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Low-Cost
Solar Array Project

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Progress Report 17

for the Period September 1980 to February 1981

and Proceedings of the 17th Project Integration Meeting

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period September 1980 to February 1981. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held at Pasadena, Calif, on February 4 and 5, 1981.

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PROGRESS REPORT

PROCEEDINGS

NOMENCLATURE

A	Angstrom(s)
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
B-T	Bias/temperature
B-T-H	Bias/temperature/humidity
CFP	Continuous-flow pyrolyzer
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-grade 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
ESGU	Experimental Sheet Growth Unit
EVA	Ethylene vinyl acetate
FAST	Fixed abrasive slicing technique
FBR	Fluidized-bed reactor
FPUP	Federal Photovoltaics Utilization Program
GRC	Glass-reinforced concrete
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
IPEG4	Improved Price Estimation Guidelines
I_{sc}	Short-circuit current
I-V	Current-voltage
LAPSS	Large-area pulsed solar simulator
LAR	Low-angle ribbon (silicon growth method)
LAS	Large-Area Silicon Sheet Task
LCP	Lifetime cost and performance
LeRC	Lewis Research Center
LSA	Low-Cost Solar Array
mgSi	Metallurgical-grade silicon
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MBS	Multiblade sawing
MEPSDU	Module experimental process system development unit
MWS	Multiwire sawing
NASA	National Aeronautics and Space Administration
NBNM	Natural Bridges National Monument
NDE	Nondestructive evaluation
NOCT	Nominal operating cell temperature
NTCR	Near-Term Cost Reduction
OTC	Optimal test conditions
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
PEBA	Pulsed electron beam annealing
P/FR	Problem-failure report
PIM	Project Integration Meeting
P_{max}	Maximum power
PMMA	Polymethyl methacrylate
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(s)
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RNHT	Relative normal hemispherical transmittance
RDI	Return on investment
RTR	Ribbon-to-ribbon (silicon crystal growth method)
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SCIM	Silicon coating by inverted meniscus
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute

SERI	Solar Energy Research Institute
$SiCl_4$	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)
TR	Technical Readiness
UV	Ultraviolet radiation
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage
$ZnCl_2$	Zinc chloride

PROGRESS REPORT

Project Summary

Construction of the Union Carbide Corp. silane-to-silicon Experimental Process System Development Unit (EPSDU) (100 MT/yr), which was started in September 1980, is progressing well. Concrete and steel are being emplaced and the large distillation column is ready for installation. Union Carbide has initiated plans for the construction of a 1000 MT/yr silicon (Si) production plant that would start commercial operation in 1985.

The experimental reactor at Massachusetts Institute of Technology has the potential of reducing the cost of Si, if incorporated into a Siemens production plant, by enabling the recycling of silicon tetrachloride (STC) in the production of trichlorosilane (TCS).

The Hamco advanced Czochralski ingot grower with melt replenishment will be completed in February 1981, except for the automatic controls, which will be [illegible] in July 1981. Capacity will be five 30-kg ingots (15-cm dia) per run.

Efforts continue to increase the throughput rates of wafering machines: internal-diameter (ID) at Silicon Technology Corp. and multiwire (FAST) at Crystal Systems. The goals are 17 wafers/cm for 15-cm-dia wafers and 25 wafers/cm for 10-cm square wafers, which have been demonstrated at 85% and 90% yields, respectively, but with low slicing rates of 0.25 wafers/min.

The design of the web ribbon experimental sheet growth unit (ESGU) by Westinghouse continues to make good progress.

Mobil Tyco has reached its growth-rate goal of 4 cm/min for a single 10-cm-wide edge-defined film-fed-growth (EFG) ribbon and has grown three 10-cm-wide ribbons at 3.3 cm/min. Cells fabricated from 10-cm-wide ribbons grown at 3.5 cm/min, with CO_2 ambient atmosphere, show efficiencies of 11.2% AM1 (AR coated, 28°C, 13-cm^2 area).

Module encapsulation technology progress, as summarized at the PIM, included:

Material and process candidates under development and evaluation meet cost goals ($14/m^2) and have 20-year life potential.

Encapsulation material requirements, specifications, and characterizations continue to evolve.

Trade-offs for various module encapsulation designs and materials are being analyzed and will be verified by test.

Durability testing of materials and modules (experimental and contemporary) is continuing in both accelerated and real time.

Ethylene vinyl acetate (EVA) developed as a module pottant is used in five of the Block IV modules.

Major material suppliers (DuPont Co., Rohm & Haas Co., 3M Co., Corning Glass Works, Schott, Masonite Corp., U.S. Gypsum Co., etc.), stimulated by the Low-Cost Solar Array Project (LSA), are participating voluntarily in encapsulation activities.

Automated solar cell and module manufacturing processes contracts were awarded (November 1980) to Solarex Corp. and Westinghouse Electric Corp. Module Experimental Process System Development Unit (MEPSDU) efforts are to demonstrate low-cost manufacturing technology:

The Solarex process uses 10 x 10-cm Semix polycrystalline wafers with spray-on front-junction formation, back-surface junction, spray-on AR coating, and electroless Ni contacts dipped in solder. The modules will be an EVA laminated glass superstrate design.

The Westinghouse process uses 2.5 x 10-cm dendritic web ribbons with diffused front junction, diffused back-surface junction, dip AR coating, and evaporated Ti/Pd/Cu-plated Cu contacts. Aluminum electrical interconnections will be ultrasonically welded to the cells. The modules will be an EVA-laminated glass superstrate design.

Analysis of non-mass-analyzed ion implantation indicates that it can be cost competitive with gaseous diffused-junction formation.

Block IV module observations and conclusions:

Manufacturers had some difficulties in evolving new designs that incorporated new technology, as evidenced by schedule slips, module problems during tests, and some retreats to conventional technology.

Price and performance progress of LSA module block purchases continues; prices are down, but the rate of decrease has slowed; efficiencies are up and reliability and durability are better, especially hail protection, moisture protection, and fault-tolerance capabilities.

Large-scale producibility will not be verified with limited purchase quantities.

Block IV module activities were critiqued by seven module manufacturers under contract in the four solicited topics listed below. The comments and ensuing discussions were well thought out, worthwhile, and mature. They will be incorporated into the Block V activities as appropriate. Major points are:

Design specifications: Module design is compromised and made more difficult by specifying both terminal voltage and module length. The module design specifications should be generalized whenever possible because they are used by many other buyers.

Environmental tests: Some believe that temperature range is excessive and humidity durations are not adequate. All would not voluntarily do as complete testing as the LSA tests.

SAMIS-SAMICS: Expensive operation and lack of confidence in results were two critical comments resulting from the inability to generate accurate inputs with the small quantities involved. The less-complex IPEG4 is more useful to the contractors as an estimation tool. Most contractors also have costing methods of their own.

General: Industry working relationship with the Jet Propulsion Laboratory (JPL) is good. Feedback and consultation by JPL specialists is helpful. Block IV module requirements are not well matched to today's market, which is primarily for stand-alone applications. The Block IV activities were a valuable learning experience.

A flat-module and array safety design workshop, held February 3 and attended by more than 100 people, was based upon an Interim Standard for Safety written primarily by Underwriters Laboratories. The two-part document draft, consisting of construction requirements and performance requirements, will be updated based upon workshop comments and discussions.

Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

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

The metallization-grid-pattern optimization effort, in cooperation with the PP&E Area, has made significant progress. The equations for the two-bus-bar design have been written and entered into the APL optimizing program.

Two different designs have been identified. The first is the present conventional design in that it is optimized using only two variables. The second is an improved design using four variables in the optimization. These designs, plus a third that uses less metal, will be used by PP&E in a large (about 50 each) sampling of solar cells. The actual output power produced from the cells will be compared with the results computed in the program.

Evaluation of the results of the near-term cost-reduction contracts has been completed. This was done in cooperation with the PP&E area; the results are presented in the Proceedings section of this document (see pp. 55-58).

A review of the SAMICS methodology is in progress. It covers the environmental requirements in SAMIS and a major update of the cost-account catalog, including labor rates, inflation rates, commodity prices and financial-organizational parameters. The user interface with SAMIS is also being reviewed to attempt to reduce the trauma experienced by first-time or occasional users. Formats A and C, the users' guide and other documentation are being reviewed. Planning is under way for a users' workshop.

The initial design was completed for the year-by-year financial reports (balance sheet, income statement, etc.) for SAMIS. Coding will start soon, after completion of a revision of the way the cost account catalog is handled in SAMIS. This will save about half the cost of that part of the computation (the savings will be about $15/run).

Sensitivity analyses were performed on the $2.70/W$_p$ PV manufacturing plant. This was the first application of IPEG4 in the LSA Project. In addition, the calibration of IPEG4 to SAMIS has been completed and IPEG4 capabilities have been expanded to include RACI (Rapid Amortization of Capital Investment) price estimates.

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

INTRODUCTION

The objective of the Silicon Material Task is to establish the practicality of processes capable of producing silicon (Si) suitable for use in the manufacture of solar cells at a rate equivalent to 500 MW_p/yr of solar arrays at a price less than $14/kg (1980 $) by 1986. 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 now fabricated from semiconductor-grade Si, which has a market price of about $65/kg. A drastic reduction in cost of material is necessary to meet the economic objectives of the LSA Project. Efforts are now under way to develop processes that will meet the Task objectives in producing semiconductor-grade Si. Another means of meeting this requirement is to devise a process for producing so-called solar-cell-grade Si material, which 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 tradeoffs concurrently with the development of high-volume, low-cost processes for producing Si. This structure has been described 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.

Thirteen contracts are in progress; these are listed in the table below.

Silicon Material Task Contractors

Contractor	Technology Area
Semiconductor-Grade Silicon Processes	
Battelle Columbus Laboratories Columbus, Ohio JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized-bed reactor
Energy Materials Corp. Harvard, Massachusetts JPL Contract No. 955269 (Near-Term Cost-Reduction Contract)	Gaseous melt replenishment system
Hemlock Semiconductor Corp. Hemlock, Michigan JPL Contract No. 955533	Dichlorosilane CVD process
Union Carbide Corp. Tonawanda, New York JPL Contract No. 954334	Silane-Si process
Solar-Cell-Grade Silicon Processes	
Dow Corning Corp. Hemlock, Michigan JPL Contract No. 954559	Electric-arc furnace process
SRI International Menlo Park, California JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corp. Trafford, Pennsylvania JPL Contract NO. 954589	Reduction of $SiCl_4$ by Na in arc heater reactor

Silicon Material Task Contractors

Contractor	Technology Area
Impuricy Studies	
Lawrence Livermore Laboratories Livermore, California NASA Defense Purchase Request No. WO-8626	Impurity concentration measurements by neutron activation analysis
Sah, C. T., Associates Urbana, Illinois JPL Contract No. 954685	Effects of impurities on solar cell performance
Westinghouse R&D Center Pittsburgh, Pennsylvania JPL Contract No. 954331	Definition of purity requirements
Supporting Studies	
AeroChem Research Laboratories Princeton, New Jersey JPL Contract No. 955491	Formation and growth of Si particles from SiH_4 at high temperatures
Lamar University Beaumont, Texas JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge, Massachusetts JPL Contract No. 955382	Hydrochlorination of metallurgical-grade silicon and $SiCl_4$

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

Four processes for producing semiconductor-grade Si were under development in this period by Battelle Columbus Laboratories, Energy Materials Corporation, Hemlock Semiconductor Corporation and Union Carbide Corporation.

Battelle Columbus Laboratories concluded the experimental phase of their effort to develop a process for producing Si based on the reduction of silicon tetrachloride ($SiCl_4$) by zinc (Zn). Battelle was given a four-month contract extension, covering October 1980 through January 1981, for the purpose of continuing shakedown and testing operations aimed at accomplishing eight-hour operation of the process development unit (PDU). Numerous modifications and repairs were made to the apparatus. However, all attempts at sustained operation failed due to system malfunctions, primarily corrosion effects, plugging with zinc-zinc chloride mixtures, and breakage of equipment during operation.

Energy Materials Corp. completed its experimental effort on an Si melt-replenishment system for Czochralski crystal growth using trichlorosilane ($SiHCl_3$), under a near-term cost-reduction contract. The concept of in situ deposition of Si in a reactor and its subsequent removal and collection by melting was demonstrated. However, Technical Feasibility as a continuous process was not accomplished. The final report is being prepared.

Hemlock Semiconductor Corp. continued development of a process for producing Si approaching semiconductor-grade quality from dichlorosilane (SiH_2Cl_2) using Siemens-type C-reactors. Construction of the Process Development Unit (PDU), which will be used to investigate the scaled-up redistribution of $SiHCl_3$ and to produce SiH_2Cl_2 for reactor testing, was begun in November, with completion scheduled in May 1981. All concrete and structural steel work was completed, and all of the major pieces of equipment were ordered.

To assess the purity of redistributed chlorosilanes, samples of $SiHCl_3$ from various sources were passed through Dowex catalyst of the type that is expected to be used in the PDU, and the resulting mixtures, containing about 11 mole % of SiH_2Cl_2, were fed to a Siemens-type reactor. Analysis of the Si product indicated that it was of high quality and that the Dowex catalyst does not contribute contamination by electrically active species.

Union Carbide Corp. continued with the construction of a 100-MT-Si/yr experimental process system development unit (EPSDU) at East Chicago, Indiana. The process consists of the hydrochlorination of metallurgical-grade Si and $SiCl_4$ to $SiHCl_3$ and rearrangement of the latter to silane (SiH_4), which is then pyrolyzed to Si. All foundations for equipment and structures were completed and the structural steel for the process gantry was erected. All underground utilities and services lines were installed and the civil-structural subcontracts were completed with installation of two pre-engineered structures, the control room and the Si powder melter building. Fabrication of process and auxiliary equipment for the EPSDU is progressing well. Equipment items started to arrive at the site.

In the UCC R&D program, the free-space reactor (FSR) PDU program was successfully completed after demonstrating long-term operability of the reactor. Three 12-hour tests and several shorter ones were completed according to plan. Fabrication of an alternative silane pyrolysis PDU, using a fluidized-bed reactor, was completed and installation is under way. Melter subcontract work by Kayex Corp. is about two months behind schedule. Most of the major components were procured and assembled. System checkout and preliminary melting tests using chunk Si will start soon.

Development of Processes for Producing Solar-Cell-Grade Silicon

Three contracts fall into this category; final reports are being prepared on each of them. SRI International's final report on the process for producing Si by the sodium reduction of SiF_4 was delayed for additional changes and is expected to be issued early in March. Dow Corning Corp. issued its final report on the direct arc-reactor process, in which silica is reduced by carbon. Westinghouse Electric Corp. is about to publish the final report on its arc heater process, involving the reduction of $SiCl_4$ by sodium.

Impurity Studies

C. T. Sah Associates is conducting a program to determine the maximum concentration of the metallic impurities -- titanium (Ti), molybdenum (Mo), Zn, and others -- that can be tolerated in the base of Si solar cells to maintain a given efficiency. To accomplish this, a computer model based on the fundamental parameters of solar cells for the determination of the effects of impurities and defects on cell performance is being developed. Three steps are employed in this study: (1) obtain the recombination rates of electrons and holes at impurity centers in Si; (2) compute the Si solar cell performance using the data obtained in (1), and (3) compare computed and measured cell performances. The voltage-stimulated capacitance transient spectroscopy and the diode reverse-switching current transient methods are employed to measure the thermal capture rates of electrons and holes at these impurity energy levels. The exact transmission line model is employed to compute the solar cell performances of n+/p/p+ and p+/n/n+ cells.

Measurements of the electron and hole capture rates at the lower Ti donor level and upper Ti acceptor level were made and compared with those published in the literature. Some of the published data are not accurate, due to the presence of large series resistance in both the Schottky barrier and diffused p/n junction diodes used. Large series resistance gives large resistance-times-capacitance time constants and seriously affects the filling rate measurements from which the majority carrier capture rates were determined. In addition to large series resistance, space-charge-limited current has also been observed in p-base Ti-doped n+/p diffused diodes at low temperatures (about 200K), and this current seriously affects the accuracy of the capture-rate measurements.

In the program by Westinghouse R&D Center to determine the effects of impurities on the performance of solar cells, spectral response measurements made in single-crystal and polycrystalline solar cells containing Mo, Ti, vanadium (V), or chromium (Cr) correlated well with cell I-V data. Both grain boundaries and impurities in polycrystalline devices were found to reduce carrier lifetime, resulting in decreased red response and cell efficiency. Deep-level transient spectroscopy (DLTS) and spectral response data taken together suggest interaction of Cr, a fast-diffusing species in Si, with grain boundaries to form precipitates.

Accelerated aging tests were completed for copper (Cu)- and nickel (Ni)-doped solar cells at 400°C, 600°C and 800°C. For Ni the data fit a model for thermally activated behavior with an activation energy of 0.673 eV. The "time to failure" (time to reduce cell efficiency to 90% of initial value) projected for cell operation at normal temperatures would be in excess of 20 years. In contrast to Ni, the time-temperature behavior of the Cu-doped devices does not fit a simple Arrhenius model.

Chromium-doped wafers were subjected to $POCl_3$ gettering at 600°C or 825°C and subsequently were step etched to reveal any variations in Cr activity with depth from the gettered surface. No activity was determined by DLTS to depths up to two mils below the junction, implying very rapid Cr outdiffusion or some form of thermal deactivation.

Supporting Studies

In a study of the formation and growth of Si particles from the decomposition of SiH_4 at high temperatures, AeroChem Research Laboratories used a high-temperature fast-flow reactor to make particle-growth measurements as functions of temperature (600°C to 1200°C), pressure (50 to 550 torr), and residence time (0.5 to 30 ms). Optical diagnostics consisting of attenuation and Mie scattering of laser light are being used to obtain information on formation, growth rates, and sizes of the particles. The extent of SiH_4 decomposition is being measured by infrared absorption spectroscopy. Particles are collected in the observation zone to check the particle concentrations and sizes, measured optically. Some of the results are presented in the Proceedings of the 17th PIM (see p. 103).

Lamar University prepared the draft final report on their process feasibility study, covering all efforts since contract inception in 1975. The report was reviewed by JPL personnel and is to be published soon.

In support of the Union Carbide program, the Massachusetts Institute of Technology is studying the production of $SiHCl_3$ by the hydrochlorination of metallurgical-grade Si and $SiCl_4$. Experiments were carried out with the objective of studying the life of the Si bed in the fluidized-bed reactor. After 238 hours of reaction, no significant change in the reaction rate was observed. The longevity of the Si bed shows that the hydrochlorination process can be operated continuously for long periods without interruption. A material balance of 92% was made on the Si. This result confirms the stoichiometry of the hydrochlorination reaction.

In a corrosion study made on Incoloy 800H, the selected material for the hydrochlorination reactor in the Union Carbide EPSDU, no measurable amount of corrosion was observed when a test sample was exposed to the hydrochlorination reaction for 238 hours at 500°C and 300 psig. A stable silicide protective film of approximately 20 μm thickness appears to form on the Incoloy 800H surface. This protective film is readily destroyed by air and moisture when it is exposed to the atmosphere but appears to be stable in the reactor environment. The study indicates that the Incoloy alloy is a good choice for this reactor.

The JPL in-house program included effort on the FBR, the conversion of SiH_4 to molten Si, consolidation of sub-μm Si powder produced by FSRs, and impurity studies.

The 2-in.-dia FBR was modified to improve instrumentation and to facilitate experiments. A series of experiments was then performed to determine how bed clogging would be affected by gas velocity. The results showed that the reactor could be operated without clogging at velocities as low as four times the minimum fluidization velocity (i.e., $U/U_{mf} = 4$) at 700°C and 10 mole % SiH_4 in hydrogen, but the velocity during the initial period of the test must be higher ($U/U_{mf} > 7$) to prevent clogging.

The silane-to-molten-silicon (SMS) conversion reactor was brought to temperatures above 1600°C on four occasions with no damage to the graphite heater or to the graphite reaction crucible. Lumps of Si obtained by melting sub-μm powder separate cleanly from the reactor walls.

Thermally stimulated capacitance measurements are being performed to determine electrically active impurity concentrations and energy levels of traps introduced by the impurities. Measurements were made on n-type substrate samples with aluminum contacts forming Schottky barrier diodes. The diode characteristics showed too much leakage to allow satisfactory measurements to be made; consequently, the diode fabrication process is being improved.

A method of consolidating sub-μm Si powder is being investigated. The top of a pedestal of Si is melted using a high-frequency generator. The sub-μm powder is extruded through a quartz tube, and partially compacted Si powder is fed into the molten Si surface and solidified by lowering the pedestal. It was shown that the surface of the pedestal can be melted successfully.

Large-Area Silicon Sheet Task

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

The improvement of the standard Czochralski ingot growth process by reduction of expendable material costs and improvement of ingot growth rate together with improved slicing techniques will produce large areas of silicon at costs meeting the goals of the LSA Project. Growth of large ingots by casting techniques, such as Heat Exchanger Method (HEM) growth, can further reduce sheet costs.

