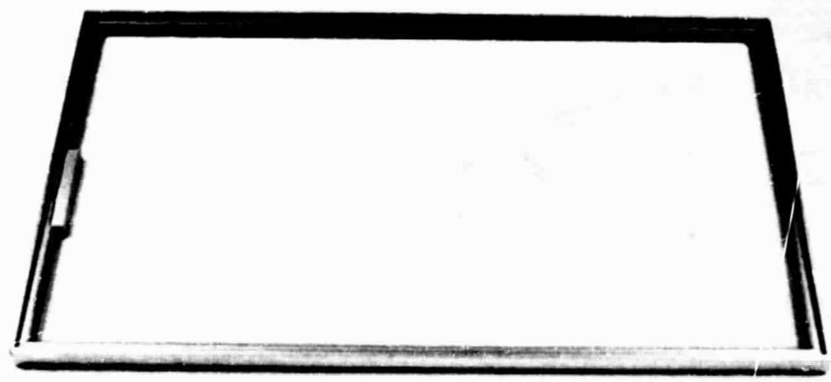
Soldering Process



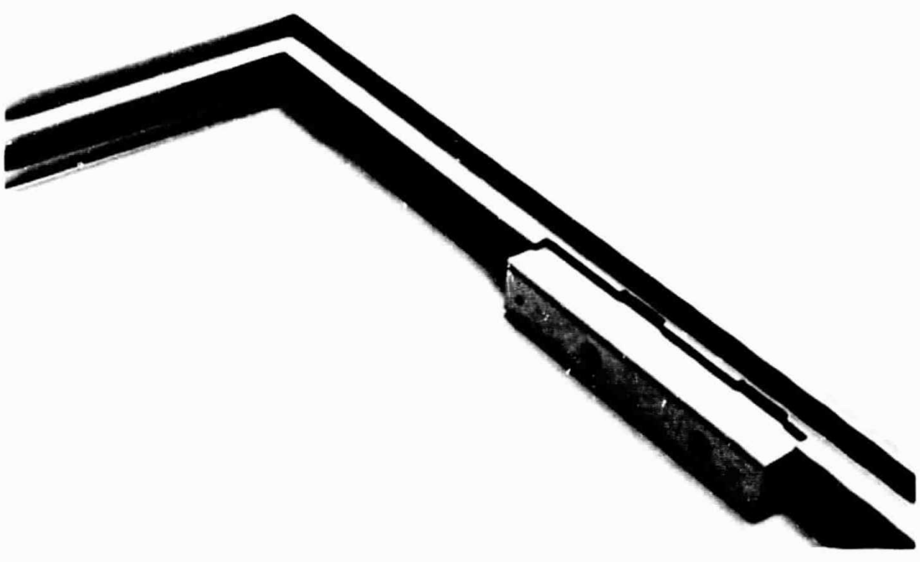
Frame Assembly

- ALUMINUM ESTRUSION - ALLOY 6063-T5
- FOUR PIECE CONSTRUCTION
- PRESS FIT MECHANICAL CORNER FASTENERS
- ANODIZED FINISH
- LIGHTWEIGHT
- STRONG
- REINFORCED MOUNTING HOLES

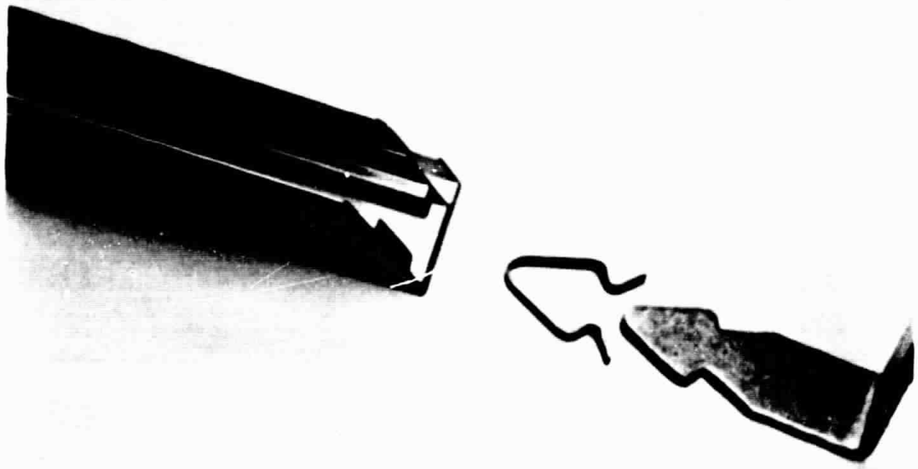
Assembled Frame



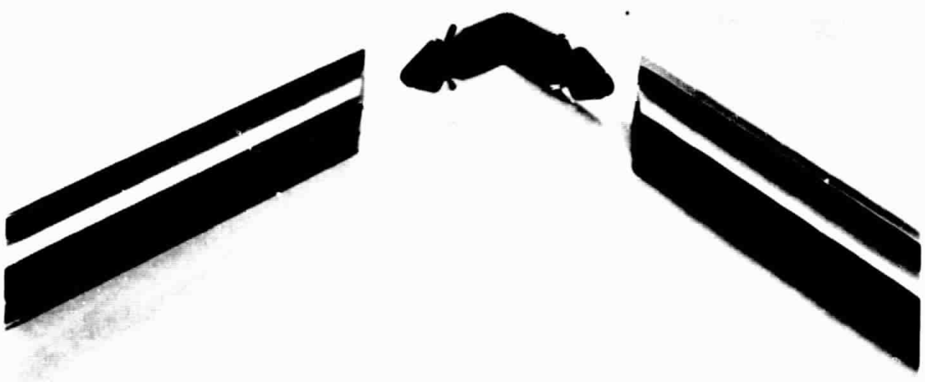
Junction Box



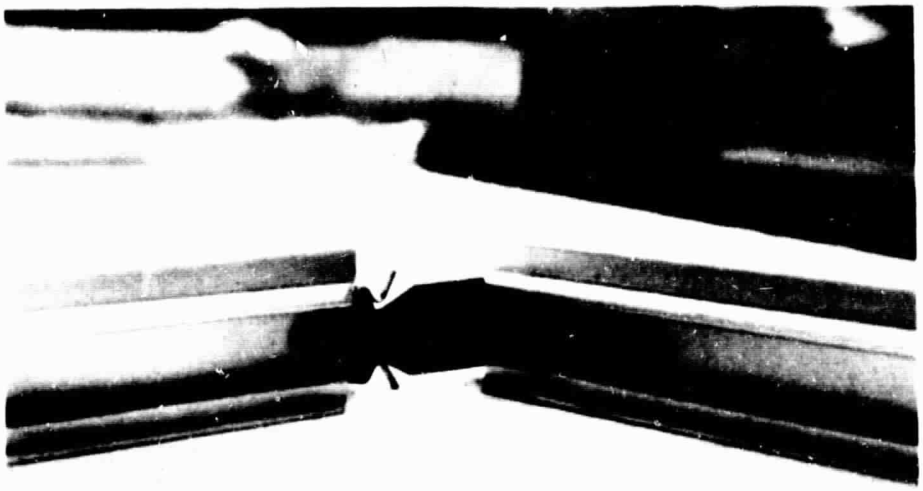
Corner Lock Brace and Spring Clips



Corner Lock Brace With Springs Installed

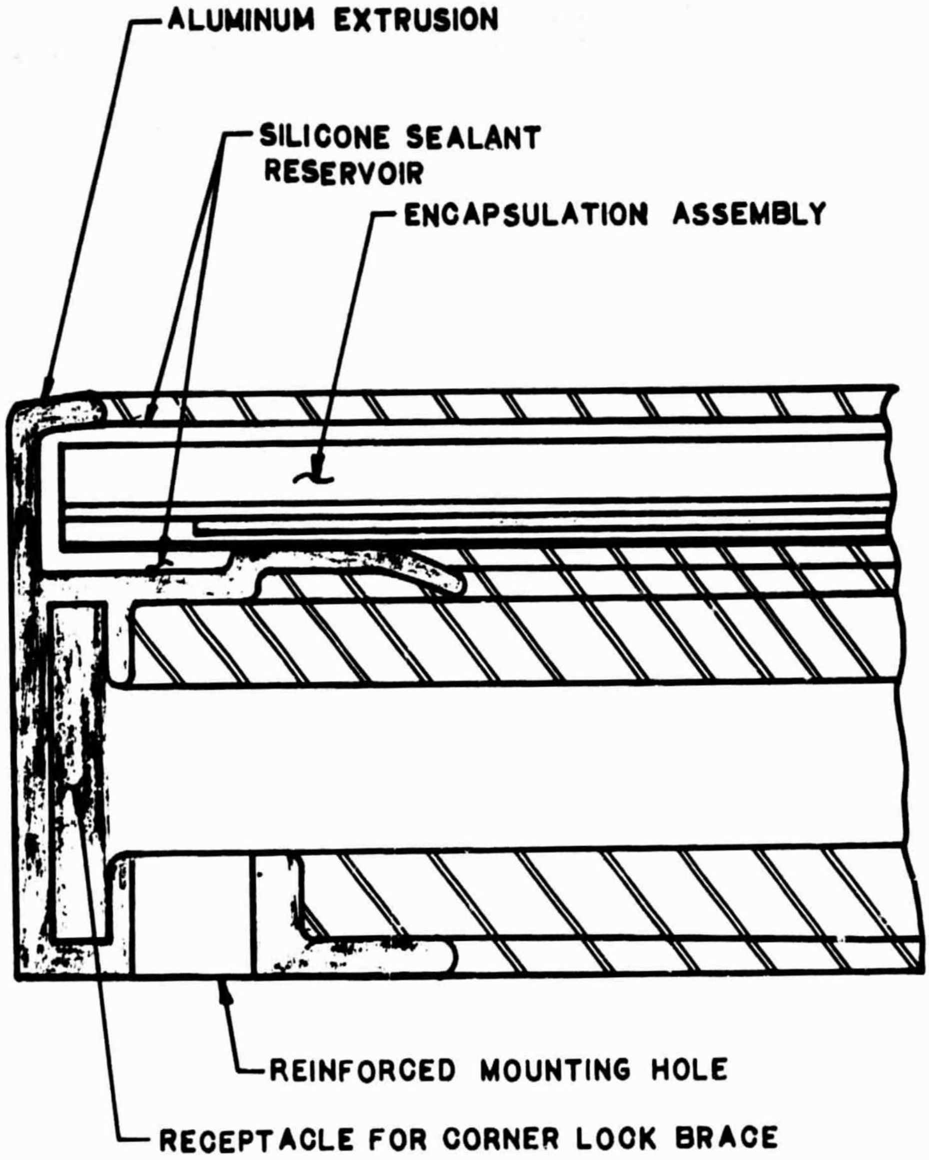


Frame With Corner Brace



Inserting Corner Brace

Section View of Frame



Module Efficiency

ESTIMATED: AT 48° (NOCT) AND AM1.5

CURRENT AT 15V AND NOCT = 6.03 AMPS

MODULE EFFICIENCY AT NOCT = 11.9%

PACKING FACTOR = 76.8%

ACTUAL DATA ON FIRST MODULE:

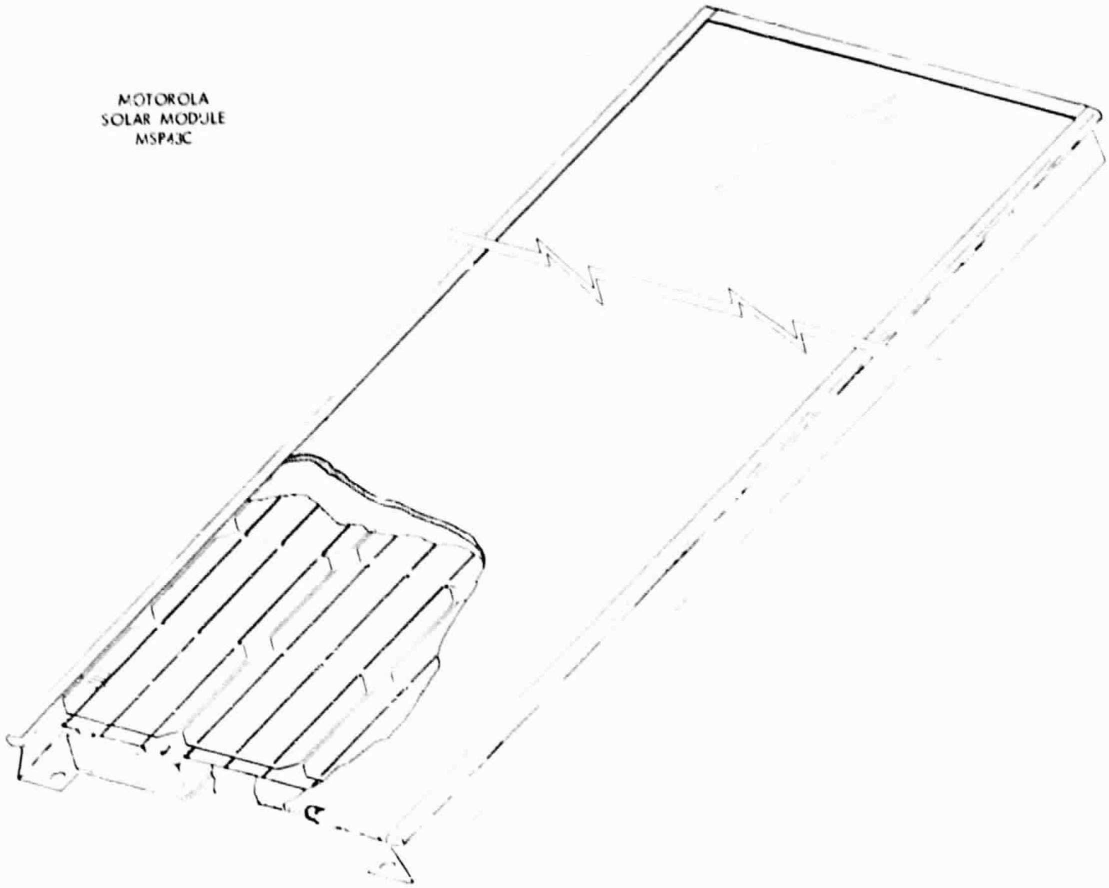
	JPL FIRST TEST	ASEC* SUNLIGHT	JPL SECOND TEST	TABLE MT.** TEST
DATE	10-12-79	10-22-79	10-22-79	11-5-79
TEMP. CORRECTED TO °C	48	48	48	48
V_{NO}, VOLTS	15	15	15	15
I, AMP	5.35	5.932	5.44	5.72
P_{NOCT}, WATTS	80.3	89	81.6	85.8
V_{OC}, VOLTS	18.4	18.9	18.5	18.6
I_{SC}, AMPS	6.7	6.64	6.69	6.78
V_{MAX}, VOLTS	13.5	15	13.8	13.8
I_{MAX}, AMP	6.3	5.932	6.21	6.51
P_{MAX}, WATTS	85	89	85.7	89.8
CFF, MAX	.680	.709	.692	.712

* 91.9 mW/cm^2

**108 mW/cm^2 (SCATTERING)

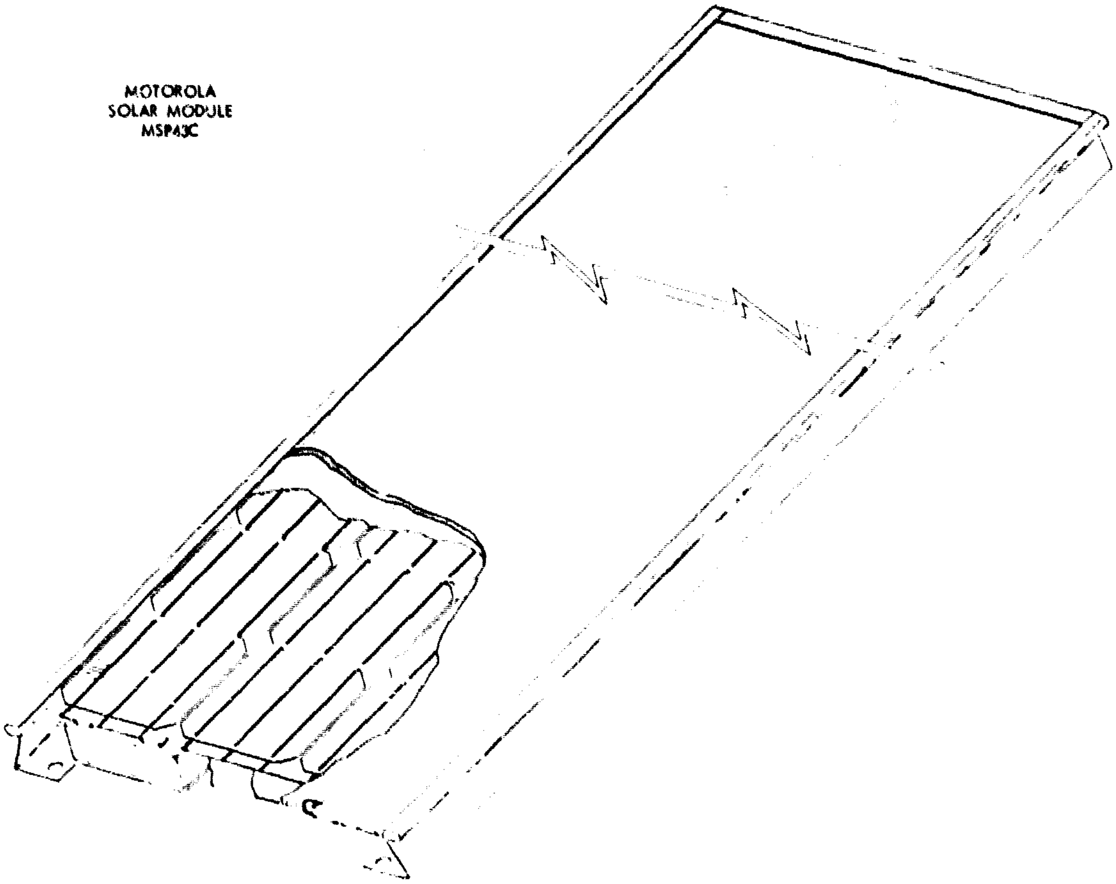
MOTOROLA, INC.

Solar Module MSF43C



MOTOROLA, INC.

Solar Module MSF43C



MSP43C Characteristics

- **ELECTRICAL:**

- 33 SERIES CELLS — NOMINAL POWER @ STC: 40W
  NOMINAL POWER @ SOC: 36W

- **DIMENSIONS:**

- LENGTH: 1200 MM (47.24")
- WIDTH: 340 MM (13.3")
- HEIGHT: 38MM (1.5")

- **CONSTRUCTION:**

- COVER GLASS: .125 THK TEMPERED (SOLATEX)
- POTTANT: POLYVINYL BUTRYAL (SAFLEX)
- BACK SKIN: AL-POLYVINYL FLUORIDE (TEDLAR) LAMINANT
- EDGE SEALANT: HOT MELT COPOLYMER
- FRAME: 304 SS
- J-BOX: PVC II GLASS FILLED POLYCARBONATE
- BINDING POSTS: NICKEL PLATED STL
- INTERCONNECT (CELL): THREE COPPER RIBBONS, CONTINUOUSLY BONDED ACROSS TOP AND BOTTOM OF CELLS.

- **OPERATIONAL CONDITIONS**

- TEMPERATURE: -40C TO 60C
- WIND: CONSTANT VELOCITY: 160 KM/HR (100 MPH)
  GUST VELOCITY: 200 KM/HR (125 MPH)

- **MECHANICAL:**

- SNOW LOADING: 290 KG/M^2 (60 PSF)
- SHOCK: .4M (15 IN) DROP PER MIL-STD-810B
- VIBRATION: VARIABLE FREQUENCY PER MIL-STD-310B
- FLEXURE: ± 1/4"/FT. PER JPL 5101-16

Development Philosophy

PROJECT STATEMENT

PROVIDE A DESIGN SOLUTION TO:

- HIGH PRESENT MODULE MAT'L AND LABOR COST/WATT
- MAJOR INDUSTRY RELIABILITY PROBLEMS
- EARLY 1980'S USER PROFILE

STRATEGY

- FEW, SIMPLE PIECE PARTS
- FEW, SIMPLE ASSEMBLY STEPS
- INCREASED PACKAGING DENSITY
- PROVIDE INHERENT SOLUTIONS TO RELIABILITY PROBLEMS
- UTILIZE A COMBINATION OF ANALYTICAL & EXPERIMENTAL APPROACHES.

OBSTACLES

- MATERIAL PROPERTIES VS. COST
- DESIGN FUNCTION VS. COST
- INTERFACE INCOMPATIBILITIES
- CODE REQUIREMENTS

CORRECTIONS

- PROVIDE MATERIALS SHELTERING FROM HARMFUL ASPECTS OF ENVIRONMENT
- SEARCH OUT COMPATIBLE MATERIAL COMBINATIONS
- PROVIDE DESIGN COMPROMISES TO MINIMIZE NEGATIVE EFFECTS
- FEEDBACK TEST RESULTS

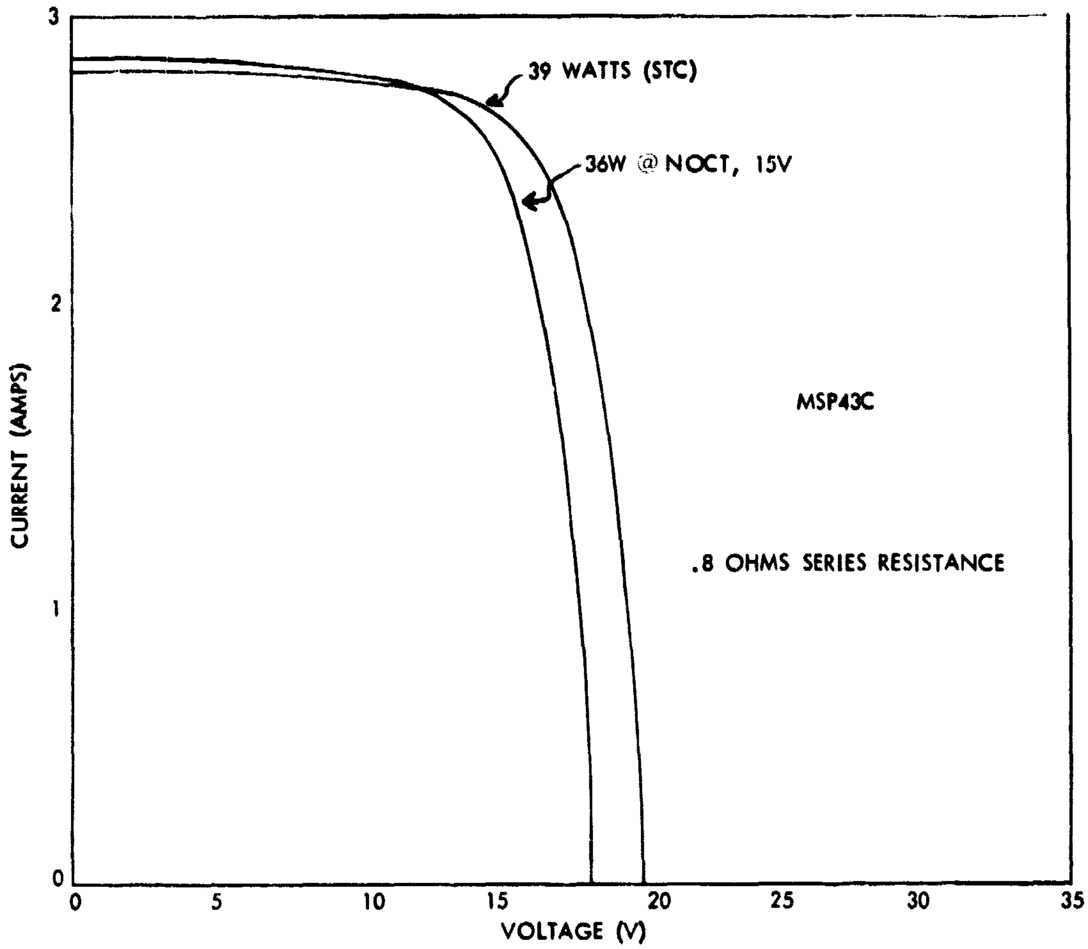
Desired Manufacturing Aspects

ASPECT	BENEFIT
. SIMPLE PIECE PARTS	. LOW VENDOR TOOLING COSTS . SHORT LEAD TIMES . LOW PIECE PARTS COSTS . MECHANIZABLE AT LOW VOLUME . WIDE CHOICE OF POTENTIAL VENDORS . EARLY SECOND SOURCING
. FEW ASSEMBLY STEPS	. LOW LABOR CONTENT . MINIMUM TRAINING REQUIREMENTS . LOW FLOOR SPACE REQUIRMENTS . LOW CAPITALIZATION REQUIREMENTS
. MECHANIZABLE ASSEMBLY PROCESSES	. RAPID GROWTH RATE POTENTIAL . HIGH EXPERIENCE CURVE SLOPES
. NO SOLVENTS UTILIZED	. REDUCED IFO COST
. KNOWN MANUFACTURING TECHNOLOGIES	. MINIMUM MANUFACTURING - TECHNICAL RISKS

Desired Customer Features

FEATURE	BENEFIT
. HIGH PACKAGING DENSITY (80%)	. MIN. BOS COST . MIN. INSTALLATION TIME
. HIGH RELIABILITY	
. REDUNDANT MODULE CONNECTIONS	. LOW $/KW-HR, INSTALLED
. REDUNDANT CELL INTERCONNECTIONS	. LOW OPERATING COST
. ACROSS-THE-CELL CONTACTS	. LOW $\partial P/\partial T$
. COMBINATION OF PROVEN WEATHERABLE MATERIALS	. IMMUNE TO CELL CRACKS
. OPTIMIZED FOR 12 VOLT SYSTEMS	
. 33 SERIES CELLS . LOW CELL TEMPERATURE	. MAXIMUM CHARGING CURRENT PER PURCHASED WATT FOR 12 VOLT SYSTEMS
. MAINTENANCE FREE CONSTRUCTION	. LOW OPERATING COST
. TEMPERED GLASS . 304 SS	
MEETS/EXCEEDS APPLICABLE CODES & STANDARDS	
. NATIONAL ELECTRICAL CODE	. SAFETY
. JPL BK IV SPEC. 5101-16	. DESIGN INTEGRITY . INTERCHANGABILITY

I-V Curve



3
2
1
0
CURRENT (AMPS)
39 WATTS (STC)
36W @ NOCT, 15V
MSP43C
.8 OHMS SERIES RESISTANCE
0
5
10
15
20
25
30
35
VOLTAGE (V)

PHOTOWATT INTERNATIONAL, INC.

Sang S. Rhee

Agenda

1. DESCRIPTION OF PRE-PRODUCTION MODULE
   - 1.1 PHYSICAL DATA
   - 1.2 ELECTRICAL DATA
   - 1.3 THERMAL & ENVIRONMENTAL DATA
2. DESIGN RATIONAL
   - 2.1 ELECTRIC PERFORMANCE
   - 2.2 ELECTRICAL DESIGN
   - 2.3 MECHANICAL DESIGN
   - 2.4 ENVIRONMENTAL DESIGN
   - 2.5 COST CONSIDERATION
3. DESIGN INNOVATIONS AND ADVANTAGES

Physical Data

(1) MODULE DIMENSIONS & RELATED DATA

LENGTH	=	1198 MM
WIDTH	=	395.5 MM
HEIGHT	=	63.5 MM
AREA	=	4737.3 CM^2
PACKING EFFICIENCY	=	80.7%

(2) MODULE ENCAPSULATIONS

GLASS/PVB/CELL/PVB/MYLAR

(3) CELL INTER-CONNECTIONS

8 CELL IN SERIES → A SUBSTRING

3 SUBSTRINGS IN PARALLEL → A SUBSTRING ASSEMBLY

5 SUBSTRING ASSEMBLY IN SERIES → A MODULE STRING

TOTAL 120 CELLS

(4) **CELL SIZE & SHAPE**

A HALF HEXAGONAL CELL

CELL AREA = 31.86 CM^2

POINT-TO-POINT DIA. = 99 MM

(5) **CELL CONFIGURATION**

$N^+ - P - P^+$ TYPE CELL

NICKEL / SOLDER METALLIZATION

"RAIL ROAD TRACK" PATTERN

(6) **ELECTRIC TERMINATIONS**

A PAIR OF TERMINALS AT EACH END.

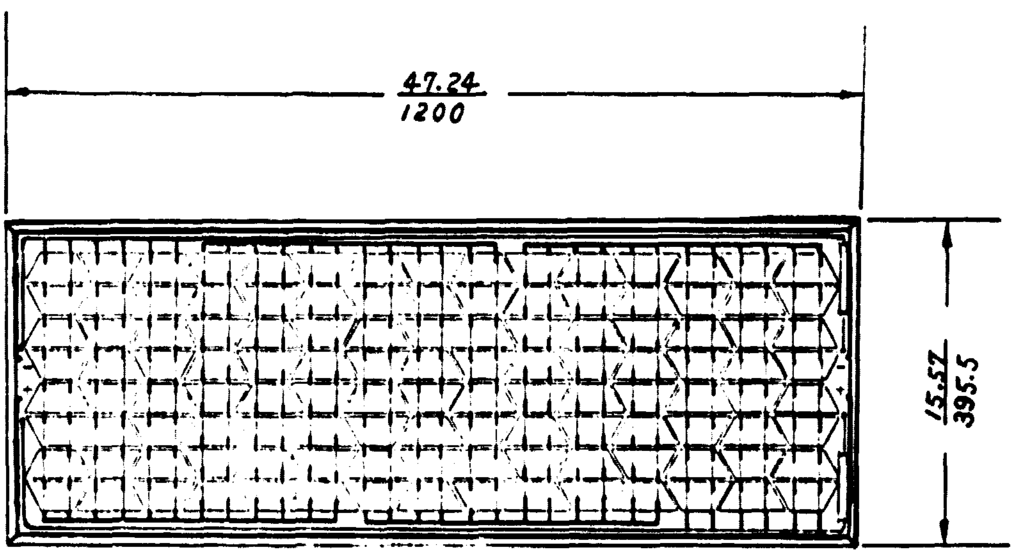
A GROUND CONNECTION STUD AT EACH END.

A BUILT-IN BY-PASS DIODE.

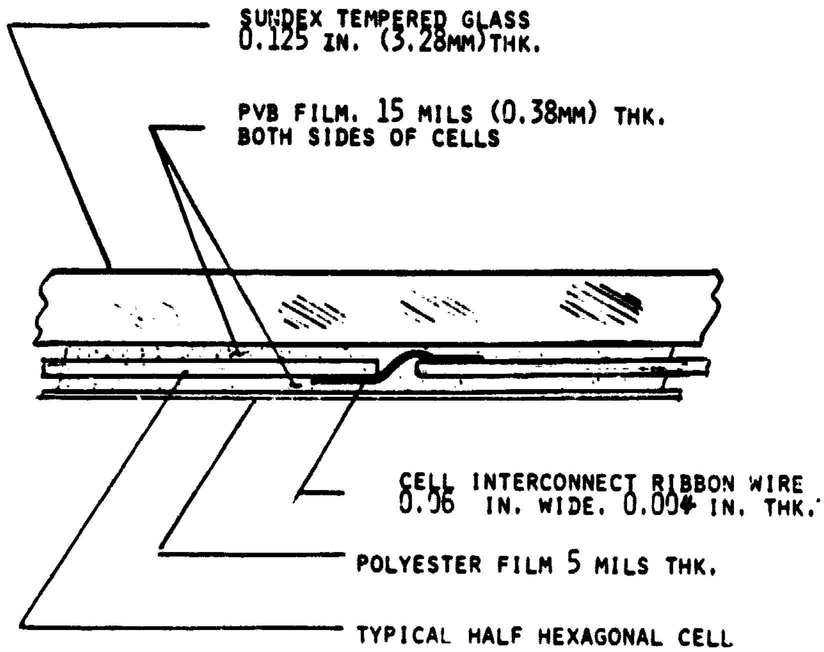
BLOCKING DIODE AS AN OPTION.

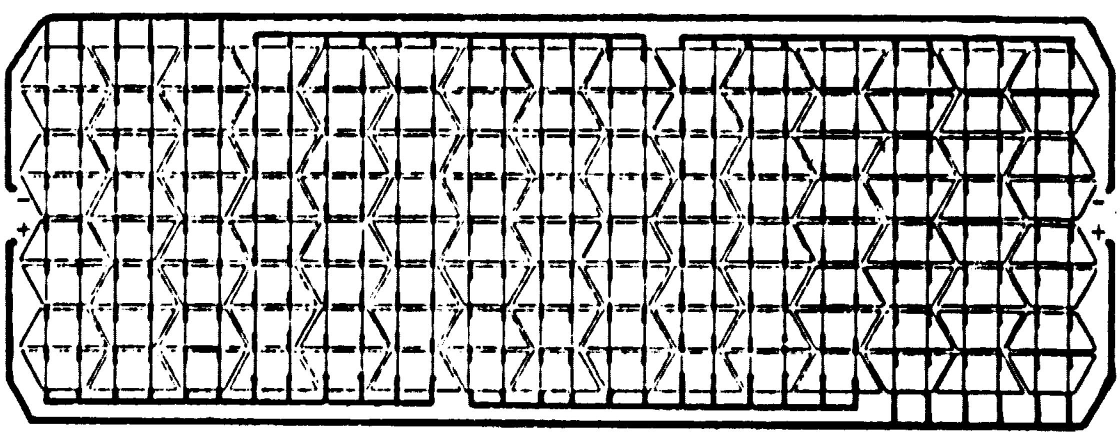
"QUICK-CONNECT" CONNECTORS.

Module Configurations

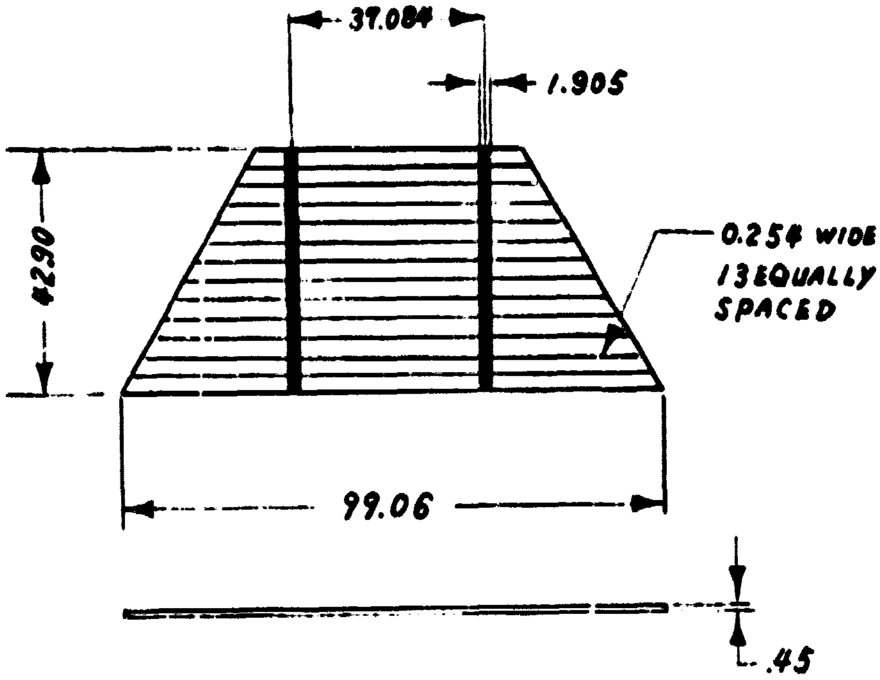


Cell Interconnect Diagram





Cell Co^figuration



Electrical & Related Data

(A) CELL ELECTRICAL PERFORMANCE AT OTC = 28°C

V_P	=	0.42 V	Isc	=	1.05 A
I_P	=	0.90 A	Voc	=	0.535 V
P_P	=	0.378 W	FF	=	0.673
Y CELL	=	11.86%			
$\Delta P/P$	=	± 8%			

(B) CELL TEMPERATURE COEFFICIENTS

$\Delta V/\Delta T$	=	-2.55 m V / CELL /°C
$\Delta I/\Delta T$	=	0.382m A / CELL /°C

* BASED ON REF. CELL NO. VS-417 & VS-419

(c) MODULE ELECTRICAL PERFORMANCES

AT OTC = 28°C, PEAK POWER POINT

POWER	=	43.09W
EFFICIENCY	=	9.10%
VOLTAGE	=	16.8V
CURRENT	=	2.57A

AT NOCT = 45°C, PEAK POWER POINT

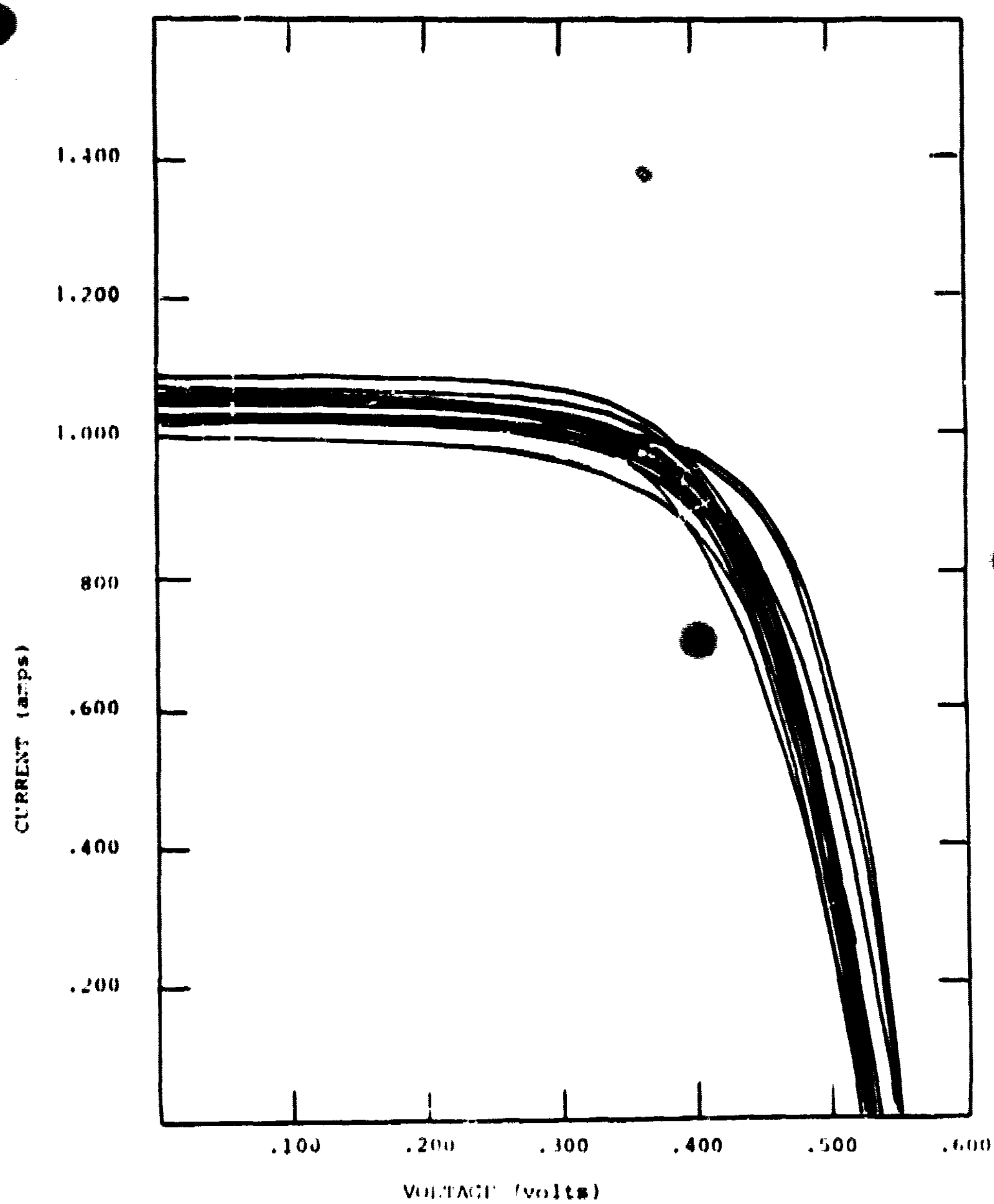
POWER	=	38.92W
EFFICIENCY	=	8.21%
VOLTAGE	=	15.07V
CURRENT	=	2.58A

AT SOC, (NOCT = 45°C, V = 15 VOLT)

POWER	=	37.90W
EFFICIENCY	=	8.00%
VOLTAGE	=	15V
CURRENT	=	2.53A

* TRANSMISSION LOSS OF SUPERSTRATE = 5%. MODULE PACKING EFFICIENCY = 80.7%

Cell Electrical Performance



AT OTC = 28°C, SAMPLE SIZE = 15 CELLS

Environmental Data

NO ENVIRONMENTAL TEST HAS PERFORMED AT PRESENT TIME*.

FOLLOWING TESTS AT TO BE PERFORMED:

NOCT MEASUREMENT A STE WIND LOAD TEST TWIST TEST	AT PHOTOWATT
THERMAL LOAD HUMIDITY LOAD	AT OUTS. E LAB.

HAZL STORM TEST - AT JPL

*TEST WILL CONDUCT ACCORDING TO THE SPECIFICATIONS IN JPL DOC. NO. 5101-16A.

Electrical Performance

(1) AVERAGE OUTPUT POWER AT SOC

MORE THAN TEN MODULES WILL BE TESTED TO DETERMINE THE RATED AVERAGE POWER OUTPUT. THE EXPECTED AVERAGE POWER OUTPUT IS ESTIMATED TO BE 38 WATT.

(2) MINIMUM MODULE POWER OUTPUT AT SOC

90% OF AVERAGE MODULE POWER OUTPUT WILL BE USED FOR ACCEPTABLE MINIMUM MODULE POWER. PREDICTED MINIMUM POWER IS 34 WATTS.

(3) NOMINAL OPERATING VOLTAGE

NOMINAL OPERATING VOLTAGE IS 15 VDC. THE PREDICTED PEAK POWER VOLTAGE AT NOCT OF 45°C IS 15.07 VDC.

(4) NOCT UNDER STANDARD THERMAL ENVIRONMENT (STE)

PREDICTION OF NOCT AT STE IS 45°C.

Electrical Design Requirements

(1) ELECTRIC VOLTAGE ISOLATION

THE INSULATION FOR EACH COMPONENT WAS DESIGNED TO MEET 500 VDC SYSTEM VOLTAGE, AND WILL WITHSTAND 2000 VDC.

(2) ELECTRICAL GROUNDING

THE ENTIRE MODULE IS LAMINATED WITH NON-CONDUCTIVE MATERIALS, EXCLUDING THE ALUMINUM FRAME. THEREFORE, ONLY THE ALUMINUM FRAME REQUIRES SAFETY GROUNDING STUDS. THIS IS PROVIDED AT THE CENTER OF BOTH ENDS OF THE ALUMINUM FRAME.

(3) MODULE ELECTRIC INTERFACE

TWO PARTS OF TERMINAL BLOCKS ARE USED FOR REDUNDANT TERMINATIONS OF MODULE OUTPUT. THESE TERMINALS ARE ALSO USED FOR THE BY-PASS DIODE (SHUNT DIODE). THE DESIGNED RATES OF THESE TERMINAL BLOCKS ARE 5 AMP AND 750 VDC.

(4) CELL STRING CIRCUIT RELIABILITY

ALL CELLS ARE INTERCONNECTED BY TWO RIBBON WIRES TO IMPROVE RELIABILITY. 8 CELLS ARE CONNECTED IN SERIES. THREE OF THESE STRING ASSEMBLIES ARE CONNECTED IN PARALLEL TO IMPROVE REDUNDANCY. AN INTEGRAL BY-PASS DIODE WILL BE PROVIDED AT THE TERMINAL BLOCK TO IMPROVE THE ARRAY RELIABILITY.

Mechanical Design Requirements

(1) MODULE GEOMETRY

A. MAXIMUM ENVELOPE DIMENSIONS ALL SATISFY DESIGN SPECIFICATIONS.

B. POLARITY OF OUTPUT TERMINALS ARE CLEARLY MARKED.

C. MOUNTING HOLE SPACINGS AND CLEARANCES SATISFY DESIGN SPECIFICATIONS.

D. CONSTRAIN OF VIEW ANGLE IS LESS THAN 30 DEGREES FROM ILLUMINATION SURFACE.

E. MAXIMUM WEIGHT IS 13 LBS.

(2) INTER-CHANGEABILITY

DIMENSIONS AND TOLERANCES ARE CHOSEN SO THAT NO PROBLEM WILL OCCUR IN VIEW OF MODULE INTER-CHANGEABILITY.

(3) OPTICAL SURFACE SOILING

TEMPERED GLASS IS USED AS A SUPERSTRATE. NO SOILING PROBLEM IS EXPECTED DUE TO SELF-CLEANING BY WIND AND RAIN.

(4) MODULE LABELING OF MANUFACTURER'S I.D.

THE FOLLOWING INFORMATION IS PROVIDED ON THE MANUFACTUER'S LABEL:

MODEL NO. 10-20-1849
SERIAL NO. XXXX
DATE OF MFG. XX-XX

MAX. SYSTEM VOLTAGE 500 VDC
NOMINAL VOLTAGE 15 VDC
NOMINAL POWER 38W

Environmental Design Requirements

(1) THERMAL LOAD

THE THERMAL LOAD DESIGN IS -40°C TO 90°C. THE CRITICAL AREAS WHICH MUST BE CONSIDERED DUE TO THIS THERMAL LOAD ARE AS FOLLOWS:

A. BETWEEN GLASS AND CELL

THE THERMAL COEFFICIENT OF GLASS IS THREE TIMES LARGER THAN THE THERMAL COEFFICIENT OF THE SILICON SOLAR CELL. THE THERMAL EXPANSION DUE TO THIS THERMAL COEFFICIENT MISMATCH CAN BE ABSORBED IF THE PVB FILM THICKNESS IS LARGER THAN 15 MILS FOR 4 IN. SILICON SOLAR CELL.

B. BETWEEN GLASS AND ALUMINUM FRAME

THE THERMAL COEFFICIENT OF ALUMINUM IS TWO AND ONE HALF TIMES LARGER THAN THE THERMAL COEFFICIENT OF GLASS. THIS MISMATCH OF THERMAL EXPANSION CAN BE ABSORBED IF THE BEARING STRIP AT THE EDGE SEALING HAS A THICKNESS OF 60 MILS OR MORE. THE REQUIRED MISMATCH DISPLACEMENT AT EACH EDGE IS 20 MILS.

C. ALUMINUM FRAME AND STEEL ARRAY MOUNTING FRAME

THE THERMAL MISMATCH AND MODULE TOLERANCES SHOULD BE ACCOUNTED FOR IN THE MOUNTING HOLE DESIGN. THE MINIMUM TOLERANCE OF THE HOLE AND BOLT MUST BE LARGER THAN 0.5 MM TO ABSORB THIS MISMATCH THERMAL EXPANSION AND MODULE TOLERANCES.

(2) HUMIDITY

MOUDLE SHOULD WITHSTAND 95% RH; FOR A PROLONGED TIME PERIOD

A. THE ENTIRE ALUMINUM FRAME IS MADE OF CORROSION RESISTANT 6063-T6 ALUMINUM, AND IT IS ANODIZED. ALL BOLTS AND NUTS ARE MADE OF STAINLESS STELL.

B. THE EDGE OF THE LAMINATED MODULE IS SEALED WITH SILICON RUBBER GASKET AND THE BACK SIDE IS PROTECTED BY POLYESTER FILM.

(3) MECHANICAL CYCLIC LOAD (WIND LOAD)

A. DESIGN REQUIREMENT IS 50 LBS/SQ.FT. LOAD FOR 1000°CYCLES.

B. PREDICTION OF GLASS STRESS IS 4059 PSI WHICH IS LESS THAN THE ALLOWABLE STRESS OF 8100 PSI.

C. MAXIMUM DEFLECTION OF GLASS IS 0.156 IN. WHICH IS SATISFACTORY.

D. CRITICAL STRESS OF ALUMINUM FRAME IS CALCULATED TO BE 3228 PSI WHICH IS LESS THAN ALLOWABLE STRESS OF 25000 PSI.

E. MAXIMUM DEFLECTION OF ALUMINUM FRAME IS 0.06 IN.

(4) TWIST TEST REQUIREMENT

NO THEORETICAL PREDICTION HAS BEEN MADE. THE CRITICAL AREA WILL BE THE CORNER JOINT AND CELLS.

(5) HAIL IMPACT TEST

ACCORDING TO JPL DOC. 5101-62, THE PREDICTED LIMIT OF HAIL SIZE WILL BE 1.25 IN. DIAMETER.

Cost Considerations

IN ORDER TO REDUCE THE MODULE COST TO MEET LSA IPEG GOAL OF \$4/WATT IN 1975 DOLLARS, THE FOLLOWING IMPROVEMENTS HAVE BEEN MADE.

(1) INCREASE OF PACKING EFFICIENCY FROM 67% TO 80.7%

TRADE-OFF COST CALCULATION SHOWS THAT THE MODULE COST WILL REMAIN THE SAME.

(2) NEW ENCAPSULATION METHOD

REPLACEMENT OF EXPENSIVE RTV AND ALUMINUM EXTRUSION WITH GLASS SUPERSTRATE MODULE REDUCES THE COST SIGNIFICANTLY.

(3) CHANGE TO LOWER COST SOLAR CELL FABRICATION PROCESSES

A. $POCl_3$ DIFFUSION IS REPLACED BY SPRAY ON DOPANT JUNCTION FORMATION.

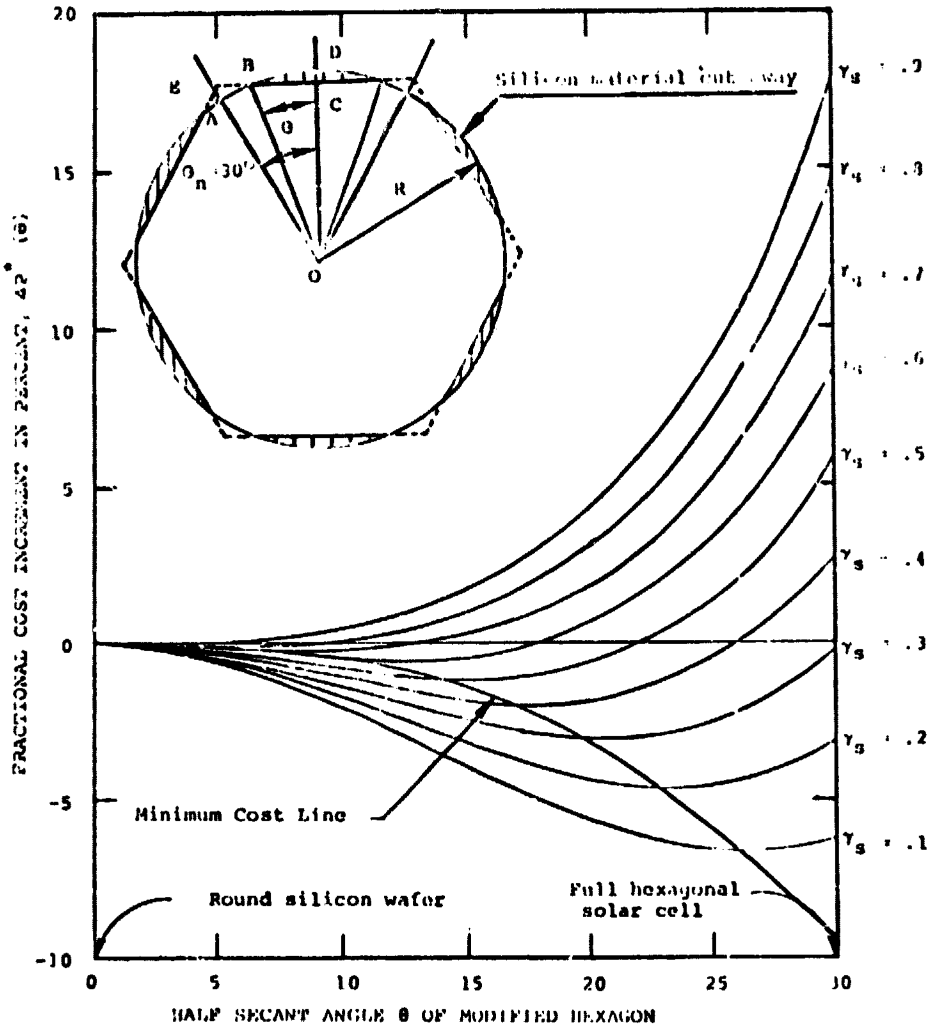
B. ALUMINUM BACK SURFACE IS REPLACED BY SPRAY ON BACK SURFACE FIELD.

C. SPRAY-ON AR COATING IS USED INSTEAD OF THE SILICON MONOXIDE EVAPORATION PROCESS.

THE INITIAL SAMICS ANALYSIS SHOWS THE PRE-PRODUCTION MODULE WILL ACHIEVE THE LSA IPEG GOAL.

Cost Summary, Type A Module, 1980 Price in 1975 $\$/W_p$

ITEMS	ELEMENT COST	SUB-TOTAL
1) WAFER PRICE (1980 IPG GOAL)		1.43
2) CELL PROCESS COST		0.91
A. SURFACE TEXTURIZING	0.015	
B. JUNCTION FORMATION	0.055	
C. METALLIZATION	0.300	
D. LASER SCRIBING	0.280	
E. SOLDER DIPPING	0.140	
F. ANTI-REFLECTIVE COATING	0.051	
G. CELL TEST	0.050	
3) MODULE ENCAPSULANT MATERIAL		0.345
A. GLASS (0.125 IN. THICK)	0.095	
B. P.V.B. FILM (TWO 15 MILS)	0.065	
C. MYLAR FILM TYPE A (5-MIL)	0.006	
D. OTHER FRAME, SEAL 2 TERMINALS	0.179	
4) MODULE ASSEMBLY		0.81
GRAND TOTAL		\$3.495/WATT



Fractional cost increment of silicon with minimum cost line and cost savings of an optimized modified hexagonal solar cell module.

Design Innovations and Advantages

(1) HIGHER MODULE EFFICIENCY

IMPROVED PACKING EFFICIENCY FROM 67% TO
80%.USE OF TEXTURIZING PROCESS.
NEW AR COATING.
ADDING BACK SURFACE FIELD

(2) LOWER COST MATERIALS AND PROCESS METHOD

LOWER COST ENCAPSULATION MATERIAL
LOWER COST SOLAR CELL PROCESSING METHODS
HIGHER PACKING EFFICIENCY
IMPROVEMENT OF MODULE EFFICIENCY

(3) IMPROVED ELECTRICAL PERFORMANCE RELIABILITY

REDUNDANT CELL CONNECTION	:	TWO WIRE INTER-CONN.
REDUNDANT STRING CONNECTION	:	THREE PARALLEL STRINGS
REDUNDANT TERMINAL OUTPUT	:	TWO PAIRS OF TERMINAL BLOCKS

(4) OTHER IMPROVEMENTS

BETTER WEATHERABILITY	:	RELIABLE EDGE SEALING
LIGHT WEIGHT	:	REDUCED FROM 4.2 LBS/SQ.FT. TO 2.4 LBS/SQ.FT.
REDUCED SOILING	:	SELF CLEANING GLASS TOP
SAFE UNDER HAIL STORM	:	TEMPERED GLASS SUPERSTRATE.

SOLAR POWER CORP.

I. OVERVIEW
- MODULE DESIGN CONSIDERATIONS
- SUBSYSTEM DESIGN TRADEOFFS

II. PRIMARY MODULE DESIGN
- TOTAL PACKAGE
- SUBSYSTEM DETAILS

III. FABRICATION TECHNIQUE

IV. ELECTRICAL PERFORMANCE
- MODULE - IV CURVE

V. DESIGN FEATURES

Module Design Considerations

- MATCH THERMAL EXPANSION COEFFICIENTS (CELLS & ENCAPSULANT PACKAGE)
- MAXIMIZE OPTICAL TRANSMISSION TO CELLS
- CHOOSE MATERIALS LEAST SUBJECT TO ATTACK BY ENVIRONMENT
- CHOOSE MATERIALS & CONSTRUCTION TECHNIQUES CONSISTENT WITH AUTOMATION
- EMPHASIZE RELIABILITY OVER COST <u>BUT</u>
- CHOOSE LOW COST MATERIALS TO ACHIEVE PERFORMANCE GOALS
- TEST INDIVIDUAL COMPONENTS AND PROTOTYPE ASSEMBLIES TO DETERMINE FAILURE MECHANISMS & THEIR LIKELIHOOD
- CONCEIVE OF MODULE AS PART OF AN ARRAY, NOT STAND ALONE ITEM

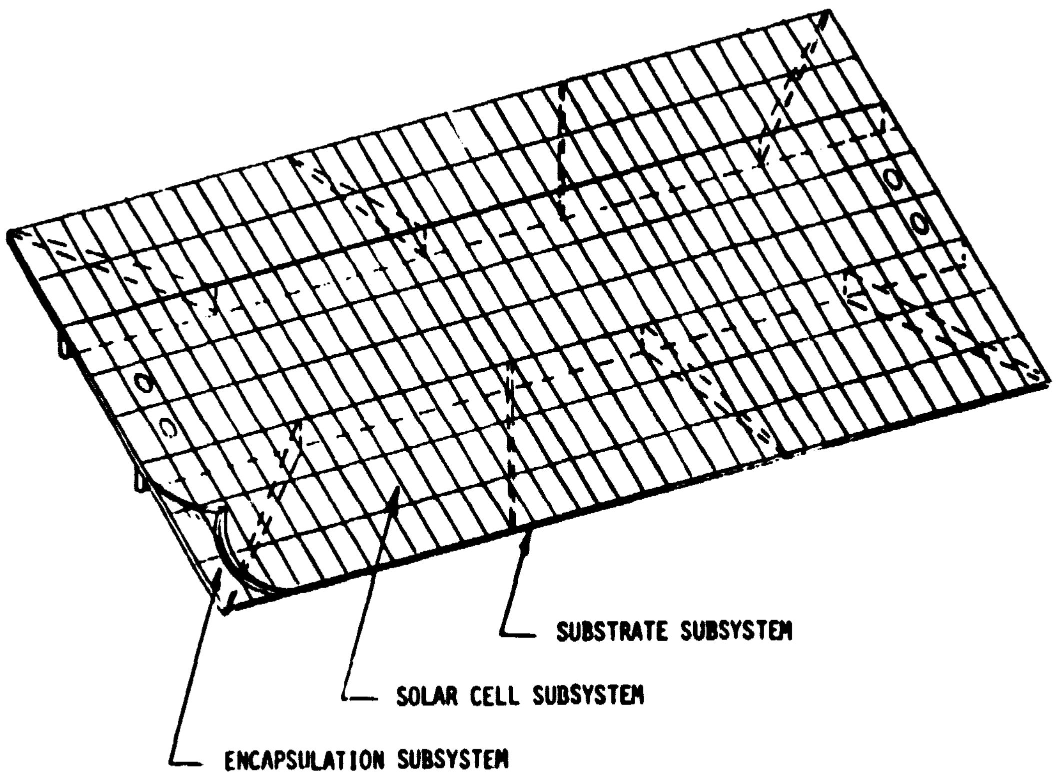
Subsystem Design Tradeoffs

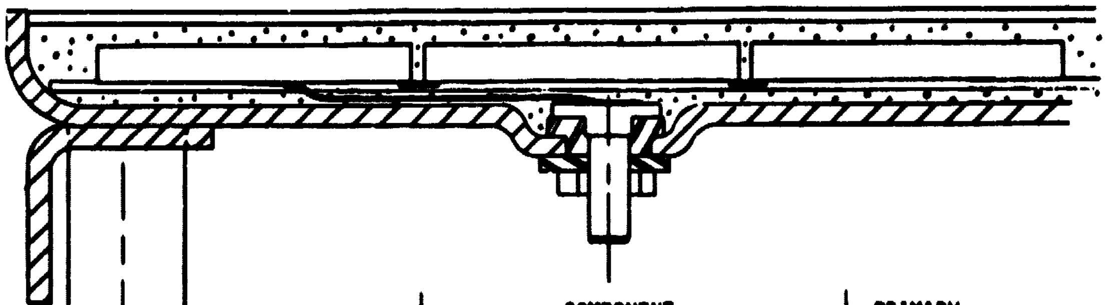
- **STRUCTURAL**
  - SUBSTRATE → MECHANICAL, $/STRENGTH, MANUFACTURABILITY, PACKING FACTOR, WEATHERABLE
  - SUPERSTRATE
  - OTHER

- **ENCAPSULATION**
  - SILICONE RUBBER
  - PVB
  - EVA → LOW MODULUS, $/LB., PROCESSABLE, OPTICAL QUALITY, CHEMICAL STABILITY
  - OTHERS

- **POWER GENERATION**
  - CIRCULAR CELLS
  - RECTANGULAR
  - RECTANGULAR SHINGLED
  - RECTANGULAR WRAP A. → MA/cm² - CELL, Wpk/ft² - MOD., AMENABLE TO AUTOMATION

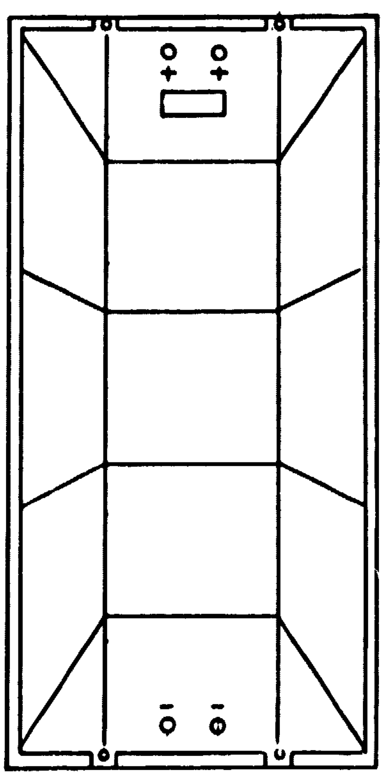
Primary Module Design





SUBSYSTEM	COMPONENT PARTS	PRIMARY FUNCTION
SUBSTRATE	LOW CARBON STEEL 2 COAT PORCELAIN ENAMEL (BLACK)	STRUCTURAL
SOLAR CELL	SINGLE CRYSTAL SILICON 5CU8.125 MESH INTER. BRASS TERMINALS HT. NYLON INSULATORS	POWER GENERATOR
ENCAPSULATION	5 MIL ACRYLIC TOP FILM .054" EVA (CLEAR) .005" FIBER GLASS SCRIM	CELL STRING PROTECTION & OPTICAL

Substrate Subsystem



MATERIALS

.042" C.R. LOW CARBON STEEL PAN, RIBS & GUSSETS
.072" C.R. LOW CARBON STEEL STIFFENERS
.687" DIA. C.R. LOW CARBON STEEL MOUNTING LUGS
.010" THICK ACID RESISTANT PORCELAIN ENAMEL COATING PER SIDE

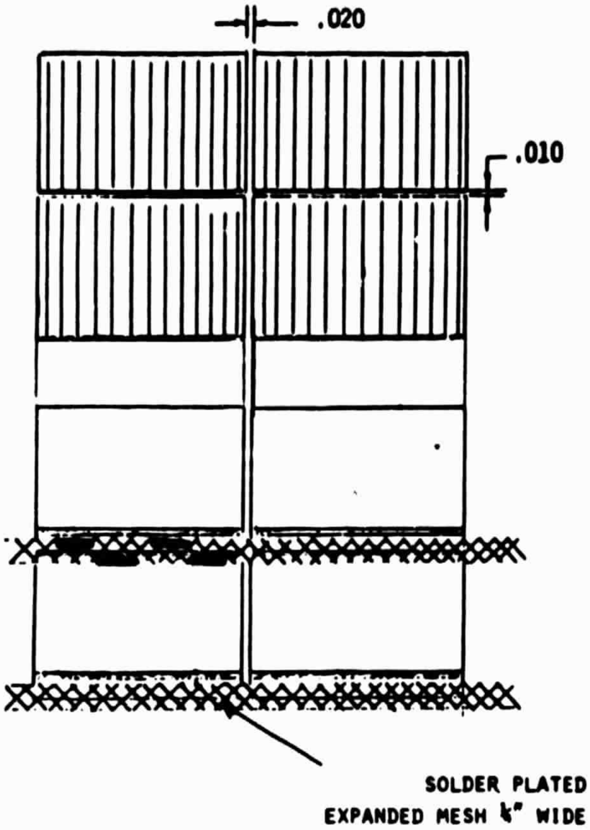
CONSTRUCTION

STAMPED & FORMED RIBS, GUSSETS & STIFFENERS-SPOT WELDED TO PAN
STAMPED OR DRAWN PAN
STUD WELDED TERMINAL LUGS
DIPPED & FIRED PORCELAIN ENAMEL (2 COATS)

STRUCTURAL DATA

DEFLECTION: .105" @ 50 PSF
FATIGUE STRENGTH: STIFFENERS & LUGS STRESSED BELOW ENDURANCE LIMIT
BUCKLING: STIFFENERS WILL WITHSTAND ≥ 120 PSF
MOUNTING LUG TORSIONAL STRENGTH: 35 FT-LBS ASSEMBLED
THERMAL EMMISSIVITY: .92 @ 72°F

Solar Cell Subsystem

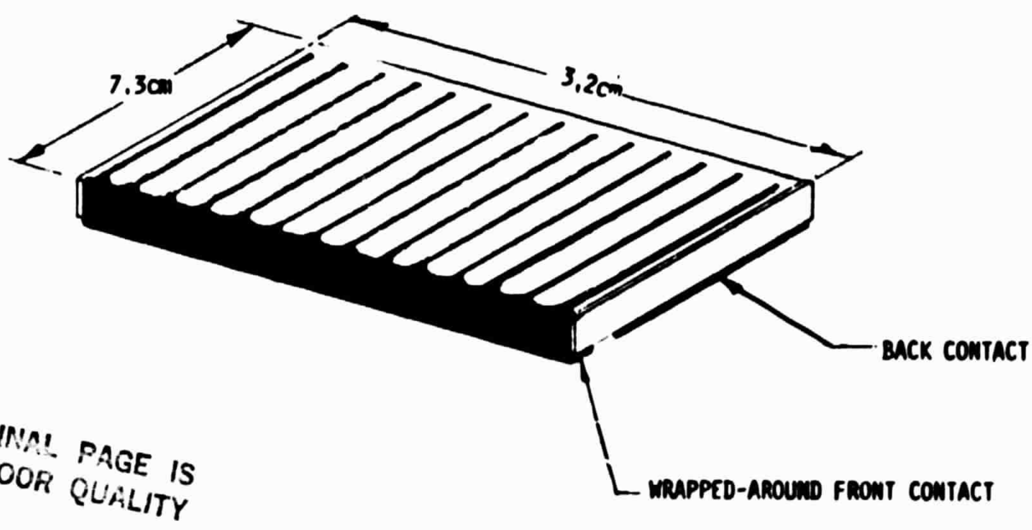


MATERIALS

- WRAPAROUND CONTACT CELLS (288)
- 5CU8.125EXPANDED MESH SOLDER PLATED ¼" WIDE
- 3/4" DIA X 1 1/8" LG BRASS TERMINALS (4)
- HT. NYLON INSULATORS (4)

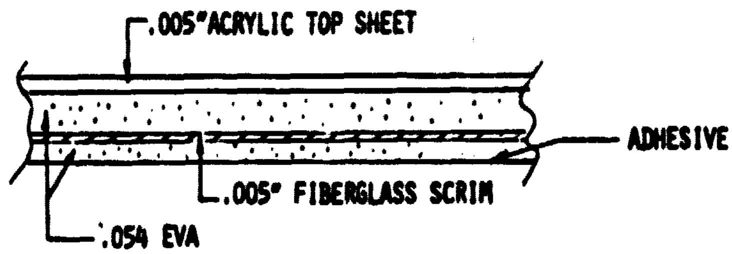
CONSTRUCTION

- 36 CELLS IN SERIES X 8 ROWS PARALLEL
- SOLDER REFLOW OF MESH TO REAR OF CELLS
- MESH PLACED ACROSS 8 ROWS
- TERMINALS SOLDERED TO LAST ROW OF MESH ON EITHER END OF STRING



Encapsulation Subsystem

MATERIALS



CONSTRUCTION

1 LAYER OF .018 THICK EVA
1 LAYER OF .005 THICK FIBERGLASS SCRIM
2 LAYERS OF .018 THICK EVA
1 LAYER OF .005 THICK ACRYLIC TOP SHEET

DEARATION OF ENTIRE SYSTEM
SCHEDULE OF HEAT AND PRESSURE
UNTIL EVA CURES & LAMINATE IS COMPLETE

DATA FOR PACKAGE

% TRANSMISSION: 93.8%

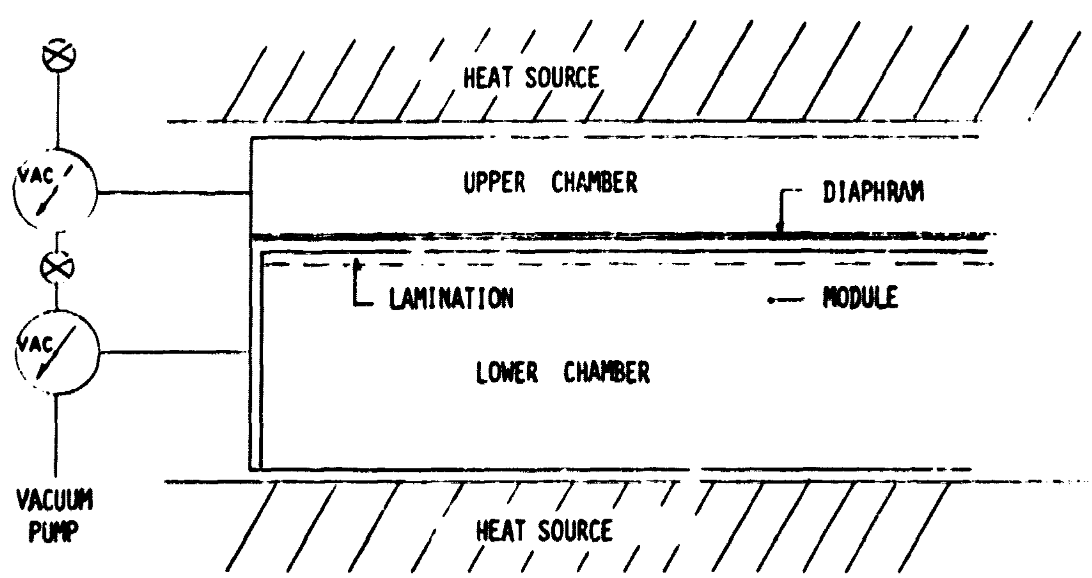
UV STABILITY: 3000 HRS RS4 ≤ 2% LOSS IN TRANSMISSION

IMPACT STRENGTH-SHOULD SURVIVE 3/4" HAIL @ 45 MPH

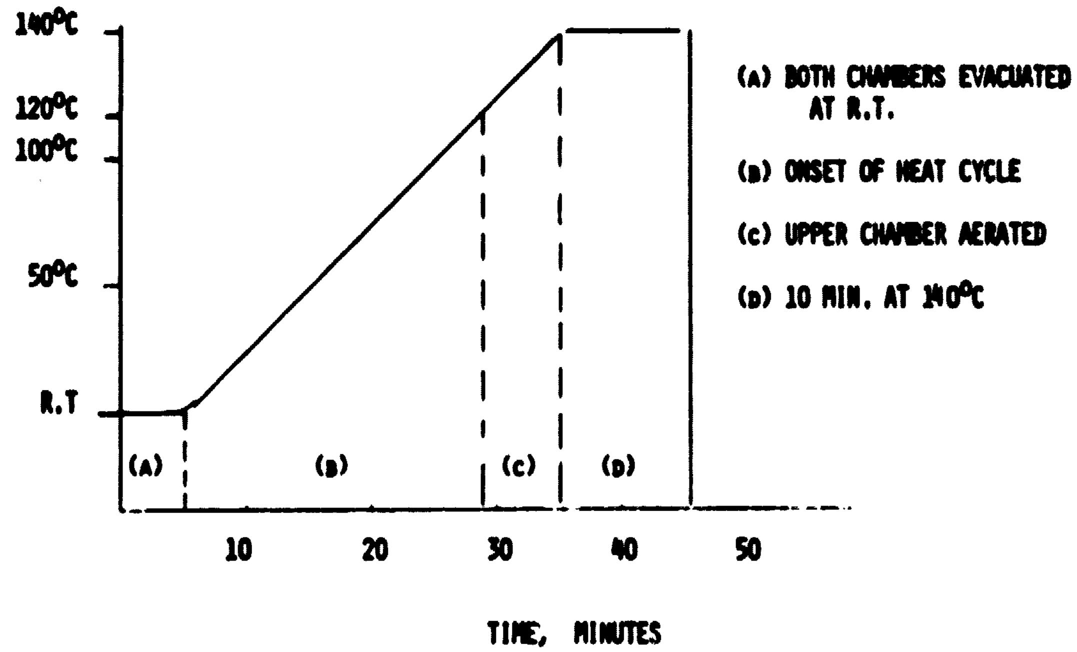
ADHESIVE STRENGTH: EXCELLENT (COHESIVE FAILURE ONLY)

THERMAL STIFFNESS: STRESS LEVELS < CELL STRENGTH AT INTERFACE

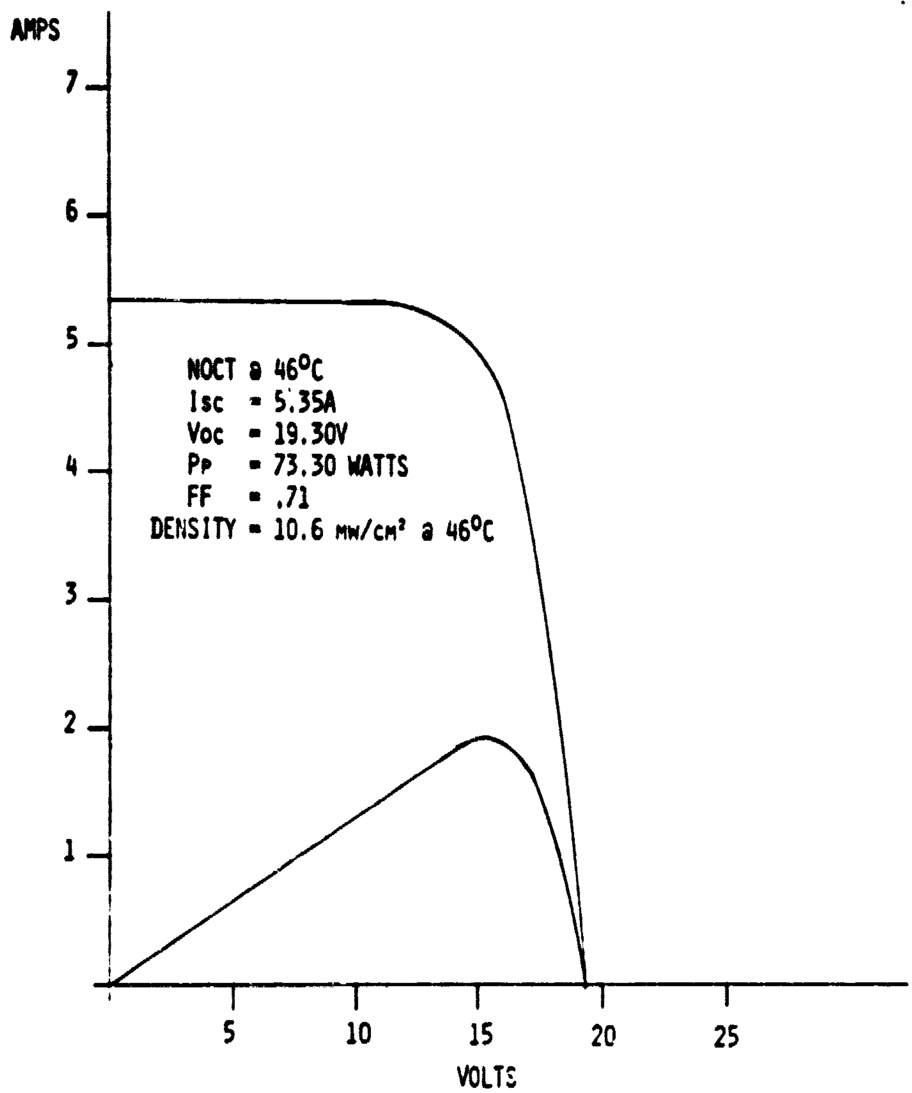
Fabrication Technique



Fabrication Cycle



Module I-V Curve



Design Features

- NEW MATERIAL EXPERIENCE
  - PORCELAINIZED STEEL
  - EVA
  - ACRYLIC COVER
  - SCRIM
  - MESH INTERCONNECT
  - WRAP AROUND CELL

- NEW FABRICATION METHODS

- LARGER & HIGHER Wpr MODULE

Module Specifications

Isc	5.35 AMPS
Vno @ SOC	15.0 Vdc
PEAK POWER AT SOC	73.3 WATTS
SERIES - PARALLEL CELL CONNECTION	36 x 8
DIMENSIONS	1.2M x .6M
ENVELOPE AREA	7200 cm^2
CELL AREA	6912 cm^2
Pn	.96

DESIGNED TO MEET JPL DOC. 5101-16 REV A.

SPIRE CORP.