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 on a number of processes to determine the capability of each of producing large areas of crystallized silicon at a low cost. The final sheet growth configurations must be suitable for direct incorporation into an automated solar array processing scheme.

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

Research and development on ribbon, sheet, and ingot growth plus multiple-blade, multiple-wire, and inner-diameter (ID) blade cutting, initiated in 1975-76, are 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 continuing. After a period of accelerated development, these methods will be evaluated and the best will be selected for advanced development. As the growth methods are refined, integrated process schemes will be developed by which the most cost-effective solar cells can be manufactured.

The Large-Area Silicon Sheet Task effort is organized into four phases: research and development of sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype development

(1981-82); development, fabrication, and operation of pilot production growth plants (1983-86).

Large-Area Silicon Sheet Contracts

Research and development contracts awarded for growing crystalline silicon material for solar cell production are listed below. Preferred growth methods for further development have been selected.

Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
Ingot Technology	
Crystal Systems, Inc. Salem, Massachusetts JPL Contract No. 954373	Heat exchanger method (HEM) ingot growth; fixed-abrasive slicing technique (FAST)
Kayex Corp. Rochester, New York JPL Contract No. 955733	Advanced Cz growth (Adv. Cz)
P.R. Hoffman Co. Carlisle, Pennsylvania JPL Contract No. 955563	Multiblade slurry slicing technique (MBS)
Siltec Corp. Menlo Park, California JPL Contract No. 955282	Inner diameter (ID) wafering
Siltec Corp. Menlo Park, California JPL Contract No. 954886	Advanced Cz growth (Adv. Cz)
Silicon Technology Corp. Oakland, New Jersey JPL Contract No. 955131	Internal diameter (ID) slicing
Semix Corp. Gaithersburg, Maryland DOE Contract No. DE-F101-80ET 23197	Ubiquitous crystallization process (UCP)

Large-Area Silicon Sheet Task Contractors (Continued)

Shaped Sheet Technology

Mobil Tyco Solar Energy Corp. Waltham, Massachusetts JPL Contract No. 955843	Edge-defined film-fed growth (EFG)
Westinghouse Research Pittsburgh, Pennsylvania JPL Contract No. 955843	Dendritic WEB growth (WEB)
Honeywell Corp. Bloomington, Minnesota JPL Contract No. 954356	Silicon-on-ceramic (SOC) substrate

Material Evaluation

Applied Solar Energy Corp. City of Industry, California JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca, New York JPL Contract No. 954852	Characterization - Si properties
Charles Evans and Associates San Mateo, California JPL Contract No. LK-694028	Technique for impurity and surface analysis
Spectrolab, Inc. Sylma, California JPL Contract No. 955055	Cell fabrication and evaluation
University of Missouri, Rolla Columbia, Mossouri JPL Contract No. 955414	Partial pressures of reactant gases
Materials Research, Inc. Centerville, Utah JPL Contract No. 957977	Quantitative analysis of defects and impurity evaluation technique

INGOT TECHNOLOGY

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

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

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

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

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

MATERIAL EVALUATION

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

University of Missouri, Rolla (UMR): UMR is investigating the effects of partial atmospheric pressures of oxygen on the reaction at the contact interface between molten silicon and fused silica in several of the ingot and shaped-sheet growth techniques.

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

Charles Evans and Associates and Cornell University are doing silicon-sheet impurity analysis and structure characterization, respectively, by electron beam techniques.

SHAPED-SHEET TECHNOLOGY

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

Westinghouse: Dendritic web is a thin, wide ribbon form of single-crystal silicon produced directly from the silicon melt. "Dendritic" refers to the two wirelike 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 solar cells for a number of reasons, including the high efficiency of the cells in arrays and the cost-effective conversion of raw silicon into substrates.

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 method to be developed is directed toward a minimum-cost process for producing solar cells with a terrestrial conversion efficiency of 12% or greater. The method consists of applying a graphite coating to one face of a ceramic substrate, and dipping that substrate in molten silicon. The silicon wets only the graphite-coated face and thus produces uniform thin layers of large-grain polycrystalline silicon. A minimal quantity of silicon is consumed.

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 that 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 Process Development. This effort includes all of the work necessary to develop, demonstrate, and qualify one or 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 analysis and testing to develop optimal 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 1986. It includes the development of a life-prediction method applicable to terrestrial photovoltaic modules and validation by application of the method to specific photovoltaic demonstration sites. Material degradation studies are being conducted to determine failure modes and mechanisms. This effort supports both the materials and processes development work and the life-prediction method development.

ENCAPSULATION TASK

SUMMARY OF PROGRESS

Materials and Process Development

Pottant Materials

Candidate pottants for development and evaluation over the next two years at Springborn Laboratories have been identified in anticipation of LSA Technology Readiness. These are divided by process. The lamination-process pottants are ethylene vinyl acetate (EVA), ethylene methyl acrylate (EMA), and a recently identified all-acrylic thermoplastic laminating film from 3M Co. The casting-process pottants are poly-n-butyl acrylate (PnBA), a polyurethane and General Electric Co.'s low-cost TRV silicon rubber. The 3M acrylic laminating film and the GE TRV silicone-rubber casting liquid will be given preliminary evaluations at Springborn, with actual development and fine tuning to be carried out by the respective material manufacturers. Future work will reduce emphasis on identifying new encapsulation material candidates and will increase emphasis on improving existing material candidates. This will be carried out by fabrication and testing of modules to improve materials in those areas of specific weaknesses that limit or affect module reliability and durability.

UV Absorbers

Dr. Otto Vogl of the University of Massachusetts is continuing work on UV absorbers by grafting reactions of 4-vinyl 2(-hydroxyphenyl) benzotriazole with various polymers. Reactions are carried out with carefully prepared and purified absorber samples. Preparation of 3-propenyl-phenol by pyrolysis is also being worked on for use in condensation of diazotized o-nitroaniline in an attempt to make 5-propenyl-IV directly. Preparation of the 5-propenyl derivative has been concentrated on the preparation of p-propenyl phenol by pyrolysis of bisphenol A. Condensation of a diazonium salt, possibly with a disubstituted bisphenol A to produce a product that can be pyrolyzed to obtain unsubstituted benzotriazole and propenyl-substituted benzotriazole, has been studied. All products (derived from bisphenol A and pyrolyzed) of this path are potential UV absorbers. A crude condensation product has been prepared and will be characterized. If identified, the sample will be sent to JPL for further evaluation.

A modified technique using vacuum-sealed tubes (allowing reactions to be carried out at about 20°C higher) instead of an open-flask system has been successful in grafting 4-vinyl tinuvin to polypropylene. Careful evaluation will be made of this method using fractionation and gel-permeation chromatography analysis. Additional grafting experiments will be carried out using other polymers (polymethyl methacrylate, PnBA), EVA copolymers, polycarbonate, and polyamides).

Technology transfer of the vinyl tinuvin process from the University of Massachusetts to Springborn Laboratories has been accomplished.

Laboratory-scale production of vinyl tinuvin (approximately 250 grams) was accomplished at Springborn. The next effort with the chemically attachable UV screening agent will be to demonstrate chemical incorporation into EVA and other candidate pottants.

Electrostatic Bonding

Ten electrostatically bonded (ESB) minimodule assemblies were received from Spire as required by contract. These are being distributed to outdoor weathering sites at JPL, Point Vicente, and Goldstone, and for JPL qualification testing and other scheduled tests. Five minimodule assemblies with mesh interconnects are scheduled to be received from Spire before completion of contract, about February 1981.

Module Design

Phase I module analysis work has been completed and Phase II certification testing has begun at Spectrolab-Hughes. A day-long technical presentation on Phase I work was presented at JPL on September 11, 1980, which was summarized at both the Module Durability and Life Testing Workshop on September 23, 1980, and at the 16th PIM on September 25, 1980. The Phase I computer analysis has identified nine encapsulation design principles useful to module designers. The principles involve design features relating to thermal, optical, structural, and electrical properties, all of which were highlighted at the PIM, and will be reported in the Spectrolab-Hughes Phase I report.

Illinois Tool Works has identified three areas of difficulty in producing a state-of-the-art performing solar cell: (1) ion-plated metallization will readily form an ohmic contact on phosphorus-enriched Si surfaces but not on boron-enriched surfaces; (2) RF heating of junctions leads to junction deterioration or promotion of metal diffusion to the junction (it is believed that RF junction heating can be stopped with the use of a Faraday cage), and (3) improper packaging for shipment of diffused but unmetallized wafers results in mechanical damage to the fragile and very thin active surfaces. All of these problem areas are being worked on.

Bonding and Primers

Springborn has supplied samples of essentially all of the candidate encapsulation materials to Dr. Edward Plueddemann for identification of appropriate primers and adhesion systems, including EMA and PnBA. A primer for EVA has already been worked out and is performing satisfactorily. Efforts have also been started to identify primers for coupling candidate antisoiling coatings to outer-cover films and glasses.

Material Degradation and Life Prediction

Photodegradation Model for EVA:

A new approach to polymer photodegradation modeling by the University of Toronto that has as its basis the prediction of chemical change occurring within the polymer system as a function of outdoor exposure time was initiated. A preliminary photooxidation mechanism has been formulated and a literature search of available rate data has been carried out.

A computer simulation package necessary to generate concentration-time profiles from the mechanical model as well as a preliminary experimental design of alkane photooxidation studies has been completed.

A new gas-chromatography photolysis diagnostic technique using a continuous-wave Hg-Cd laser to irradiate weathered polyurethane samples and to monitor carbon monoxide evolved has been developed and assembled at Toronto. Preliminary studies on the development of an automatic sequential sampling system for the 50 to 100 solid samples have also been carried out. The development of this instrument would permit early detection of early weathering damage in solid plastic samples and give data necessary to test computer models.

An automatic viscometer has been demonstrated by sequential routine measurements of both solvents and polymer solutions. Preliminary measurements of weathered samples of EVA (clear and white) supplied to Toronto by Springborn indicate that there is an increase in the viscosity of solutions of the polymers (exposed outdoors in Toronto, April-October) compared with the unweathered samples. Viscosity tests are continuing.

Initial experiments on the photooxidation of n-decane as a model for polyethylene are being done. The gas-chromatograph conditions for effective product separation to afford quantitative data for validation of the computer model are being optimized.

Corrosion Diagnostics and Modeling:

A new method of rapid computer-aided analysis for ac impedance response of solar arrays has been developed at Rockwell Science Center. This analysis is being implemented to characterize mechanical damage efforts, corrosive aging mechanisms and consequent performance degradation.

Three analysis methods have been developed for nondestructive evaluation of impedance measurements of solar cells and solar arrays. These methods include: (1) a current-voltage (I-V) response model, (2) a model for distribution of impedance parameters, and (3) an analysis of frequency dependence of ac impedance response.

These models can now be combined to provide a computer-based interpretation of solar array performance in terms of ac impedance.

A particular cell-failure mode of cracking was analyzed by Rockwell Science Center using Auger electron spectroscopic profiling. Although cracking may or may not be induced by corrosive mechanisms, the void produced by a crack is a potential region for concentration of electrolytic impurities that aggravate the failure. Work at JPL has indicated that corrosion couples with the cracking process.

In order to investigate this possibility, an Auger profile of a fracture surface adjacent to the metallization was made on a sample supplied by JPL. The cell was cracked and exposed to light with intermittent soaks in distilled water. The front-surface metallization of the solar cell consisted of a Pb/Sn solder whose major components were Pb, Sn and Fe with observable quantities of S, Cl, K, O, Cr, Ni, and C. The substrate (back-surface) electrode is a Ni/Pb alloy.

After a 200-sec sputter of superficial organic contamination, the fracture surface of the Si shows primarily Fe, Ni, and Cr. The distribution suggests a migration of Cr and Fe species from the upper electrode, possibly as a result of a corrosive mechanism. Some migration of Ni is also indicated. The metals that have apparently migrated are expected to be the most active from a thermodynamic point of view since the thermodynamic tendency to electrochemical oxidation takes the order C Fe-Ni Pb Sn.

A full year's corrosion-monitor recordings have been accumulated at Mead, Nebraska; these experiments are being interrupted to return the corrosion monitors to the Science Center for calibration and analysis.

Fracture and Crack Modeling:

The TEXGAP program, a FORTRAN-coded finite-element computer program, is being procured from the University of Texas. The main feature of the program, not available in existing commercial programs, is the availability of a finite-element code that has been developed for the analysis of cracks in structures due to differential temperature loading. The program will be used to predict the stress-intensity factor at the tip of a crack or at the interface between two dissimilar materials of a solar array. The results of this analysis will be used for solar array life prediction.

The mechanical modeling of modules has continued in house as follows:

(1) A series of computer analyses with various material properties and thicknesses of encapsulants has been completed. The data are being compiled and analyzed.

(2) A study investigating the stresses in cells bonded directly to the support frame (minimum thickness of adhesive) has been completed.

(3) An extension of (2) is in progress to study the effect of thickness of adhesive on the stresses in cells.

Module Life Testing:

Validation of the Battelle accelerated-test plan* continued in house through 40 days of accumulated test time. Fatigue cracks appeared in some of

*G. B. Gaines et al, Report No. DOE/JPL 954328-79/13, June 7, 1979.

the interconnects. One module exhibited an electrical open at +95°C. Electrical power output curves, however, were normal for all modules at ambient temperature.

Nine types of minimodules being weathered at the JPL site have endured six months of weathering with no visual degradation and no significant reduction in electrical output except that two of three Springborn-Solar Power minimodules with EVA pottant and Super Dorlux (a wood product) substrates showed reductions of maximum power output of 67% and 33%. Failure analysis showed the cause to be cracked cells (three and one, respectively). It is assumed that the cell cracks were caused by humidity expansion of the Super Dorlux substrate. It is not known whether the cells were cracked during manufacture with humidity expansion widening the cracks, or cracks were initiated by the humidity expansion. An in-house program is under way to determine the temperature and moisture characteristics of Super Dorlux.

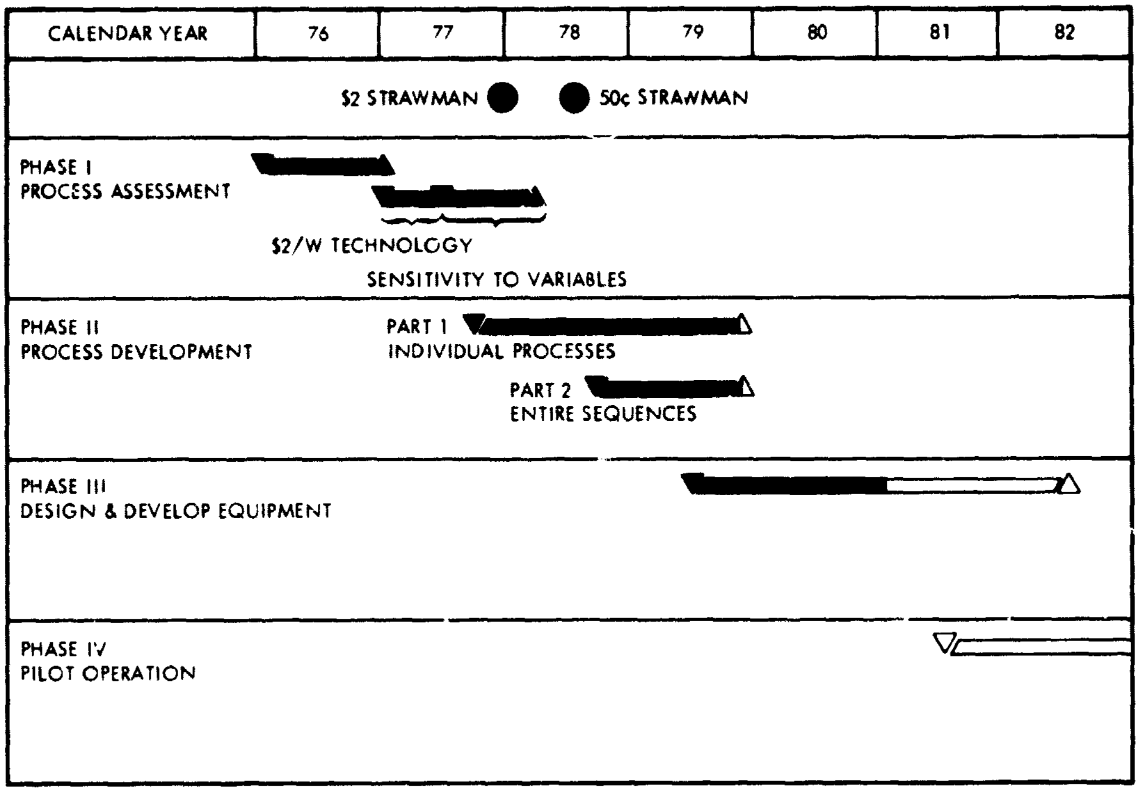
Two Controlled Environment Reactors (CER) have been constructed and tested in house. They were shipped to Springborn Laboratories (October 29, 1980) for accelerated weathering of sample modules. The CER provides acceleration of UV radiation up to 30 suns while maintaining temperature ($\pm$ 1°C) on the absorbing surface between 30°C and 60°C. It is equipped with rain and fog nozzles.

It was discovered that ventilation is extremely important during accelerated weathering. Springborn was instructed to purge the system continuously during testing using air, N_2, or any other gas mixture. The CER testing temperature range can be expanded to 100°C by installing a heating unit. Installation instructions were given to Springborn. An inspection of available accelerated testing facilities (RSA sun lamp) was also made and advantages of CER over RSA sun lamp were discussed.

PRODUCTION PROCESS AND EQUIPMENT AREA

AREA OBJECTIVES

The Production Process and Equipment Area is chartered to work with the Large-Area Sheet Task, the Encapsulation Task and the Engineering Task by selecting and developing manufacturing processes and by developing trade-offs designed to minimize the cost per watt of assembled solar modules. This work is divided into the phases shown in the figure below. At present PP&E is on schedule with Phase III, the design and development of equipment leading to demonstrations of 1982 Technical Readiness.



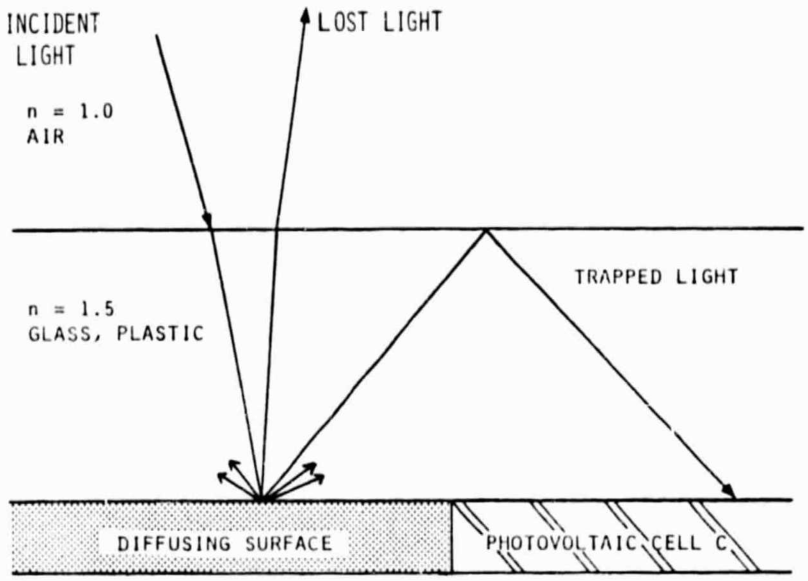
Production Process and Equipment Area Phase Schedule

SUMMARY OF PROGRESS

The main Phase II efforts, the MEPSDU contracts with Solarex and Westinghouse, are under way and are approaching preliminary design reviews. Major milestones have involved approval of program plans and work breakdown structures.

Light-Trapping Concept

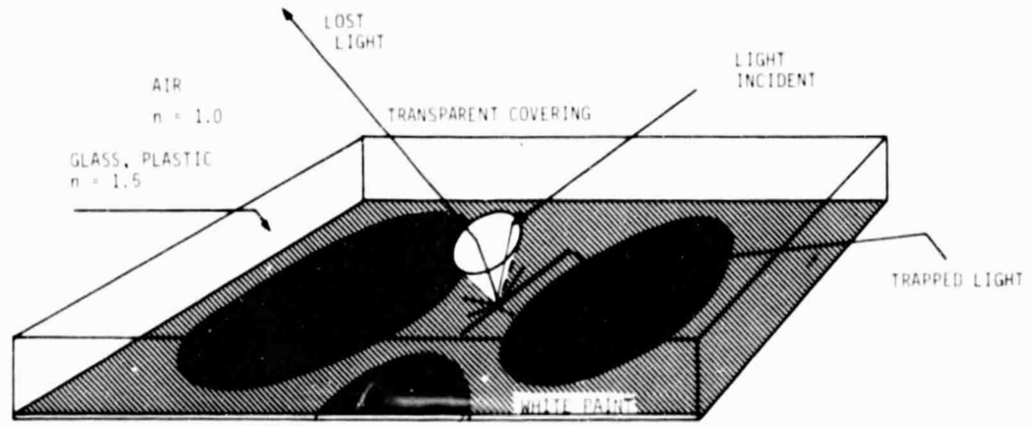
- USE OF HIGH INDEX OF REFRACTION MATERIALS
- DIFFUSELY REFLECTING INTERCELL AREA



Light Trapping by Diffuse Reflection in Thick Film

DIFFUSE LIGHT TRAPPING IS ACCOMPLISHED WHEN AN INCIDENT RAY ENTERS A HIGHER INDEX TRANSPARENT LAYER AND IS SCATTERED.

AN EXAMPLE RELATED TO PHOTOVOLTAIC MODULES IS SHOWN BELOW:



Process Sequence Development

An evaluation of approximately 500 advanced-Cz wafer samples indicated that excessive saw damage and microcracking result in a loss in electrical and mechanical yields.

Both Phase III contracts (Solarex and Westinghouse) were signed on November 26, 1980. These are two-year contracts culminating in the demonstration of Technical Readiness by 1982.

A contract was started with Motorola to investigate problems associated with processing non-Cz Si material into solar cells. The processes developed under Contract No. 954847 will be applied to this material. The contractor has agreed to investigate these processes on several non-Cz substrates, e.g., RTR and web.

Westinghouse has characterized its ultrasonic bonding of 0.001 aluminum foil with regard to the sintering of the cell metallization, the bonding pressure and power setting, and the resulting bond pull strength. The ultrasonic seam bonder was moved from Kulicke and Soffa (K&S) to their AESD Division. The seam-bonding test will be conducted at AESD by Westinghouse personnel.

Junction Formation

Spire Corp. has progressed through the construction phase of the PEBA (Pulsed Electron Beam Annealer). This machine is designed to anneal ion-implanted junctions at a rate of 10 MW/yr. Preliminary testing has been encouraging and final adjustment work has begun.

The effects of non-mass-analyzed beam parameters have been established. Sixty 2 x 2-cm samples were ion implanted without mass analysis in August and were sent to Applied Solar Energy Corp. for processing and testing. These cells were AR coated but have no back-surface field. In addition, data indicated a lack of sensitivity to implant energy over a range of 5 to 15 KeV. A reduction in dose increased the sheet resistance linearly. ASEC says that the metallization system could be optimized to achieve a fill factor of 0.76 without losing active area, up to a sheet resistance of about 500 ohms per square. This corresponds to a dose level of about 2×10^{14} atoms/cm^2.

Lockheed has successfully laser annealed back-surface fields, as well as front cell junctions, using their quartz 90° light-pipe homogenizer on the neodymium glass laser.

Metallization

The Solarex development effort to plate nickel directly on silicon has ended. PP&E is concerned about the marginal results of temperature cycling of sample cells. Efforts to verify this process in the PP&E laboratory have failed to obtain good adherence to cell p+ (Al BSF) surfaces. More work is necessary to ready this process for production.

Spectrolab has modified its previous process sequence to remedy problems with the Midfilm process. The junction cleanup step (laser scribing) is now being performed after the metallization step instead of after the junction formation step. This alleviates problems with the metal shunting the edge of the junction. The Ag powder (four types)-resin (three types) matrix has been completed with the best results obtained using 95% Thick Film Systems (TSF) spherical powder with 5% 3347D TFS frit and the newly formulated Ferro RG4933 resin, which is less humidity-sensitive. Early results gave unacceptable high series resistance (Rs) readings. The probable cause was insufficient removal of the resin from under the collector grid. Experiments involving time, temperature, pre-baking and oxygen content have produced Rs of 31 mΩ, down from the unacceptable 80 mΩ range.

Bernd Ross Associates has terminated AVX as a subcontractor for ink formulations. In order to provide more insight into the process variables and their tolerances, a more detailed study of the fabrication of the pastes is being carried out. A facility that will allow complete control of materials and processes by contract scientific personnel is being developed. Since silver fluoride is the most problem-prone component of the present base-metal paste, and since it was one of three SiO etching agents during the initial Contract No. 955164, it is of interest to examine some of the other materials in combination with base-metal pastes. The first such material is Teflon powder. This is a deviation from the original program plan.

Assembly

Kulicke & Soffa has requested and received permission to exhibit the solar module assembly-line machine, developed under PP&E near-term cost-reduction contract, to prospective buyers at their Horsham facilities, and at the IEEE PV Conference in Florida. K&S will pay all transportation costs.

ARCO Solar is continuing work to debug the automated soldering machine. The ribbon-feed mechanism is being reworked at Albuquerque Laboratories to achieve more uniform cell-to-cell spacing. Final cell-to-interconnect alignment adjustments will follow after the spacing problem has been solved. The contractor hopes for a verification demonstration run in February 1981.

JPL has stressed that Science Applications Task I, the Optical Design Rules task, should receive relatively more emphasis than Task II. During November the Task I work studied more cases of minimum-design-change modules. Work on the Task II cost-analysis area was continued. Based on preliminary test data, the optimum packing fraction for modules was calculated as a function of time. Results indicate that by using white diffuser optical concentration, the 1979 cost of field-installed arrays can be reduced by a factor of 0.63. These calculations are based upon present array costs of \$5.68/W, structure costs of \$8.00/m^2, and land cost of \$5.40/m^2.

The final report from ASEC on the high-efficiency p/n cell and module assembly contract has been approved. Tooling developed on this contract is deliverable. This tooling was used for fabrication of modules for the JPL Block IV purchase and was shipped to PP&E when no longer required.

PRODUCTION PROCESS AND EQUIPMENT AREA

Tracor MBA is continuing development of its automated laminating station. This station has three major components: (1) the vacuum-platen end effector used for robotic transfer of cell arrays and sheet materials, (2) the lamination preparation station, and (3) an automated lamination chamber. The vacuum platen has been built and tested. The platen can pick up, by means of its 35 vacuum cups, a 1 x 4-ft array of interconnected cells, glass and finished modules. All detail components of the automated lamination station are on order or are being fabricated in house at Tracor MBA.

ENGINEERING AREA

INTRODUCTION

During the reporting period, activities within the Engineering Area emphasized array requirements generation, array subsystem development, array component engineering, module specification and test requirements development, and performance criteria and test standards development. A summary of Engineering Area in-house and contracted efforts in these areas of activity is presented in the Proceedings section of this document. An expanded description of the status of each of the Engineering Area contracts was included in the 17th PIM handout. Active contracts are listed on pp. 35-36 below.

ARRAY REQUIREMENTS

A in-house investigation of array maximum power point fluctuation during the normal range of operating conditions has been initiated. Selection of the optimum input voltage window for power conditioning is influenced by the array voltage fluctuations due to site weather conditions. SOLMET Typical Year data tapes are now being used to generate yearly array power output for 26 sites as a function of irradiance level and cell temperature. Since the voltage at maximum power of an I-V curve is a function of temperature and since the maximum power output is a function of both temperature and irradiance level, the fraction of yearly power generated for a given voltage range can be determined. The optimum voltage range (expressed as $\Delta V/V$) for a power conditioner is the minimum $\Delta V/V$ for which a desired fraction of available power is actually within the operating range (input voltage range) of the power conditioner. These data will be developed for both fixed-voltage and maximum tracking arrays.

In conjunction with the 17th PIM, an industry workshop on Module and Array Safety was conducted jointly by LSA Engineering and Underwriters Laboratories at JPL on February 3, 1981. A broad spectrum of module manufacturers, systems designers and PV users were represented by 100 workshop participants. The presentations and discussions centered on a draft version of an interim safety requirement document that had been jointly prepared by JPL and UL and forwarded in advance to workshop pre-registrants. Proposed requirements and test methods were described in detail. A significant result of the workshop was a clarification of the roles of UL and the NEC and the positive influence of early development of safety requirements on user acceptance of PV systems, especially for residential and ILC applications.

Also in support of the development of module safety requirements, JPL has recently completed an assessment of requirements concerning the ability of the capacitance of a photovoltaic module to hold a hazardous charge after extraction of the module from a high-voltage array. Results to be presented in the workshop indicate permissible capacitance levels from cell string to module ground. Current modules easily meet the requirements.

Carnegie-Mellon University, which had an LSA contract to perform an exploratory study, "Safety and Product Liability Considerations for

Photovoltaic Modules and Panels," released the final report, DOE/JPL 955846-81/1, in January. The report addressed legal issues as they apply to module design, manufacture and application and suggested a methodology to be used during design of a photovoltaic module or array to eliminate or minimize perceived hazards.

Burt Hill Kosar Rittelmann Associates completed work on the study of commercial-industrial PV module and array code requirements. Preparation of the final report was initiated, with release scheduled March 30, 1981.

Results from the second part of the wind-tunnel tests have been received by the Boeing Co. The increased end-loading problem described in the September report can be reduced 50% to 70% by putting end plates on the arrays. The dynamic pressure data are being analyzed by Boeing. The Phase IV effort was initiated and the dynamic modes of two possible configurations have been determined as well as the seismic loads for those configurations. A draft of the Phase III report was received in January and is scheduled for release in March, 1981.

ARRAY SUBSYSTEM DEVELOPMENT

A design data package describing the large ground-mounted array displayed at the 16th PIM was completed including detailed panel and array structure design drawings. JPL Drawings 10097880, 10097881, and 10097882 provide sufficient detail to permit adaptation to a variety of module configurations. Copies are available from the LSA Engineering Area. A task report documenting the overall structure design effort is in press. In addition, a descriptive brochure, JPL No. 400-104, "JPL Low-cost Solar Array Structure," January 1981, was prepared for release and general distribution by DOE to interested photovoltaic-industry participants.

Contracts for the integrated residential photovoltaic array development effort have been signed with the AIA Research Corp. (JPL Contract No. 955893) and the General Electric Co. (JPL Contract No. 955894). The effort addresses the optimization of the PV array subsystem-roof interface and delivery of a prototypical section.

AIARC sponsored an eight-hour workshop on January 12, 1981, for the subcontractors performing the conceptual design work associated with the Integrated Residential PV Array Development effort. The objective of the workshop was to provide a consistent basis for the design effort and to answer questions and concerns with respect to the design boundary conditions and assumptions relative to cost.

General Electric Co. has completed a preliminary evaluation matrix of 19 residential array concepts, which were combined into 14 distinctively different module/array types. Thirty-nine evaluation criteria were grouped into seven broad categories and used to rank the concepts. Results of a preliminary assessment indicate that direct-mounted, overlapped shingle-type installation ranked highest.

ARRAY COMPONENT ENGINEERING

The module soiling studies report was published and distributed during this reporting period. The report, JPL Publication No. 5101-131 (DOE/JPL 1012-41), Photovoltaic Module Soiling Studies May 1978-October 1980, November 1, 1980, describes the results to date of the in-house experimental study to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate photovoltaic modules and cover materials. This report is available through the LSA Data Center and NTIS.

A task report (JPL Publication No. 5101-163), Determining Terrestrial Solar Cell Reliability, which documents the proceedings of the solar cell reliability workshop held May 1-2, 1980 at Clemson University, Clemson, South Carolina, was published during this reporting period. Included in the report are reproductions of graphic presentation materials and highlights of discussions related to solar cell reliability test methods. The report is available from the Data Center or from NTIS as Report No. DOE/JPL 954929-81/8. In the follow-on phase of cell reliability testing at Clemson there will be a strong focus on those cell types and metallization systems that will be used in modules designed for residential application demonstrations. This activity will be coordinated through MIT-LL.

During this reporting period, the series-parallel effort concentrated on the development of a hot-spot qualification test and, in turn, a better understanding of the operation of cells under back bias conditions. Several problems in connection with the analytical prediction of hot-spot problems and subsequent correlation of these results with tests are under investigation. These include the significance of power dissipation in a cell relative to the cell area, uniformity of power generation loci, and the uniformity of the light beam over the surface of the cell under test. The infrared camera equipment is being used to determine the temperature gradients over the surface of test cells. A hot-spot qualification test has been included in the Block V procurement package and test results were presented at the 12th PIM.

The solar cell fracture-mechanics effort continued during this reporting period. Optical microscopy and SEM examination of solar cells from Applied Solar Energy Corp. that were fracture-mechanics tested indicated that the fracture-initiating flaws for these cells are edge chips and cracks, some of which were not observed before the fracture testing. These cracks were sometimes covered by metallization and AR coating and were not obvious. A quantitative correlation of fracture strength and flaw size is under way.

A major effort in examining the mechanical fatigue life of cell interconnects is also continuing. The predictive model presented at the last PIM correlated well with interconnect failures experienced at Schuchuli, Arizona. Applying this failure prediction technique to similar modules at the Mead, Nebraska, site indicates that interconnect-fatigue problems should be expected there within two years. During the reporting period, an interconnect-fatigue cycling apparatus was fabricated and large numbers of interconnects tested to failure. Several additional configurations will be tested in the future. In the meantime a formal cost-optimal-design algorithm has been developed and its practicality demonstrated. The algorithm yields 20-year array power reduction and required interconnect redundancy to achieve minimum life-cycle energy cost. Future work includes refining the algorithm (based upon additonal interconnect tests) and developing charts and nomographs from which to compute interconnect strain levels (without the substantial cost impact of using a finite element computer code). An expanded predictive module based on observed probabalistic failure statistics together with the test data was presented at the 17th PIM.

In the area of PV/thermal module development, tests were completed on an unglazed PV/T module configuration to verify the feasibility of a PV/T test method proposed as part of the IPC. Preliminary indications are that the test method will be applicable to a variety of collector types and configurations. Work has been initiated on a joint task report with Arizona State University to document the background and rationale for the electrical and thermal performance test methods being developed for flat-plate PV/T and concentrator modules.

In the area of environmental test development, evaluation of the use of a "greenhouse" effect accelerated aging environmental exposure technique is continuing. After 75 days of exposure, minimodules from the outdoor hot box test have been taken down, inspected, flashed and tested for voltage breakdown. There has been some cosmetic degradation of several of the modules, but no electrical degradation. The post-exposure voltage breakdown test results are being studied. The modules are back in the hot box for further exposure.

In the Voltage Isolation Task a variety of activities continued. The low-voltage film breakdown apparatus fabrication is in progress. Sheldahl delivered the test samples on February 3, 1981. The order was placed for the Biddle Partial Discharge Test apparatus, with delivery scheduled for October 1981. Cell-string flaw-characterization test-fixture fabrication was completed and initial air-gap and film-breakdown tests will begin after the 17th PIM. Several material test samples were received for electrical isolation capability testing including hardcoat anodized aluminum plates (intended for PV/T collector substrates) and laminate sections representing the Motorola Block IV design back surface composite. Humidity sensors and monitors were received and mounted in modules that will be installed at the JPL Field Site No. 1 High Voltage Facilty. The decision was made to expand the test voltage capability to 3000 Vdc and to add a second test rack at this facility. Work on the facility modification is in progress.

IIT Research Institute released the first quarterly report on LSA Engineering Area Support Contract No. DOE/JPL 955720-80/1, on development of elements of a reliability design guidebook for flat-plate photovoltaic modules and arrays. This report documents work performed and completed by IITRI through September 1980 on two subtasks. It is available upon request from the LSA Data Center.

The DSET Laboratories Spectral Measurement contract, which is gathering data on relative global vs direct vs diffuse irradiance for the New River, Arizona, site, demonstrated fully automatic solar spectrum data acquisition, reduction and curve plotting using their NOVA-30 computer. Solar spectrum measurements at resolutions ranging from 1 nanometer to 5 nanometers, depending on the portion of the spectrum being measured, have been initiated at regular monthly intervals and will continue over the next two-year period.

MODULE SPECIFICATIONS

As part of developing design test and qualifications criteria for the Block V Module Production RFP, drafts were completed of both residential and intermediate-load specifications. The drafts, along with the new interim safety standard, were forwarded to approximately 80 PV industry participants on January 21, 1981, with a request for review and comments by February 10th. Release of the two specifications, JPL Publication No. 5101-161 for intermediate-load requirements and JPL Publication No. 5101-162 for residential requirements, was scheduled for February 20, 1981. Work was initiated on a preliminary draft of a Central-Station Application Preliminary Specification.

PERFORMANCE CRITERIA AND TEST STANDARDS

The Array Subsystem Task Group met in Huntsville, Alabama, on November 19 and 20, 1980. The Electrical Performance Subgroup of the Array Subsystem Task Group met in October and November 1980, and January 1981. Test methods for actively and passively cooled concentrator modules were reviewed. Principal issues were: (1) the appropriateness of using reference cells for the I-V characterization of concentrator modules; (2) the advantages and disadvantages of several different formats for presenting electrical and thermal performance data; (3) new criteria in safety and durability and test methods for salt spray and SO_2.

The PV/Thermal Subgroup of the Array Subsystem task group met in Huntsville on November 18, 1980 at Wyle Laboratories. The subgroup discussed a draft of the Operating Cell Temperature Determination Test for Flat Plate Actively Cooled Modules and several performance criteria statements. A final version of the test method was prepared for the Task Group. Several of the criteria statements were also prepared for final review by the Task Group.

In support of the SERI-funded JPL standards efforts, Wyle Laboratories was awarded a contract to identify and document corrosion sensitivities and failures associated with outdoor exposure of photovoltaic modules and components and to document performance criteria and candidate test methods for inclusion in IPC-2. A data package on the corrosion observations at JPL field site prepared by LSA Quality Assurance was delivered to Wyle.

Engineering Area Contractors

Contractor	Contract Number	Description
AIA Research Corp. Washington, DC	955893	Integrated residential PV array development
Boeing Co. Seattle, WA	954833	Wind-loading study on module and array structures
Burt Hill Kosar Rittelmann Associates Butler, PA	955614	Residential module O&M requirements study

Engineering Area Contractors (Cont'd)

Contractor	Contract Number	Description
Clemson University Clemson, SC	954929	Solar cell reliability test
DSET Laboratories, Inc Phoenix, AZ	713131	Accelerated sunlight exposure of modules
DSET Laboratories, Inc Phoenix, AZ	713137	Spectral radiometric measurements and standards
General Electric Co. Philadelphia, PA	955894	Integrated Residential PV Array Development
IIT Research Institute Chicago, IL	955720	Reliability engineering of modules and arrays
Underwriters Laboratories Melville, NY	955392	Solar array and module safety requirements

OPERATIONS AREA

MODULE PRODUCTION TASK

Block IV Design and Qualification

Applied Solar Energy Corp., Motorola, Inc., Solar Power Corp., and Spire Corp. have completed work on the design and qualification phase of this task. ARCO has delivered intermediate-load modules for testing, but has not yet completed an approved set of drawings for the residential module; hence, residential modules have not yet been fabricated for test. Photowatt has delivered intermediate-load modules that are now in the environmental test sequence. Solarex Corp. has provided both residential and intermediate-load modules for testing but a completely satisfactory lamination sequence has not yet been demonstrated.

The physical features, encapsulation systems, cell features and electrical characteristics of these modules are tabulated in the Proceedings of the 17th PIM and are to be considered a part of this Progress Report (see pp. 71-74). A summary of the problems encountered in the course of the qualification testing and a brief summary of price analysis also appears in the Proceedings (see pp. 75-81).

Generally, the following observations and conclusions hold:

-- New design and technology were assimilated, but with some difficulty. Schedules slipped, tests were failed, and there were a few retreats to conventional approaches.

-- Large-scale production was not tested.

-- Prices are down; efficiencies have risen; reliability and durability appear to have improved because of better hail protection, improved moisture protection and fault-tolerant cell-circuit arrangement.

-- Most designs are to be offered commercially.

Block IV Production

Although purchase orders have been issued to six of the eight participants in the Block IV design phase, modules have been received from only two contractors. Motorola has delivered all but 10 modules ordered and will be the first contractor to complete the order. Solar Power has provided seven modules of a commercial configuration to be tested in lieu of the module designed under Block IV. ASEC, GE and Spire are in the fabrication mode. Solarex has not yet been given the go-ahead, since the drawing packages are not approved. ARCO Solar and Photowatt purchase orders have not yet been issued, and await qualification testing of the modules under Phase I.

Block V

The Block V RFP was prepared and made ready for issue, but was held back because of rebudgeting.

MODULE TEST AND EVALUATION

Environmental Testing

Two special series of tests were run in this period, both related to the Block V specifications. One of these was an extended sequence of thermal cycling tests of various modules to determine susceptibility to interconnect-fatigue cracks. This test was initiated after interconnect failures of Block II and III modules (Y type) in the field in less than two years. In the long-term temperature-cycling tests, opens occurred in Y-type modules in less than 100 cycles and in V-type Block III modules in less than 200 cycles. The proposed Block V 200-cycle temperature test should effectively uncover field interconnect problems that might occur in the first two to four years.