Peter R. Younger

Module Features

- 40 X 120 CM (16 X 48 IN.)
- 152 CLOSELY PACKED RECTANGULAR CELLS
- REDUNDANT INTERCONNECTIONS
- 50 WATTS @ SOC
- SUNADEX GLASS COVER
- EVA ENCAPSULANT
- STAINLESS STEEL FRAME

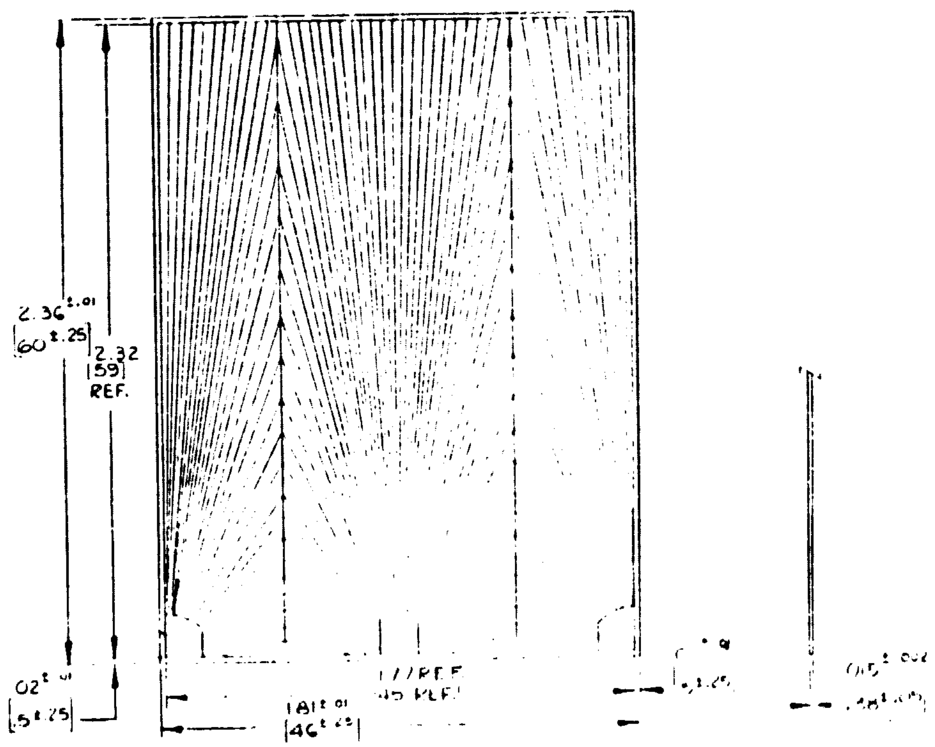
Module Interconnections

- CELL CONFIGURATION
    - 152 RECTANGULAR CELLS
    - 4 PARALLEL X 38 SERIES
- INTERCONNECTIONS
    - 3 POINTS EACH CELL FRONT
    - 4 POINTS EACH CELL BACK
    - MATERIAL - EXPANDED COPPER MESH
    - CONNECTION - SOLDERING
- PARALLEL CROSS TIES
    - AT EVERY SERIES CONNECTION

Cell Features

- $N^+/P\ P^+$ SILICON
- ION IMPLANTED JUNCTION AND BSF
- HIGH EFFICIENCY TO 15% (AM 1.5/25°C/POWER POINT)
- RECTANGULAR SHAPE FOR HIGH PACKING DENSITY
  - 4.6 X 6.0 CM
- OPTIMIZED CONTACT PATTERN

Solar Module Cell



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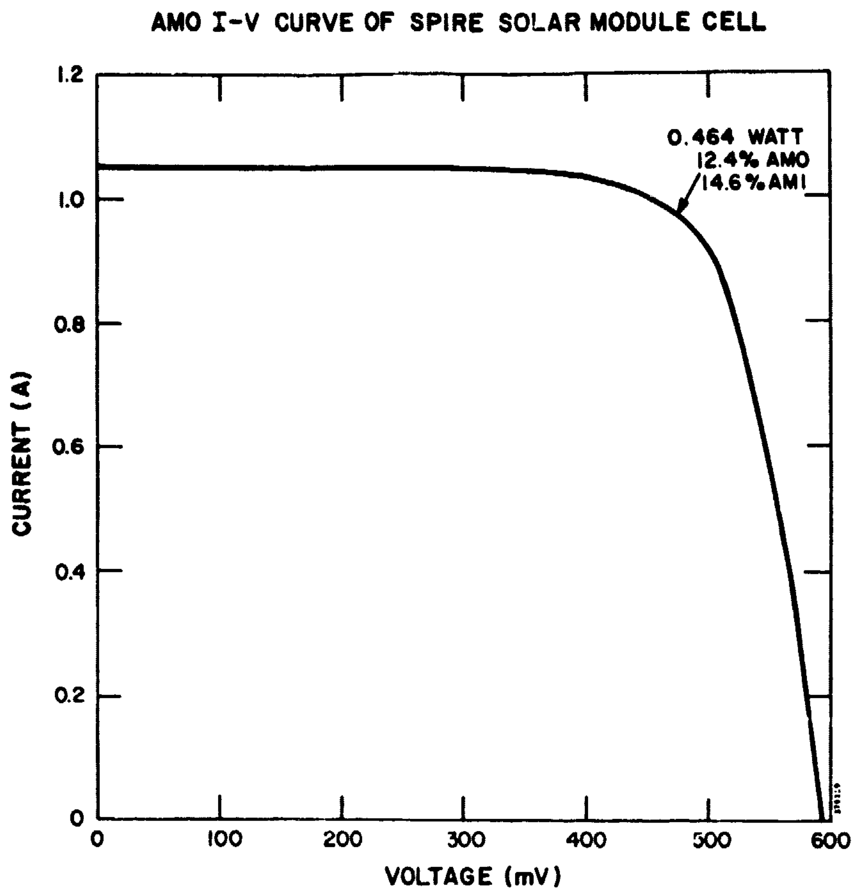
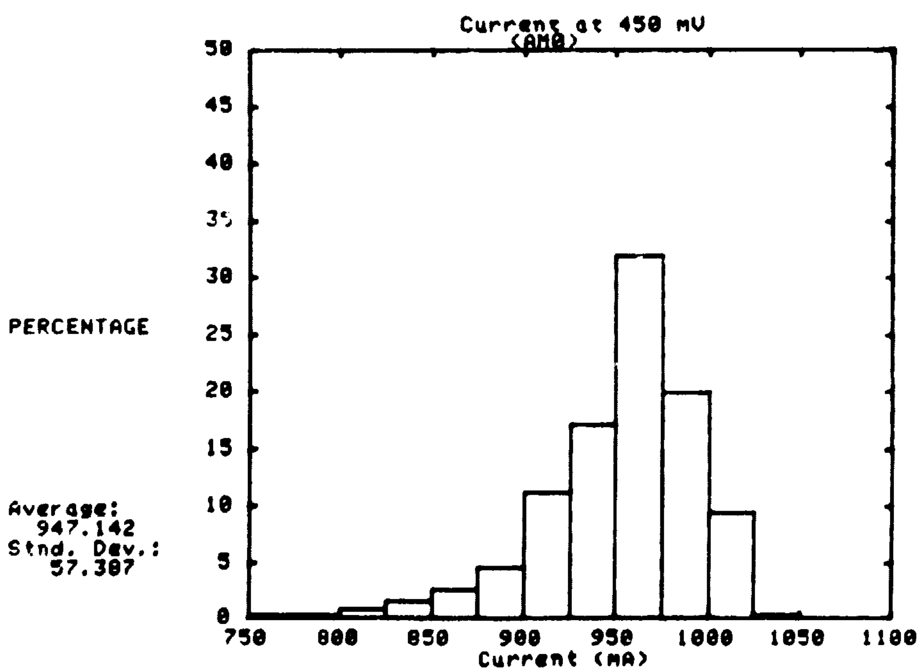


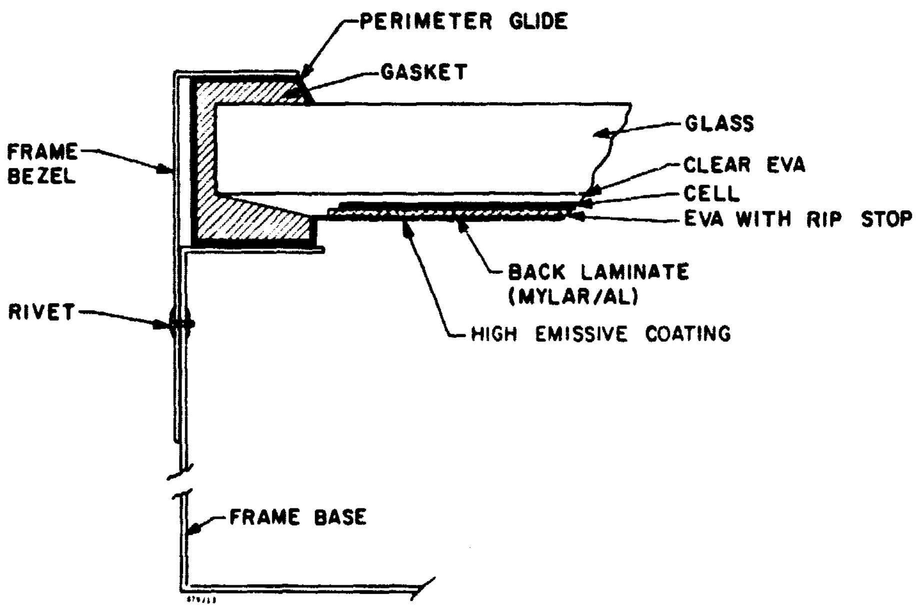
Performance Distribution, 400 Block IV Module Cells



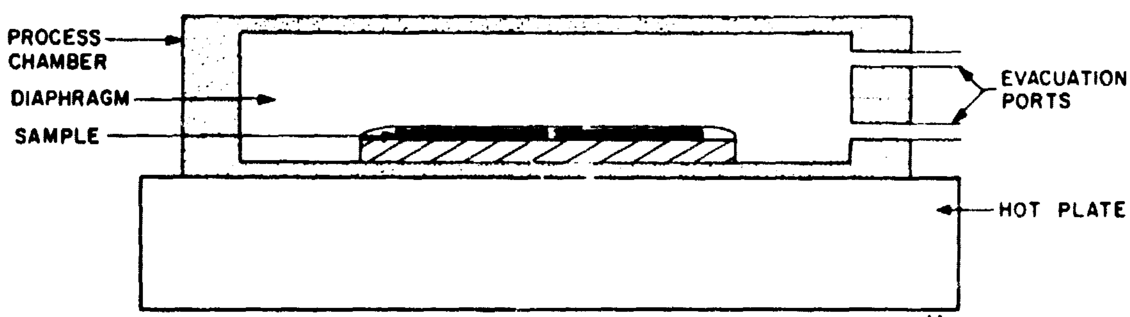
Encapsulation System Components

- SUNADEX GLASS
- CLEAR EVA
- CELLS
- POLYESTER RIP STOP
- MYLAR/ALUMINUM BACKING
- HIGH EMISSIVITY COATING ON BACK

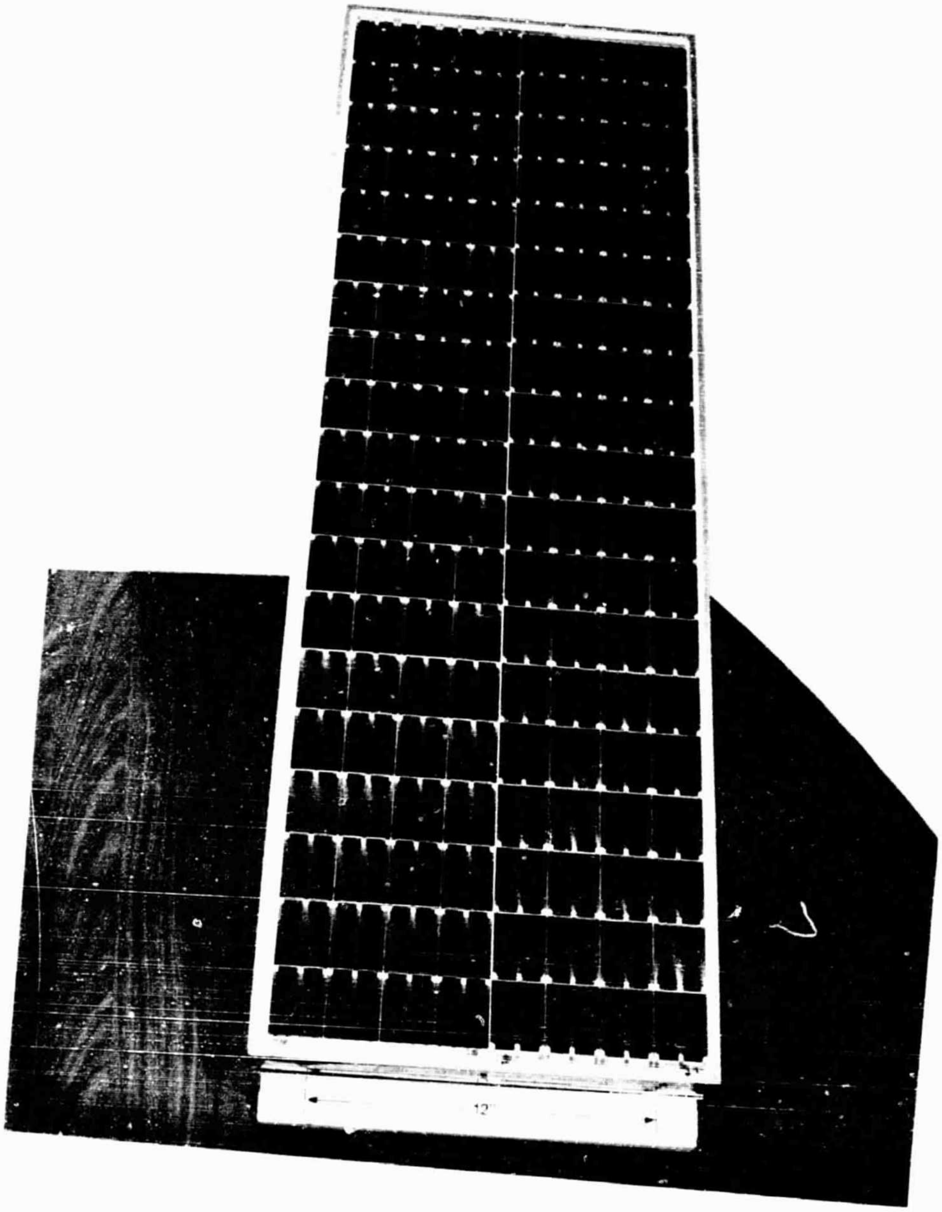
Major Components



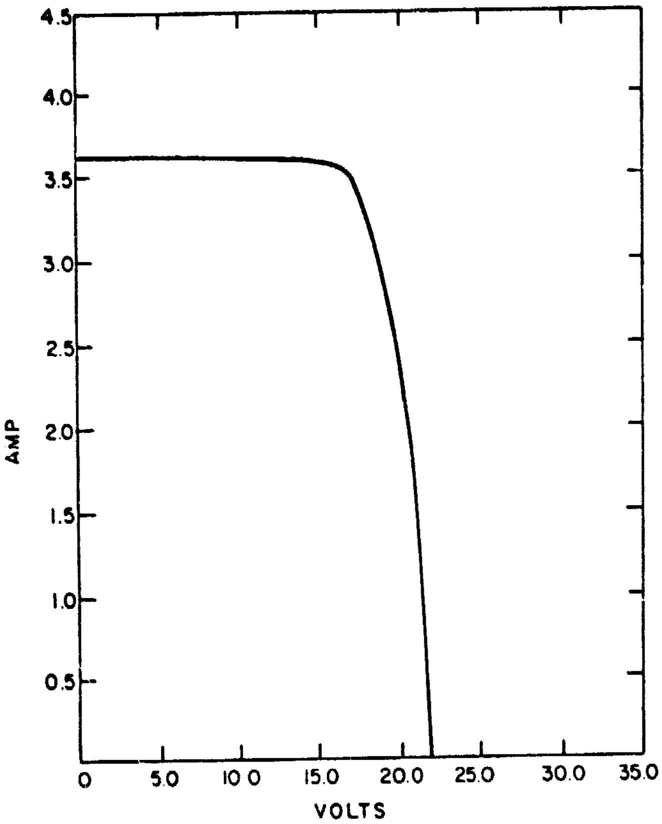
EVA Curing System



Block IV Module



Characteristics



SPIRE SOLAR MODULE

- 4 CELLS IN PARALLEL
- 38 CELLS IN SERIES
- DIMENSIONS 120 X 40 CM
- P_{max} = 60.3 WATTS
- PANEL EFFICIENCY 12.6% (28°C)

Performance Data

- PROGRAM GOAL
  - DELIVER 20 MODULES
  - 45 WATTS PER MODULE
    - AT SOC
    - V_{no} = 15 VOLTS
- PROTOTYPE MODULE PERFORMANCE
  - AT 28°C
    - P_{max} = 60.3 WATTS
    - PANEL EFFICIENCY 12.6%
  - AT SOC, V_{no}
    - P_{15V} = 53.6 WATTS
    - PANEL EFFICIENCY = 11.2%

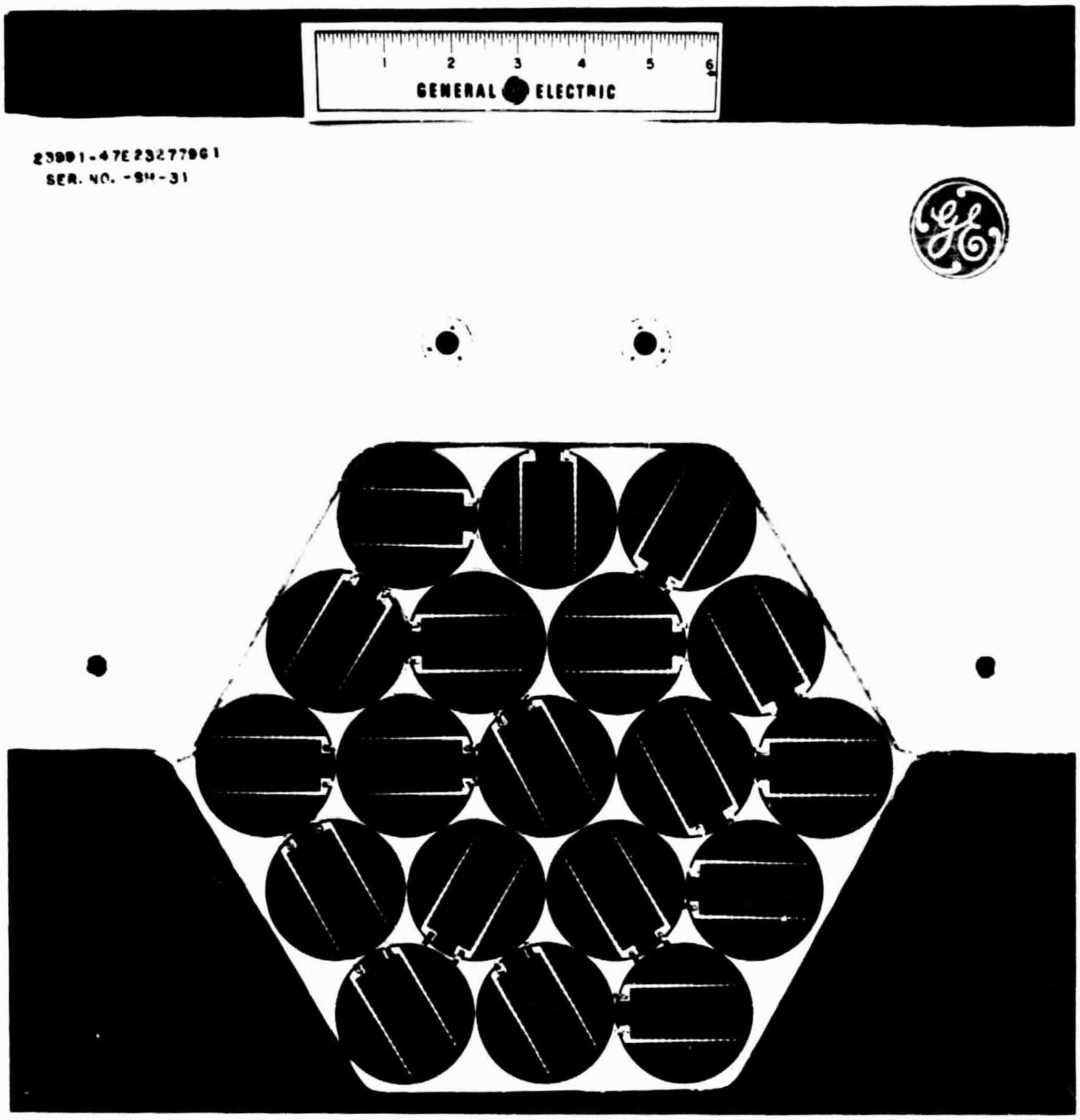
Program Status and Summary

- PROTOTYPE MODULE FABRICATED
  - ALL DESIGN ELEMENTS VERIFIED
  - ALL FABRICATION PROCESSES DEMONSTRATED
  - PERFORMANCE GOAL EXCEEDED
- MODULE FABRICATION
  - QUALIFICATION MODULES BEING MADE

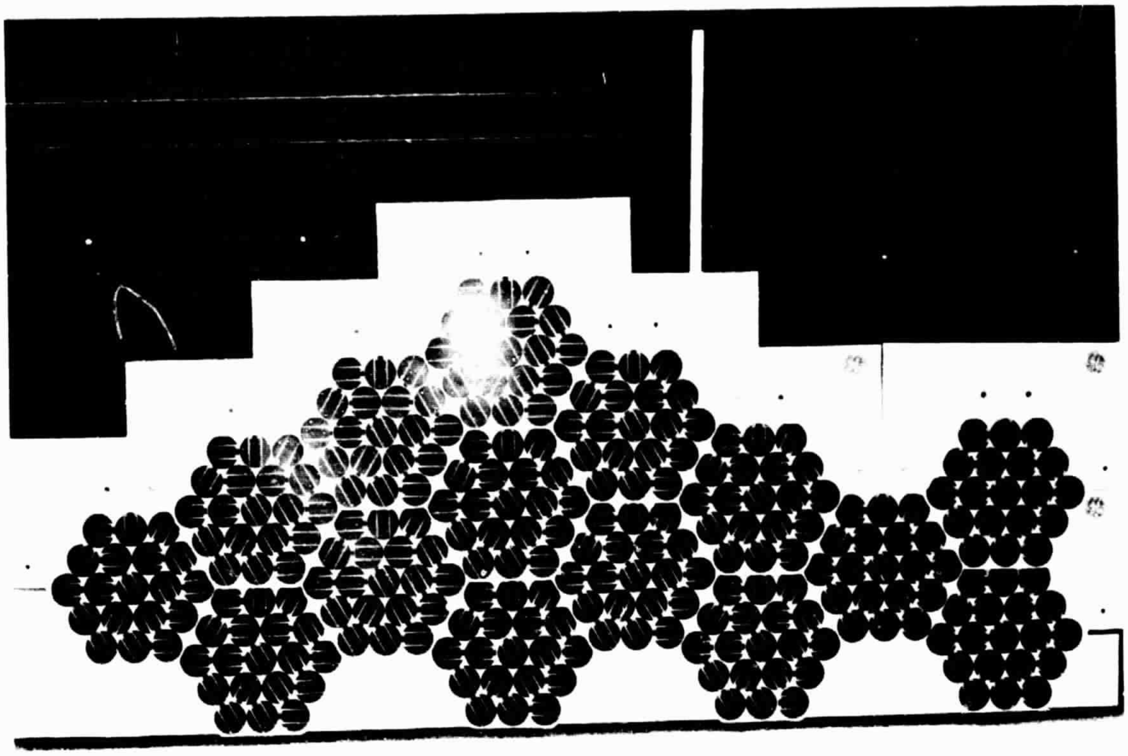
GENERAL ELECTRIC CO.

Neal Shepherd

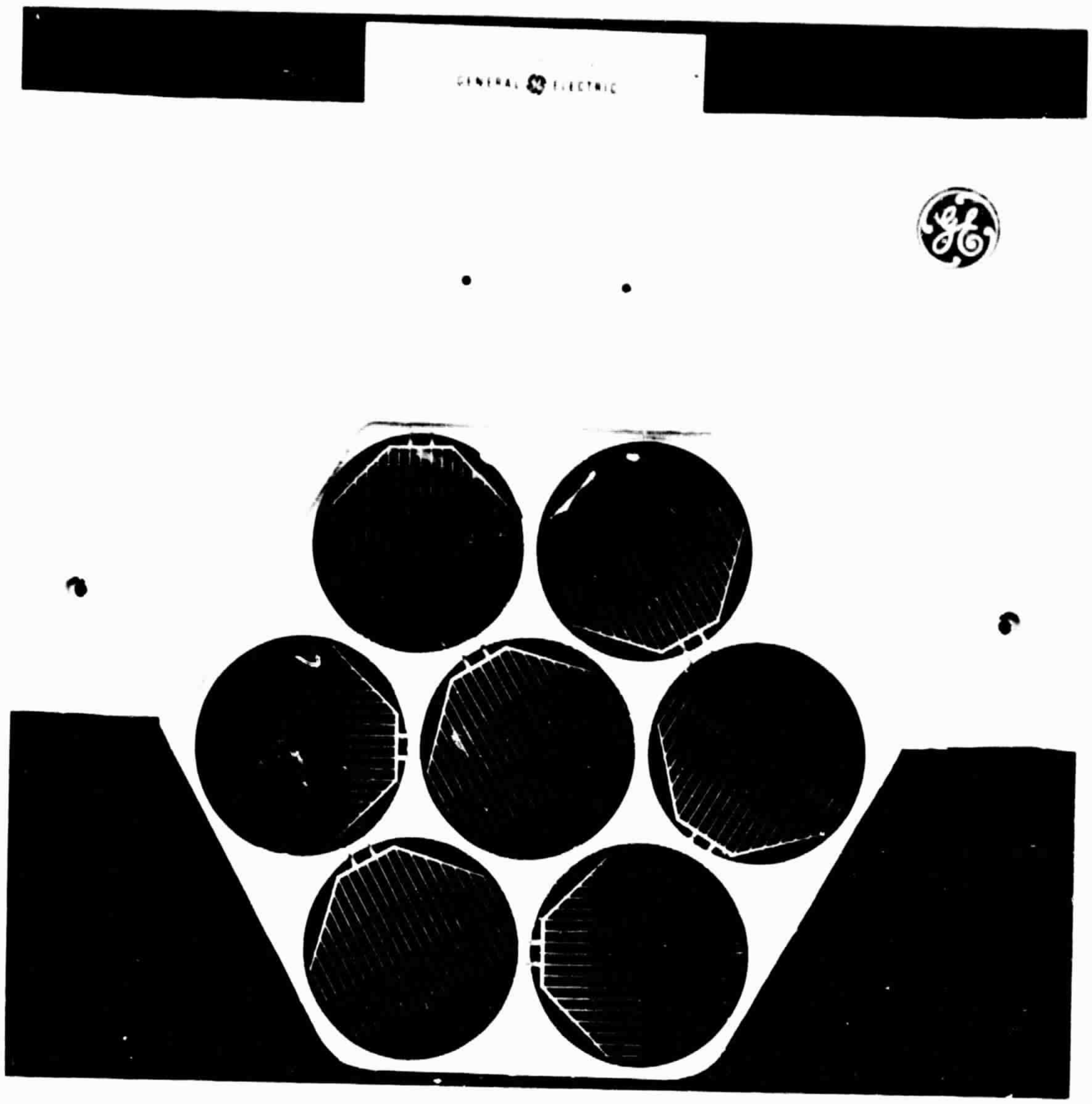
First-Generation Shingle Module



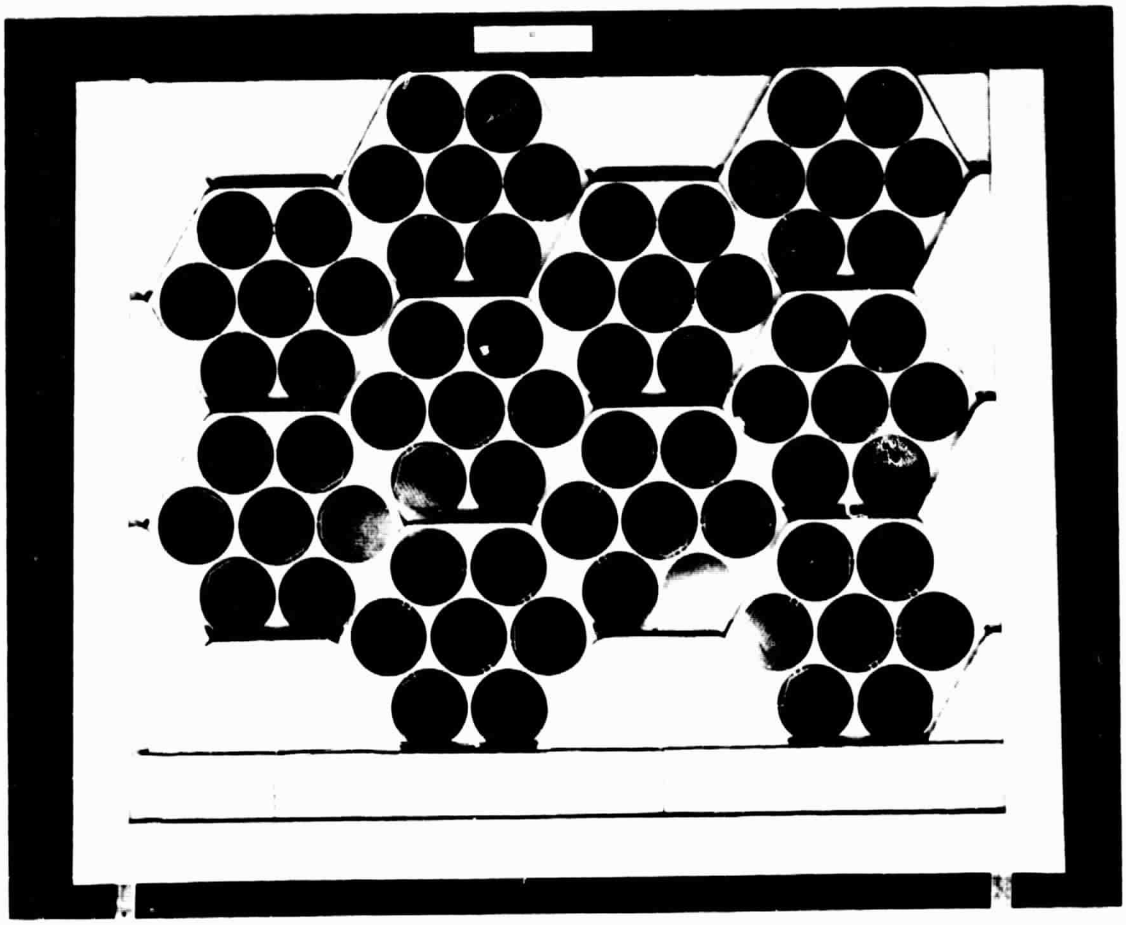
Array of First-Generation Shingle Modules

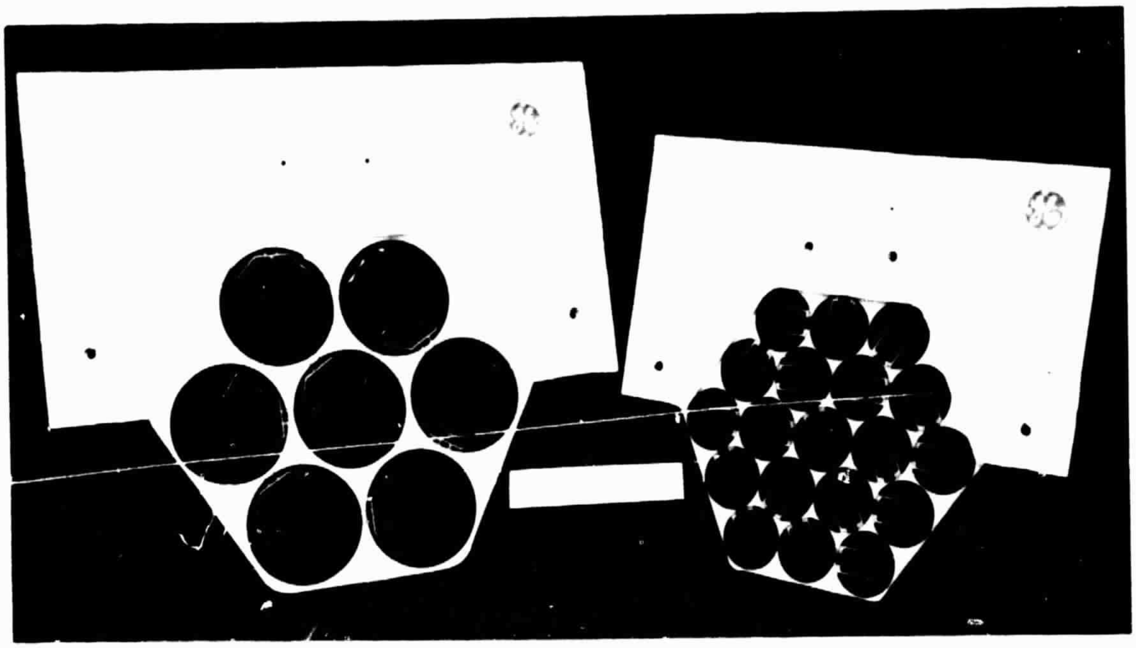


Second-Generation Shingle Module



Array of Second-Generation Shingle Modules





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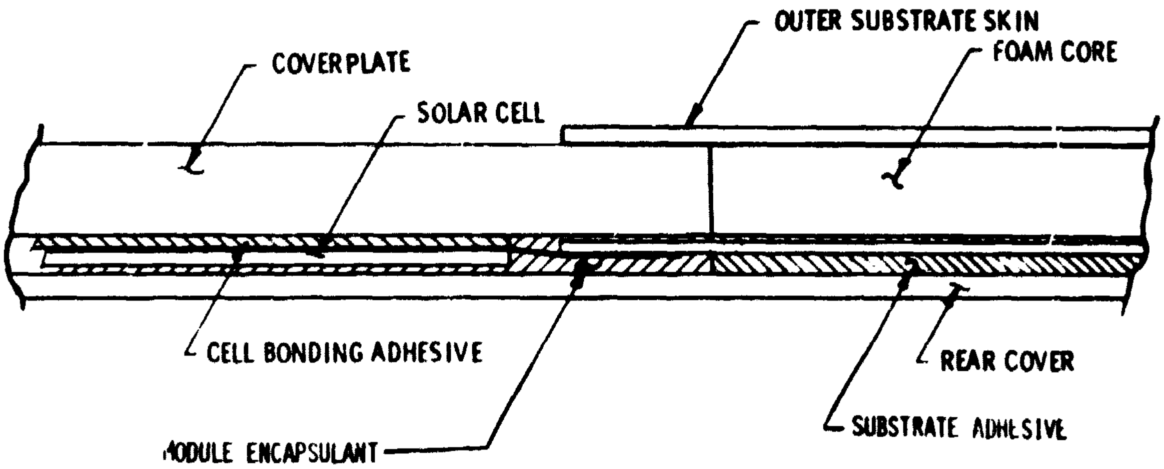
Comparison of Shingle Module Designs

PARAMETER	First-Generation (JPL 954607)	Second-Generation (PRDA-38)	Third-Generation (JPL 955401)
Solar Cell Diameter (mm)	53	100	100
Solar Cell Supplier	Spectrolab	Solarex	Arco-Solar
Number of Solar Cells	19	7	19
Total Solar Cell Area (m^2)	0.0419	0.0550	0.1481
Exposed Module Area (m^2)	0.0507	0.0743	0.1955
Module Packing Factor	0.826	0.740	0.758
NOCT (°C)	61 (1)	57 (1)	64 (2)
Maximum Power Output at SOC (watts)	4.93 (1)	5.88 (1)	17.14 (2)
Areal Specific Output (W/m^2 module area)	97.2	79.1	87.7
Module Weight (kg)	1.00	1.45	3.85
Areal Specific Weight (kg/m^2 module area)	19.7	19.5	19.7
Power-to-Weight Ratio (W/kg)	4.93	4.06	4.45

(1) NOCT at 80 mW/cm^2 insolation

(2) NOCT at 100 mW/cm^2 insolation

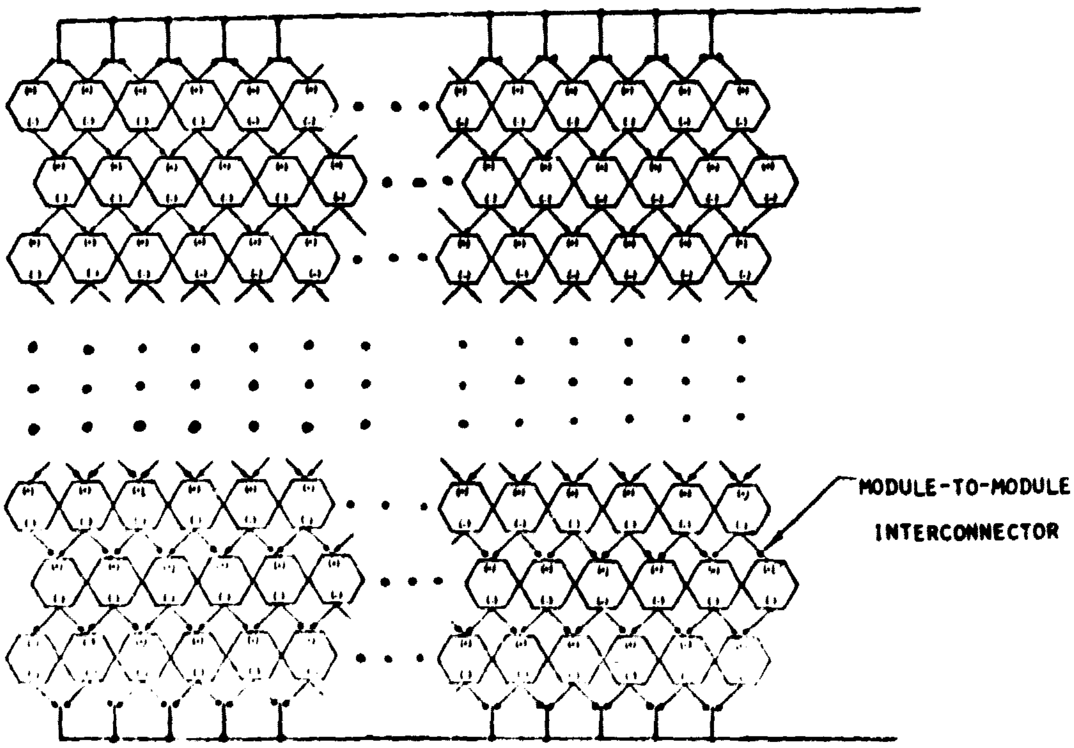
Shingle Module Construction



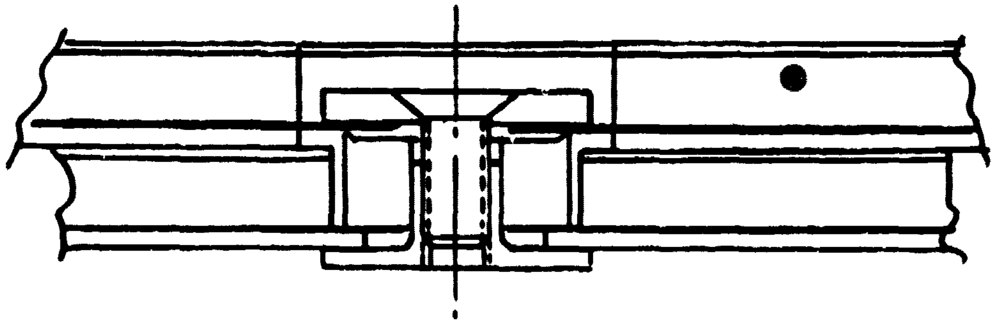
Shingle Materials

COMPONENT	MATERIAL
COVERPLATE	SUNADEX GLASS, THERMALLY-TEMPERED, .188 IN. THICK
OUTER SUBSTRATE SKIN	FLEXSEAL WHITE SUPPORTED HYPALON WITH 6 X 6 POLYESTER SCRIM
FOAM CORE	L-200 MINICELL POLYETHYLENE FOAM, .188 IN THICK
REAR COVER	PAN-L BOARD, .056 IN. THICK
CELL BONDING ADHESIVE	GE 534-044 SILICONE POTTANT
MODULE ENCAPSULANT	GE 1202 SILICONE CONSTRUCTION SEALANT
SUBSTRATE ADHESIVE	M6338 SILAPRENE

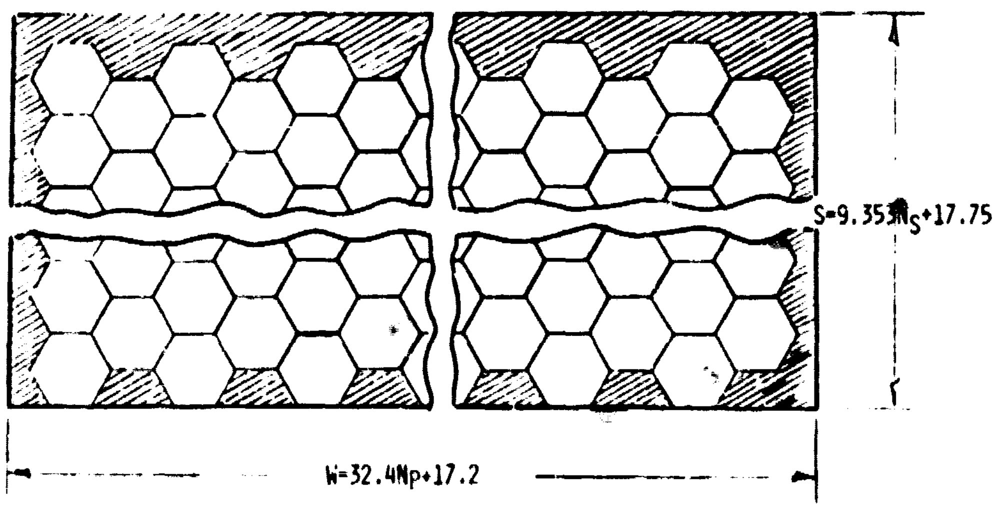
Module Interconnection Electrical Schematic



Module-to-Module Interconnection



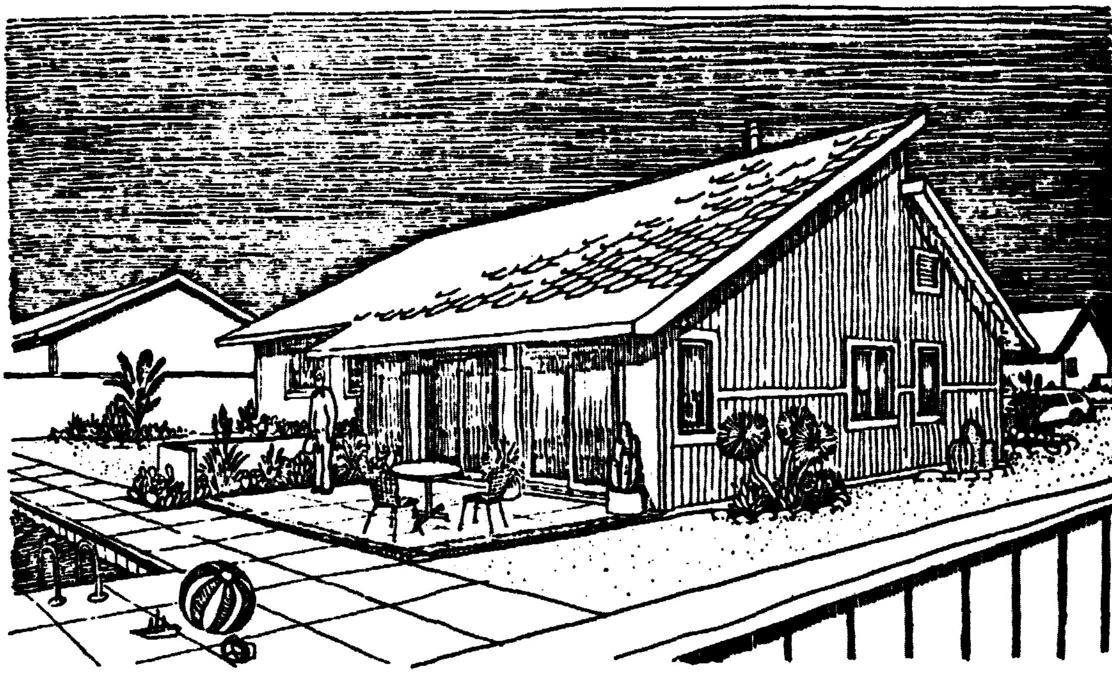
Shingle Arrangement on a Rectangular Roof



N_S = NUMBER OF SERIES-CONNECTED MODULES

N_P = NUMBER OF PARALLEL-CONNECTED MODULES

Residential House Perspective



Typical Residential System Performance

PARAMETER	VALUE
NUMBER OF MODULES (25 SERIES X 19 PARALLEL)	475
TOTAL SOLAR CELL AREA (M^2)	70.3
TOTAL EXPOSED MODULE AREA (M^2)	92.9
TOTAL GROSS ROOF AREA (M^2)	104.3
ARRAY OUTPUT AT SOC (kW PEAK) NOCT = 64°C	8.03

	PHOENIX	ALBUQUERQUE
ANNUAL DC ENERGY INPUT TO INVERTER (kWh)	19763	20682
ANNUAL AC ELECTRICAL ENERGY OUTPUT (kWh)	17455	18336
ANNUAL INSOLATION ON ARRAY SURFACE		
ANNUAL INSOLATION ON ARRAY SURFACE (kWh/M^2)	2348	2350
OVERALL SYSTEM EFFICIENCY $\frac{\text{SYSTEM AC OUTPUT}}{\text{INSOLATION X MODULE AREA}}$	8.0%	8.4%

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SOLAREX CORP.

Contract Scope

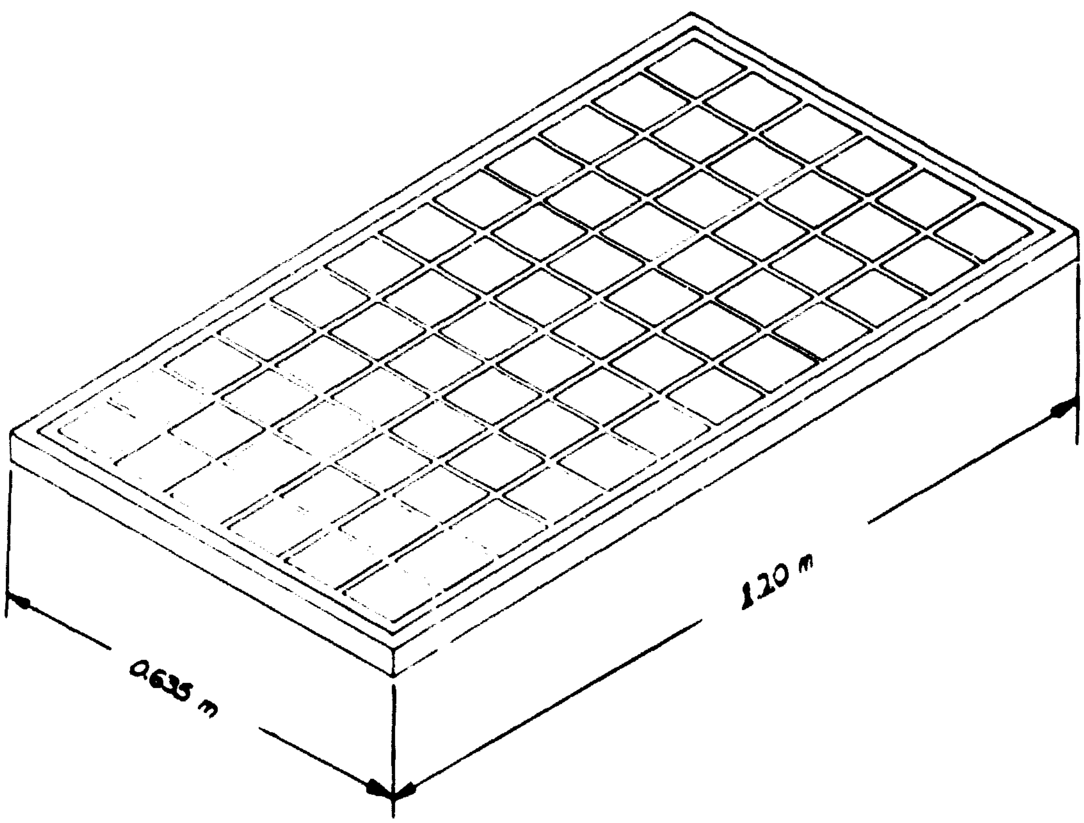
18 INTERMEDIATE LOAD MODULES

18 RESIDENTIAL LOAD MODULES

FIVE OF EACH TYPE TO JPL ENVIRONMENTAL TEST

SAMIS/SAMICS PARTICIPATION

36 2 x 2cm REFERENCE CELLS



Design Characteristics

- 63.5 CM X 120 CM OUTSIDE DIMENSION
- 9.5 CM X 9.5 CM SEMICRYSTALLINE CELLS
- ARRAY CONFIGURATION - 6 WIDE X 12 LONG
- 3/16" TEMPERED GLASS
- EVA POTTANT
- WHITE TEDLAR MOISTURE BARRIER

Electrical Design, Intermediate Load

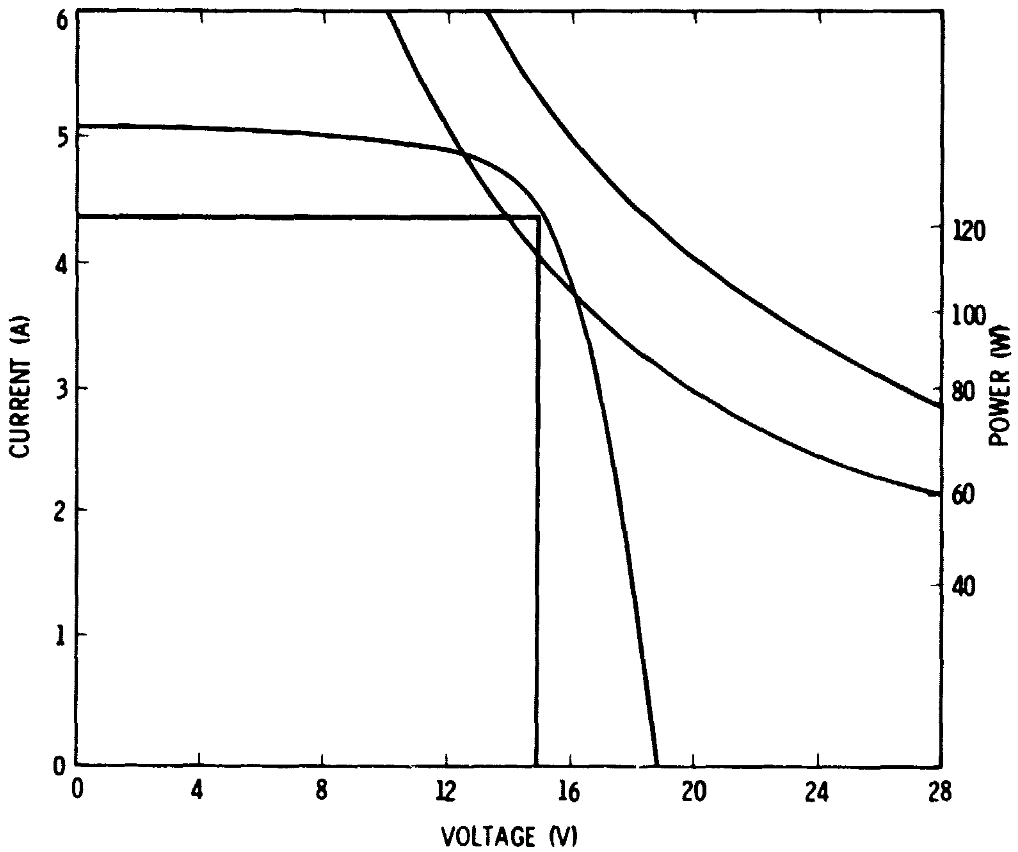
- Two 36 CELL STRINGS
- EACH CELL CONNECTED IN PARALLEL WITH ONE OTHER
- 2 P x 36 S x 36 SEB CONFIGURATION
  AT: NOCT ($51^{o}C$)
  $100 MW/CM^2$

V_{OC} = 18.8 VOLTS

I_{SC} = 5.08 AMPS

V_{PP} = 14.6 VOLTS

POWER (15 VOLTS) = 65.4 WATTS

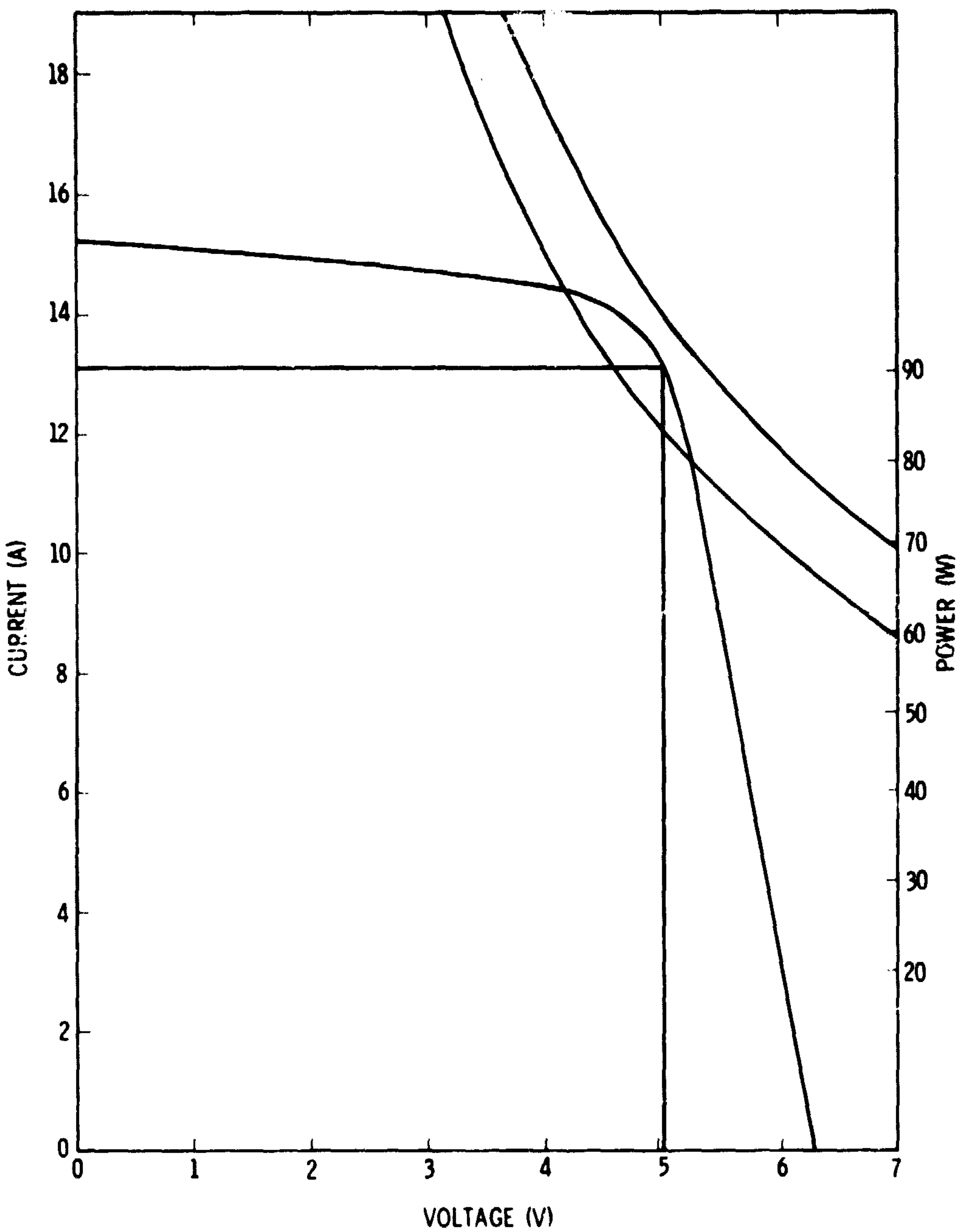


Electrical Design, Residential

- Six 12 cell strings
- Every six cells connected in parallel
- 6 P x 12 S x 12 SEB configuration

AT: NOCT (51°C)
100 MW/CM^2

V_{OC} = 6.3 VOLTS
I_{SC} = 15.24 AMPS
V_{PP} = 4.9 VOLTS
POWER (5 VOLTS) = 66.0 WATTS



Cell-Interconnect Design

SIX PADS PER CELL

AFTER TABBING - ALL INTERCONNECTS FROM BACK

INTERCONNECT MATERIAL - COPPER CLAD FLUORO-GLASS

Frame Design, Intermediate Load

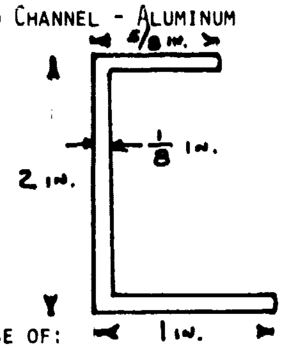
ONE PIECE

ANODIZED ALUMINUM

MODIFIED CHANNEL

Frame, Intermediate Load

1/8" MODIFIED CHANNEL - ALUMINUM



CHOSEN BECAUSE OF:

- SIMPLICITY
- EASE OF MANUFACTURE
- ECONOMY
- MOUNTING SIMPLICITY
- RIGIDITY

FEATURES:

- ONE PIECE
- MECHANICAL SUPPORTS IN CORNERS AND NEAR "SPLIT"
- DRAIN HOLES
- GROUNDING PROVISION

TECHNOLOGY DEVELOPMENT AREA

Encapsulation Task

During the PIM Module Design session a presentation outlined the design and performance criteria developed for each of the functional elements making up a complete solar module encapsulation system. The functional elements reviewed were the module front surface, front cover, pottant, spacers, structural panels, back cover, and edge frame support and seal. Within the LSA 1986 price goal allocation guidelines for the encapsulation materials of $14/m^2 (1980 $) or 10¢ to 14¢/Wpk, several candidate material systems have been developed. These material systems are now undergoing intensive evaluation by industry and by JPL relative to potential module service life, preferred fabrication methods and effects on module performance. A summary of the status of these candidate materials is given in a following chart.

The major unknown in the selection of the lowest-cost candidate encapsulation system is the potential of achieving a 20-year service life. However, available data and current research on individual module degradation mechanisms (such as polymer degradation, metal corrosion or module structural damage) indicate that a 20-year life is reasonable for one or more of the candidate material systems.

The emphasis of the LSA-supported effort has been on developing new and very low-cost encapsulation material systems and process for meeting the 1986 price goals and beyond. The near-term solar module applications that are cost-effective at $2.00 to $5.00/Wpk can consider more rugged designs costing 15¢ to 30¢/Wpk or more than $30/m^2 for materials. This larger allocation justifies the use of low-iron tempered-glass superstrates with glass or metal backside panels. Silicones or polyvinyl butyral are currently used as pottants in commercial solar modules. In properly sealed packages, solar arrays should certainly last 20 years or more. For the extreme stresses experienced by navigational aids subject to tropical or arctic marine environments, an all-borosilicate-glass sealed envelope filled with silicone rubber is state-of-the-art.

An advanced concept developed by Spire Inc. and under evaluation is the electrostatic bonding (ESB) of solar cells directly to glass with a backside panel of shaped glass bonded at the module periphery forming a complete hermetic envelope for the solar cells.

The LSA approach to developing the lowest-costing encapsulation system has been to define the minimum performance requirements for each functional element and then surveying all possible low-cost materials or material combinations that could meet the performance criteria with appropriate designs and have the potential of a 20-year service life.

This effort has resulted in identifying several materials, including ethylene vinyl acetate (EVA), as low-cost pottant candidates. A curable laminating sheet product of EVA that was developed has been selected by a number of firms for industrial evaluation.

The lowest-costing structural panel materials identified were the reconstituted wood-fiber boards (e.g. hardboard or strandboard). Problems associated with dimensional stability and long life appear solvable. An initial approach is to encapsulate the hardboard along with the solar cells using the EVA polymer.

A full report on the development and status of these low-cost-material concepts will be published as an LSA report early in 1980.

As these materials are characterized and sufficient environmental test experience is compiled, the module manufacturers are expected to undertake their own evaluations and develop marketable module designs. Polyvinyl butyral has been thus adopted and EVA has been incorporated into several Block IV module designs.

A demonstration of the development by MBAssociates of glass-fiber-reinforced concrete (GRC) as a solar array structural panel and substrate was provided by an MBAssociates display at the PIM. An active 4 x 8 ft GRC solar panel mounted on wood posts was set up with a variety of electrical loads in operation.

Increasing effort of the Encapsulation Task is given to developing test and analysis methodologies to establish module power degradation rate predictions for a 20-year service life. These rate predictions will be based on degradation mechanism models and experimental data from carefully designed accelerated stress testing of modules, components, and individual material systems. These module degradation-rate predictions can then be supplied to existing LSA life-cycle cost-analysis programs to optimize material selection and module designs.

Quantitative relationships that relate environmental stresses such as solar ultraviolet, wind, temperature extremes, and moisture to the rate of degradation of module performance and structural integrity are objectives of the Encapsulation Task in-house efforts. These activities are integrated with contractual activities to develop an over-all module life-prediction methodology.

Photodegradation rates and mechanisms and ultraviolet absorption characteristics of polymeric encapsulants are being measured as a function of polymer composition and test exposure conditions. Data are being obtained for silicones, EVA, and PnBA. Additional materials will be characterized during the coming year.

Encapsulation material degradation data for low-cost advanced encapsulant systems is being gathered using various test hardware such as mini-modules (12 x 16 in.), one- and two-cell modules and individual material samples. Exposure facilities include JPL laboratory reactors and selected field test sites such as Point Vicente, JPL, and Goldstone.

A thermomechanical computer model of a photovoltaic module has been formulated and is being refined and used to study failure modes associated with temperature and moisture expansion stresses within the module encapsulation system. The Mead NB array hardware has been used in this initial analytical study.

A long-term accelerated module life test is being implemented to evaluate the validity of a life testing plan developed by Battelle. A closely controlled and monitored module degradation-rate experiment with accelerated temperature cycling, high humidity and applied current flow will be conducted with 10 prototype modules simultaneously over a 4-to-6 month test period.

ENCAPSULATION MATERIALS SUMMARY

MODULE ELEMENT	CANDIDATES	STATUS	CONTINUING DEVELOPMENT
TOP SURFACE	Antireflective coating	• High transmission demonstrated by Motorola process	• Scale-up of process plus environmental testing
	Abrasion-resistant hard coats	• Effectiveness on polymer covers demonstrated on several types	• Life and soiling characteristics unkown
	Soil-resist treatments for polymers	• Glass cleans with rain; polymers not self cleaning	• R&D on surface treatments including surface modification and ion-plating
COVERS			
Superstrate	Glasses	• Current commercial use	• Selection for optimum cost/performance
	Soda lime	• Structurally analyzed	
	Low-iron tempered	• Bonding criteria available	
	Borosilicate	• Electrostatic bond directly to cells	• Scale-up of electrostatic bond process

ENCAPSULATION MATERIALS SUMMARY (Continued)

MODULE ELEMENT	CANDIDATES	STATUS	CONTINUING DEVELOPMENT
Polymer Sheet (with UV screen)	Acrylics	• Korad UV-screen	• Stabilized UV screen film synthesis for cost/life/spectral cut-off optimization
	Fluorocarbons	• Fluorocarbon films available have cost and processing limits	
	Silicone/ Acrylic	• Silicone/acrylic films under development (Dow Corning/ Springborn)	
	Copolymers	• UV screen candidates synthesized for copolymer films	
POTTANTS	Silicones	• Current commercial use • High cost, soil adheres, good weatherability, some delamination problems	• Lower cost silicones and designs using less material • Suitable cover film and surface treatment
	Polyvinyl butyral	• Current commercial use • Subject to weathering if not sealed • Intermediate cost • Process & storage constraints	
	Ethylene vinylacetate	• Undergoing industrial evaluation in commercial modules • Processes for high volume available • Extensive life modeling started	• Scale-up of sheet production Improved handling and storage qualities • Develop and demonstrate best adhesion methods • Large area module designs and processes

ENCAPSULATION MATERIALS SUMMARY (Continued)

MODULE ELEMENT	CANDIDATES	STATUS	CONTINUING DEVELOPMENT
POTTANTS (continued)	Acrylic elastomer poly-n-butyl-acrylate (PnBA)	• Polymer specimens formulated • Mini-module built and tested • Photodegradation studies started	• Improve and scale-up formulation methods • Module design, fabricate, and test • Develop compatible cover film • Develop best application method (cast, film laminate, direct extrusion, etc.)
	PVC Plastisol Ethylene propylene rubber (EPR) Polyurethane	• Mini-module feasibility demonstrated in temperature cycle • Potentially cost effective • Can be protected behind UV screen	• Develop industrial processes and fabrication methods • Characterize life limitations • Scale-up designs • Provide material for industrial evaluation
SPACER (scrim)	Non-woven glass mat	• Lowest-cost scrim and separator sheet • Aids lamination process to avoid bubbles	• Selection of thickness and fabrication sequence • Evaluate as transparent top cover filler to enhance ruggedness and safety
SUBSTRATE PANEL	Aluminum	• Current commercial use • High cost, high thermal expansion • Good thermal dissipation	
	Fiberglass reinforced polymers (epoxy, polyester)	• Current commercial use • Higher cost • Subject to outgassing and delamination	

ENCAPSULATION MATERIALS SUMMARY (Continued)

MCLULE ELEMENT	CANDIDATES	STATUS	CONTINUING DEVELOPMENT
SUBSTRATE PANEL (continued)	Steel -Porcelainized -Galvanized -Polymer coat	● Under industrial evaluation ● Subject to distortion in flat panels ● Intermediate cost ● Demonstrated good corrosion resistance and thermal performance	● Optimize panel design for structural efficiency and fabricability ● Improve coating systems for cost/thermal/life/fabricability trade-offs
	Wood -Hardboard -Strandboard	● Commercial panels have shown 20 year weatherability ● Cost study shows this to be the lowest cost structural panel ● JPL mini-modules have passed temperature/humidity cycle	● Design modules and panels for stability in outdoor environment using coatings and films ● Scale-up designs for large panels with integral ribs
	Concrete -Fiberglass reinforced (GRC)	● 4' x 8' prototype panels and array structure under field test ● Automated panel lay-up fabrication method demonstrated ● Cost effective integration of PV module and field array structure shown	● Improved encapsulation system design to mount PV cells on concrete surface ● Determine environmental effects on encapsulants and concrete (electrical, thermal)
BACK COVER	Polymer films	● Current commercial use of Teldar and Mylar ● Films are weatherable and bonded to pottant but are not a full moisture barrier	● Determination of module life limits due to film permeability and types of solar cell and interconnects used

ENCAPSULATION MATERIALS SUMMARY (Continued)

MODULE ELEMENT	CANDIDATES	STATUS	CONTINUING DEVELOPMENT
BACK COVER (continued)	Flexible metal foil laminates	● Aluminum foil/polyester film laminates under industrial evaluation ● Steel foil/polyester film under industrial evaluation	● Determination of electrical isolation ● Development of edge seal design criteria and determination of failure mode and life limits
	Glass mat/EVA film	● Used as weather barrier for hardboard and steel substrates	● Evaluation of weathering and life limits of encased hardboard ● Evaluation of dimensional stability of encased hardboard ● Evaluation of electrical isolation and corrosion resistance of encased steel substrates

TECHNOLOGY SESSION

C. D. Coulbert, Chairman

Task Objectives

MATERIAL AND PROCESSES

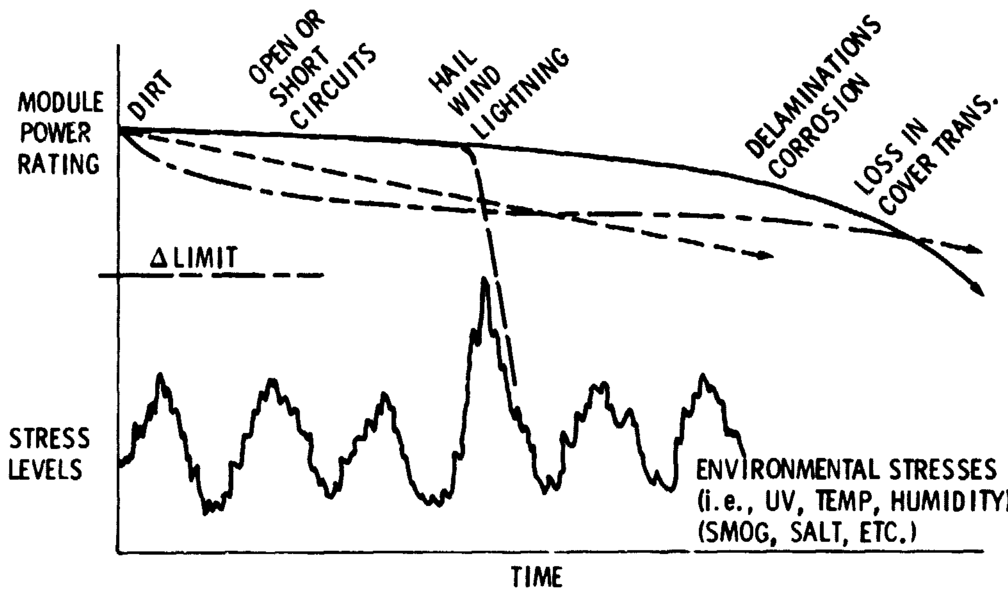
DEFINE, DEVELOP, DEMONSTRATE AND QUALIFY ENCAPSULATION SYSTEMS, MATERIALS, AND PROCESSES WHICH MEET THE LSA PROJECT LIFE, COST AND PERFORMANCE GOALS.

LIFE PREDICTION METHODOLOGY

DEVELOP AND VALIDATE A MODULE LIFE PREDICTION METHODOLOGY BASED ON MODELING LIFE-LIMITING FAILURE MODES AND ON CONDUCTING AND ANALYZING ACCELERATED AGING TESTS OF CANDIDATE ENCAPSULATION SYSTEMS

TRANSFER TECHNOLOGY TO INDUSTRY

Potential Failure and Degradation Rates



Material Systems Development

CONTRACTOR	MATERIAL TECHNOLOGY	ACCOMPLISHMENTS IN 1979
SPRINGBORN	LOW-COST ENCAPSULANTS	• COMPLETE CANDIDATE SYSTEMS DESIGNED, FABRICATED & PROCESSES DEFINED. • SUPERSTRATE & SUBSTRATE DESIGNS DEMONSTRATED AT LESS THAN $6.00/M^2 • MATERIALS UNDER INDUSTRIAL EVALUATION
DOW CORNING	SILICONE/ACRYLICS	• SILICONE-ACRYLIC COVER FILM WITH UV SCREEN FORMULATED AND EVALUATED.
MB ASSOCIATES	GLASS-REINFORCED CONCRETE	• FULL-SCALE GRC SUBSTRATE PANELS PLUS ACTIVE MINIMODULES FABRICATED FOR EVALUATION. • PANELS MEET COST & STRUCTURAL GOALS.
UNIV. OF MASS	UV SCREENS	• UV SCREEN (VINYL TINOVIN) SYNTHESIZED • DEMONSTRATED STABILIZED COPOLYMER FILMS
E. PLUEDDEMANN (CONSULTANT)	ADHESIVES & PRIMERS	• MATERIALS & CRITERIA FOR BONDING 1986 MATERIAL SYSTEMS IDENTIFIED
JPL (IN-HOUSE)	POLY-nBUTYL ACRYLATE	• FORMULATION & PROCESSING STEPS FOR P-nBA DEVELOPED

Process and Design Studies

CONTRACTOR	TECHNOLOGY AREA	ACCOMPLISHMENTS IN 1979
SPIRE	ELECTROSTATIC BONDING (ESB)	• ROUTINE PRODUCTION OF ESB CLOSE-PACKED RECTANGULAR CELLS ACHIEVED • TRAPPED WIRE MESH CELLS WITH GOOD I-V DEMONSTRATED
MOTOROLA	AR COATED GLASS SHEET	• HIGH TRANSMISSION DEMONSTRATED • PROCESS FOR LARGE GLASS SHEET COATING DEMONSTRATED • ABRASION-RESISTANCE EVALUATED • OPTIMIZATION STUDIES UNDER WAY
ILLINOIS TOOL WORKS	ION-PLATING	• NEW CONTRACT STARTED ON CORROSION-RESISTANT AND HIGH-TEMPERATURE METALLIZATION AND COATING CONCEPTS
SPECTROLAB	DESIGN, ANALYSIS, TEST VERIFICATION OF ADVANCED (1986) ENCAPSULATION SYSTEMS	• NEW CONTRACT TO INTEGRATE AND OPTIMIZE ENCAPSULATION SYSTEM TECHNOLOGY

Life Prediction Methodology

CONTRACTOR	TECHNOLOGY AREA	ACCOMPLISHMENTS IN 1979
ROCKWELL SCI. CTR.	ENCAPSULATION INTERFACE PHENOMENA (CORROSION)	• ATMOSPHERIC CORROSION MODEL DEVELOPED • ATMOSPHERIC CORROSION SIMULATOR DESIGNED • DIAGNOSTIC INSTRUMENTS AND TECHNIQUES EVALUATED
CASE WESTERN	AGING AND DIFFUSION MECHANISMS	• STARTED AGING-RATE MEASUREMENT AND MODELING FOR P-nBA
UNIV. OF TORONTO	PHOTODEGRADATION MODEL FOR EVA	• NEW CONTRACT
CALTECH	FRACTURE AT INTERFACES	• EXPANSION STRAINS VERSUS TIME, TEMPERATURE, AND MOISTURE MEASURED AND CORRELATED • EXPERIMENTAL MODEL FOR DEBOND EXTENSION DEVELOPED
BATTELLE	LIFE TEST PLAN	• EXPERIMENTAL PLAN FOR ACCELERATED TEST DEFINED AND FEASIBILITY TESTING INITIATED

In-House Studies

TECHNOLOGY AREA	ACCOMPLISHMENTS IN 1979
UV DEGRADATION	• UV TEST REACTOR FOR ENCAPSULATED CELLS COMPLETED AND OPERATING • CRITERIA FOR ACCELERATED UV AGING OF DIFFERENT POLYMERS
FIELD MEASUREMENT OF INTEGRATED UV	• DEVELOPED AND CALIBRATED UV ACTINOMETERS FOR FIELD DEPLOYMENT IN 1980
THERMOMECHANICAL MODEL	• FINITE ELEMENT MODEL DEVELOPED AND USED TO PREDICT STRESSES AND STRAINS IN MODULE ENCAPSULATION SYSTEM.
ADVANCED ENCAPSULANT FIELD TESTING	• MINIMODULES FABRICATED AND TEST SITES PREPARED AT JPL, SAN VICENTE, GOLDSTONE

EVA Photodegradation Studies

- TRANSPARENT EVA (REVISED BATCH) PROCURED FROM SPRINGBORN
- ROLE OF RESIDUAL CROSS LINKING AGENT IN INITIATING PHOTODEGRADATION
- NATURE OF PHOTODEGRADATION FT-IR, EXTRACTION / GPC, UV-VISIBLE SPECTROSCOPIC DATA
- LONG TERM RATES (UNDER MEASUREMENT)
- EFFECT OF PHOTODEGRADATION ON MODULUS, STRESS / STRAIN RESPONSE

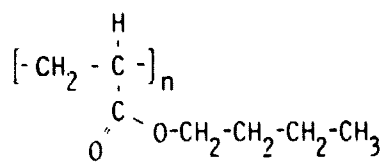
Suitability of Use of PnBA as Pottant

- HIGH TRANSPARENCY
- EXCELLENT ADHESION TO GLASS, WOOD, METALS, SOLAR CELLS, CLOTH
- CAN BE THERMALLY CYCLED (-50^0 TO $+90^0$) WITHOUT FRACTURE
- POTENTIAL LONG LIFE → MAY NOT NEED HIGH LEVEL OF UV SCREENING
- CAN BE PROCESSED BY SOLVENT FREE CASTING METHOD → CURE CONDITIONS DETERMINED AT JPL
- LOWEST COST ACRYLIC → MONOMER AT 45¢/lb FOR TANK CAR QUANTITIES

DISADVANTAGE

- NO MATERIAL AVAILABLE FOR INDUSTRIAL EVALUATION YET

What Is PnBA?

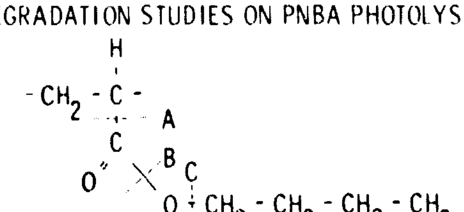


IT IS USED AS A CROSS-LINKED, ELASTOMERIC POTTANT AND APPLIED BY A SOLVENT FREE CASTING TECHNIQUE

T_g	= -55^0C APPROX
TRANSMISSION (20 MIL)	= > 94%
DENSITY	= 1.09 ± 0.01
MODULUS (10% STRAIN)	3×10^6 n/m^2 APPROX

Results

PHOTO DEGRADATION STUDIES ON PNBA PHOTOLYSIS AT 2537 Å



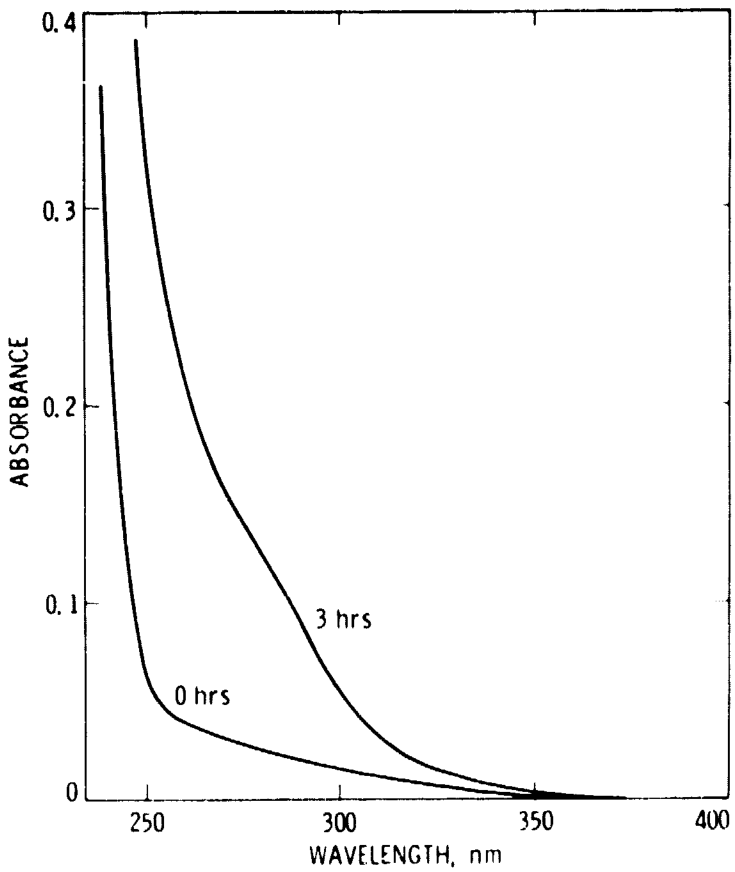
SCISSION MODE A n-bu-C(=O)-O· → CO_2 + n-bu· → BUTENE

SCISSION MODE B n-bu-O· → n-bu-OH, CH_2O, PROPENE

SCISSION MODE C n-bu· + P-$\dot{C}O_2$ → BUTENE + CO_2

IN ALL CASES THERE WILL BE SIMULTANEOUS CHAIN SCISSION AND CROSS LINKING

PnBA Photodegradation, 2537 Å Irradiation



Plan for Further Work on PnBA

- PROCESSING STUDIES
  - •DIPPING AND CURING
  - •TWO STAGE ENCAPSULATION

DELIVERABLE MAKE 6 ONE CELL/TWO CELL MODULES (JUNE 80)

- CURING / FORMULATION STUDIES
  - •ADD POLYMERIZABLE UV STABILIZERS IN SYRUP
  - •STUDY CURING AT 90°C / IN AIR

DELIVERABLE REPORT ON SYRUP COMPOSITION / CURE (AUGUST 80)

- DEGRADATION / PHOTODEGRADATION STUDIES
  - •ASSESS NEED FOR UV SCREENING / BACK COVER PROTECTION

DELIVERABLE REPORT ON PHOTODEGRADATION MODEL (NOVEMBER 80)

PRODUCTION PROCESS AND EQUIPMENT AREA

On Tuesday, December 4th, 1979, the PP&E Area held a contractor's summary meeting in the new PP&E Laboratory. All contractors except those who were working on copper metallization and automation studies presented summaries of their efforts at this time.

On Wednesday afternoon those contractors involved with copper metallization summarized their efforts and on Thursday afternoon the "Automated Module Assembly Studies" session covered this subject.

Salient points of the meeting and plans for the next period follow:

REPORTED PROGRESS SINCE LAST PIM

Surface Preparation:

- Gettering must be evaluated on specific materials
- NH_4OH - H_2O_2 cleaning solution is replenishable
- Spray-on AR coating being perfected
- Texture/polish option still open.

Junction Formation Processes:

- Technique is important in forming Al BSF
- Carbonaceous layer formed during ion implanation
- Investigating current increase after plasma etching outermost surface
- Spray-on junctions successful
- Ion implanted cells using non-mass-analyzed source.

Metallization Processes:

- Nickel is a barrier to copper migration
- Thick-film metal systems have been successfully doped with AlSi and AlGe eutectics
- Copper sinters well using Pb frit
- Progress is being made in Ni plating directly on Si.

Assembly:

- Laminating chamber developed
- Induction soldering of ribbon to cell successful
- Single-pass IR soldering of multiple strings
- Automated soldering is dependent upon cell metallurgy.

Plans For Next Period

- Receive Phase III proposals and begin evaluation
- Establish control-cell capability in PP&E Lab
- Begin development of pulsed electron beam anneal (PEBA) machine
- Continue development of low-cost metallization system.

TECHNOLOGY SESSION

D.B. Bickler, Chairman

PRODUCTION PROCESSES AND EQUIPMENT, PHASE II

MOTOROLA, INC.

Process Sequence

1. PLASMA SILICON ETCH (ONE SIDE)
2. APPLY WAX MASK*
3. TEXTURE ETCH (ONE SIDE)
4. REMOVE WAX MASK*
5. ION IMPLANT BACK SURFACE FIELD
6. ION IMPLANT P-N JUNCTION
7. ACTIVATION ANNEAL OF IMPLANT**
8. DEPOSIT SILICON NITRIDE (LPCVD)**
9. PLASMA PATTERN NITRIDE
10. PLATE METAL
11. CELL TEST AND INTERCONNECT
12. ENCAPSULATE

*ELIMINATED IF PLASMA TEXTURE ETCHING IS CHOSEN
**MAY BE COMBINED

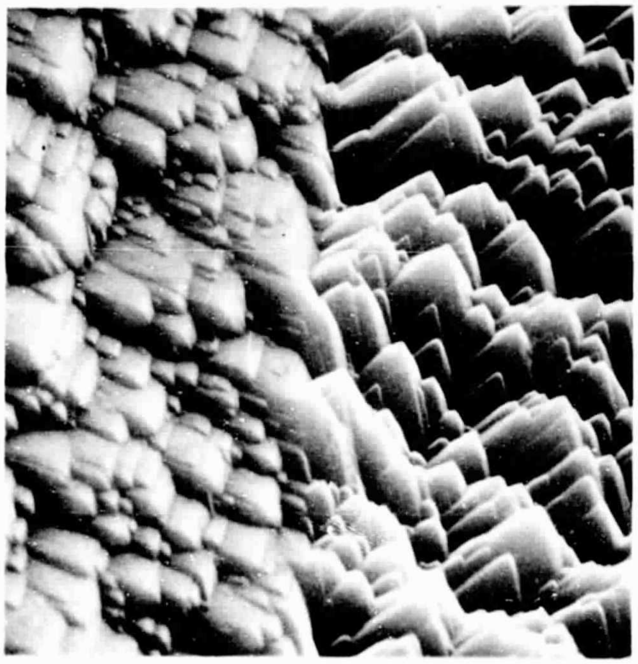
Texture Etching

SILICON RIBBONS WITH MULTIPLE ORIENTATIONS ARE READILY TEXTURED.

- STRONG PREFERRED ORIENTATION OF GRAINS
- FAR LESS THAN 5% IS ORIENTED NEAR (111)

HAS MAJOR IMPACT ON ION IMPLANTER DESIGN.

Texture-Etched RTR Surface



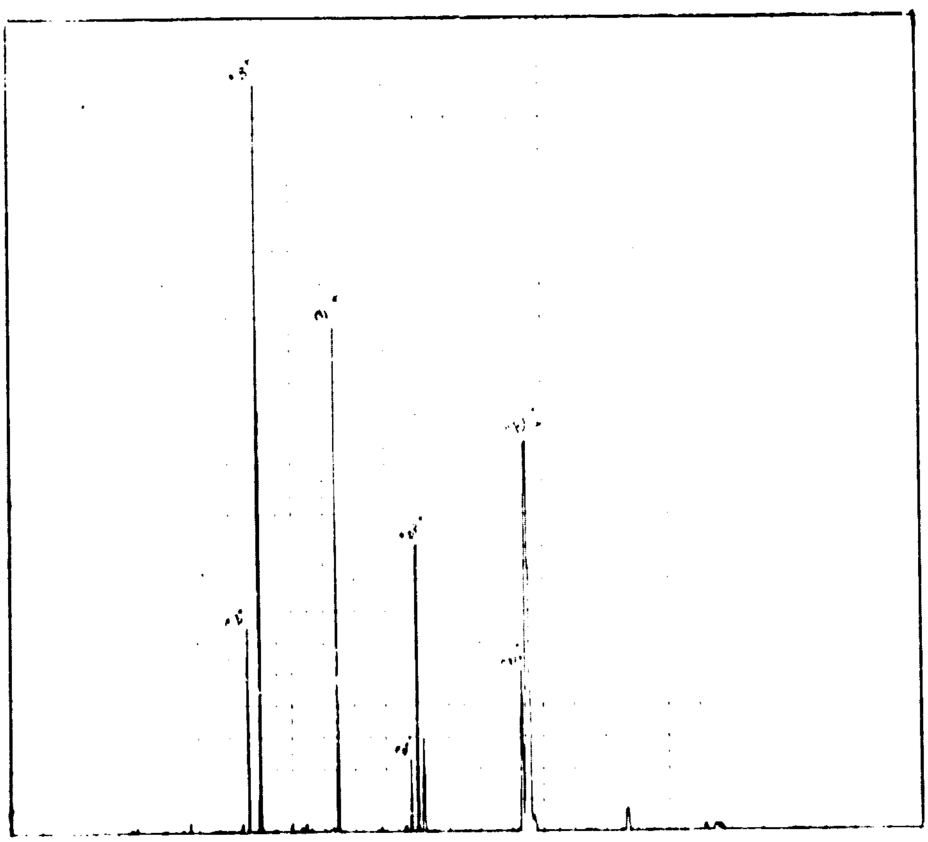
Ion Implantation

1. FORMATION OF CARBONACEOUS LAYER OBSERVED
   - WAFER NOT HYDROPHOBIC IN HF
   - OXIDATION PLUS HF RETURNS HYDROPHOBIC FEATURE
   - RELATED TO VACUUM PUMP OIL

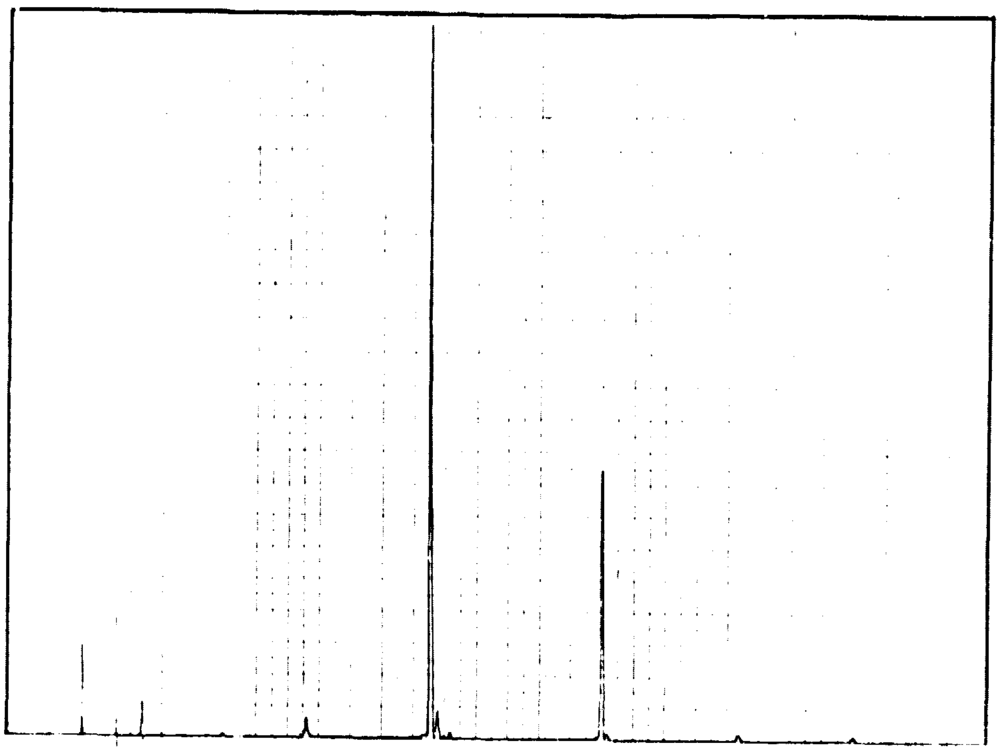
2. PERFORMING SIMULATED NON-MASS-ANALYZED IMPLANT
   - GASEOUS SOURCES OF PH_3, AsH_3, BF_3
   - IMPLANT PROPORTINATELY FOR EACH MAJOR MASS COMPONENT IN SPECTRUM.
   - IMPLANTED CELLS ARE INDISTINGUISHABLE FROM MASS-ANALYZED IMPLANTED CELLS

3. TRUE UNANALYZED BEAM IMPLANT
   A. UTILIZED ION MILLING MACHINE
      - PH_3 SOURCE
      - IMPLANT AT ~2 KEV
      - BEAM CURRENT ~200 MILLIAMPS (UNCALIBRATED)
      - NON-TEXTURED WAFER

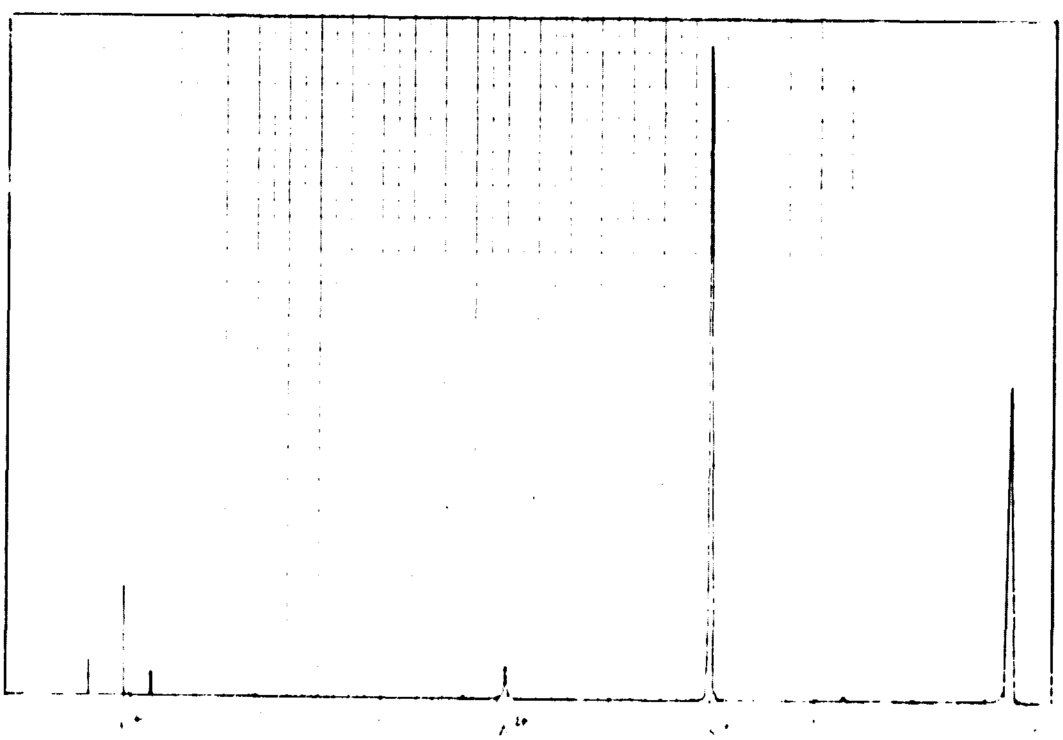
Typical BF_3 Spectrum



Typical PH_3 Spectrum



Typical AsH_3 Spectrum



Ion Implantation (Continued)

B. TIME OF IMPLANT EXCESSIVE
   - NEAR 20 SECONDS
   - PROBABLE DOSE GREATER THAN 10^{16}

C. ANNEALED 30 MINUTES (900°C), SILICON NITRIDE (780°C-45 MINUTES), 550°C-2 HOURS.

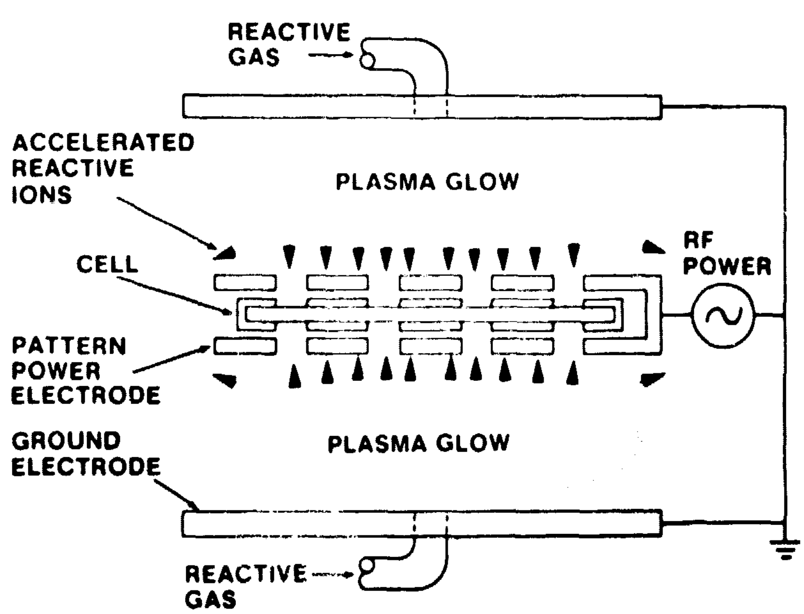
D. V_{OC} = 593 MILLIVOLTS
   I_{SC} = 1450 MILLIAMPS

Plasma Patterning

1. DEMONSTRATED SIMULTANEOUS FRONT AND BACK PATTERNING OF SILICON NITRIDE
   - REACTIVE ION ETCHING MODE
   - SPACING ALLOWED BETWEEN MASK AND CELL WHILE STILL ACHIEVING MASK REPLICATION
   - ALLOWS TEXTURED AND/OR NON-PLANAR SUBSTRATES

2. PROCESS IS MASK MATERIAL DEPENDENT
   - NICKEL AND MOLYBDENUM MASKS QUENCH PLASMA REACTION
   - ALUMINUM MASKS ARE SUITABLE

Mechanically Masked Plasma Patterning



Plated Metallization

1. BASELINE PROCESS CONTAINED:
   - IMMERSION PALLADIUM (DISPLACEMENT)
   - ELECTROLESS PALLADIUM (AUTOCATALYTIC)
   - ELECTROLESS NICKEL
   - SOLDER

2. ELIMINATED NEED FOR ELECTROLESS PALLADIUM
   - WAS THE MAJOR METAL MATERIAL COST FACTOR
   - ELECTROPLATE NICKEL CONTACT
   - JIGGING DIFFICULT, BUT FEASIBLE

3. RE-EVALUATING ELECTROLESS NICKEL
   - DIFFERENT FORMULATIONS
   - ELIMINATE (OR EFFECTIVELY MINIMIZE) SILICON OXIDATION
   - MOST SUCCESSFUL WITH IMMERSION PALLADIUM LAYER

4. COPPER PLATING HAS BEEN DEMONSTRATED FOR REPLACING SOLDER

SILICON WAFER TEXTURIZING

PHOTOWATT INTERNATIONAL, INC.