The other special test was the proposed Block V humidity cycling test. Results were reported by John Griffith at the 17th PIM (see p. 373). This single test is more effective than the Block IV temperature and humidity tests combined, both in severity and in the variety of degradation observed.

Tests have been completed on World Bank modules and results were also reported at the PIM (see p. 373).

Other environmental test results are summarized in the following tables. Modules tested include Block IV MIT-LL Residential Experiment Station (RES), and two commercial types (one with CdS cells).

Recent Qualification Test Results

Block IV	Construction	Prinicpal Problems
VENDOR CODE	(From Top Down)	
RS	Glass, PVB, Tedlar/Al/Tedlar. Modified edge sealant includes glass tape and a butyl tape between laminate and SS frame	This latest version passed all hi-pot tests; backing material delaminated at J-box area
US	Glass, PVB, Tedlar/steel/Tedlar; steel backing now grounded to frame	Earlier ungrounded back surface modules failed hi-pot but this latest version passed; edge sealant extruded from ends of modules during temperature cycling
VS	Glass, PVB, Tedlar/Al/Tedlar, Al frame	Modules were electrically unstable with variations to ±4%; many cracked cells found in the first to be received; after temperature cycling, there was frame separation at the corner of one, terminal covers loosened and fell off, some delamination at frame seal, 2 cell cracks
YR, YS	Glass, EVA, Tedlar	Latest set of two modules each have completed temperature and humidity cycling; in temperature cycling, frame seal delamination and Tedlar delamination and blistering occurred; all four modules degraded electrically in humidity cycling--10, 14, 16, and 45%, respectively; internal shorting was discovered in one; some cells moved closer and are touching

Recent Qualification Test Results (Continued)

MIT-LL Res Program/ Application Area	Construction	Principal Problems
MB/NE	Glass, PVB, Tedlar	J-Boxes came loose, warped; terminal strip loosened; backside Tedlar delamination
YB/NE	Glass, EVA, Tedlar	Tedlar delamination and blistering, encapsulant air bubbles in temperature

Recent Commercial Module Test Results; Temperature and Humidity Cycling Only

Vendor Code	Construction	Results
BN	Glass, encapsulant, Al substrate and frame	Satisfactory after temperature cycling
BV	Clear acrylic, silicone gel encapsulant, white acrylic substrate, Al side rails	Catastrophic failure in temperature cycling; acrylic substrate corners broken, one cover sheet broken, delamination and bubbles over cells, electrical failures (18%, 29%, 50% and 52% loss, respectively)
EB	Glass, PVB, CdS cells, plastic screen, copper pan, paint; hermetically sealed	In temperature cycling, encapsulant bubbles developed at ends of cells; voltage-regulator plastic covers melted; one module has 25% power loss after humidity cycling; electrical measurements made in natural sunlight because of slow response time of CdS; power increased at low ambient temperatures after tests but stayed nearly the same at about 60°C

Performance Measurements

The spectral response of cells presently used for Block IV modules manufactured by ASEC, GE, and Photowatt do not match that of the reference cells now in use. New reference cells are being selected, fabricated and calibrated. Reference cells are also being selected, fabricated and calibrated for MIT Lincoln Laboratory to be used for testing ASEC, ARCO Solar, Inc., Solec International, Inc., Solarex, Motorola and Spire (photovoltaic/thermal) modules.

LAPSS 2 is functioning properly and is being used for module evaluation. Four types of modules with a maximum power of from 20 to 60 watts were measured using LAPSS 1 and LAPSS 2. Results indicate that LAPSS 1 P_{max} measurements average 1.2% higher than LAPSS 2 P_{max} measurements. Most of this difference is attributed to a similar difference in the measurement of module current (1.1% at I_{sc} and I_{mp}). This difference is considered to be within the normal measurement error of the system.

Field Tests

A draft of the annual report for the year ending August 31, 1980, is in press and is expected to be distributed by mid-February. The key conclusionfrom analysis of the data covered in the report is that no fundamental life-limiting mechanisms have been identified that could prevent the 20-year life goal being met.

Preparation began for deployment of the Block IV modules. To accommodate these modules a reorganization of the test site network is underway:

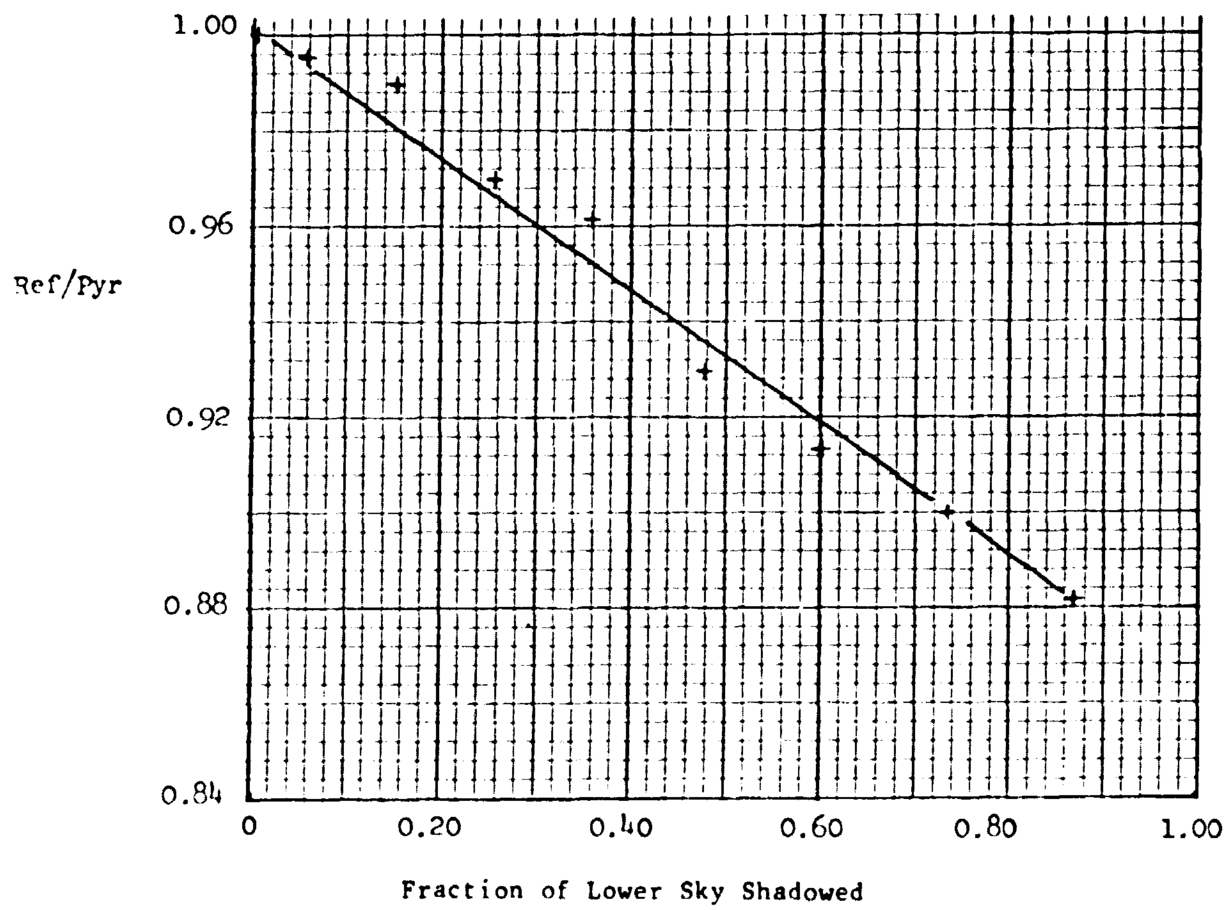
-- Eight of the Continental Remote sites -- Canal Zone, Key West, New Orleans, Houghton, New London, Albuquerque, Fort Greely (Alaska), and Mines Peak -- will double in size from four to eight 4 x 8-ft test stands. Most of the Block II modules will be removed and replaced with Block IV intermediate load modules; approximately four of each type will be deployed.

-- The operating mode at the Continental Remote sites at Seattle, Crane, San Nicolas Island and Dugway will be changed to one of reduced activity. No Block IV modules will be deployed and the scheduled yearly acquisition of performance data on the remaining Block II modules will occur as time is available.

-- At the local remote sites, Goldstone, Point Vicente and Table Mountain, all of the Block I modules and about half of the Block II and III modules will be removed and replaced with the same quantity and type of intermediate-load modules as deployed at the Continenal Remote sites. In addition, small arrays composed of Block IV residential modules will be deployed.

-- At the JPL site, approximately 85% of the Block I modules and 70% of the Block II modules will be removed. The quantity of Block IV modules to be deployed will be two to three times the number at the local remote sites. The residential modules will be mounted as roof-section arrays on the large support in the northeast corner of the field.

On December 22, 1980 a diffuse-sky shadowing experiment was conducted at the JPL test site to confirm results obtained the previous year by the Performance Measurement Group. The purpose of the experiment was to determine the difference in insolation from the top to the bottom of a test subarray that is located behind (north of) another subarray. The difference is attributable to the shadowing of a portion of the sky by the forward subarray. All data were taken within 15 minutes of solar noon. The sky was hazy with high cirrus cloud formations. Insolation varied between 80 to 90 mw/cm^2 during the test period. A Li-Cor pyranometer was placed at the top of the array while a reference cell was moved down the subarray face in 6-in. increments. Readings from both instruments were recorded simultaneously. The subarrays were tilted 50° during the test period. The results, shown graphically in the following figure, indicate that the insolation at the bottom of the subarray could be as much as 13% less than at the top for the conditions stated and that the loss of insolation is almost linear as a function of the fraction of the sky below the sun that is shadowed or blocked out. This experiment will be repeated for other sky conditions.



Failure Analysis

Analysis of a number of modules returned from Mead, Schuchuli, and Mount Laguna from one Block II and III manufacturer were found to have broken cell interconnects and opens due to cracked cells. The interconnect was found to have failed because of improper interconnect stress-relief loop forming, short active length for flexing, and thermal mismatch between the polyester glass substrate, the cell, and the copper interconnect. MIT Lincoln Labs also returned 20 modules from the Natural Bridges National Monument Application for analysis. Sixteen of the module failures involved shorts to ground, which were caused by the interconnect foil contacting ground, generally between the edges of the foil and the metal substrate or in the terminal area. The 17th PIM presentation on shorts to ground covered this problem in detail (see pp. 399-410). Three laminated-design modules with broken cover glasses were found to have edge chips, which initiated fractures during diurnal temperature cycling. One module failed due to a cracked cell, which fractured both main current collectors on the front surface of the cell. There was also a notable amount of discoloration at cell edges and where cell cracks existed in this PVB-encapsulated module.

The Mount Laguna Solar array was visited in January 1981. The number of 30W modules in the bypass mode (open-circuited) has increased from 128 in August 1980 to 160 in January 1981. The 20W module bypass increased from 14 to 20 during the same period. The next on-site evaluation is planned for July-August of 1981. It is expected that the latter module bypass rate will show a further increase at that time, since the predominant failure mode (fractured interconnects) tends to show open circuits at elevated temperatures.

Applications Interface

Test and Applications Project support provided:

- Attendance and follow-up support to 22 reviews (Quarterly and Critical) at both Sandia for PRDA applications and Lincoln Laboratory for residential applications.

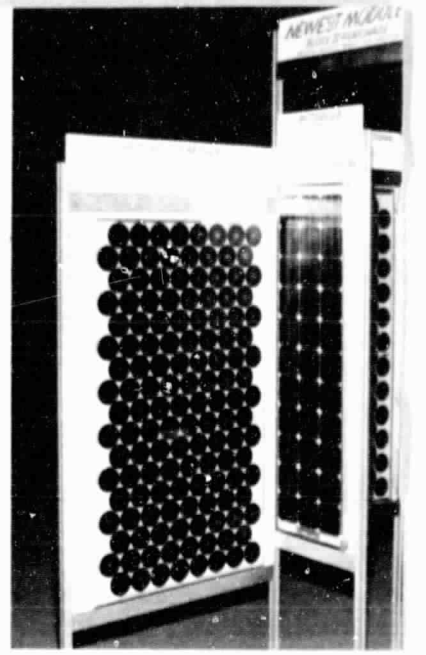
- Coordination and follow-up support of module failure analysis activity as associated with field failures at various MIT-LL and Lewis Research Center installations.

- Coordination of field survey of the PV installation at Mount Laguna.

- Received modules from PRDA and residential applications for qualification testing.

- Received and processed requests from Lincoln Laboratory for 10 reference cells to support the current residential applications. Number of required cells will probably increase as more experiments are undertaken. Sandia's request for 40 reference cells (to support concentrator PRDAs) has been received and is being discussed with Sandia.





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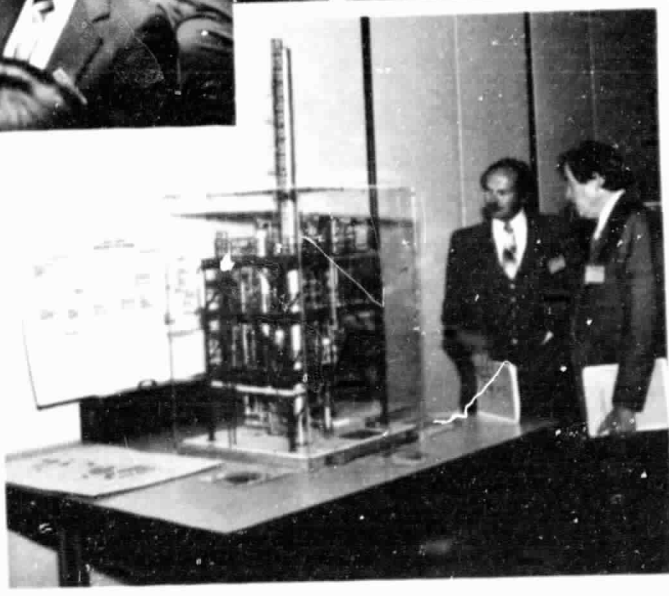


PROCEEDINGS

Proceedings Summary

Highlights of the 17th Project Integration Meeting held February 4 and 5, 1981, at the Pasadena Center, Pasadena, California:

The first day of the meeting consisted of a summary of a panel discussion on the Role of Government in Photovoltaics by invited industry executives and JPL management at The California Institute of Technology on the previous day. Highlighted were consensus items such as the need for emphasis on central-power-station demonstration work, continued underwriting of high-risk research and technology development, and the agreement that while $0.70/W modules will be produced, debate persists on whether that will be the common selling price in 1986.

In addition, the first day's session presented a summary of Union Carbide Corp. Si refinement activities. Also presented was a summary of the hydrogenation work on silicon tetrachloride being done by MIT and the significance of that work on the potential improvements in conventional Siemens deposition processes.

A summary was also presented on the results of approximately two and a half years' work in near-term cost-reduction activities. Numerous predicted cost reductions were realized through the contract actions that were completed.

A comprehensive discussion was held on encapsulation materials and design principles for photovoltaic module encapsulation packaging. Various aspects of material characteristics, compatibility with module requirements, lifetime potential and costs were presented.

The results of a Safety Design Workshop held the previous day were presented, highlighting the many safety considerations under study by LSA and its principal safety contractor, Underwriters Laboratories. Specific engineering procedures have been developed as a result of this work, which is still under way.

Block IV module procurement results were presented regarding physical and performance characteristics and attention was invited to the definite improvements over previous module purchases by LSA.

Presentations were made by both Westinghouse and Solarex on their MEPSDU contracts. Considerable interest was shown by the audience in both contract efforts, then just starting.

The computerized price estimation technique, IPEG4, was demonstrated to illustrate the flexibility of this new analytical tool. Example analyses were manipulated by audience request in real time.

PROCEEDINGS SUMMARY

Participants were privileged to hear two notable speakers. Eddie Mlavsky, for many years directly involved in the U.S. Photovoltaics Program, discussed some international perspectives on photovoltaics that were of interest in view of his work in Israel during the past two years. Paul MacCready presented an exciting film and a talk on his adventures and successes with the Gossamer Penguin and with the Solar Challenger photovoltaics-powered light aircraft.

Plenary Session

TECHNOLOGY DEVELOPMENT AREA
Silicon Material Task

Plenary Session **K.M. Koliwad, Chairman**

Union Carbide reported on the status of development of the silane (SiH_4)-to-silicon (Si) process. An experimental process system development unit (EPSDU) with a Si capacity of 100 MT/yr is being constructed at East Chicago, Indiana. All foundations were completed, the structural steel for the process gantry was erected, and all underground utilities and service lines were installed. Process equipment is being fabricated, with delivery of some items already taking place.

The free-space reactor process development unit (PDU) effort was successfully completed, with demonstration of long-term operability of the reactor.

Hydrochlorination of mgSi and $SiCl_4$ for Si Processes (MIT)

Development of a process for producing low-cost trichlorosilane ($SiHCl_3$), which is used to make SiH_4 in the Union Carbide process and from which Si is deposited in the conventional (Siemens) process for producing semiconductor-grade Si, was described by MIT. The study has shown the conditions under which the hydrochlorination reaction should be carried out. Copper was shown to be an effective catalyst.

Significance of the Hydrochlorination Results (JPL)

The MIT hydrochlorination process, which converts metallurgical-grade Si (mgSi) and $SiCl_4$ to $SiHCl_3$ in a low-cost operation, has wider potential commercial application than only to the Union Carbide silane-to-silicon process. Relatively large amounts of $SiCl_4$ are produced as a byproduct in the conventional (Siemens) process for making semiconductor-grade Si and also in other processes using chlorosilanes as intermediates. Economic advantage could accrue from conversion of this $SiCl_4$ to $SiHCl_3$, thereby eliminating $SiCl_4$ disposal costs and attaining nearly complete Si utilization. It was recommended that trade-off studies be conducted to evaluate the potential savings.

STATUS OF UNION CARBIDE EPSDU

UNION CARBIDE CORP.

Hiroshi Morihara

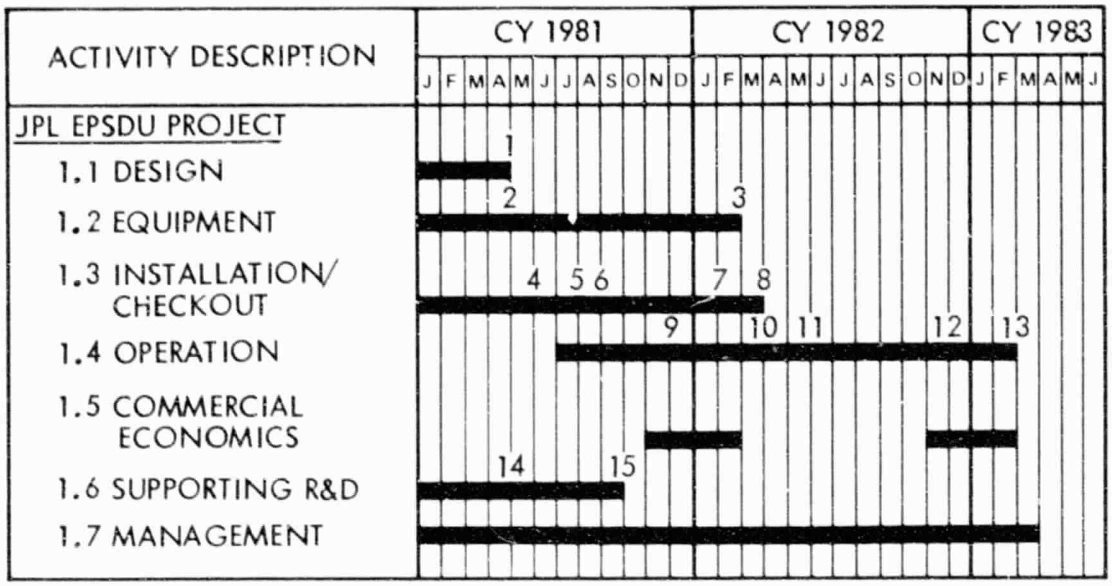
TECHNOLOGY	**REPORT DATE**
POLYCRYSTALLINE SILICON	02/04/81
APPROACH HIGH-PURITY SILANE PRODUCTION FROM METALLURGICAL-GRADE SILICON; AND SILANE PYROLYSIS AND CONSOLIDATION TO FORM SEMICONDUCTOR-GRADE POLYCRYSTALLINE SILICON **CONTRACTOR** UNION CARBIDE CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY AND ENGINEERING PRACTICALITY. • ESTABLISH TECHNOLOGY READINESS USING "EPSDU" SIZED TO 100 MT/YR. • SILICON PRICE OF LESS THAN $14/KG FOR HIGH VOLUME PROCESS. • DEFINE PROCESS ECONOMICS.	**STATUS** DESIGN & ENGINEERING WORK ON THE EPSDU • THE CIVIL-STRUCTURAL SUBCONTRACT TO BE COMPLETED IN MID-FEBRUARY. • PROCESS AND AUXILIARY EQUIPMENT STARTED TO ARRIVE AT THE JOB SITE. • DETAILED INSTALLATION DRAWINGS FOR MECHANICAL AND ELECTRICAL SUBCONTRACTS TO BE COMPLETED WITHIN TWO MONTHS. SILANE PYROLYSIS R & D • THE FREE-SPACE REACTOR PDU WORK SUCCESSFULLY COMPLETED. • QC METHOD DEVELOPMENT WORK SUCCESSFULLY COMPLETED. • THE Si POWDER MELTER/SHOTTER ASSEMBLED AND READY FOR SYSTEM CHECKOUT. • ASSEMBLY OF THE FLUID-BED PYROLYSIS PDU NEARING COMPLETION AND READY FOR CHECKOUT IN A WEEK.