Gregory T. Jones

Aim and Objectives

1. LOW-COST WAFER CLEANING
2. LOW-COST WAFER DRYING
3. TWO-STAGE TEXTURIZING PROCESS
4. GETTERING PROCESS

Specific Goals

THE SPECIFIC GOALS FOR THIS STUDY OF WAFER SURFACE TEXTURIZING FOR NEAR TERM IMPLEMENTATION OF FLAT PLAT COST REDUCTIONS ARE:

(1) REDUCE THE CLEANING MATERIALS COST FROM 3.7 CENTS PER PEAK WATT TO LESS THAN 0.7 CENTS PER PEAK WATT.

(2) PRODUCE CONSISTENT SOLAR CELL EFFICIENCIES GREATER THAN 10% IN PRODUCTION OVER A SIMILAR BATCH OF SOLAR CELLS WITHOUT TEXTURIZATION.

Project Status

PROJECT COMPLETED IN AUGUST 1979. FINAL REPORT IS BEING SUBMITTED TO JPL FOR FINAL REVIEW PRIOR TO PUBLICATION.

Project Results

LOW-COST WAFER CLEANING

(1) LOW-COST CLEANING METHOD WAS FOUND TO BE SUITABLE TO LARGE SCALE PRODUCTION.

(2) CLEANING METHOD USES RECYCLED FREON TMS IN AN ULTRASONIC VAPOR DEGREASER.

(3) COST GOAL ACHIEVED. COSTS FOR WAFER CLEANING IS LESS THAN 0.7 CENTS PER PEAK WATT.

LOW-COST WAFER DRYING

(1) LOW-COST CLEAN AIR SYSTEM IS SUITABLE FOR LARGE SCALE PRODUCTION.

(2) CLEAN AIR CAN REPLACE NITROGEN.

(3) AIR CONVECTION DRYING IS NOT COST EFFECTIVE DUE TO LONG DRYING TIME.

(4) FORCE AIR DRY TUNNEL SYSTEM IS COST EFFECTIVE AT AN INITIAL WAFER DRYING TEMPERATURE OF 80 C.

TWO-STAGE TEXTURIZING PROCESS

(1) UNDER LABORATORY CONTROLLED CONDITIONS, PROCESS TIME PER STEP THE TWO-STAGE TEXTURIZING PROCESS (10%/1% NAOH) IS FIVE MINUTES.

(2) CURRENT CONDITIONS IN LARGE SCALE PRODUCTION WHERE WAFER SURFACE CHARACTERISTICS ARE NOT CONTROLLED, PROCESSING TIME WAS VARIABLE AND REQUIRED MORE THAN FIVE MINUTES.

GETTERING PROCESS

(1) LARGE IMPROVEMENT IN AVERAGE SOLAR CELL EFFICIENCY CAN BE ACHIEVED BY UTILIZING A LOW TEMPERATURE GETTERING TREATMENT IN COMBINATION WITH A TWO STAGE TEXTURIZING PROCESS SEQUENCE.

(2) INTERMEDIATE GETTERING PRODUCED THE HIGHEST BATCH EFFICIENCY, 13.3% (WITH SIO) IN PRODUCTION.

(3) HIGHEST EFFICIENCY ACHIEVED IN PRODUCTION WAS 14.3%.

(4) OPTIMUM INTERMEDIATE GETTERING TEMPERATURE IS 875 C, 35 MINUTES.

(5) LOW TEMPERATURE INTERMEDIATE GETTERING MINIMIZED EFFICIENCY AND FILL FACTOR DISPERSIONS.

(6) GETTERING IMPROVED THE QUALITY OF SILICON MATERIAL. QUALITY OF SILICON MATERIAL IS DEFINED IN TERMS OF THE CHARACTERISTIC I-V CURVES FOR A BATCH OF SOLAR CELLS.

(8) RECYCLED GETTERING IS FEASIBLE AND COST EFFECTIVE.

(9) THE AVERAGE EFFICIENCY 12.3% (WITHOUT A.R. COATING) OF THE TEXTURIZED/GETTERED BATCH OF SOLAR CELLS WAS FOUND TO BE 18.3% HIGHER THAN THE AVERAGE EFFICIENCY, 10.4% OF THE ISOTROPIC SURFACE ETCHED/GETTERED SOLAR CELLS.

(10) THE EFFICIENCY GOAL WAS ACHIEVED FOR THE WAFER SURFACE TEXTURIZING STUDY FOR THE NEAR TERM IMPLEMENTATION OF FLAT PLATE PHOTOVOLTAIC COST REDUCTION.

PROCESS EQUIPMENT COST ANALYSIS

(1) TEXTURIZING PROCESS COST INCLUDING, CLEANING, DRYING AND TEXTURIZING AMOUNTED TO 1.26 CENTS PER PEAK WATT (1975 CENTS).

(2) GETTERING COST WAS 0.97 CENTS PER PEAK WATT.

(3) THE WAFER SURFACE PREPARATION COST INCLUDING THE TEXTURIZATION PROCESS AND GETTERING PROCESS STEPS WAS FOUND TO BE IN LINE WITH THE 1986 JPL LOW-COST SOLAR ARRAY PROJECT GOAL (IN 1975 CENTS) OF 50 CENTS PER PEAK WATT.

Comparison of Characteristic I-V Curves Of the Texturizing-Gettering Process

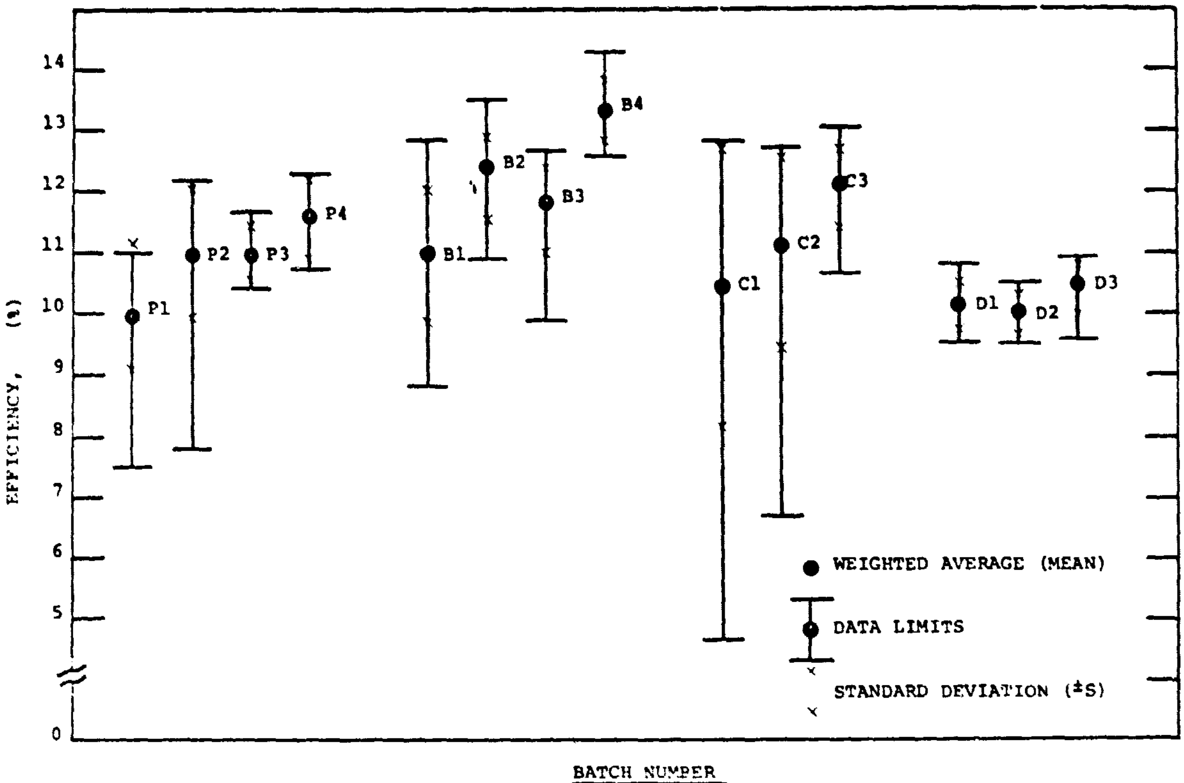
(1) INITIAL EXPERIMENTS -- GETTERING PLACEMENT AND TEMPERATURE.

(2) GETTERING ($POCl_3$, 875 C, 35 MINUTES).

(3) GETTERING TEMPERATURE.

(4) GETTERING SURFACE ETCHED WAFERS.

Texturizing-Gettering Batch Test Results



Texturizing Gettering Batch Tests

P1 - Control cells, texturized, 54.91cm^2 active areas.
P2 - Intermediate gettered (1000 C).
P3 - Pregettered (875 C).
P4 - Intermediate gettered (875 C)

B1 - Control cells -- texturized, 41.4cm^2 active areas.
B2 - Intermediate gettered (875 C).
B3 - Pregettered (875 C).
B4 - Intermediate gettered (875 C) with SiO.

C1 - Intermediate gettered (1050 C), 41.4cm^2 active area.
C2 - Intermediate gettered (975 C).
C3 - Intermediate gettered (900 C).

D1 - Controll cells -- surface etched, 42.6cm^2 active area. Intermediate gettered (1000 C).
D2 - Intermediate gettered (925 C).
D3 - Intermediate gettered (875 C).

AUTOMATED ARRAY ASSEMBLY, PHASE II

RCA LABORATORIES

Objective of the Current Program

TO ASSESS THREE SOLAR-CELL MANUFACTURING SEQUENCES WITH REGARD TO PROCESS COMPATIBILITY, ACCOMMODATION TO THE FORM OF STARTING SILICON, AND TO PERFORM AN OVERALL COST/PERFORMANCE EVALUATION AND COMPARISON FOR THESE SEQUENCES.

Outline

I. PROGRESS IN THE STUDY OF THREE MANUFACTURING SEQUENCES
- A. MATERIAL AND PROCESS COMPATIBILITY PROBLEMS
  - a. SOLAR-GRADE WAFERS AND ION-IMPLANTATION
  - b. SCREEN-PRINTED THICK-FILM METALIZATION
  - c. SPRAY-ON AR COATING
- B. EVALUATION OF SEQUENCE I, II AND III PROCESSING
  - a. OVERALL COMPARISONS
  - b. "GETTERING" – EFFECT ON EFFICIENCY AND COST

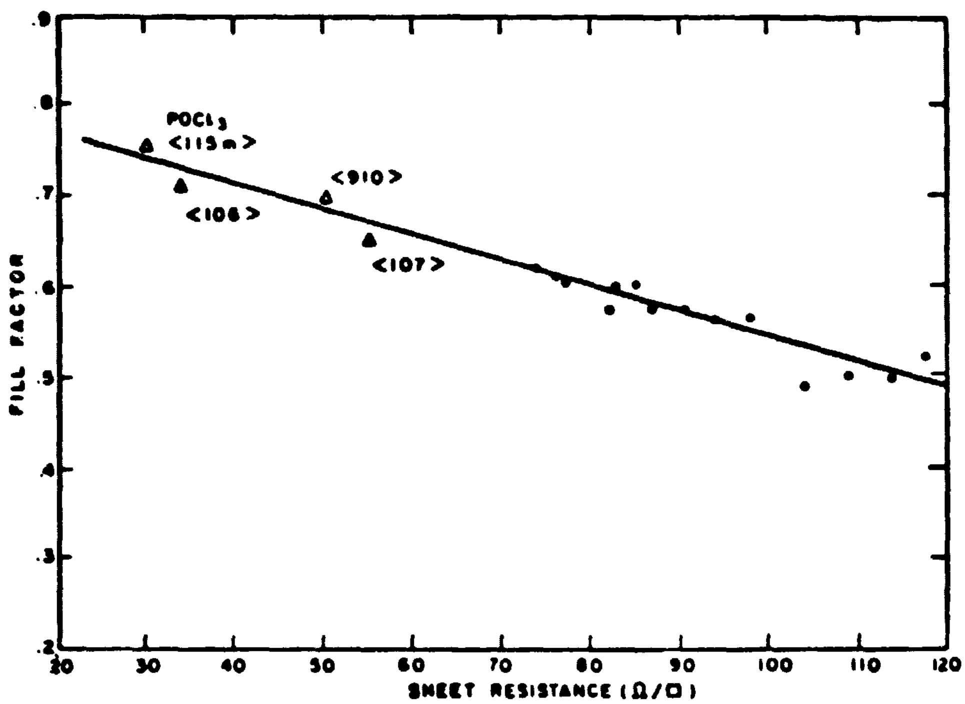
II. INTERCONNECT AND PANEL ASSEMBLY PROCESSES
- A. REFLOW SOLDER INTERCONNECT PROCESS
- B. DOUBLE-GLASS LAMINATION PROCESS

III. CONCLUSIONS AND PLANS

Fill Factor as Function of Sheet Resistance Incl. Avg. Values For Lots 106, 107, 910, 115m

Lot No.	$\overline{J_{sc}}$ (mA/cm^2)	$\overline{V_{oc}}$ (mV)	$\overline{FF}$ -	$\bar{\eta}$* (%)	$\overline{R_{\square}}$ (Ω/□)
107P	21.7	552	0.659	7.9	58
106P	20.7	557	0.710	8.2	34
910P	20.5	560	0.700	8.0	52
950 - 952	19.5	499	0.518	5.1	75-150

*No AR Coating



Average Cell Parameters: Sequences I, II and III

MANUFACTURING SEQUENCE	Structure	MEASURED – NO AR $\overline{I_{sc}}$ mA	$\overline{V_{oc}}$ mV	$\overline{F.F.}$ –	$\overline{\eta}$[a] %	ESTIMATED – WITH AR $\overline{I_{sc}}$ mA	$\overline{V_{oc}}$ mV	$\overline{F.F.}$ –	$\overline{\eta}$ %	BEST MEASURED WITH AR $\overline{I_{sc}}$ mA	$\overline{V_{oc}}$ mV	$\overline{F.F.}$ –	$\overline{\eta}$ %
I	$n^+/p/p^+$	870	557	0.701	8.1	1140	567	0.673	10.4	1140	571	0.685	10.7
II	$n^+/p/p^+$	870	574	0.675	8.0	1200	584	0.690	11.6	1260	578	0.680	11.8
III	$p^+/n/n^+$	1020	585	0.686	9.7	1330	595	0.660	12.5	1360	597	0.670	13.0
$POCl_3$	$n^+/p/p^+$	867	584	0.765	9.3	1177[b]	604[b]	0.748[b]	12.7[b]	1205	610	0.761	13.2

(a) Cell area = 42 cm^2.

(b) Measured values.

Cell Interconnect Process

1. SCREEN PRINT SOLDER PASTE – FRONT AND BACK.
2. SOLDER PREFORMED TABS TO CELL – RADIANT HEAT
3. CLEAN CELLS TO REMOVE FLUX.
4. LAYOUT CELL ARRAY AND TRANSFER TO REFLOW TABLE.
5. INTERCONNECT ARRAY BY RADIANT-HEAT MASS REFLOW.

SPECTROLAB

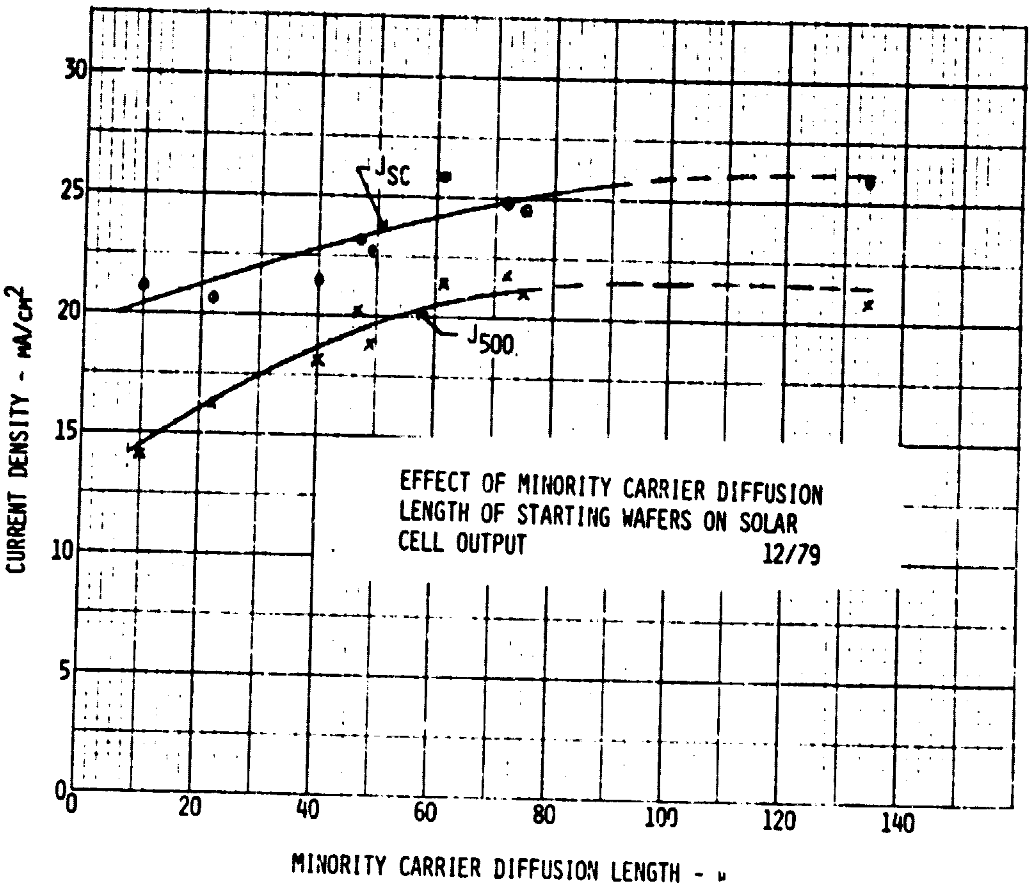
William E. Taylor

Comparison of IR and Tube Furnace Firing of Printed Contacts

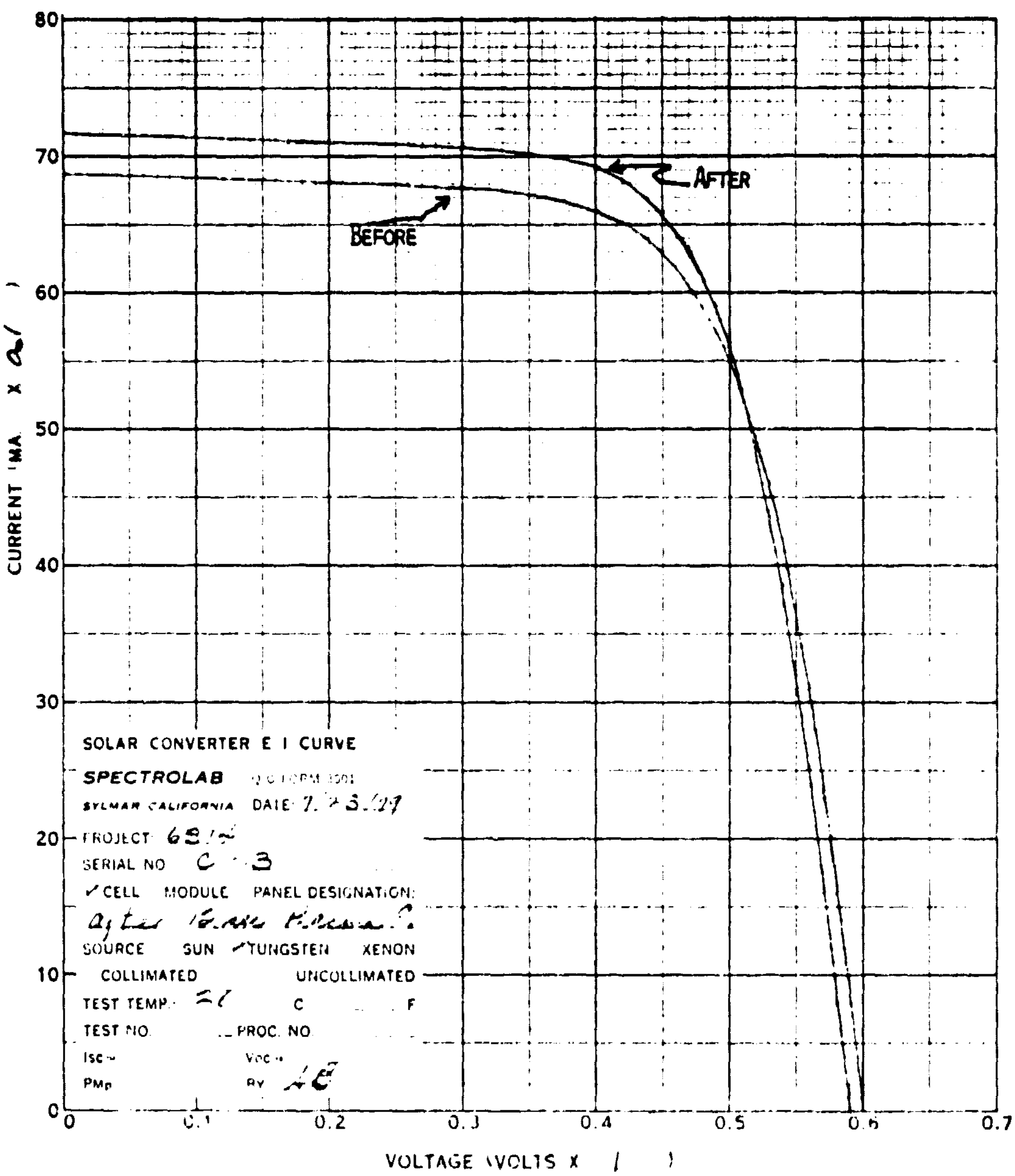
		V_{OC}-MV		I_{SC}-MA		I_{500}-MA		R_{SH}	
		TUBE	IR	TUBE	IR	TUBE	IR	TUBE	IR
SET 1	$\bar{x}$	591.1	591.6	596.5	602.2	390.9	411.8	3.2	4.2
	$\hat{\sigma}$	3.3	4.6	15.5	18.2	38.4	45.7		
SET 2	$\bar{x}$	599.3	599.0	628.2	631.9	561.6	564.2	20.1	17.2
	$\hat{\sigma}$	1.1	1.0	9.6	7.8	12.7	9.5		
SET 3	$\bar{x}$		599.0		698.0		598.8		73.0
	$\hat{\sigma}$		1.6		7.9		11.9		

SETS 1 AND 2: AG FRONT CONTACTS

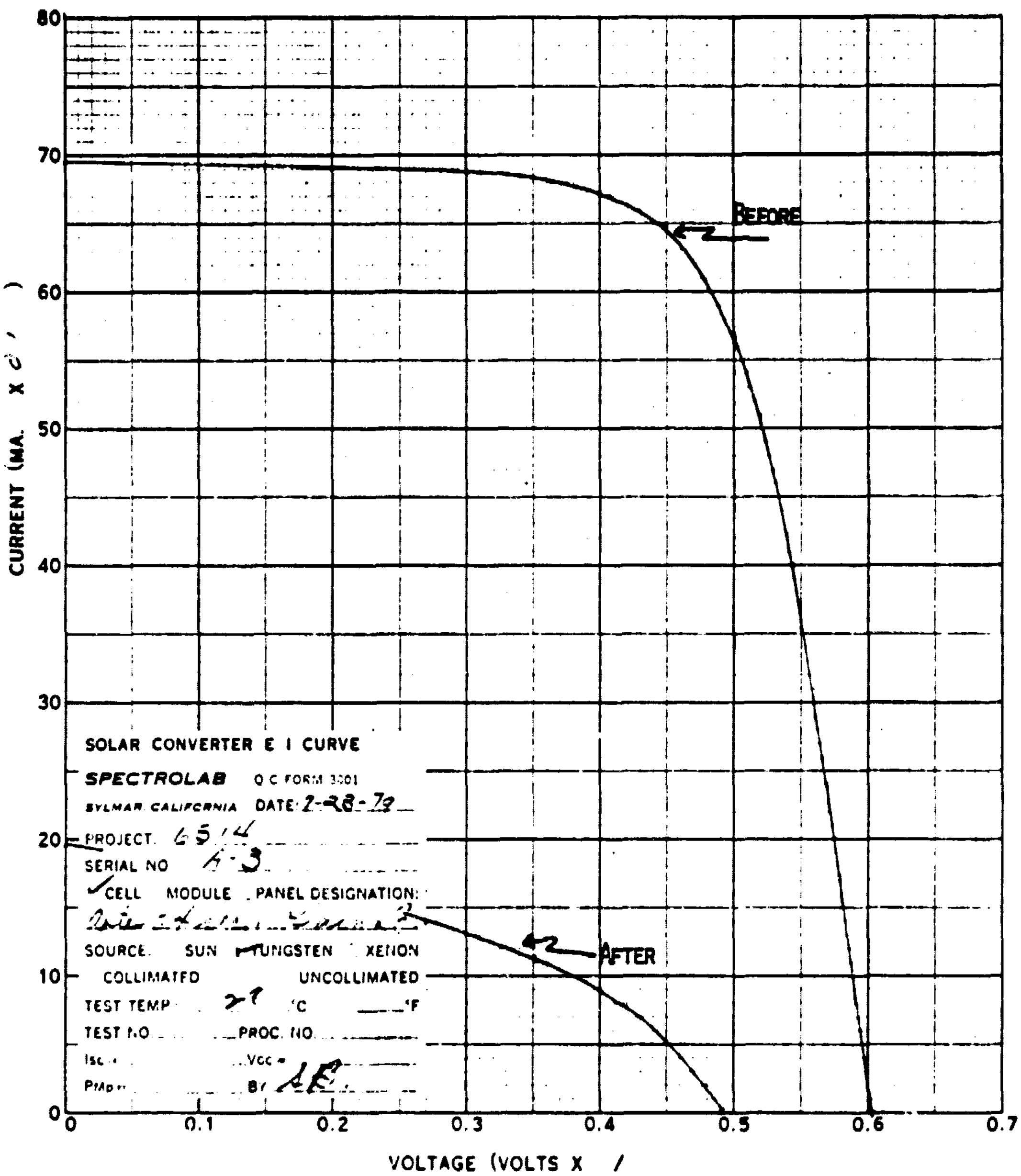
SET 3: AL BACK CONTACT

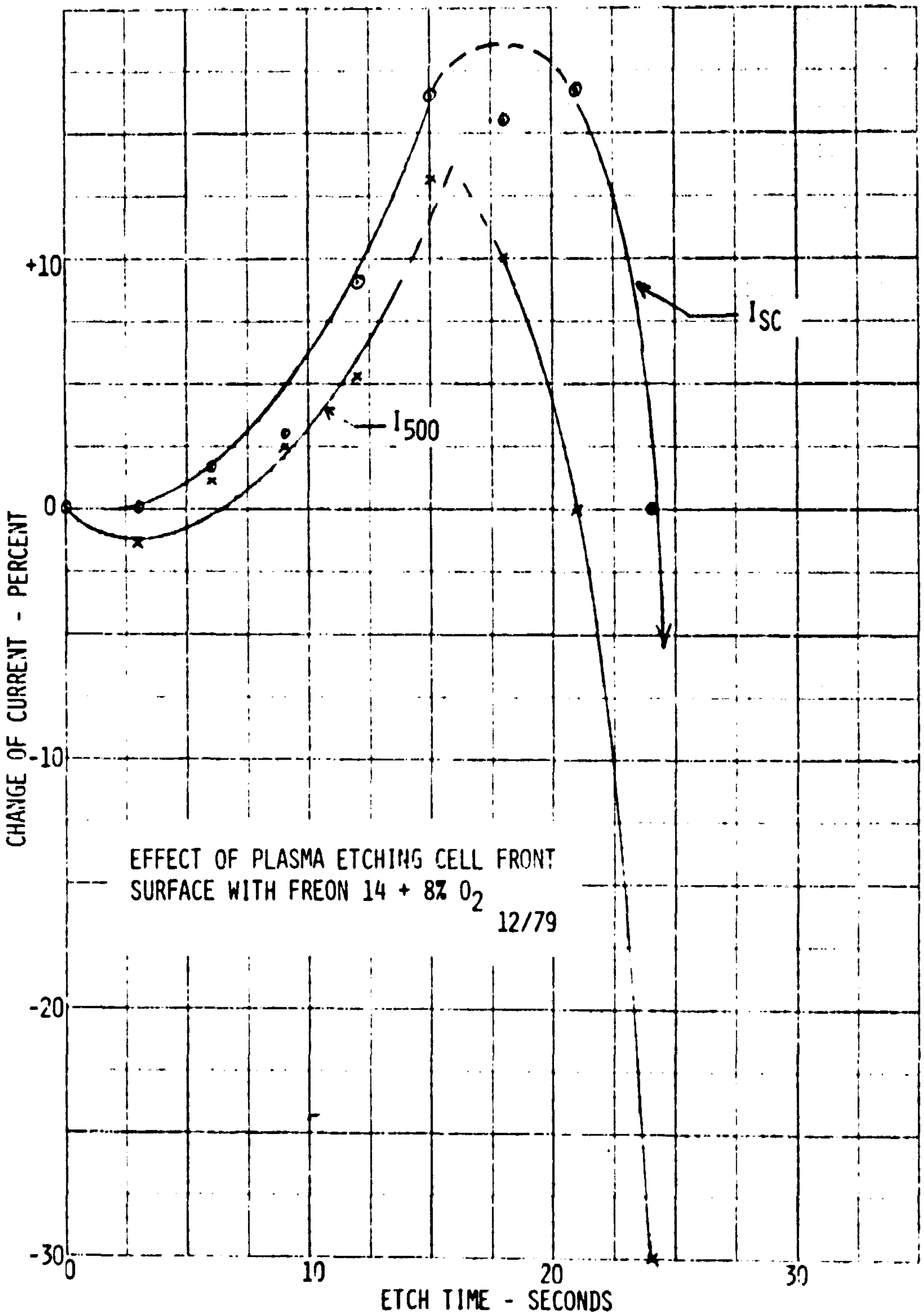

CURRENT DENSITY - mA/cm^2
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
J_{SC}
J_{500}
MINORITY CARRIER DIFFUSION LENGTH - μ
EFFECT OF MINORITY CARRIER DIFFUSION LENGTH OF STARTING WAFERS ON SOLAR CELL OUTPUT 12/79

Cell After 12 sec Plasma Etch

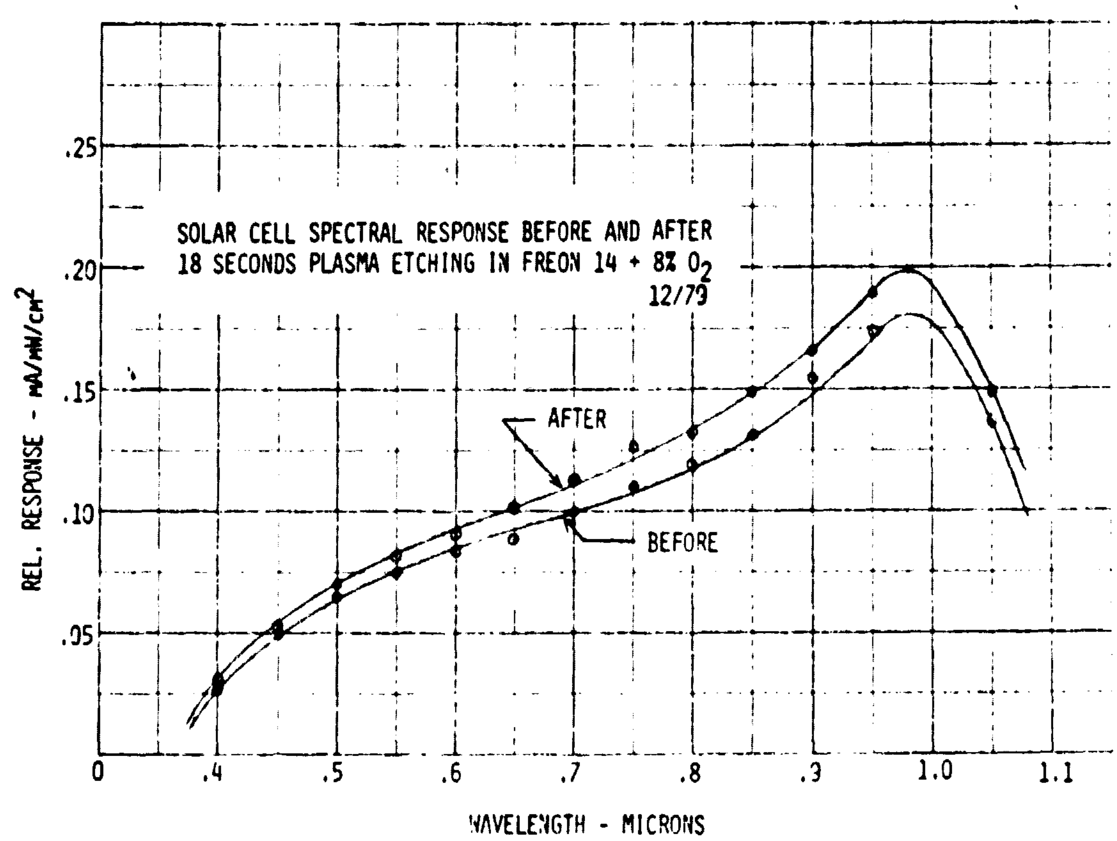


Cell After 24 sec Plasma Etch



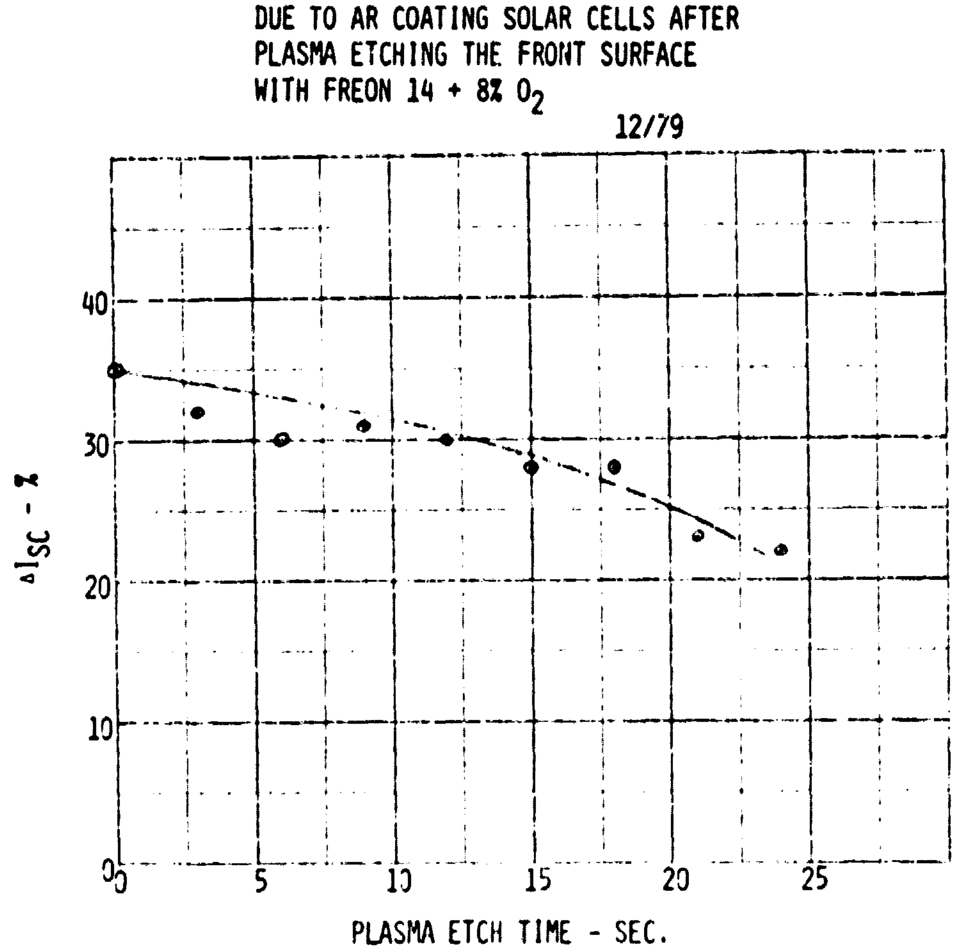


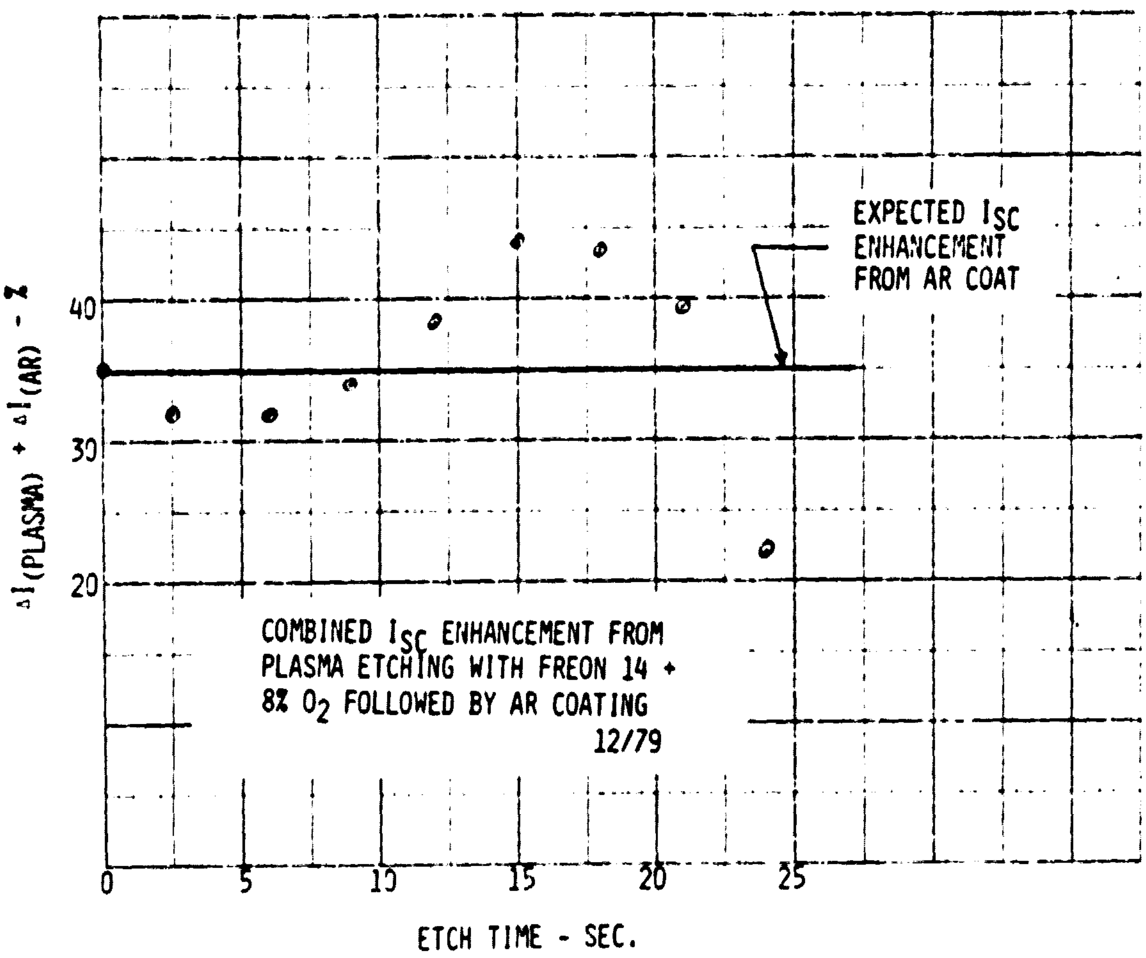
+10
0
-10
-20
-30
CHANGE OF CURRENT - PERCENT
I_{SC}
I_{500}
EFFECT OF PLASMA ETCHING CELL FRONT SURFACE WITH FREON 14 + 8% O_2
12/79
0
10
20
30
ETCH TIME - SECONDS



SOLAR CELL SPECTRAL RESPONSE BEFORE AND AFTER
18 SECONDS PLASMA ETCHING IN FREON 14 + 8% O_2
12/79
AFTER
BEFORE
REL. RESPONSE - mA/mW/cm^2
.25
.20
.15
.10
.05
0
.4
.5
.6
.7
.8
.9
1.0
1.1
WAVELENGTH - MICRONS

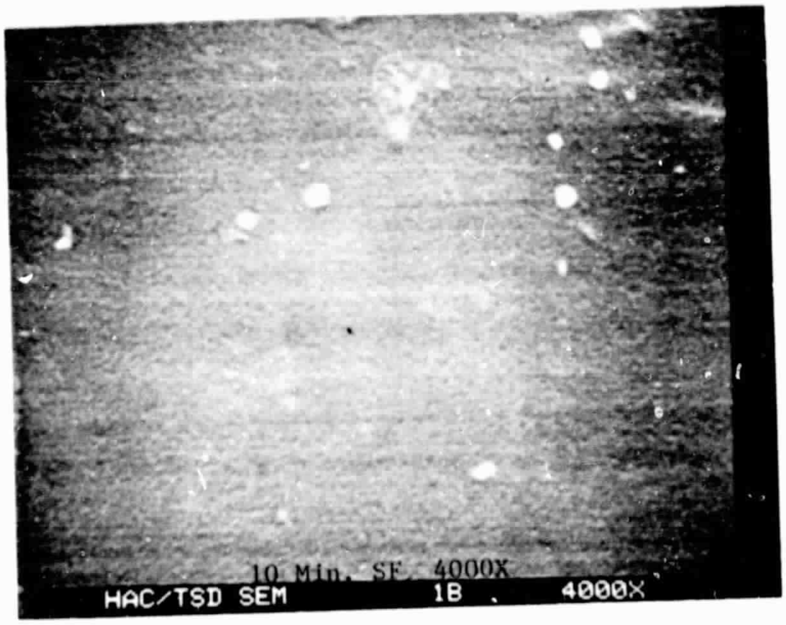
Increase of I_{sc}

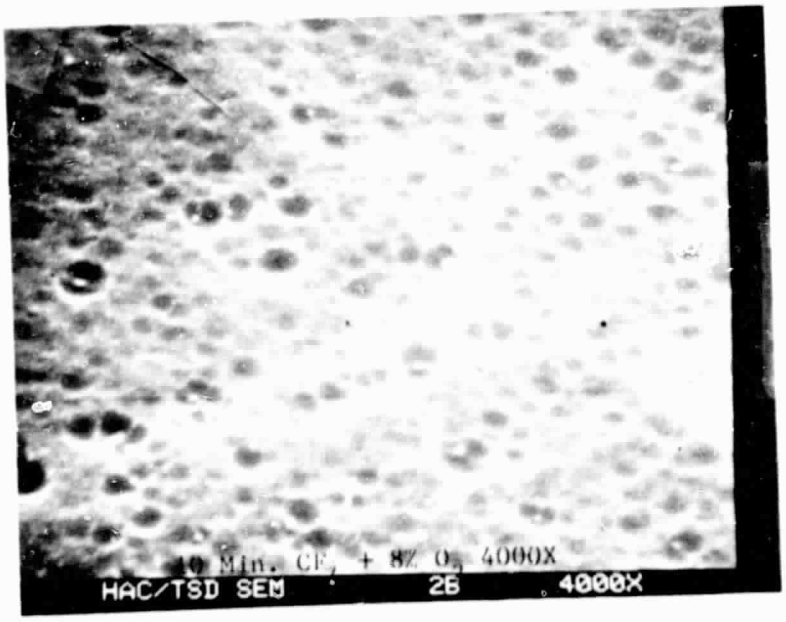


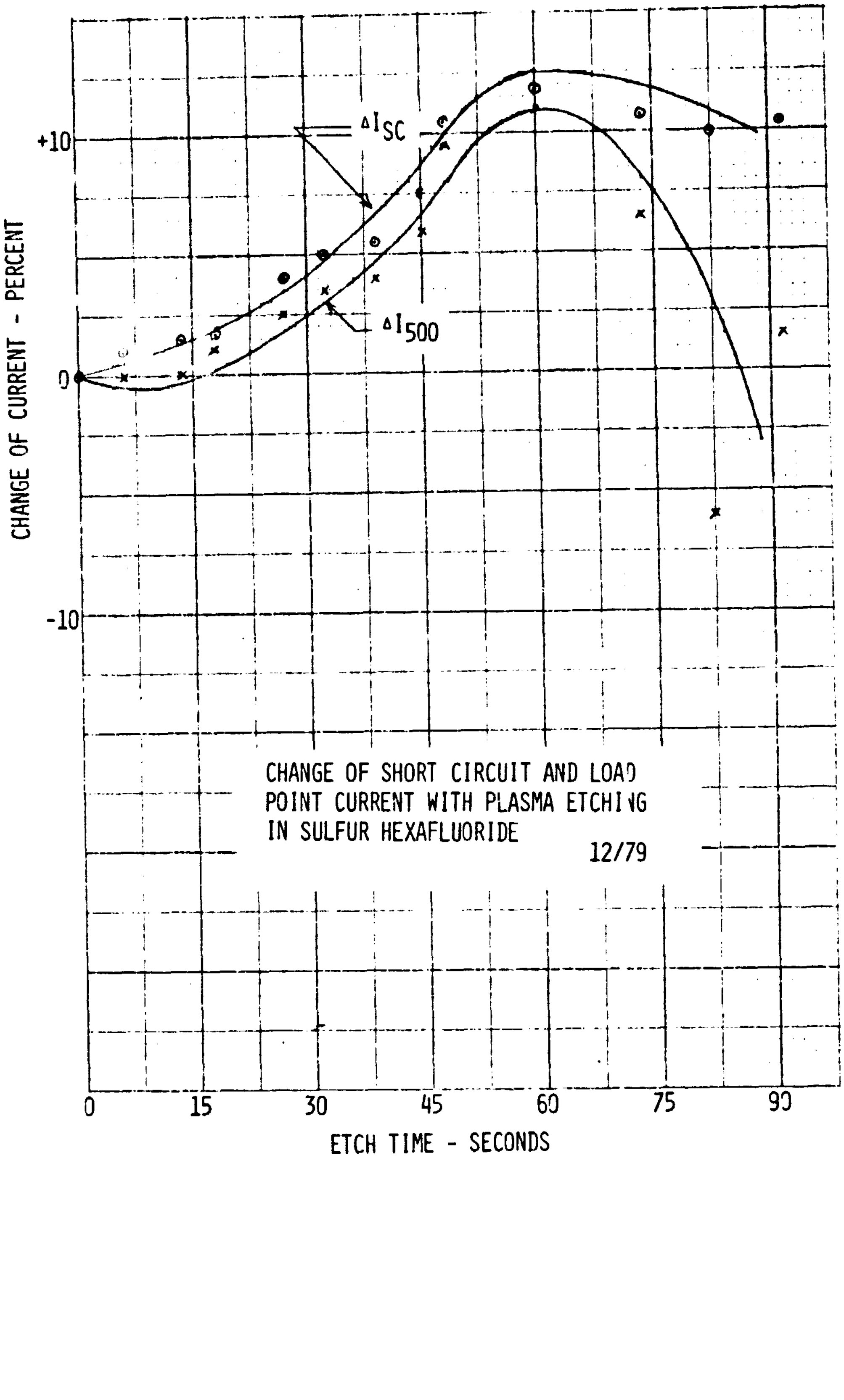


EXPECTED I_{SC} ENHANCEMENT FROM AR COAT
COMBINED I_{SC} ENHANCEMENT FROM PLASMA ETCHING WITH FREON 14 + 8% O_2 FOLLOWED BY AR COATING
12/79
$\Delta I_{(PLASMA)} + \Delta I_{(AR)}$ - %
40
30
20
0
5
10
15
20
25
ETCH TIME - SEC.

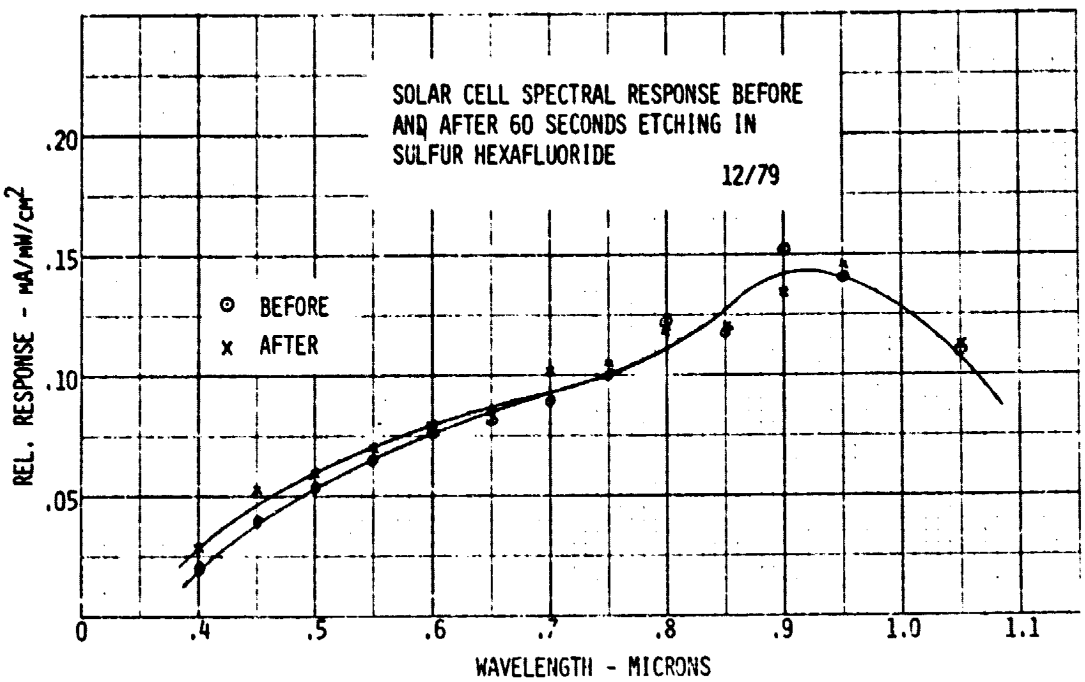
Phosphorus-Diffused (Ps-35 Ω/□) Plasma Etched







CHANGE OF CURRENT - PERCENT
+10
0
-10
ΔISC
ΔI500
CHANGE OF SHORT CIRCUIT AND LOAD POINT CURRENT WITH PLASMA ETCHING IN SULFUR HEXAFLUORIDE
12/79
0
15
30
45
60
75
90
ETCH TIME - SECONDS


SOLAR CELL SPECTRAL RESPONSE BEFORE
AND AFTER 60 SECONDS ETCHING IN
SULFUR HEXAFLUORIDE
12/79
BEFORE
AFTER
REL. RESPONSE - mA/mW/cm²
.20
.15
.10
.05
0
.4
.5
.6
.7
.8
.9
1.0
1.1
WAVELENGTH - MICRONS

HIGH-RESOLUTION, LOW-COST SOLAR CELL CONTACT DEVELOPMENT (MIDFILM)

SPECTROLAB

Nick Mardesich

Standard Cell Processing

SURFACE PREPARATION - 30% NaOH

JUNCTION FORMATION - SPIN-ON DIFFUSION SOURCE

ALUMINUM BACK SURFACE FIELD - SCREEN PRINTED ALUMINUM PASTE

CLEAN RESIDUAL ALUMINUM AND DIFFUSION OXIDE - HF AND BRUSH

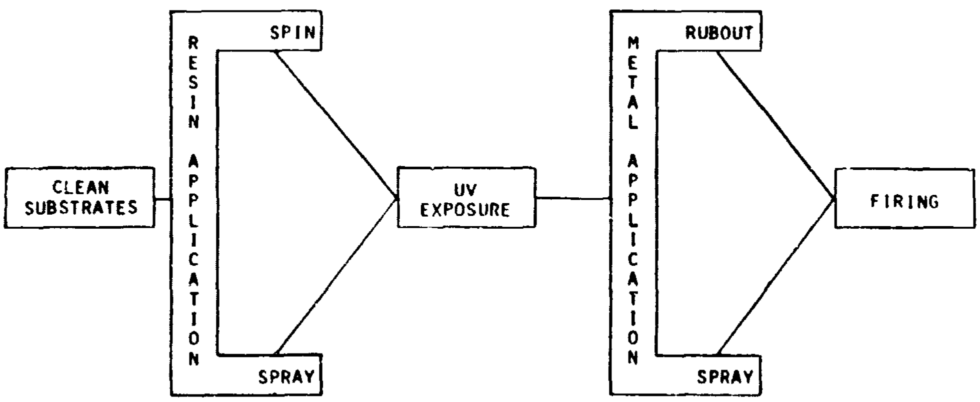
JUNCTION CLEAN - LASER SCRIBE

*FRONT CONTACT - MIDFILM

AR COAT - EVAPORATED SiO_x

*FRONT CONTACT APPLIED AT FERRO IN OHIO AND SHIPPED TO SPECTROLAB FOR FIRING.

Ferro E-100 Midfilm Process



Program Task

I. EXPLORATORY DEVELOPMENT

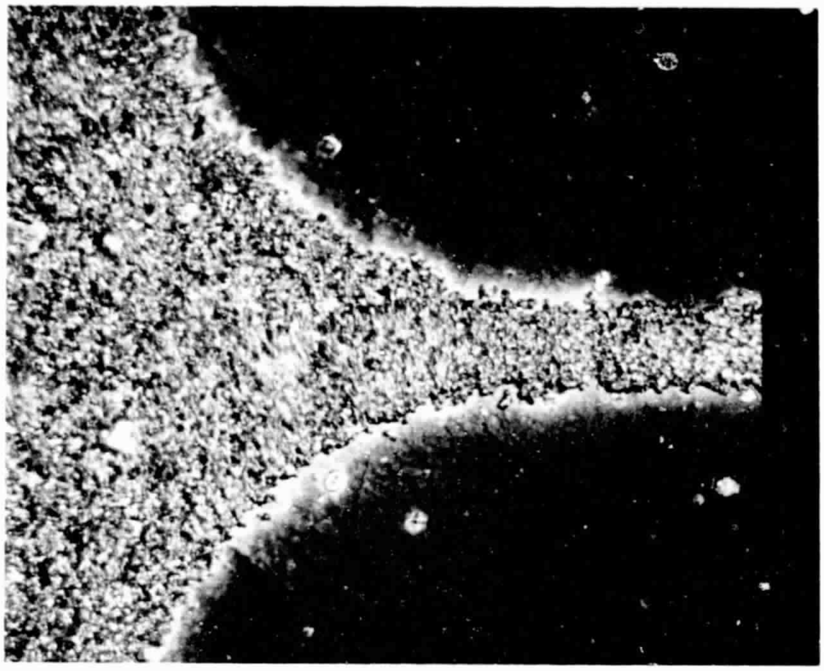
II. ENVIRONMENTAL EVALUATION

III. INVESTIGATION OF ALTERNATE METALS

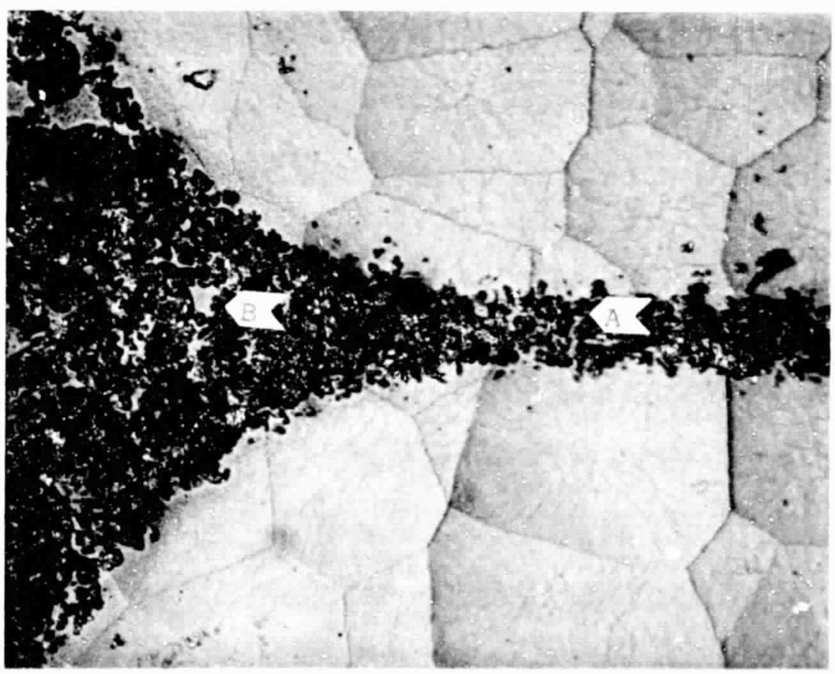
Silver Powder Evaluated

POWDER COMPOSITIONS	EVALUATION			
	GRIDLINE THICKNESS (μ)	SURFACE COVERAGE	R_{SHUNT}	R_{SERIES}
1. 98% FINE FLAKE SILVER POWDER; 2% DRAKENFELD FRITZ METZ "C" (80)PbO(10)B_2O_3-(10)SiO_2 (WT %)	4	LOW	LOW	HIGH
2. 98% FERRO SILVER POWDER; 2% DRAKENFELD FRIT	8.5	HIGH	LOW	OK
3. TFS 3347 COMPOSITION WITHOUT SCREENING MEDIUM	5	LOW	OK	HIGH
4. 98% FERRO SILVER POWDER; 2% SPECTROLAB FRIT #2-	7	OK	LOW	-
5. 98% FERRO SILVER; 2% FERRO BISMUTH FRIT #3	8.5	LOW	LOW	HIGH
6. 95% FERRO SILVER POWDER; 5% TFS 3347 FRIT	7	LOW	OK	HIGH

Photomicrographs of Midfilm Metallization

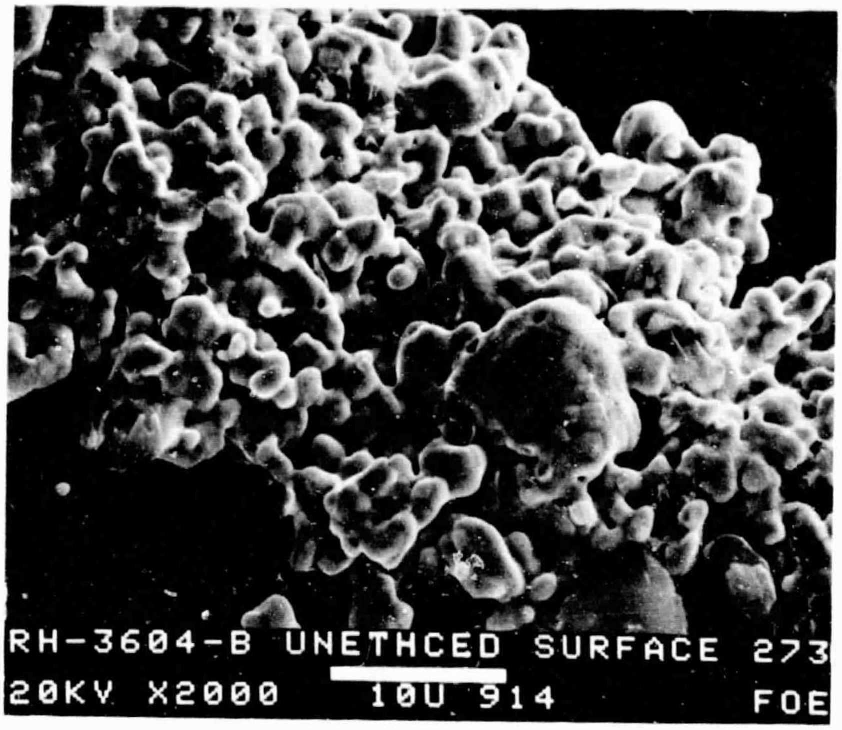


Good Metallization of Composition
No. 2 250X Mag.



Poor Metallization of Composition
No. 3 250X Mag.

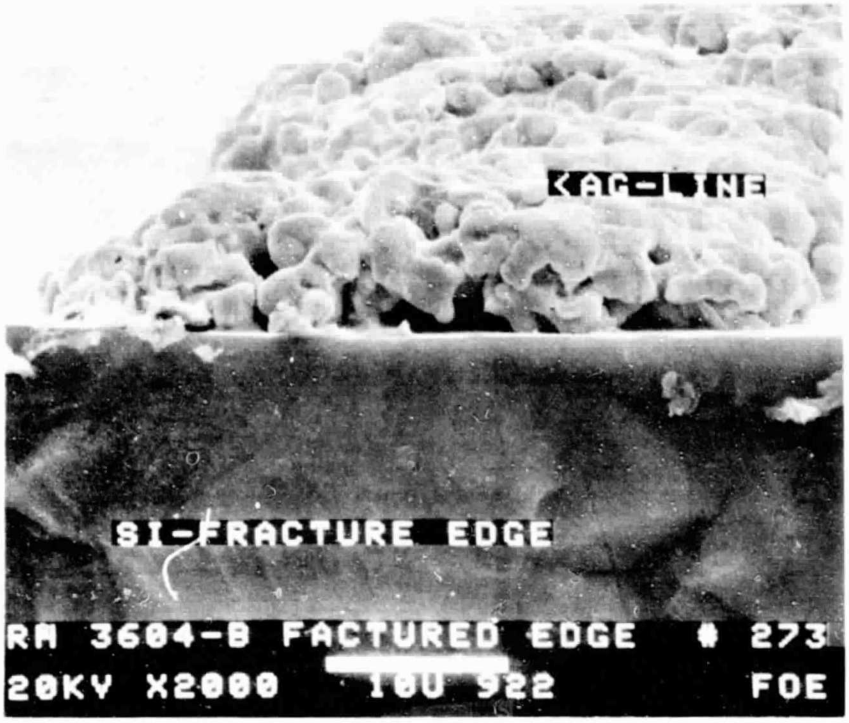
Surface of Applied and Fired Silver-Frit Powders



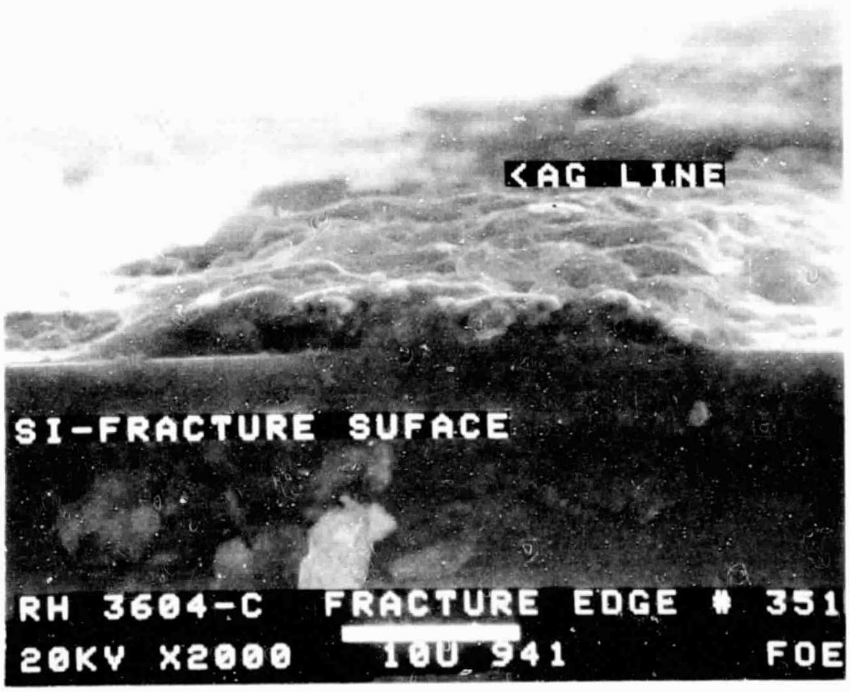
Composition 2, 2000X Magnification

Composition 3, 2000X Magnification

Cross Section of Gridline and Substrate

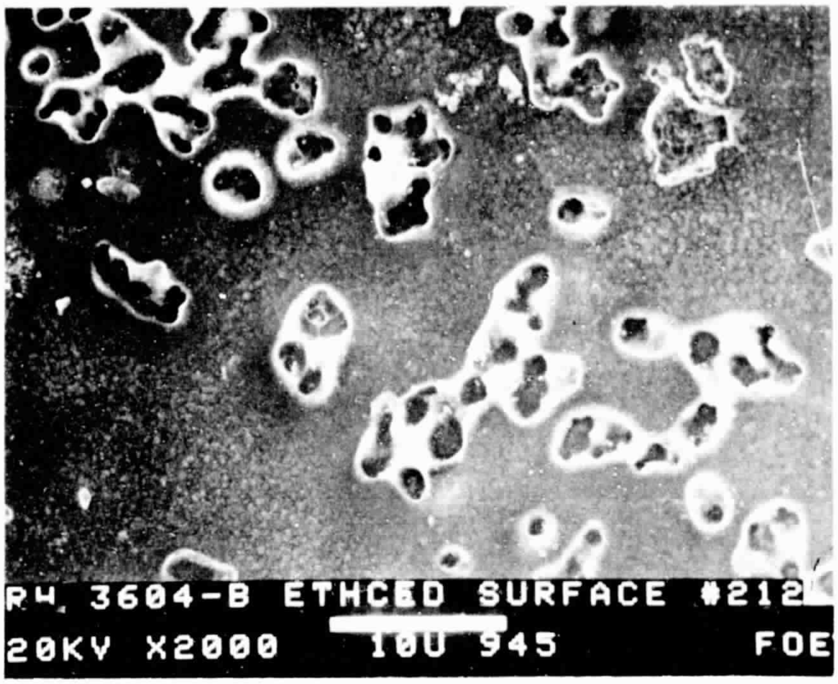


Composition 2, 2000X Magnification

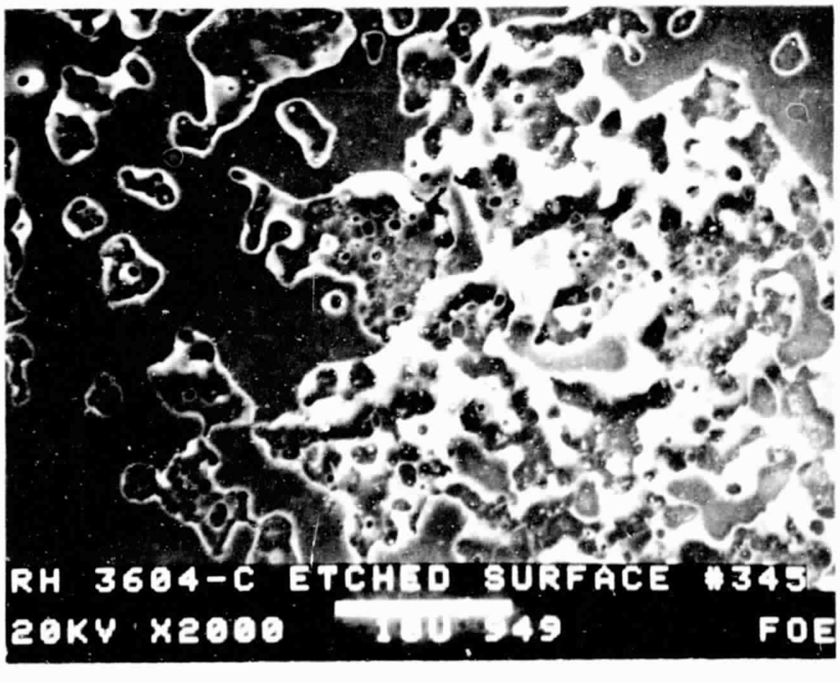


Composition 3, 2000X Magnification

Surface of Cell After Silver
Was Etched Away Leaving Only Frit



Composition 2, 2000X Magnification



Composition 3, 2000X Magnification

Distribution of Midfilm Contact

IR FIRED CELLS, POWDER COMPOSITION #2
NO AR COATING
BELT SPEED 48 INCHES/MIN., ZONE 1, 2, 3, 4: 0, 900, 700, 700

Cell No.	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{sh} (ohm)	R_{series} (m-ohm)	η** %
* 8	593	189	99	128.2	-	
36	602	200	121	98.0	890	9.55
38	597	194	132	147.0	615	10.4
40	603	195	144	90.9	560	11.4
42	600	205	124	90.5	825	9.8
*44	597	190	78	167.0	-	
*45	601	199	104	135.0	-	
48	605	199	165	116.0	360	13.0
52	609	205	175	87.7	150	13.8
53	608	202	182	102.0	150	14.4
54	604	199	165	119.0	350	13.0
59	608	203	184	89.3	150	14.5
61	607	202	180	90.9	160	14.2
63	602	196	120	156.0	825	9.5
*65	Broken					
66	605	202	165	116.0	375	13.3
67	608	204	176	200.0	300	13.9
70	605	200	158	109.0	415	12.5
72	597	202	150	128.0	400	11.8
89	603	202	135	104.0	700	10.7
AVERAGE	603.9	200.6	154.8	115.3	451.6	12.2
σ	3.73	3.34	22.7	30.4	255.7	1.8

*Not taken into average.

**I_{500} increased by 34% to account for AR coating.

Midfilm Metallization Process

Cell No.	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{shunt} (ohm)	R_{series} (m ohm)	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{shunt} (ohm)	R_{series} (m ohm)	After Tape Pull V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)
				Environmental Evaluation - Humidity Test									
59	608	203	184	89	150	606	204	181	106	250	603	204	180
52	609	205	175	88	150	607	208	177	132	350	603	208	166
66	605	202	165	116	375	603	205	154	192	500	601	207	147
40	603	195	144	91	560	598	196	97	133	1150	594	178	79
42	600	205	124	91	825	597	202	99	125	1100	broken		
				Environmental Evaluation - Thermal Shock									
61	607	202	180	91	160	605	200	178	91	150	603	198	175
67	608	204	176	200	300	607	201	176	250	250	606	201	175
54	604	199	165	119	350	605	197	162	139	350	603	196	157
72	597	202	150	128	400	599	198	148	135	400	596	201	140
38	597	194	132	147	615	597	188	126	152	700	594	193	126
				Environmental Evaluation - 5 min. boiling									
53	608	202	182	102	150	604	202	172	104	156	604	199	178
70	605	200	158	109	415	602	197	150	109	450	600	196	143
48	605	199	165	116	360	600	197	153	125	365	601	198	155
89	603	202	135	104	700	600	200	130	114	610	599	201	120
36	602	200	121	98	890	598	198	117	100	865	597	198	103

Midfilm Problems

PROBLEMS	SOLUTIONS
1) HIGH SERIES RESISTANCE	OPTIMUM POWDER COMPOSITION OPTIMUM APPLICATION PROCEDURE MINIMUM HANDLING OF WAFERS
2) LOW SHUNT RESISTANCE	OPTIMUM FIRING CONDITIONS WITH 3347 TFS FRIT OR EQUIVALENT
3) SILVER - SOLDER INTERACTION	SOLDER THAT DOES NOT LEACH OUT SILVER

Cost Effectiveness

$P_R = (0.49{:}EQPT + 97 \cdot SOFT + 2.1 \cdot DLAB + 1.3 \cdot MATS + 1.3 \cdot UTIL)/QUAN.$

EQPT = \$210,000 + 6,000 - 10,000 = \$206,000

SOFT = 1,500

DLAB = 1.0 PRSN.YRS./SHIFT x 4.7 x \$8,100
+ 0.4 PRSN.YRS./SHIFT x 4.7 x 11,000 = \$58,750/YR

MATS = (0.025 GM Ag POWDER @ \$0.58/GM
+ 0.205 ML RESIN @ \$.01717/ML)
x 55,890,000 CELLS/YR
= \$1,007,129/YR

UTIL = .0055 kWh/CELL x 55,890,000 CELLS/YR x \$.0452/kWh
= \$13,894/YR

QUAN = 7500 CELLS/HR x .90 x 8280 HR/YR x
= 55,890,000 CELLS/YR

P_R = (100,940 + 145,500 + 123,375 + 1,309,268 + 18,062/55,890,000
= 0.0304/CELL

IF η = .13

POWER/CELL = 10.16^2 cm^2 x .1 x .13
= 1.342 WATTS/CELL

P_R = 0.0226/WATT

ASSUMING NO YIELD LOSS.

PULSE PROCESSING OF SOLAR CELLS

SPIRE CORP.

Contract Summary

DEVICE TECHNOLOGY

- OPTIMIZED IMPLANT PARAMETERS
  - -- Low Energy (10-50 keV)
  - -- Junctions and BSF
- FABRICATED REPRODUCIBLE 16.5% AM1 CELLS
  - -- 3" Diameter
  - -- Implant Compatible Metallization
- PROCESS CONFIRMED BY JPL CONTRACTORS

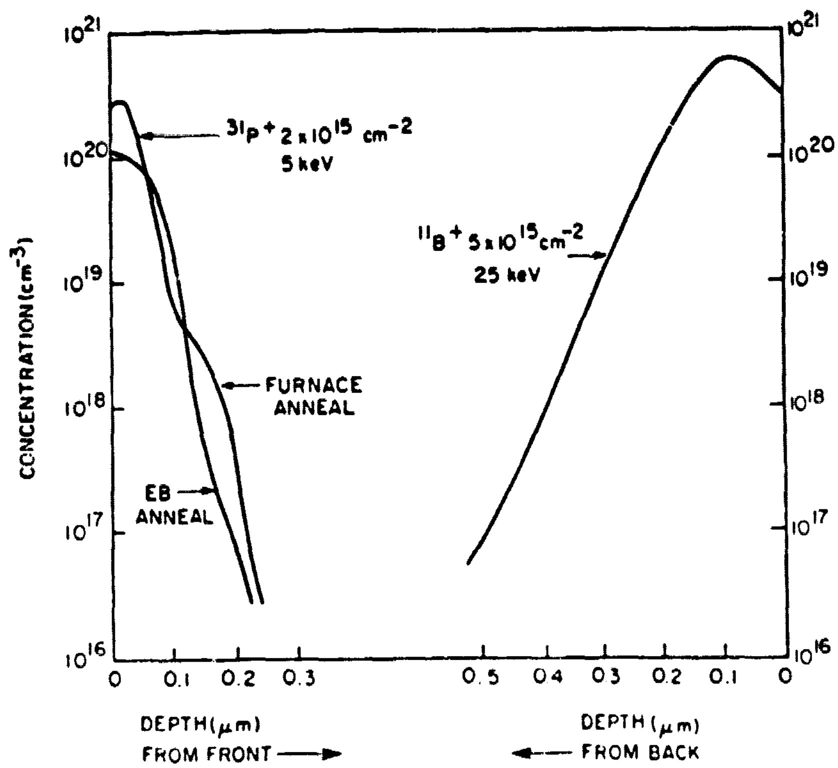
EQUIPMENT TECHNOLOGY

- INSTALLED FIRST SOLAR CELL IMPLANTER
  - -- 300 Wafers/Hour
  - -- Low Energy (10-50 keV)
- DESIGNED 100 MW/YR IMPLANTER
  - -- 180 M^2/Hour for 1986

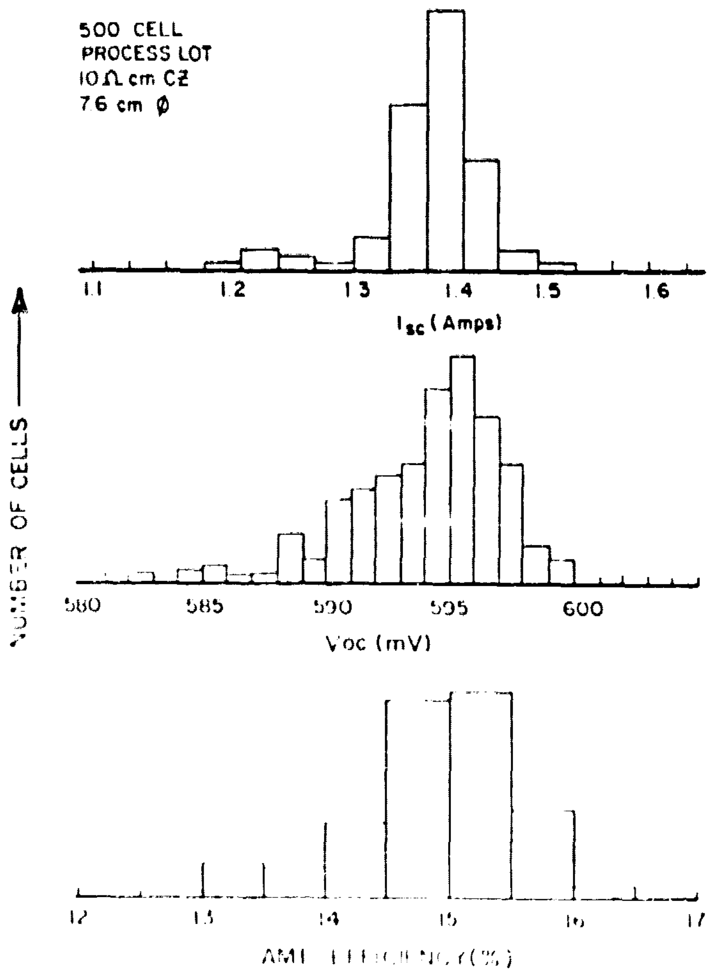
Advantages of Ion Implantation

- MAXIMUM CELL EFFICIENCIES
  - -- Reproducible
  - -- High Yield
  - -- Operator Independent
- CONTINOUS MODE OPERATION
  - -- High Throughputs
  - -- Unlimited Scale-up
- MINIMUM ADDITIONAL PROCESSING
  - -- No Wet Chemistry
  - -- Line of Sight Process
  - -- No Edge Etching

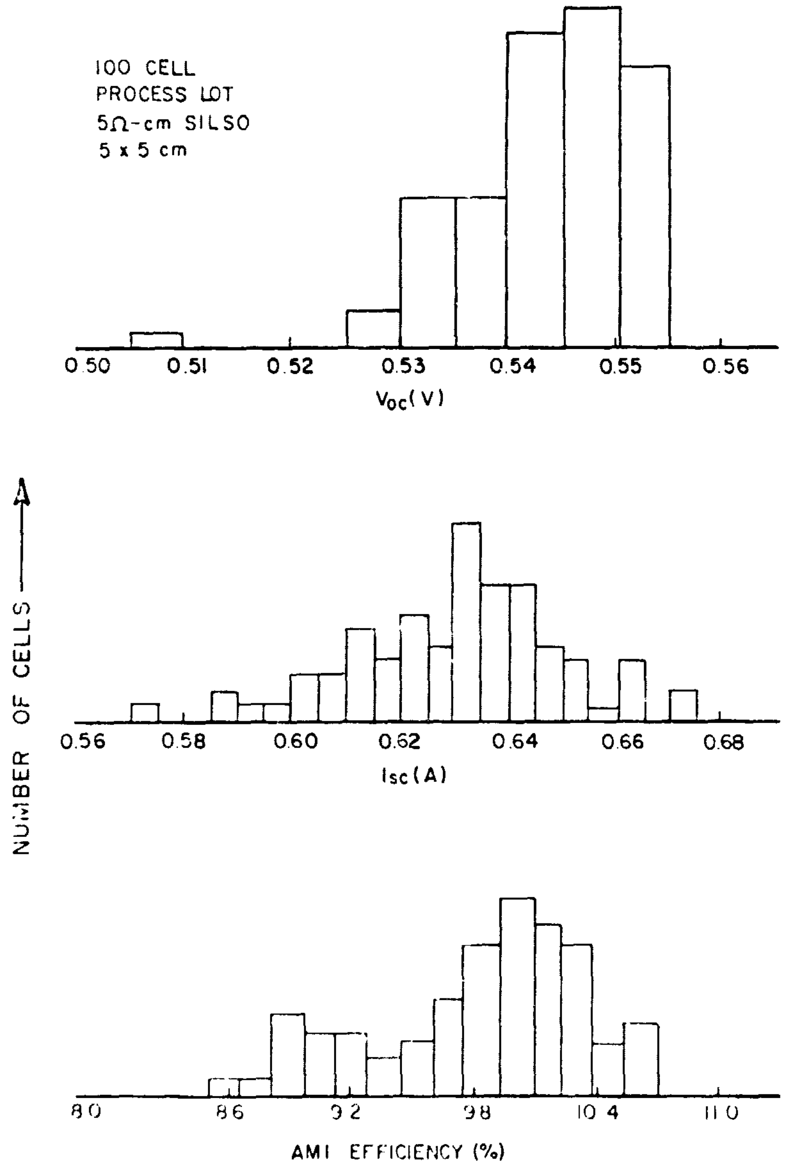
Solar Cell Structure



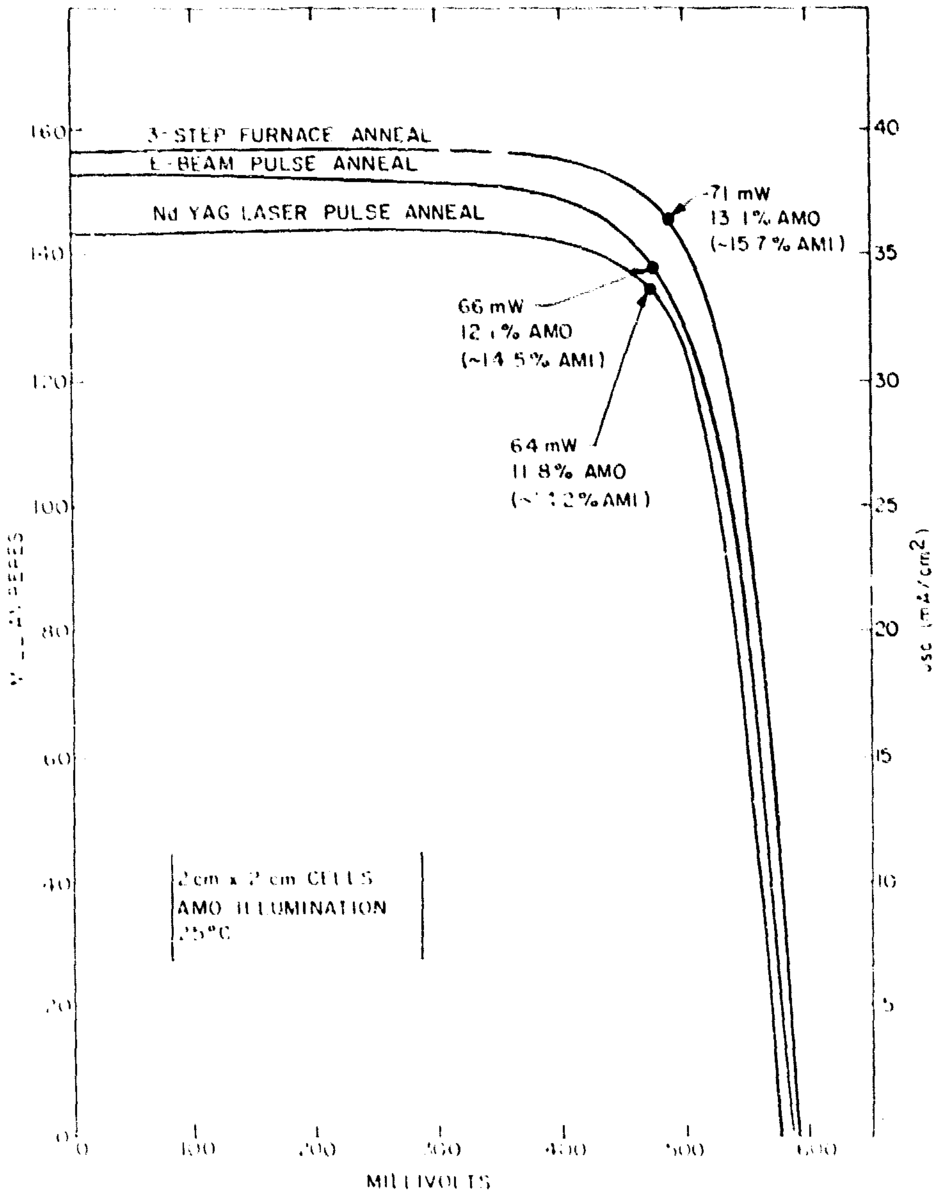
Ion-Implanted Furnace-Annealed Solar Cells



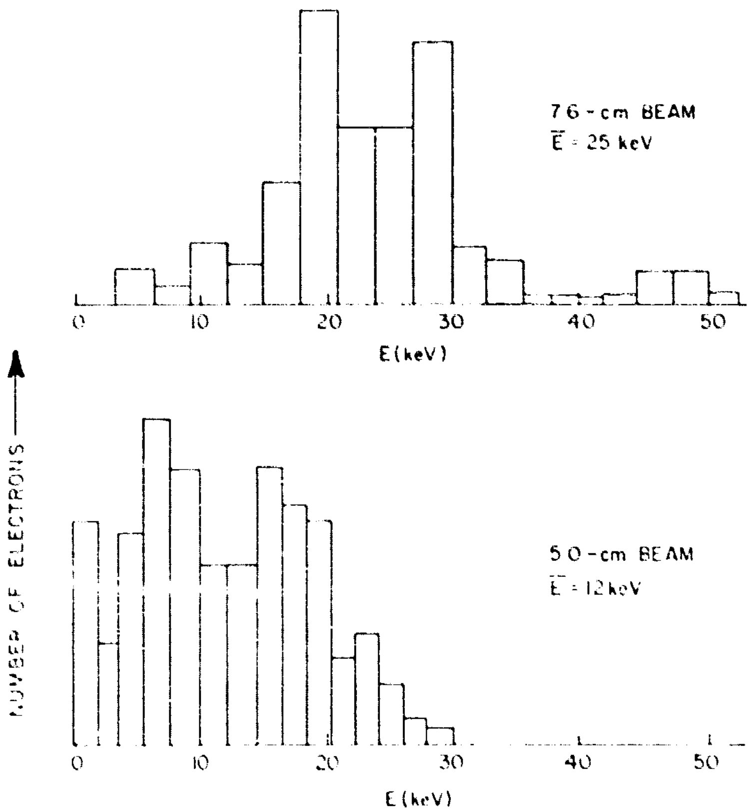
Ion-Implanted Furnace-Annealed Silso Solar Cells



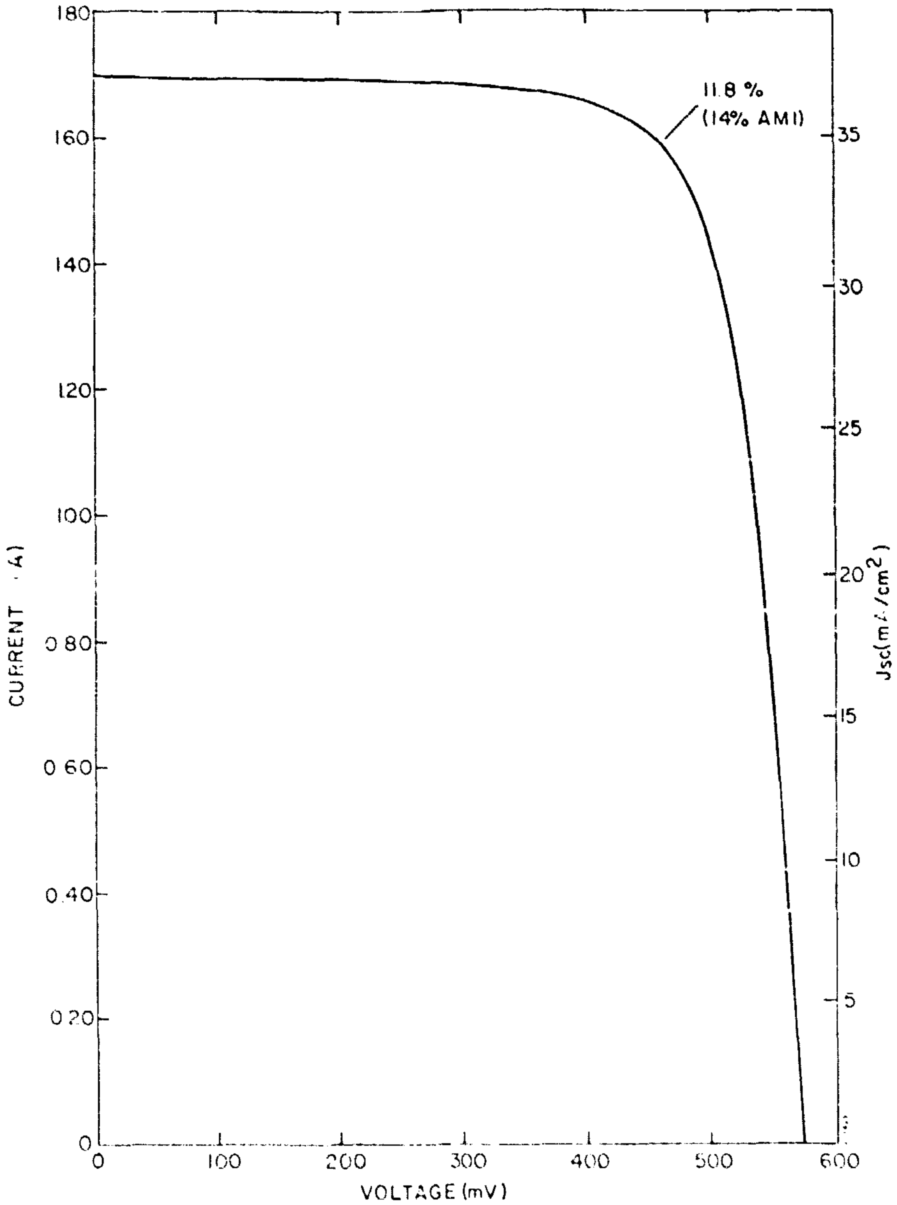
2 x 2 cm Cells AM0 25°C



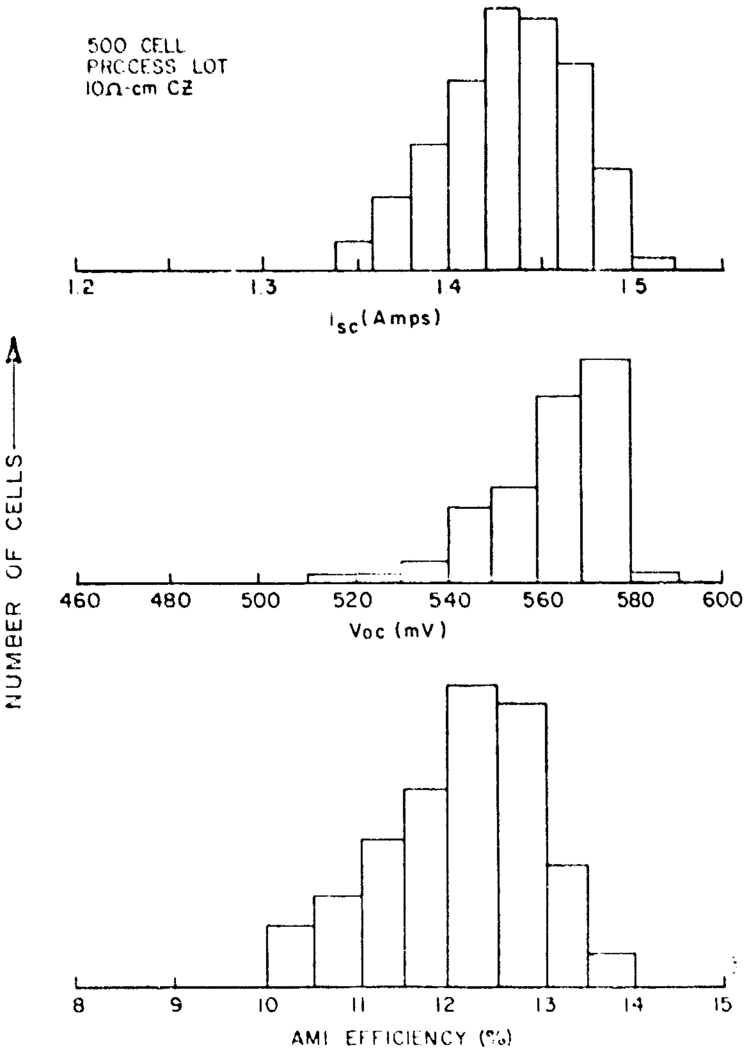
Pulsed Electron Beam Energy



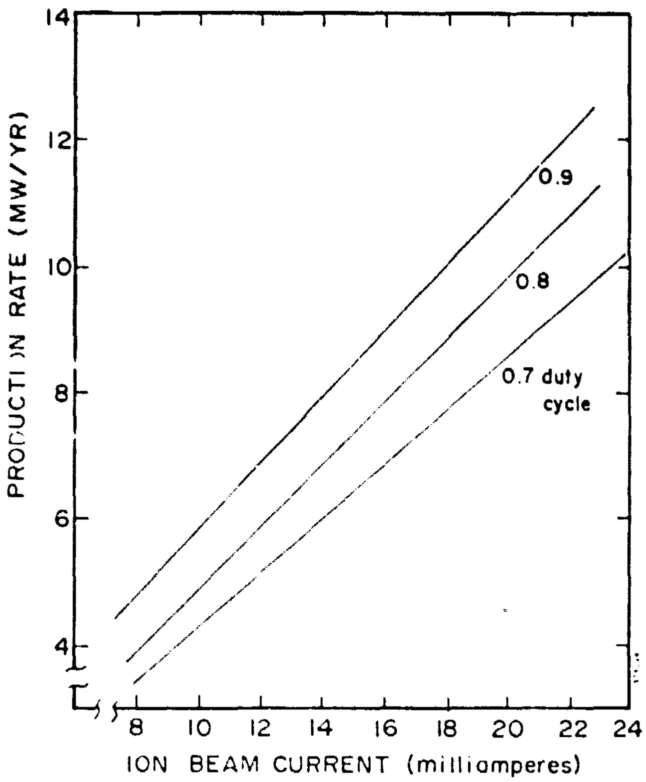
Implanted/Pulse EB Annealed Cell 2138-2
AM0 25°C, 7.6 cm ϕ Cell n^+pp^+



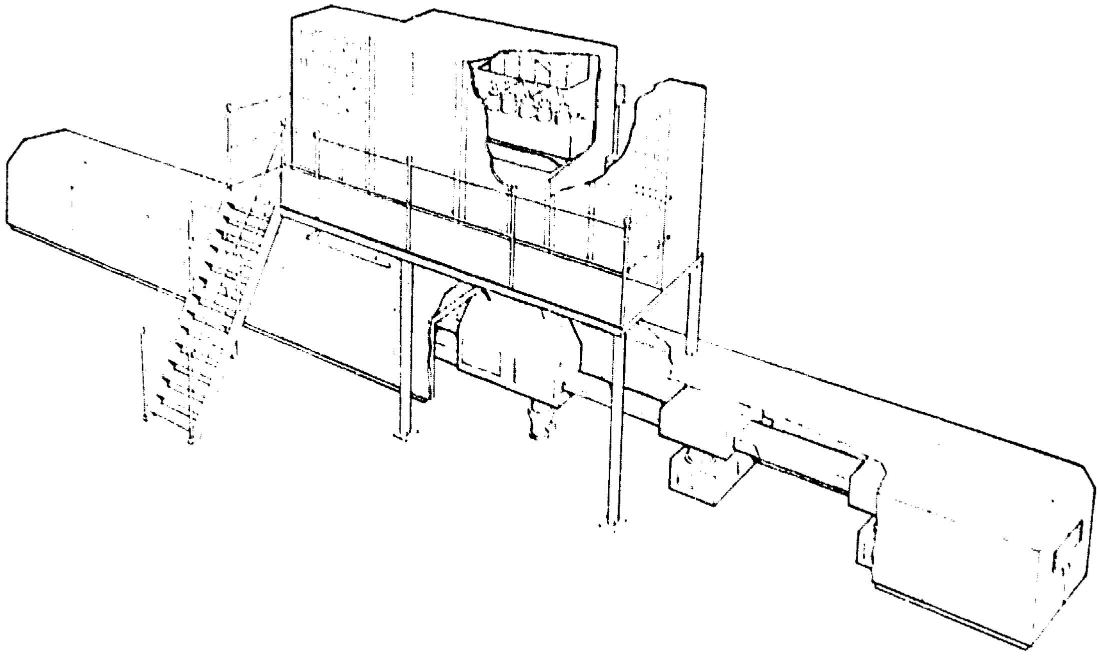
Ion-Implanted Pulse-Annealed Solar Cells



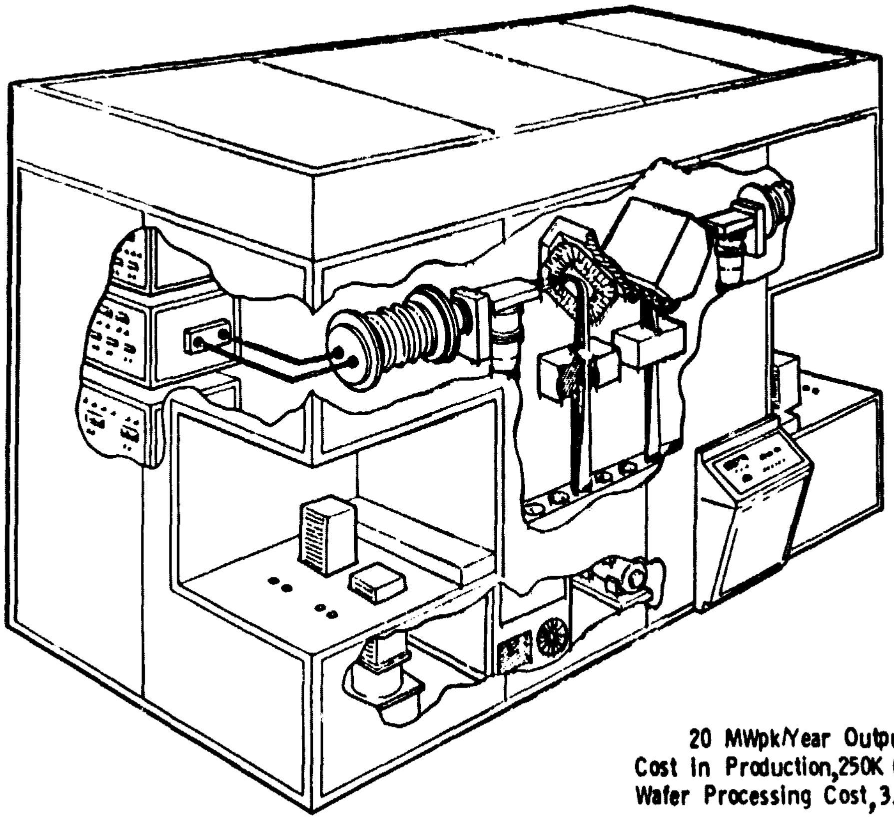
Annual Production Rates



Conceptual Drawing of a 100 mA Automated Production Implanter

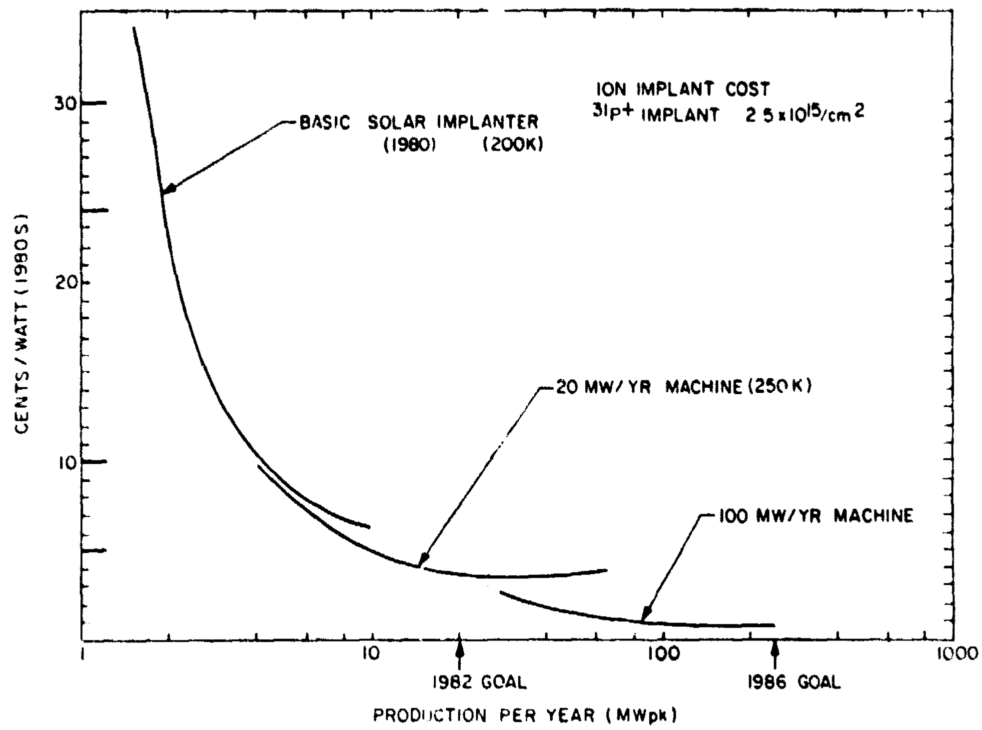


Commercial Solar Ion Implanter for 1982 Goals

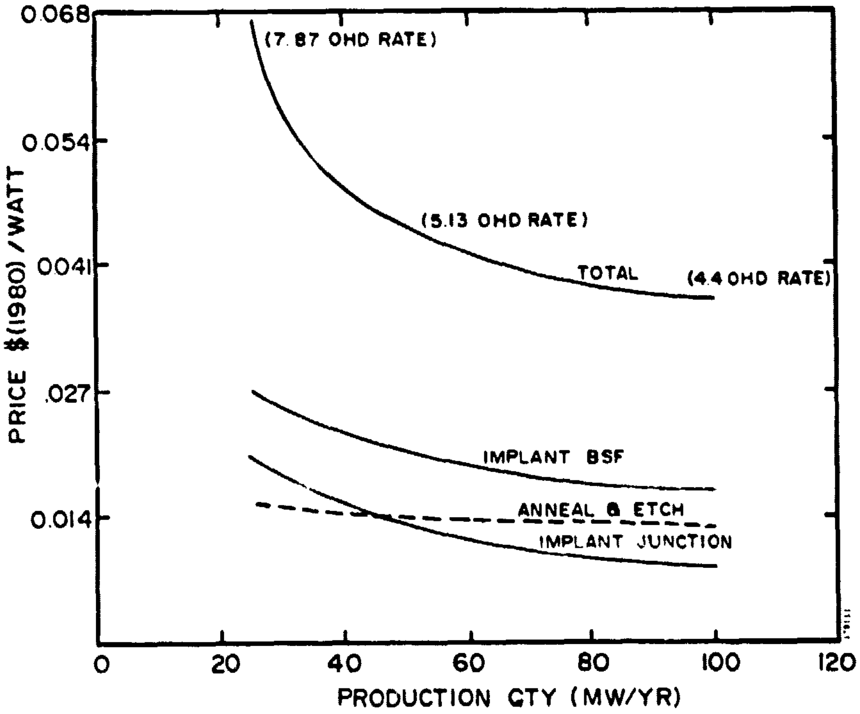


20 MWpk/Year Output
Cost In Production, 250K (1980$)
Wafer Processing Cost, 3.5¢/Watt (1980$)

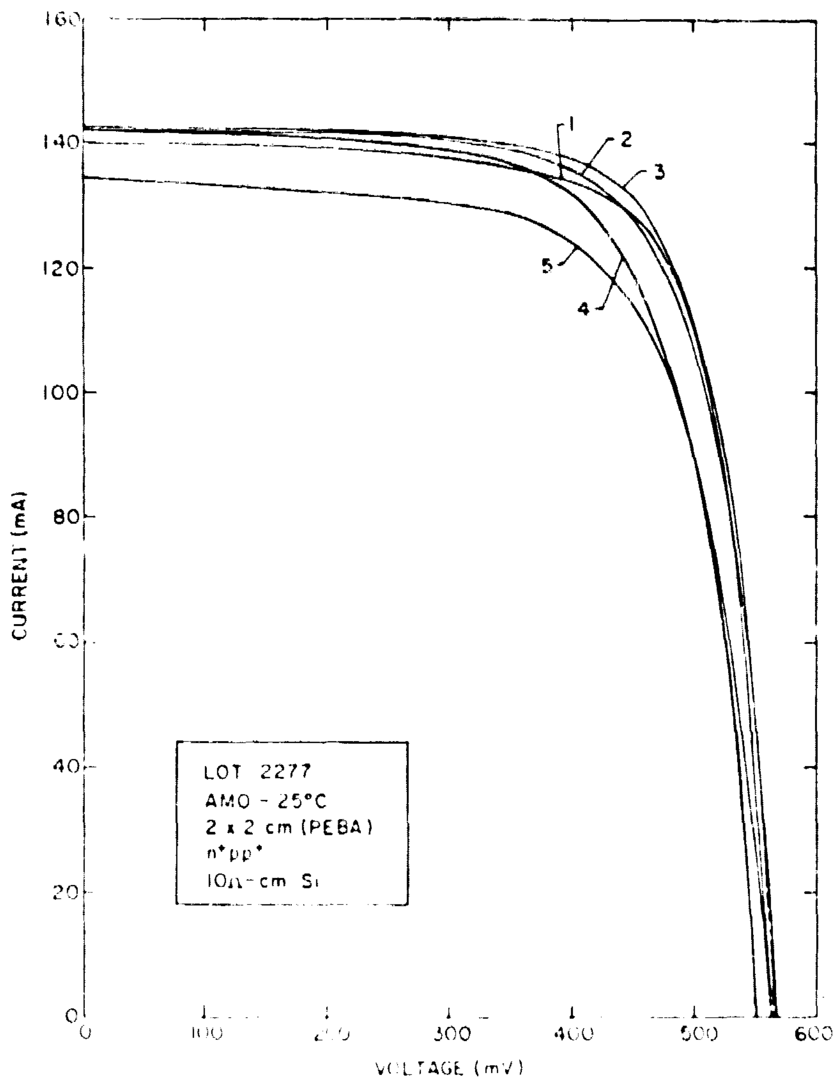
Ion Implant Cost



SAMIS Cost Estimates



PEBA Cell Uniformity

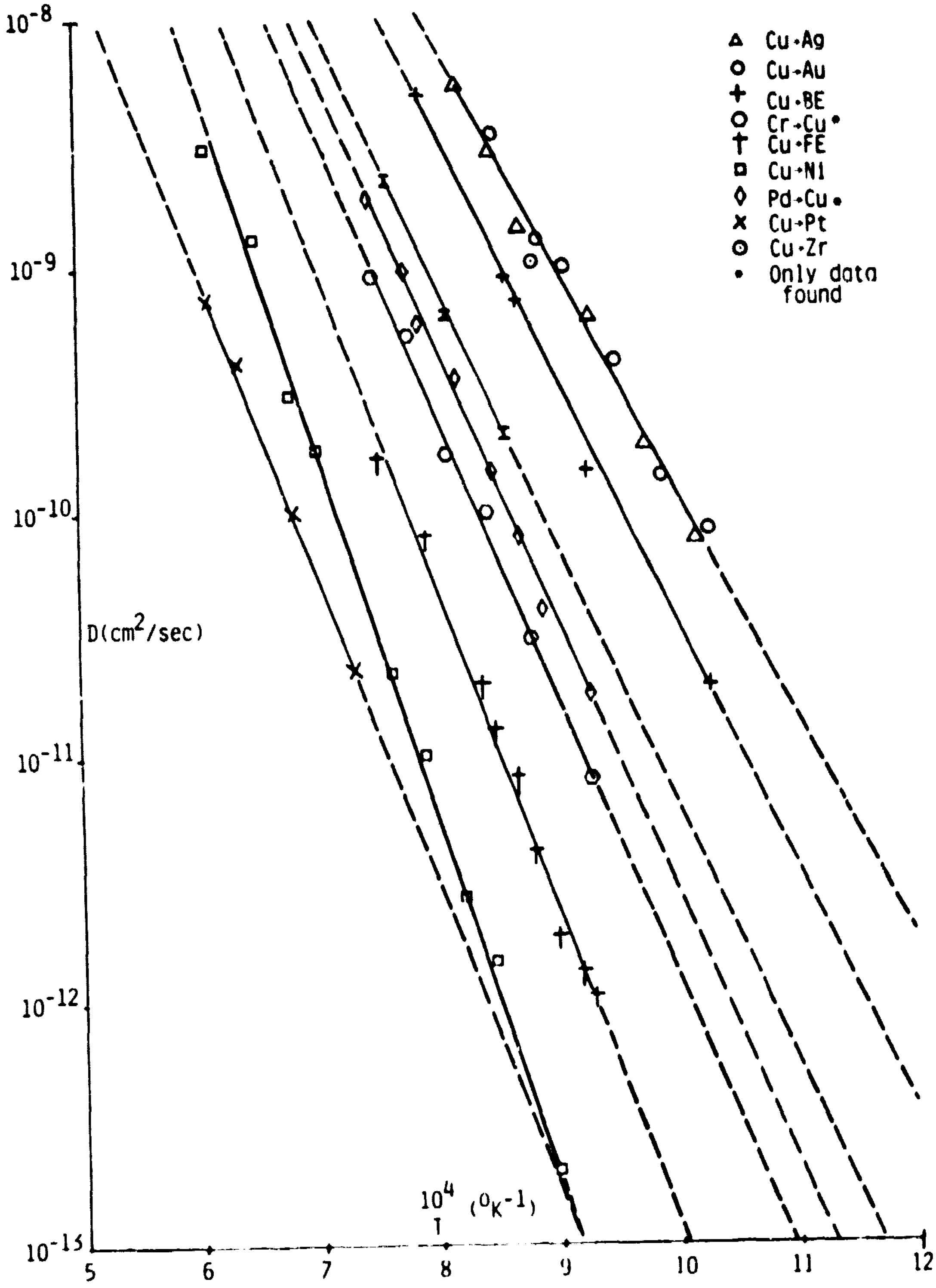


PEBA CELL UNIFORMITY

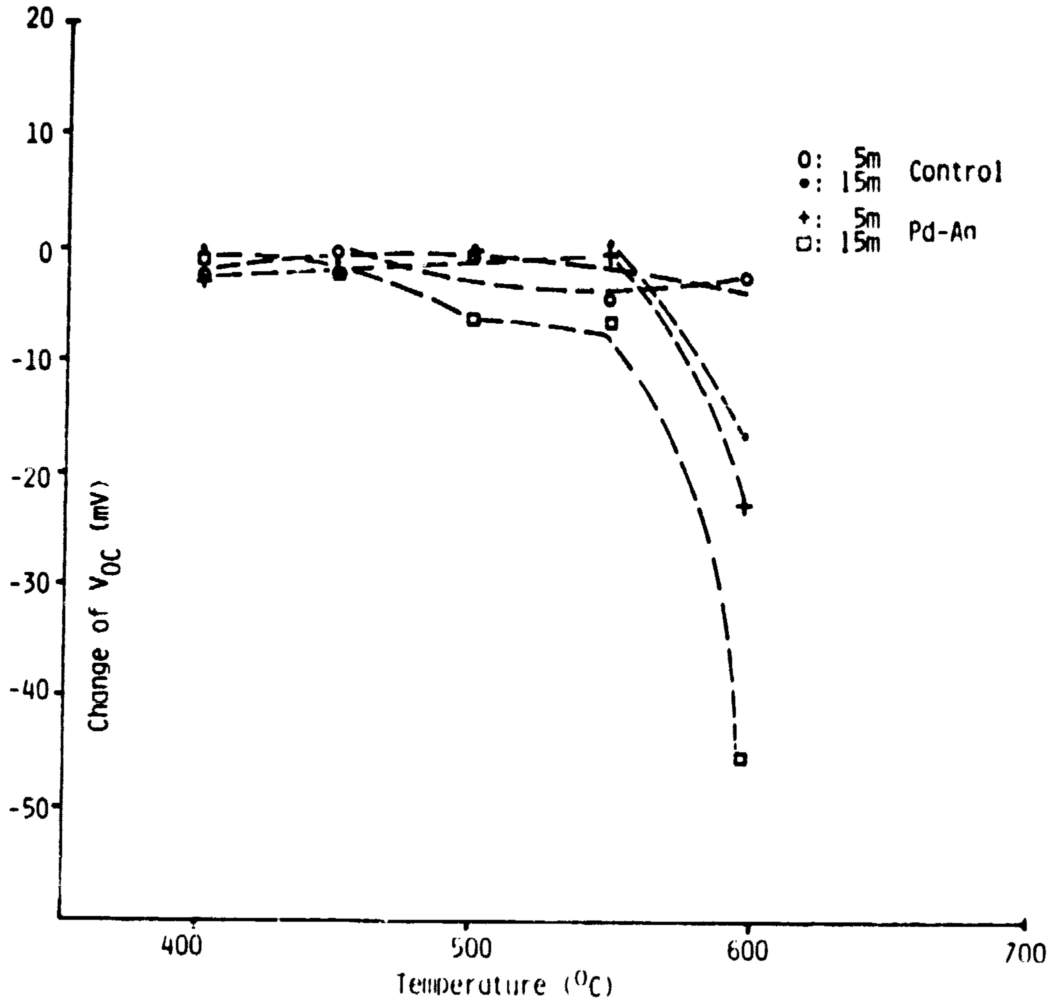
CONTACT DEVELOPMENT

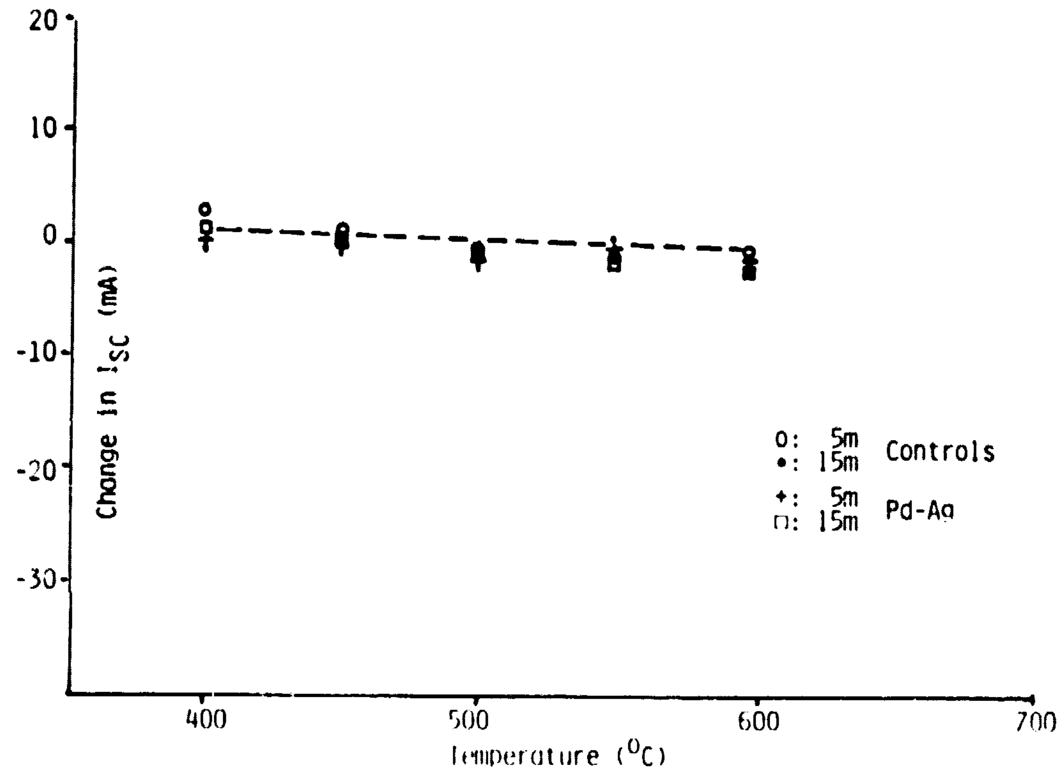
APPLIED SOLAR ENERGY CORP.

Diffusion Data



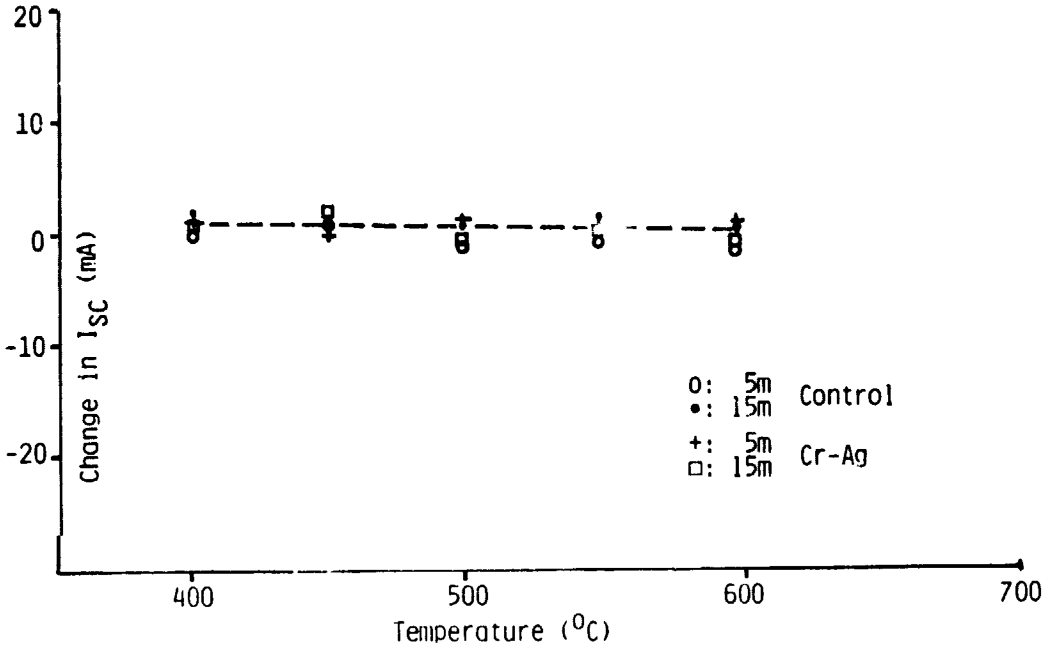
2000A Pd——Thick Ag

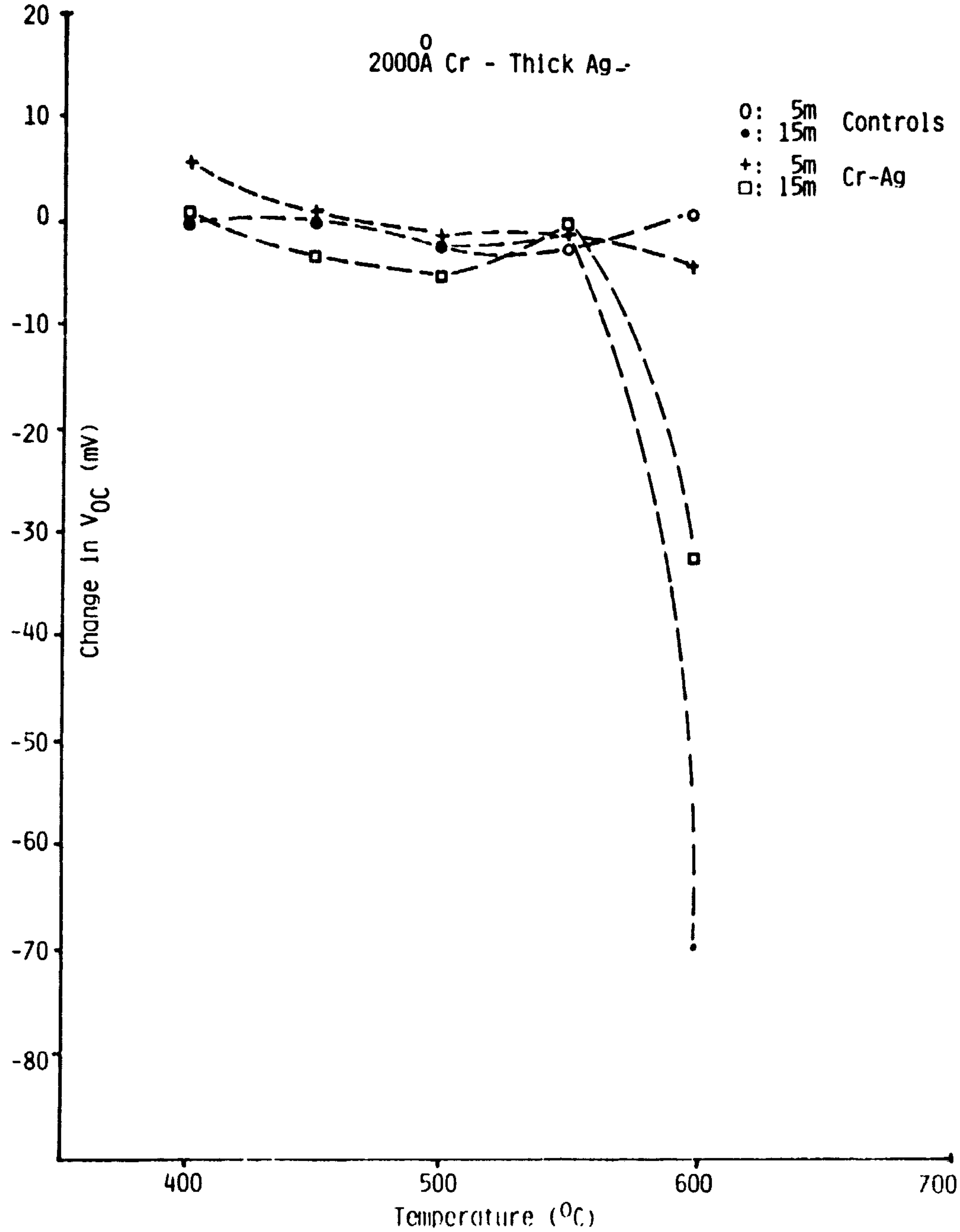




20
10
0
-10
-20
-30
Change in I_{SC} (mA)
400
500
600
700
Temperature (^{0}C)
o: 5m
•: 15m
Controls
+: 5m
□: 15m
Pd-Ag

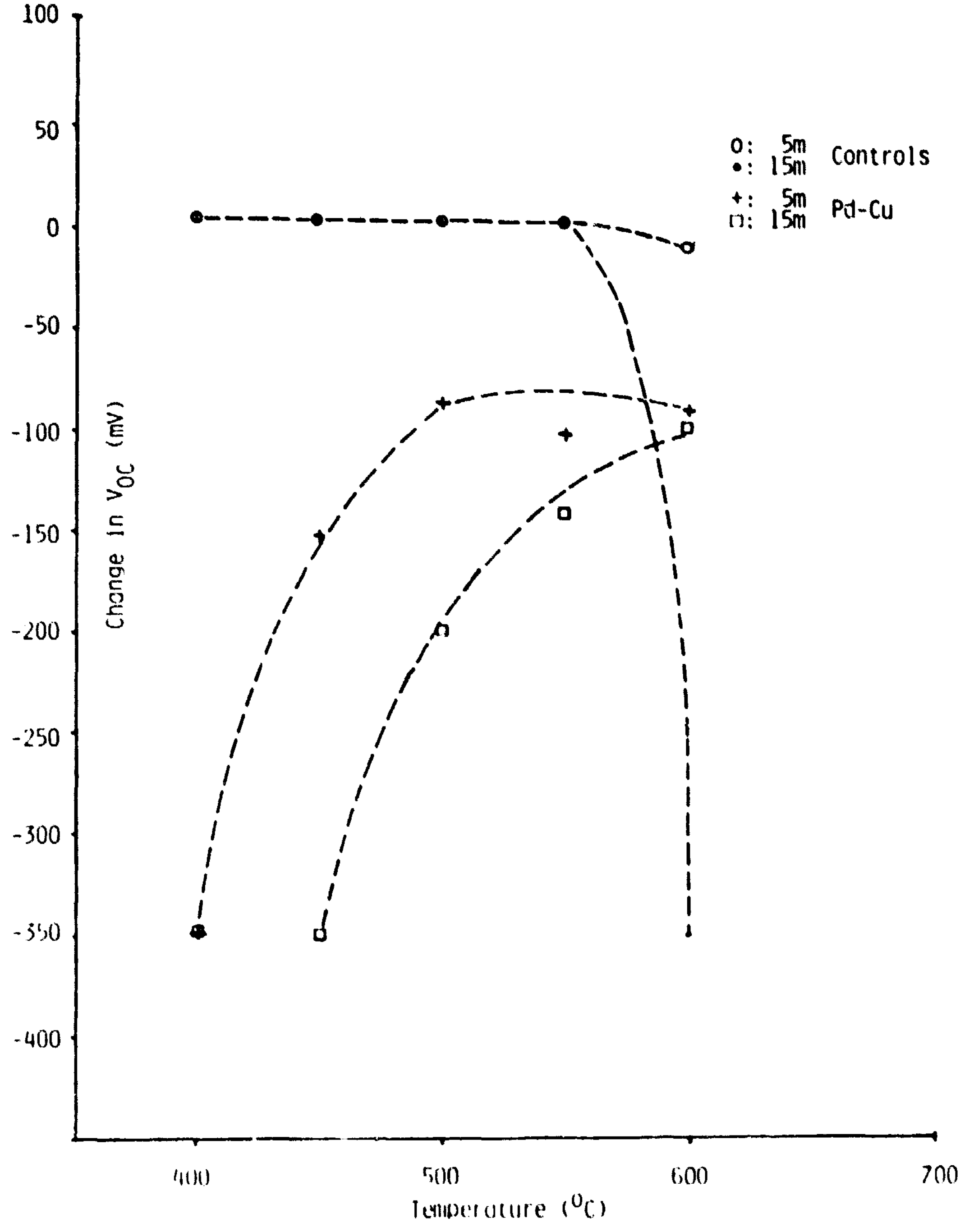
2000A Cr——Thick Ag

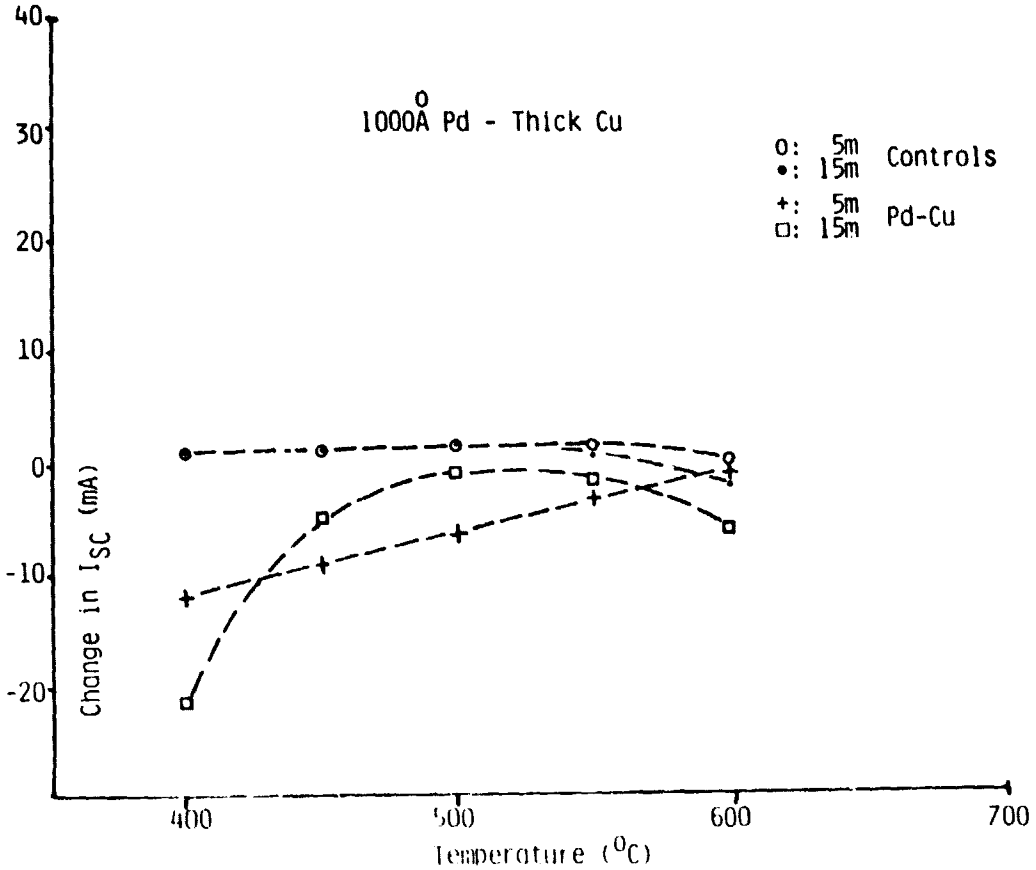




2000Å Cr - Thick Ag
o: 5m
•: 15m
Controls
+: 5m
□: 15m
Cr-Ag
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Change in V_{OC} (mV)
400
500
600
700
Temperature (°C)

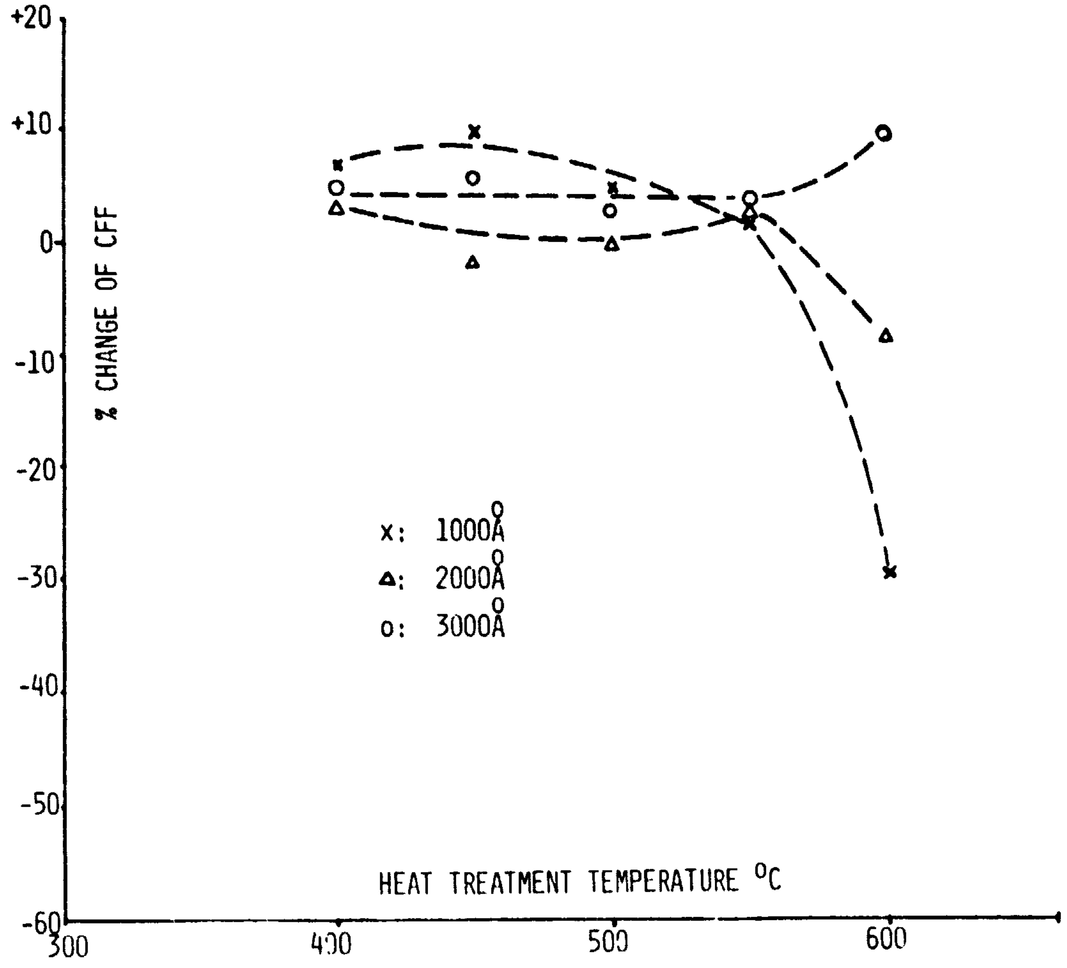
1000A Pd----Thick Cu

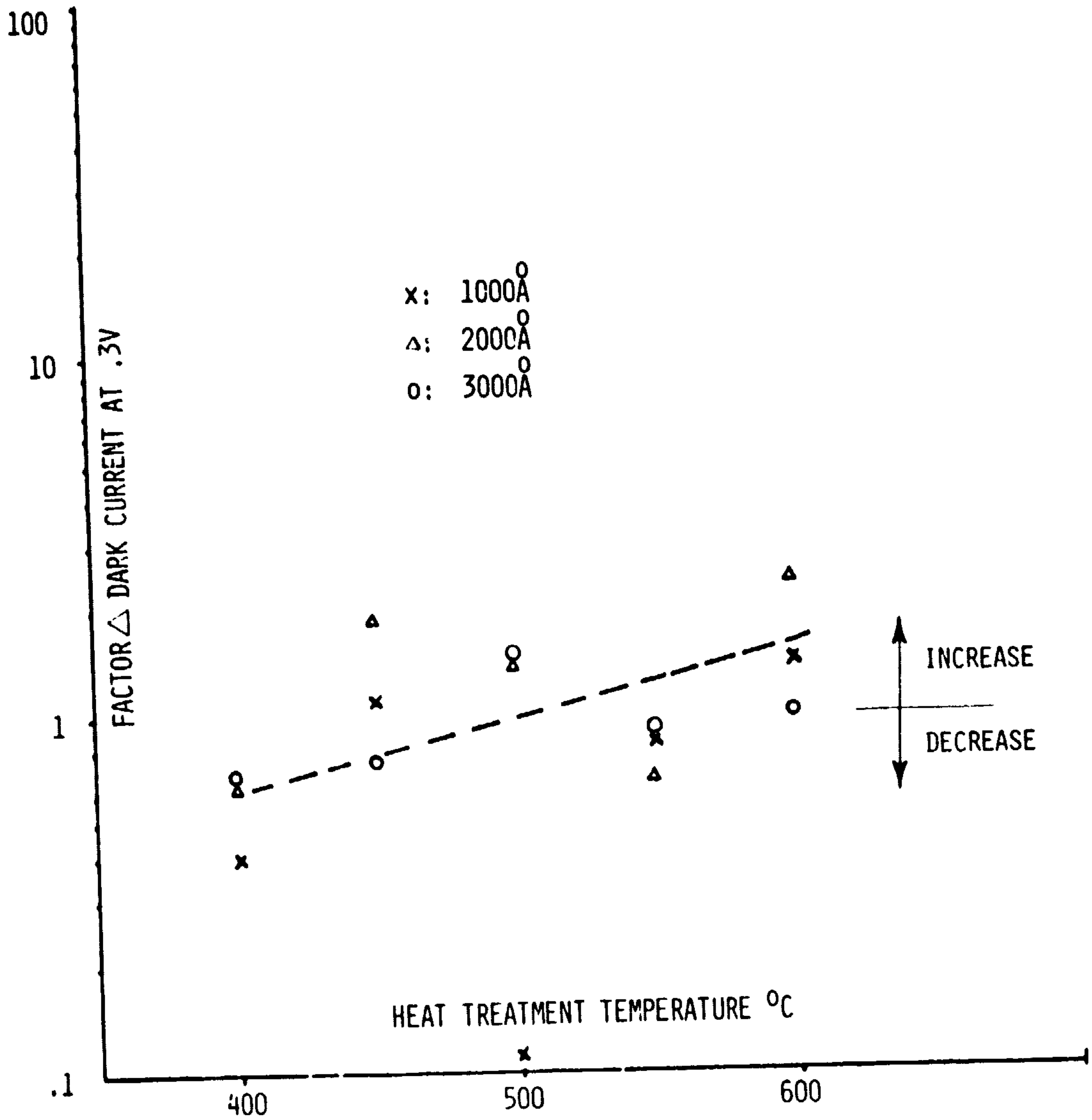




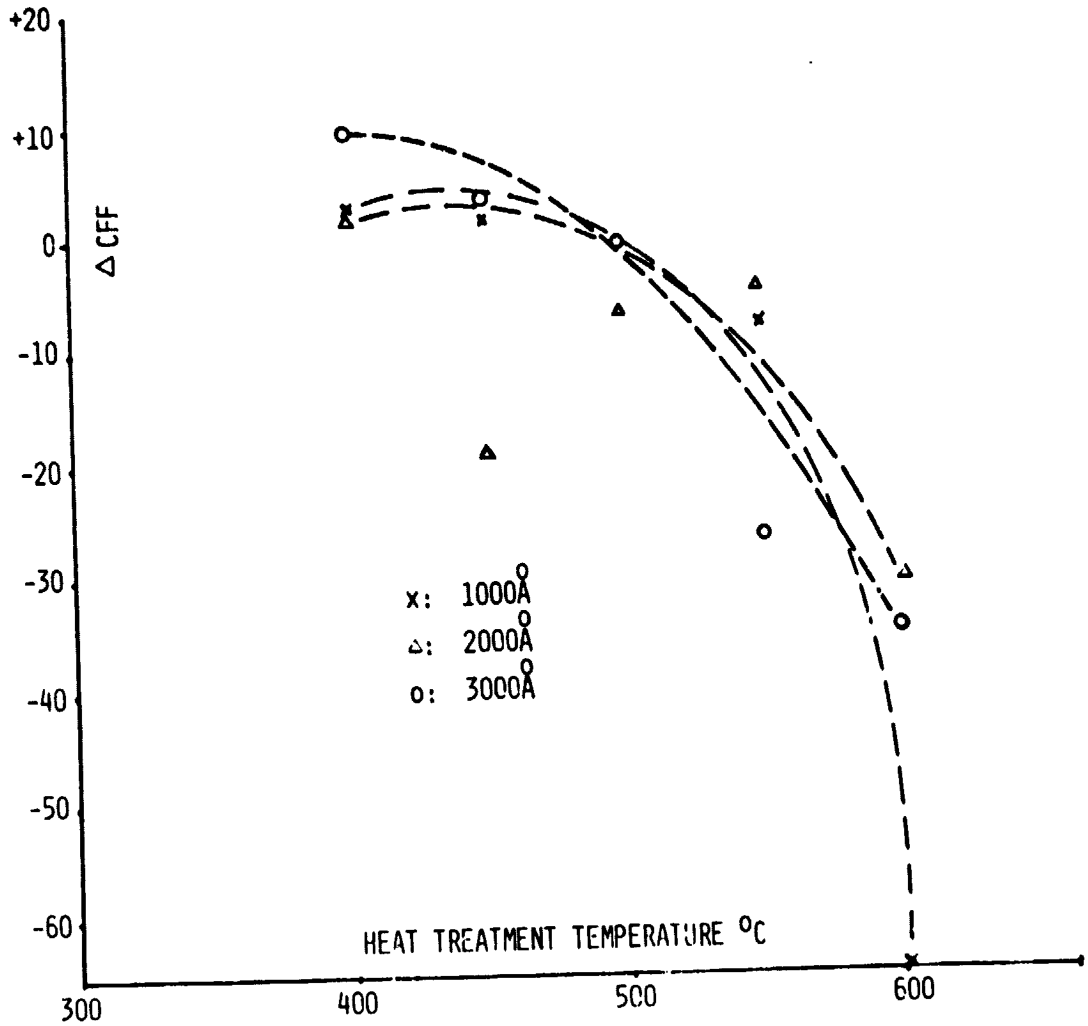
40
30
20
10
0
-10
-20
1000Å Pd - Thick Cu
o: 5m
•: 15m
Controls
+: 5m
□: 15m
Pd-Cu
Change in I_{SC} (mA)
400
500
600
700
Temperature (^{0}C)

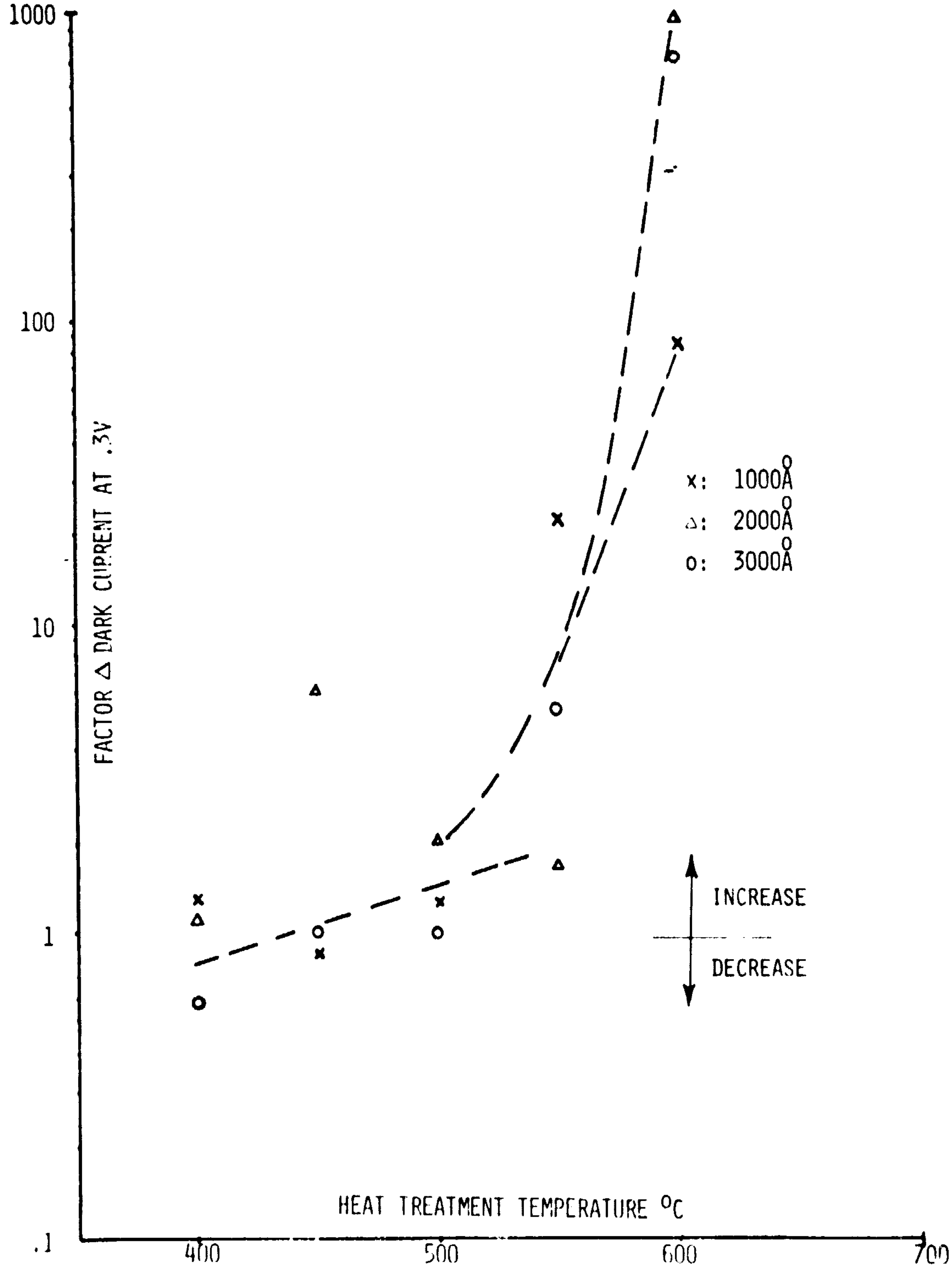
Chromium-Copper Contacts:
Result of 5-min Heat Treatment



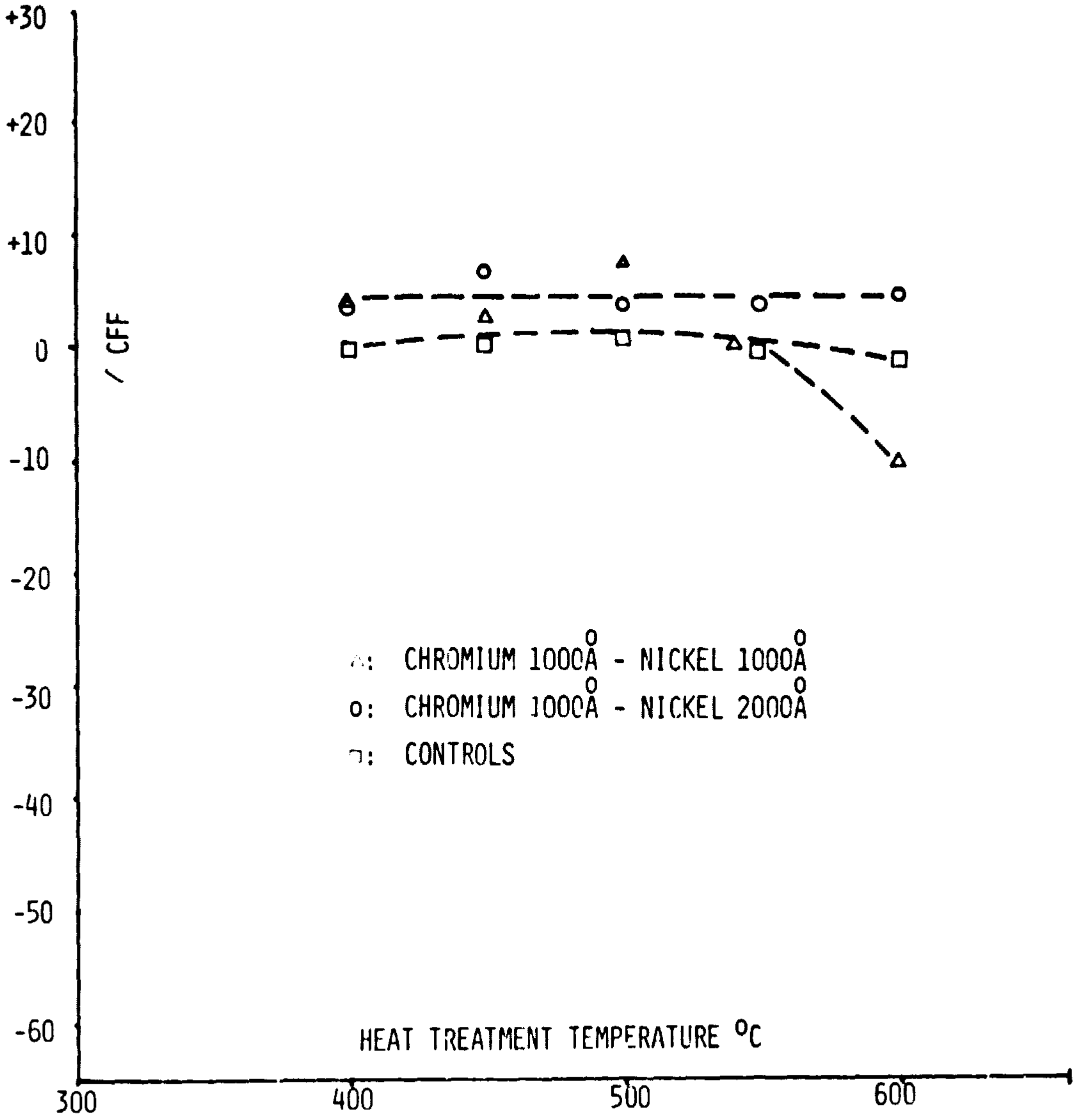

100
10
1
.1
FACTOR △ DARK CURRENT AT .3V
x: 1000Å
△: 2000Å
o: 3000Å
INCREASE
DECREASE
HEAT TREATMENT TEMPERATURE °C
400
500
600

Chromium-Copper Contacts: Result of 15-min Heat Treatment

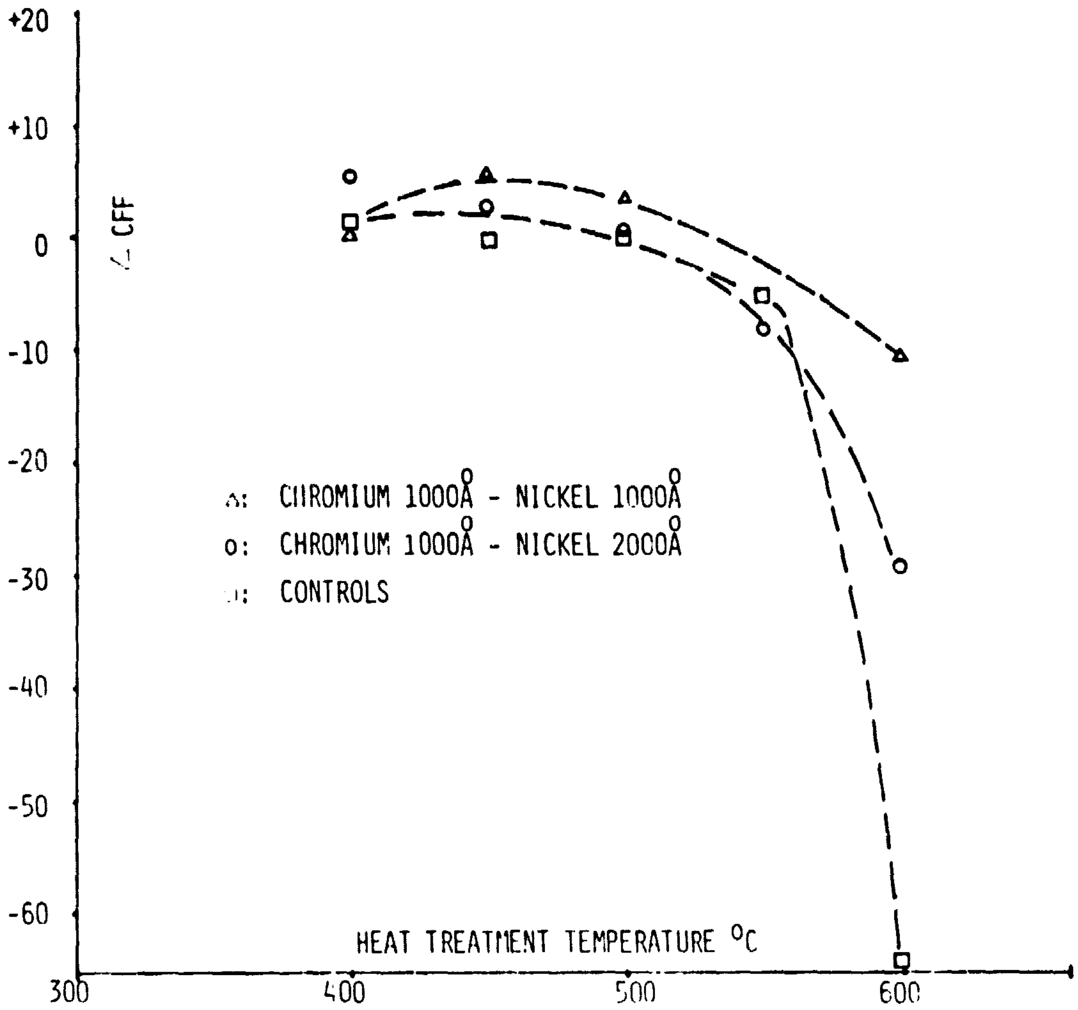


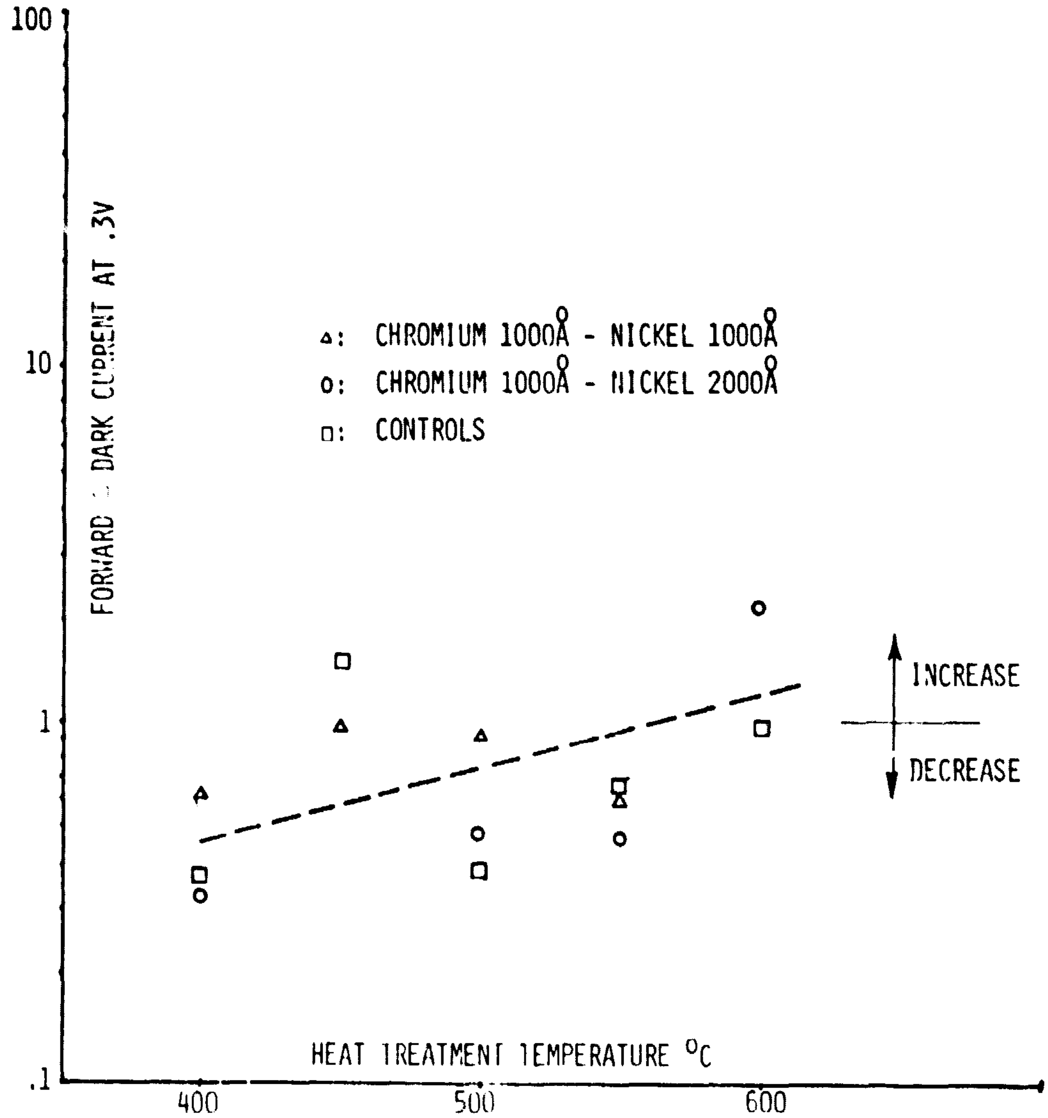

1000
100
10
1
.1
FACTOR Δ DARK CURRENT AT .3V
x: 1000Å
Δ: 2000Å
o: 3000Å
INCREASE
DECREASE
HEAT TREATMENT TEMPERATURE °C
400
500
600
700

Chromium-Nickel-Copper Contacts:
Result of 5-min Heat Treatment

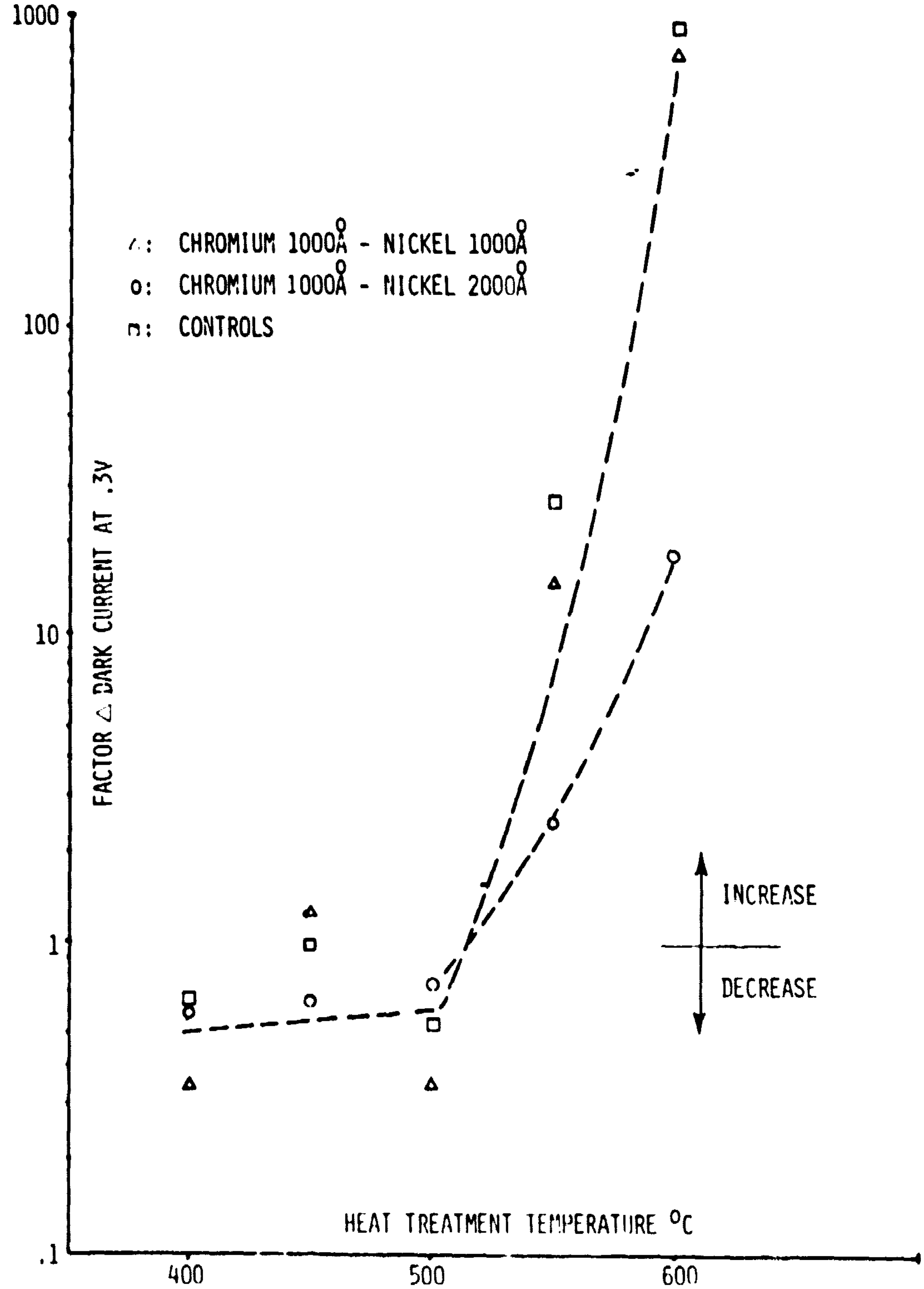


Chromium-Nickel-Copper Contacts: Result of 15-min Heat Treatment



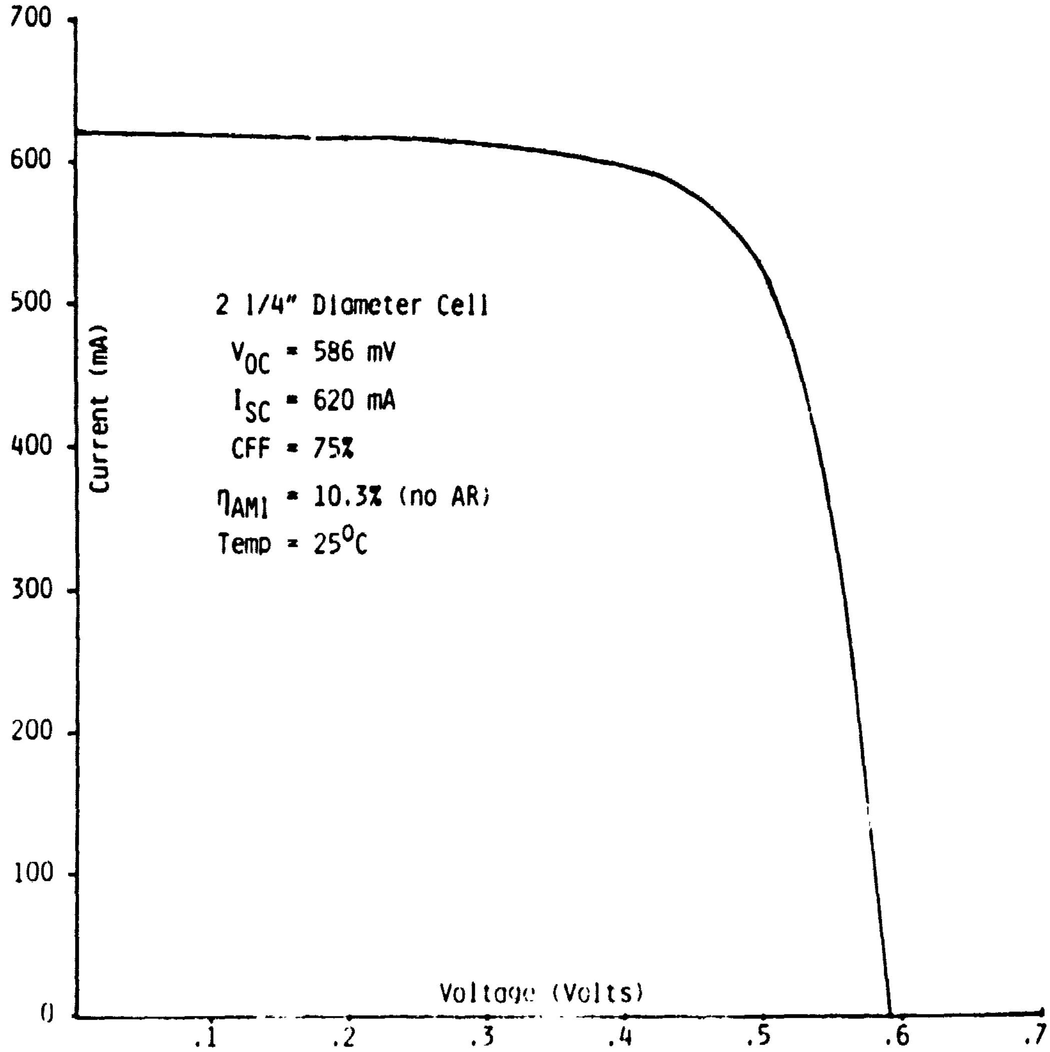


100
10
1
.1
FORWARD : DARK CURRENT AT .3V
△: CHROMIUM 1000Å - NICKEL 1000Å
o: CHROMIUM 1000Å - NICKEL 2000Å
□: CONTROLS
INCREASE
DECREASE
HEAT TREATMENT TEMPERATURE °C
400
500
600

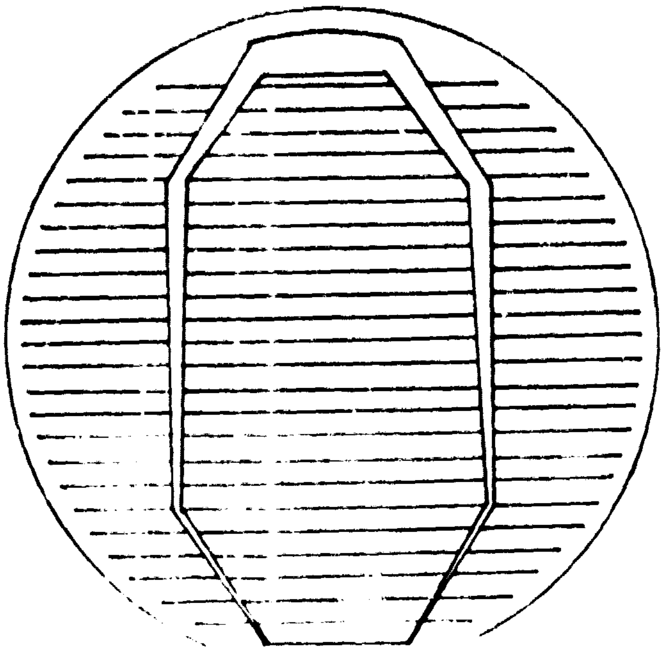


1000
100
10
1
.1
△: CHROMIUM 1000Å - NICKEL 1000Å
o: CHROMIUM 1000Å - NICKEL 2000Å
□: CONTROLS
FACTOR △ DARK CURRENT AT .3V
INCREASE
DECREASE
HEAT TREATMENT TEMPERATURE °C
400
500
600

Plated Pd-Cr-Cu Cell With Print-on Plating Mask



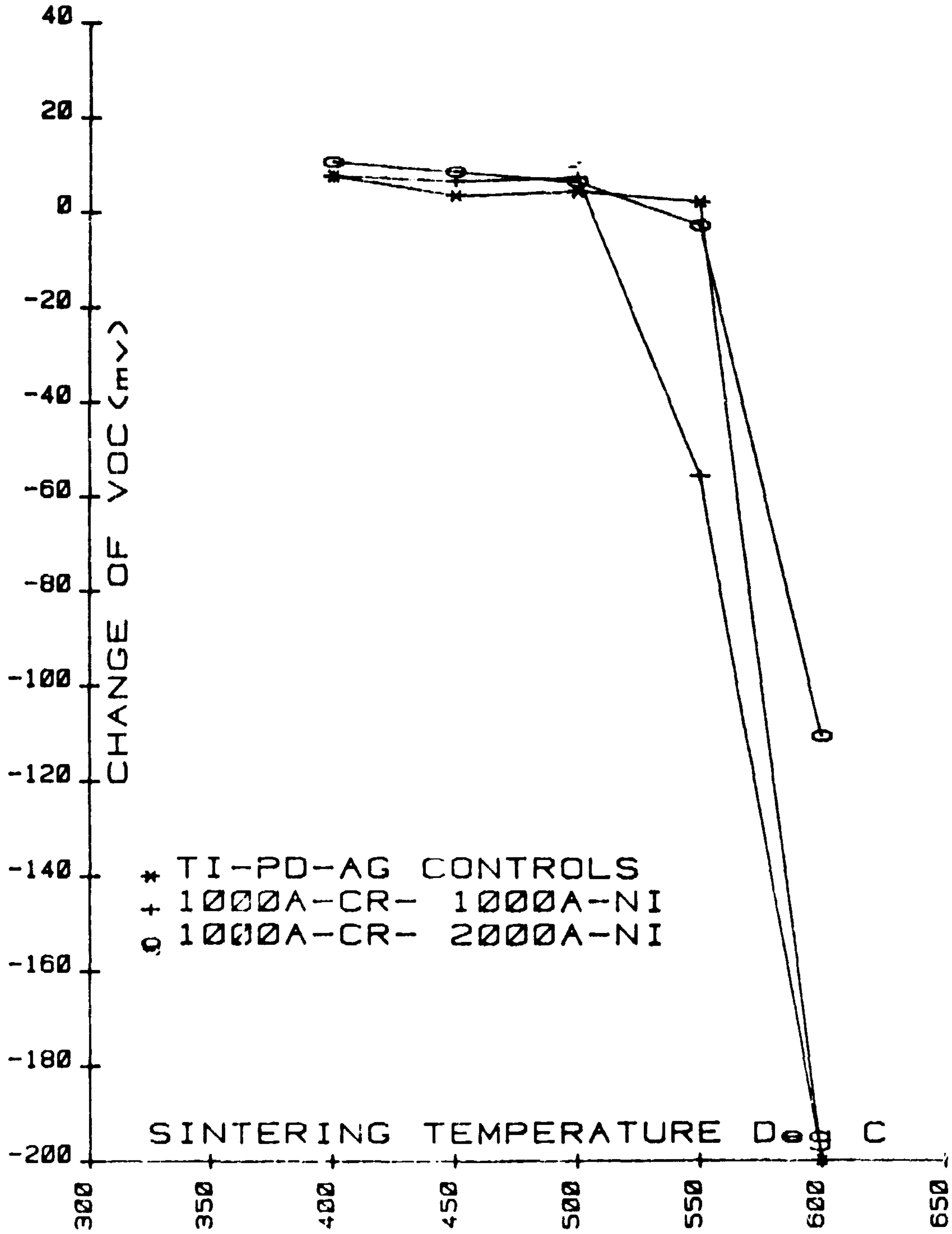
2.25-in. Dia Contact Pattern



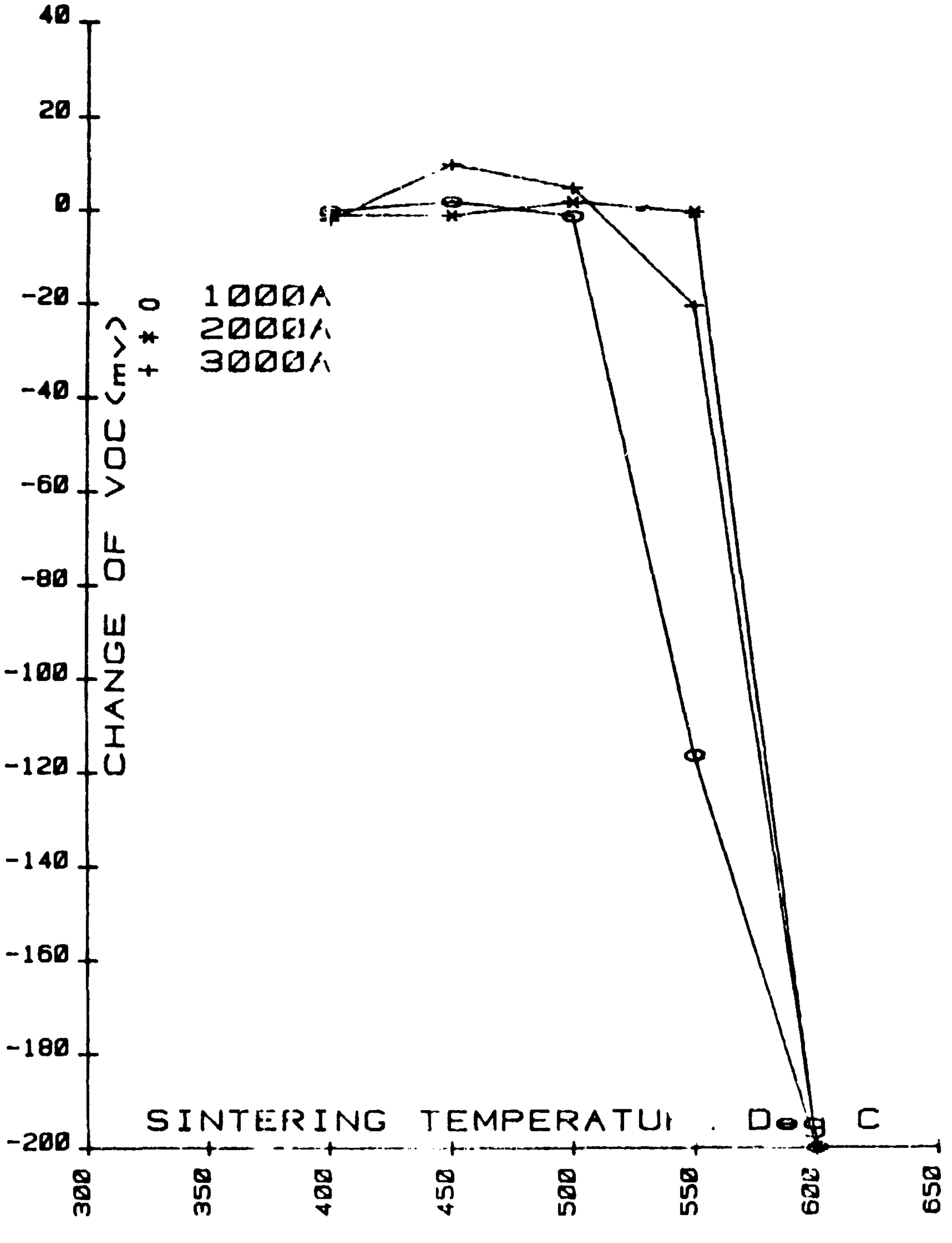
Contact Coverage: 12%

Grid Line Thickness: <5 mil

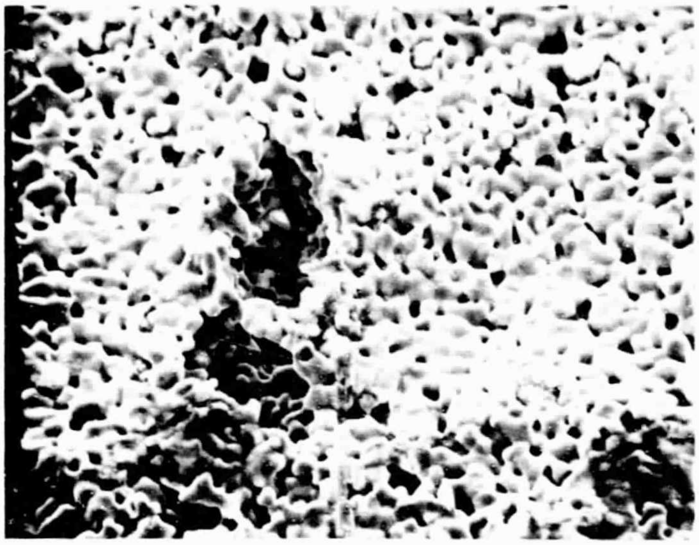
Cr-Ni-Cu Contacts: 15 min Heating



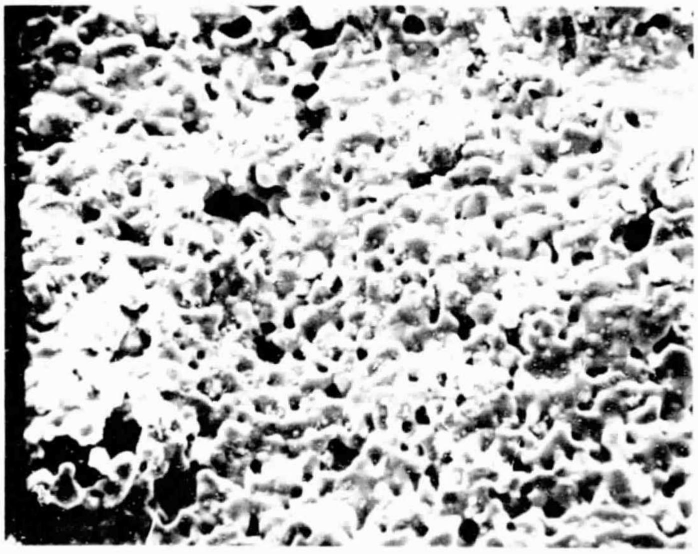
Cr-Cu Contacts: 15 min Heating



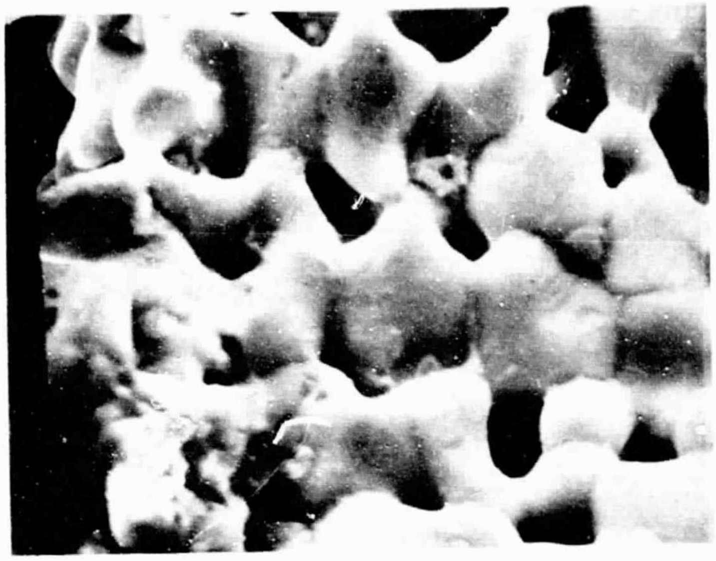
The Following are SEM Photomicrographs of Copper Ink S079 Containing 5% AgF 5% Al-S: Eutectic and 5% Pb as a Function of Temperature. The Fifth Photo Shows Similar Ink with 5% Al-Ge Eutectic Instead of Silicon (Compare with First Photo)



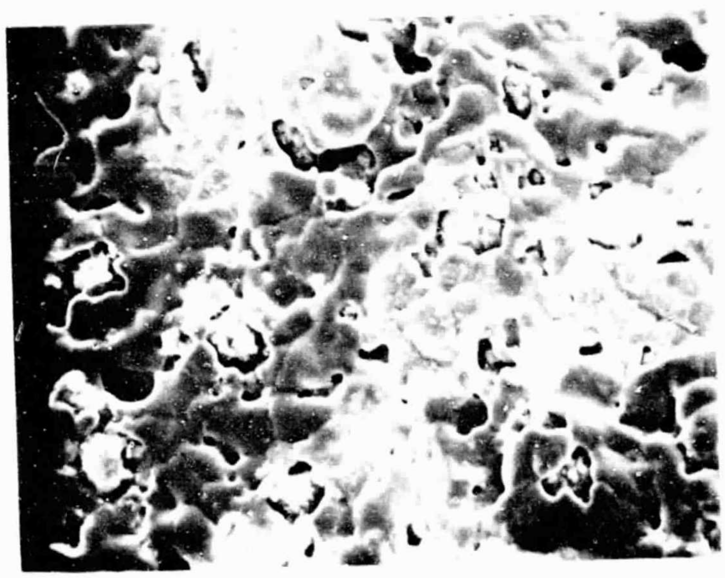
(a) 975X



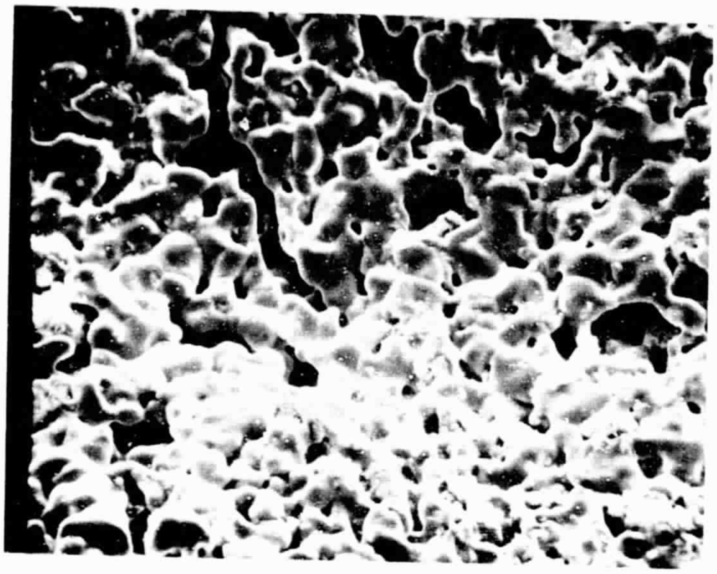
(b) 975X; N760^{o}C, H760^{o}C



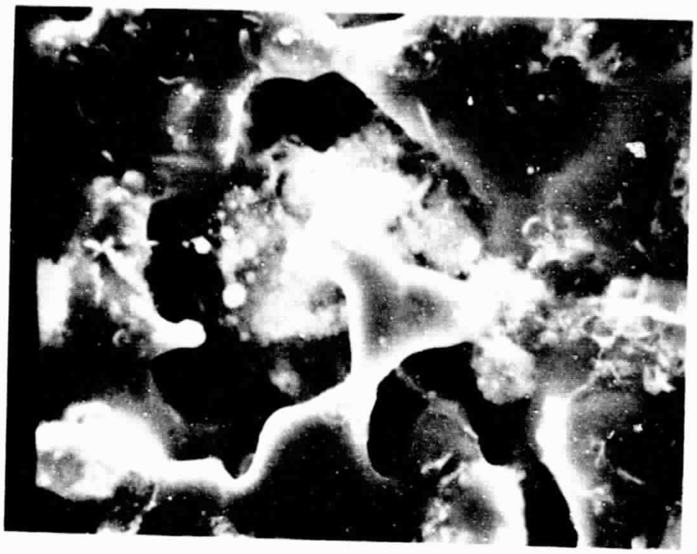
(c) 975X; N760°C, H860°C



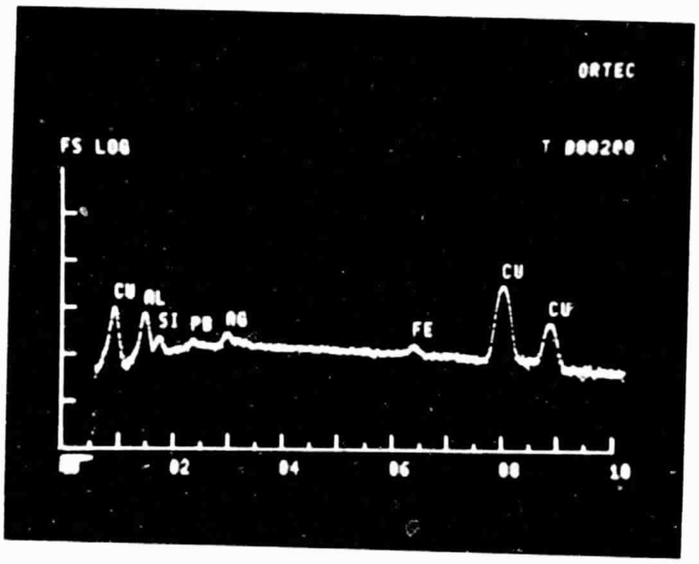
(d) 4800X; N760°C, H658°C



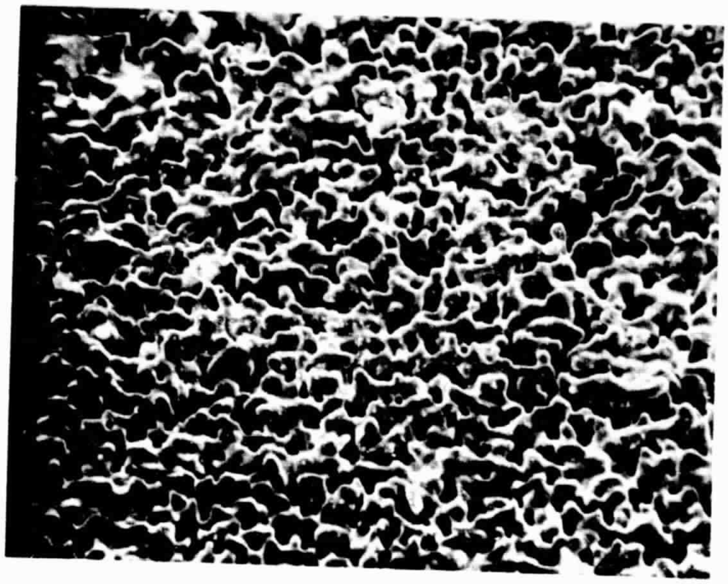
(e) 975X; N760°C, H658°C



SEM Photomicrograph of Doped Cu Ink S079
Containing 5% Si Al Eutectic,
5% Pb and 5% AgF; 480X

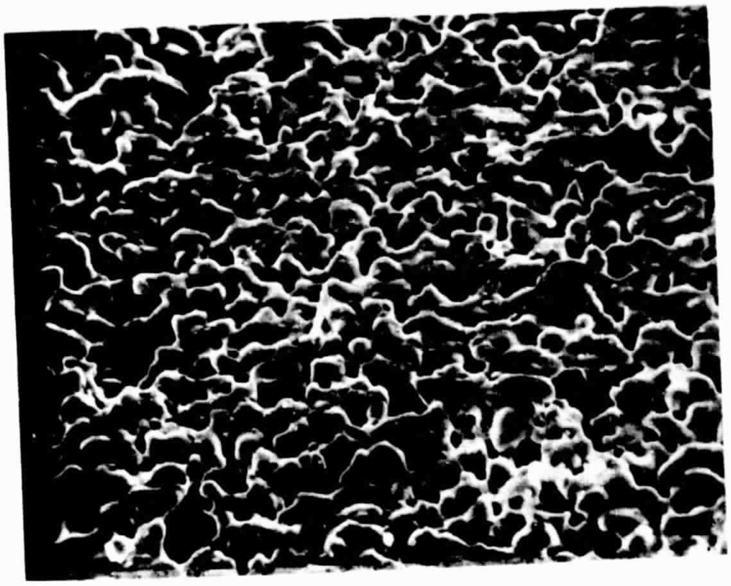


X-Ray Fluorescence Scan on Above. Log
Intensity vs X-Ray Energy in keV.