DEVELOPMENT OF HYDROCHLORINATION REACTOR

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Jeffrey Mui

EPSDU PROGRAM MAJOR MILESTONES



1. BID PACKAGE READY FOR MECHANICAL & ELECTRICAL INSTALLATION.
2. MOST EQUIPMENT FOR SILICON-TO-SILANE DELIVERED TO SITE.
3. EQUIPMENT FOR SILANE PYROLYSIS DELIVERED TO SITE.
4. SUBCONTRACT AWARD FOR MECHANICAL INSTALLATION AND OFF-SITE SUBASSEMBLY STARTED.
5. START OF ON-SITE INSTALLATION.
6. START OF ON-SITE ELECTRICAL INSTALLATION.
7. END OF INSTALLATION & START OF CHECKOUT.
8. END OF CHECKOUT.
9. OPERATING MANUAL COMPLETE & START OF OPERATOR TRAINING.
10. START OF STARTUP.
11. STARTUP COMPLETE AND START OF DATA ACQUISITION.
12. END OF DATA ACQUISITION AND START OF DURABILITY ASSESSMENT.
13. END OF TEST PROGRAM.
14. START OF FLUID-BED PDU TESTING.
15. END OF FLUID-BED TESTING.

What Is the Hydrochlorination Reactor?

UNION CARBIDE SILANE-TO-SILICON PROCESS

I HYDROCHLORINATION: $3\ SiCl_4 + 2\ H_2 + Si \rightleftarrows 4\ SiHCl_3$

II REDISTRIBUTION: $2\ SiHCl_3 \rightleftarrows SiCl_4 + SiH_2Cl_2$

$SiH_2Cl_2 \rightleftarrows SiHCl_3,\ SiH_2Cl_2,\ SiH_3Cl,\ SiH_4$

III PYROLYSIS: $SiH_4 \longrightarrow 2\ H_2 + Si$

- HYDROCHLORINATION STEP ENABLES A CLOSED LOOP PROCESS BY RECYCLING BY-PRODUCT $SiCl_4$
- REACTOR PROCESSES ABOUT 65 LBS OF $SiCl_4$ FOR ONE POUND OF Si METAL PRODUCED
- COST SAVING ON THIS STEP HAS A LARGE IMPACT ON THE ECONOMICS OF THE OVERALL PROCESS

What Has Been Done

HYDROCHLORINATION REACTOR DEVELOPMENT AT
THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

I ENGINEERING DATA
- REACTION KINETICS, YIELD, CONVERSION
- CATALYST, IMPURITIES
- SILICON PARTICLE SIZE, MASS LIFE
- CORROSION STUDY

II CONCLUSIONS
- EFFICIENT REACTION, HIGH YIELD AND CONVERSION
- COPPER CATALYST DOUBLES REACTION RATE
- LONG PERIODS OF CONTINUOUS OPERATION
- CONVENTIONAL METAL ALLOYS FOR REACTOR

III RECOMMENDATION
- MAXIMIZE REACTOR PRESSURE 500 PSIG
- ADD COPPER CATALYST TO INCREASE RATE
- INCOLOY 800 AS MATERIAL OF CONSTRUCTION FOR THE REACTOR

What Remains to Be Done

I REFINE ENGINEERING DATA FOR SCALE-UP

- OPTIMIZE PROCESS PARAMETER, FLUIDIZED-BED, PACKED-BED DESIGN
- MAXIMIZE RAW MATERIAL UTILIZATION, RECYCLE BY-PRODUCT WASTE STREAM
- QUALITY CONTROL, ORGANIC AND INORGANIC IMPURITIES IN CHLOROSILANE PRODUCTS

II CORROSION STUDY

- MECHANISM OF CORROSION
- SCREEN MATERIAL OF CONSTRUCTION FOR THE HYDROCHLORINATION REACTOR

Potential Application to Polycrystalline Silicon Technology

I THE CURRENT SIEMENS TECHNOLOGY FOR POLY SILICON

$$SiHCl_3 + H_2 \xrightarrow{1000°C} Si,\ SiCl_4,\ HCl,\ \text{LITES, HEAVIES}$$

II THE HYDROCHLORINATION OF $SiCl_4$

$$3\ SiCl_4 + 2\ H_2 + Si \rightleftarrows 4\ SiHCl_3$$

- IT PRODUCES THE STARTING $SiHCl_3$ FOR THE SIEMENS TYPE REACTOR AT ESSENTIALLY 100% EFFICIENCY
- IT CONSUMES THE BY-PRODUCT $SiCl_4$
- IT CAN ALSO CONVERT HCl AND OTHER BY-PRODUCTS TO $SiHCl_3$
- IT FITS PERFECTLY INTO THE SIEMENS PRODUCTION SCHEME TO FORM A CLOSED LOOP PROCESS
- SUBSTANTIAL SAVINGS ON RAW MATERIAL COST CAN BE REALIZED

SIGNIFICANCE OF HYDROCHLORINATION RESULTS

JET PROPULSION LABORATORY
Ralph Lutwack

- STC- A BY-PRODUCT OF CHLOROSILANE PROCESSES
  - SIEMENS PROCESS
  - UNION CARBIDE PROCESS
  - FLUIDIZED BED REACTOR PROCESSES

- PRESENT STC UTILIZATION
  - PRODUCTION OF SILICA
  - EPITAXIAL DEPOSITION

- ADVANTAGES OF HR USE
  - STC DISPOSAL COSTS ELIMINATED
  - COMPLETE Si UTILIZATION

  COMPARATIVE PRODUCT VALUES
    - STC
    - SEMICONDUCTOR GRADE Si

- CONCLUSION AND RECOMMENDATION

  ECONOMIC ADVANTAGES
  TRADEOFF STUDIES

PLENARY SESSION: PRODUCTION PROCESS AND EQUIPMENT AREA

NEAR-TERM COST-REDUCTION RESULTS

JET PROPULSION LABORATORY

D.W. Boyd

Near-Term Activity Evolution

LEGISLATION

PUBLIC LAW 95-238, SECT. 208(b) (FEB., 1978);
SUPPLEMENTAL APPROPRIATIONS BILL (PAUL TSONGAS, MA.)

$6.0M AUTHORIZED FOR NEAR-TERM TECHNOLOGY DEVELOPMENT OF PHOTOVOLTAIC SYSTEMS (ESPECIALLY COST REDUCING PRODUCTION TECHNOLOGIES)

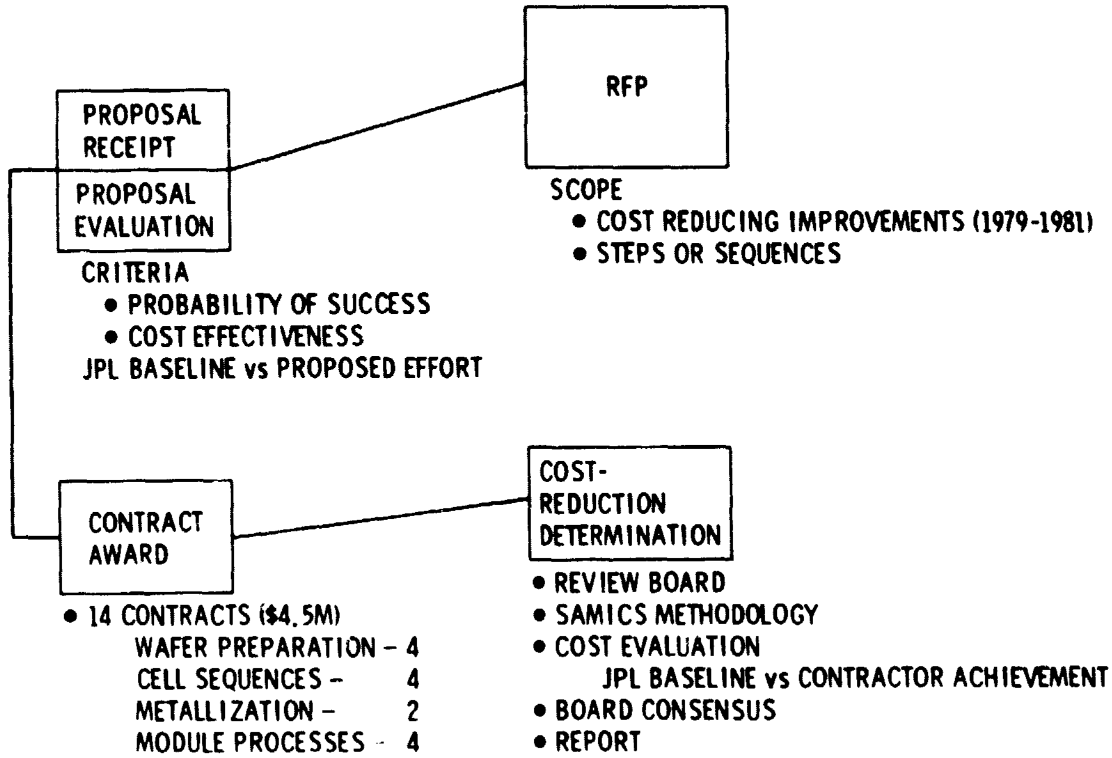
GOALS

- ACCELERATE REDUCTION IN FLAT-PLATE PHOTOVOLTAIC MODULE MANUFACTURING COSTS (1979-1981)
- DEMONSTRATE NEAR-TERM COST REDUCTION IMPACT OF ADVANCED PROCESSING APPROACHES
- TRANSLATE COST-REDUCING MANUFACTURING TECHNIQUES INTO COMMERCIAL PRACTICE
- PROVIDE FOR MAXIMUM TECHNOLOGY TRANSFER TO INDUSTRY TO ENSURE COMMON BENEFIT

PROGRAM

- LSA PROJECT ADD-ON
- $4.5M FOR DEVELOPMENT OF COST REDUCTIONS IN MATERIAL, EQUIPMENT, MODULE DESIGN, PROCESSES AND AUTOMATION

Contract Selection and Evaluation Process



LSA Baseline Process Sequence

GROW INGOT
CROP AND GRIND
ID SAW
TEXTURIZE
SPIN-ON DOPANT
DIFFUSION
BACK SURFACE ETCH
SCREEN PRINT BACK
SCREEN PRINT FRONT
EDGE GRIND

AR COAT
ELECTRICAL TEST
ASSEMBLE INTERCONNECTS IN PVB
SOLDER CELLS/INTERCONNECTS
INSPECT SOLDER
LAMINATE
INSPECT LAMINATION
ASSEMBLE TERMINALS
TEST MODULE

Near-Term Contract Cost-Reduction Results

COMPANY	TECHNOLOGY	PREDICTED COST REDUCTION ($/Wp)*	ACTUAL COST REDUCTION ($/Wp)*
1. KULICKE & SOFFA	MODULE ASSEMBLY	2.32	0.77
2. ARCO SOLAR	NON-CZ SHEET	2.16	-
3. SILTEC	CRYSTAL SLICING	1.46	0.33
4. ARCO SOLAR	MODULE ASSEMBLY	1.43	1.76
5. ENERGY MAT'L CORP.	PHOTOVOLTAIC MATERIAL	1.40	0
6. SENSOR TECHNOLOGY	CELL PROCESS SEQUENCE	0.74	0
7. KAYEX	CZ GROWTH	0.43	0.62
8. MOTOROLA	METALLIZATION PATTERNING	0.38	0
9. MOTOROLA	CELL PROCESS SEQUENCE	0.37	0.68
10. MOTOROLA	ENCAPSULATION	0.26	0.11
11. SENSOR TECHNOLOGY	ETCHING	0.21	0.23
12. SOLLOS	METALLIZATION DEPOSITION	0.10	0.09
13. MB ASSOCIATES	ENCAPSULATION	0.08	0
14. RCA	MEGASONIC CLEANING	0.07	-

*1975 DOLLARS

Project Baseline/Near-Term Composite Common Parameters

CELL SIZE	3 in. dia
NO. CELLS/MOD	316
MODULE SIZE	4 ft x 4 ft
HARDWARE PERFORMANCE	100 W_p
MODULE EFFICIENCY	6.7%
CELL EFFICIENCY	10%

Process Sequence Using Near-Term Contracts

PROCESS STEP	PROJECT BASELINE: VALUE ADDED \$/Wpk	PROJECT BASELINE: YIELD %	NEAR-TERM COMPOSITE: ALTERNATE STEP NAME	NEAR-TERM COMPOSITE: VALUE ADDED \$/Wpk	NEAR-TERM COMPOSITE: YIELD %	COMPOSITE COMPONENTS (NEAR-TERM)
GROWINGOT	3.737	-	GROWK23	3.040		KAYEX-MOLY SHIELD
CROPGRIND	0.035	95		0.029		
IDSHW	0.844	96	IDSILTEC	0.742	96	SILTEC - DYNAMIC FILTER CONTROL
TEXTURIZE	0.020	99.8		0.018		
1 SPIN-ON	0.400	95		0.378		
1 POCL	0.075	99		0.071		
4 BSE	0.314	99.9		0.295		
AGSPB	0.184	98	MOSPO2	0.089	98	SOL/LOS-MOLY TIN METALLIZATION
2 HGSPF	0.720	98	MOSPF2	0.144	98	
2 GRINDIN	0.041	95		0.038		
3 ARCONTI	0.030	99		0.029		
2 TEST	0.078	90		0.075		
INTASSY	1.339	-	INTERCEPTOR	2.491	99.9	K&S - AUTOMATED ASSEMBLY
CELLASY	1.741	98		-	-	
SOLDINSP	0.065	95		-	-	
-	-	-	ARGLASS	0.102	-	MOTOROLA - AR GLASS
LAM	0.203	95		0.203		
LAMINSP	0.059	95		0.059		
TERASSY	0.076	98		0.076		
MODTEST	0.002	98		0.002		
Σ\$(1980)/Wpk	9.463			$7.931 \left(\frac{10}{10.2}\right) = 7.775$		
Σ\$(1975)/Wpk	7.084			$5.937 \left(\frac{10}{10.2}\right) = 5.821$		

Conclusions

NEAR-TERM CONTRACT ACTIVITY WAS BENEFICAL

- LOW FUNDS EXPENDITURE
- SHORT TIME PERIOD
- FOCUS ON SPECIFIC TECHNOLOGY

RESULTED IN

- TIMELY IDENTIFICATION OF PROMISING AND LESS-CERTAIN PRODUCTION PROCESS IMPROVEMENTS

NEAR-TERM PAYBACK IS FEASIBLE

STATUS OF ENCAPSULATION MATERIALS AND OF ENCAPSULATION DESIGN PRINCIPLES

JET PROPULSION LABORATORY

E.F. Cuddihy

LSA Encapsulation Task

(17th PIM Meetings)

1) WOOD SUBSTRATE WORKSHOP
2) GENERAL PRESENTATION ON STATUS OF ENCAPSULATION MATERIALS AND DESIGN PRINCIPLES
3) CONTRACTOR PRESENTATIONS
4) FORUM ON ENCAPSULATION MATERIALS AND DESIGN PRINCIPLES FOR IN-DEPTH QUESTIONS AND DETAILS

Post-PIM Publication

1) ENCAPSULATION HANDBOOK

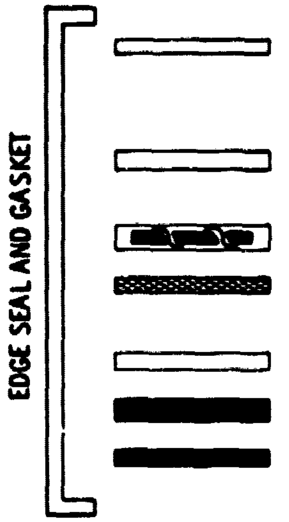
Program Divisions

• MATERIALS, PROCESSES, AND MODULE DESIGNS	MATERIAL IDENTIFICATION AND DEVELOPMENT, MODULE FABRICATION PROCESSES, MODULE DESIGNS, ENGINEERING SPECIFICATIONS FOR MATERIALS AND MODULES
• MODULE LIFE AND RELIABILITY	ACCELERATED, ABBREVIATED, AND OUTDOOR TESTING; CHEMICAL AND DESIGN REQUIREMENTS FOR MATERIALS AND MODULES TO ASSURE LONG-TERM SERVICE LIFE, PERFORMANCE, DURABILITY, AND RELIABILITY

ENCAPSULATION MATERIALS

Module Construction Elements

MODULE SUNSIDE

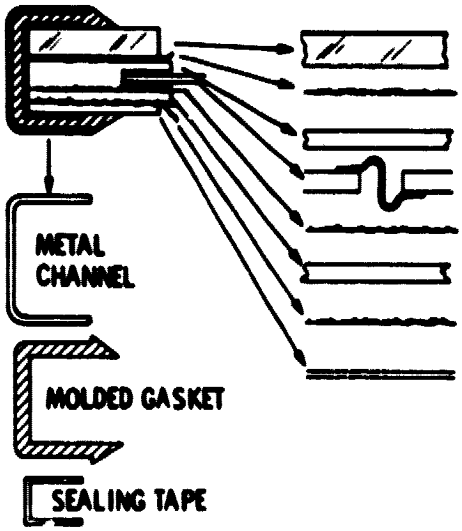


LAYER DESIGNATION	FUNCTION
SURFACE 1) MATERIAL 2) MODIFICATION	• LOW SOILING • EASY CLEANABILITY • ABRASION RESISTANT • ANTIREFLECTIVE
FRONT COVER	• UV SCREENING • STRUCTURAL SUPERSTRATE
POTTANT	• SOLAR CELL ENCAPSULATION
POUROUS SPACER	• AIR RELEASE • MECHANICAL SEPARATION
DIELECTRIC	• ELECTRICAL ISOLATION
SUBSTRATE	• STRUCTURAL SUPPORT
BACK COVER	• MECHANICAL PROTECTION • WEATHERING BARRIER • INFRA-RED EMITTER

PLUS NECESSARY PRIMERS/ADHESIVES

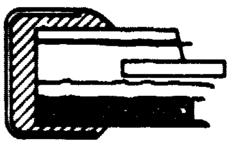
Cost Distribution*

SUPERSTRATE DESIGN



	COST - $/M²
GLASS (LOW IRON)	$5.50 - 8.50
SPACER	0.10 - 0.10
POTTANT	0.70 - 1.00
SILICON CELLS	- -
SPACER	0.10 - 0.10
POTTANT	0.70 - 1.00
SPACER	0.10 - 0.10
BACK COVER	1.00 - 2.00
SUBTOTAL	8.20 - 12.80
EDGE SEAL & GASKET	1.10 - 2.60
MODULE TOTAL	$9.30 - 15.40/M²

SUBSTRATE DESIGN



UV COVER FILM
POTTANTS
SUBSTRATE (WOOD OR STEEL)
EDGE SEAL & GASKET

MODULE TOTAL $5.00 - 13.00/M²

*IN 1980 DOLLARS FOR LARGE VOLUME PURCHASES

Lamination Pottants

MATERIAL	PROJECTED COST	STATUS
1) ETHYLENE VINYL ACETATE	≈$0.95/POUND	AVAILABLE (SPRINGBORN)
2) ETHYLENE METHYL ACRYLATE	≈$0.95/POUND	BEING DEVELOPED (SPRINGBORN)
3) ACRYLIC ELASTOMER	≈$1.50/POUND	IMMINENT AVAILABILITY (3M)
4) POLY VINYL BUTYRAL	≈ $3.00/ POUND	COMMERCIAL

Formulation of Industrial-Ready EVA

INGREDIENT	FUNCTION	SPRINGBORN FORMULATION IDENTIFICATION NUMBER A-9918 CLEAR (phR)*	A-99308 PIGMENTED (phR)*
ELVAX 150	BASE EVA	100	100
LUPERSOL 101	CURING AGENT	1.5	1.5
NAUGARD-P	ANTIOXIDANT	0.2	-
TINUVIN 770	UV STABILIZERS	0.1	-
CYASORB UV-531	UV STABILIZERS	0.3	-
TiO_2	WHITE PIGMENTS	-	2.0
ZnO_2	WHITE PIGMENTS	-	5.0
FERRO AM-105	UV STABILIZER	-	0.5