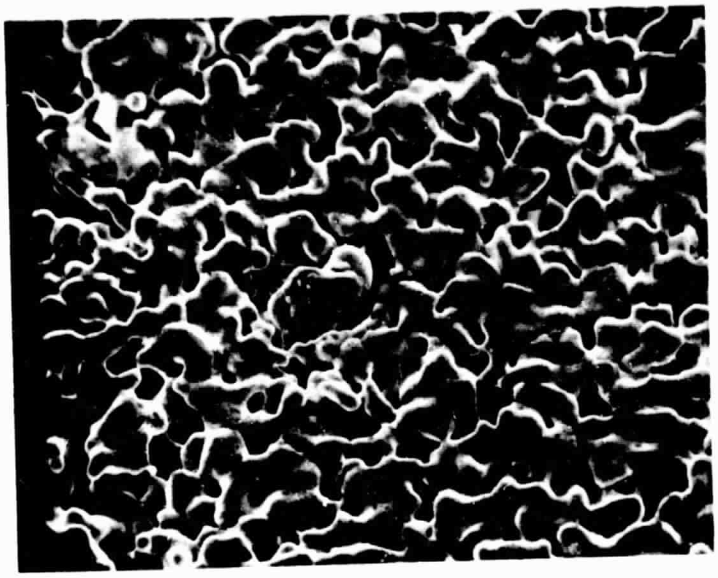
(a) 975X; 596°C N_2, 596°C H_2

(b) 4800X; 596°C N_2, 596°C H_2



(c) 975X; 658°C N_2, 658°C H_2

(d) 4800X, 658°C N_2, 658°C H_2



(e) 975X; 658^{o}C N_2, 710^{o}C H_2

(f) 4800X; 658^{o}C N_2, 710^{o}C H_2

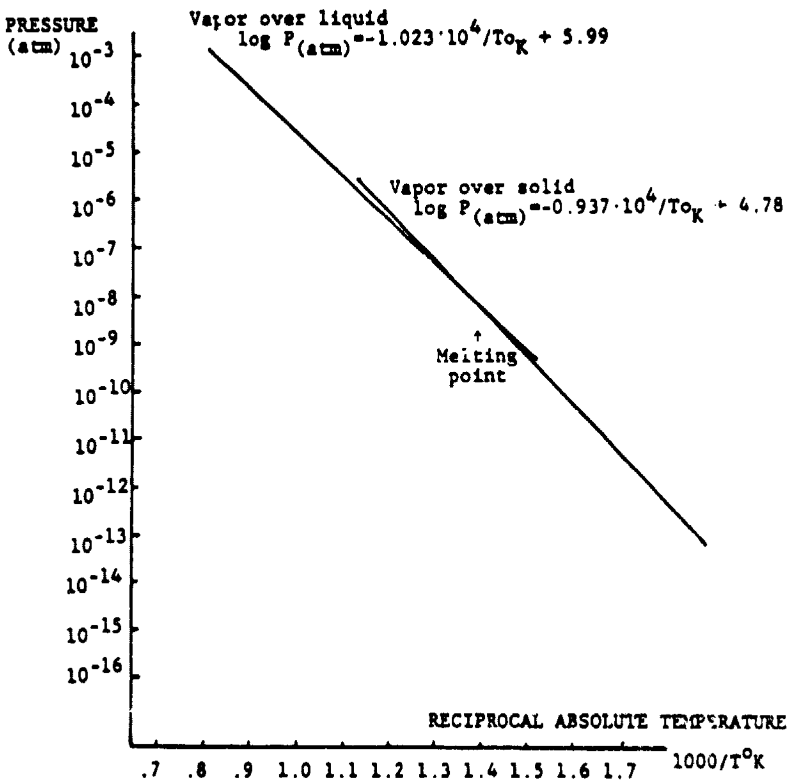
SEM Photomicrographs of S071 Copper Paste, Containing 5% AgF and 5% Pb, as a Function of Temperature

DEVELOPMENT OF ECONOMICAL IMPROVED THICK-FILM SOLAR CELL CONTACTS

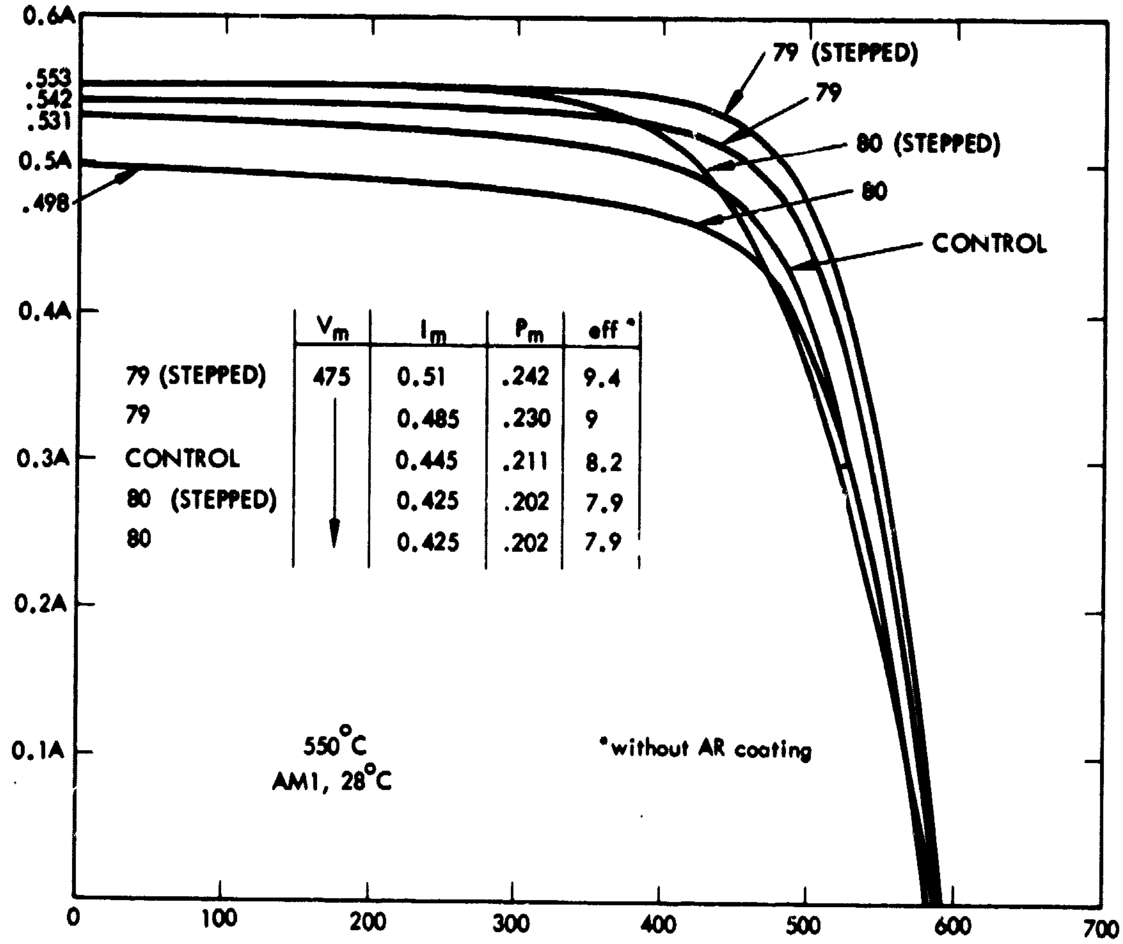
BERND ROSS ASSOCIATES

Bernd Ross

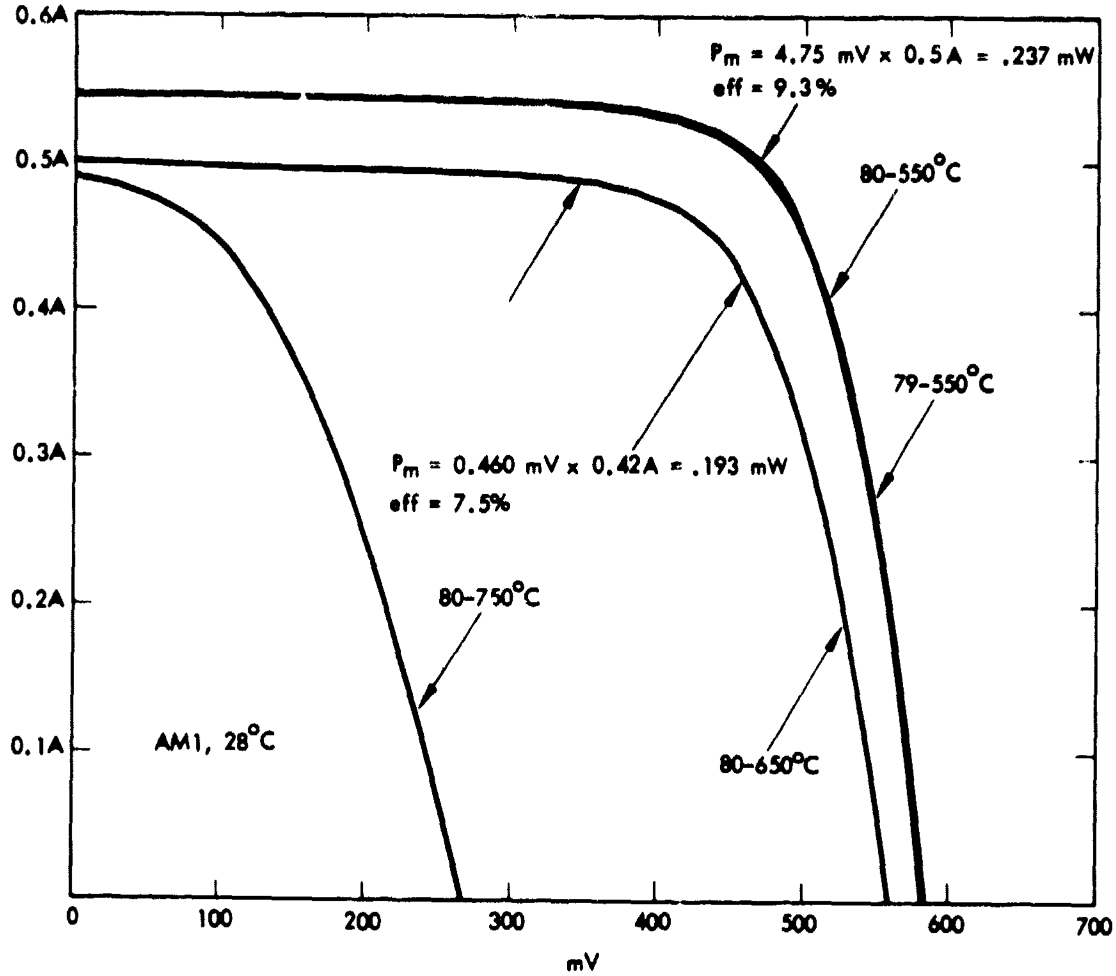
Corrected* Vapor Pressure Over Silver Fluoride



* H. Goldman, Private Comm. (Sep 1979)



	V_m	I_m	P_m	eff *
79 (STEPPED)	475	0.51	.242	9.4
79	↓	0.485	.230	9
CONTROL		0.445	.211	8.2
80 (STEPPED)		0.425	.202	7.9
80		0.425	.202	7.9


0.6A
0.5A
0.4A
0.3A
0.2A
0.1A
0
100
200
300
400
500
600
700
mV
Pm = 4.75 mV x 0.5A = .237 mW
eff = 9.3%
80-550°C
79-550°C
Pm = 0.460 mV x 0.42A = .193 mW
eff = 7.5%
80-750°C
80-650°C
AM1, 28°C

Initial Test Results From Cu Pastes (AM1)

PASTE	CELL	SHORT CIRCUIT CURRENT	OPEN CIRCUIT VOLTAGE	MAXIMUM POWER POINT VOLTAGE	CURRENT	POWER	FILL FACTOR	EFFICIENCY BARE	COATED
		I_{SC}(A)	V_{OC}(V)	V_{MP}(V)	I_{MP}(A)	P_M(W)	F	%	%
S079	(1)	0.553	0.592	0.475	0.510	.242	0.740	9.4	13.1
S079	(2)	0.542	0.588	0.475	0.485	.230	0.723	9.0	12.6
CONTROL	(2)	0.531	0.585	0.475	0.445	.211	0.653	8.2	11.5
S080	(1)	0.552	0.585	0.475	0.425	.202	0.625	7.9	11.0
S080	(2)	0.498	0.585	0.475	0.425	.202	0.694	7.9	11.0
S079	(3)	0.545	0.583	0.475	0.500	.238	0.749	9.3	13.0
S080	(3)	0.545	0.583	0.475	0.490	.233	0.733	9.1	12.7

S079 COPPER PASTE CONTAINING 5% AgF 5% Pb 5% Al-Si EUTECTIC
S080 " " " " " 5% AlGe EUTECTIC

(1) ASEC 2.25 IN OD SOLAR CELL APPROX 2 OHM-CM N/P MEDIUM JUNCTION DEPTH, STEPPED COLLECTOR
(2) ASEC 2.25 IN OD SOLAR CELL APPROX 2 OHM-CM N/P MEDIUM JUNCTION DEPTH, STRAIGHT COLLECTOR
(3) FRONT CONTACT APPLIED AFTER BACK CONTACT WAS FIRED

NO BSF, FRONT CONTACT Ti-Pd-Ag, BACK CONTACT PASTE
ALL PASTE CONTACTS SHOWN, FIRED AT 550°C

Conclusions

1. THE ALLMETAL PASTE SYSTEM HAS BEEN METALLURGICALLY DEMONSTRATED.

2. SILVER-LEAD, NICKEL-LEAD, AND COPPER LEAD ADHERENT STRUCTURES HAVE BEEN FABRICATED.

3. A TWO STEP SYSTEM OF FIRING HAS BEEN DEVISED ALLOWING AgF ACTIVATION IN NITROGEN, AND BASE METAL SINTERING IN HYDROGEN.

4. FOR SOLAR CELL BACK CONTACTS, THE COPPER PASTE USING EUTECTIC Al-Si DOPING HAS GIVEN GOOD RESULTS YIELDING 13% AM1 EFFICIENCIES AND FILL FACTORS OF 0.74$^+$.

5. WHILE ALL SYSTEMS ARE SOLDERABLE AND SEEM STABLE METALLURGICALLY, MORE ENVIRONMENTAL TESTS ARE REQUIRED.

COPPER CONDUCTOR LAYER FOR Si SOLAR CELLS

MOTOROLA, INC.

M. G. Coleman, R. A. Pryor and T. G. Sparks

Comparison of Metal Conductor Layers

	SOLDER (60SN-40PB)	COPPER	SILVER
COST PER POUND* ($ ON 3-29-79)	4.67	1.00	104.22
RESISTIVITY (MICRO OHM-CM)	14.5	1.673	1.59
DENSITY (GM/CM^3)	8.53	8.96	10.49
RELATIVE WEIGHT PER UNIT CONDUCTIVITY	8.26	1.0	1.11

* BASED ON PURE METAL COMPONENT COSTS

RESULT: TO ACHIEVE IDENTICAL CONDUCTIVITY, FROM A MATERIALS COST STANDPOINT ONLY,

1. SOLDER IS ABOUT 40 X AS EXPENSIVE AS COPPER.
2. SILVER IS ABOUT 115 X AS EXPENSIVE AS COPPER.

Cost of Metal Conductors ($/lb)
(Based on Pure Metal Prices)

DATE	SOLDER (60 SN-40 PB)	COPPER	SILVER
10-6-77	3.77	0.60	64.50
10-6-78	4.32	0.685	80.62
3-29-79	4.67	1.00	104.22
11-29-79	5.18	1.005	254.65

REGARDLESS OF THE TIMEFRAME,

COPPER HAS A SIGNIFICANT COST ADVANTAGE!

Diffusion Kinetics

1. $D = D_0 \, E^{-\frac{Q}{RT}}$

   D = DIFFUSION COEFFICIENT
   D_0 = FREQUENCY FACTOR
   Q = ACTIVATION ENERGY
   R = GAS CONSTANT
   T = ABSOLUTE TEMPERATURE

2. $C = C_0 \, E^{-\frac{X^2}{NDT}}$ (LIMITED SOURCE)

   $C = C_0 \, \mathrm{ERF} \, \frac{X}{\sqrt{NDT}}$ (INFINITE SOURCE)

   C = CONCENTRATION AT DISTANCE X FROM SURFACE
   C_0 = SURFACE CONCENTRATION OR INITIAL CONCENTRATION
   N = GEOMETRY FACTOR
   T = TIME OF DIFFUSION
   D = DIFFUSION COEFFICIENT

THE QUANTITY $\sqrt{DT}$ IS A DISTANCE

- COMMON MEASURE OF IMPURITY PENETRATION
- AT A DISTANCE FROM THE SOURCE OF $10\sqrt{DT}$, THE AMOUNT OF IMPURITY IS VANISHINGLY SMALL
- A SUITABLE BARRIER FOR DIFFUSION MUST HAVE A THICKNESS OF AT LEAST $10\sqrt{DT}$

C-5

Cost of Metal Conductors ($/lb)
(Based on Pure Metal Prices)

DATE	SOLDER (60 SN-40 PB)	COPPER	SILVER
10-6-77	3.77	0.60	64.50
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   Q = ACTIVATION ENERGY
   R = GAS CONSTANT
   T = ABSOLUTE TEMPERATURE

2. $C = C_0 e^{-\frac{x^2}{nDt}}$ (LIMITED SOURCE)

   $C = C_0 \operatorname{erf} \frac{x}{\sqrt{nDt}}$ (INFINITE SOURCE)

   C = CONCENTRATION AT DISTANCE X FROM SURFACE
   C_0 = SURFACE CONCENTRATION OR INITIAL CONCENTRATION
   N = GEOMETRY FACTOR
   T = TIME OF DIFFUSION
   D = DIFFUSION COEFFICIENT

THE QUANTITY $\sqrt{Dt}$ IS A DISTANCE

- COMMON MEASURE OF IMPURITY PENETRATION
- AT A DISTANCE FROM THE SOURCE OF $10\sqrt{Dt}$, THE AMOUNT OF IMPURITY IS VANISHINGLY SMALL
- A SUITABLE BARRIER FOR DIFFUSION MUST HAVE A THICKNESS OF AT LEAST $10\sqrt{Dt}$

Copper Diffusion in Silicon

1. EXTRAPOLATE DATA* FROM NEAR 400°C

T (°C)	D (cm²/sec)	$\sqrt{Dt}$ (cm) (t = 20 years)
50	3.0×10^{-10}	0.44
80	1.35×10^{-9}	0.92
100	3.15×10^{-9}	1.4
120	6.7×10^{-9}	2.1

2. QUALITATIVELY VERIFIED AT MOTOROLA

*R.M. HALL, ET. AL. (REFERENCE IN JULY QUARTERLY)

COPPER DIFFUSES RAPIDLY INTO SILICON

AND DEGRADES THE P-N JUNCTION

MUST, THEREFORE, HAVE A COPPER BARRIER

Nickel

1. PROMISING DIFFUSION BARRIER FOR COPPER.
2. NICKEL AND COPPER FORM COMPLETE SOLID SOLUTIONS.
3. NUMEROUS STUDIES OF INTERDIFFUSION OF COPPER AND NICKEL.
   - ALL AT HIGH TEMPERATURES
   - SHOW SIMILAR DIFFUSION PARAMETERS
4. EXTRAPOLATION OF DIFFUSION DATA IN FACE-CENTERED-CUBIC METALS IS A GOOD APPROXIMATION.

Diffusion of Copper in Nickel

EXTRAPOLATION FROM DATA** USING TYPICAL VALUES OF

Q = 60 KCAL/G. ATOM
D_0 = 1.5 CM^2/SEC

τ = 20 YEARS

T (^{o}C)	D (CM^2/SEC)	Dτ (CM)
100	7.8×10^{-36}	7×10^{-14}
200	2.2×10^{-28}	3.7×10^{-14}
300	1.6×10^{-23}	1×10^{-7}

τ = 30 MINUTES

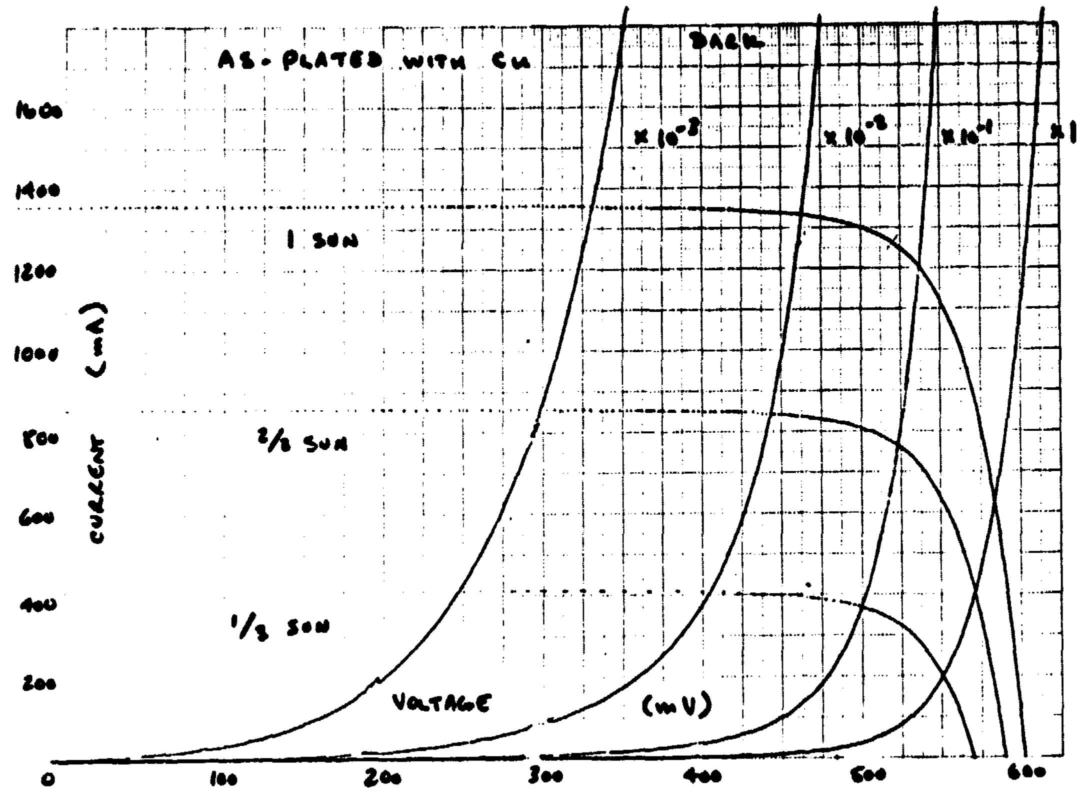
300	1.6×10^{-23}	1.7×10^{-10}

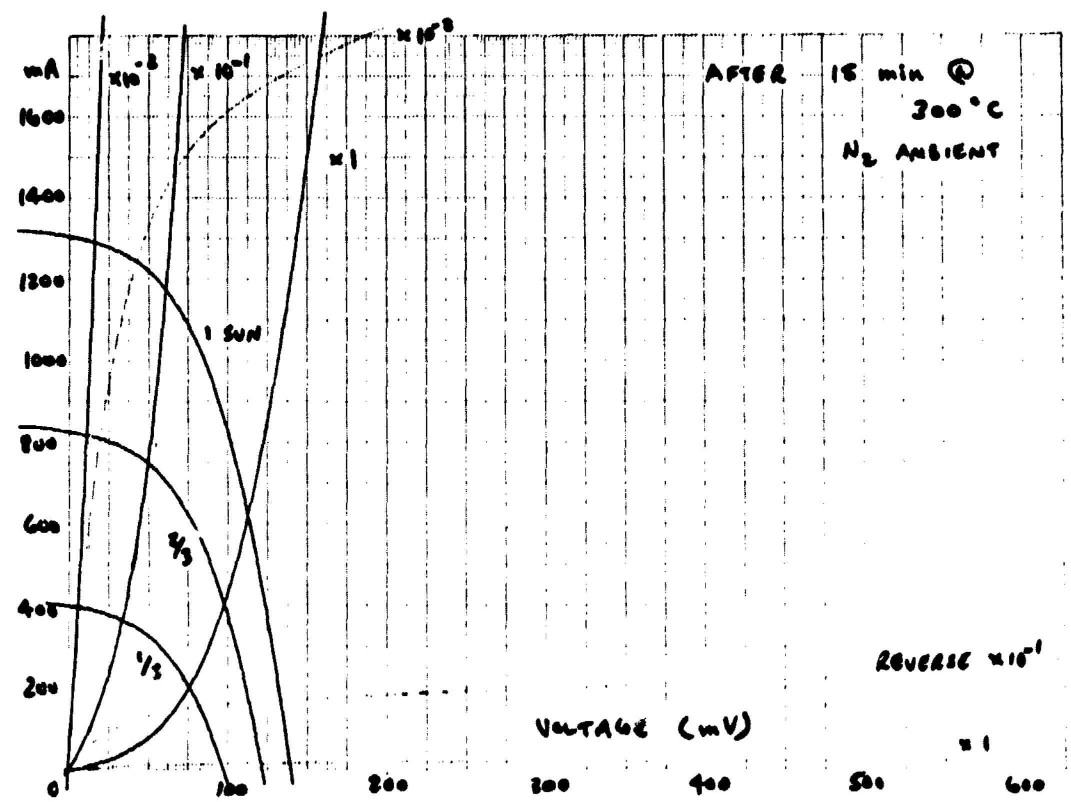
**JOHN ASKILL, TRACER DIFFUSION DATA FOR METALS, AND SIMPLE OXIDES, IFI/PLENUM DATA CORP. NEW YORK, 1970.

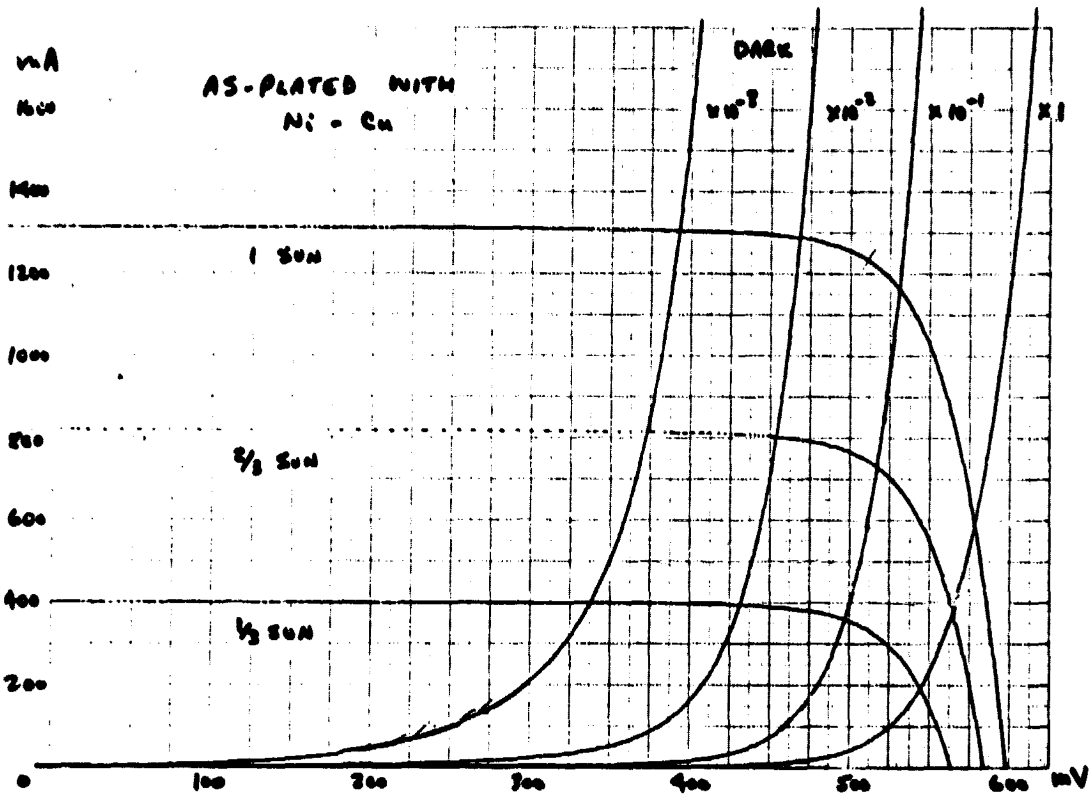
A PROMISING METALLIZATION SYSTEM, THUS, IS (PALLADIUM) - NICKEL - COPPER.

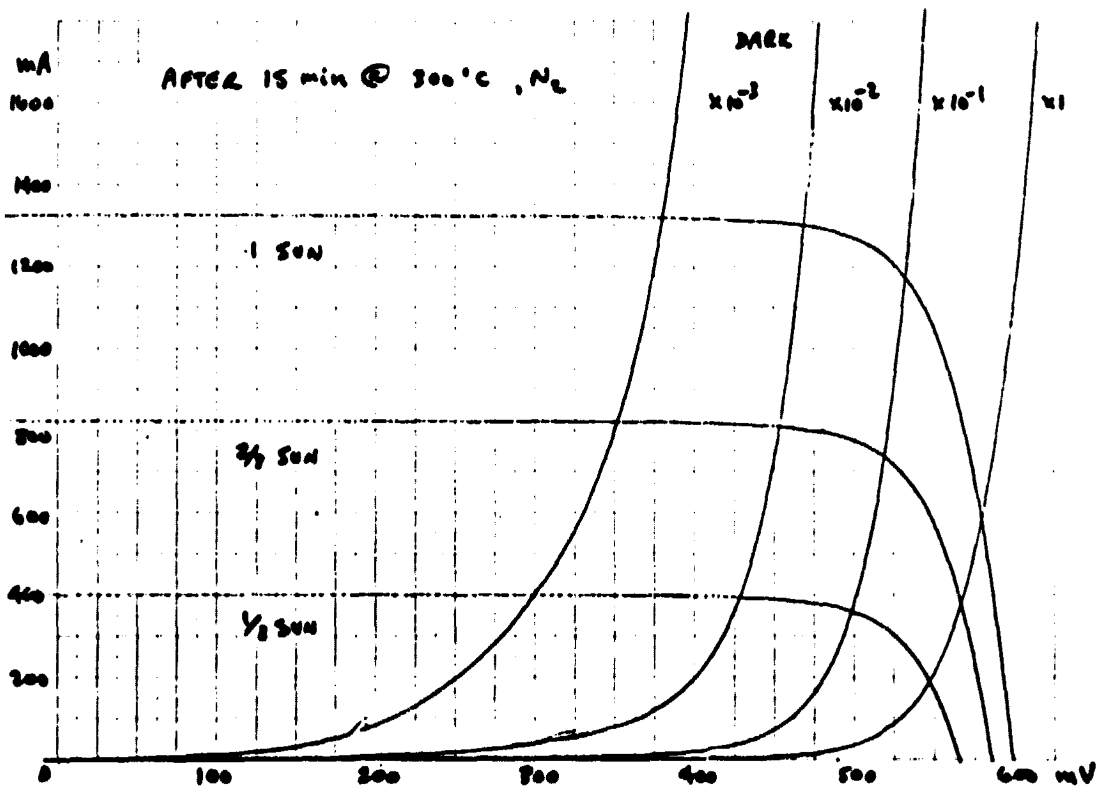
Metallization Process Sequence

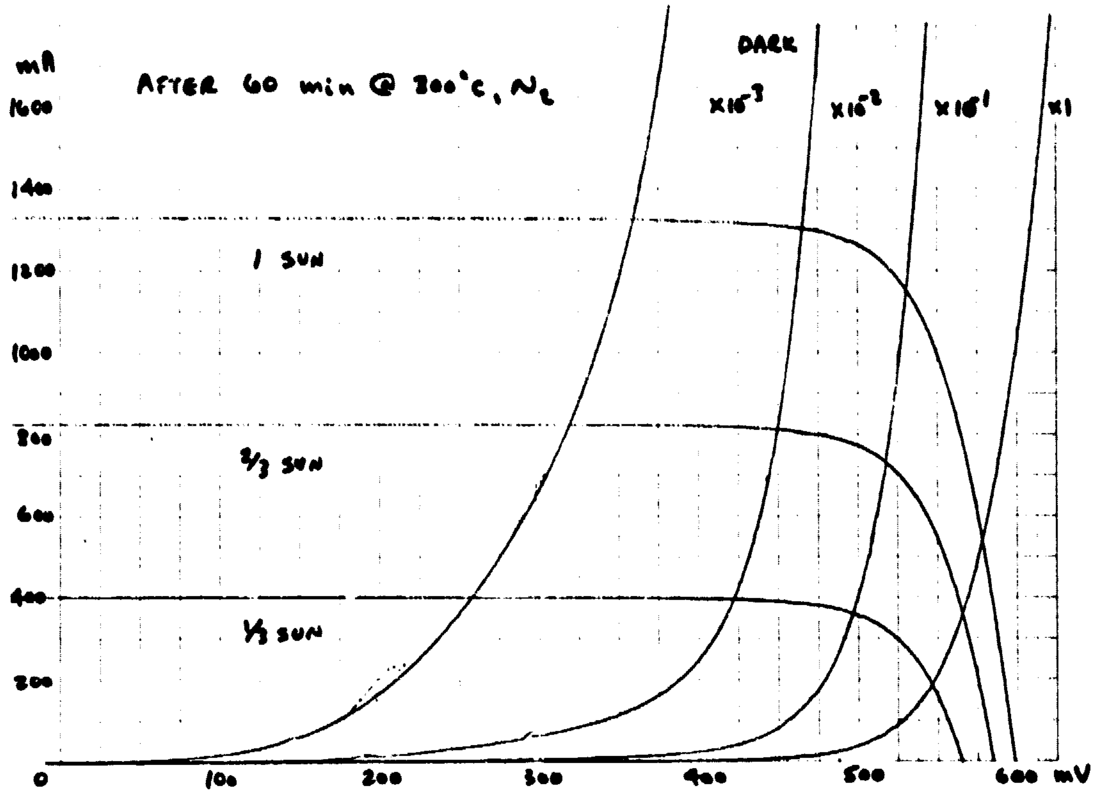
1. IMMERSION PALLADIUM PLATE
2. HEAT TREATMENT: 15 MINUTE AT 250^{o}C
3. ELECTROLESS NICKEL PLATE
4. CONTACT FORMATION: 30 MINUTE AT 250^{o}C.
5. ELECTROLYTIC COPPER PLATE

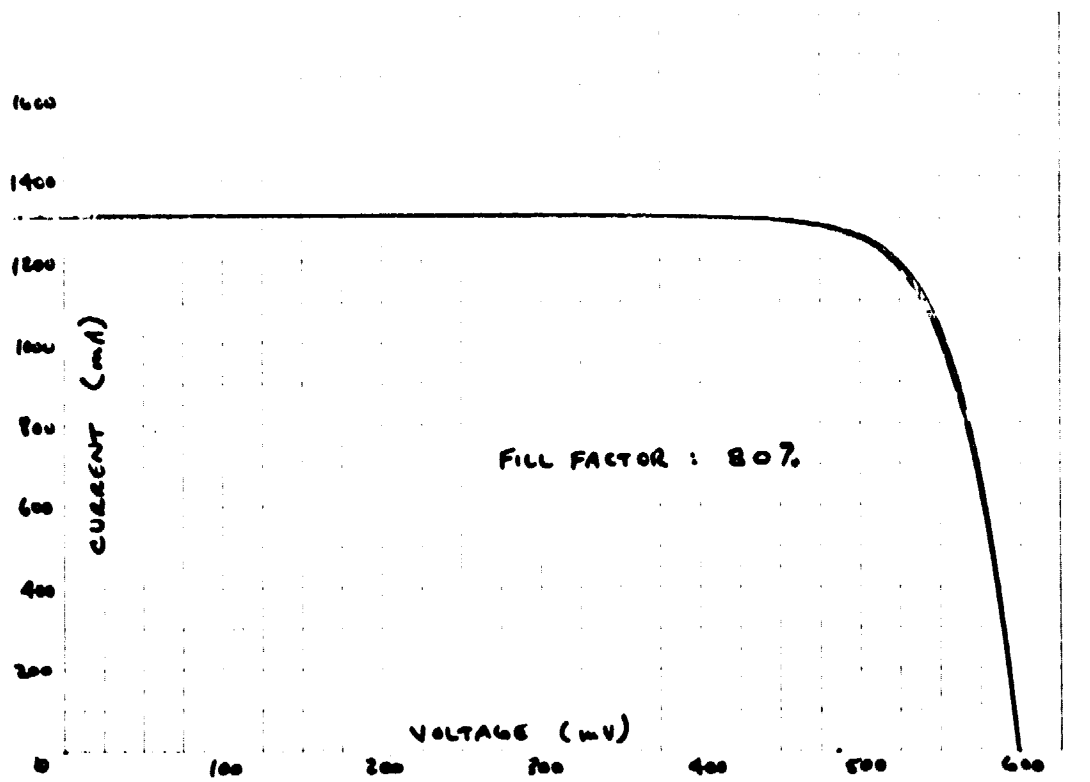

AS-PLATED WITH Cu
DARK
CURRENT (mA)
VOLTAGE (mV)
1 SUN
2/3 SUN
1/3 SUN


mA
AFTER 15 min @ 300 °C
N_2 AMBIENT
1 SUN
VOLTAGE (mV)
REVERSE


mA
1600
1400
1200
1000
800
600
400
200
0
AS-PLATED WITH
Ni - Cu
DARK
x10^-3
x10^-2
x10^-1
x1
1 SUN
2/3 SUN
1/3 SUN
100
200
300
400
500
600
mV


mA
1600
1400
1200
1000
800
600
400
200
0
AFTER 15 min @ 300°C , N2
DARK
x10^-3
x10^-2
x10^-1
x1
1 SUN
2/3 SUN
1/3 SUN
100
200
300
400
500
600
mV


AFTER 60 min @ 300°C, N2
mA
DARK
x10^-3
x10^-2
x10^-1
x1
1 SUN
2/3 SUN
1/3 SUN
1600
1400
1200
1000
800
600
400
200
0
100
200
300
400
500
600 mV


1600
1400
1200
1000
800
600
400
200
0
CURRENT (mA)
FILL FACTOR : 80%
VOLTAGE (mV)
100
200
300
400
500
600

COPPER METALLIZATION

WESTINGHOUSE RESEARCH

ADVANTAGES

- o Copper Less Expensive than Silver
- o Copper Has Nearly the Same Electrical Conductivity as Silver
- o Electroplating of Copper is Industrial Practice

APPROACH

- o Evaluate Following Systems on Silicon:

  Cu
  Pd Cu
  Ti Pd Cu
  Ti Cu

- o Determine Requirements for Barrier Metal

Electroless Copper Plating Solution

The electroless copper plating solutions have been obtained from Shipley Co., In., Newton, MA. The system consists of three solutions CP 70A, CP 70M and Cuposit Z. The proportions used are as follows:

1. Add 1 part CP 70A and 2 parts CP 70M to 16 parts of deionized water.
2. Add 1 part Cuposit Z to the mixture just before plating.
3. Maintain bath temperature at 49°C ± 2°.
4. Time 20 seconds.
5. Rinse in running deionized water for 10 minutes.
6. Dry with N_2.

Electrolytic Copper Plating Solution

1. Dissolve 200 grams of $Cu\ SO_4 \cdot 5H_2O$ in 1 liter of deionized water.
2. Add carefully, 30 ml of H_2SO_4.
3. Plating temperature 20 - 40°C
4. Current density 20 - 40 mA/cm^2.
5. Ratio of cathode to anode 1:1.
6. Anode - copper.

Evaporated or Plated Cu on Silicon

- Yield - 30 - 40%
- Survived Samples - η - 10 - 11%
  - R_s - .5 Ω
  - R_{sh} - 2-5K Ω

- Yield losses associated with low shunt resistance and large excess junction current. Presumably due to copper diffusing to junction and precipitating during cell processing.
  (T_{MAX} - 150°C)

Screened Ag on Silicon

- SAMPLES HEATED AT 250°C FOR 18 HRS. EXCESS JUNCTION CURRENT INCREASED BY FACTOR OF 10; EFFICIENCY DECREASED BY 1.5%

Evaporated Pd-Plated Cu Contacts

	800Å Pd +4 µm Cu		3000Å Pd + 4 µm Cu	
	Unsintered	Sintered	Unsintered	Sintered
η(%)	12.7	6.63	13.0	4.25
I_{sc}(mA)	30.5	29.7	29.8	29.8
V_{oc}(V)	0.542	0.501	0.552	0.360
FF	0.727	0.426	0.746	0.4
R_s(Ω)	0.8	0.4	0.6	0.3
$R_{sh}\|_{IV}$ (KΩ)	46	40	33	30
$I_J\|_{0.3V}$(mA)	0.01	5.67	0.082	14

- Sintering was done at 300°C for 15 min. in N_2.
- Sintering severely degrades the junction response
- Unsintered Pd is unable to form a barrier for Cu diffusion regardless of Pd thickness.
- AM-1, AR-coated

Sintered Pd-Plated Cu Contacts

	800 Å Pd (Sintered at 300°C) + 4µm Plated Cu		3000 Å Pd (Sintered at 300°C) + 4 µm Plated Cu	
	System Unsintered	System Sintered (150°C)	System Unsintered	System Sintered (300°C)
η(%)	12.5	6.6	12.4	3.5
I_{sc}(mA)	29.0	29.0	29.7	26.3
V_{oc}(V)	0.538	0.488	0.543	0.298
FF	0.755	0.458	0.725	0.420
R_s(Ω)	1.5	0.46	0.8	0.3
R_{SH} at -1V (KΩ)	100	60	250	10
I_J at 0.3V (mA)	0.019	4.5	0.038	11

- o Heat Treatment of System (Sintered Pd + Plated Cu) Severely Degrades Junction
- o Pd Sintered at 300°C Does Not Serve as a Barrier for Cu Diffusion
- o AM-1 - AR Coated

Ti-Pd-Cu System

	(Evaporated Ti-Pd-Ag)	Vs	(Evaporated Ti-Pd-Plated Cu)		
	Ti-Pd-Ag	Ti-Pd-Cu	Ti-Pd-Cu 300°C Sinter	Ti-Pd-Cu 400°C Sinter	Ti-Pd-Cu 500°C Si
η (%)	14.0	14.1	14.2	13.2	10.6
I_{sc} (mA)	30.7	30.5	30.6	30.9	27.1
V_{oc} (V)	.572	.580	.580	.574	.544
FF	.74	.754	.76	.731	.667
R_s (Ω)	.5	.6	.45	.5	.5
R_{sh} (kΩ)	2.5	2.5	2.5	2	1.1
I_j/.3V (mA)	.044	.044	.040	.27	1.4
τ_{ocd} (µsec)	11	11.5	11.5	10	6

Dendritic web cells
AR coated; AM-1

Test for Stability of Ti-Pd-Cu System

Test Cond.	I_{sc} (mA)		V_{oc} (V)		Eff (%)	
	Ti Pd Ag	Ti Pd Cu	Ti Pd Ag	Ti Pd Cu	Ti Pd Ag	Ti Pd Cu
As Fabricated	30.4	29.8	.512	.520	11.5	11.6
75 hrs./225 C in N_2	30.4	29.8	.520	.518	11.6	11.6
23 hrs./225 C in N_2	30.0	29.5	.520	.518	11.5	11.5
375 hrs./225 C in N_2	30.0	29.5	.522	.522	11.5	11.5
600 hrs./225 C	30.0	29.7	.521	.522	11.5	11.6

- o Cells AR coated
- o Measured at AM-1; 91.6 mW/cm^2
- o TiPdCu is as stable as baseline TiPdAg

Ti-Cu System

FORMATION OF $TiSi_2$

- o SILICIDE FORMED AT 700°C IN H_2 AS DETERMINED BY RESISTIVITY MEASUREMENTS
- o IN Ti CONTACT SYSTEMS, Ti - NOT $TiSi_2$-IS ACTING A BARRIER MATERIAL

Comparison of Costs (Based on SAMICS)

CU VS. AG ELECTROPLATING

(1980 $ PER PEAK WATT)

o COST OF AG ELECTROPLATING PROCESS	.... $0.034
o POSTION OF PROCESS COST APPLICABLE TO AG METAL	.... $0.018
o COST OF CU METAL PLUS CU FLASH AND WET CLEANING BEFORE PLATING	.... $0.007
o COST SAVING USING CU PLATING	.... $0.011

$0.018 - $0.007 = $0.011

(DOES NOT TAKE INTO ACCOUNT ANY YIELD DIFFERENCES)

Conclusions

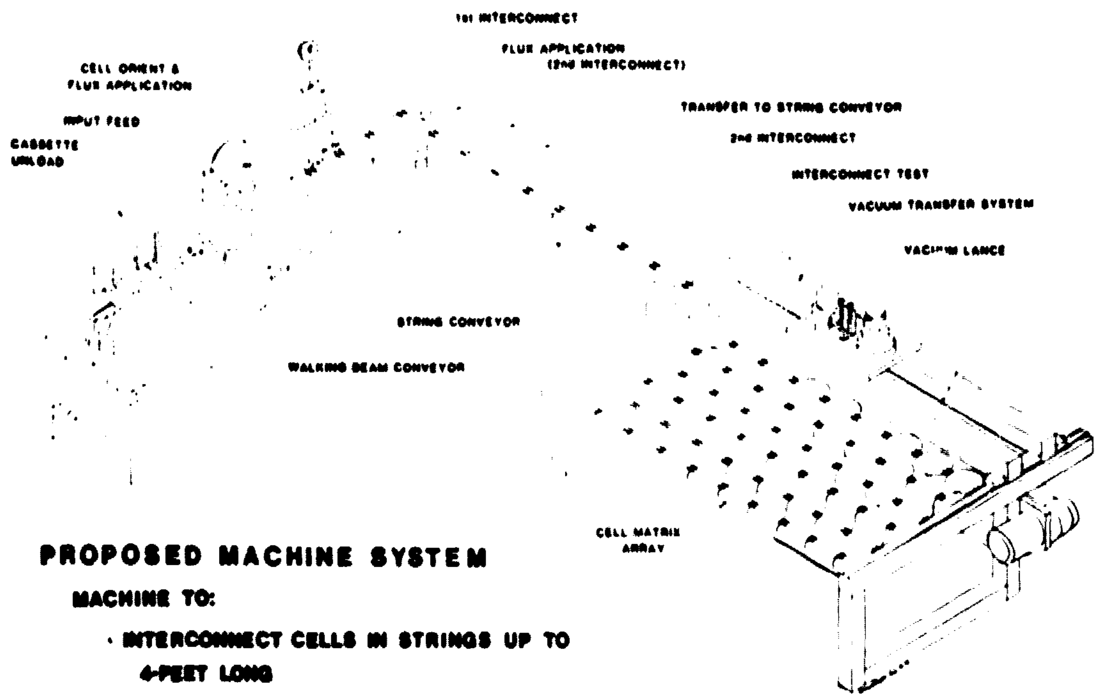
- Best adherance achieved only when electroless copper flash used before copper electroplating
- Ti required as a barrier metal
- TiPdCu is equal to TiPdAg

AUTOMATED SOLAR MODULE ASSEMBLY

KULICKE & SOFFA INDUSTRIES

Max Bycer

Automated Solar Module Assembly Machine



PROPOSED MACHINE SYSTEM

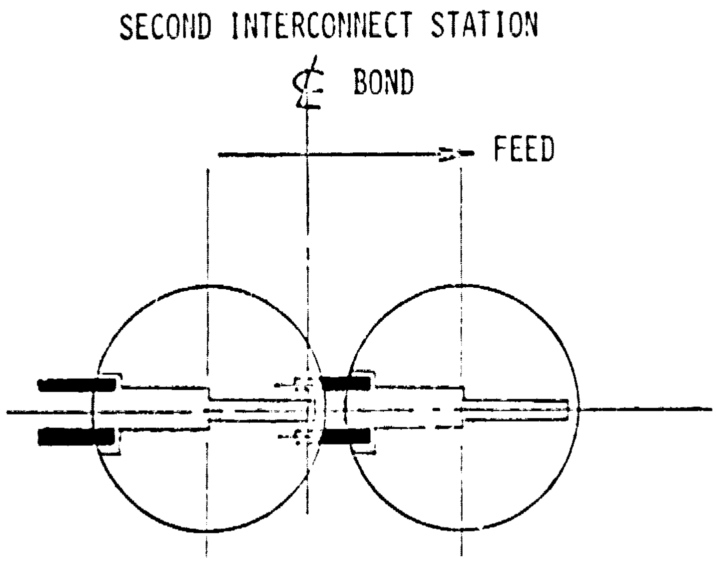
MACHINE TO:

- INTERCONNECT CELLS IN STRINGS UP TO 4-FEET LONG
- HANDLE 3-INCH DIAMETER SOLAR CELLS (ADAPTABLE TO 100 mm DIAMETER CELLS)
- ELECTRICALLY TEST CELL INTERCONNECTS

TARGET MACHINE CYCLE:

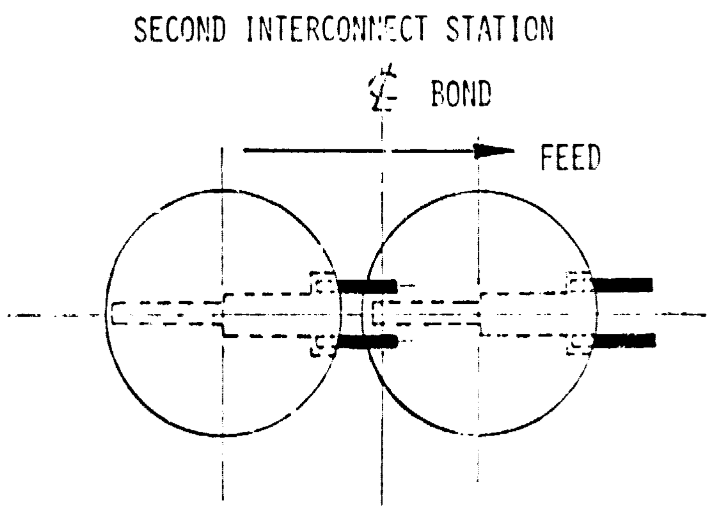
- 5 SECONDS/CELL AT 95% MINIMUM YIELD

Bonding Without Inversion of Cell



COLLECTOR SIDE UP - BOND TAKES PLACE ON UNDERSIDE OF SECOND CELL

Bonding With Inversion of Cell

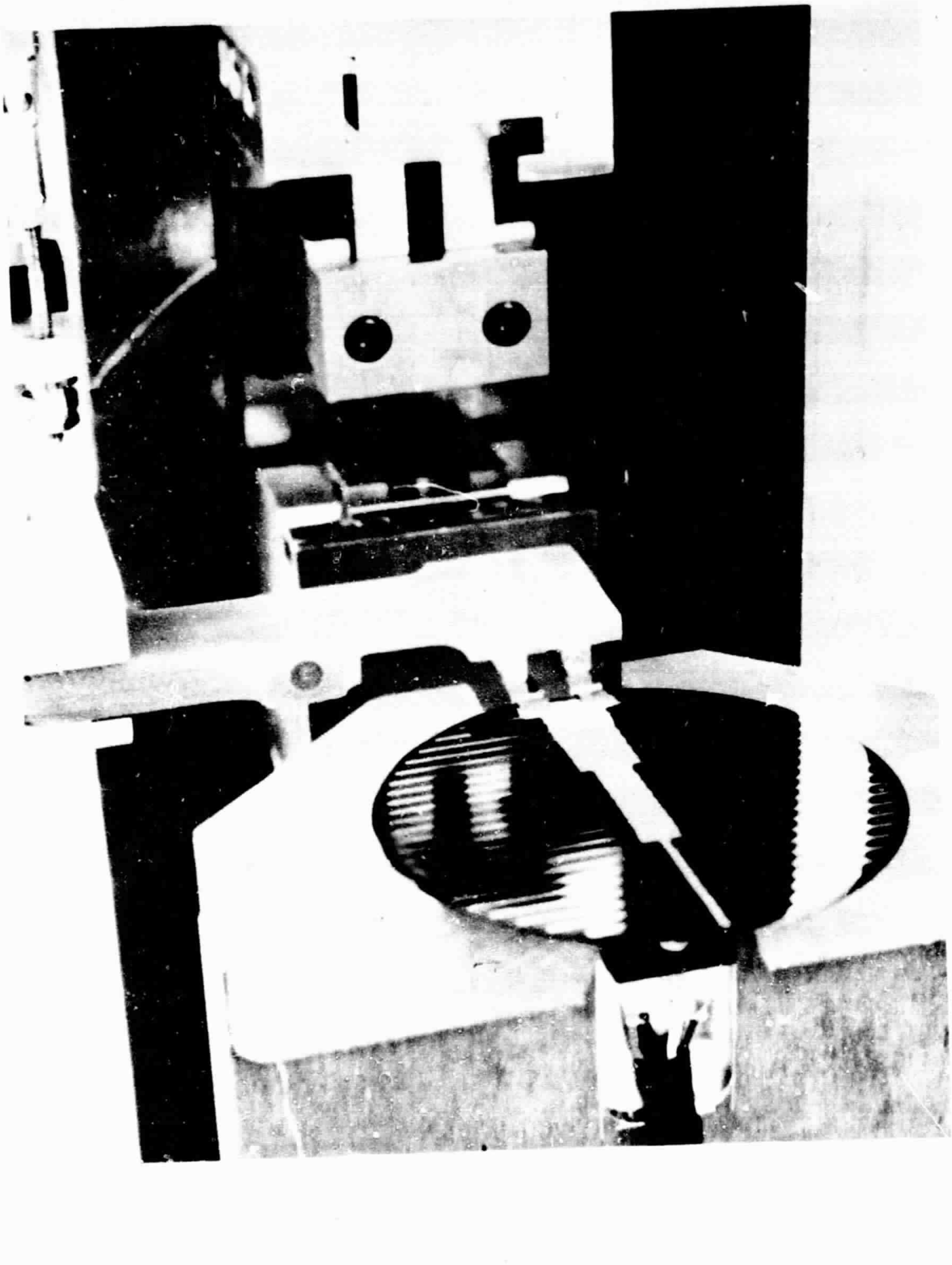


COLLECTOR SIDE DOWN - BOND TAKES PLACE ON TOP SIDE OF FIRST CELL

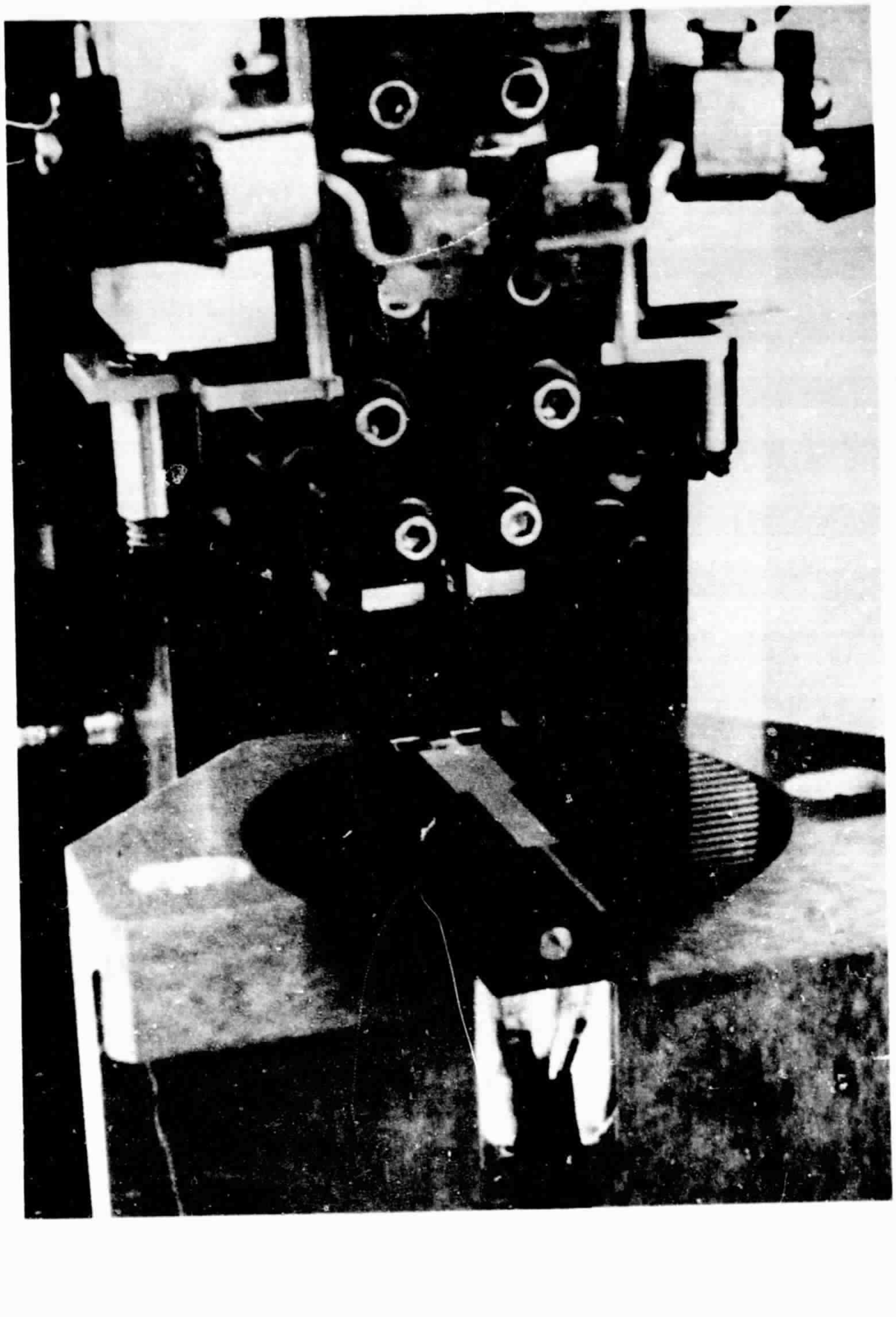
Advantages of Inverting Cell at Bonding Step

1. IT MINIMIZES CONTACT ON THE SUN (COLLECTOR) SIDE OF THE CELL.
2. INVERTING THE CELLS ALLOWS BONDING OF SECOND INTERCONNECT FROM THE TOP SIDE.
3. INVERTING THE CELLS FACILITATES MAKING STRING INTERCONNECTIONS IN THE MODULE ARRAY.

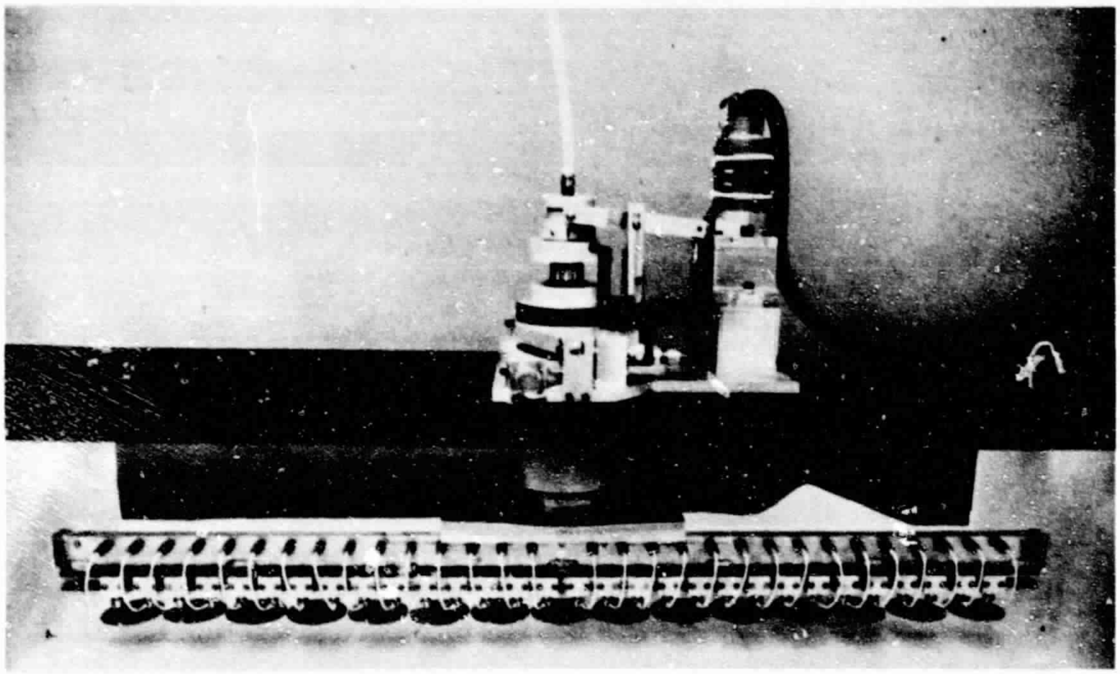
Tabs Formed and Placed Before Bonding



Tabs Bonded on Collector Side



Vacuum Pickup Lance of Bonded String



AUTOMATED PROCESS DEVELOPMENT

MBASSOCIATES

PROCESSING STEPS:

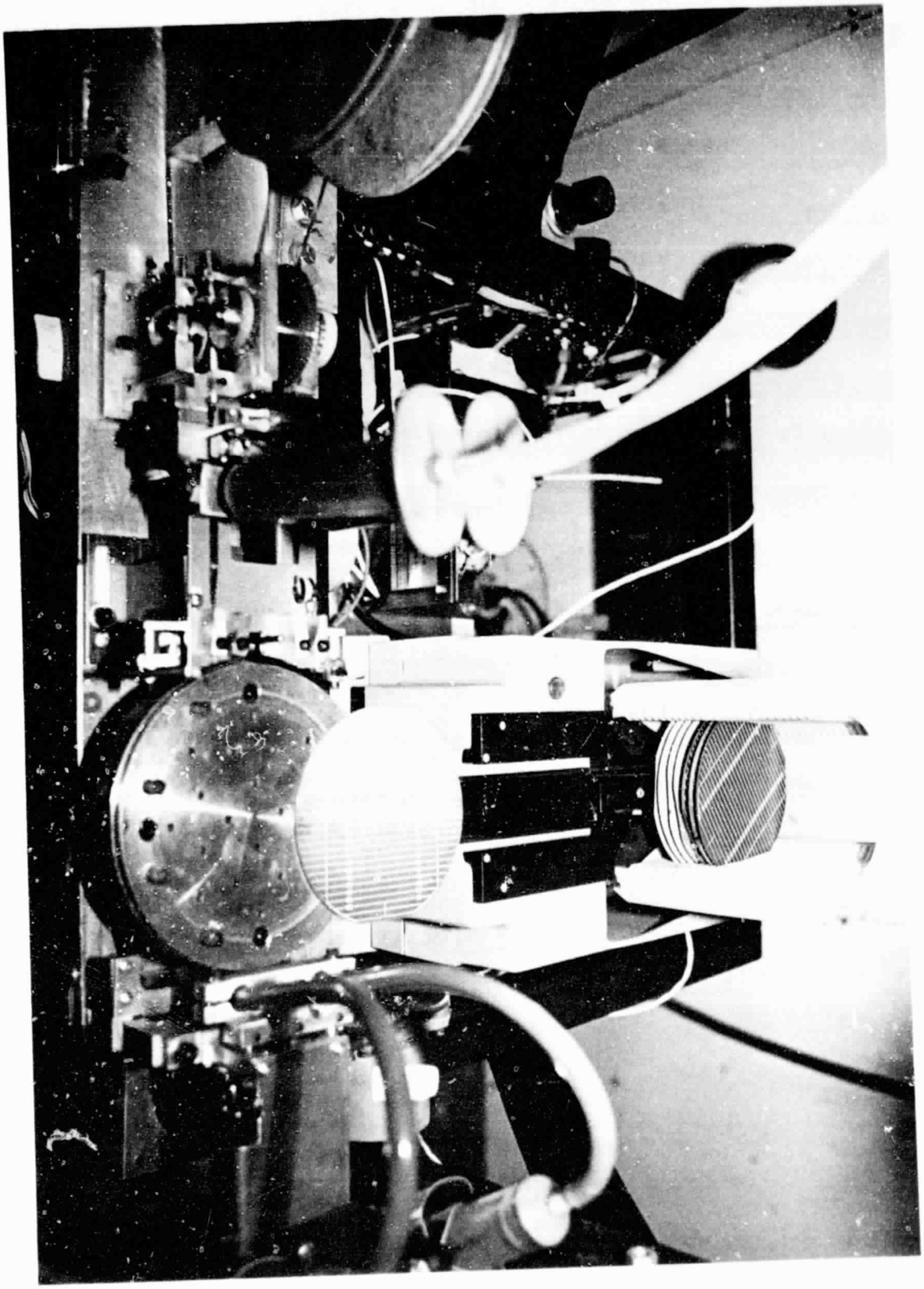
PREPARATION AND FEED STATION

1. FEED CELL FROM CASSETTE
2. VACUUM CLAMP CELL
3. OPTICALLY ORIENT CELL
4. DISPENSE SOLDER PASTE TO CELL
5. FEED INTERCONNECT RIBBON AND FORM STRAIN RELIEF CRIMP
6. FEED INTERCONNECT RIBBON ONTO CELL AND APPLY SOLDER PASTE TO TRAILING LEADS
7. CUT INTERCONNECT RIBBON

ROBOT

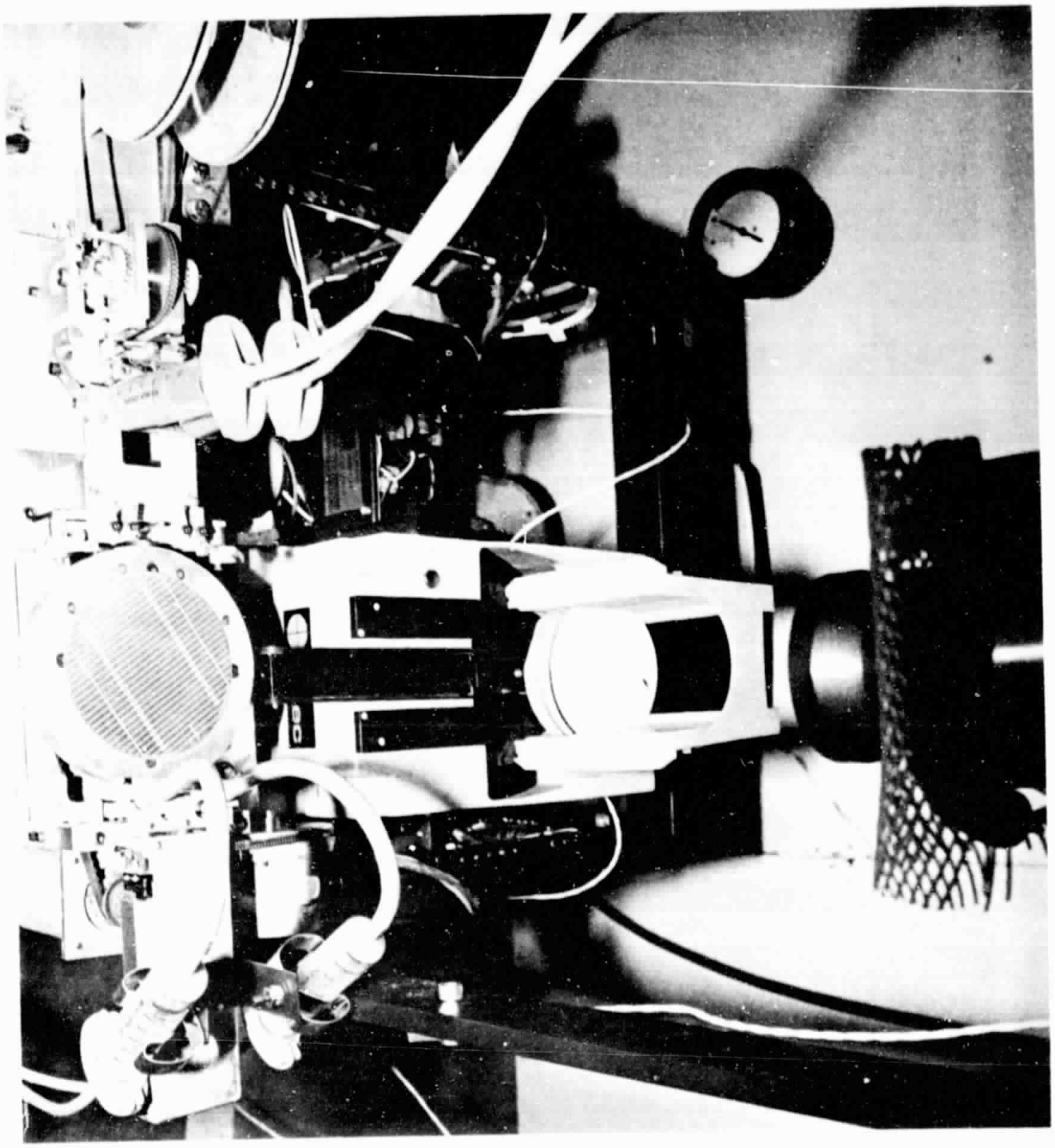
1. VACUUM PICKUP PREPARED CELL
2. MOVE AWAY FROM PREPARATION AND FEED STATION AND BEGIN INDUCTION HEATING
3. PLACE CELL ON TOP OF PREVIOUS CELL CONTACTS
4. INDUCTION HEAT UNTIL SOLDERED
5. ROBOT LEAVES CELL TO CONTINUE CYCLE

Feed Cell From Cassette

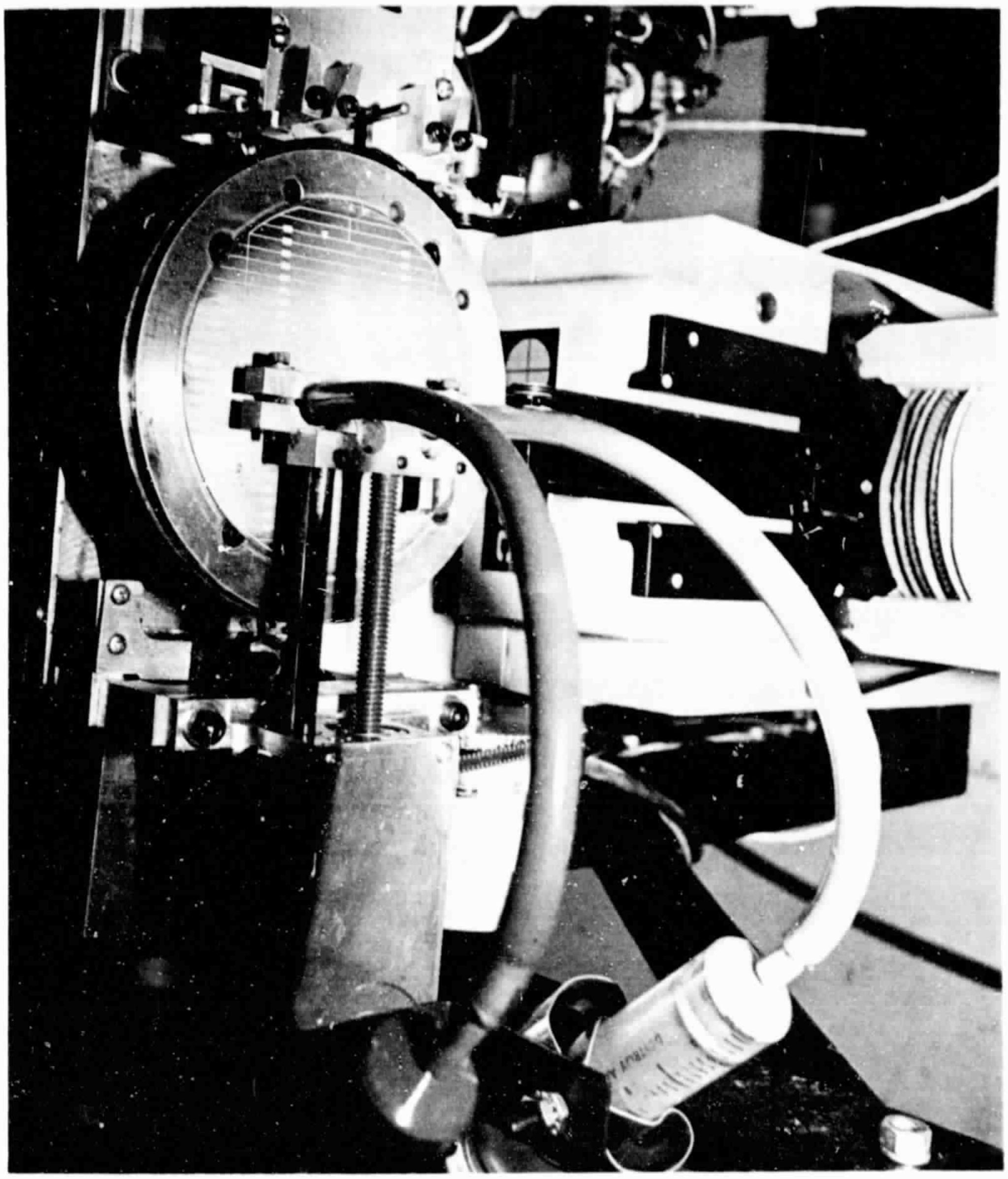


Vacuum Clamp Cell

Optically Orient Cell

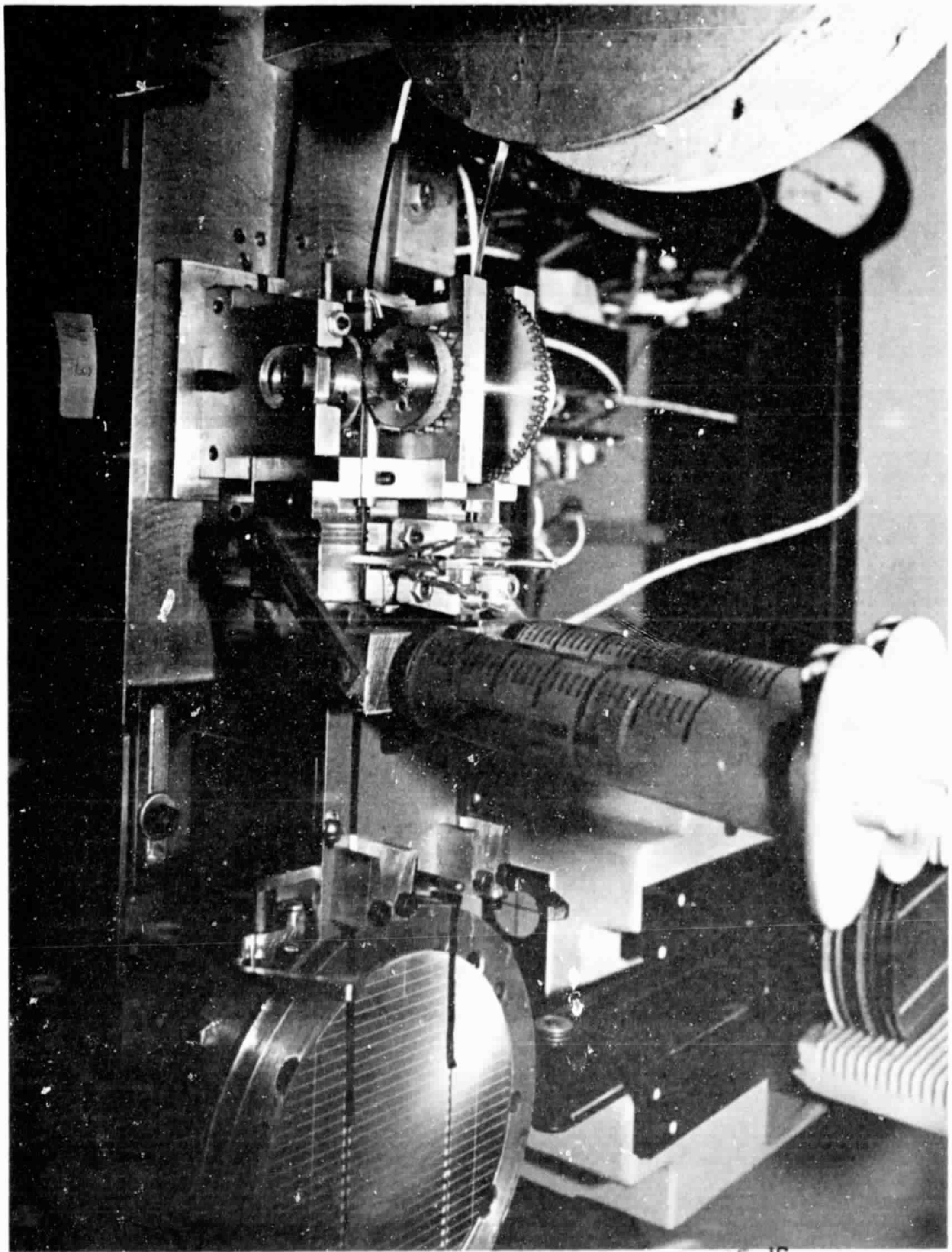


Dispense Solder Paste to Cell



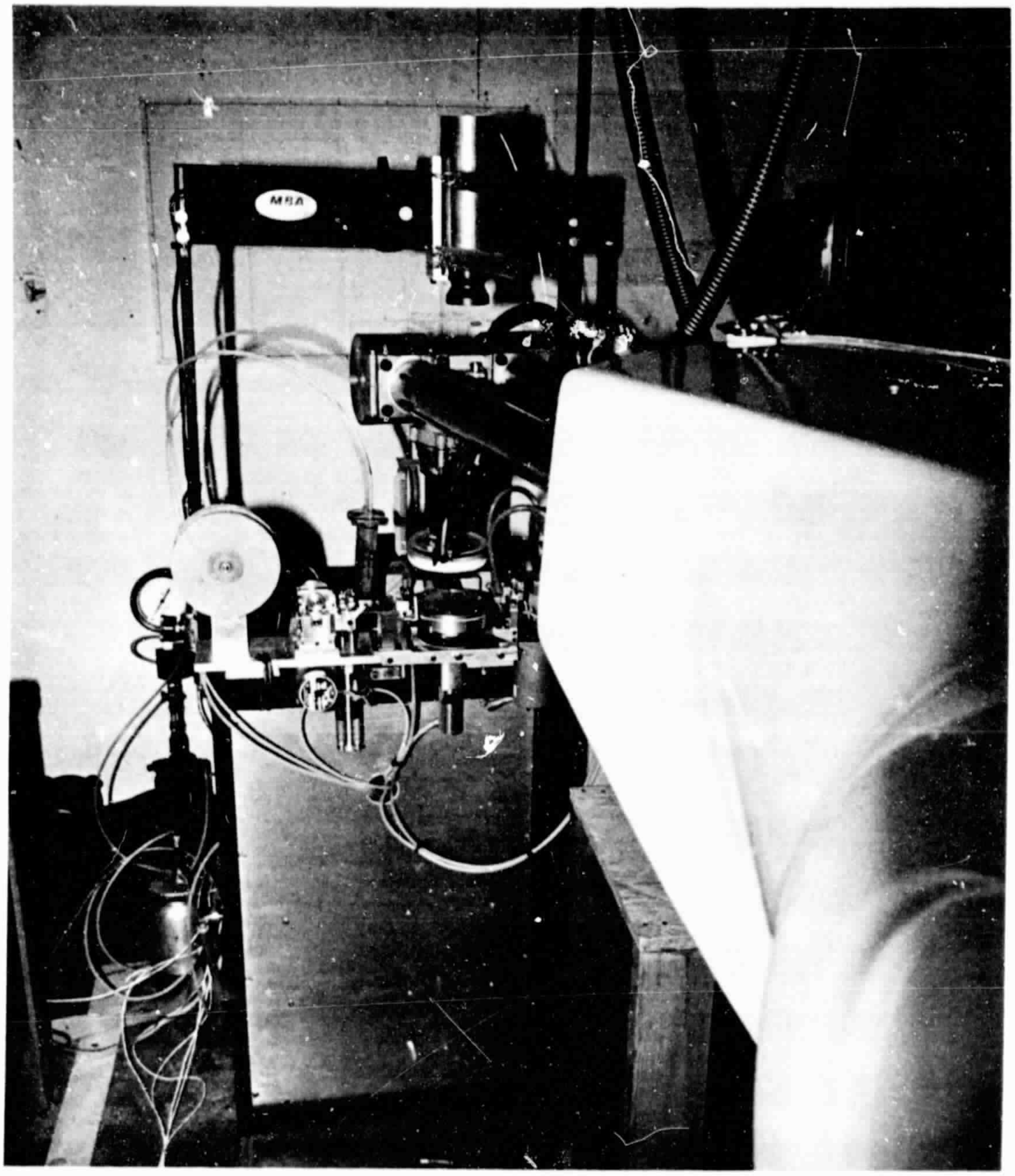
Feed Interconnect Ribbon and Form
Strain Relief Crimp

Feed Interconnect Ribbon Onto Cell
and Apply Solder Paste to Trailing Leads
Cut Interconnect Ribbon

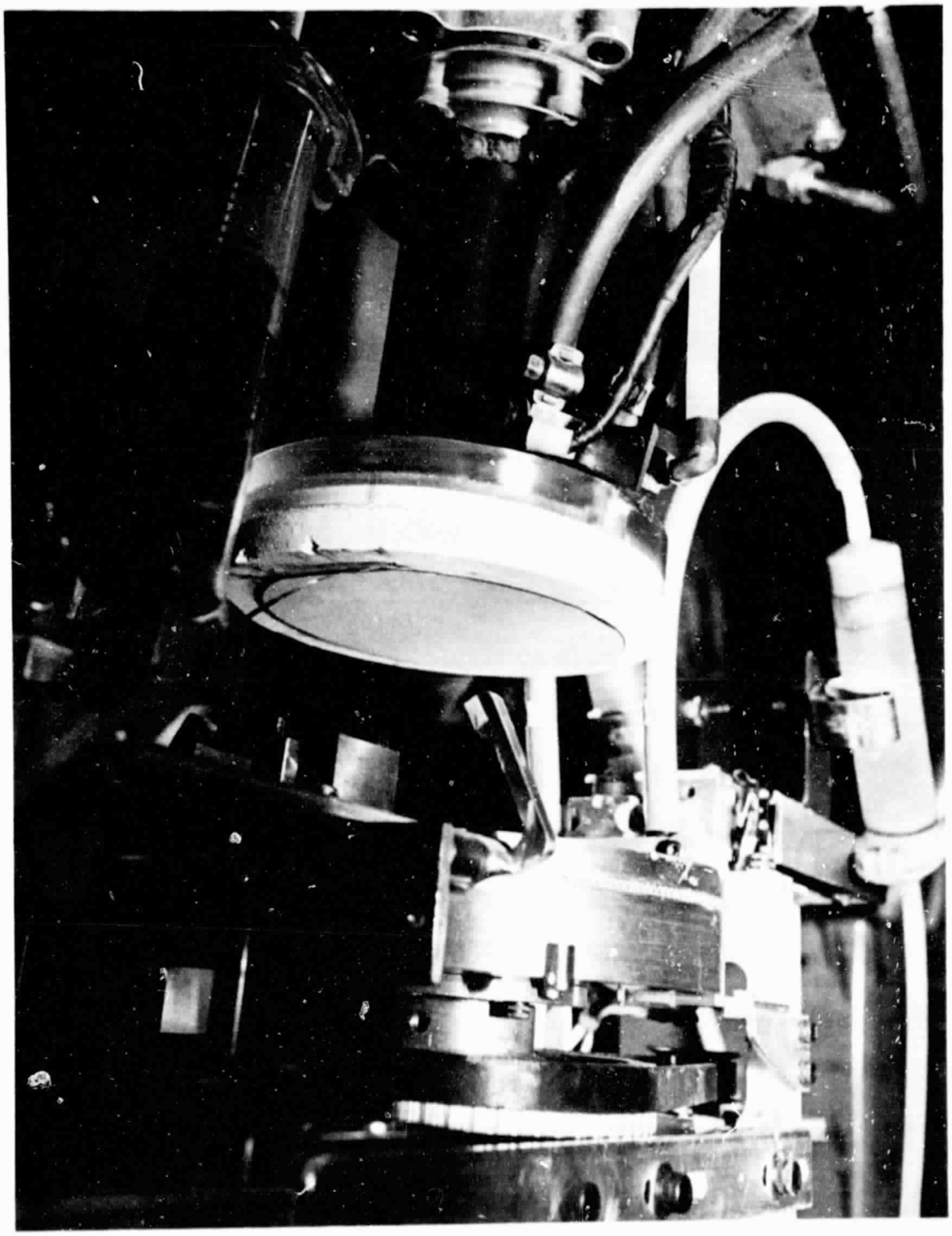


ORIGINAL PAGE IS
OF POOR QUALITY

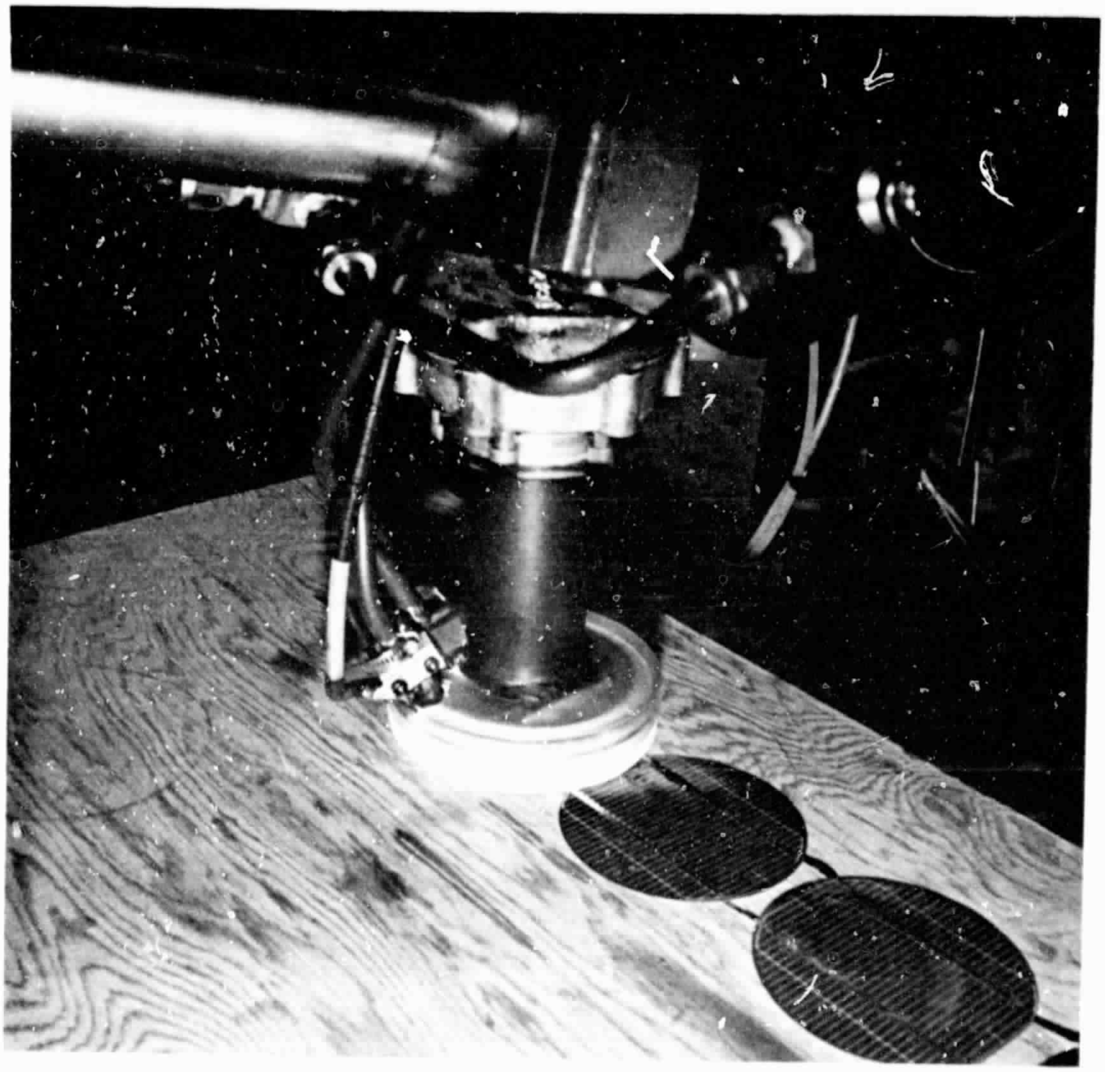
Vacuum Pickup Prepared Cell



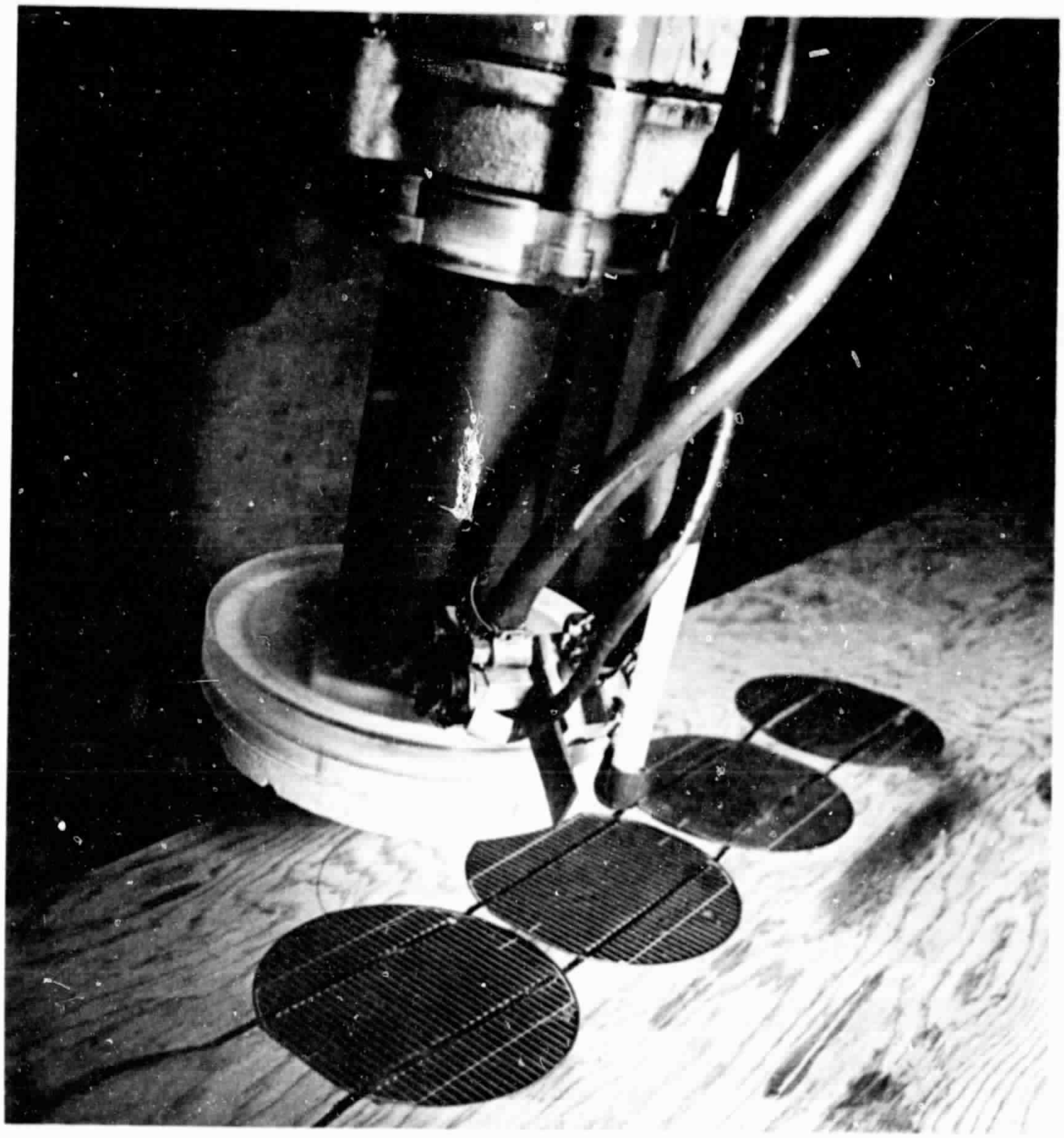
Move Away From Preparation and Feed
Station and Begin Induction Heating



Place Cell on Top of Previous Cell Contacts
Induction Heat Until Soldered



Robot Leaves Cell to Continue Cycle



ENGINEERING AREA

In keeping with the theme of this PIM, Module Design, presentations by Engineering Area in-house personnel and contractors (see below) concentrated on Module Design Technology. Two of these presentations, "Lessons Learned that Affect Module Design" and "Module/Array Design," are described in detail (pp. 3-15 and 383-455, respectively). The remaining presentations are described below along with their supporting graphic material. A number of major Engineering Area in-house activities and contracts were not reported on at this PIM, but are listed for reference on Page 353. Descriptions of th unreported Engineering Area contractor activities appeared in the PIM handout (5101-140).

Engineering Area Presentations

- LESSONS LEARNED IN MODULE ENGINEERING
- MODULE/ARRAY DESIGN OPTIMIZATION
  - ELECTRICAL CIRCUIT DESIGN
  - MECHANICAL/STRUCTURAL DESIGN
  - ENVIRONMENTAL REQUIREMENTS
  - ELECTRICAL SAFETY
- MODULE TERMINALS STUDY (MOTOROLA)
- GLASS SIZING STUDY (JPL)
- LOW-COST STRUCTURES DEVELOPMENT (JPL/KAISER)
- PRODUCT LIABILITY (CARNEGIE-MELLON)

Unreported Engineering Activities

- RESIDENTIAL ARRAY O&M STUDY (BURT HILL)
- RESIDENTIAL ARRAY INDUSTRIAL DESIGN (T&E)
- RESIDENTIAL INTEGRATED ARRAY DESIGN (RFP)
- PV-THERMAL MODULE DEVELOPMENT (JPL/RFP)
- ARRAY WIND TUNNEL TESTING (BOEING)
- CELL FRACTURE MECHANICS TESTING (JPL)
- ENVIRONMENTAL TEST DEVELOPMENT
  - HOT-SPOT ENDURANCE (JPL)
  - EMMAQUA (DSET)
  - SOILING (JPL)
  - INSULATION DURABILITY (JPL)
- ARRAY STANDARDS (W/SERI)

PROJECT ANALYSIS AND INTEGRATION AREA, ENGINEERING AREA AND OPERATIONS AREA

In the Engineering/Operations/PA&I Intertechnology Session (Wednesday, 3:45 pm) presentations were made covering the status of IPEG 2, module termination requirements, and module/array structural design investigations. R. W. Aster (JPL) described recent changes and updating of IPEG to incorporate the experiences gained from the last two years of working with SAMIS. The new annual revenue input data coefficients were provided and a sample case described to show the comparison between IPEG and IPEG-2. F. Mosna of Motorola described the results of the module termination requirements contract. Selection of criteria and rating methods, typical candidate hardware features and capabilities, life-cycle cost data, and recommendations of promising termination types were provided. Don Moore (JPL) described the results of extensive finite element analyses that have led to development of a recommended design method for thickness sizing of glass superstrate or substrate modules. Both the theory and example problems were described. Details including the necessary deflection versus load nomographs for application of this design method will be the subject of LSA Document 5101-148, scheduled for release in March 1980. In a related presentation A. Wilson (JPL) described in-house activities supporting design, fabrication and test of low-cost array structures for intermediate load applications. Cost estimates for a variety of panel and foundation approaches were provided. A full scale 8 x 16 ft. panel structure that was successfully fabricated and tested to a 50 lb/ft^2 loading was described. The panel was on display during coffee. The graphic material supporting these four presentations follows.

INTER-TECHNOLOGY SESSION

J.C. Arnett, Chairman

WED. 3:30-5:30

1) IPEG 2	- R. ASTER, JPL
2) MODULE TERMINATIONS	- F. MOSNA, MOTOROLA
3) GLASS SIZING	- D. MOORE, JPL
4) ARRAY STRUCTURES	- A. WILSON, JPL

IPEG 2

IMPROVED PRICE ESTIMATION GUIDELINES

JET PROPULSION LABORATORY

R. W. Aster

- MOTIVATION AND BASIC CHANGES
- NEW EQUATION
- COMPARISONS
- PLANS

Motivation and Basic Changes

- INCORPORATE 2 YEARS OF SAMIS EXPERIENCE INTO IPEG
  - IPEG 2 FACILITIES COSTS NOW MATCH SAMIS
  - IPEG 2 EQUIPMENT RELATED COSTS ARE LARGER, AND NOW MATCH SAMIS
  - IPEG 2 STARTUP COSTS ARE NOW SMALLER
- IPEG 2 ALLOWS SEVERAL EQUIPMENT LIFETIMES
- IPEG 2 WILL GIVE MANUFACTURING PRICE ESTIMATES IN 1980 DOLLARS

The New Equation for Required Annual Revenue

INPUT DATA	EQPT (3-20 YEAR LIFETIME) 3	5	7	10	15	20	FT^2	DLAB	MATS & UTIL
COEFFICIENT	.83	.65	.57	.52	.48	.46	109.	2.1	1.2

WHERE:

- EQPT IS THE INSTALLED COST OF EQUIPMENT IN 1980 DOLLARS
- FT^2 IS THE PROCESS AREA REQUIRED BY THE EQUIPMENT AND ITS OPERATORS, IN SQUARE FEET
- DLAB IS THE ANNUAL COST OF LABOR (INCLUDING FRINGE BENEFITS)
- MATS & UTIL IS THE ANNUAL COST OF MATERIALS, SUPPLIES, AND UTILITIES

Comparisons

	OLD IPEG	NEW IPEG
EQUIPMENT COEFFICIENT (7 YR)	0.49	0.57
FT^2 COEFFICIENT (1980 DOLLARS)	135.8	109.0
DLAB COEFFICIENT	2.1	2.1*
MATS & UTIL COEFFICIENT	1.3	1.2
A RECENT SAMIS PRINTOUT (SAMIS PRICE = 0.90 \$/Wp)	0.97	0.93

*THIS IS FOR DIRECT LABOR WITH FRINGE BENEFITS. INCREASE THIS COEFFICIENT TO 2.8 IF FRINGE BENEFITS ARE NOT INCLUDED.

Operating Costs and Other Costs

(7-YEAR EQUIPMENT LIFETIME CASE)

OPERATING COST = 6 x FT^2 + 1.7 x DLAB + 1.0 x (MATS + UTIL)

OTHER COSTS:

- RETURN ON EQUITY
- INTEREST EXPENSE
- ONE-TIME COSTS
- INCOME TAXES (LESS INVESTMENT TAX CREDIT)
- PROPERTY TAXES
- INSURANCE
- REPLACEMENT OF CAPITAL INVESTMENT
- MISCELLANEOUS EXPENSE

FINAL COST = 0.57 x EQPT + 109 x FT^2 + 2.1 x DLAB + 1.2 x (MATS + UTIL)

PV MODULE ELECTRICAL TERMINATION DESIGN REQUIREMENTS

MOTOROLA, INC.

F. Mosna

Study Summary

OBJECTIVE:
DEVELOP INFORMATION TO FACILITATE THE SELECTION AND IMPROVEMENT OF LIFE-CYCLE COST-EFFECTIVE ELECTRICAL TERMINATION HARDWARE

APPROACH:
DEVELOP REQUIREMENTS
IDENTIFY EXISTING HARDWARE
EVALUATE CANDIDATES

STATUS:
FINAL REPORT TO BE AVAILABLE MID-DECEMBER

TASK 1

DEVELOP MODULE AND ARRAY DESIGN REQUIREMENTS.

A. ANALYSIS AND SURVEY OF MANUFACTURERS, USERS, AND CODE GROUPS.
B. DEVELOP ELECTRICAL TERMINATION SELECTION CRITERIA.

TASK 2

IDENTIFY EXISTING ELECTRICAL TERMINATION CANDIDATE HARDWARE.

A. SURVEY MANUFACTURERS, USERS, AND GOVERNMENT AGENCIES.
B. RANK CANDIDATE TERMINATION HARDWARE.
C. SUMMARIZE ATTRIBUTE DEPENDENCIES.

TASK 3

EVALUATE CANDIDATES AND POTENTIAL IMPROVEMENTS

A. IDENTIFY PROMISING HARDWARE.
B. IDENTIFY IMPROVEMENTS FOR COST REDUCTION.
C. IDENTIFY COST DRIVERS/REQUIREMENT MODIFICATIONS FOR COST REDUCTION.

Selection Criteria

FUNCTIONAL

VOLTAGE RATING
CURRENT RATING
INSULATION AND SEAL LEVEL
GROUND PROVISION
HEAT DISSIPATION
DISCONNECT CYCLES
CONTACT RESISTANCE AND PRESSURE
RELIABILITY (MTBF)

MANUFACTURING

PREPARATION TIME
PRODUCIBILITY
REPAIRABILITY
LABOR SKILL LEVEL
SPECIAL TOOLS
SAFETY

ENVIRONMENTAL DURABILITY

MOISTURE
TEMPERATURE CYCLING
CORROSIVE ATMOSPHERE AND CONTAMINATION
VANDALISM
UV RADIATION
VIBRATION AND STRAIN RELIEF

UTILITY

SERIES AND PARALLEL CONNECTIONS
WIRE-TO-WIRE CONNECTIONS
PANEL-TO-WIRE CONNECTIONS

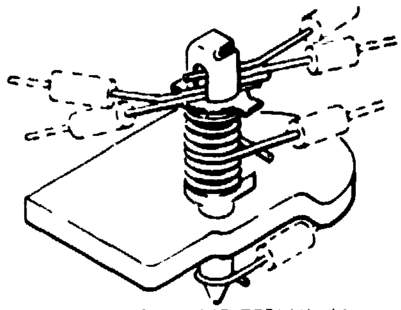
CODE

NEC

COST

Candidate Hardware

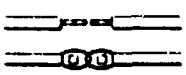
I. SPRING CLIP
II. CRIMP
   BUTT SPLICE
   PARALLEL SPLICE
   CLOSED END
III. TWIST-ON
IV. PLUG/RECEPTACLE
V. INSULATION DISPLACEMENT
VI. HAND-SOLDER
VII. SCREW
VIII. WELD
IX. WIRE WRAP



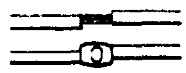
SPRING - CLIP TERMINAL
(VECTOR ELECTRONICS CO.)

WIRE NUT

0.350 IN. DIA. BY 0.550 IN. LG.



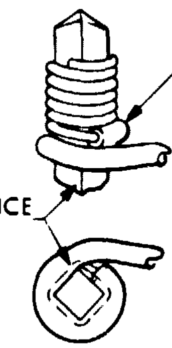
(A) BUTT CONNECTOR (2 CRIMPS)



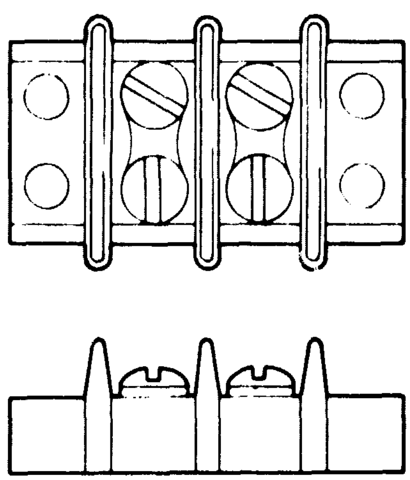
(B) PARALLEL CONNECTOR (1 CRIMP)

(C) PIGTAIL CONNECTOR (1 CRIMP)

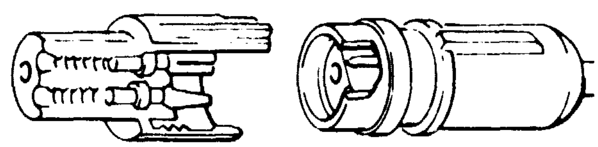
THREE METHODS OF SPLICING WIRES WITH CRIMPING TOOL AND CONNECTORS.



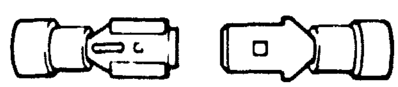
(A) GARDENER DENVER'S WIRE WRAP



TERMINAL BLOCK



CANNON SURE-SEAL CONNECTOR



AMP PUSH-ON CONNECTOR

Rating System Method

- ASSIGN VALUES TO EACH TERMINATION TYPE FOR EACH SELECTION CRITERION

- ASSIGN WEIGHTING FACTORS TO EACH SELECTION CRITERION ON THE BASIS OF APPLICATION (REMOTE, RESIDENTIAL, INTERMEDIATE, INDUSTRIAL)

- MULTIPLY TERMINATION VALUE WITH APPLICATION FACTOR FOR EACH TERMINATION TYPE IN EACH APPLICATION

- TERMINATION RECEIVING HIGHEST ALGEBRAIC SUM IS BEST-SUITED ELECTRICAL TERMINATION IN EACH APPLICATION

Termination Attributes

TERMINATION TYPE	FUNCTIONAL									MANUFACTURING					
	VOLTAGE RATING	CURRENT RATING	INSUL. LEVEL	SEAL LEVEL	GND PROVIS.	HEAT DISS.	DISCON. CYCLES	CONTACT RES.	RELIAB. (MTBF)	PREP TIME	PRODUC-IBILITY	REPAIR-ABILITY	LABOR SKILL LEVEL	SPEC. TOOLS	SAFETY
I SPRING CLIP	1	1	1	2	1	3	4	4	2	2	3	4	4	4	1
II CRIMP	4	4	3	3	1	3	1	4	4	3	3	4	4	3	3
III TWIST-ON	3	3	4	3	1	3	4	3	3	3	3	4	4	4	2
IV PLUG RECEPTACLE	4	4	4	4	4	1	4	2	3	2	4	3	2	2	4
V INSUL. DISP.	2	2	2	4	1	2	2	3	4	4	3	2	3	3	2
VI HAND-SOLDERED	4	4	1	4	1	3	1	4	2	2	2	3	1	2	1
VII SCREW	4	4	1	4	4	4	4	4	2	2	3	4	2	4	2
VIII WELDED	4	4	1	4	1	3	1	4	4	2	2	1	2	1	1
IX WIRE WRAP	1	1	2	4	1	3	1	3	4	3	3	2	4	3	2

TERMINATION TYPE	DURABILITY								UTILITY				CODE
	MOIST.	TEMP. CYCLE	CORROS ATM.	CONTAM	VANDAL	UV RAD.	VIB. (JOINT STR)	STRAIN RELIEF	SERIES CONN.	PARA. CONN.	WIRE TO WIRE	PANEL TO WIRE	N*
I SPRING CLIP	2	4	3	4	3	4	3	4	4	4	4	4	1
II CRIMP	3	3	3	3	4	3	4	4	4	4	4	1	4
III TWIST-ON	3	3	3	3	2	3	2	1	4	4	4	1	3
IV PLUG/RECEPTACLE	4	4	4	4	2	4	4	4	4	4	4	4	3
V INSUL. DISP.	4	4	4	4	4	4	2	4	4	4	4	4	3
VI HAND-SOLDERED	4	2	3	3	4	3	3	3	4	4	4	4	2
VII SCREW	4	3	3	4	3	4	3	4	4	4	4	4	4
VIII WELDED	3	4	3	3	4	3	4	3	4	4	4	1	3
IX WIRE WRAP	3	3	3	4	4	4	4	3	4	4	4	4	1

* - All termination types considered <u>sealed</u> in some manner

1 = poor, unacceptable; 2 = fair, average; 3 = good, above average; 4 = excellent

Application Attribute Weighing Factors*

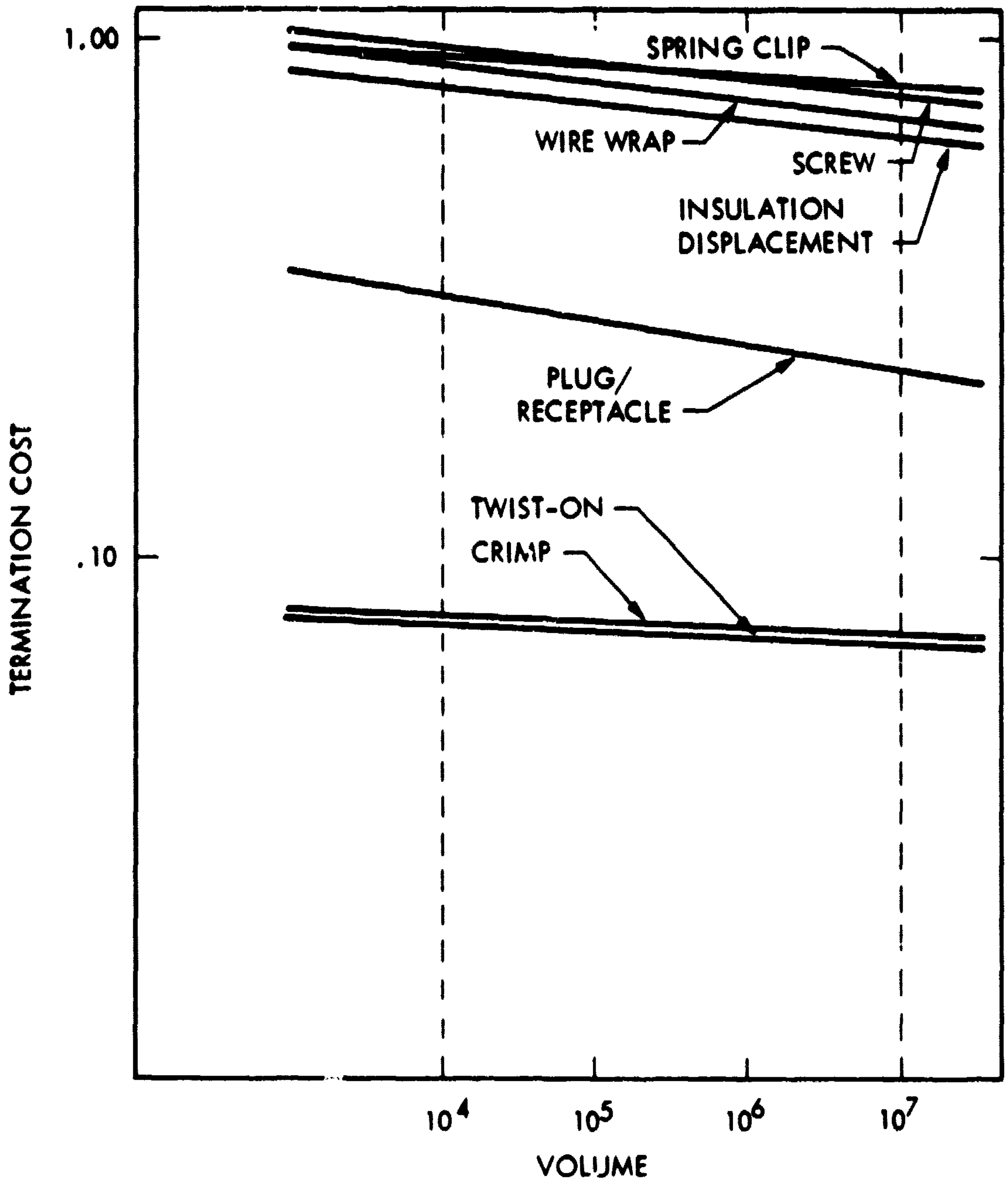
ATTRIBUTES / APPLICATIONS	DURABILITY								FUNCTIONAL									MANUFACTURING						UTILITY				CODE		
	MOISTURE	TEMP. CYCLING	CORROS. ATM.	CONTAMINATION	VANDALISM	UV RADIATION	VIBRATION	STRAIN RELIEF	VOLTAGE RATING	CURRENT RATING	INSUL LEVEL	SEAL LEVEL	GND PROVISION	HEAT DISS.	DISCONN. CYCLES	CONTACT RES.	RELIABILITY (MTBF)	PREPARATION	PRODUCIBILITY	REPAIRABILITY	LABOR SKILL LEVEL	SPECIAL TOOLS	SAFETY	SERIES CONN.	PARALLEL CONN.	WIRE-TO-WIRE	PANEL-TO-WIRE	NEC		
REMOTE	4	4	4	4	4	4	4	4	4	4	4	4	1	4	1	4	4	2	2	3	2	2	4	1	4	4	1	2		
RESIDENTIAL	3	2	1	2	2	3	2	2	4	4	4	4	4	1	1	1	2	2	2	3	2	2	4	2	3	3	2	4		
INTERMEDIATE	4	4	3	2	2	4	2	2	4	4	4	4	4	2	1	2	3	2	2	3	2	2	4	3	2	2	3	4		
INDUSTRIAL	3	2	4	3	2	3	2	3	4	4	4	4	4	4	1	4	4	2	2	3	2	2	4	4	1	1	4	4		

* - These factors to be multiplied by termination attribute ratings (above) for final ranking.

Ranking by Numerical Order

RANK \ APP'L	REMOTE	RESIDENTIAL	INTERMEDIATE	INDUSTRIAL
1	PLUG/RECPT (301)	PLUG/RECPT (254)	PLUG/RECPT (284)	PLUG/RECPT (289)
2	CRIMP (293)	CRIMP (239)	SCREW (267)	SCREW (283)
3	SCREW (287)	SCREW (238)	CRIMP (260)	CRIMP (272)
4	INSL. DISP. (271)	INSL. DISP. (213)	INSL. DISP. (244)	INSL. DISP. (256)
5	WELDED (260)	TWIST-ON (209)	TWIST-ON (231)	TWIST-ON (240)
6	TWIST-ON (259)	HAND-SOLDER (197)	WELDED (226)	HAND-SOLDER (237)
7	WIRE-WRAP (256)	WELDED (198)	WIRE-WRAP (224)	WIRE-WRAP (237)
8	HAND-SOLDER (249)	WIRE-WRAP (195)	HAND-SOLDER (223)	WELDED (236)
9	SPRING CLIP (242)	SPRING CLIP (180)	SPRING CLIP (209)	SPRING CLIP (222)

Typical Initial Costs of Generic Termination Types
(Wire Size 12AWG, Maximum Current 40 Amps)

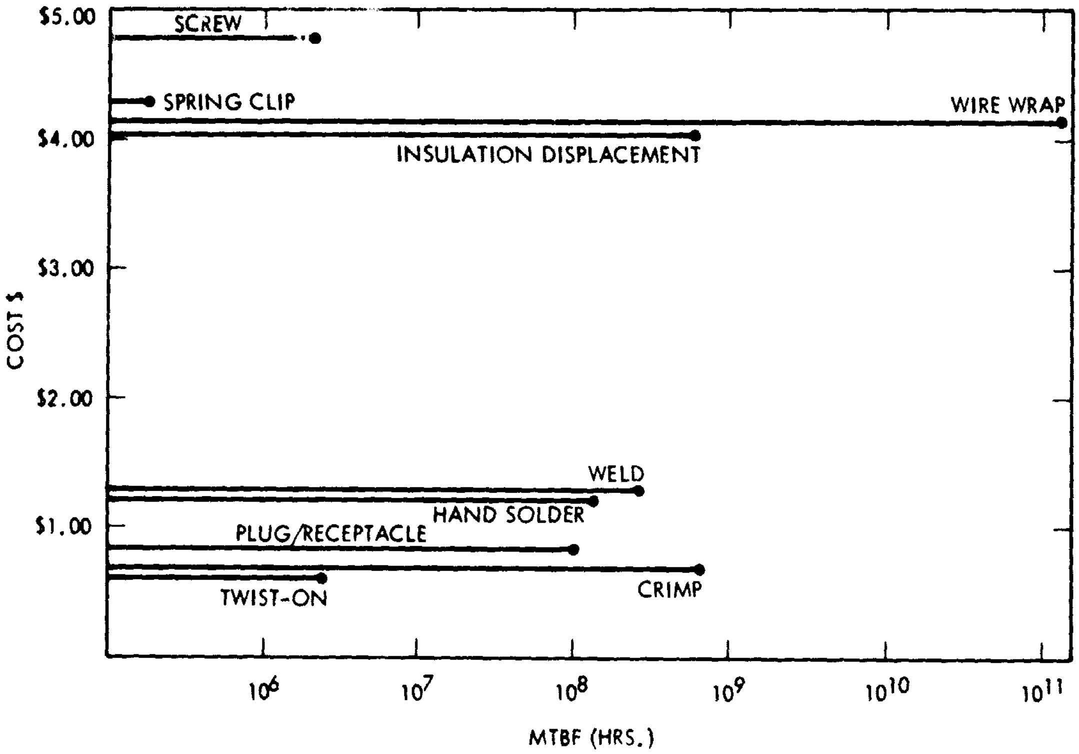


(WIRE SIZE #12AWG; MAXIMUM CURRENT 40 AMPS)

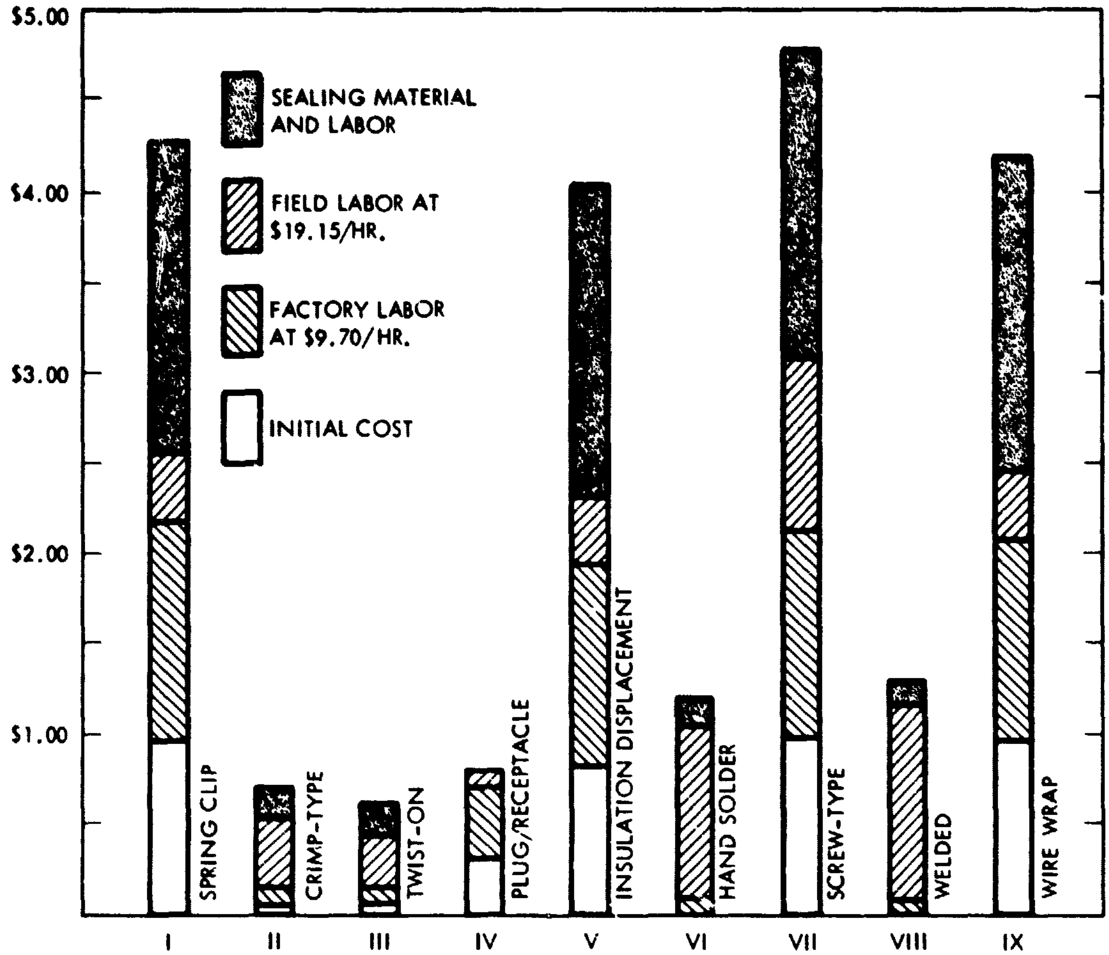
Factors Affecting Cost

- MANUFACTURING MATERIAL, EQUIPMENT, LABOR
- INSTALLATION LABOR, SKILL, EQUIPMENT
- SEALING MATERIAL, LABOR

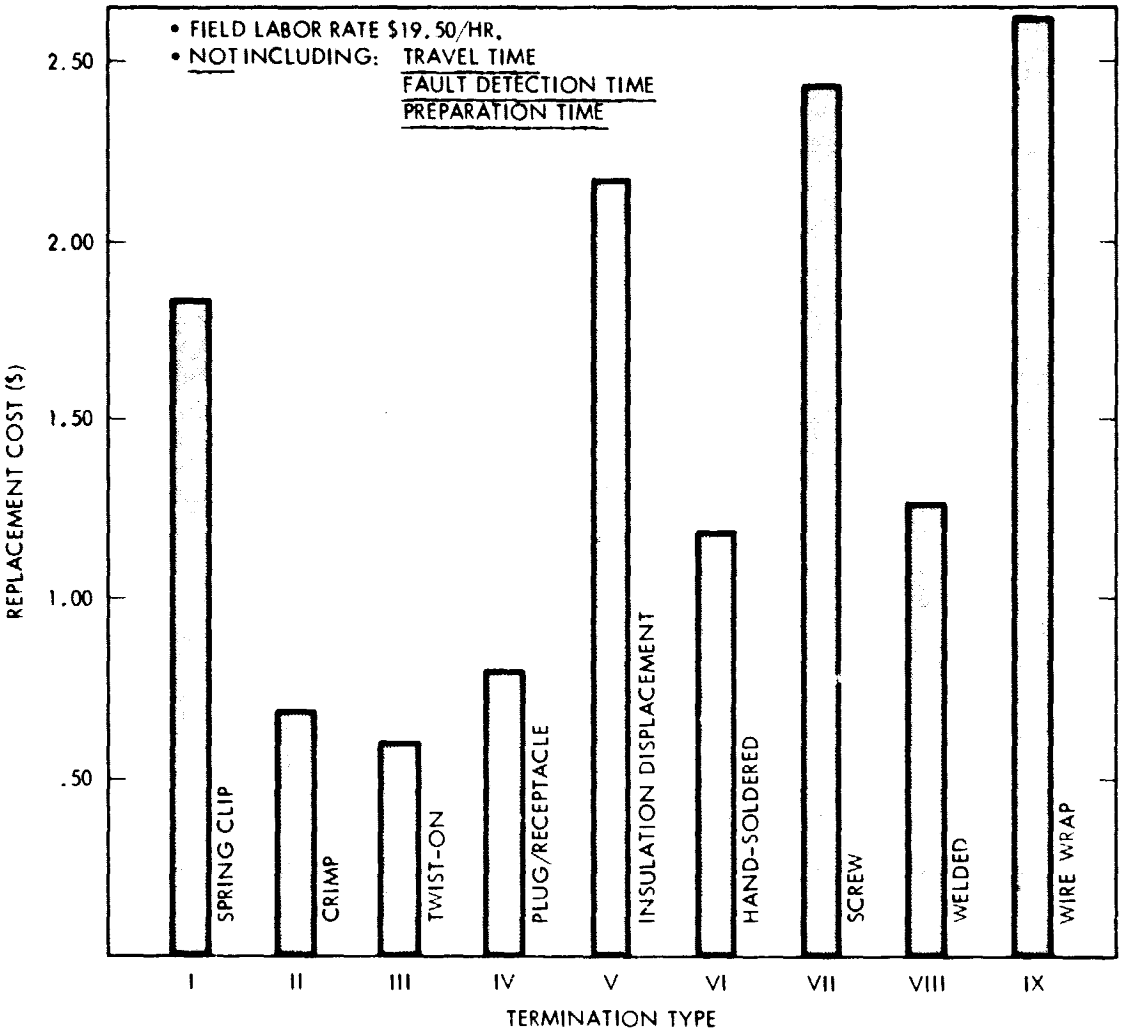
Cost vs MTBF



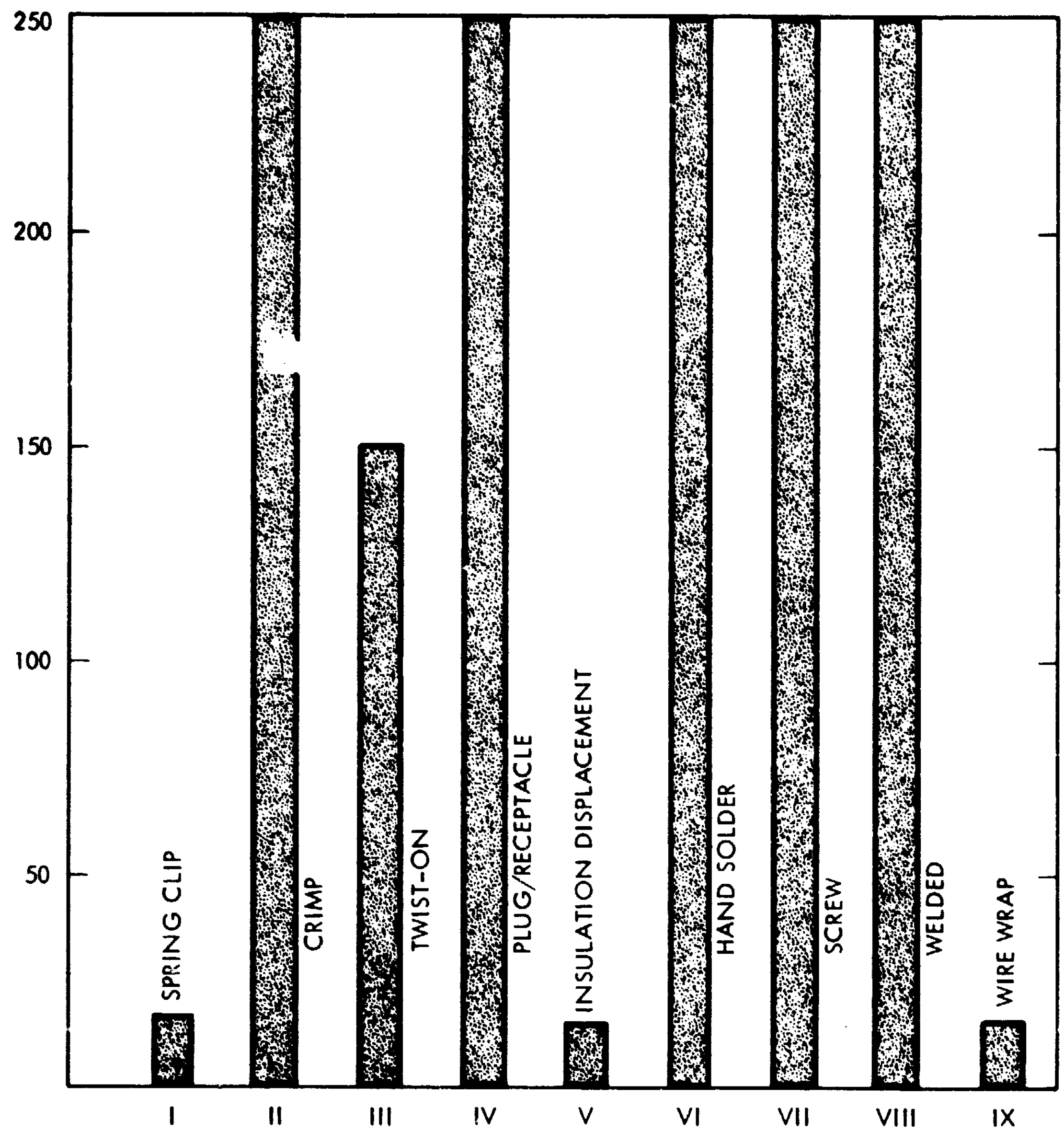
Factory and Field Assembly Costs For Termination Types



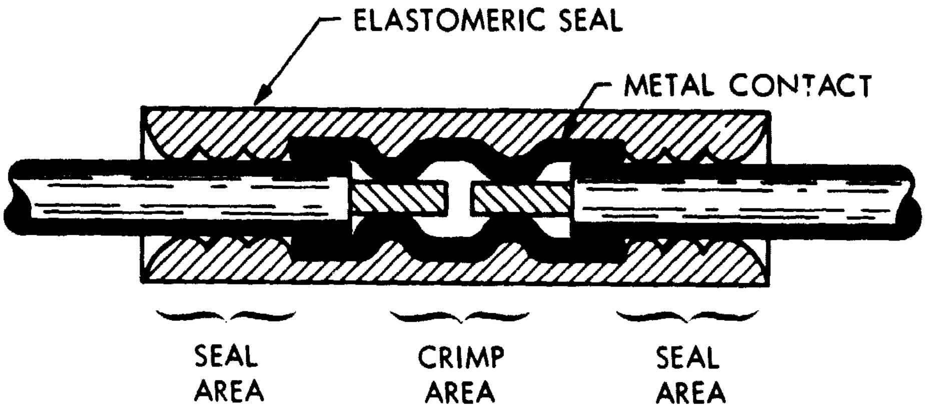
Field Termination Replacement Due to Termination Failure



Termination Current Capabilities vs Type



Suggested Crimp Termination Seal



Existing Electrical Terminations Most Suitable for Use With PV Systems

CRIMP-TYPE
(SEALED)

PLUG/RECEPTACLE

GLASS THICKNESS SIZING METHOD

JET PROPULSION LABORATORY

D. Moore

Background

CLASSICAL APPROACH

- LINEAR PLATE THEORY
- TRADITIONAL GLASS STRENGTH • 1500 psi

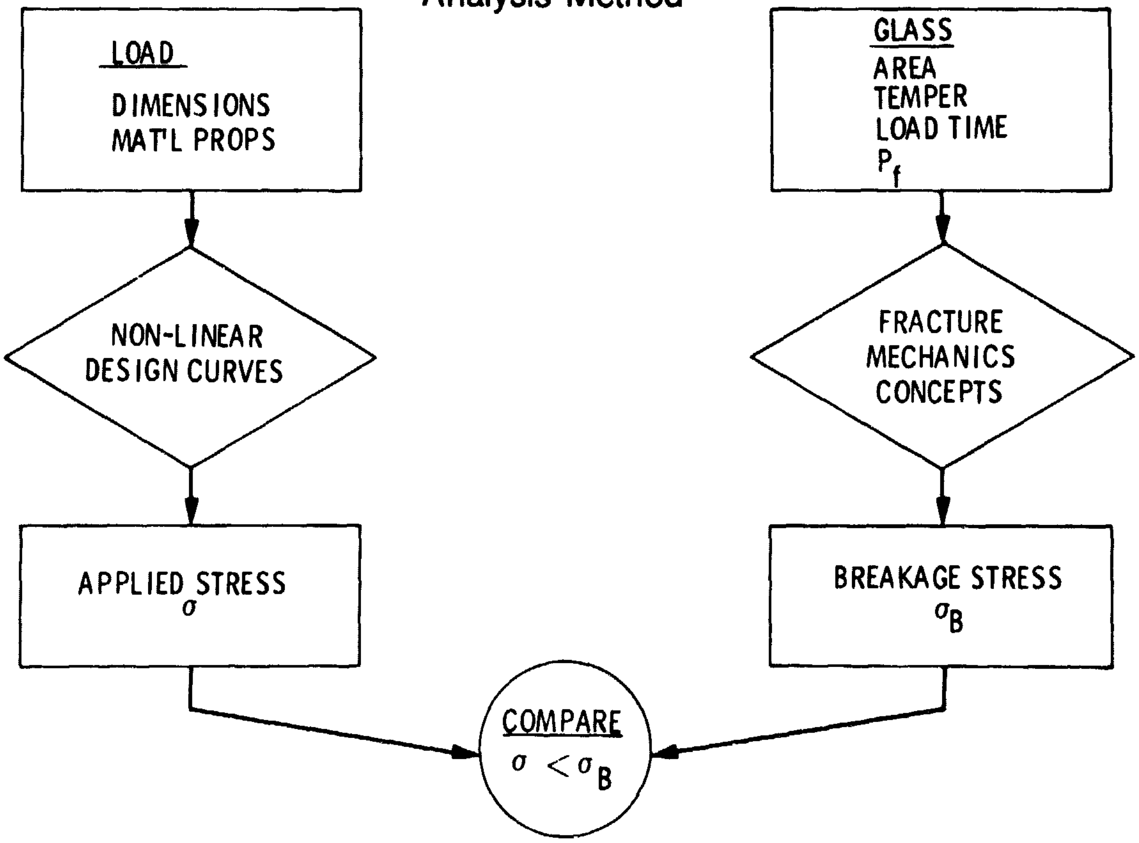
GLASS DESIGN CONSIDERATIONS

- NON-LINEAR STRESS ANALYSIS
- GLASS FRACTURE CONSIDERATIONS
  - PROBABILISTIC IN NATURE
  - STATIC FATIGUE
  - GLASS AREA DEPENDENT

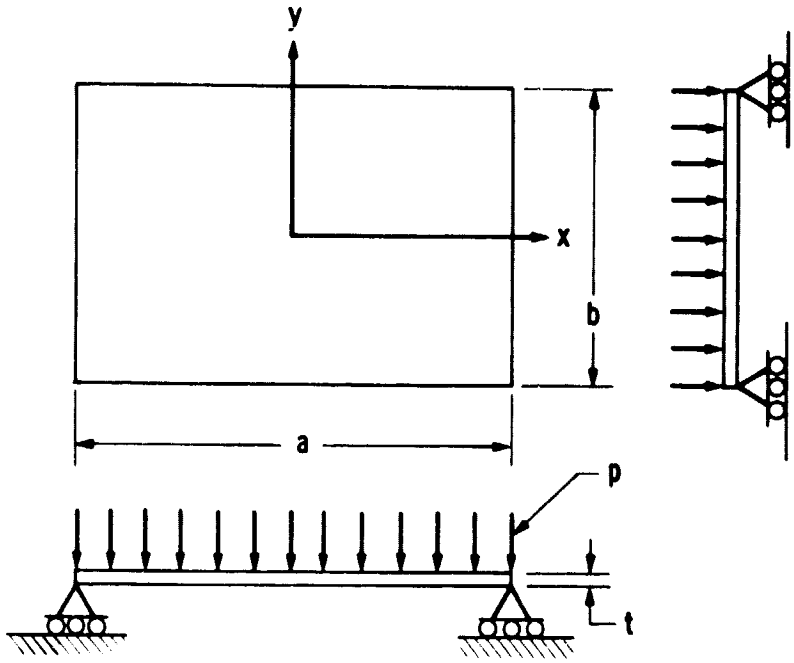
CURRENT WINDOW DESIGN PRACTICE

- EMPIRICALLY DEVELOPED CURVES
- GLASS THICKNESS vs AREA AND LOAD FOR 8 FAILURE PER 1000

Analysis Method



Problem Definition



a = LENGTH OF PLATE

b = WIDTH OF PLATE

t = THICKNESS OF PLATE

E = YOUNG's MODULUS

ν = POISSON's RATIO

D = FLEXURAL RIGIDITY

$$= \frac{Et^2}{12\,(1 - \nu^2)}$$

Dimensionless Parameters

- LOAD

$$\text{LIF} \equiv \text{LOAD INTENSITY FACTOR} \equiv \frac{pb^4}{Dt}$$

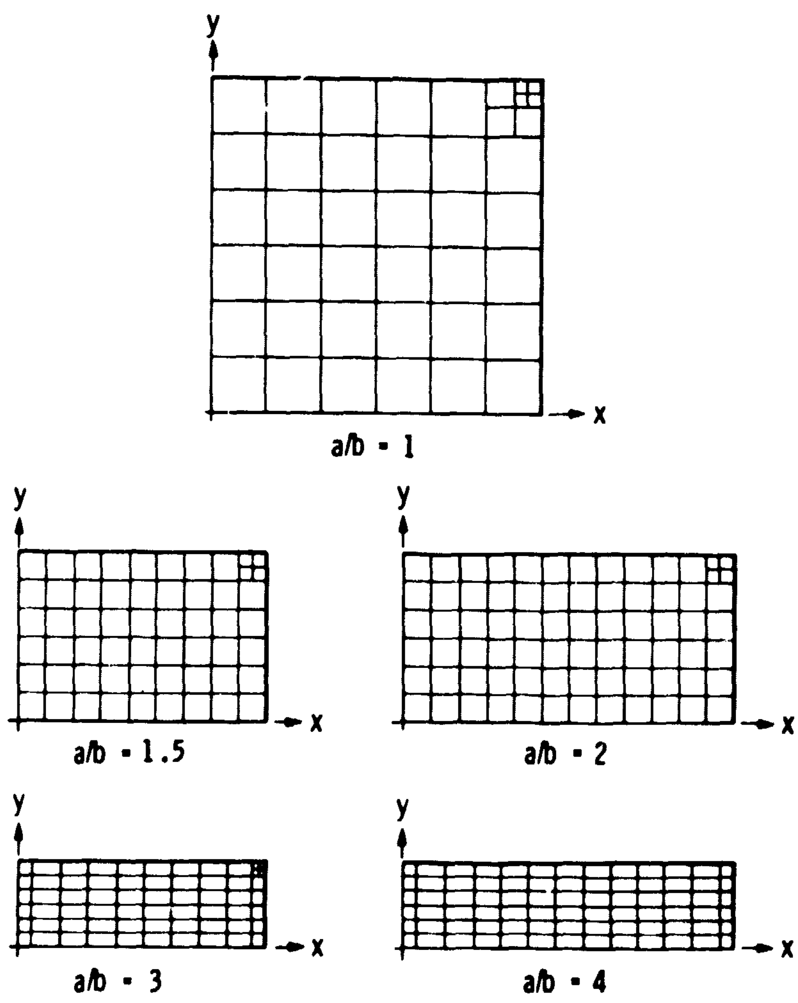
- DEFLECTION

$$\frac{w_{max}}{t} \equiv \text{CENTER DEFLECTION} \div \text{PLATE THICKNESS}$$

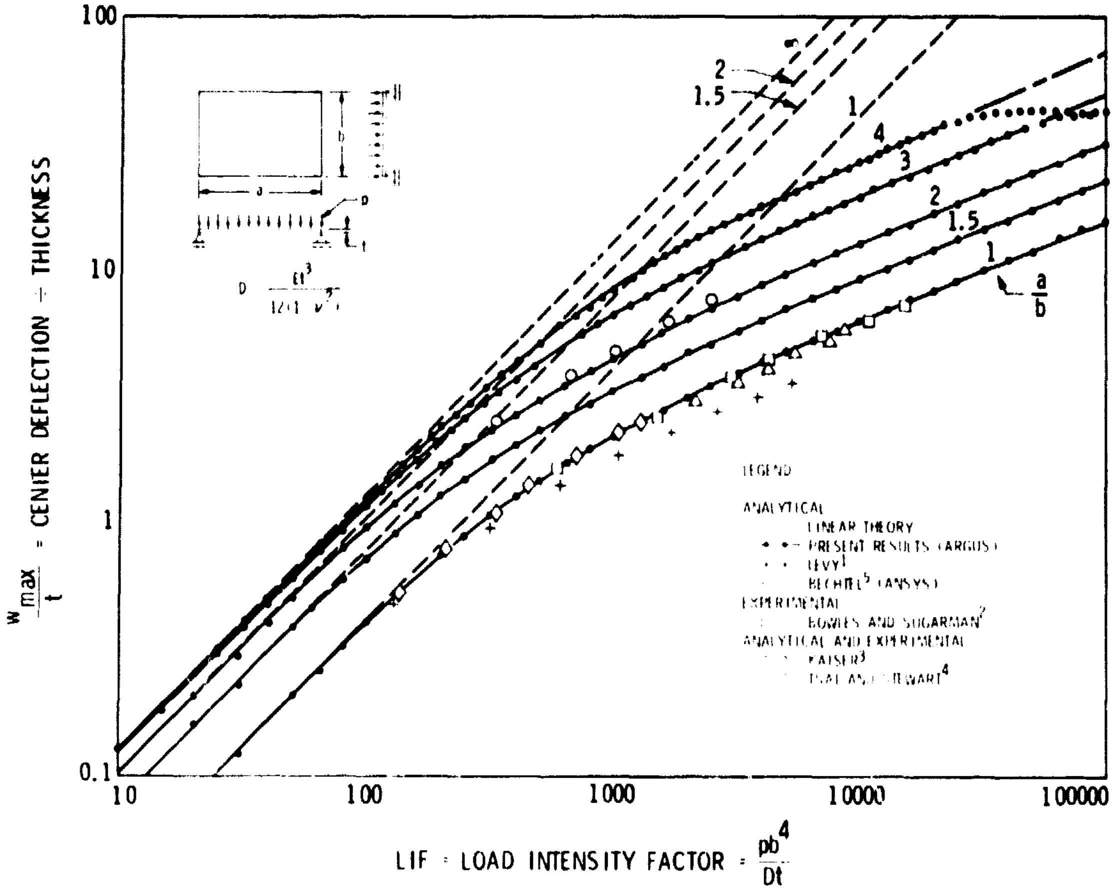
- STRESS

$$\text{SIF} \equiv \text{STRESS INTENSITY FACTOR} \equiv \frac{\sigma b^2 t}{D}$$

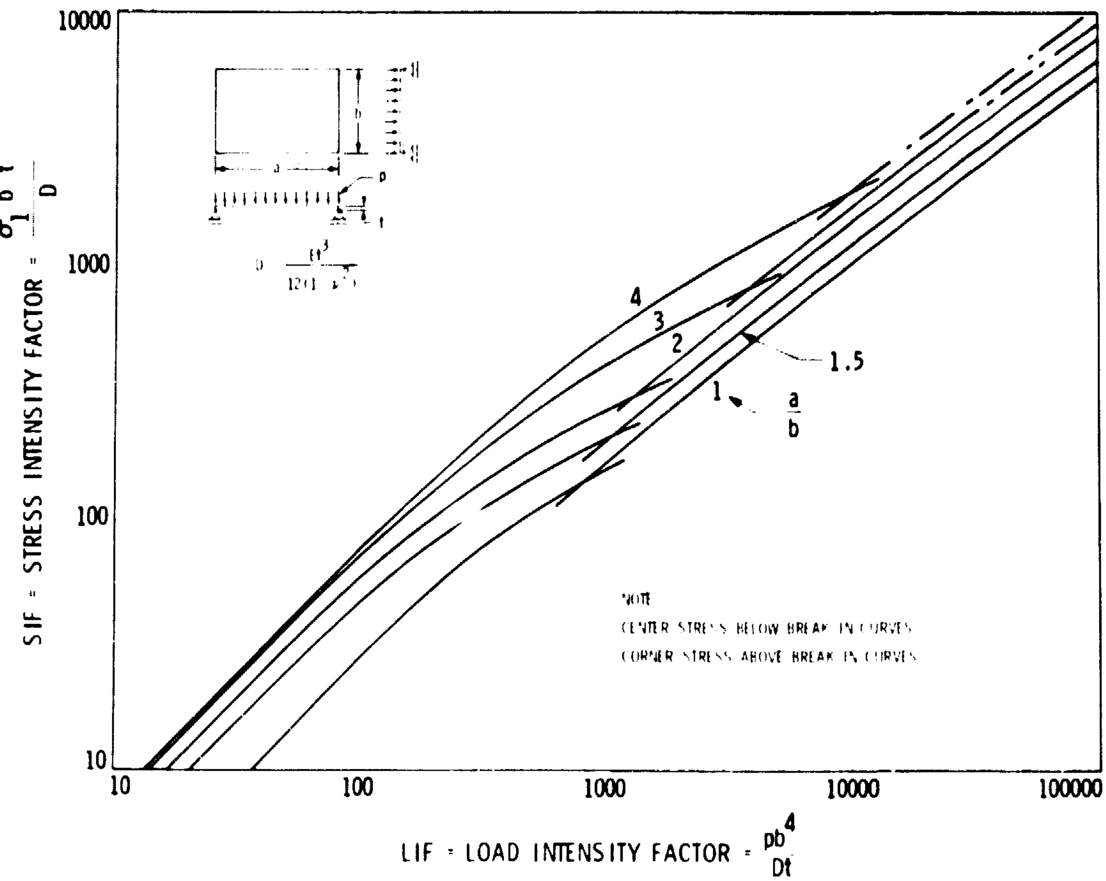
Finite Element Models



Deflection vs Load



Maximum Principal Stress vs Load



Glass Breakage Stress

FUNCTION OF

- LOAD DURATION TIME
- GLASS TYPE
  SHEET, FLOAT, PLATE
- GLASS TEMPER
  ANNEALED, TEMPERED, SEMI-TEMPERED
- PLATE SURFACE AREA

PROPOSED FORMULATION

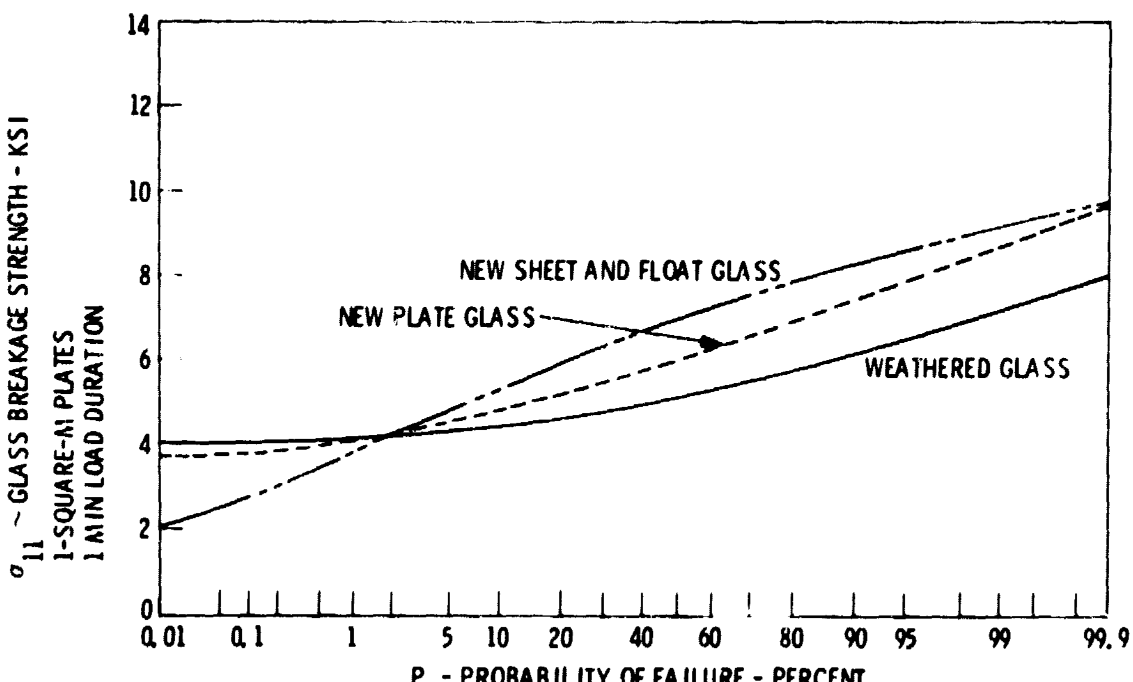
$$\sigma_B = f_T \left(\frac{1}{A}\right)^{1/6} \sigma_{11}$$

WHERE σ_{11} = GLASS PLATE BREAKAGE STRESS NORMALIZED TO 1 MIN, 1 M^2

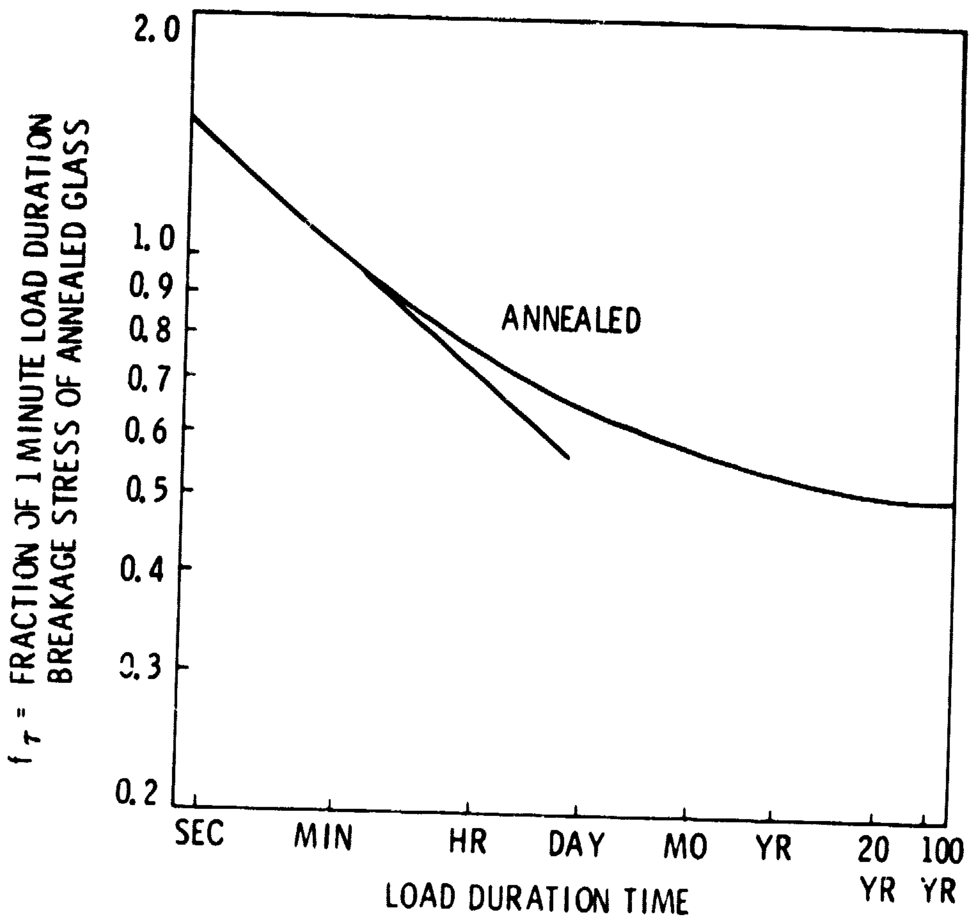
f_T = FUNCTION TIME (SEE CURVE)

A = PLATE AREA IN M^2

Design Values



F_T vs Load Duration Time



Sample Problem

DESIGN A 1-M-SQUARE, SIMPLY SUPPORTED ANNEALED GLASS PANEL TO SUSTAIN A 50 lb/ft^2 LOAD OF 15 MIN DURATION WITH A PROBABILITY OF FAILURE OF 1%.

CALCULATE THE STRESS

$a = 39.4'$ $\quad P = 50\ psf = 0.3472\ psi$

$b = 39.4''$ $\quad E = 10{,}000{,}000\ psi$

TRY $t = 0.155''$ $\quad \nu = 0.22$

$$D = \frac{Et^3}{12\,(1-\nu^2)} = 3261$$

$$LIF = \frac{Pb^4}{Dt} = 1655$$

→ $SIF = 230$ (FROM DESIGN CURVE)

$$\sigma = \frac{D}{b^2 t}\ SIF = 3117\ psi$$

DETERMINE GLASS BREAKAGE STRESS

FOR $P_f = 1\%$, $\sigma_{11} = 3800\ psi$

FOR $\tau = 15\ MIN$, $f_\tau = 0.825$

$$\sigma_B = f\left(\frac{1}{A}\right)^{1/6}\sigma_{11} = 3135$$

COMPARE

3117 · 3135 ∴ OK

ADVERTISEMENT

LSA TASK REPORT
PROPOSED METHOD FOR DETERMINING THE GLASS THICKNESS OF RECTANGULAR GLASS SOLAR COLLECTOR PANELS SUBJECTED TO UNIFORM NORMAL PRESSURE LOADS

Donald M. Moore

ARRAY STRUCTURE COST REDUCTION STUDY

JET PROPULSION LABORATORY

Abe Wilson

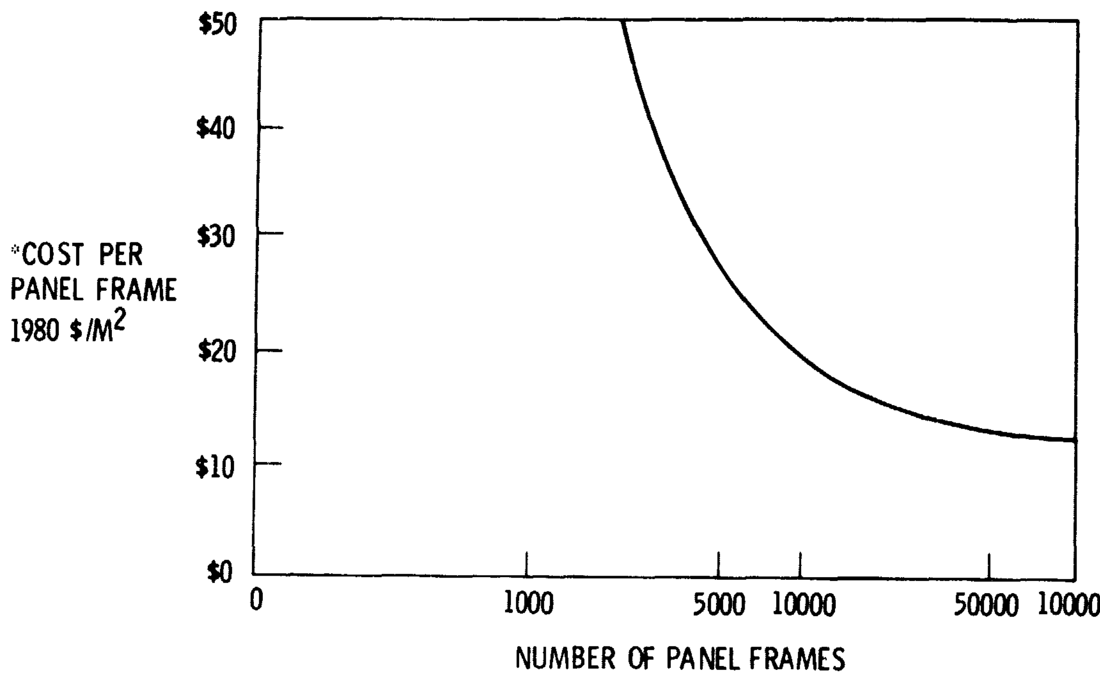
OBJECTIVE

- IDENTIFY MEANS FOR REDUCING THE COST OF FLAT-PLATE ARRAY STRUCTURES FOR LARGE INDUSTRIAL/CENTRAL STATION ARRAYS
  - PANEL FRAME (8 x 16 FOOT)
  - ARRAY STRUCTURE
  - ARRAY FOUNDATION

APPROACH

- DESIGN AND FABRICATE LOW-COST PANEL FRAME AND PROOF TEST TO FAILURE
- DISCUSS DESIGN WITH MASS PRODUCTION VENDORS AND OBTAIN COST ESTIMATES ON EQUIVALENT DESIGN
- FABRICATE EQUIVALENT PANEL AND PROOF TEST
- DESIGN AND FABRICATE LOW-COST FOUNDATION AND STRUCTURE
- TEST DESIGN FOR SEVERAL SOIL CONDITIONS
- DISCUSS DESIGN WITH VENDORS:
  - HOLE DRILLING, PILE DRIVING
  - WOOD TREATING, GALVANIZING
- CONSIDER EFFECT OF NUMBER OF HOLES ON OVERALL COST
- ESTIMATE COST OF ARRAY FOUNDATION AND STRUCTURE
- FABRICATE AND PROOF TEST COMPLETE STRUCTURE WITH FOUNDATION

Panel Frame Cost/Quantity Sensitivity



*PER QUOTE BY KAISER STEEL

Preliminary Study Results (1980 $/m²)

- SIGNIFICANT COST REDUCTIONS ARE POSSIBLE

DATE OF ESTIMATE	(1) BARE PANEL FRAME	(2) * PANEL FRAME	(3) ARRAY FOUNDATION MATERIAL	(4) ARRAY FOUNDATION AND STRUCTURE	(5) TOTAL (1)+(4)
AUG '78	$18.90	$28.42	CONCRETE	$40.32	$59.22
NOV '79	$13.45	$22.97	EARTH	$ 7.56	$21.01

*BARE PANEL FRAME COST PLUS $9.52 FOR GASKET, GROUND CONNECTORS ASSEMBLY LABOR, FREIGHT AND INSTALLATION LABOR, PER BECHTEL STUDY.

ENGINEERING AREA

MODULE DESIGN

JET PROPULSION LABORATORY

R. Ross, Chairman

The module design theme of this PIM was addressed in detail during a special four-hour session Thursday morning. LSA Engineering, Encapsulation and Quality Assurance personnel expanded discussion of the specific design parameters, approaches, experience and recommendations that had been summarized by Ross and Dumas in the Wednesday session titled "Lessons Learned that Affect Module Design". Nine presentations were made, as indicated in the session agenda. The graphic material from these presentations appears below.