*COMPOSITION - PARTS PER HUNDRED OF RUBBER

Castable Pottants

MATERIAL	PROJECTED COST	STATUS
POLY-n-BUTYL ACRYLATE	≈$0.85/POUND	BEING DEVELOPED (JPL/SPRINGBORN)
ACRYLIC LIQUID	?	DEVELOPMENT BEING CONSIDERED (RICHARDSON)
ALIPHATIC POLYETHER URETHANE	≈$1.30/POUND	BEING DEVELOPED (SPRINGBORN)
SILICONES	≈$ 10.00/ POUND	COMMERCIAL
G E SILICONES	≈$ 3.00/ POUND	EXPERIMENTAL

Pottants: Evolving Specifications and Requirements

- GLASS TRANSITION TEMPERATURE < -40°C
- MECHANICAL CREEP RESISTANCE AT 90°C
- TENSILE MODULUS < 2000 PSI at 25°C
- OPTICAL TRANSMISSION (0.4 TO 1.1 μm), > 90%
- HYDROLYSIS RESISTANCE (TO BE DEFINED)
- ULTRAVIOLET REACTION SENSITIVITY (WAVELENGTH CUT-OFF)
- THERMAL OXIDATION RES'^TANCE AT 60°C
- PEAK SERVICE TEMPERATURE CALL-OUT
- CHEMICAL INERTNESS (COPPER, NICKEL, SOLDER, ETC)
- OTHERS

Front Covers for Substrate Designs
UV-Screening Plastic Films

MATERIAL	COMMERCIAL COST	STATUS
ACRYLIC		
a) X - 22416, 2 MILS	≈ 4.8¢/FT²	AVAILABLE, 3M
b) X - 22417, 3 MILS	≈ 6.7¢/FT²	
FLUOROCARBON		
a) TEDLAR 100 BG 30 UT, 1 MIL	≈ 6¢/FT²	AVAILABLE, DUPONT
b) TEDLAR 200 XRB 160 SE, 2 MIL	≈ 12¢/FT²	BEING DEVELOPED, DUPONT
ACRYLIC/FLUOROCARBON ALLOYS		
BLENDS OF POLY VINYLIDENE FLUORIDE AND POLY METHYL METHACRYLATE		
a) FLUOREX-A, 1.8 MILS	?	BEING DEVELOPED, REXHAM

Edge Gasket Materials Survey
(Elastomeric Molding)

CANDIDATES
- ETHYLENE/PROPYLENE (EPDM)
- ETHYLENE VINYL ACETATE (EVA)
- NEOPRENE
- SILICONE

NOT CANDIDATES
- NATURAL RUBBER
- STYRENE/BUTADIENE
- BUTYL/HALOGENATED BUTYL RUBBERS
- NITRILE/BUTADIENE
- POLYSULFIDE
- HYPALON
- FLUOROELASTOMERS

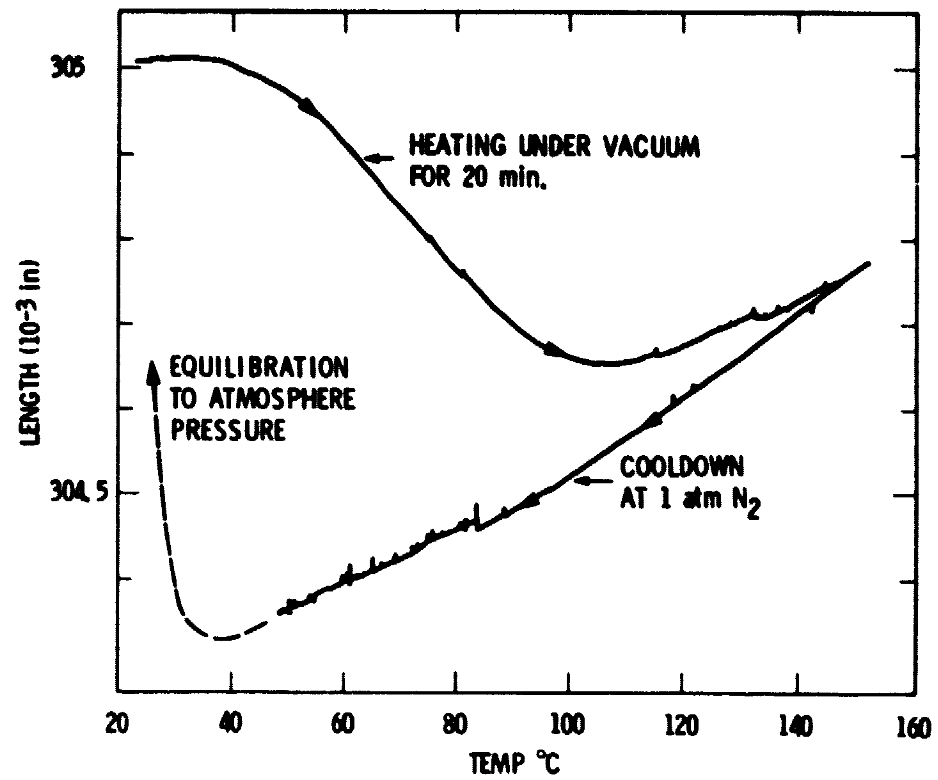
Edge-Seal Materials Survey
(Tacky Filler)

- BUTYLS
- POLYSULFIDES
- POLYURETHANES
- SILICONES
- HYPALONS
- NEOPRENES
- POLYAMIDES
- ACRYLICS

Edge Gaskets
Evolving Specifications and Requirements

- GLASS TRANSITION TEMPERATURE, $< -40^{\circ}C$
- WEATHER STABLE
- NON-STAINING
- UNPLASTICIZED
- LOW COMPRESSION SET AT 60°C
- CHEMICAL INERTNESS
- ACCOMMODATE MODULE EXPANSION/CONTRACTION
- FABRICABLE AS SEAMLESS, ONE-PIECE UNIT

Dimensional Change of Masonite Under Vacuum-Bag Lamination Processing Condition



Commercial Corrosion-Prevention Coatings for Mild Steel

COATINGS	COST, BOTH SIDES ¢/FT^2
• POLYVINYLIDENE FLUORIDE (PRIMER + ENAMEL) PPG INDUSTRIES, 10 YEARS OUTDOOR TO DATE	11.2
• SILICONE/POLYESTER DEXTER - MIDLAND, PROTOTYPES TO 20 YEARS	5.4
• POLYESTER DEXTER - MIDLAND, 5-10 YEARS OUTDOORS	4.0
• ACRYLIC COATING PPG INDUSTRIES, 5 YEARS OUTDOORS	4.0
• POLYESTER (COMPLIANCE COAT) DEXTER - MIDLAND, 5 YEARS OUTDOORS	4.0
• ACRYLIC EMULSION COATING DEXTER-MIDLAND, 5 YEARS (EXTRAPOLATED)	5.2
• POLYESTER POWDER COATING DEXTER - MIDLAND	5.6
• "BONDERITE" PRIMER TREATED CONVERSION; TO BE APPLIED PRIOR TO COATING	0.2

Back Covers for Glass Superstrate Designs

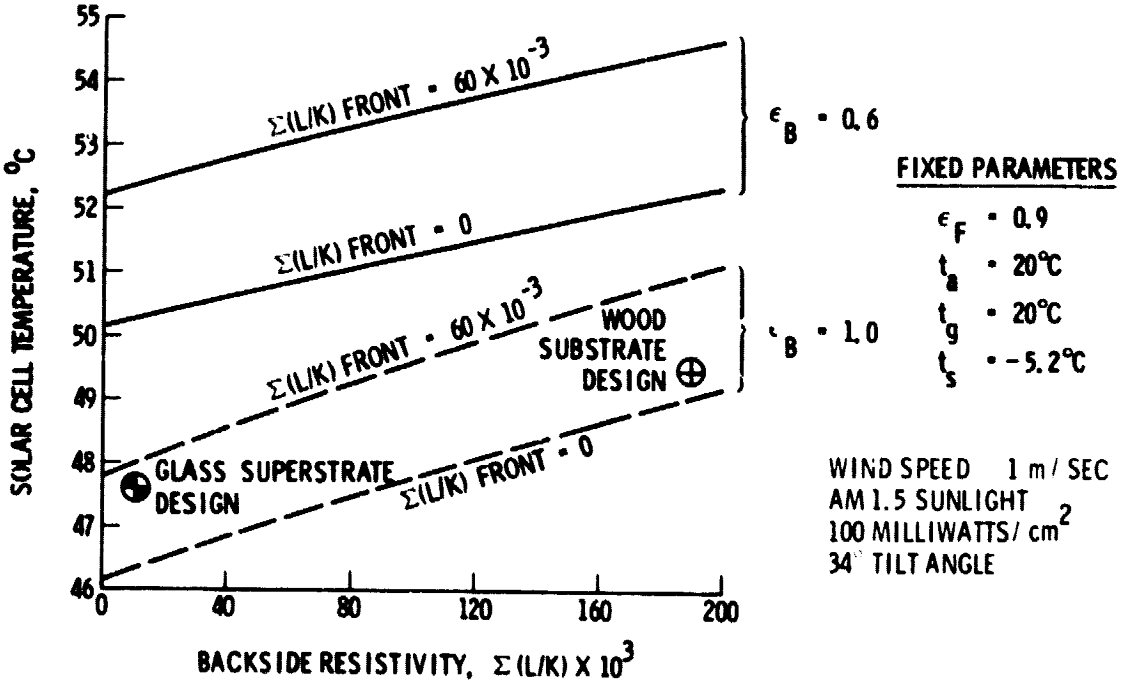
- WHITE PIGMENTED POTTANTS (SPRINGBORN)
- SCOTCHPAR 10-CP-WHITE POLYESTER FILM (3M)
  - a) 1 MIL STANDARD ≈ 2¢/FT^2
  - b) 2 MIL STANDARD ≈ 4¢/FT^2
  - c) 2 MIL HI-FILLED ≈ 5¢/FT^2
- WHITE PIGMENTED VERSIONS OF X-22416 AND X-22417 UV SCREENING ACRYLIC FILMS, BEING DEVELOPED BY 3M
- PLASTIC FILM/METAL FOIL LAMINATES
- MYLAR
- TEDLAR

Candidate Anti-Soiling Coatings Or Surface Treatments

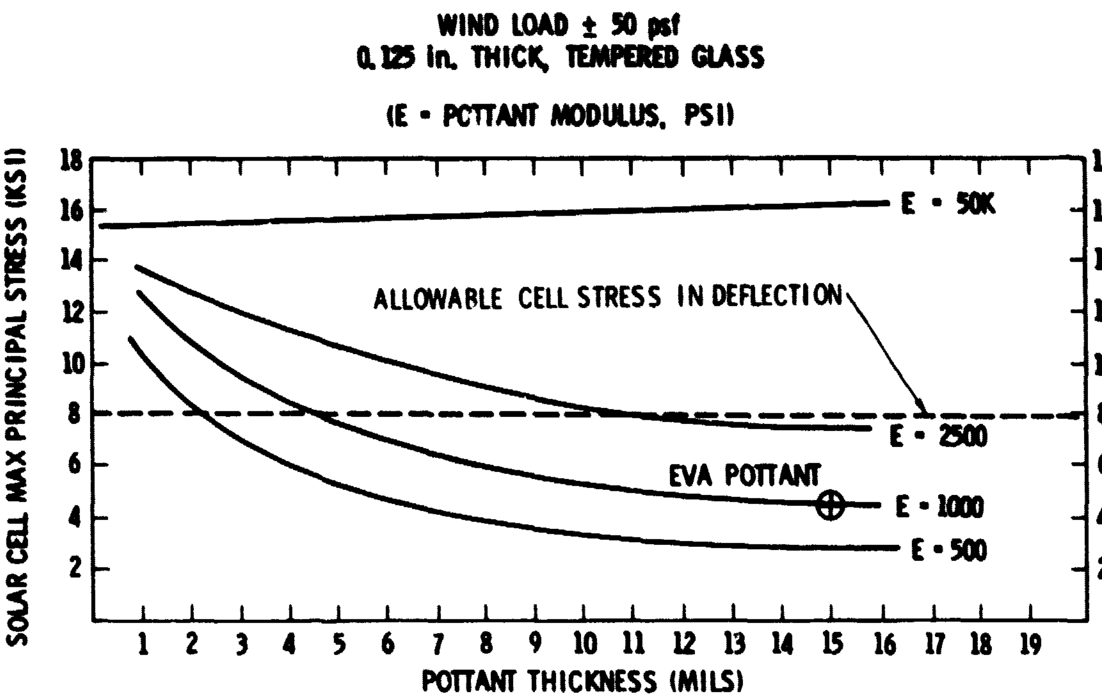
1) FLUORINATED SILANE, L-1668 (3M)
2) FC-721 AND FC-723, FLUORINATED ACRYLIC POLYMER (3M)
3) PERFLUORODECANOIC ACID WITH CHEMICAL COUPLING PRIMER
4) GLASS RESIN 650 (OWENS-ILLINOIS)
5) WL-81 ACRYLIC (ROHM AND HAAS)
6) SANTICIZER 141 SURFACTANT (MONSANTO) WITH CHEMICAL COUPLING PRIMER Q3-6060 (DOW CORNING)
7) SHC-1000 ANTI-ABRASION COATING (GENERAL ELECTRIC)
8) MAGNESIUM FLUORIDE ANTI-REFLECTIVE COATING (DEPOSITED ON GLASS BY ION-PLATING, ITW)

Solar Cell Temperature

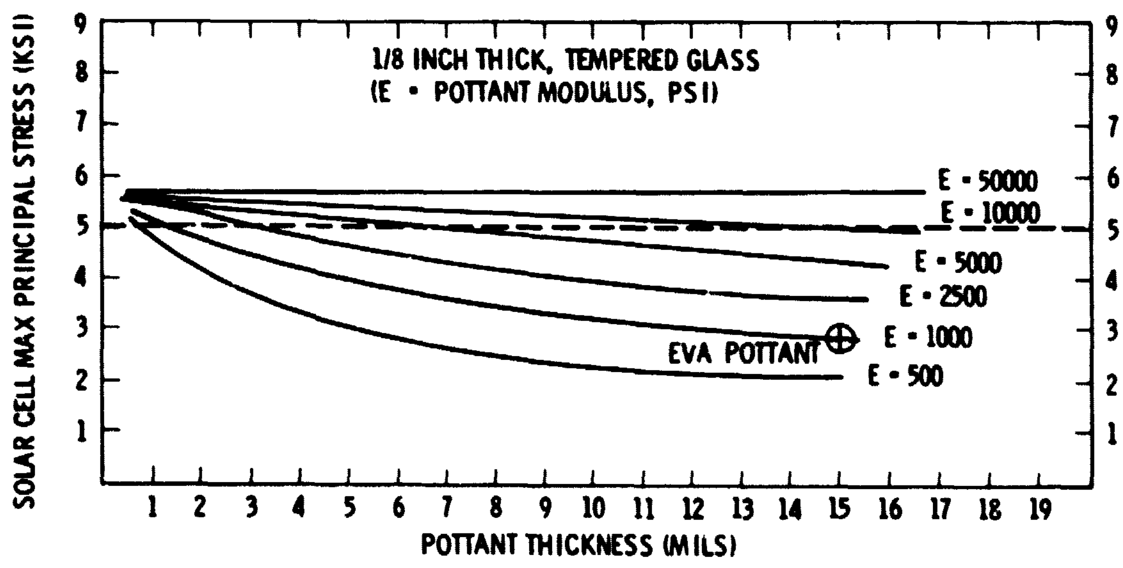
Illustrative Trend as Function of Thermal Resistivities and Backside Emissivity



Deflection Analysis
(Glass Superstrate Design)



Thermal Stress Analysis (ΔT = 100°C)
(Glass Superstrate Design)



DOTTED LINE - ALLOWABLE CELL STRESS IN TENSION

Engineering Design: Trends and Guidelines

1) TEMPERATURE CONTROLLED PRIMARILY BY EMISSIVITY, AIR CIRCULATION, NOT BULK THERMAL CONDUCTION
2) AR COATING ON CELL A MUST
3) RIBS ARE NECESSARY ON SUBSTRATE MODULES
4) AL SUBSTRATE NOT COST EFFECTIVE FOR LARGE CELLS
5) ENCAPSULANT SHOULD BE ELASTOMERIC
6) LOW IRON TEMPERED GLASS COST EFFECTIVE
7) CRANE GLASS MATS ABOVE CELLS OKAY
8) FRAME DESIGN: 3/8" BITE, 1/16" GASKET
9) MINIMUM POTTANT THICKNESS HAS STRUCTURAL DEPENDENCE

BLOCK IV MODULE RESULTS

JET PROPULSION LABORATORY
Larry Dumas

Outline

- CONTRACT OVERVIEW
  - OBJECTIVES
  - APPROACH
  - SCHEDULE
- MODULE CHARACTERIZATION
  - MECHANICAL
  - ELECTRICAL
- ENVIRONMENTAL TEST EXPERIENCE
- PRICE ANALYSES
- SUMMARY AND CONCLUSIONS

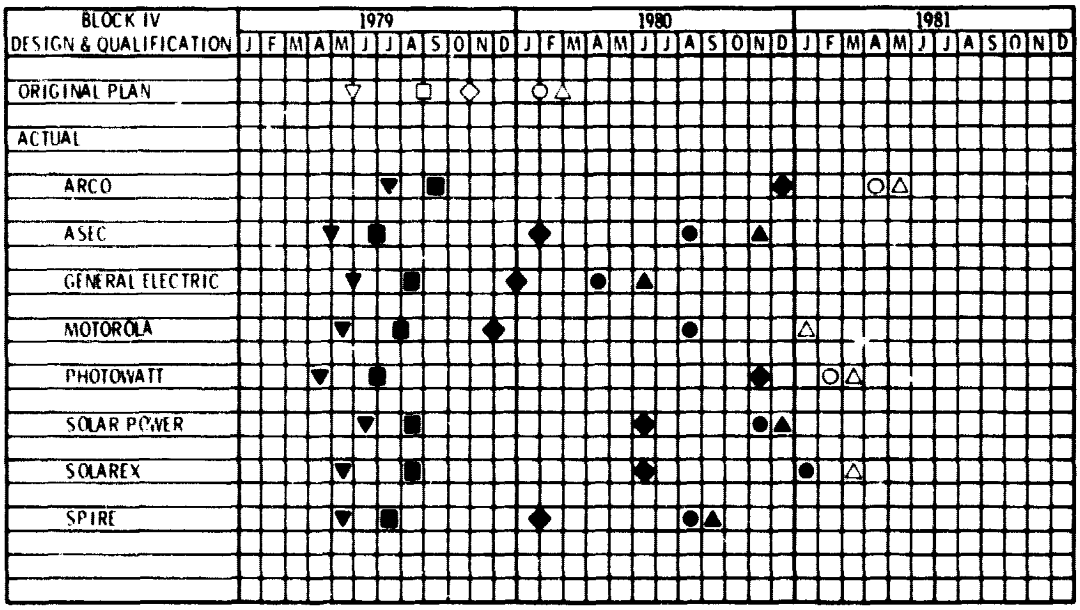
Contract Objectives

- STIMULATE USE OF LATEST IMPROVEMENTS IN PRODUCTION TECHNOLOGY
- PROVIDE PROVEN, STATE-OF-THE-ART RESIDENTIAL & INTERMEDIATE-LOAD MODULE DESIGNS FOR DOE PROCUREMENTS
- ASSESS PROGRESS IN MEETING INTERIM PRICE AND PERFORMANCE GOALS
- PROVIDE INDUSTRY WITH PRODUCT PERFORMANCE DATA

Third-Generation Designs

- IMPROVED SPECIFICATION OF POWER OUTPUT
- FAULT TOLERANCE FOR INCREASED RELIABILITY (IMPROVED YIELD)
- MECHANICAL AND ELECTRICAL CONFIGURATIONS ARE ADDRESSED TO GENERALLY LARGER APPLICATIONS
- IMPROVED ARRAY EFFICIENCY IS ENCOURAGED
- ENVIRONMENTAL QUALIFICATION PROCEDURES AND LEVELS ARE CONSISTENT WITH AND RESPONSIVE TO APPLICATION FACTORS
- PROCESS-CONTROL-RELATED QA PROGRAMS ARE EMPHASIZED
- INNOVATIVE DESIGN APPROACHES DEMONSTRATING TECHNOLOGY READINESS (CELLS, MATERIALS, PROCESSES)