AGENDA

TIME		
8:00	OVERALL DESIGN OPTIMIZATION	R. ROSS
8:20	ELECTRICAL CIRCUIT DESIGN	C. GONZALEZ
9:10	SAFETY DESIGN	A. LEVINS (UL)
9:30	ELECTRICAL TERMINAL DESIGN	R. SUGIMURA
9:45	COFFEE	
10:00	MECHANICAL CONFIGURATION	J. ARNETT
10:20	STRUCTURAL DESIGN	D. MOORE
10:40	ENVIRONMENTAL REQUIREMENTS	A. HOFFMAN
11:00	ENCAPSULATION AND PROCESSING	E. CUDDIHY
11:45	QUALITY ASSURANCE	W. BISHOP

OVERALL MODULE AND ARRAY DESIGN OPTIMIZATION

Overall Module Requirements

- GENERATE POWER
  - EFFICIENTLY
  - SAFELY
- INTEGRATE INTO ARRAY
  - ELECTRICALLY
  - MECHANICALLY
  - THERMALLY
- PROVIDE LONG LIFE AND LOW MAINTENANCE
  - ELECTRICAL CIRCUIT RELIABILITY
  - STRUCTURAL ENDURANCE
  - ENVIRONMENTAL ENDURANCE
- BE INEXPENSIVE TO MANUFACTURE
- MAINTAIN HIGH QUALITY CONTROL

Overall Module/Array Design Optimization

OBJECTIVE: MINIMIZE ARRAY LIFE-CYCLE ENERGY COST

METHODOLOGY:

LIFE-CYCLE BENEFIT = LIFE-CYCLE COST

$$(\$/\text{kW-h}) \times \left(\begin{array}{c}\text{LIFE-CYCLE}\\ \text{ENERGY}\end{array}\right) = \text{LIFE-CYCLE COST}$$

THEREFORE:

OPTIMUM MODULE = MINIMUM ($/kW-h)

$$= \text{MINIMUM}\left(\frac{\text{LIFE-CYCLE COST}}{\text{LIFE-CYCLE ENERGY}}\right)$$

Optimization Algorithm

$$\text{OPTIMUM} = \text{MINIMUM}\left(\frac{\text{LIFE-CYCLE COST}}{\text{LIFE-CYCLE ENERGY}}\right)$$

$$= \underset{L}{\text{MINIMUM}}\left(\frac{C_0 + \sum_{n=1}^{L} C_n (1+k)^{-n}}{E_0 \sum_{n=1}^{L} \epsilon_n (1+k)^{-n}}\right)$$

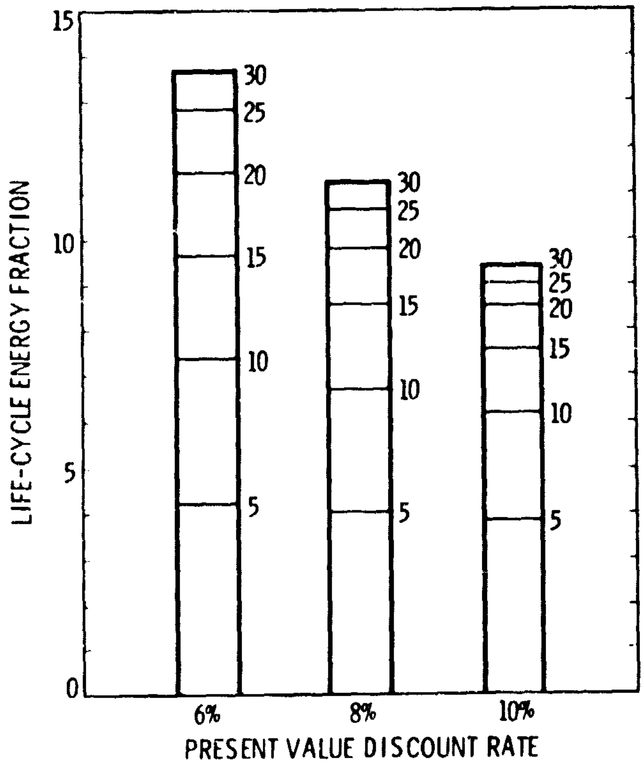
THEREFORE:

$$\text{OPTIMUM} = \underset{L}{\text{MINIMUM}} \frac{\left(\begin{array}{c}\text{INITIAL}\\ \text{COST/m}^2\end{array}\right) + \left(\begin{array}{c}\text{L-C O\&M}\\ \text{COST/m}^2\end{array}\right)}{\left(\begin{array}{c}\text{INITIAL}\\ \text{ARRAY}\\ \text{EFFICIENCY}\\ 80\,\frac{\text{mW}}{\text{cm}^2},\ \text{NOCT}\end{array}\right) \times \left(\begin{array}{c}\text{ANNUAL}\\ \text{INSOLATION}\\ \text{kW-h/m}^2\text{/yr}\end{array}\right) \times \left(\begin{array}{c}\text{L-C ENERGY}\\ \text{FRACTION*}\end{array}\right)}$$

$$\text{*L-C ENERGY FRACTION} = \sum_{n=1}^{L}\left(\frac{\text{POWER IN YEAR } n}{\text{INITIAL POWER}}\right)(1+k)^{-n}$$

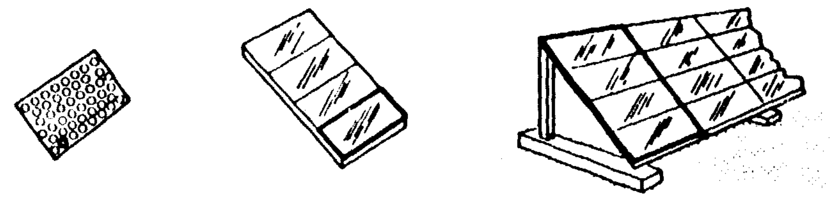
$$= \text{1/FCR, (FOR CONSTANT POWER)}$$

Life-Cycle Energy Fraction
No Degradation With Time



Example Design Problem

- DETERMINE OPTIMUM MODULE CONFIGURATION FOR LARGE GROUND-MOUNTED ARRAY
  - MECHANICAL CONFIGURATION/MODULAR SIZE
  - CIRCUIT DESIGN
  - MAINTENANCE/REPLACEMENT REQUIREMENTS
- ARRAY CONFIGURATION:



Nominal Array Costs (1975 $)

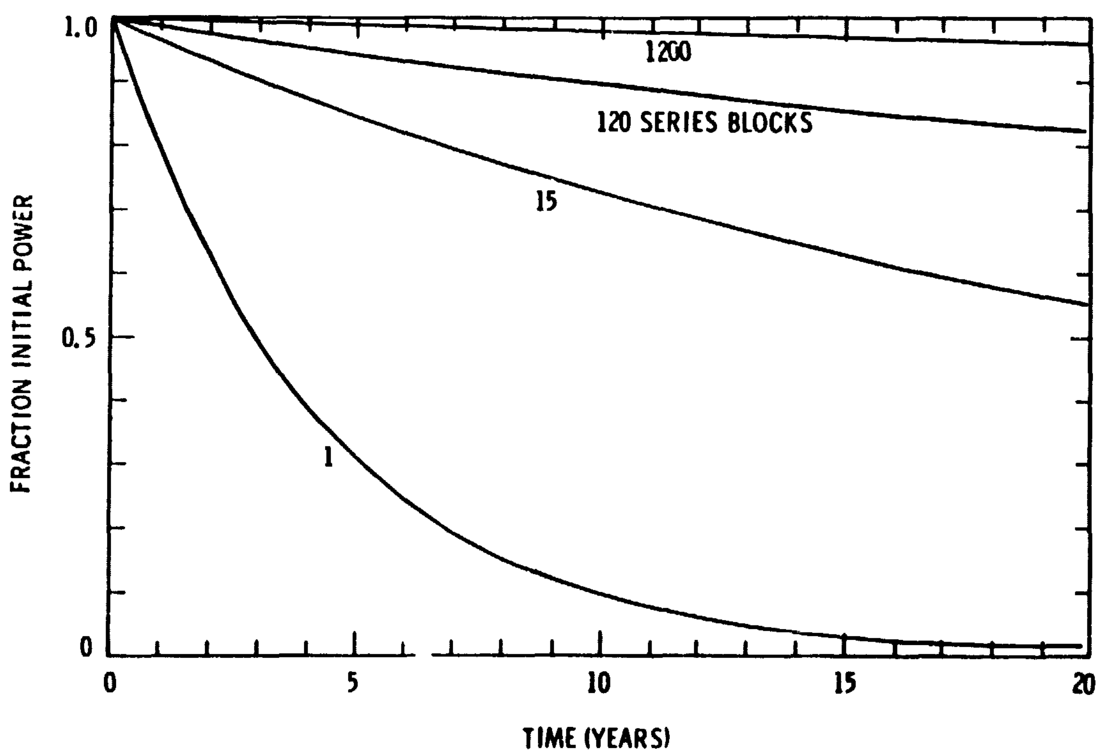
ELEMENT	UNITS	MODULE SIZE (ft x ft) 2 x 4	4 x 4	4 x 8
INITIAL:				
MODULE DIRECT COST	$/m^2$	60	60	60
MODULE YIELD COST*	$/m^2$	0-5	0-8	0-23
• MODULE SUBTOTAL	$/m^2$	60-65	60-68	60-83
PANEL FRAME	$/m^2$	24	18	15
PANEL WIRING	$/m^2$	2-4	2-3	1-2
• PANEL SUBTOTAL	$/m^2$	26-28	20-21	16-17
PANEL INSTALLATION	$/m^2$	1	1	1
INSTALLED ARRAY STRUCT	$/m^2$	22	22	22
• ARRAY TOTAL	$/m^2$	109-116	103-112	99-123
PER REPLACEMENT ACTION:				
FAULT IDENTIFICATION	$/PANEL	4	4	4
PANEL SUBSTITUTION LABOR	$/PANEL	21	21	21
MODULE REPLACEMENT LABOR	$/MOD	12	12	12
REPLACEMENT MODULE PARTS (INC 1% INVENTORY COST)	$/m^2$	61-66	61-69	61-84

*1 CELL FAILURE PER 1000 DURING ASSEMBLY/SHIPPING/INSTALLATION

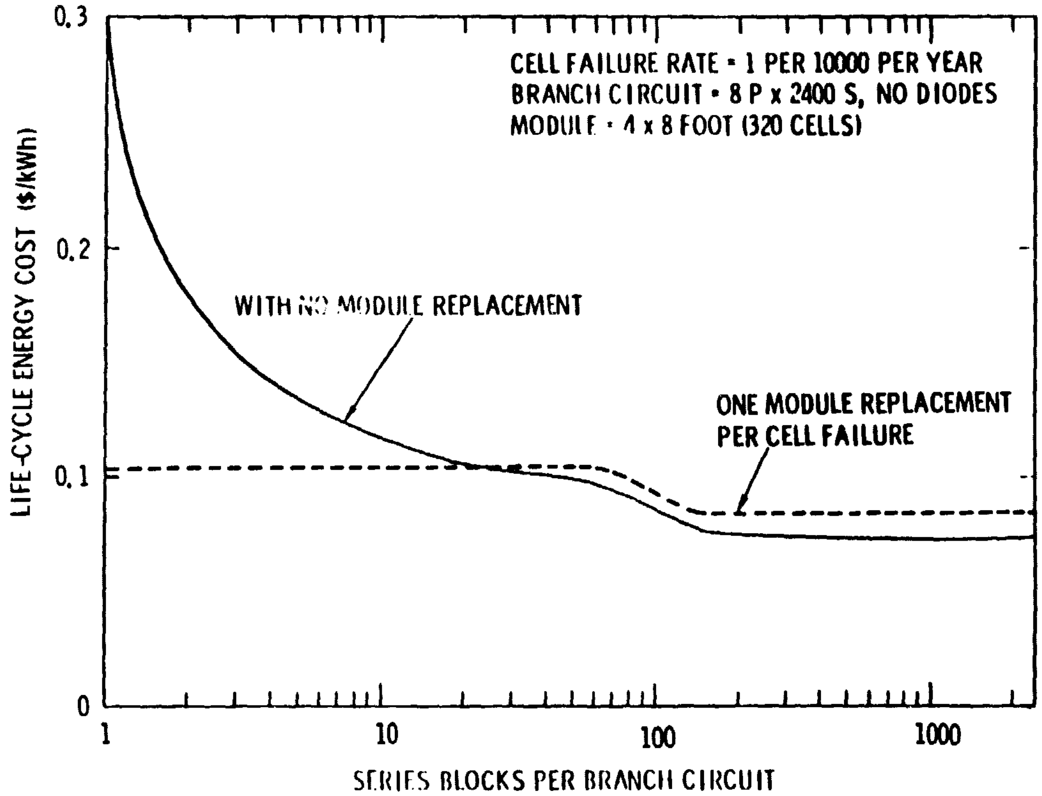
Nominal Performance Parameters

	MODULE SIZE (ft x ft)		
INITIAL ARRAY EFFICIENCY	2 x 4	4 x 4	4 x 8
ENCAP. CELL EFFICIENCY	0.15	0.15	0.15
NOCT EFFICIENCY	0.92	0.92	0.92
PACKING EFFICIENCY	0.89	0.91	0.93
ARRAY EFFICIENCY SUBTOTAL	0.123	0.126	0.128
BALANCE-OF-PLANT EFFICIENCY			
ELECTRICAL EFFICIENCY	0.92		
MODULE SOILING EFFICIENCY	0.92		
BALANCE-OF-PLANT SUBTOTAL	0.85		
BALANCE-OF-PLANT COSTS (1975$)	150 $/kW		
DISCOUNT RATE (OVER INFLATION)	10%		
ANNUAL INSOLATION	1825 kW-h/m^2/yr		

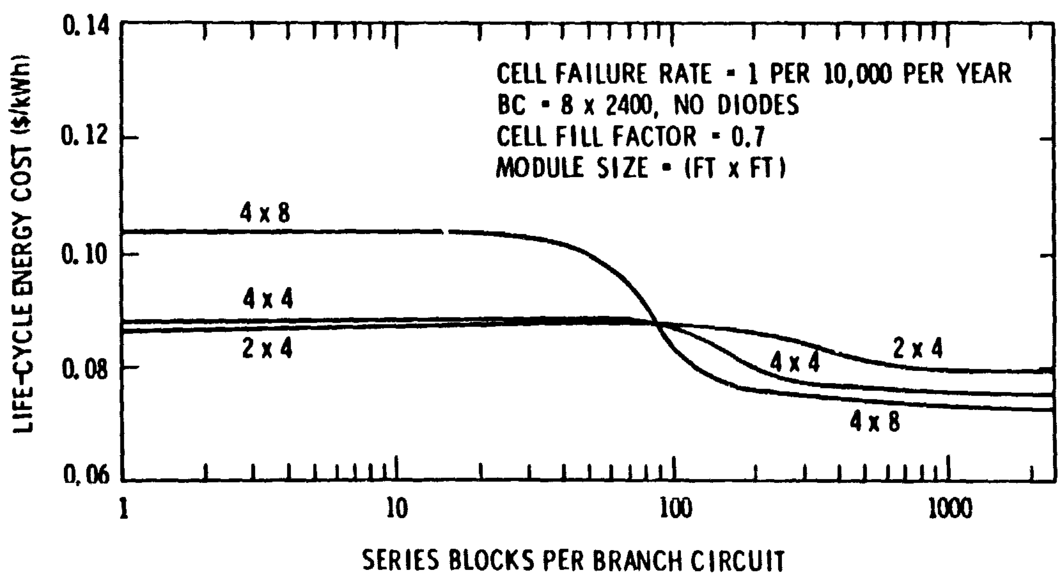
Array Power Degradation vs Circuit Redundancy



Life-Cycle Energy Cost vs Circuit Configuration



Life-Cycle Energy Cost vs Module Size



Module/Array Design Optimization

CONCLUSIONS:

- MODULE/ARRAY DESIGN OPTIONS AND COSTS ARE HIGHLY INTERDEPENDENT
  - MODULAR SIZE
  - STRUCTURAL DESIGN
  - MECHANICAL INTERFACES
  - ELECTRICAL CIRCUIT DESIGN
  - MAINTENANCE/REPLACEMENT STRATEGY
- MODULE/ARRAY OPTIMIZATION MUST BE CARRIED OUT SIMULTANEOUSLY
- ALL COST ELEMENTS MUST BE INCLUDED
  - INITIAL COSTS INCLUDING INSTALLATION
  - MAINTENANCE/REPLACEMENT COSTS

MODULE AND ARRAY CIRCUIT GUIDELINES

JET PROPULSION LABORATORY

C. Gonzalez

Statement of Problem

- SELECTION OF APPROPRIATE ELECTRICAL CIRCUIT CONFIGURATION FOR PHOTO-VOLTAIC MODULES

Areas of Consideration

- GENERAL DESIGN CONSTRAINTS
  - MODULE SIZE/NUMBER OF CELLS
  - VOLTAGE/CURRENT LEVEL
  - SAFETY CONSIDERATIONS
- MODULE PERFORMANCE CRITERIA
  - MODULE MISMATCH LOSSES
  - MODULE MANUFACTURING YIELD
  - ARRAY FAULT TOLERANCE

General Design Constraints

- MODULE SIZE/NUMBER OF CELLS
- VOLTAGE/CURRENT LEVEL
  - APPLICATION/BATTERY CHARGING, 15 VOLTS @ NOCT
- SAFETY CONSIDERATIONS
  - $V_{OC} < 30$ VOLTS @ $-20^{\circ}C$

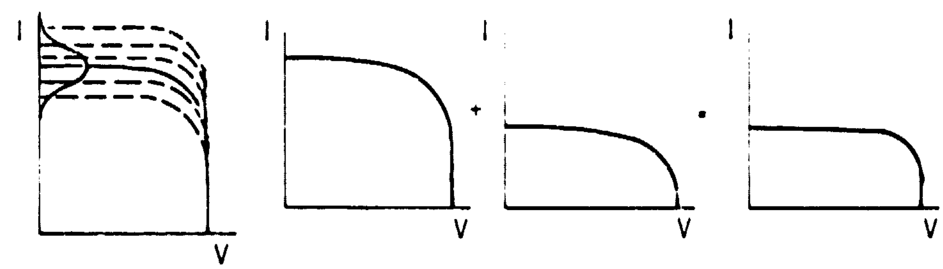
Module Performance Criteria

- MISMATCH LOSSES
- MODULE MANUFACTURING YIELD
- FAULT TOLERANCE

Mismatch Losses

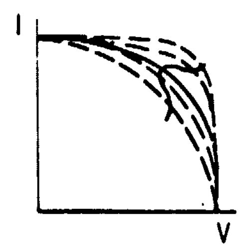
- PROBLEM STATEMENT
  - REDUCE ELECTRICAL LOSSES DUE TO CELL MISMATCH WITHIN MODULES
- APPROACH
  - INTRODUCE CIRCUIT REDUNDANCY TO REDUCE MISMATCH LOSSES TO ACCEPTABLE LEVEL (< 5%)
- ANALYTICAL PROCEDURE
  - DETERMINE I_{SC} DISTRIBUTION
  - USE MONTE CARLO TECHNIQUES TO SELECT I_{SC} IN RANDOM WAY
  - COMBINE CELL IV CURVES TO COMPUTE LOSSES

- SIMULATED BY USING RANDOM DISTRIBUTION OF I_{sc} AND FF
- I_{sc}



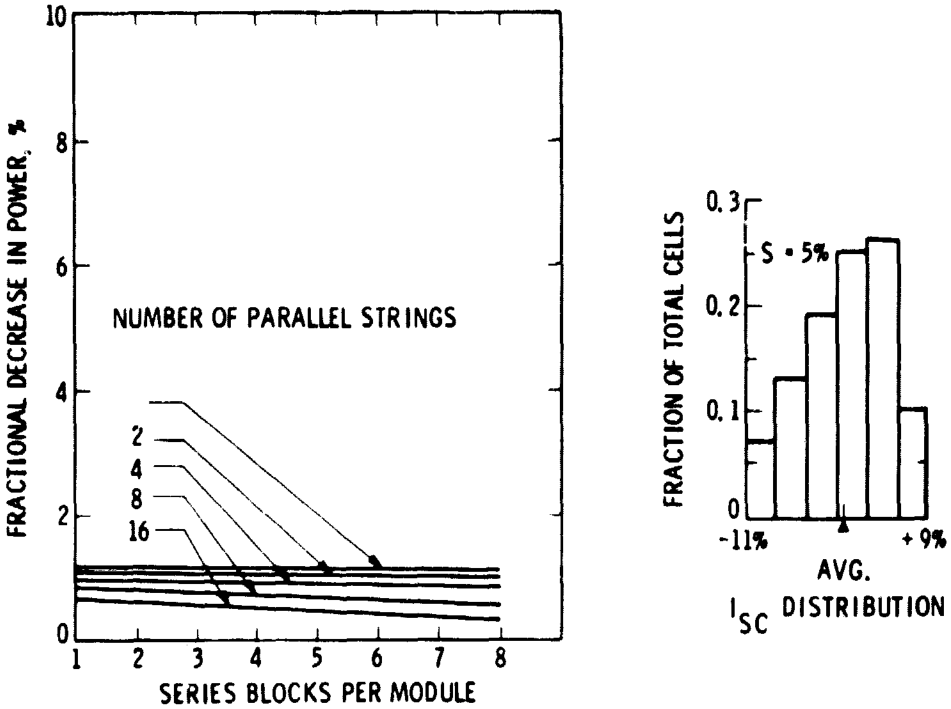
- MISMATCH EFFECTS MOST SEVERE WHERE COMBINING ALONG CONSTANT CURRENT LINES

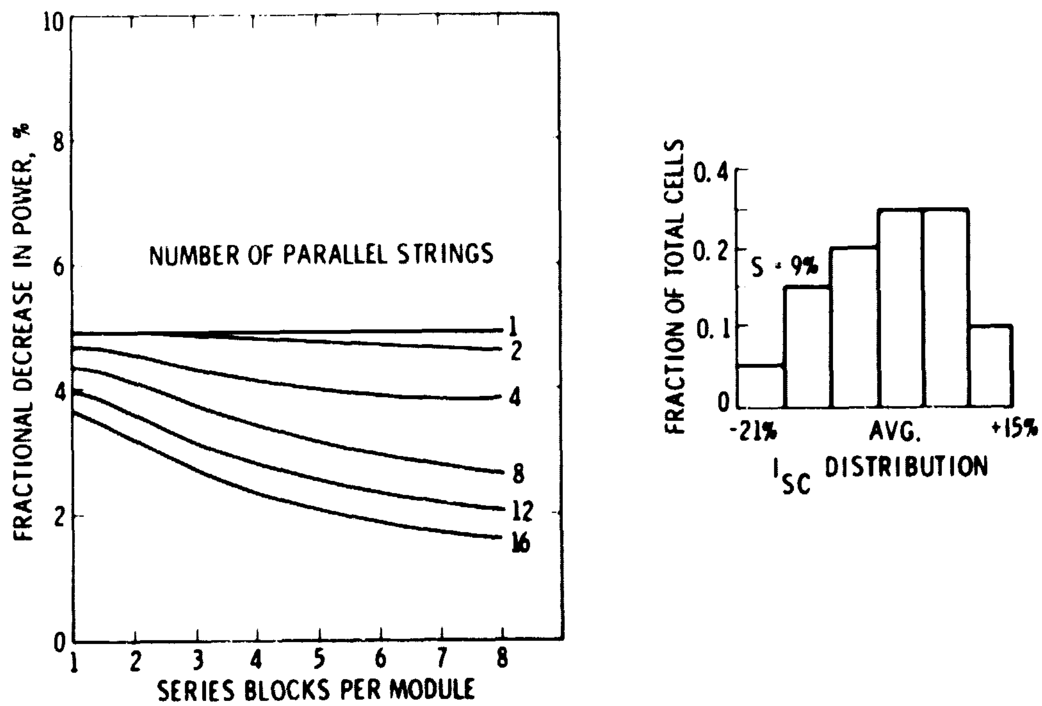
- FF

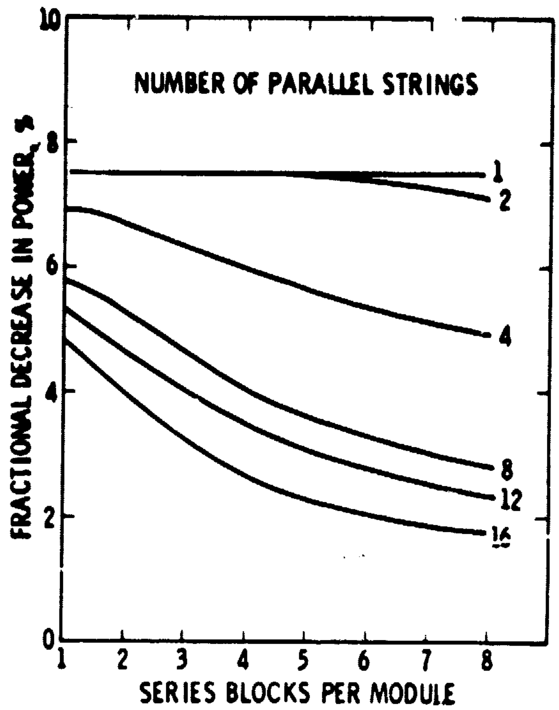


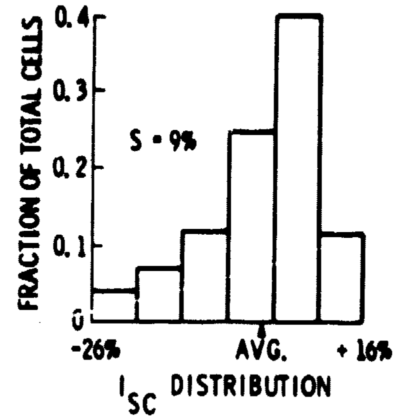
- MISMATCH EFFECTS LESS SEVERE THAN THOSE DUE TO VARIATION IN I_{sc}

Module Mismatch vs Cell I_{sc} Distribution And Module Series/Paralleling









Mismatch Loss Conclusions

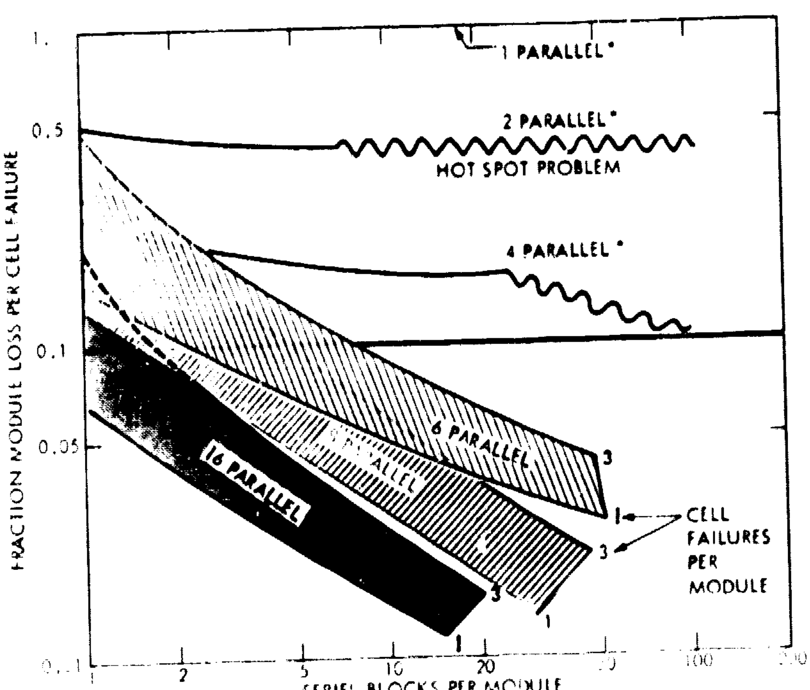
- KEY FACTORS DETERMINING AMOUNT OF MISMATCH
    - I_{SC} DISTRIBUTION SHAPE AND HALF-WIDTH
    - RATIO OF $I_{MAX\ POWER}$ TO I_{SC}
    - CELL SHUNT RESISTANCE
- FOR 0.7 FILL FACTOR
    - A 10% HALF-WIDTH LEADS TO 1% OR LESS MISMATCH LOSSES INDEPENDENT OF SERIES/PARALLELING
    - A 20% HALF-WIDTH LEADS TO MISMATCH LOSSES OF 5% OR MORE, DROPPING TO 2% WITH EXTENSIVE SERIES PARALLELING

Module Manufacturing Yield

- PROBLEM STATEMENT
  - REDUCE NUMBER OF MODULE REJECTS DUE TO FAILURES DURING MODULE ASSEMBLY, SHIPPING AND INSTALLATION
- APPROACH
  - INTRODUCE CIRCUIT REDUNDANCY TO REDUCE SINGLE-FAILURE POWER LOSS BELOW ACCEPTABLE LEVEL (10%)
- ANALYTICAL PROCEDURE
  - DETERMINE SINGLE-FAILURE DEGRADATION AS A FUNCTION OF NUMBER OF PARALLEL STRINGS AND SERIES BLOCKS IN MODULE
  - CALCULATE FRACTION OF MODULES CONTAINING FAILURES ASSUMING 1 FAILED CELL PER 1000 AND GIVEN NUMBER OF CELLS PER MODULE
  - CALCULATE FRACTION OF MODULES WITH POWER DEGRADATION GREATER THAN ACCEPTABLE LEVEL (10%)

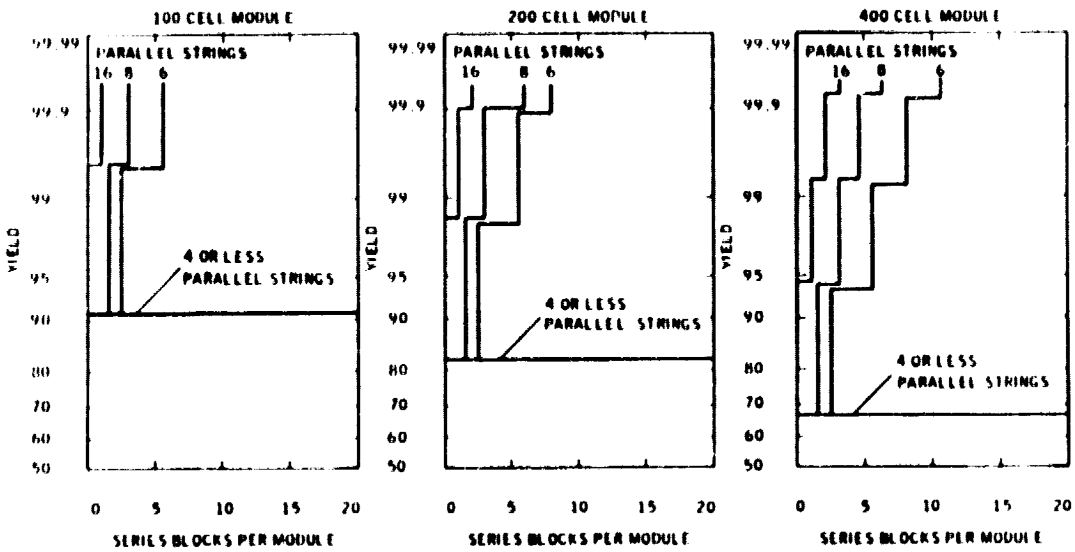
Module Power Loss vs Module Series/Paralleling

(1 TO 3 FAILED CELLS PER MODULE)



*1, 2, 4 PARALLEL STRINGS BASED ON 1 CELL FAILURE ONLY

Manufacturing Yield Due to Cell Breakage Vs Module Series/Paralleling



Manufacturing Yield Conclusions

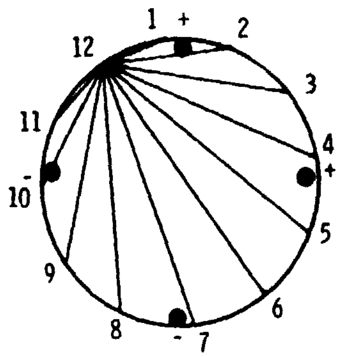
- FOR MODULES OF 100 CELLS OR LARGER WITH FOUR PARALLEL STRINGS, YIELD IS 90% OR LESS AND IS INDEPENDENT OF NUMBER OF SERIES BLOCKS
- FOR MODULES WITH 6 PARALLEL STRINGS, YIELD CAN BE INCREASED TO 99% BY ADDING UP TO 6 SERIES BLOCKS
- FOR MODULES WITH 8 OR MORE PARALLEL STRINGS YIELD CAN BE INCREASED TO 99% BY ADDING UP TO 3 SERIES BLOCKS

Techniques for Enhancement of Fault Tolerance

- MULTIPLE CELL CONTACTS
- SERIES/PARALLELING
- USE OF BYPASS DIODES

Multiple Cell Contacts

- PROBLEM STATEMENT
  - REDUCE CELL AREA LOSS DUE TO CRACKING
- APPROACH
  - INTRODUCE REDUNDANT CONTACTS TO REDUCE CELL AREA LOSS TO LESS THAN 10%
- ANALYTICAL PROCEDURE
  - DETERMINE AMOUNT OF CELL AREA LOST TO [illegible]CUIT
    - FOR DEFINED CRACK PATTERNS
    - FOR GIVEN CONTACT CONFIGURATIONS
  - SUM ALL CASES LEADING TO OPEN CELL OR HOT-SPOT FAILURE



Fraction of Cracked Cells Leading to Failed Cells For Various Multiple Cell Contacts

PERCENT LOSS OF CELL AREA	+ 0° −	+ + 60° − −	+ + 90° − −	+ -180°- +	− +	− + − + − +
0-5	.36	.42	.50	.64	.36	.91
5-10	.09	.15	.18	.18	.14	.09
10-20	.06	.12	.12	.12	.12	0
20-40	.03	.06	.06	.06	.11	0
40-70	0	0	0	0	.04	0
100	.45	.24	.14	0	.23	0
SUM OF ≥ 10	.54	.42	.32	.18	.50	0

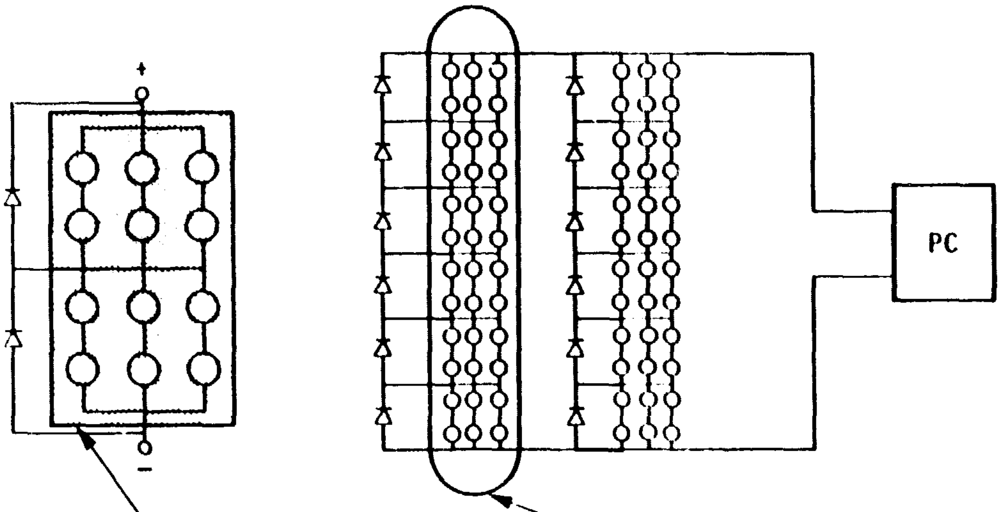
Multiple Cell Contact Conclusions

- SINGLE CONTACTS LEAD TO A 50% FAILURE RATE AMONG CRACKED CELLS
- USE OF DOUBLE TABS REDUCES FAILURE RATE BY 20%-60%, DEPENDING ON ORIENTATION
- USE OF TRIPLE TABS LEADS TO NEGLIGIBLE FAILURE RATE

Series/Paralleling/Diodes

- PROBLEM STATEMENT
  - REDUCE SYSTEM POWER DEGRADATION DUE TO CELL AND MODULE FAILURES
- APPROACH
  - INCREASE SYSTEM FAULT TOLERANCE BY PROVIDING REDUNDANT CURRENT PATHS
- ANALYTICAL PROCEDURE
  - CONDUCT PARAMETRIC ANALYSES TO DETERMINE FIELD POWER DEGRADATION FOR GIVEN LEVELS OF SERIES/PARALLELING/DIODES, PARAMETERS INCLUDE:
    - CELL FILL FACTOR AND SHUNT RESISTANCE
    - NUMBER OF PARALLEL STRINGS AND SERIES BLOCKS
    - NUMBER OF CELLS PER MODULE
    - NUMBER OF BYPASS DIODES
    - CELL FAILURE RATE
  - DETERMINE EXISTENCE OF HOT SPOT PROBLEMS

Series/Parallel Nomenclature



MODULE:
3 PARALLEL STRINGS
2 SERIES BLOCKS
2 CELLS PER SUBSTRING
2 DIODES PER MODULE

BRANCH CIRCUIT:
3 PARALLEL STRINGS
6 SERIES BLOCKS
2 CELLS PER SUBSTRING
1 DIODE PER SERIES BLOCK

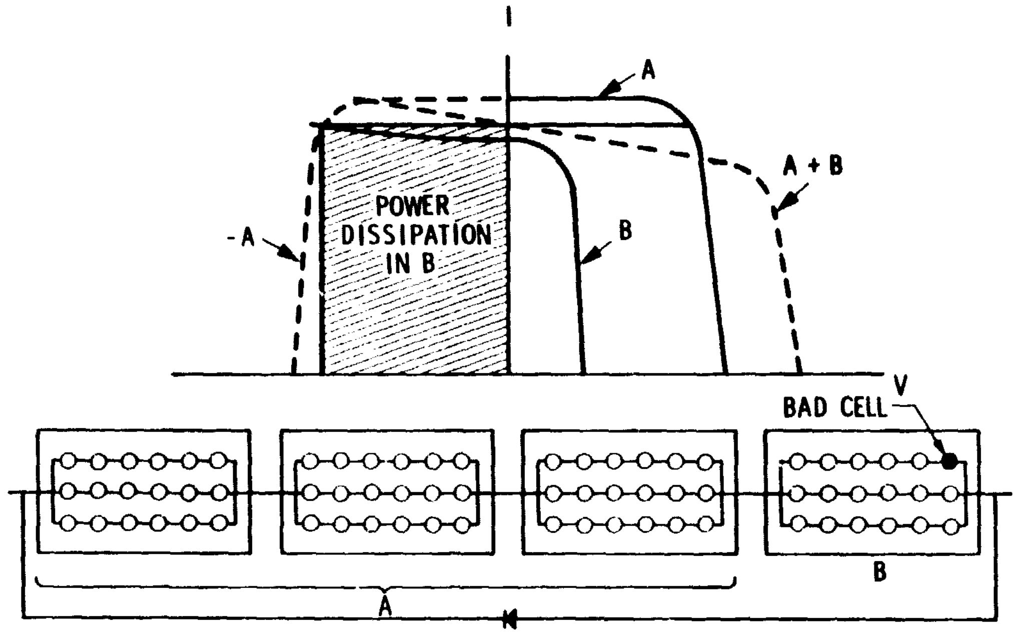
Technique for Determining System Power Degradation

- COMPUTE SUBSTRING FAILURE DENSITY (F_{SS}) FOR GIVEN SERIES/PARALLEL CONFIGURATION, CELL FAILURE DENSITY (F_C), AND NO. OF CELLS PER SUBSTRING (N) USING:

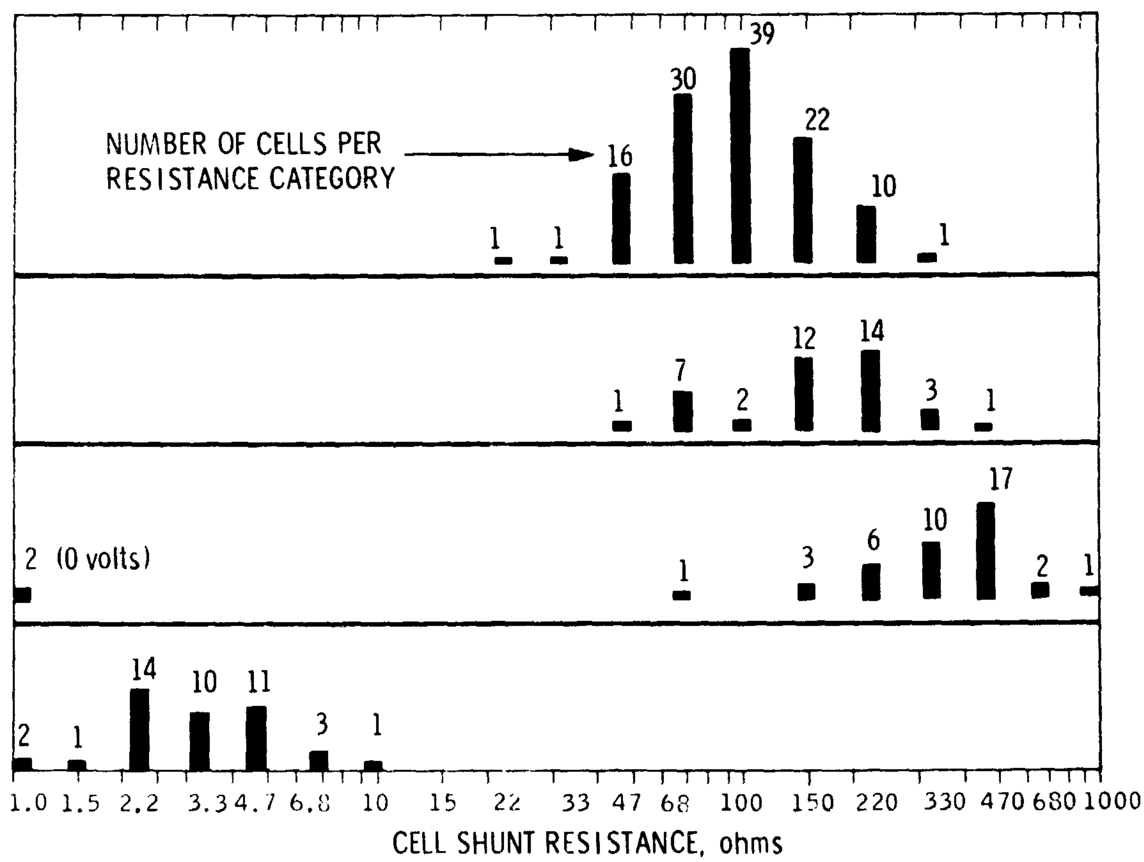
  $$F_{SS} = 1 - (1-F_C)^N$$

- DETERMINE FRACTION OF BRANCH CIRCUITS WITH GIVEN LEVELS OF FAILED SUBSTRINGS
- USE COMPUTER MODEL TO CALCULATE BRANCH CIRCUIT POWER LOSS BY COMBINING I-V CURVES OF:
  - FAILED ELEMENTS
  - UNFAILED ELEMENTS
- COMBINE POWER DEGRADATION OF BRANCH CIRCUITS TO OBTAIN SYSTEM DEGRADATION

Visualization of Hot-Spot Cell Heating

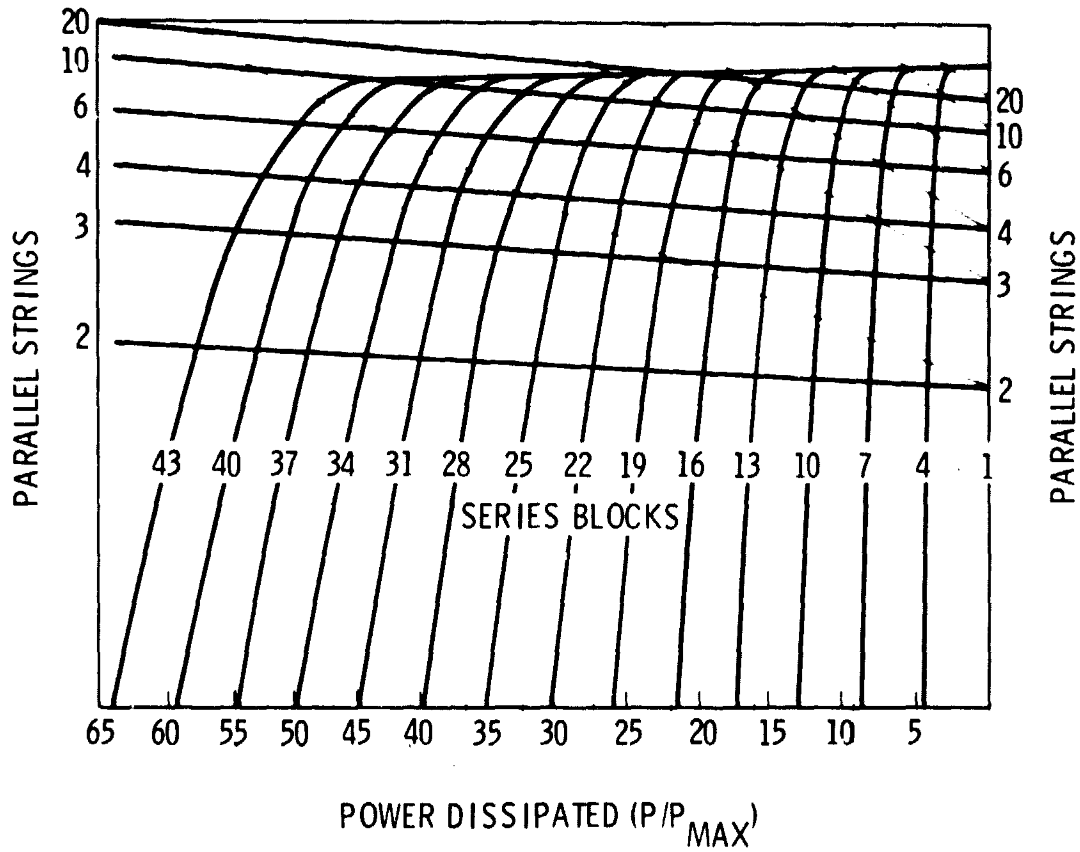


Cell Shunt Resistance



Effect of Series/Paralleling on Hot-Spot Cell Heating

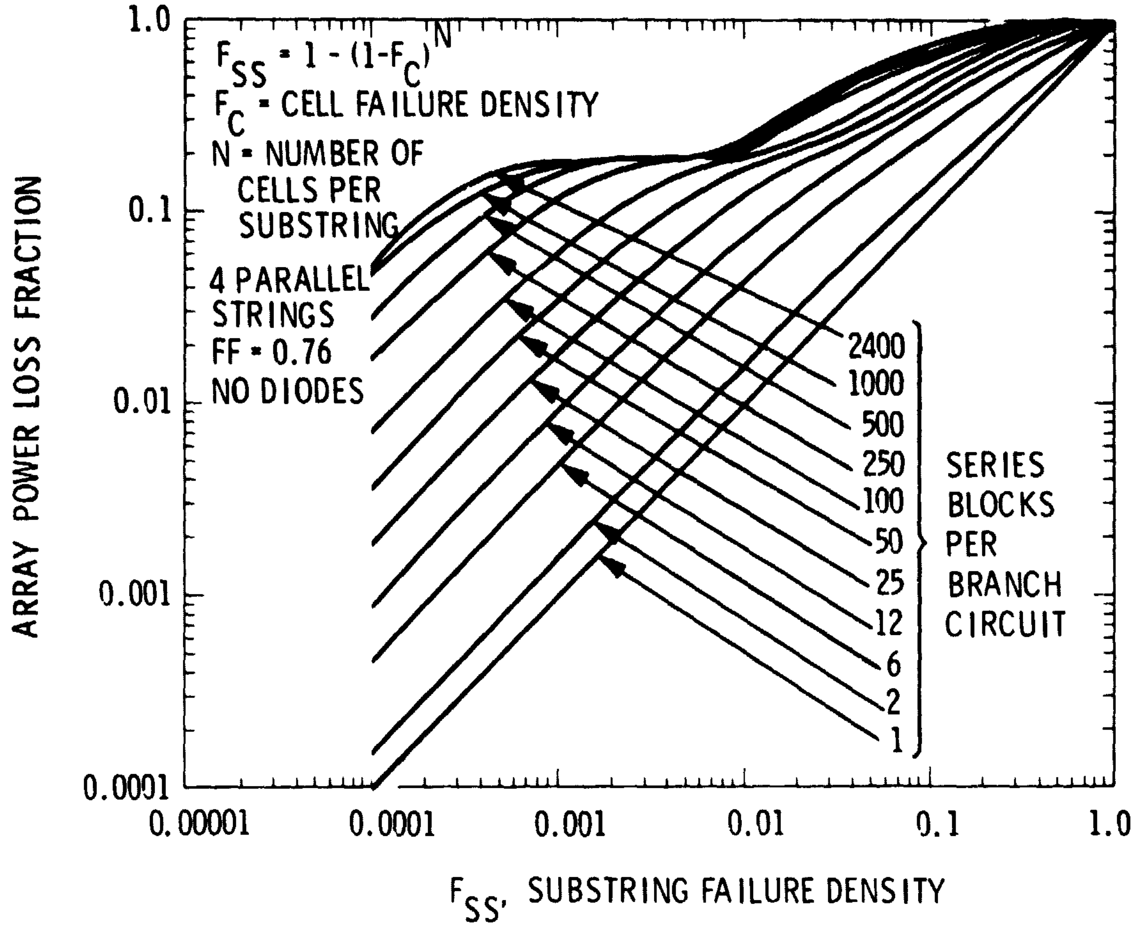
(SHUNT RESISTANCE = 100Ω)

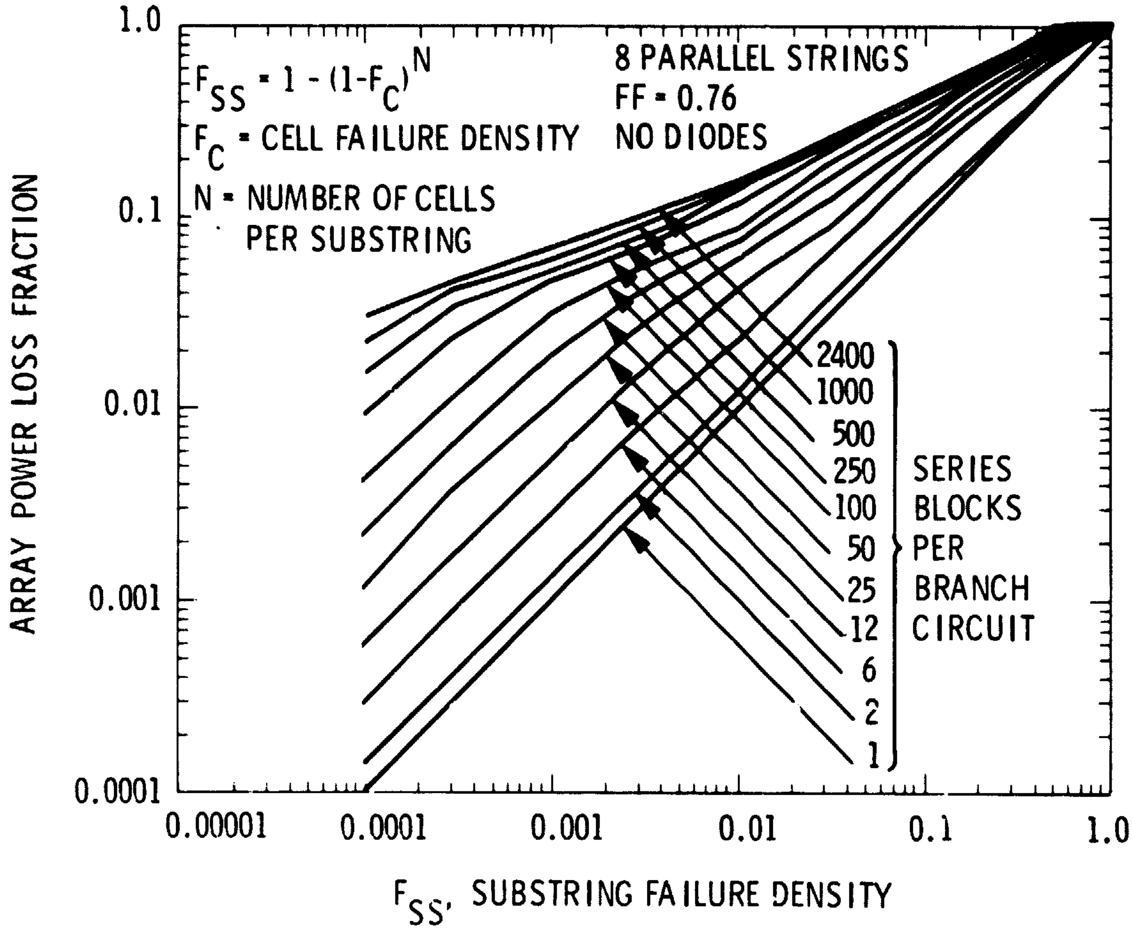


Example Problem

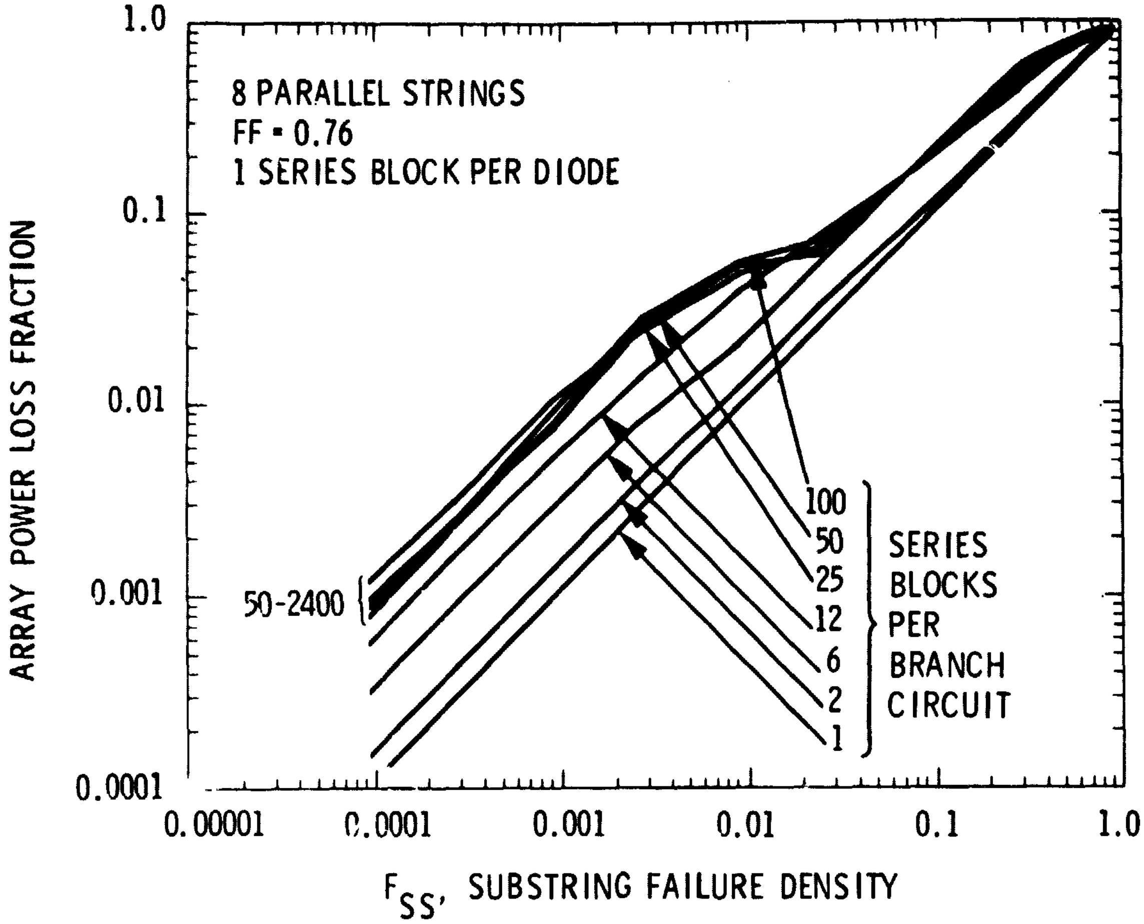
- PROBLEM STATEMENT - DETERMINE OPTIMUM CIRCUIT CONFIGURATION FOR ARRAY OF MODULES
- FIXED MODULE AND SYSTEM PARAMETERS
  - 40 CELL MODULE
  - 250 VOLT SYSTEM
- MODULE AND SYSTEM PARAMETER OPTIONS
  - 1, 4, 8 PARALLEL STRINGS PER MODULE
  - 0, 1, 2, 3, 4 BY-PASS DIODES PER MODULE
  - SINGLE, DOUBLE, AND TRIPLE CELL CONTACTS
  - 14, 56, 112 MODULES PER BRANCH CIRCUIT
  - 1, 4, 8 PARALLEL STRINGS PER BRANCH CIRCUIT
  - 1, 5 SERIES BLOCKS PER MODULE

Array Power Loss





$F_{SS} = 1 - (1-F_C)^N$
F_C = CELL FAILURE DENSITY
N = NUMBER OF CELLS PER SUBSTRING
8 PARALLEL STRINGS
FF = 0.76
NO DIODES
2400
1000
500
250
100
50
25
12
6
2
1
SERIES BLOCKS PER BRANCH CIRCUIT
ARRAY POWER LOSS FRACTION
1.0
0.1
0.01
0.001
0.0001
0.00001
0.0001
0.001
0.01
0.1
1.0
F_{SS}, SUBSTRING FAILURE DENSITY


8 PARALLEL STRINGS
FF = 0.76
1 SERIES BLOCK PER DIODE
1.0
0.1
0.01
0.001
0.0001
ARRAY POWER LOSS FRACTION
50-2400
100
50
25
12
6
2
1
SERIES BLOCKS PER BRANCH CIRCUIT
0.00001
0.0001
0.001
0.01
0.1
1.0
F_{SS}, SUBSTRING FAILURE DENSITY

System Power Loss for Solar-Power Options

MODULE S x P	CELL CONTACTS	PARALLEL CELLS/BC	SERIES BLOCKS PER BC	DIODES PER MODULE	CELLS PER DIODE	SYSTEM POWER LOSS, %	P/P MAX OPEN	P/P MAX CRACK	MANUFACT YIELD	MIS-MATCH
40 x 1		1	1	0	560	96	0	∞		
40 x 1		1	1	1	40	32	0	53		
40 x 1		1	1	2	20	16	0	26	96%	
40 x 1		1	1	4	10	$\boxed{7}$	$\boxed{0}$	$\boxed{12}$		
40 x 1		1	1	1	40	22	0	53		
40 x 1		1	1	1	40	14	0	53		
40 x 1		1	1	1	40	$\boxed{0}$	$\boxed{0}$	53	$\boxed{100\%}$	7.5%
40 x 1		4	14	0	560	65	16	∞		
40 x 1		4	14	1	40	35	0	53	96%	
40 x 1		8	14	0	560	40	15	∞		
40 x 1		8	14	1	40	35	0	53		
10 x 4		4	56	0	560	36	∞	∞		
10 x 4		4	56	1	10	22	0	12		7.0%
5 x 8		8	112	0	560	18	∞	∞		$\boxed{5.8\%}$
5 x 8		8	112	1	5	$\boxed{8}$	$\boxed{0}$	$\boxed{5}$		
5 x 8		8	560	1	5	$\boxed{5}$	$\boxed{5}$	$\boxed{5}$	$\boxed{100\%}$	$\boxed{3.7\%}$

Conclusions and Recommendations

- MULTIPLE CELL CONTACTS CONSIDERABLY REDUCE RISK OF FAILURE DUE TO CELL CRACKING
- USE OF BYPASS DIODES BEST CIRCUIT DESIGN TOOL TO REDUCE POWER LOSS AND HOT SPOT PROBLEMS
- PARALLELING OF CELL STRINGS WITHIN MODULES EFFECTIVE FOR REDUCING CELL MISMATCH AND MODULE YIELD LOSS
- USE OF INCREASED NUMBER OF SERIES BLOCKS CAN EXACERBATE HOT SPOT PROBLEM - SHOULD BE ACCOMPANIED BY USE OF BYPASS DIODES
- DETERMINATION OF POTENTIAL HOT SPOT PROBLEMS - SHOULD BE ACCOMPLISHED BY TESTING MODULES HAVING ARTIFICIALLY INDUCED HOT SPOTS
- NUMBER OF PARALLEL CELLS PER MODULE CAN BE CHOSEN TO GIVE PROPER POWER PER BRANCH CIRCUIT

MODULE AND ARRAY SAFETY

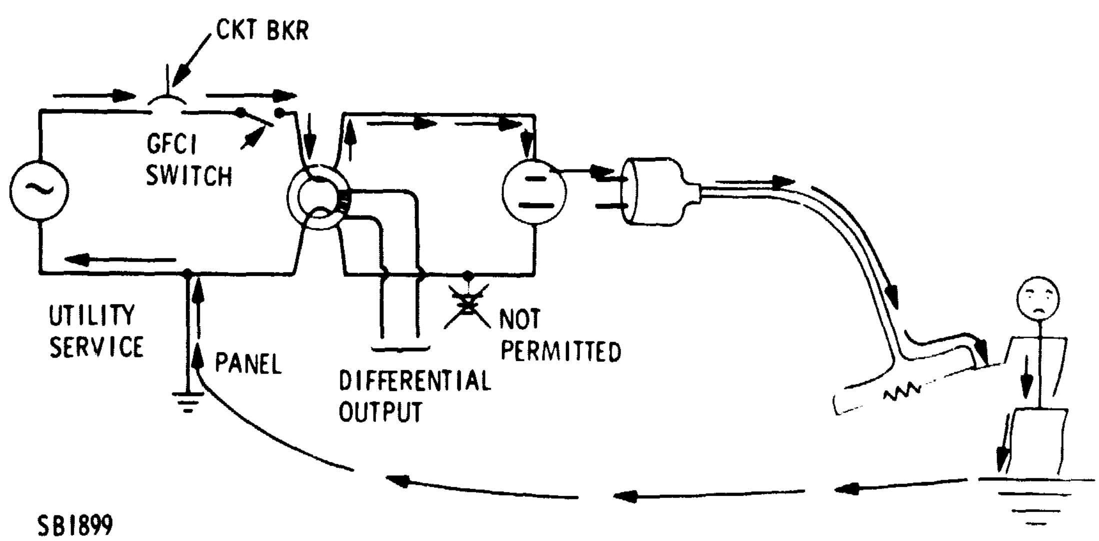
UNDERWRITERS LABORATORIES

A. Levins

Module and Array Safety Considerations

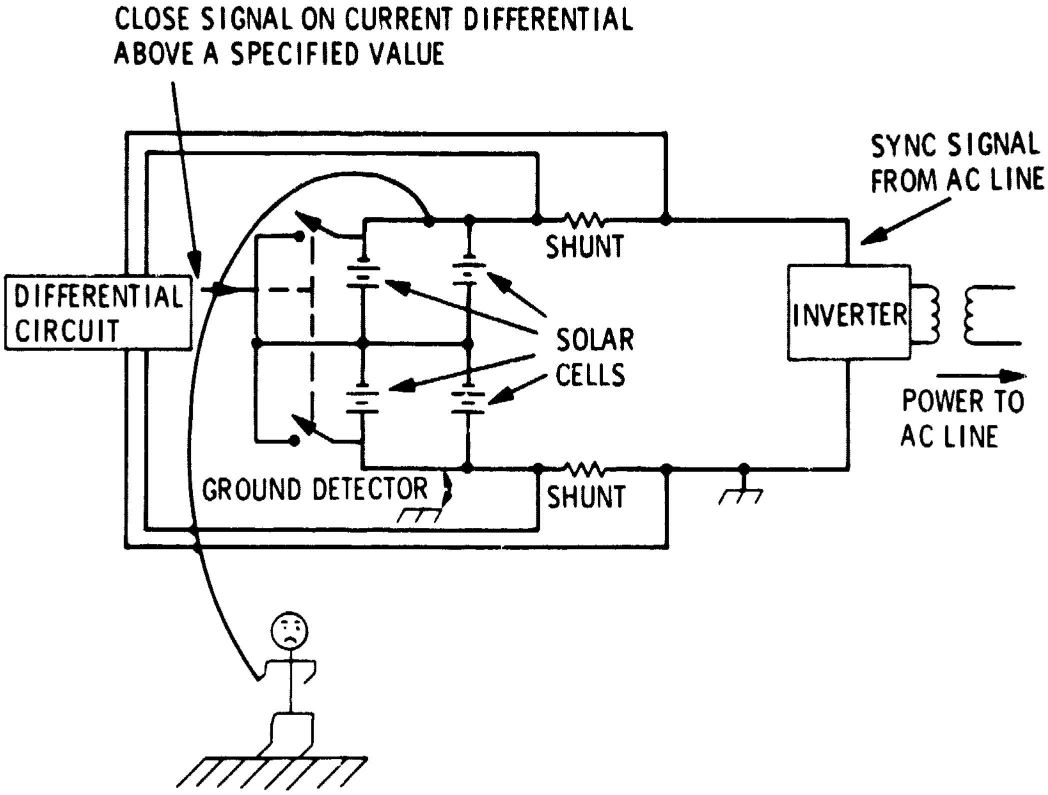
- NATIONAL ELECTRICAL CODE
- BUILDING CODES
- UL INTERFACE WITH CODES
- FIRE SAFETY
- POLYMERIC MATERIAL EVALUATION
- BURN HAZARD
- GROUND FAULT PROTECTION
- MODULE VOLTAGE/CURRENT LEVELS
- GROUNDING

Standard AC Ground-Fault Interrupter



SB1899

DC Ground-Fault Disabler



MODULE TERMINATION DESIGN

JET PROPULSION LABORATORY

Russ Sugimura

Constraints on Module Termination Design

(Based on Studies by Motorola,
Underwriters Laboratories, and
Burt Hill Kosar Rittelmann Assoc.)

- AMPACITY
- PROTECTION
- COST
- NATIONAL ELECTRIC CODE

Code Considerations

- NATIONAL ELECTRIC CODE
  - IMPACT: RESIDENTIAL AND INTERMEDIATE APPLICATION
  - APPROVAL

Protection and Cost Considerations

- PROTECTION OF THE TERMINATION
  - MOUNTING
  - SEALING
  - SAFETY

- COST: TOTAL COST OVER THE LIFE OF THE MODULE

$$\text{TOTAL COST} = \begin{pmatrix}\text{INITIAL}\\ \text{COSTS}\end{pmatrix} + \sum_{\substack{\text{MODULE}\\ \text{LIFE}}} \begin{pmatrix}\text{DISCOUNTED}\\ \text{MAINTENANCE \&}\\ \text{REPAIR COSTS}\end{pmatrix}$$

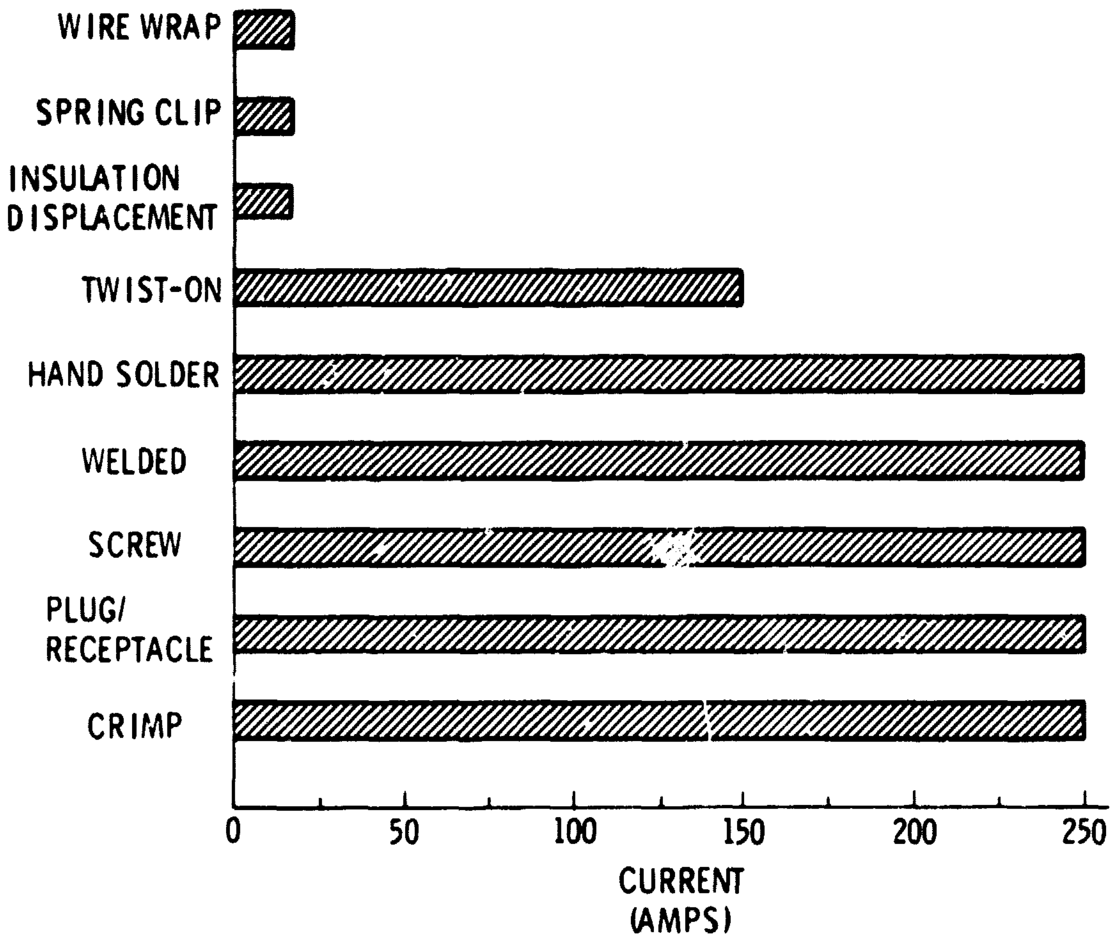
  - INITIAL COSTS
    - PARTS
    - FACTORY LABOR
    - FIELD LABOR
  - MAINTENANCE & REPAIR COSTS
    - FAILURE DETECTION
    - PARTS, SHIPPING
    - SHOP LABOR
    - FIELD LABOR
    - LOST ENERGY

Ampacity Constraints

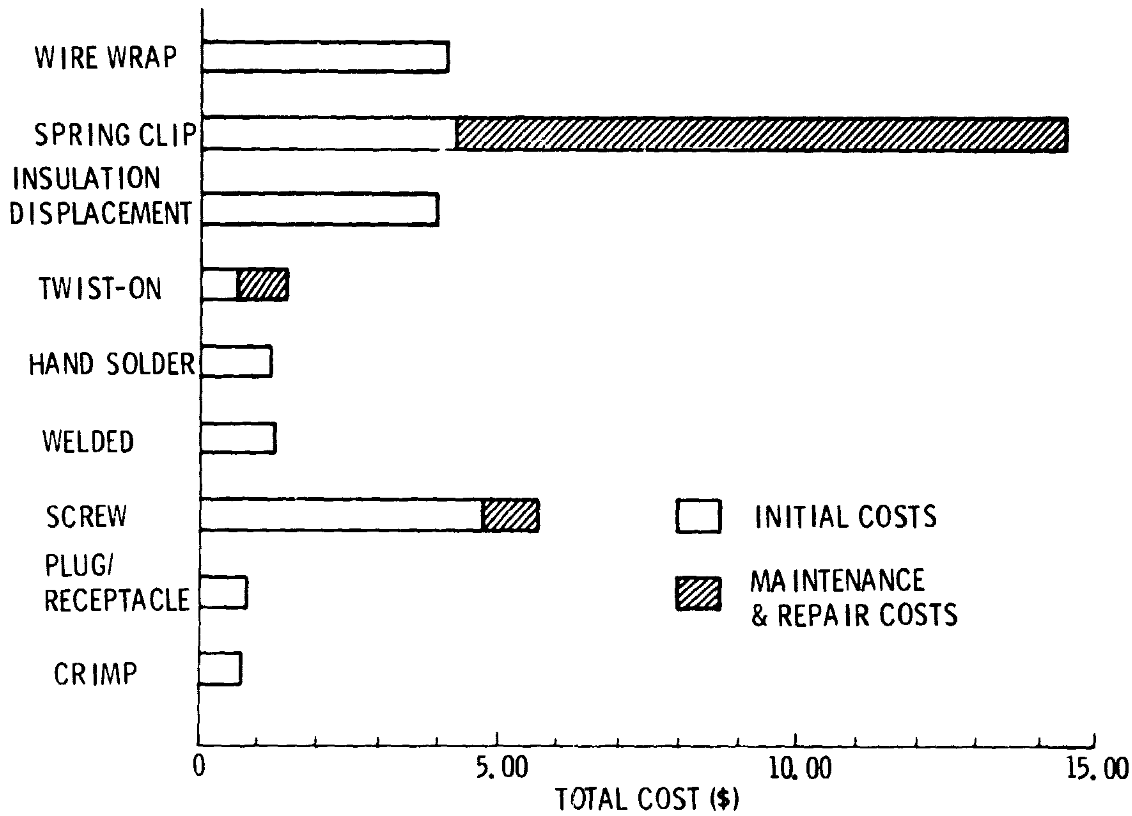
- AMPACITY IS CONSTRAINED BY
  - APPLICATION
  - MODULE VOLTAGE
  - INTERCONNECTION OF CELLS
  - MODULE SIZE

MODULE SIZE	POWER	MODULE CURRENT
1 x 2 FT	22 W_p	1-5A
2 x 4 FT	86 W_p	5-20A
4 x 4 FT	173 W_p	10-40A
4 x 8 FT	345 W_p	20-100A

Termination Choices vs Ampacity



Total Termination Cost



Conclusions and Recommendations

CONCLUSIONS

- MODULE TERMINATION SELECTION MUST CONSIDER:
  - SAFETY: MANUFACTURE / INSTALLATION / OPERATION / MAINTENANCE
  - AMPACITY: CONSTRAINED BY MODULE SIZE
  - TOTAL COST OVER THE LIFE OF THE MODULE
- MODULE TERMINATIONS MUST COMPLY WITH NEC REQUIREMENTS FOR RESIDENTIAL AND, MOST LIKELY, INTERMEDIATE APPLICATIONS

RECOMMENDATION

- MODULE MANUFACTURERS SHOULD BECOME FAMILIAR WITH GENERAL AND SPECIFIC ELECTRICAL REQUIREMENTS CURRENTLY ENFORCED BY THE NEC

MECHANICAL CONFIGURATION DESIGN GUIDELINES

JET PROPULSION LABORATORY

J.C. Arnett

Mechanical Configuration

- EFFICIENCY CONSIDERATIONS
- STRUCTURAL / SIZING
- THERMAL PERFORMANCE

Factors Influencing Module Configuration

- CELL SIZE/SHAPE
- CIRCUIT ARRANGEMENT (S/P)
- ENCAPSULATION MATERIALS
    - SUPERSTRATE
    - SUBSTRATE
- EFFICIENCY CONSIDERATIONS
- MOUNTING PROVISIONS/RESTRICTIONS
- INTERCHANGEABILITY/REPLACEMENT
- THERMAL PERFORMANCE
    - NOCT
    - HOT-SPOT RESISTANCE
- ENVIRONMENTAL CONSTRAINTS
- APPLICATION (USER) CONSTRAINTS

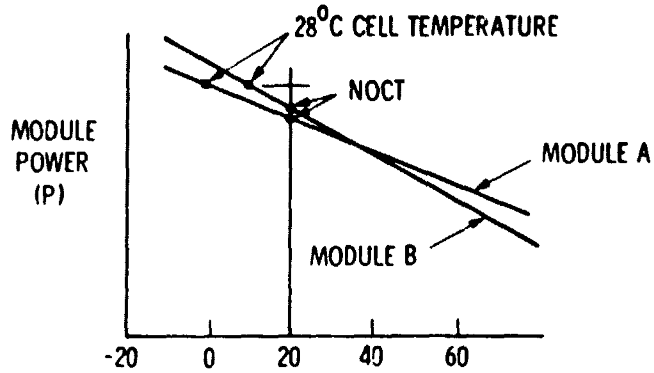
Cell-Related Factors

- NUMBER/MODULE
- SIZE
- SHAPE
  - CELL-TO-CELL SPACING
  - INTERCONNECT LOCATION
  - PACKING FACTOR
- CIRCUIT ARRANGEMENT
  - SERIES/PARALLEL RESTRICTIONS
  - DIODE PLACEMENT REQUIREMENTS
  - OUTPUT TERMINATION LOCATION
- AR COATINGS

Efficiency Considerations

- ENCAPSULANT MATERIAL INFLUENCE
- CHOICE OF AR COATINGS
- CELL OPERATING TEMPERATURE
- PACKING FACTOR AFFECTED BY:
  - CELLS / SIZE / SHAPE / SPACING
  - CELL NESTING
  - BORDER/MOUNTING AREA
  - SERIES/PARALLEL CIRCUIT ROUTING
  - LOCATION OF OUTPUT TERMINATIONS
- TRANSMISSION LOSSES OF FRONT SURFACE

Cell Operating Temperature Efficiency

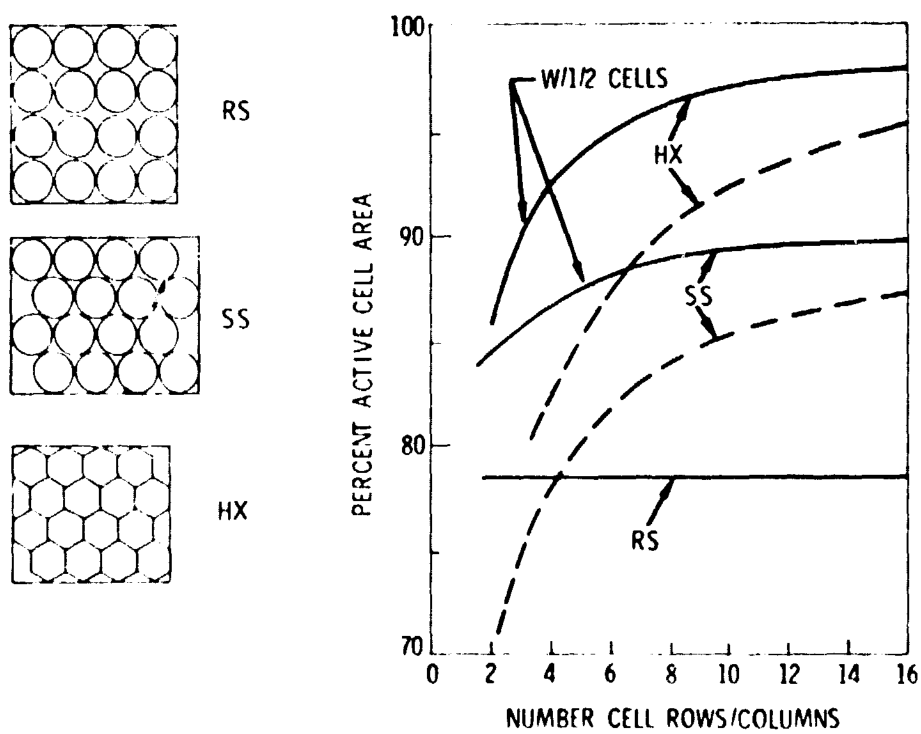


$$\eta_{NOCT} = \frac{P \text{ at NOCT}}{P \text{ at } 28^{\circ}C} = \boxed{1 - \frac{\frac{\Delta P}{\Delta T}(NOCT - 28)}{P \text{ at } 28^{\circ}C}}$$

where:

NOCT = NOMINAL OPERATING CELL TEMPERATURE
= CELL TEMPERATURE FOR:
80 mW/cm INSOLATION
20°C AIR TEMPERATURE
1 M/SEC WIND VELOCITY
OPEN BACK SIDE

Module Cell Packing Efficiency



Near-Term Efficiency Goals

ENCAPSULATED CELL	12%	
NOMINAL OPERATING CELL TEMP	97%	
BORDER	96%	86%
BUS	99%	
INTERCONNECT	98%	
NESTING	92%	

MODULE EFFICIENCY $= \eta_{EC} \times \eta_{NOCT} \times \eta_{p}$

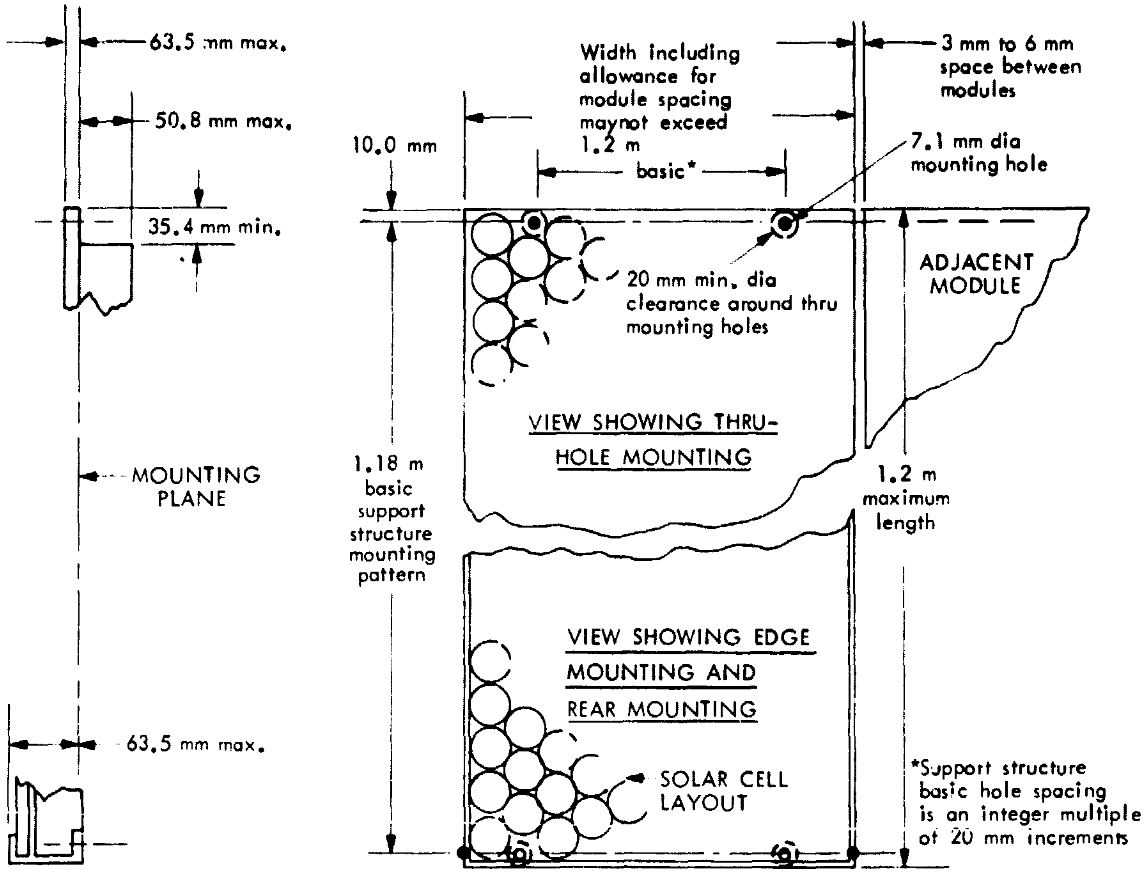
$= 12\% \times 97\% \times 86\% = 10\%$ GOAL

$= 11\% \times 96\% \times 85\% = 9\%$ MIN

Structural and Sizing Considerations

- STANDARDIZED MOUNTING INTERFACES COMPATIBLE WITH VARIETY OF ASSEMBLY / SUPPORT ARRANGEMENTS
- SUBSTRATE / SUPERSTRATE THICKNESS OPTIMIZED FOR LOADING
- LARGER CELLS DICTATE LARGER MODULES TO SATISFY VOLTAGE, SERIES / PARALLEL CONSTRAINTS
- LARGER MODULES MINIMIZE BORDER / BUS AREAS
- INTEGRATED MODULE / ARRAY SUPPORT STRUCTURE

Module Configuration Requirement



NOCT Specification

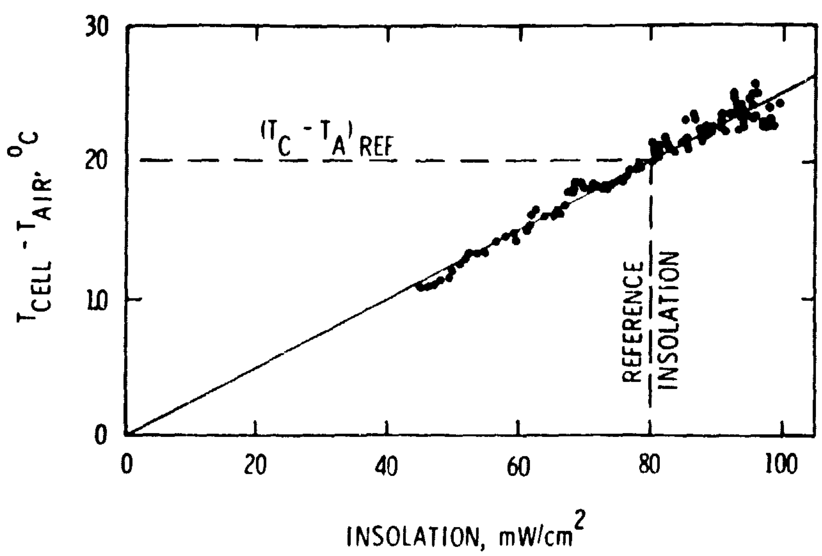
- **OBJECTIVE:**
  - TO ALLOW THE ELECTRICAL PERFORMANCE OF MODULES OF VARIOUS THERMAL DESIGNS TO BE SPECIFIED AND COMPARED AT AN OPERATING POINT REPRESENTATIVE OF TYPICAL FIELD OPERATING CONDITIONS

- **APPROACH:**
  - SPECIFY ELECTRICAL PERFORMANCE AT A CELL TEMPERATURE (NOCT) WHICH REFLECTS THE MEASURED CELL OPERATING TEMPERATURE IN THE NOMINAL TERRESTRIAL ENVIRONMENT:

    AIR TEMPERATURE = 20°C
    WIND VELOCITY = 1 m/s
    INSOLATION = 80 mW/cm^2
    MOUNTING = OPEN BACK, TILTED

NOCT Measurement Procedure

- MEASURE $T_{CELL} - T_{AIR}$ VERSUS INSOLATION LEVEL



- INTERPOLATE $(T_C - T_A)_{REF}$ VALUE FOR REFERENCE INSOLATION LEVEL
- CALCULATE NOCT $(T_C - T_A)_{REF}$ + REFERENCE AIR TEMP.