Schedule



▽ CONTRACT START
□ PRELIM. DESIGN REVIEW
◇ MOD. TO JPL FOR TEST
○ FINAL DESIGN REVIEW
△ FINAL REPORT

Physical Features

MANUFACTURER	MODEL NO.	SIZE (m)	MASS (kg)	ELECTRICAL TERMINATION	CELL CONFIGURATION					CELL PACKING FACTOR
					TOTAL	SERIES	PARALLEL	PER SERIES BLOCK	SERIES PER DIODE	
RESIDENTIAL										
ARCO SOLAR	ASI 15 2200	1.20 x 0.58	4.8	PIGTAILS	60	20	3	20	20	0.79
GE	4TE258296G1	0.27 HEX	3.9	CRIMP FCC	19	19	1	19	NONE	0.76
SOLAREX	BT 580 R	1.19 x 0.63	11.2	PIGTAILS	72	12	6	1	1	0.87
INTERMEDIATE LOAD										
ARCO SOLAR	ASI-16-2300-20	1.22 x 0.30	5.3	J-BOX	35	35	1	35	35	0.77
ASEC	60-3062	1.20 x 0.70	13.5	PIGTAILS	136	34	4	5-6	34	0.74
MOTOROLA	MSP 43040G	1.20 x 0.36	5.8	J-BOX	33	33	1	33	NONE	0.76
PHOTOWATT	20-10-1961	1.20 x 0.45	7.4	CONNECTOR	72	12	6	12	12	0.62
SOLAR POWER	5175	1.20 x 0.60	10.0	J-BOX	72	12	6	12	12	0.76
SOLAREX	BT 580-L	1.20 x 0.64	13.9	PIGTAILS	72	36	2	1	1	0.85
SPIRE	058-0007	1.20 x 0.42	7.4	CONNECTOR	108	36	3	3	36	0.84

Encapsulation

	SUPERSTRATE OR TOP COVER	POTTANT	SPACER	SUBSTRATE OR BACK COVER	FRAME
RESIDENTIAL					
ARCO SOLAR	TEDLAR	EVA	-	STEEL	BATTEN-SEAM
GE	3/16 in. GLASS	RTV	POLYETHYLENE FOAM	WEATHERPROOF PAPER	NONE
SOLAREX	3/16.in. GLASS	EVA	CRANEGLASS	TEDLAR	GASKET
INTERMEDIATE LOAD					
ARCO SOLAR	1/8 in. GLASS	PVB	-	TEDLAR-Fe-TEDLAR	ALUMINUM
ASEC	3/16 in. GLASS	PVB	-	TEDLAR	ALUMINUM
MOTOROLA	1/8 in. GLASS	PVB	-	TEDLAR-Al-TEDLAR	STAINLESS STEEL
PHOTOWATT	1/8 in. GLASS	PVB	-	TEDLAR-Al-TEDLAR	ALUMINUM
SOLAR POWER	LLUMAR	EVA	GLASSFIBER	ACRYLIC	STEEL
SOLAREX	3/16 in. GLASS	EVA	CRANEGLASS	TEDLAR	ALUMINUM
SPIRE	1/8 in. GLASS	EVA	PELLON	MYLAR-Al-COAT	STAINLESS STEEL

Cell Features

	SIZE (cm)	BASE MATERIAL	JUNCTION	FRONT METALLIZATION	BACK METALLIZATION	ENCAPSULATED CELL η AT SOC (%)	ENCAPSULATED CELL η AT 28° (%)
RESIDENTIAL							
ARCO SOLAR	10 (DIA)	Cz	n/p	PRINTED-Ag	Al	10.0	12.3
GE	10 (DIA)	Cz	n/p	PRINTED-Ag	PRINTED-Ag	10.1	12.5
SOLAREX	9.5 x 9.5	SEMI-XTL	n/p p+	Ti-Pd-Ag	Ti-Pd-Ag	8.5	9.9
INTERMEDIATE LOAD							
ARCO SOLAR	10 (DIA)	Cz	n/p	PRINTED-Ag	Al	10.9	12.3
ASEC	7.62 (DIA)	Cz	n/p	Ti-Pd-Ag	Ti-Pd-Ag	11.5	13.8
MOTOROLA	10 x 10	Cz	n/p p+	Pd-Ni-SOLDER	Pd-Ni-SOLDER	10.1	11.6
PHOTOWATT	7.6 (DIA)	Cz	n/p p+	Ni-SOLDER	Ni-SOLDER	7.9	10.3
SOLAR POWER	10 (DIA)	Cz	p/n	Ni-SOLDER	Ni-SOLDER	10.2	11.2
SOLAREX	9.5 x 9.5	SEMI-XTL	n/p p+	Ti-Pd-Ag	Ti-Pd-Ag	8.6	9.8
SPIRE	6.4 x 6.4	Cz	n/p p+	Ti-Pd-Ag	Ti-Pd-Ag	11.7	13.7

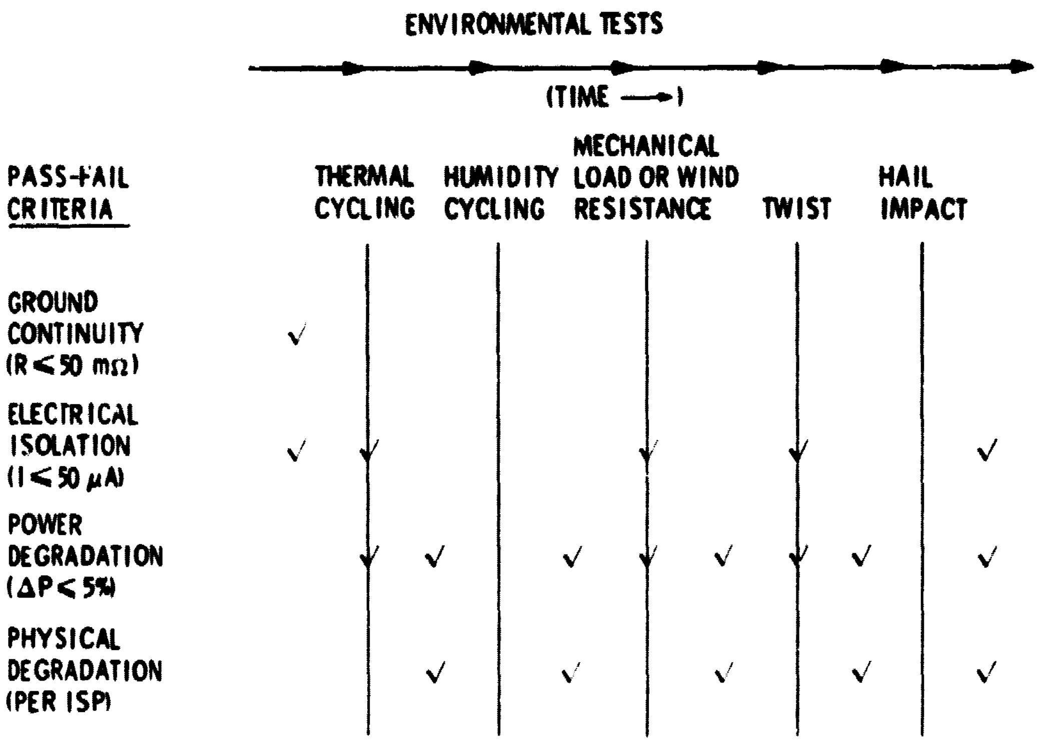
Electrical Characteristics

	RATED VOLTAGE AT SOC (volts)	RATED POWER AT SOC (watts)	NOMINAL OPERATING CELL TEMPERATURE (NOCT) (°C)	MODULE η AT SOC (%)	MODULE η AT 28°C (%)
RESIDENTIAL					
ARCO SOLAR	7.7	49	65	8.0	9.7
GE	7.0	15	68	7.7	9.4
SOLAREX	4.5	56	56	7.4	8.6
INTERMEDIATE LOAD					
ARCO SOLAR	15	32	47	8.7	9.8
ASEC	14	71	55	8.5	10.2
MOTOROLA	15	33	56	7.7	8.8
PHOTOWATT	5	26	56	4.9	6.4
SOLAR POWER	5	56	46	7.8	8.6
SOLAREX	14	56	56	7.3	8.3
SPIRE	15	50	56	9.8	11.5

Qualification Tests for Flat-Plate Modules

TESTS	MODULES BLK I	BLK II	BLK III	PRDA-38	BLK IV ILC/RES	MTR '82 ILC	TEST LEVELS
THERMAL CYCLE	X	X	X	X	[redacted]	X	-40°C, +90°C 50 CYCLES
HUMIDITY CYCLE	X	X	X	X	[redacted]	X	5 CYCLES, 95%, +40°, +28°C
MECHANICAL LOADING		X (100)	X (100)	X (100)	[redacted]	X	2.4 kPa, 10,000 CYCLES
WIND RESISTANCE					[redacted]		UL 997
TWIST		X	X	X	[redacted]	X	±2 cm/m
HAIL IMPACT				X	[redacted]	X	20 mm HAIL/25 mm HAIL
ELECTRICAL ISOLATION		X	X	X	[redacted]	X	2 X SYSTEM VOLTAGE PLUS 1000 VDC
GROUND CONTINUITY			X	X	[redacted]	X	50 milliohm TEST
HOT-SPOT ENDURANCE					[redacted]	X	100 h SHORT-CIRCUITED AT SOC

Qualification Test Sequence



Summary of Qualification Test Results

TEST	NUMBER OF PASS-FAIL CHECKS	NUMBER OF PROBLEMS	% PROBLEMS
THERMAL CYCLING	160	37	[illegible].1
HUMIDITY CYCLING	78	12	15.4
MECHANICAL LOAD OR WIND RESISTANCE	132	9	6.8
TWIST	128	4	3.1
HAIL IMPACT	90	6	6.7
TOTAL	588	68	11.6

Nature of Test Problems

PASS-FAIL CRITERIA	NUMBER OF PASS-FAIL CHECKS	NUMBER OF PROBLEMS	% PROBLEMS
ELECTRICAL ISOLATION ($I < 50 \mu A$)	135	3	2.2
POWER DEGRADATION ($\Delta P < 5\%$)	279	7	2.5
PHYSICAL DEGRADATION (PER ISP)	174	58	33.3
TOTAL	588	68	11.6

Electrical Isolation Problems

- 1 OF 6 MANUFACTURERS
  3 OF 40 MODULES
- CAPACITIVE COUPLING OF CELL STRING TO FLOATING BACK FOIL; BREAKDOWN BETWEEN FOIL AND FRAME
- CORRECTED BY IMPROVING ISOLATION BETWEEN FOIL AND FRAME

Power Degradation

- 3 OF 6 MANUFACTURERS
  4 OF 40 MODULES
- CRACKED CELLS (2 MODULES)

  UNDETERMINED (2 MODULES)
- LAMINATION PROBLEMS LIKELY CONTRIBUTOR IN ALL CASES
  - CRACKED CELLS
  - UNCURED EVA

Physical Degradation

6 OF 6 MANUFACTURERS

37 OF 40 MODULES

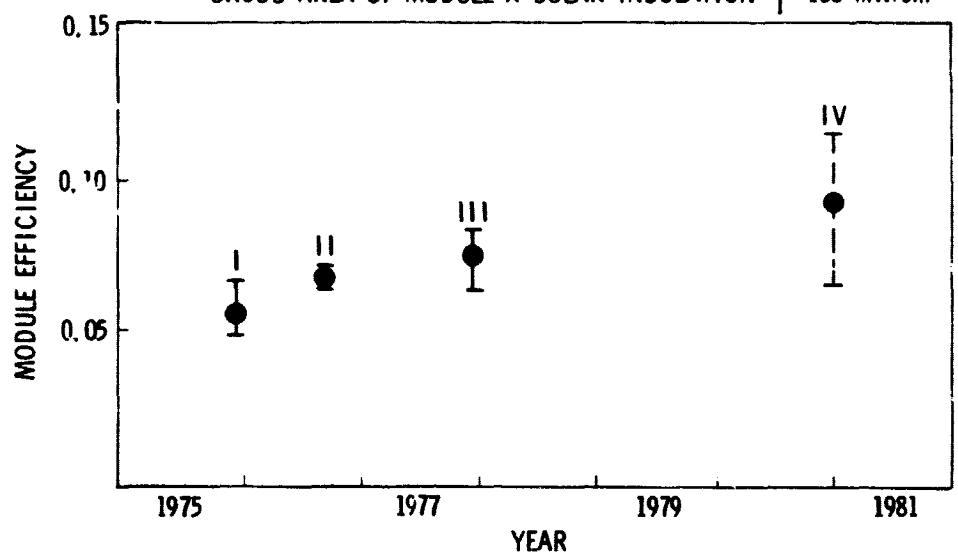
CONDITION	#MFRS	#MODULES	PROBABLE CAUSE
ENCAPSULANT DELAMINATION	6	21	PROCESS SEQUENCE; WORKMANSHIP
CRACKED CELLS	5	14	LAMINATION DAMAGE; ENVIRONMENTAL STRESS
METALLIZATION DISCOLORATION	2	3	FLUX RESIDUE
J-BOX THREADS STRIPPED	1	3	DESIGN/WORKMANSHIP
SEALANT EXTRUDED	1	6	MATERIAL SELECTION
BROKEN FRAME CORNER	1	1	DESIGN/WORKMANSHIP

SAMIS/SAMICS Results for 1 MW/yr (1980 $)

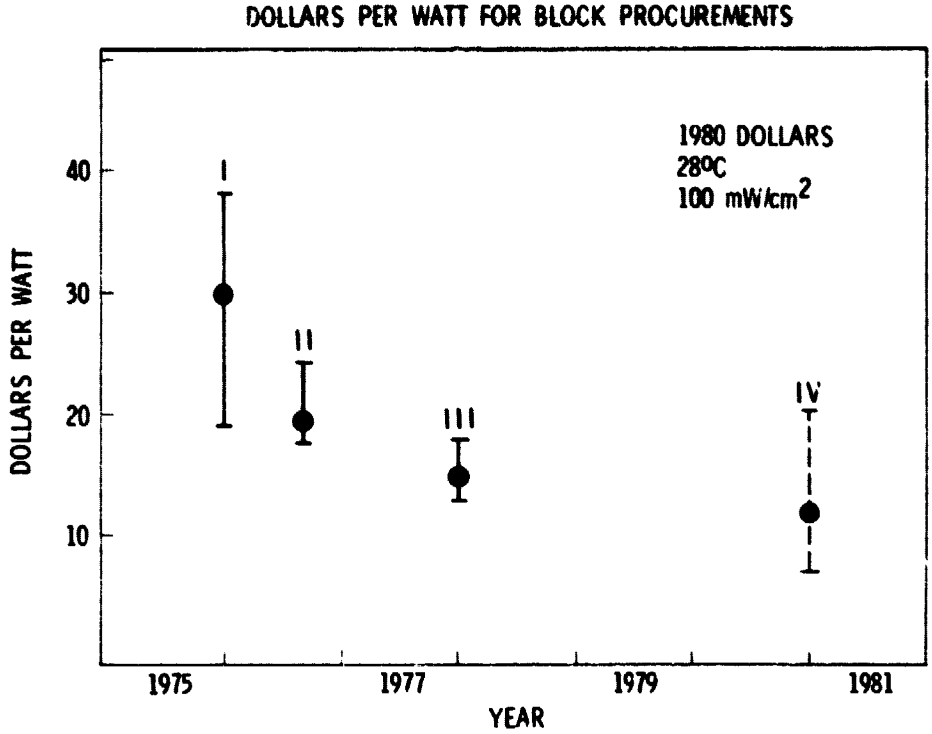
MANUFACTURER	MODULE ($/WATT)	CELL ($/WATT)	NON-CELL ($/WATT)	$\frac{\text{CELL}}{\text{MODULE}}$ (%)
ASEC	9.55	8.79	0.76	92
GE	15.38	12.35	3.03	80
MOTOROLA	6.93	5.23	1.70	75
PHOTOWATT	10.65	8.59	2.06	81
SOLAREX RES.	9.55	7.59	1.96	79
SOLAREX IL	10.35	7.59	2.76	73
SOLAR POWER	8.79	7.48	1.31	85
SPIRE	20.20	14.49	5.71	72

Module Efficiency, Block Procurements

$$\eta_M = \frac{\text{MODULE POWER}}{\text{GROSS AREA OF MODULE X SOLAR INSOLATION}} \Bigg|_{\substack{28^\circ\text{C} \\ 100\ \text{mW/cm}^2}}$$



Module Price History



Quality Assurance Recommendations

- IMPLEMENT INSPECTION SYSTEM PLANS AS WRITTEN
- PROVIDE FOR TRAINING OF INSPECTORS AND PRODUCTION PERSONNEL
- FOCUS ON PROCESS CONTROL AT PIECE PART AND ASSEMBLY LEVELS
- PROVIDE FOR RAPID FEEDBACK OF INSPECTION DATA FOR CORRECTIVE ACTION IMPLEMENTATION
- GIVE MANAGEMENT ATTENTION TO THE APPLICATION AND EFFECTIVENESS OF QUALITY ASSURANCE ACTIVITIES

Observations and Conclusions

- NEW DESIGNS AND TECHNOLOGIES WERE ASSIMILATED WITH SOME DIFFICULTY
    - SCHEDULE SLIPS
    - TEST PROBLEMS
    - RETREATS TO CONVENTIONAL APPROACHES
- LARGE-SCALE PRODUCIBILITY UNTESTED
- PRICE AND PERFORMANCE PROGRESS CONTINUES
    - PRICES ARE DOWN
    - EFFICIENCIES ARE UP
    - RELIABILITY AND DURABILITY BETTER
        - HAIL PROTECTION
        - MOISTURE PROTECTION
        - FAULT TOLERANCE
- MOST DESIGNS WILL BE OFFERED COMMERCIALLY

MODULE EXPERIMENTAL PRODUCTION SYSTEM DEVELOPMENT UNITS

JET PROPULSION LABORATORY

PLENARY SESSION D.B. Bickler, Chairman

The Module Experimental Production System Development Unit (MEPSDU) presentations for the Production Process and Equipment Development Area were intended to acquaint the industry with the purpose and extent of these new contracts. After the two companies made their presentations a panel of industry representatives discussed concerns that they had identified from their experiences Comments were also taken from the audience. Several concerns were identified by PP&E to be discussed at the contractor preliminary design reviews.

PREVIEW OF SOLAREX'S MEPSDU PROGRAM

SOLAREX CORP.

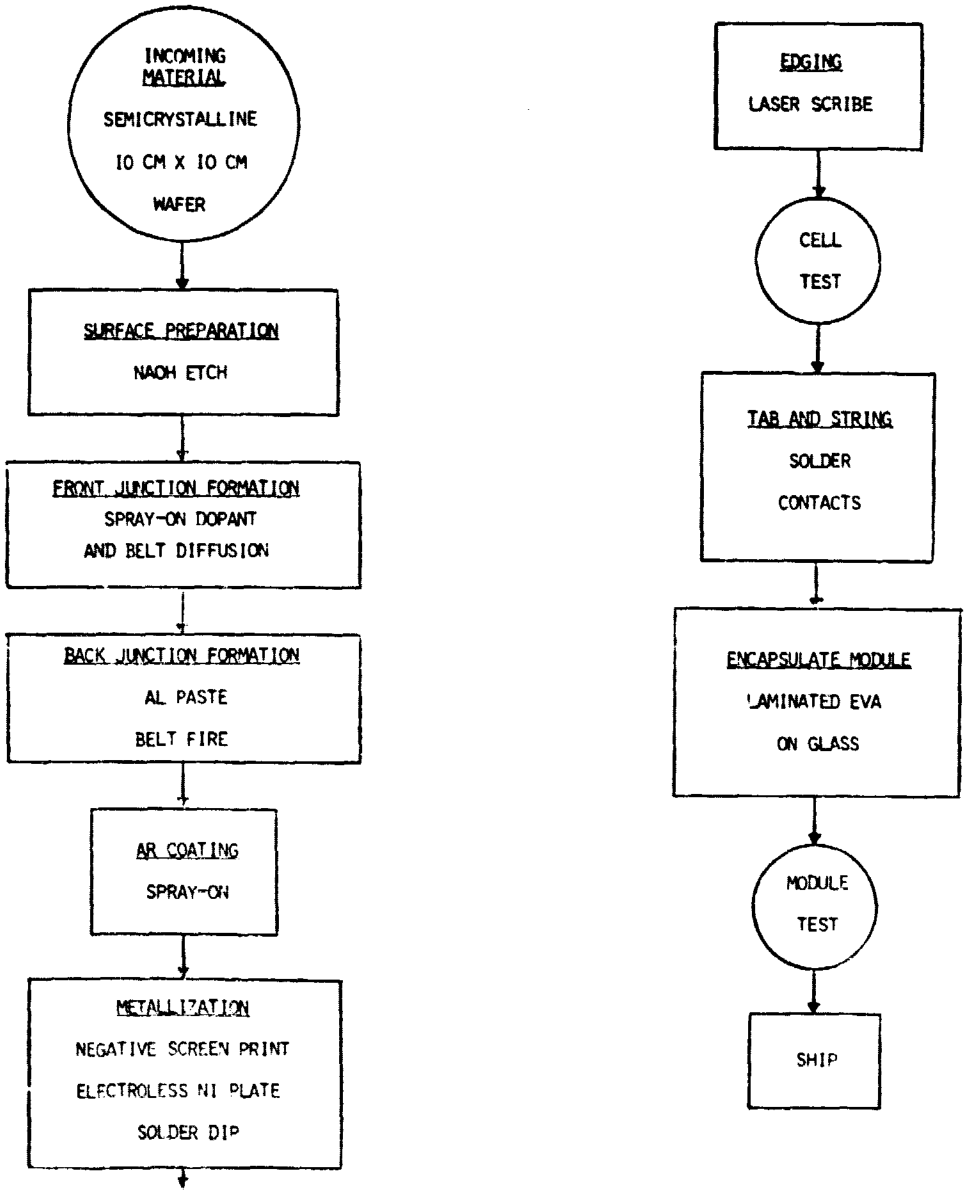
John Wohlgemuth

Design Philosophy

- USE PROCESSES THAT HAVE ALREADY BEEN VERIFIED, IN MOST CASES BY MORE THAN ONE CONTRACTOR.
- USE COMMERCIALLY AVAILABLE EQUIPMENT OR MODIFICATIONS OF SUCH EQUIPMENT.
- USE PRODUCTION EQUIPMENT, NOT LABORATORY-SCALE EQUIPMENT.
- NO MANUAL HANDLING OF CELLS.