Thermal Test Summary

CONDITION	ΔNOCT
ROOF MOUNT (INSULATED REAR SIDE)	+4°C
MAX. POWER OUT (vs OPEN CIRCUIT)	-3°C
DIRTY MODULE (vs CLEAN)	+2°C
FINS (vs NO FINS)	-3°C

Typical Values for NOCT

MODULE CONSTRUCTION	NOCT (°C)
FINNED ALUMINUM SUBSTRATE	40
CLEAR GLASS SUBSTRATE	41
ALUMINUM SUBSTRATE (NO FINS)	43
FIBERGLASS/PLASTIC SUBSTRATE	47
DOUBLE PANE WITH AIR GAP	60

$$T_{CELL} = T_{AIR} + \frac{(NOCT-20)}{80} S, \ ^\circ C$$

$$S = \text{INSOLATION}, \ {}^{mw}/_{cm^2}$$

Thermal Performance

- LOWER NOCT LEADS TO:
  - INCREASED MODULE EFFICIENCY
  - EXTENDED ENCAPSULANT MATERIAL LIFETIME
  - REDUCED BACKGROUND TEMP IN HOT SPOTS
  - REDUCED PERSONNEL BURN HAZARD
- NOCT AFFECTED BY:
  - ENCAPSULATION MATERIAL SELECTION
  - SUB/SUPERSTRATE GEOMETRY, THICKNESS
  - MOUNTING PROVISIONS
  - SOILING

Application (User) Constraints

- SPECIALIZED SUPPORT STRUCTURES
- FIELD CABLE ROUTING
- FIELD MAINTENANCE/REPAIR
- MAXIMUM SIZE FOR HANDLING
- INVENTORY/SPARES POLICY
- INTERCHANGEABILITY/REPLACEMENT

Mechanical Design Recommendations

- CLOSE-PACKED, SHAPED CELLS
- END-TO-END CIRCUIT RUNS
- MINIMIZE BORDER AREA
- HIGH-TRANSMISSION OPTICAL SURFACES
- STANDARD MOUNTING INTERFACES
- LONG-LIFE, HIGHER TEMP ENCAPSULANTS
- REDUCE NOCT
- SIMPLE CABLING INTERFACES
- OPTIMIZE STRUCTURE FOR EXPECTED LOADS
- LARGEST MODULES WITHIN MANUFACTURING, ASSEMBLY, YIELD CONSTRAINTS

MODULE STRUCTURAL DESIGN

JET PROPULSION LABORATORY

D. Moore

Module Structural Considerations

UNIFORM NORMAL PRESSURE LOADS (ANSI A58.1 - 1972)
- WIND
- EARTHQUAKE
- SNOW
- ICE
- DEADWEIGHT

CONSTRAINT LOADS
- FOUNDATION SETTLEMENT (NON-PLANAR MOUNTING SURFACES)
- THERMAL EXPANSION/CONTRACTION

IMPACT/HANDLING LOADS
- HAIL IMPACT
- TRANSPORTATION
- HANDLING
- INSTALLATION

Uniform Normal Pressure Loads

WIND LOAD

- SHORT TIME DURATION
- HIGH LOCAL PRESSURES
  - ARRAY STRUCTURE 20-30 lb/ft^2
  - MODULE 50 lb/ft^2

GLASS THICKNESS SIZING METHOD

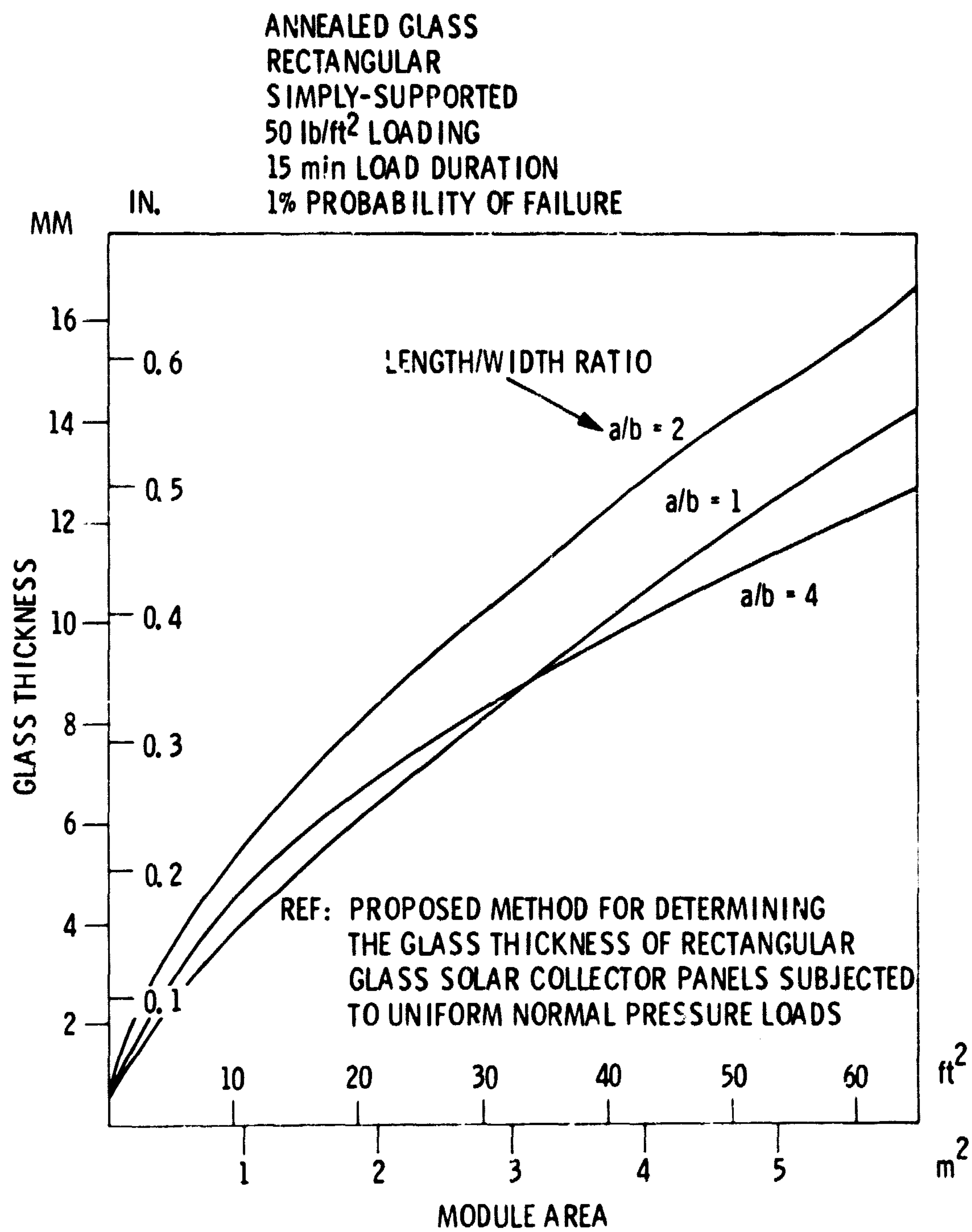
DETERMINE GLASS THICKNESS FOR

- SIMPLY SUPPORTED RECTANGULAR PLATES
- UNIFORM NORMAL PRESSURE LOADS
- GLASS TYPE - ANNEALED, TEMPERED
- PROBABILITY OF FAILURE

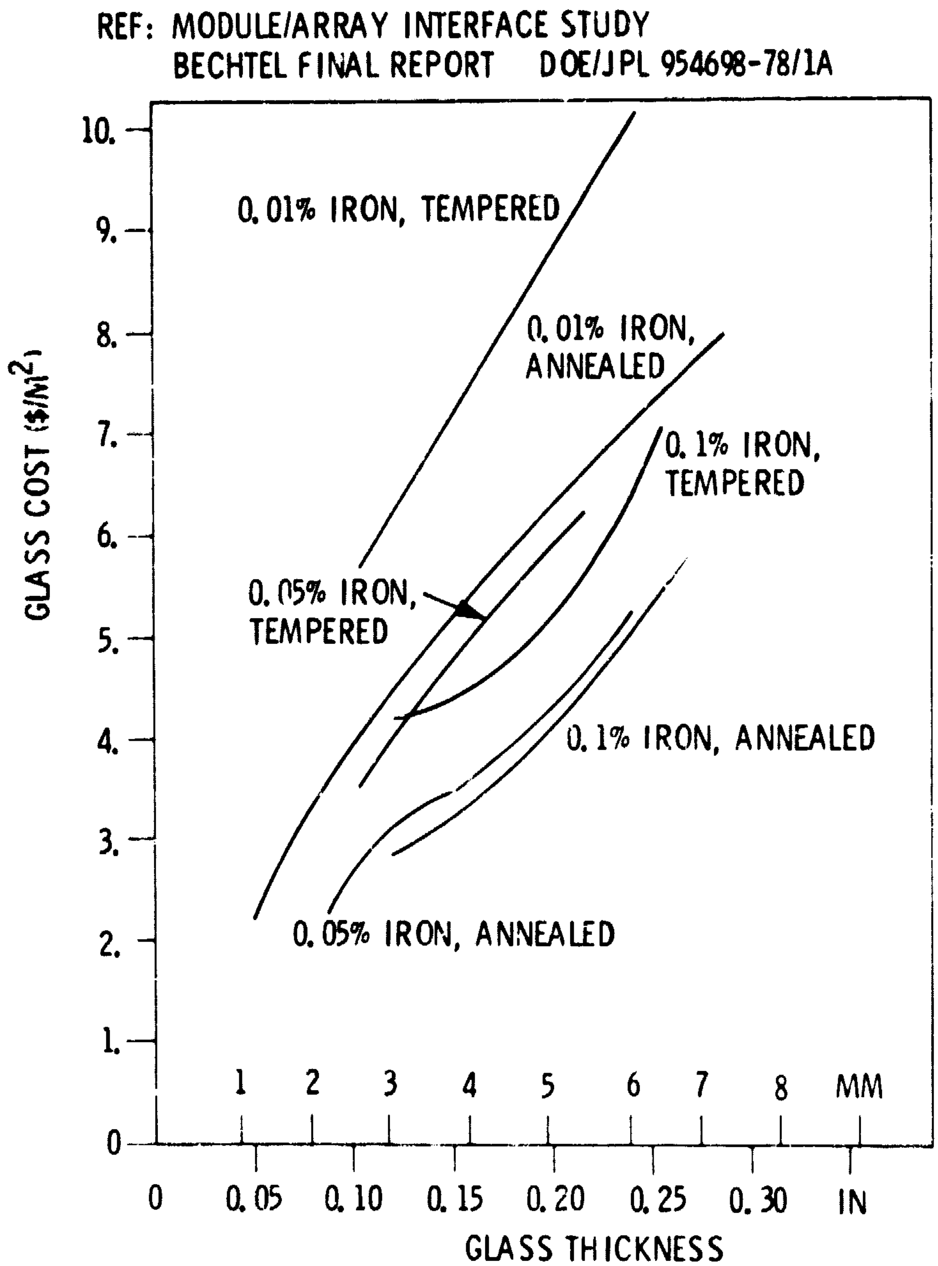
SAMPLE PROBLEM

- 1-m SQUARE PLATE
- 50 lb/ft^2 LOADING FOR 15 MIN
- 1% PROBABILITY OF FAILURE
- ANNEALED GLASS
- REQUIRED THICKNESS = 0.155 in.

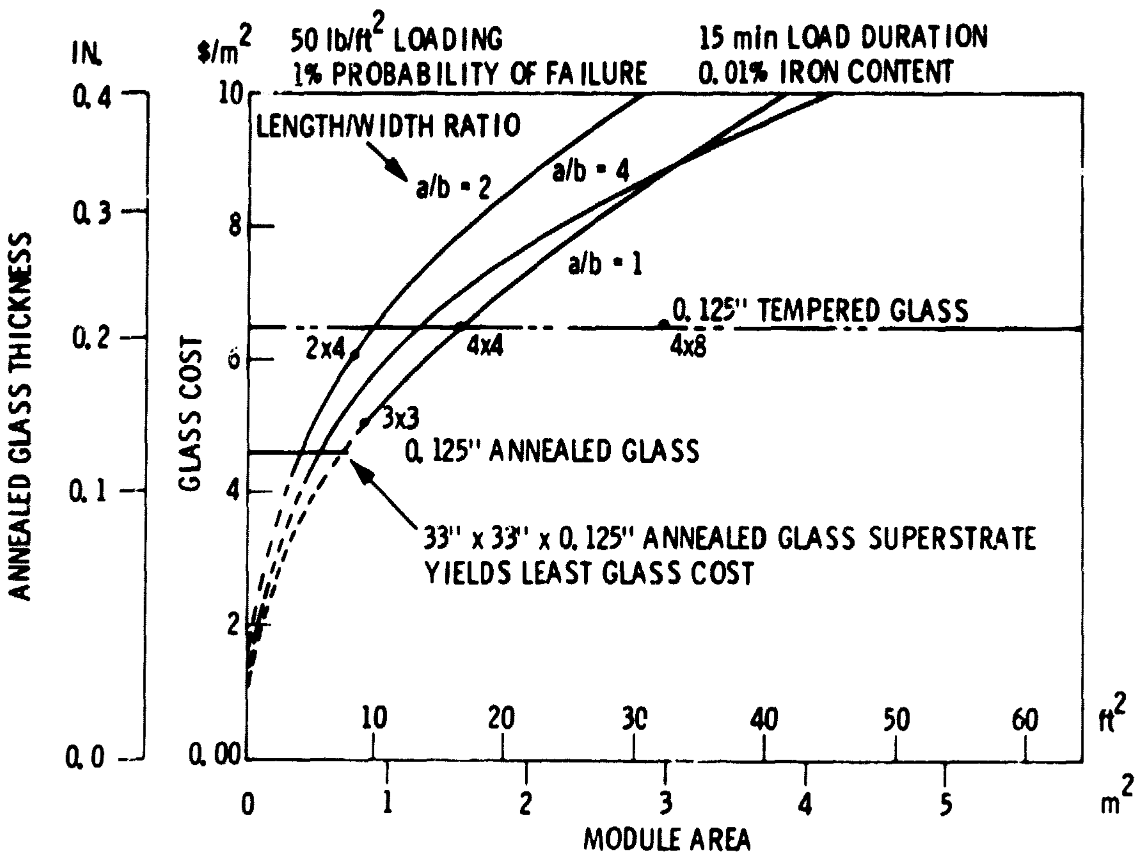
Glass Cost vs Module Area



Glass Cost Data



Glass Thickness vs Module Area



Constraint Loads

MOUNTING INDUCED LOADS

- WARPED MOUNTING SURFACES
- HANDLING LOADS

THERMAL LOADS

- DIFFERENTIAL THERMAL EXPANSION
  - INTERCONNECT STRESS
  - MODULE STRUCTURAL COMPONENTS
- LOCAL "HOT SPOTS"
  - BACK-BIASED CELLS
  - STRESS IN GLASS SUPERSTRATE (80 psi/°C)

Impact Criteria

TRANSPORTATION, HANDLING & INSTALLATION
- TO BE CONSIDERED
- PARTLY COVERED BY MINIMUM HAIL REQUIREMENTS

HAIL IMPACT RESISTANCE (LARGER OF)
- 1 in. dia SIMULATED HAILSTONE @ 52 mph
- dia. DEPENDENT ON GEOGRAPHIC LOCATION OF PHOTOVOLTAIC MODULE INSTALLATION

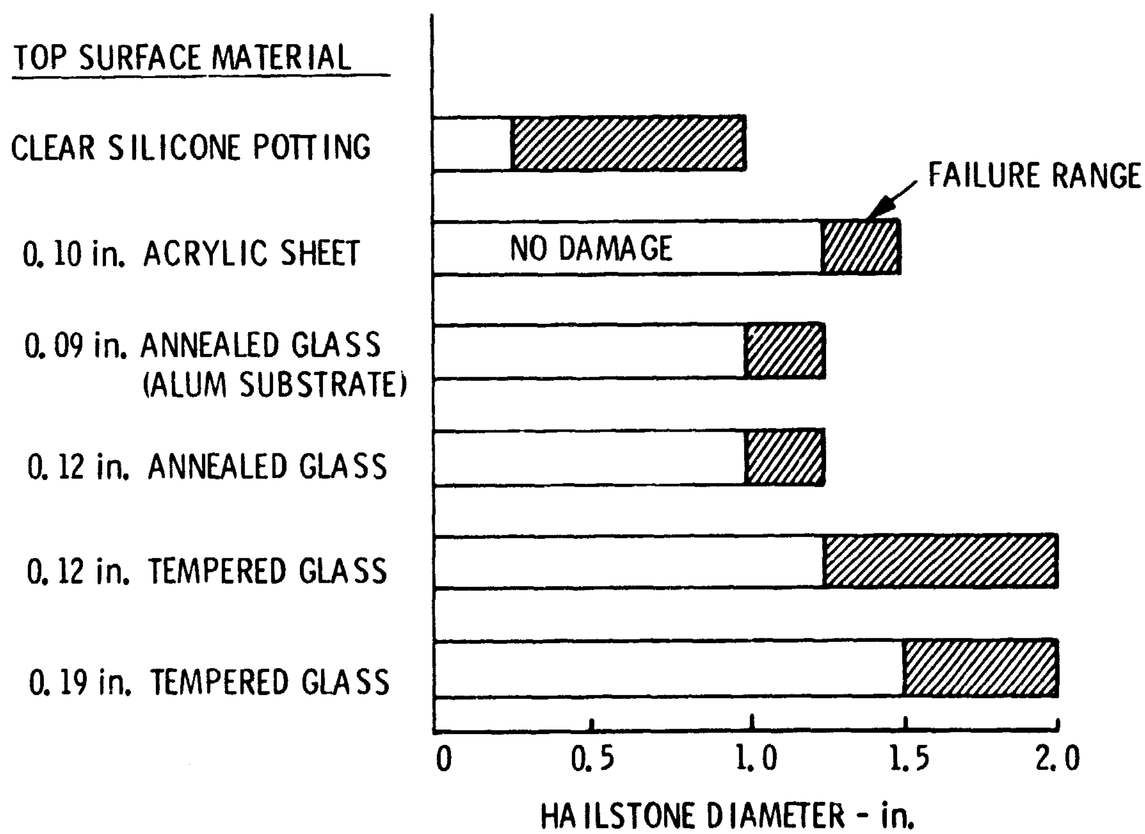
$$\text{dia} = 0.3 \left(\begin{array}{l}\text{AVERAGE NO. OF HAIL DAYS} \\ \text{PER YEAR - FROM HUD}^{*}\end{array}\right)$$

VELOCITY = FREE FALL TERMINAL VELOCITY IN STILL AIR

* "HUD INTERMEDIATE MINIMUM PROPERTY STANDARDS SUPPLEMENT FOR SOLAR HEATING AND DOMESTIC HOT WATER SYSTEMS", DOCUMENT NO. 4930.2, VOL. 5, HUD, 1977.

Hail Impact Resistance

REF: PHOTOVOLTAIC SOLAR PANEL RESISTANCE TO HAIL
LSA TASK REPORT 5101-62, DOE/JPL-1012-78/6



C-6

ENVIRONMENTAL REQUIREMENTS

JET PROPULSION LABORATORY

Alan R. Hoffman

Hail-Resistant Design

FAILURE MECHANISM
- LOCAL BENDING AT POINT OF IMPACT
- TENSION FAILURES ON REVERSE SIDE

GLASS SUPERSTRATE
- FAILURES AT EDGES
- EDGES WELL SUPPORTED
- SMOOTH EDGES

POLYMERIC ENCAPSULANT
- CELL FAILURE
- UNIFORM, FIRM SUPPORT
  - MINIMUM SOLDER BUILDUP ON CELLS
  - SMOOTH SUBSTRATE
  - MINIMUM CELL/SUBSTRATE GAP

Environmental Qualification Testing

- OBJECTIVE:
  - DISCOVER POTENTIAL FIELD-FAILURE MODES AND MECHANISMS TO ALLOW FOR THEIR ASSESSMENT AND CORRECTION
- APPROACH:
  - SUBJECT MODULES TO CAREFULLY CHOSEN ENVIRONMENTS WITH KNOWN IMPORTANCE
- PHILOSOPHY:
  - MINIMUM TEST COMPLEXITY TO REDUCE COST
  - MAXIMUM TEST STABILITY ALLOW CORRELATION AND COMPARISON

Module Environmental Testing Categories
For Manufacturers and Users

- MODULE DEVELOPMENT AND CHARACTERIZATION
  - EXPLORATORY
  - DESIGN OPTIMIZATION
  - PRE-QUALIFICATION
- MODULE DESIGN/WORKMANSHIP VERIFICATION
  - QUALIFICATION (+ APPLICATION DEPENDENT)
  - SAFETY (+ APPLICATION DEPENDENT)
  - IN-PROCESS VERIFICATION
  - ACCEPTANCE
- MODULE LIFE PREDICTION
  - FIELD
  - LABORATORY

Key Failure Modes and Mechanisms

- ELECTRICAL INTERCONNECT BREAKAGE
  - THERMAL CYCLING
  - WIND LOADING (CYCLIC PRESSURE LOADING, WIND RESISTANCE)
- SOLAR CELL CRACKING
  - THERMAL CYCLING
  - HAIL IMPACT
- ENCAPSULANT DELAMINATION AND CRACKING
  - THERMAL CYCLING
  - HUMIDITY
  - ULTRAVIOLET
- CORROSION (CELL METALLIZATION, WIRE, TERMINAL)
  - HUMIDITY
- ELECTRICAL INSULATION BREAKDOWN
- OPTICAL SURFACE SOILING

Temperature Cycling Requirement

- OBJECTIVE:

  TO VERIFY ABILITY OF MODULE TO WITHSTAND THERMAL STRESS CAUSED BY DIURNAL AND CLIMATIC VARIATIONS

- APPROACH:
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - MODULE MOUNTED IN TEST FRAME SIMULATING FIELD SUPPORT
  - 50 TEMPERATURE CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- SUSCEPTIBLE PARTS:
  - ENCAPSULANT SYSTEM
  - BONDING MATERIALS
  - CELLS
  - INTERCONNECTS

Humidity Cycling Requirement

- OBJECTIVE:

  TO VERIFY ABILITY OF MODULE TO TOLERATE EXPOSURE TO MOISTURE DURING SERVICE

- APPROACH:
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - 5 HUMIDITY CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- SUSCEPTIBLE PARTS:
  - ENCAPSULANT SYSTEM
  - BONDING MATERIALS
  - CELL METALLIZATION
  - INTERCONNECTS

Cyclic Pressure Loading Requirement

- OBJECTIVE:

  TO VERIFY ABILITY OF MODULE TO WITHSTAND PRESSURE LOADS (±) CAUSED BY WIND GUSTING

- APPROACH:
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - 10,000 PRESSURE CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- SUSCEPTIBLE PARTS
  - CELL INTERCONNECTS
  - CELLS
  - ENCAPSULANT SYSTEM

Twisted Mounting Surface Requirement

- OBJECTIVE:

  TO ASSURE THAT MODULE CAN FUNCTION UNDER SUSTAINED DISTORTION CAUSED BY MOUNTING ON NON-PLANAR STRUCTURE

- APPROACH:
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - MODULE MOUNTED TO FLAT SURFACE
  - SURFACE TWISTED 20 mm/m

- SUSCEPTIBLE PARTS:
  - CELLS
  - INTERCONNECTS
  - ENCAPSULANT SYSTEM

Hail Impact Requirement

- OBJECTIVE:

  TO VERIFY ABILITY OF MODULE TO WITHSTAND HAIL IMPACT FOR EXPECTED ARRAY APPLICATIONS

- APPROACH:

  - EXPLORATORY TESTING OF SAMPLE MODULE(s) TO DETERMINE IMPACT-SENSITIVE LOCATIONS
  - 10 IMPACTS
    - 25.4mm (1 in) ICE BALL
    - 23.2m/sec (52 mph)
  - POST-IMPACT INSPECTION/PERFORMANCE

- SUSCEPTIBLE PARTS:

  - CELLS (ESPECIALLY EDGES NEAR ELECTRICAL CONTACTS)
  - ENCAPSULANT SYSTEM (CORNERS AND EDGES, POINTS OF SUPERSTRATE SUPPORT, POINTS OF MAXIMUM DISTANCE FROM SUPERSTRATE SUPPORT)

Wind Resistance Requirement

- OBJECTIVE:

  TO VERIFY ABILITY OF SHINGLE MODULES TO WITHSTAND AERODYNAMIC LIFT CAUSED BY WINDS

- APPROACH:

  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - LIFT FORCE 1.7 kPa (35 lb/ft^2)
  - POST-TEST INSPECTION/PERFORMANCE

- SUSCEPTIBLE PARTS

  - CELL INTERCONNECTS
  - CELLS
  - ENCAPSULANT SYSTEM

Salt Fog Requirement

APPLICATION DEPENDENT

- OBJECTIVE:

  TO VERIFY MODULE TOLERANCE OF SALT-LADEN ENVIRONMENT AT MARINE SITES

- APPROACH:
  - 48-h EXPOSURE
  - POST-TEST INSPECTION PERFORMANCE

- SUSCEPTIBLE PARTS:
  - MODULE FRAME
  - WIRING

Module Environmental Test Levels For 1982 Technical Readiness

• TEMPERATURE CYCLING:	-40 TO $+90^{\circ}$C, 100°C/h, 50 cycles
• HUMIDITY CYCLING:	MIL-STD-810C, 507.1, V
• CYCLIC PRESSURE LOADING:	$\pm$ 2400 pascals ($\pm$50 lb/ft^2), 10,000 cycles
• TWISTED MOUNTING SURFACE:	$\pm$2 cm/m ($\pm$0.25 in/ft)
• HAIL IMPACT:	10 HITS ON MODULE, BY 2.54cm (1 in) ICE BALL
• WIND RESISTANCE (SHINGLE MODULES)	UNDERWRITERS LAB STANDARD 997

ENCAPSULATION MATERIALS SELECTION AND PROCESSING

STATUS OF MATERIALS, MATERIALS DEVELOPMENT AND ENCAPSULATION PROCESSES

JET PROPULSION LABORATORY

E.F. Cuddihy

Encapsulation Requirements

● OUTDOOR LIFE	20 YEARS
● OPTICAL TRANSMISSION TO SOLAR CELLS	> 90% OF INCIDENT
● MODULE POWER DECREASE AFTER 20 YEARS	> 50% OF INITIAL
● PROCESSING AND FABRICATION	AUTOMATED
● STRUCTURAL PERFORMANCE (INCLUDING HANDLING AND WEATHERING)	NO FAILURES

1986 Encapsulation Cost Goals

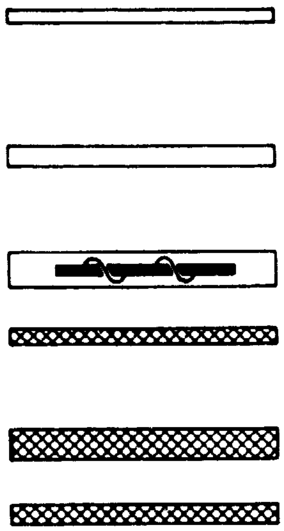
$<$ \$14.00/m^2 (\$1.40/ft^2)

INCLUDING FRAME CONFIGURATION COMPATIBLE WITH

OUTDOOR RACK MOUNTING REQUIREMENTS

(1980 Dollars)

Generalized Flat-Module Design



MODULE SUNSIDE	LAYER DESIGNATION	FUNCTION
	SURFACE 1) MATERIAL 2) MODIFICATION	● LOW SOILING ● EASY CLEANABILITY ● ABRASION RESISTANT ● ANTIREFLECTIVE
	TOP COVER	● UV SCREENING ● STRUCTURAL SUPERSTRATE
	POTTANT	● SOLAR CELL ENCAPSULATION
	SPACER	● ELECTRICAL ISOLATION ● MECHANICAL SEPARATION
	SUBSTRATE	● STRUCTURAL SUPPORT
	BACK COVER	● BACKSIDE MECHANICAL PROTECTION ● BACKSIDE WEATHERING BARRIER

Known Weatherable and Transparent Commercial Materials

MATERIAL	EXAMPLE	APPLICATION
● GLASS	● LOW-IRON GLASS	● TOP COVER/SUPERSTRATE
● ACRYLICS	● PLEXIGLAS, LUCITE	● TOP COVER/SUPERSTRATE
● SILICONES	● SYLGARD 184, RTV 615, GEL ● QR-4-3117 RESIN	● POTTANT (CASTABLE) ● TOP COVER (SPRAY)
● FLUOROCARBONS	● TEDLAR	● TOP COVER/BACK COVER

Other Encapsulation Materials Used Industrially

MATERIAL	APPLICATION
POLYVINYL BUTYRAL	LAMINATION POTTANT
ALUMINUM	SUBSTRATE
NEMA-G10	SUBSTRATE
GLASS-REINFORCED POLYESTER	SUBSTRATE
PORCELAINIZED STEEL	SUBSTRATE
MYLAR	BACK COVER

Encapsulation Materials Identified, Developed, Or Under Development by Task III

TOP COVERS (WITH UV SCREENING)

- KORAD 212
- TEDLAR 100-BG-30-UT
- SILICONE/ACRYLIC COPOLYMER

SPACER

- NON-WOVEN GLASS MATS

SUBSTRATE PANELS

- HARDBOARDS
- STRANDBOARDS
- MILD STEEL (INCL. GALV.)
- GLASS REINFORCED CONCRETE

POTTANTS

- ETHYLENE VINYL ACETATE (EVA)
- ETHYLENE PROPYLENE RUBBER
- POLY-n-BUTYL ACRYLATE
- POLYVINYL CHLORIDE PLASTISOL
- POLYURETHANE
- SILICONE ELASTOMER
- Q1-2577 SILICONE RESIN
- SILICONE/ACRYLIC COPOLYMER

BACK COVERS

- POLYMER FILMS (KORAD)
- METAL FOILS (ALUMINUM)
- WHITE-PIGMENTED EVA

Transparent Polymeric Pottants

- MODES OF OUTDOOR WEATHERING DEGRADATION
  1) THERMAL OXIDATION
  2) HYDROLYSIS
  3) UV PHOTO-OXIDATION
  4) UV PHOTOLYSIS

- COST/WEATHERING RELATIONSHIP

> \$1.50/pound	• GENERALLY WEATHERABLE
\$0.55 TO \$1.50/pound	• UV SENSITIVE • RESISTANT TO THERMAL OXIDATION/ HYDROLYSIS
< \$0.55/pound	• GENERALLY UNWEATHERABLE

REQUIREMENTS

- COMMERCIALLY AVAILABLE BASE POLYMERS OR MONOMERS
- USEFUL AS IS, OR AMENABLE TO LOW-COST MODIFICATION OR POLYMERIZATION
- POTENTIAL FOR AUTOMATED FABRICATION
- SELF-BONDING (DELAMINATION RESISTANCE)
- NON-TOXIC
- CHEMICALLY INERT

Materials Available for Industrial Evaluation

MATERIAL	ENCAPSULATION PROCESS	PROJECTED OR COMMERCIAL COST
POLYVINYL CHLORIDE PLASTISOL	CAST	$0.83/pound
ETHYLENE VINYL ACETATE	LAMINATION	$0.95/pound
ETHYLENE PROPYLENE RUBBER	LAMINATION	$1.09/pound
ALIPHATIC POLYETHER URETHANE	CAST	$1.29/pound
SILICONE ELASTOMER, 534-044	CAST	$3.00/pound
SILICONE RESIN, QI-2577	SPRAY	$11.26/pound

MATERIAL	TOP COVER REQUIRED FOR: UV SCREENING	SOIL PROTECTION
POLYVINYL CHLORIDE PLASTISOL	YES	YES
ETHYLENE VINYL ACETATE	YES	YES
ETHYLENE PROPYLENE RUBBER	YES	YES
ALIPHATIC POLYETHER URETHANE	YES	YES
SILICONE ELASTOMER, 534-044	NO	YES
SILICONE RESIN, QI-2577	NO	NO

Ethylene Vinyl Acetate Compared With Polyvinyl Butyral

COMMENTS FROM INDUSTRIAL EVALUATION

EVA ADVANTAGES

- COST
- APPEARANCE
- CLARITY
- NON-YELLOWING
- LOW-BLOCKING
  - ELIMINATES COLD STORAGE
- DIMENSIONAL STABILITY
- PROCESSING ADVANTAGES
  - REDUCES TIME
  - ELIMINATES PRESSURE AUTOCLAVE
- GOOD FLOW PROPERTIES AND VOLUMETRIC FILL

Ethylene Vinyl Acetate: Directions for Improvements And Questions Resulting From Industrial Evaluation

IMPROVEMENTS

INCORPORATE PRIMER

INCREASE WHITING CONTENT

REDUCE TIME/TEMP. FOR FASTER PROCESSING

EMBOSS FOR AIR REMOVAL AND FILM WINDING

AVOID GASSING ADDITIVES

QUESTIONS

MAXIMUM STORAGE TIME/HUMIDITY?

MAXIMUM HANDLING TEMPERATURE (BLOCKING) ?

REPAIRABILITY?

LIFE?

Materials Under Development

PROCESS AND PROJECTED COST	PROCESS	COST
POLY-n-BUTYL ACRYLATE	CAST	<\$1.50/pound
SILICONE/ACRYLIC COPOLYMER	SPRAY	<\$3.40/pound

TOP COVERAGE REQUIREMENTS	UV	SOIL
POLY-n-BUTYL ACRYLATE	?	YES
SILICONE/ACRYLIC COPOLYMER	NO	?

Polymer Film Top Covers With UV Screening Property

MATERIAL	STATUS	UV SCREENING PROPERTY	PROJECTED OR COMMERCIAL COST
KORAD 212	AVAILABLE	TEMPORARY*	1.5¢/ft^2 mil
SILICONE/ACRYLIC COPOLYMER	UNDER DEVELOPMENT	PERMANENT	~3.5¢/ft^2 mil
TEDLAR 100-BG-30-UT	AVAILABLE	PERMANENT	5.0¢/ft^2 mil

* PERMANENCE OF UV SCREENING PROPERTY UNDER DEVELOPMENT

Substrate Panels

WOOD	STATUS	PROJECTED OR COMMERCIAL COST
HARDBOARDS	AVAILABLE	1/8-inch THICKNESS; $\approx 12¢/ft^2$
STRANDBOARDS	UNDER DEV'L	3/8-inch THICKNESS; $\approx 16¢/ft^2$
METAL		
MILD STEEL	AVAILABLE	0.028-inch THICKNESS; $\approx 24¢/ft^2$
GALVANIZED STEEL	AVAILABLE	$\approx$15% HIGHER THAN MILD STEEL
ENAMELED STEEL	AVAILABLE	$\gg$15% HIGHER THAN MILD STEEL
CONCRETE		
GLASS-REINFORCED	UNDER DEV'L	1/4-inch THINKNESS; $\approx 62¢/ft^2$

Wood Substrate Panels

- MODES OF OUTDOOR WEATHERING DEGRADATION

  1) WATER ROT

  2) UV PHOTO-OXIDATION

  3) MECHANICAL BREAKDOWN FROM EXTREMES OF HYGROSCOPIC EXPANS'ON AND CONTRACTION

- WEATHER-PROOFING APPROACH

  ENCAPSULATION WITHIN A PIGMENTED AND UV STABILIZED CONFORMAL POLYMETRIC COATING

Mild Steel Substrate Panels

- PRIMARY MODE OF OUTDOOR DEGRADATION

  CORROSION

- CORROSION PROTECTION APPROACHES

  1) CONFORMAL COATING ENCAPSULATION WITH CHEMICAL COUPLING AGENTS

  2) ION-PLATED CORROSION-RESIST SURFACE COATINGS

  3) ENAMELING

Non-Woven Glass Mats* for Electrical and Mechanical Spacer Application

	Cost ¢/ft^2				
	Thickness, mils				
TYPE	3	5	7	9	12
230	1.32	1.76	2.2	2.8	3.7
210	-	-	1.56	-	-
200	0.66	0.78	0.97	1.36	1.81

*CRANEGLAS, DISTRIBUTED BY
ELECTROLOCK, INC.
CHAGRIN FALLS, OHIO

Back Covers

GLASS SUPERSTRATE DESIGNS

- MYLAR
- KORAD
- TEDLAR
- ALUMINUM
- ALUMINUM/POLYMER LAMINATES

SUBSTRATE DESIGNS WITH WOOD AND MILD STEEL

- PIGMENTED AND UV-STABILIZED POTTANTS AS CONFORMAL COATINGS
- (e.g. WHITE-PIGMENTED EVA)

Surface Materials & Modifications to Top-Cover Surfaces

REQUIREMENTS

1) TRANSPARENT
2) LOW-SOILING
3) EASILY CLEANED
4) ABRASION RESISTANT
5) ANTIREFLECTIVE

Soiling Theory

ATMOSPHERIC SOILING MATERIALS

1) ORGANICS
   a) VAPORS
   b) PARTICULATES
2) INORGANICS
   a) WATER SOLUBLE
   b) WATER INSOLUBLE

NATURAL CLEANING

1) WIND
2) RAIN

LOW-SOILING SURFACE REQUIREMENTS

1) HARD
2) HYDROPHOBIC
3) OLEOPHOBIC

Outdoor Soiling Experience of PV Modules With Different Exterior Surfaces

POWER RECOVERY AFTER CLEANING

	SOFT SILICONE ELASTOMERS RTV615	SYLG. 184	SILICONE HARD COAT	GLASS
DSET 161 DAYS	+9	+9	+4	+1
CARIBBEAN (1 yr.)	+9	+9	0	+2
MIT	+13 (5 mo.)	+14	+10 (5 mo.)	+6 (5 mo.)
NYU	+23 (6) +33 (12)	+29 (5) +38 (12)	+22-26	+11
COLUMBIA U.	+21 (6) +29 (12)	+22 (6) +33 (12)	-	+12 (6)

DECREASING OIL, RH ENVIRONMENT

INCREASING SURFACE HARDNESS

Commercial Surfacing Materials

1) FLUOROCARBONS

TEDLAR	(DU PONT)
KYNAR	(PENNWALT)
HALAR	(3M)
TEFLON	(DU PONT)
ABSITE	(DU PONT)

2) GLASS RESINS

GLASS RESIN 650 (OWENS-ILLINOIS)

3) SILICONE RESINS WITH COLLOIDAL SILICA

ARC	(DOW CORNING)
SAR	(DU PONT)
SHC-1000	(GENERAL ELECTRIC)

Surface Materials & Modifications Under Investigation

ACTIVITY	FUNCTION
CHEMICAL ETCHING OF GLASS SURFACE	ANTIREFLECTION
IONIC CROSSLINKING OF KORAD SURFACE	SOILING AND ABRASION RESISTANCE
ION-PLATED DEPOSITION OF SILANES	1) SOILING AND ABRASION RESISTANCE 2) ANTIREFLECTION

Adhesives & Primers for Solar Cells And Encapsulation Materials

	SOLAR CELLS	GLASS	KORAD	EVA	SILICONE ELASTOMER	HARDBOARD	ETC.
SOLAR CELLS							
GLASS	1, 2, 3, 7						
KORAD	X	X					
EVA	5	5, 6	U				
GE SILICONE ELASTOMER		4		X			
HARDBOARD	2	X	X	5, 6			
ETC.							

List of Primers, Adhesives & Non-Material Bonding Techniques

ADHESIVES

1) X1-2561 (DOW CORNING)
2) Q1-2577 (DOW CORNING)
3) Q96-083 (DOW CORNING)

PRIMERS

4) 2-6020 (DOW CORNING)
5) 2-6020/2-6030 MIX (DOW CORNING)
6) SS-4179 (GENERAL ELECTRIC)

NON-MATERIAL

7) ELECTROSTATIC BONDING (SPIRE)

Encapsulation Processes

1) LAMINATION
2) CAST
3) SPRAY
4) EXTRUSION

Task III & Task III Contractors' Successful Experience With Encapsulation Processes

(PASSES JPL THERMAL CYCLE TEST)

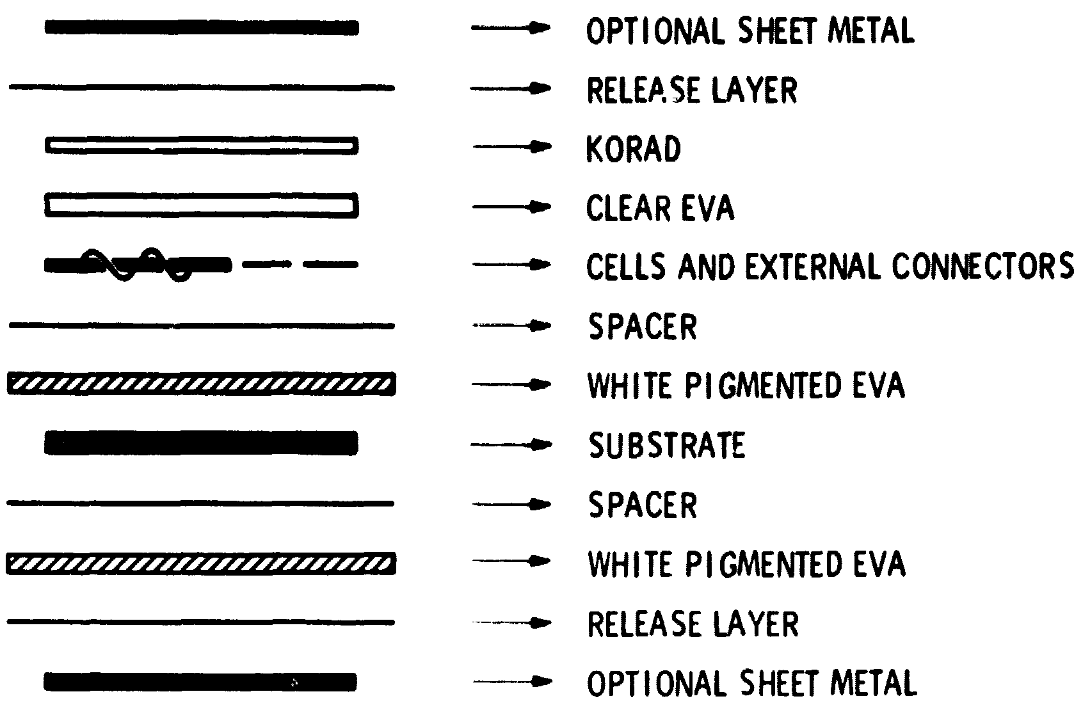
	MODULE DESIGN		
	SUBSTRATE		SUPERSTRATE
PROCESS	WOOD	METAL	GLASS
LAMINATION	YES	—	YES
CAST	YES	—	—
SPRAY	YES	—	YES
EXTRUSION	—	—	—

Fabricated Modules

PROCESS	WOOD	METAL
LAMINATION	YES	YES
CAST	NO	NO
SPRAY	YES	NO
EXTRUSION	NO	NO

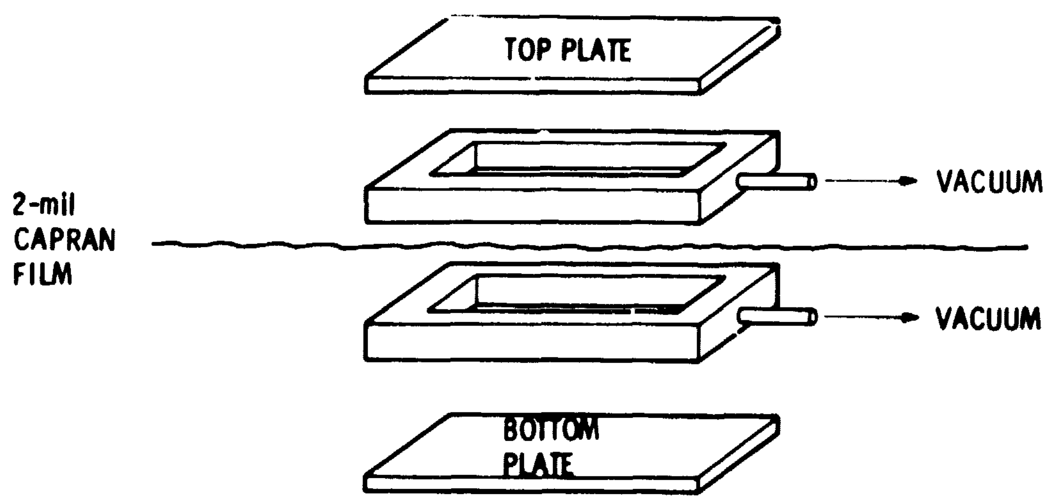
Vacuum-Bag Lamination

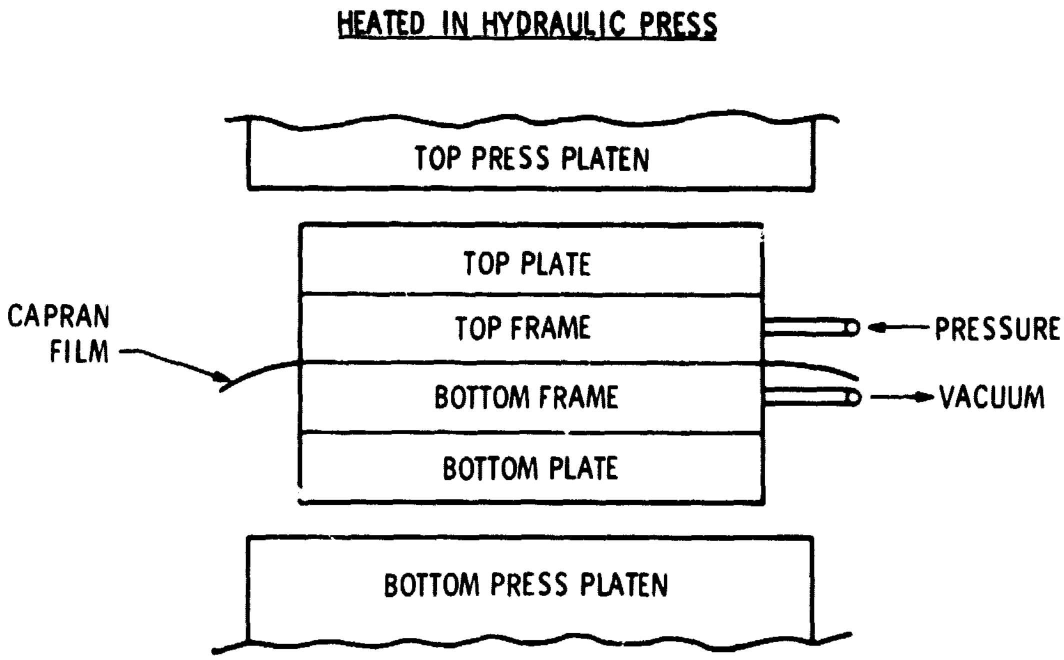
MATERIALS LAYUP



ALL DRY FILMS, NO SOLVENTS

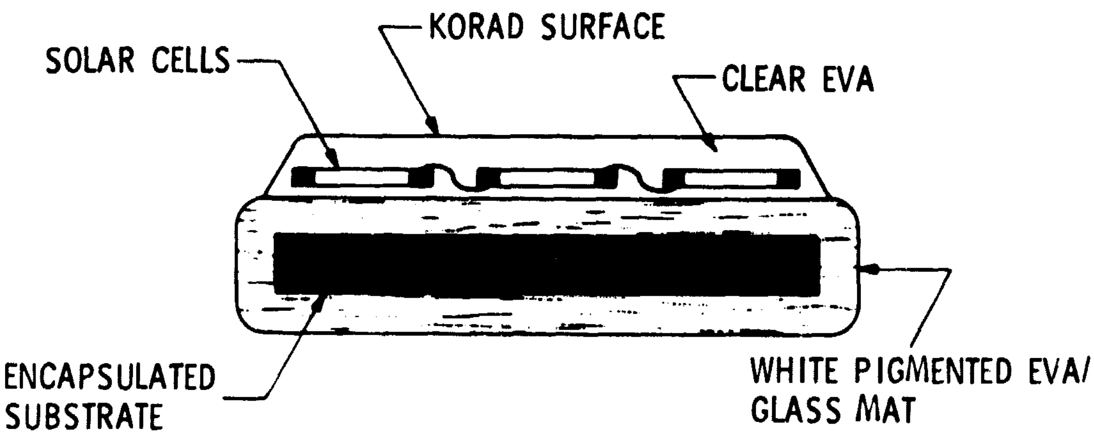
Vacuum-Bag Fixture





EVA CURE SCHEDULE: 20 minutes AT 140 TO 150°C, UNDER VACUUM

Fabricated Substrate Module With EVA Pottant



Electrical Breakdown of a Glass Superstrate Module With EVA

MODULE MATERIALS

1) SODA-LIME WINDOW GLASS

2) 20 mil CLEAR EVA FILM

3) CELL STRING

4) 5 mil NON-WOVEN GLASS MAT

5) 12 mil WHITE PIGMENTED EVA FILM

6) 1 mil ALUMINUM FOIL

D. C. ELECTRICAL BREAKDOWN VOLTAGE

5.8 kV

Vacuum-Bag Process

CONCERNS

- HANDLING OF LARGE-AREA PREFABRICATED CELL STRINGS
- AIR REMOVAL FROM LARGE AREA LAMINATED MODULES
- PROVISIONS FOR EXTERNAL CONNECTORS AND LEADS
- CELL SHIFTING

Spray Process

POSSIBLE ADVANTAGES

- ELIMINATE HANDLING OF PRE-FABRICATED CELL STRINGS
    1) ADHESIVELY BOND CELLS WITH INTERCONNECT TABS TO SUBSTRATE/SUPERSTRATE
    2) FINISH INTERCONNECTION IN-PLACE
- EXTERNAL LEADS AND CONNECTORS MORE EASILY ACCOMMODATED
- NO CELL SHIFTING

POSSIBLE CONCERNS

- CLEANLINESS
- INCOMPLETE COVERAGE
  - a) SHADOWING AND FILLING
- THIN COVERAGE
  - a) EXPOSED ELECTRICAL CONDUCTORS
  - b) STEPPED CELL EDGES
    - i) MECHANICAL DAMAGE
    - ii) CRACKING AND FRACTURING OF COATING (THERMAL EXP.)
- MATERIAL WASTE FROM SPRAY LOSSES
  - a) HEALTH

The Future

- ACCELERATED/ABBREVIATED LIFE PREDICTION METHOD
- SOILING RESISTANCE AND MAINTENANCE
- EVALUATION OF ALL PROCESSING TECHNIQUES
  - MATERIALS APPROPRIATELY FORMULATED FOR AUTOMATION
- OPTIMAL MODULE DESIGN
  - COST
  - STRUCTURAL
  - OPTICAL
  - ELECTRICAL ISOLATION
  - THERMAL
  - PROTECTION OF CELLS, INTERCONNECTS, WIRES, ETC.
- CONTINUE MATERIALS DEVELOPMENT
  - UV SCREENS, POTTANTS, PRIMERS, SURFACE MATERIALS/MODIFICATION
  - SUBSTRATES

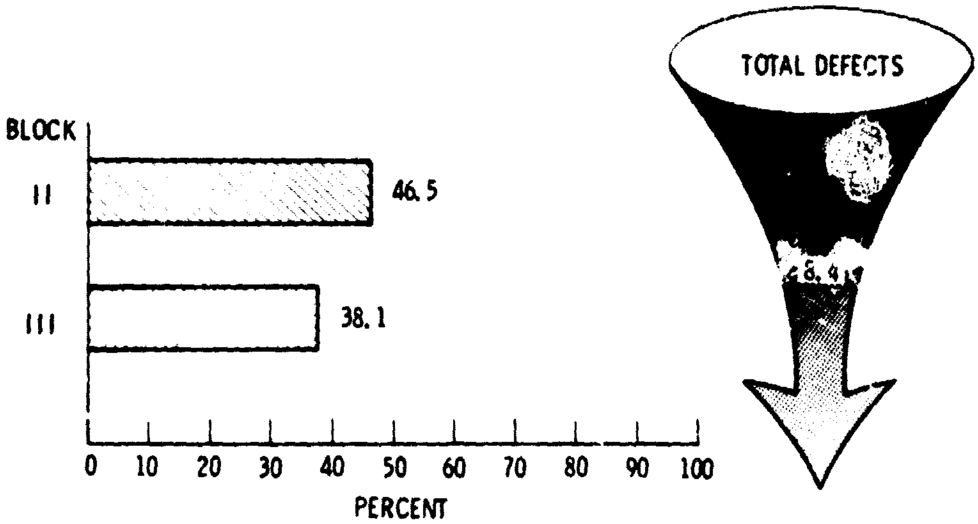
DISCREPANCIES

BLOCK II AND BLOCK III

JET PROPULSION LABORATORY

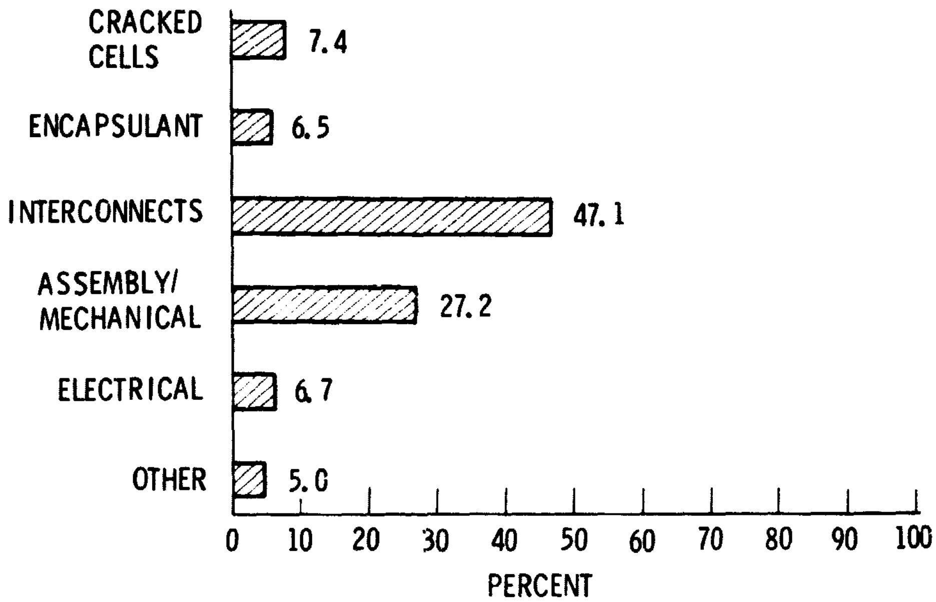
Walter E. Bishop

Discrepancy Rate: All Defects, All Suppliers

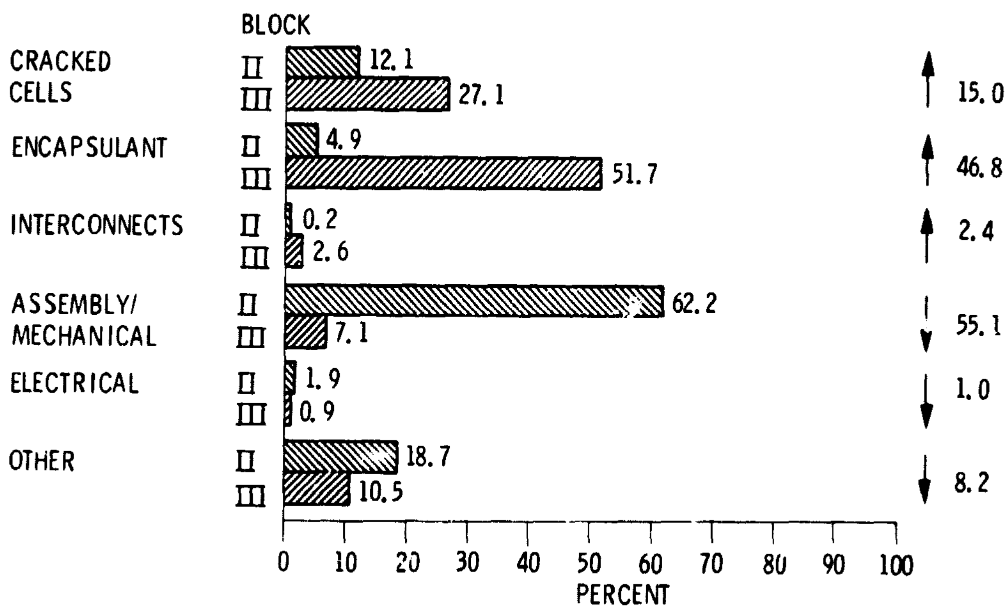


CATEGORY DISCREPANCY RATES

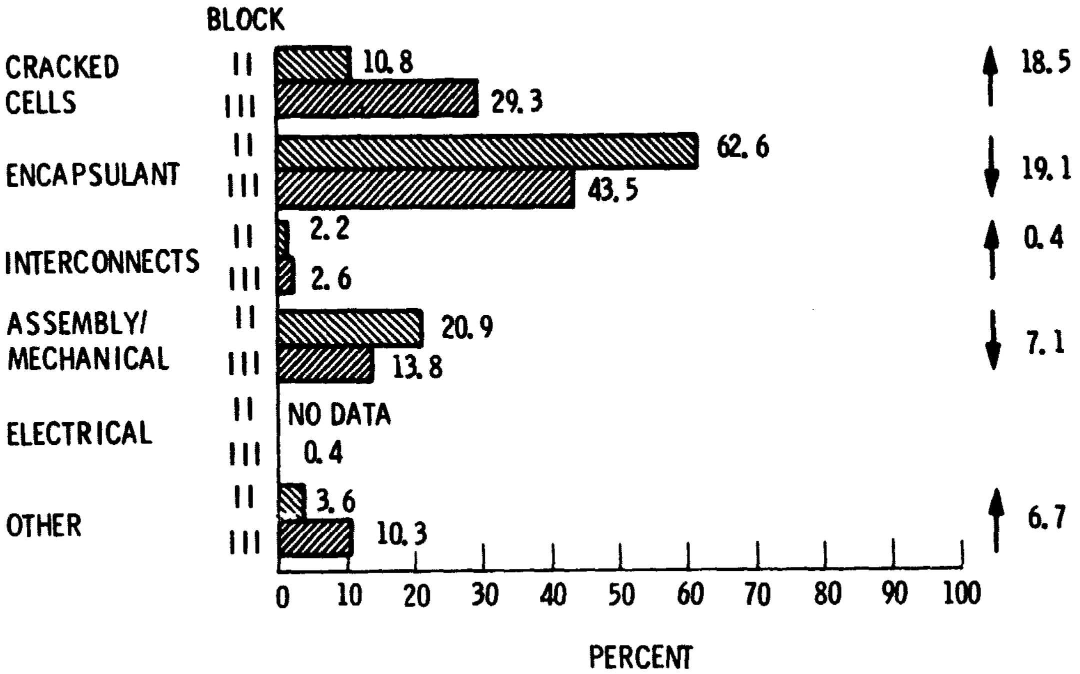
All Defects, Supplier A (Block III Only)



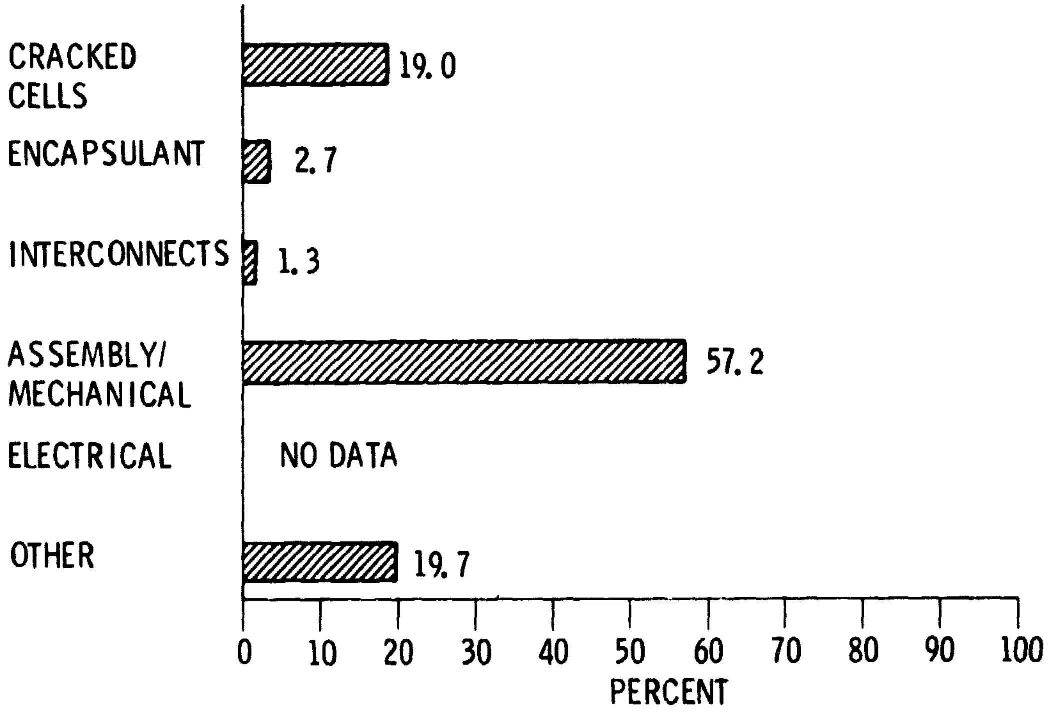
All Defects, Supplier B



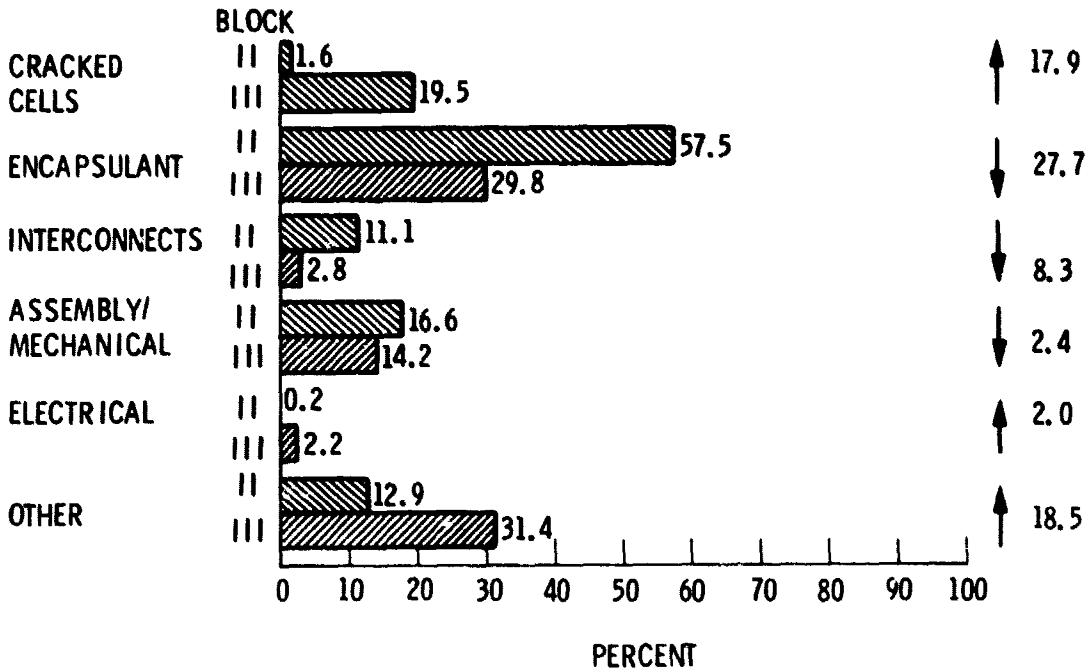
All Defects, Supplier C



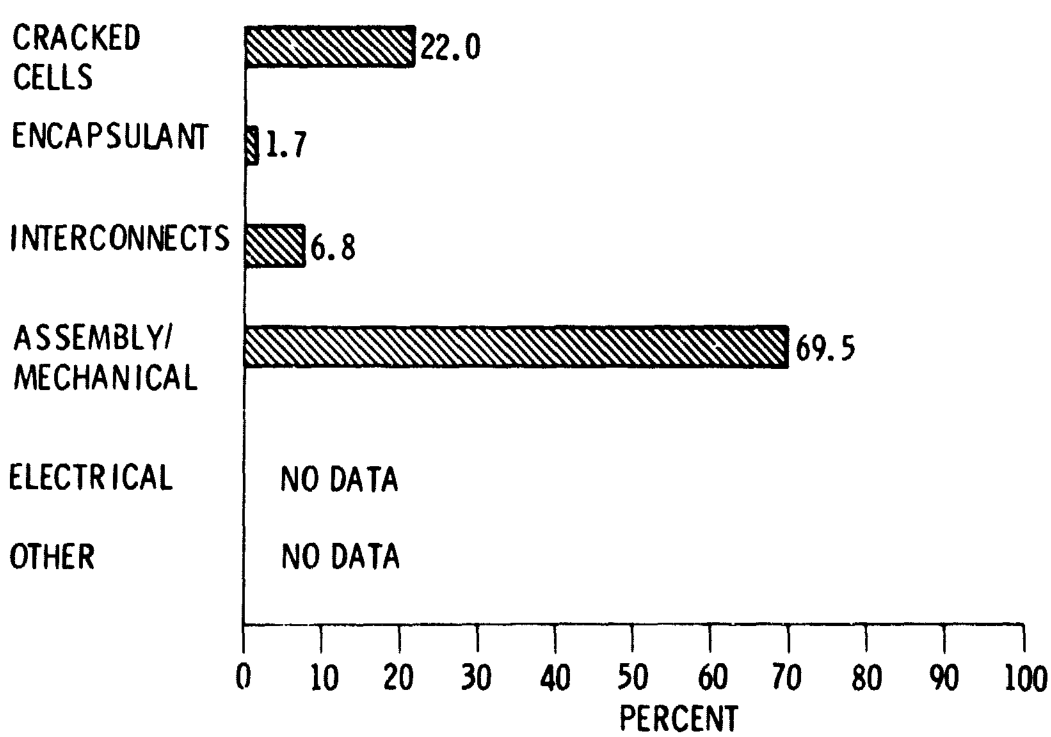
All Defects, Supplier D (Block III Only)



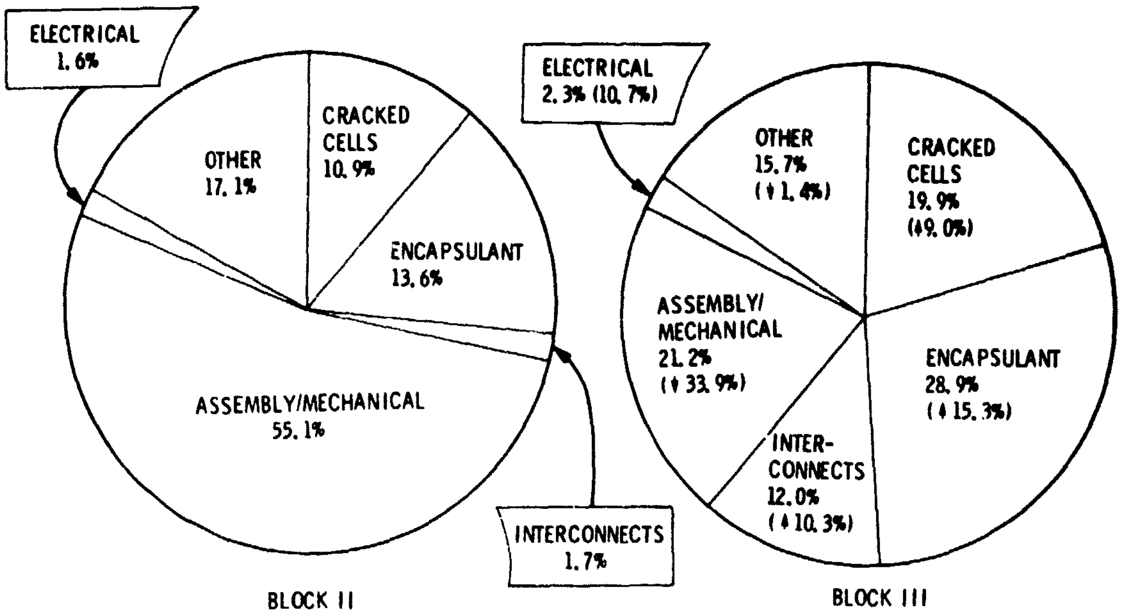
All Defects, Supplier E



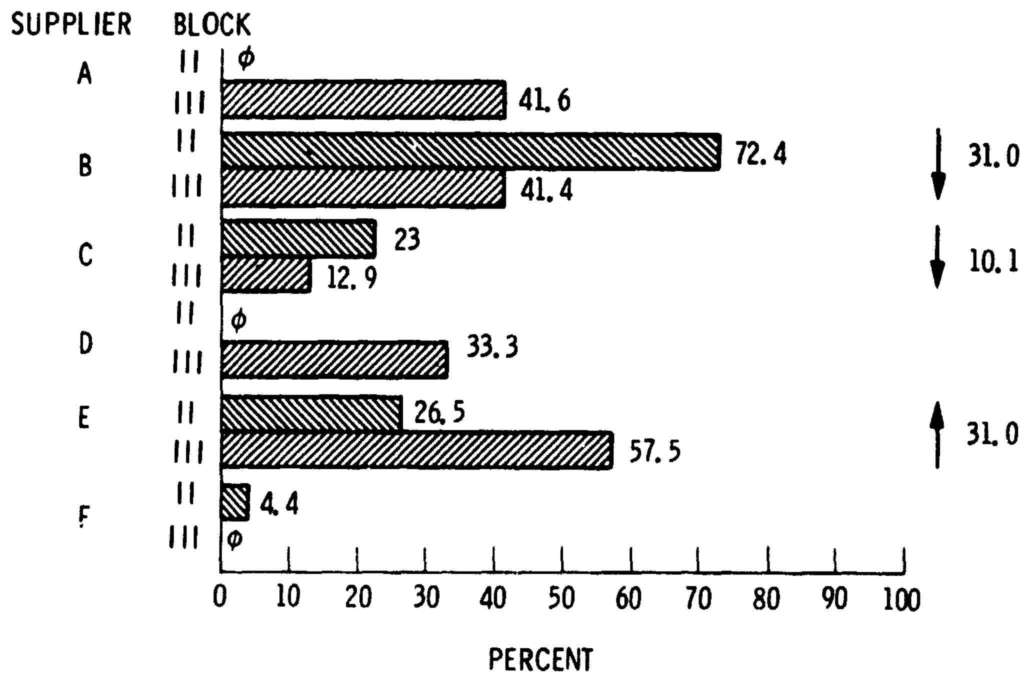
All Defects, Supplier F (Block II Only)



All Defects, All Suppliers



Discrepancy Rate
All Defects, All Suppliers



OPERATIONS AREA

TEST AND APPLICATIONS

The Thursday-afternoon session on test and applications was initiated by an overview of T&A experiments status and plans given by Dr. John Hesse of the TD&A Lead Center. Covering those projects underway in stand-alone, intermediate load, residential, and congressionally mandated application sectors, Dr. Hesse made it clear that the Program is on the verge of fielding a great quantity and variety of PV systems. Special attention was given to the potential impact if PV power systems are selected for the Missile-X Program. An expanded version of Dr. Hesse's talk is available in the Proceedings of the DOE Semiannual Review, conducted at Pinehurst, N.C., on November 5-7, 1979.

Dr. Steve Forman updated T&A session participants on experience at MIT/LL test sites. The cumulative module failure total for all sites over the past two years is 3%. A significant problem has occurred at the University of Texas (Arlington) residential test site, where 22% of the Block II modules in use there have failed. The principal failure mode at that site is cracked cells, probably related to back-bias heating when circuit strings were short-circuited. Dr. Forman will present a paper on MIT/LL field experience at the IEEE PV Specialists Conference in San Diego on January 7-10, 1980.

Jim Deyo, Manager of the NASA LeRC PV Project, gave a summary of experience with stand-alone applications. Over the past three and a half years, 6% of the Block I and II modules installed in their applications have failed (a third of these were lost to high waves in a RAMOS installation). Array performance and public acceptance of PV systems have been good, with particular interest in village power systems displayed by the international community. Adequate load data for system sizing and the logistics of maintenance at remote sites were noted as continuing problems.

Ron Baisley of the LSA Project provided an update on the status of the 60 kW Mt. Laguna array. Failures to date stand at 2% of the array, although 18% of one module type there contain cracked cells and 36% of the second module type contain cracked cells. The former effect is believed to have been caused by a hailstorm at the site; the latter effect is a form of progressive cell cracking aggravated by gas generation under these cells, caused by back-bias heating. Design features needed to prevent the recurrence of such problems in future module types are in hand, and a discussion of available options was presented in Engineering Area sessions.

In looking forward, it is expected that the evaluation of the technology innovations of Block IV modules and the performance of the systems being now being fielded at an accelerated pace will provide the basis for a new round of lessons learned, leading to further improvements in module price, performance, and reliability.

TECHNOLOGY SESSION

TEST AND APPLICATIONS EXPERIENCE

L. Dumas, Chairman

STAND-ALONE APPLICATIONS PROJECT

APPLICATION EXPERIENCE

NASA LEWIS RESEARCH CENTER
James L. Deyo

MODULES
POWER SYSTEM
LOADS

MAINTENANCE

PUBLIC INTEREST

Power System

- GENERAL OPERATION SATISFACTORY
- PROBLEM AREAS INVOLVED:

  VOLTAGE REGULATORS/CONTROLS
  RUN TIME METERS
  AMP-HOUR METERS
  ARRAY CONNECTORS

Loads

LOADS HAVE BEEN MAJOR SOURCE OF PROBLEMS

LOAD PROFILES: OPERATION DIFFERS FROM PREDICTED

IMPROPER LOAD DEVICE OPERATION:
- REFRIGERATOR OPEN DOORS/DEFROSTING/LOCATION
- GRINDER PLATE WEAR
- DUST STORM SIGN WINTER USE

REFRIGERATORS:
- COMPRESSOR MOTORS
- REFRIGERANT CHARGE
- INADEQUATE CABINET INSULATION

WEATHER SYSTEM: DATA LINKS, BATTERIES, TRANSMITTER

DUST STORM SIGN: ACTUATOR MECHANISM

USERS SOMETIMES MISTAKENLY PERCEIVE A FAILURE OF THE LOAD DEVICE AS A PV/LOAD SYSTEM FAILURE.

Maintenance

FOR REMOTE SITES, MAJOR PROBLEMS HAVE BEEN:
- DISCOVERING PROBLEM IN A TIMELY WAY
- SHIPPING, AND TRANSPORTATION OF MATERIAL AND PERSONNEL TO SITES SIGNIFICANTLY DELAY MAINTENANCE AND FAULT CORRECTION
- ONLY ROUTINE MAINTENANCE NEEDED CONSISTS OF:
  - BATTERY ELECTROLYTE LEVEL CHECK
  - ARRAY WASHING (OCCASIONALLY, SOME SYSTEMS)

Public Interest

- GENERAL REACTION POSITIVE
- CONTINUING HIGH LEVEL OF INTEREST IN SCHUCHULI AND UPPER VOLTA ESPECIALLY FROM INTERNATIONAL COMMUNITY

Summary

- LOAD DEVICES HAVE BEEN A MAJOR SOURCE OF PROBLEMS
- MODULES HAVE NOT BEEN A PROBLEM
- MAINTENANCE PROBLEMS HAVE BEEN RELATED TO REMOTENESS OF LOCATIONS RATHER THAN THE MAINTENANCE REQUIRED

Module Experience

APPLICATION	NUMBER	MFGR	JPL BLOCK	FAILURES	CAUSE	INSTALLED
ISLE ROYALE REFRIG.	24	SX	I	0		5/76
SIL NAKYA REFRIG.	36	SX	I	2	CRACKED CELL/OPEN	7/76
FOREST LOOKOUT	64	SX	I	0		10/76
DUST STORM SIGN	20	ST	I	1	VANDALISM	4/77
INSECT TRAP	32	ST	I	1	OPEN	5/77
RAMOS	64	SX	I	28	12 STORM/10 LOW OUTPUT	5/77-10/77
	240			32		
RAMOS	1	ST	II	1	VANDALISM	10/77
LONE PINE	48	ST	II	0		9/77
SCHUCHULI	192	SX	II	2	1 OPEN/1 HAIL	12/78
UPPER VOLTA	100	SX	GSA (II)	1	OPEN?	2/79
	342			4		
TOTALS	581			36		
SYSTEMS TEST FACILITY	112	SX	I	1	INTERCONNECT	4/76
	642	ST	I	0		9/76
	644	SP	I	1	INTERCONNECT	12/76
	1920	ST	III	0		6/79

STATUS REPORT: MT. LAGUNA AIR FORCE STATION

JET PROPULSION LABORATORY

Ron Baisley

History

- DEDICATION - AUGUST 15, 1979
- SCOPE OF INVESTIGATION (JULY 21-OCTOBER 30)
  - 11 VISUAL, IR & FUNCTIONAL FIELD AUDITS
  - JPL FIELD TESTS
  - LABORATORY ANALYSIS
  - ANALYTICAL MODELING
- OPERATING CONDITIONS
  - SYSTEM CHECKOUT/LIMITED OPERATION - (JULY-AUG. 15)
  - FULL OPERATIONAL/MAX POWER TRACK (AUG. 15-OCT. 5 AND NOV. 3-PRESENT)
  - FULL OPERATIONAL/REDUCED POWER (OCT. 6-NOV. 2)

Observations

ELECTRICAL PERFORMANCE

- BYPASSED MODULES

OCT 5	37
OCT 23	40

- DEGRADATION - DIFFICULT TO DETERMINE WITH PRESENT DATA SYSTEM

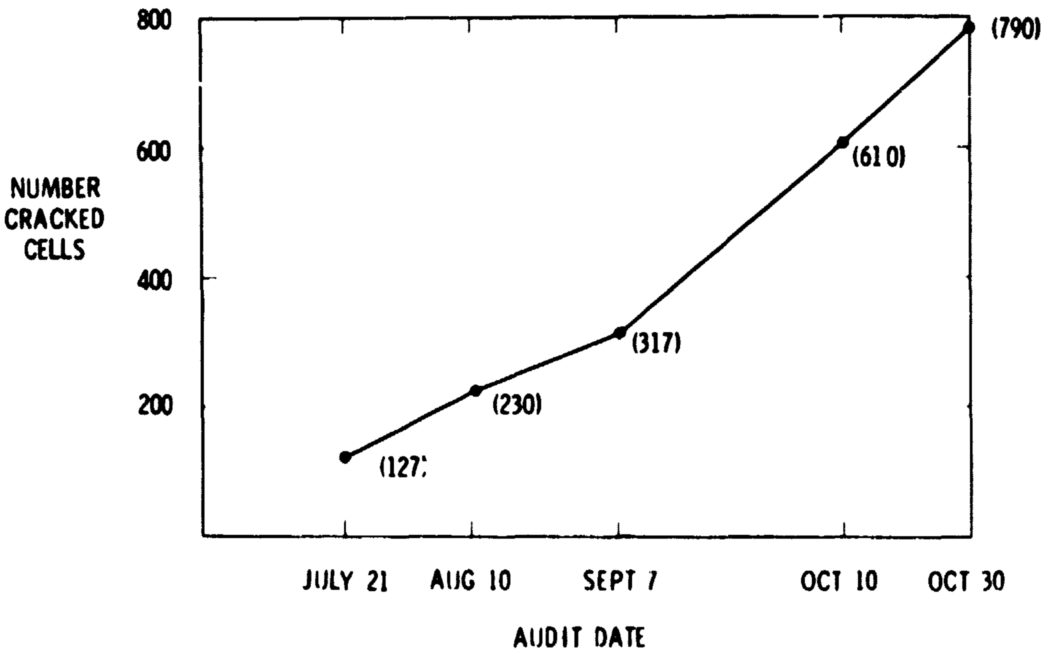
Observations—Visual
Cracked Cells/Impact Fractures

- 217 CRACKED CELLS IN 136 MODULES
- 136 OF 756, OR 18% OF SOLAREX MODULES AFFECTED
- TYPICAL OF IMPACT CRACKS
- HAILSTORM 07/22/79

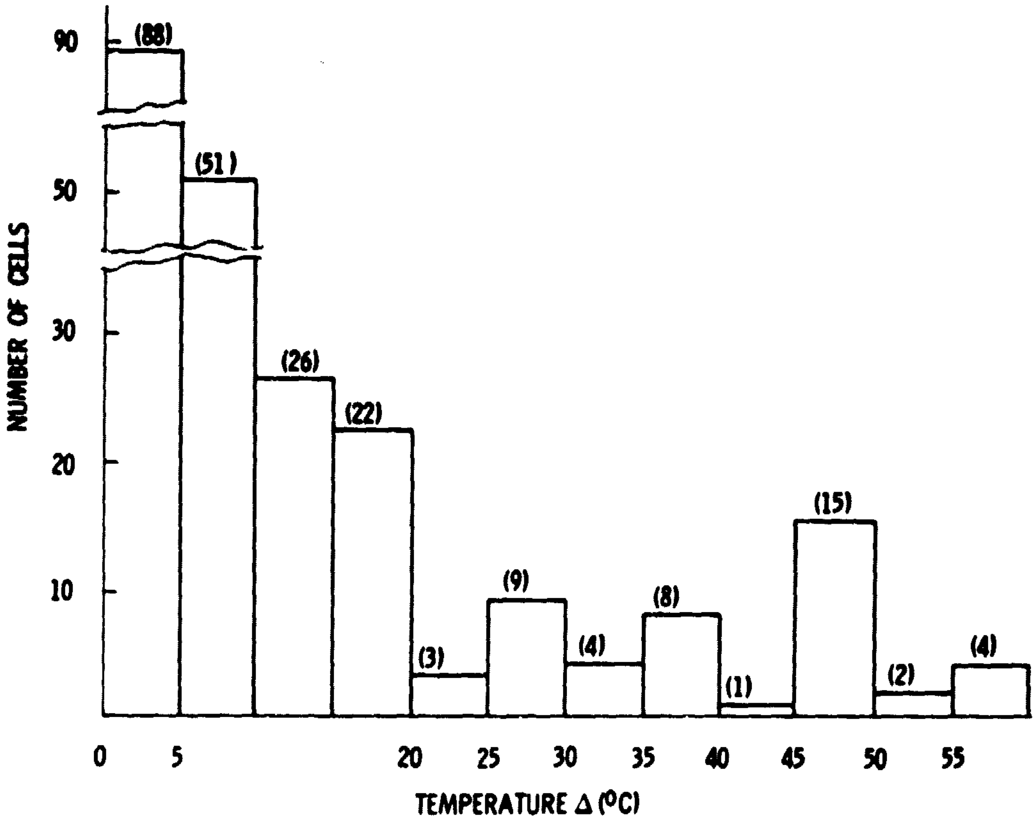
Observations—Visual
Cracked Cells/Burst-Type Fractures

- OCCURRENCE - 790 CELLS (573 MODULES)
- DELAMINATION - 238 CELLS
- HOT CELLS - 240 CELLS (2-70 $C^{o}\Delta$)
- CORRELATION
  - CRACK/BURST ——→ HOT CELL - VARYING WITH AUDIT
- DISTRIBUTION - NON-UNIFORM

Observations—Visual
Cracked Cells/Burst Fracture History



Observations—IR
Cell Temperature Distribution



System Power Loss, Mt. Laguna Array Configuration
(1% Cracked Cells, 560 Series/BC)

MODULE S x P	CELL CONTACTS	PARALLEL CELLS/BC	SERIES BLOCKS PER BC	DIODES PER MODULE	CELLS PER DIODE	SYSTEM POWER LOSS, %
40 x 1		1	1	0	560	96
40 x 1		1	1	1	40	32
40 x 1		1	1	2	20	16
40 x 1		1	1	4	10	7
40 x 1		1	1	1	40	22
40 x 1		1	1	1	40	14
40 x 1		1	1	1	40	<5
40 x 1		4	14	0	560	65
40 x 1		4	14	1	40	35
40 x 1		8	14	0	560	40
40 x 1		8	14	1	40	35
10 x 4		4	56	0	560	36
10 x 4		4	56	1	10	22

Conclusions

- BURST-CELL PHENOMENON IS CONTINUING
- PROBABLE "TRIGGER"

  CRACKED CELL - OPERATIONAL AND/OR ENVIRONMENTAL STRESSES
  CELL MISMATCH - MANUFACTURING AND/OR DEGRADATION
- IMPACT FRACTURES
  - PROBABLE CAUSE - HAILSTORM
- PROSPECT FOR ARRAY SURVIVAL IS UNKNOWN
  - INSUFFICIENT DATA
  - CRACKED CELL FAILURE MODE/LIFE NOT UNDERSTOOD
- VALUABLE SOURCE OF DATA
  - ARRAY DYNAMICS
  - ON-SITE TROUBLESHOOTING TECHNIQUES

Recommendations
Mt. Laguna

- IMPROVE DATA SYSTEM
- CONTINUE ON-SITE AUDITS
- CONTINUE FAILURE ANALYSES

Recommendations
Future Generations

MANUFACTURERS

- PROVIDE MULTIPLE CELL CONTACTS
- CONSIDER INTERNAL SERIES/PARALLELLING AND BYPASS DIODE PROTECTION
- ELIMINATE ENCAPSULANT MATERIALS WITH OUTGASSING TENDENCIES
- IMPROVE CELL MATCHING

JPL

- REVISE MODULE DESIGN AND TEST SPECIFICATIONS TO ENCOMPASS WORSE-CASE OPERATIONAL CONDITIONS

ENGINEERING AREA

SAFETY AND PRODUCT LIABILITY

Professor A. Weinstein of Carnegie-Mellon University, an expert in the field of product liability, was an invited speaker at the 14th PIM. In his talk, titled "Safety and Product Liability," he alerted the LSA photovoltaic community to possible penalties of introducing unsafe products for commercial use. Highlights of his talk included a discussion of concerns relative to litigations that might result should injury be caused by a defective product.

Of the various legal theories upon which action might be based, three were mentioned: negligence, breach of warranty and strict liability. The area of most concern is that of strict liability; with such cases, no proof of fault is required. In a certain landmark decision by the California state Supreme Court, strict liability was once established when a product was shown to present <u>unreasonable</u> danger to an extent beyond that which an ordinary user or consumer might contemplate. Professor Weinstein further explained that even posting warnings of danger on a product is not sufficient to avoid liability in most instances. It was noted that a product can also be considered defective if excessive preventable danger can be shown to exist.

Professor Weinstein concluded that establishment of safety and product liability guidelines by the photovoltaic community should be initiated now. He emphasized that safety and product liability factors can be introduced as a part of basic design, overall risk-benefit analyses and in the development of standards.

A. Weinstein
Carnegie-Mellon University

Considerations for Liability

<u>PRODUCT RELIABILITY</u>

SPECIFICATIONS
WARRANTIES
USEFUL LIFE

<u>PRODUCT SAFETY</u>

HAZARDS/RISKS OF INJURY
PROPERTY DAMAGE

Legal Bases for Liability

DESIGNER/ENGINEER

NEGLIGENCE

MANUFACTURER/ASSEMBLER/SELLER

NEGLIGENCE
EXPRESS WARRANTY/MISREPRESENTATION
STRICT LIABILITY

Basic Legal Principles in Product Liability

1. NEGLIGENCE WHICH TESTS THE CONDUCT OF THE DEFENDANT;

2. EXPRESS WARRANTY AND MISREPRESENTATION WHICH TESTS THE PERFORMANCE OF PRODUCTS AGAINST THE EXPLICIT REPRESENTATIONS MADE ON THEIR BEHALF BY THE MANUFACTURER AND SELLERS; AND

3. STRICT LIABILITY AND IMPLIED WARRANTY WHICH TEST THE QUALITY OF THE PRODUCT.

Indicia for Unreasonably Dangerous Defect

1. THE USEFULNESS AND DESIRABILITY OF THE PRODUCT

2. THE AVAILABILITY OF OTHER AND SAFER PRODUCTS TO MEET THE SAME NEED

3. THE LIKELIHOOD OF INJURY AND ITS PROBABLE SERIOUSNESS

4. THE OBVIOUSNESS OF DANGER

5. COMMON KNOWLEDGE AND NORMAL PUBLIC EXPECTATION OF THE DANGER (PARTICULARLY FOR ESTABLISHED PRODUCTS)

6. THE AVOIDABILITY OF INJURY BY CARE IN USE OF THE PRODUCT (INCLUDING THE EFFECT OF INSTRUCTIONS AND WARNINGS)

7. THE ABILITY TO ELIMINATE THE DANGER WITHOUT SERIOUSLY IMPAIRING THE USEFULNESS OF THE PRODUCT OF MAKING IT UNDULY EXPENSIVE.

Elements ot Design Procedure: The Reasonably Safe Product

A. DELINEATION OF PRODUCT USES

B. IDENTIFICATION OF ENVIRONMENTS WITHIN WHICH THE PRODUCT WILL BE USED

C. DESCRIPTION OF USER POPULATION

D. POSTULATE ALL POSSIBLE HAZARDS, TOGETHER WITH SOME ESTIMATE AS TO PROBABILITY OF OCCURRENCE AND SERIOUSNESS OF THE RESULTING HARM

E. DELINEATE ALTERNATIVE DESIGN OR PRODUCTION FEATURES INCLUDING WARNINGS AND INSTRUCTIONS, THAT WOULD EFFECTIVELY MITIGATE OR ELIMINATE THE HAZARDS

F. EVALUATE SUCH ALTERNATIVE FEATURES RELATIVE TO THE EXPECTED PERFORMANCE STANDARDS OF THE PRODUCT, INCLUDING
   1. EFFECT ON THE SUBSEQUENT USEFULNESS OF THE PRODUCT
   2. EFFECT ON THE SUBSEQUENT COST OF THE PRODUCT
   3. COMPARISON TO SIMILAR PRODUCTS

G. DECISION AS TO WHICH FEATURES TO INCORPORATE IN FINAL DESIGN TO PROVIDE THE REASONABLY SAFE PRODUCT