PRECEDING PAGE BLANK NOT FILMED

General Process Description



Module Design

72 10 cm x 10 cm Semicrystalline cells

2 Parallel - 36 Series

Approximate Envelope Dimensions

66 cm x 125 cm
26" x 49.3"

Design Voltage - 14.5 v

Glass Superstrate

Ethylene Vinyl Acetate Encapsulant

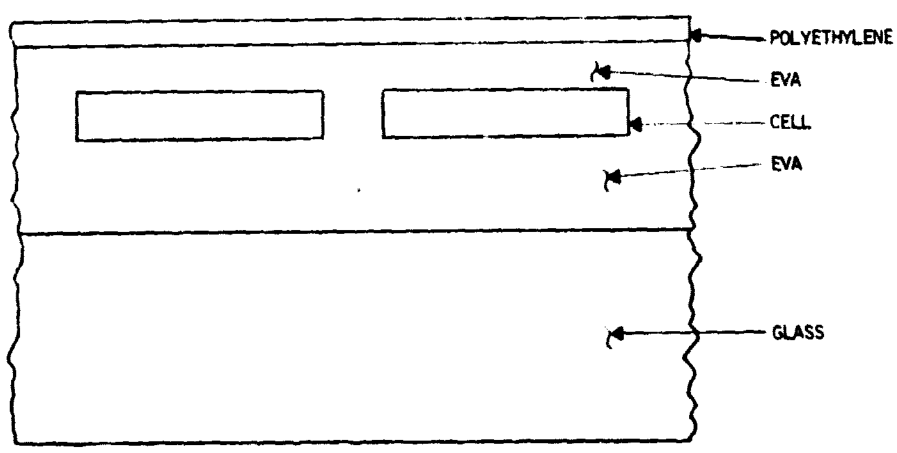
Polyethylene Vapor Barrier

Gasket for Mounting (No frame)

AMP Output Connectors

Internal Diode Protection - 3 Diodes per module

Module Cross Section



Incoming Material

SEMICRYSTALLINE 10 CM X 10 CM WAFERS

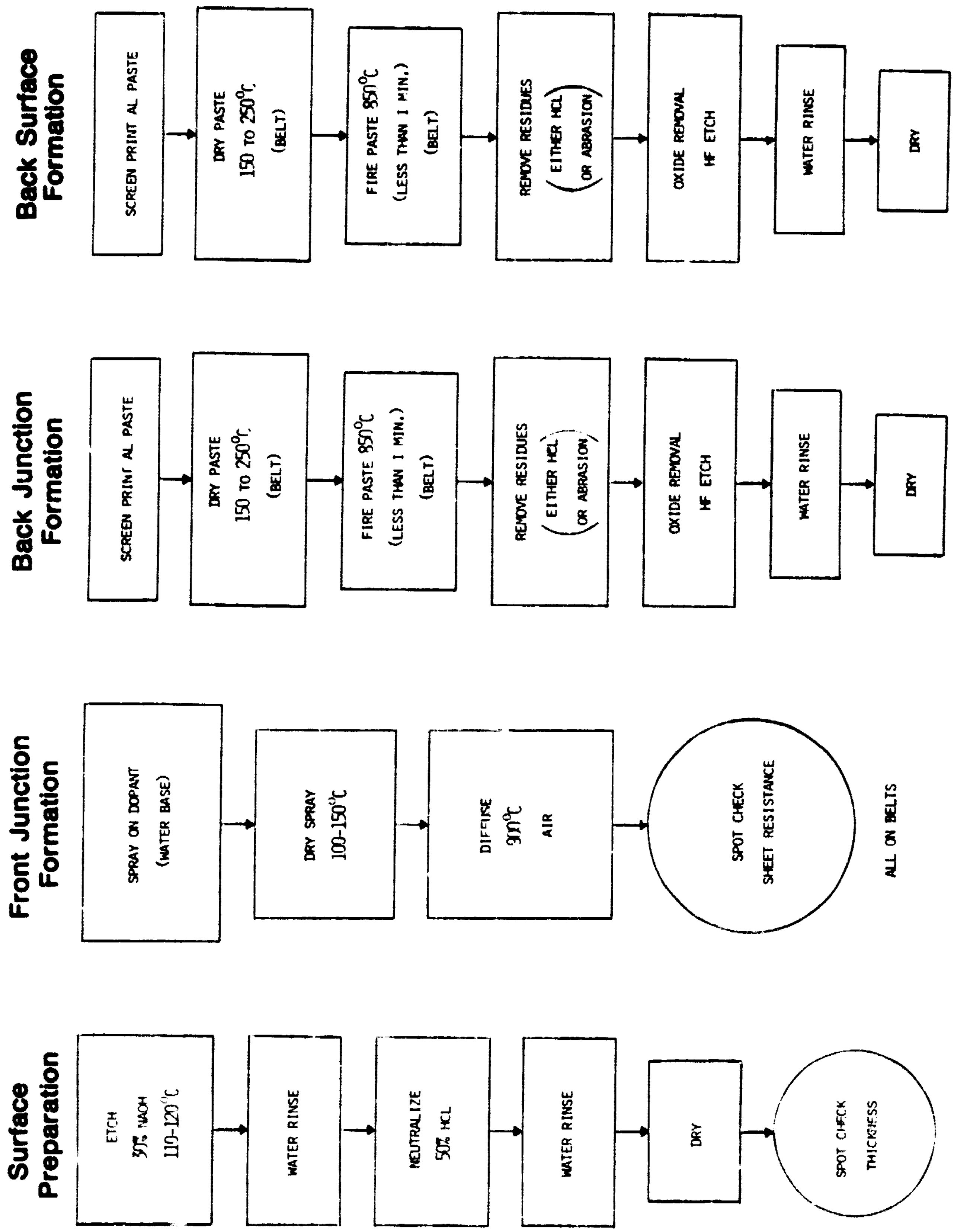
CHOSEN BECAUSE:

- AVAILABLE FOR USE NOW.
- CLOSELY RELATED TO OTHER ADVANCED SHEET MATERIALS.
- CONSISTENT WITH 70¢/WATT COST GOAL.
- SOLAREX HAS SUFFICIENT EXPERIENCE WITH ITS PROCESSING TO UNDERSTAND ITS BEHAVIOR THROUGH THE PROPOSED PROCESS STEPS.

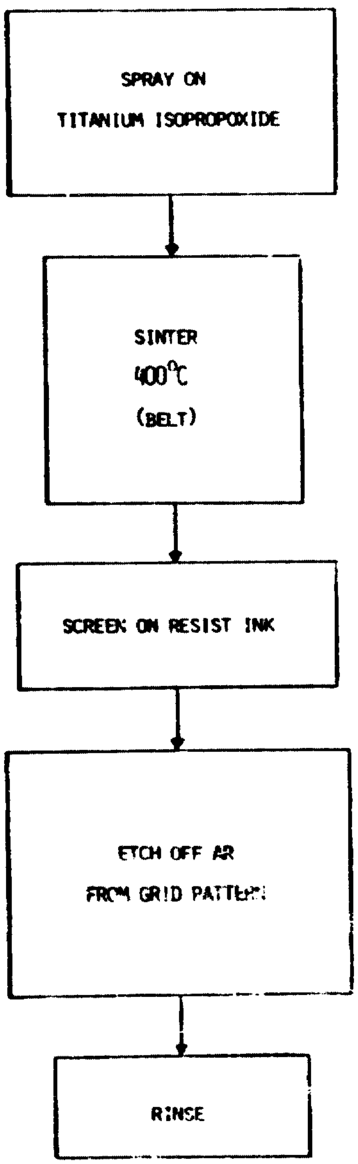
QUALITY ASSURANCE:

MEASURE LIFETIME AND BULK RESISTIVITY USING MICROWAVE TECHNIQUE.

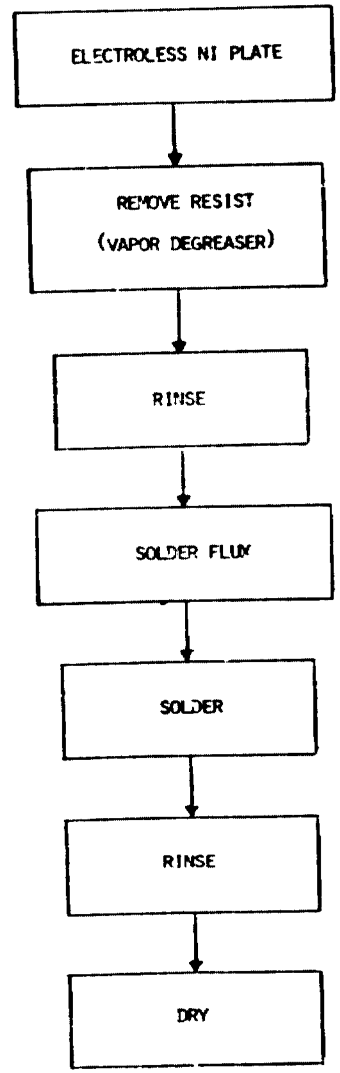
GOOD CORRELATION BETWEEN THE MEASUREMENT AND SUBSEQUENT CELL PERFORMANCE.


Surface Preparation
ETCH 30% NaOH 110-120°C
WATER RINSE
NEUTRALIZE 50% HCL
WATER RINSE
DRY
SPOT CHECK THICKNESS
Front Junction Formation
SPRAY ON DOPANT (WATER BASE)
DRY SPRAY 100-150°C
DIFFUSE 900°C AIR
SPOT CHECK SHEET RESISTANCE
ALL ON BELTS
Back Junction Formation
SCREEN PRINT AL PASTE
DRY PASTE 150 TO 250°C (BELT)
FIRE PASTE 850°C (LESS THAN 1 MIN.) (BELT)
REMOVE RESIDUES (EITHER HCL OR ABRASION)
OXIDE REMOVAL HF ETCH
WATER RINSE
DRY
Back Surface Formation
SCREEN PRINT AL PASTE
DRY PASTE 150 TO 250°C (BELT)
FIRE PASTE 850°C (LESS THAN 1 MIN.) (BELT)
REMOVE RESIDUES (EITHER HCL OR ABRASION)
OXIDE REMOVAL HF ETCH
WATER RINSE
DRY

AR Coating



Metallization

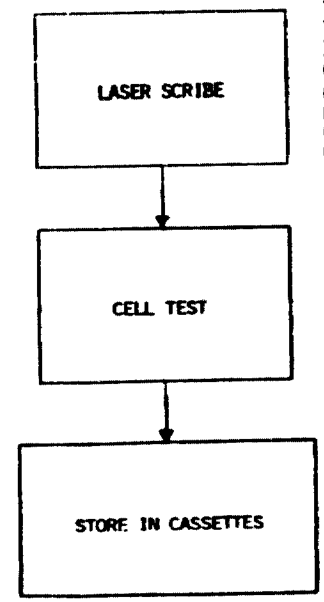


Edging

LASER SCRIBE

LINE WIDTH≈ 0.003"

PENETRATION ≈0.001"



Tabbing and Stringing

USE K&S MACHINE

PULSED HEAT SOLDER BONDS

ONE PIECE STAMPED COPPER INTERCONNECT WITH SOLDER PLATE FOR WRAPAROUND AND SERIES CONNECTION TO NEXT CELL.

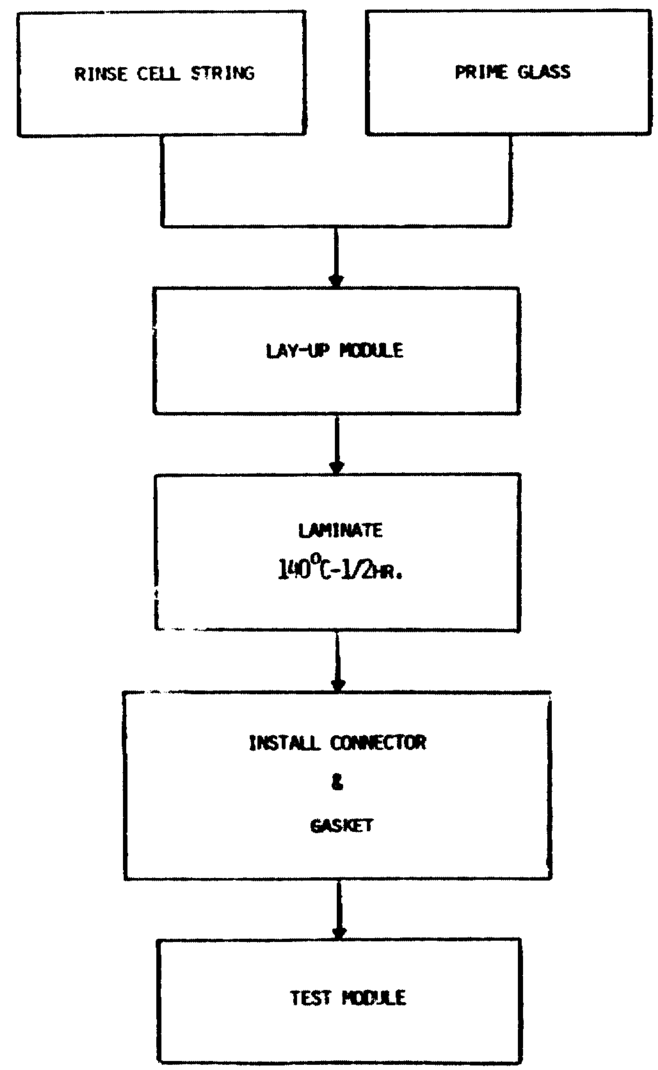
TWO INTERCONNECTS PER CELL WITH 4 BONDS TOP AND BOTTOM.

MACHINE MAKES SERIES STRINGS OF 12 CELLS.

THEN PLACES STRING IN POSITION AND MAKES REQUIRED PARALLEL CONNECTIONS.

PRODUCES LAYOUT OF MODULE READY FOR ENCAPSULATION

Encapsulate Module



Cost Analysis

ASSUMPTIONS

50 MW PER YEAR PRODUCTION RATE.

15% EFFICIENT ENCAPSULATED CELLS
AMI-100mW/cm^2 - 25^o c

93% YIELD FROM WAFER TO MODULE

\$0.306 PER WATT WAFER COST

RESULTS

IPEG - \$0.691 PER WATT

LITERATURE - \$0.661 PER WATT
(COMPILATION OF OTHER'S COST ANALYSIS FOR SAME PROCESS STEPS)

(ALL IN 1980 DOLLARS)

Efficiency of Semicrystalline Material

SMALL AREA SAMPLES (2 cm x 2 cm)
BEST - 17%
BEST LOT AVERAGE - 16.5%

LARGE AREA SAMPLES (9.5 cm x 9.5 cm)
BEST - 13.5%
BEST LOT AVERAGE - 12%

TYPICAL PRODUCTION
10 - 11% LOT AVERAGE

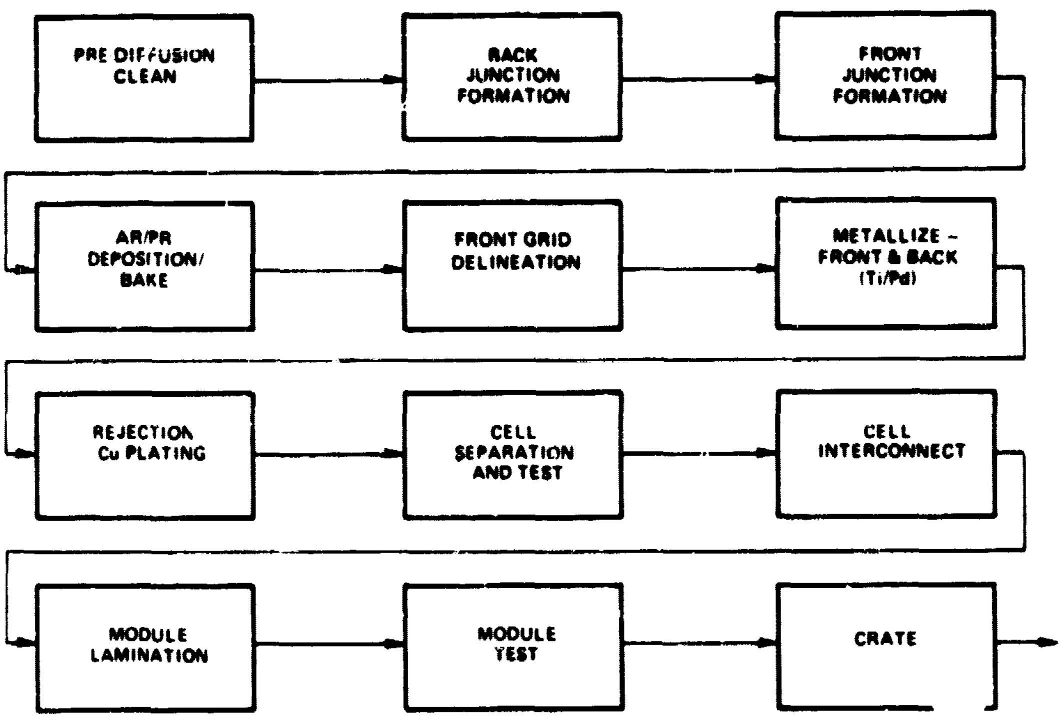
ALL EFFICIENCIES MEASURED AT 100mW/cm^2 - AMI - 25^{o}c.

MEPSDU: APPROACH TO DEMONSTRATION OF TECHNICAL READINESS

WESTINGHOUSE ADVANCED ENERGY SYSTEMS DIVISION

C.M. Rose

Westinghouse MEPSDU Baseline Process Sequence



Pre-Diffusion Cleaning

PURPOSE: PREPARE WEB FOR DIFFUSION BY REMOVAL OF SURFACE CONTAMINANTS

PROCESS:
- HF/DI H_2O/DRY
- PLASMA CLEAN

INPUT: 17" LENGTHS OF AS-GROWN WEB

CONTROLS:
- 200 ±10 WATTS RF POWER
- 300 ±10 CC/MIN OF O_2
- 3 MINUTE HOLD AT $T < 130°C$

OUTPUT: 17" LENGTHS OF CLEANED WEB

VALUE ADDED: \$0.04/PEAK WATT; 25 MW/YR PRODUCTION

ALTERNATE: EXTENSIVE AND LESS AUTOMATABLE CHEMICAL CLEANING PROCESSES

Back Junction Formation

PURPOSE: FORMATION OF P+ BACK JUNCTION INTO P-BASE WEB

PROCESS:
- COAT FRONT SURFACE OF WEB WITH SiO_2;
- BBr_3 DIFFUSION IN STANDARD DIFFUSION FURNACE;
- ETCH WEB TO REMOVE OXIDE

CONTROLS:
- 1200 ± 200 Å THICK COATING OF SiO_2
- 6 ± 1 CC/MIN Ar THROUGH BBr_3
- 90 ±9 CC/MIN O_2
- 2400 ± 240 CC/MIN Ar CARRIER GAS
- TEMPERATURE = 960 +5/-10°C
- TIME = 20 ±4 MIN
- COOLING RATE = 5 ±1°C/MIN FROM T = 960°C TO $T \lesssim 700°C$

OUTPUT: BACK SURFACE DIFFUSED WEB WITH 60 +5/-20 Ω/□ SHEET RESISTIVITY

VALUE ADDED: \$0.023/PEAK WATT (1980 \$, 25 MW/YEAR PRODUCTION)

ALTERNATIVES:
1. ALUMINUM BACK SURFACE FIELD
2. ION IMPLANTATION

Front Junction Formation

PURPOSE:	FORMATION OF N+ FRONT JUNCTION INTO P-BASE WEB
PROCESS:	COAT BACK SURFACE OF WEB WITH SiO_2; $POCl_3$ DIFFUSION IN STANDARD DIFFUSION FURNACE; ETCH WEB TO REMOVE OXIDE
INPUT:	17" LENGTHS OF WEB WITH FORMED BACK JUNCTIONS
CONTROLS:	1200 $\pm$200 Å THICK COATING OF SiO_2 200 $\pm$20 CC/MIN N_2 THROUGH $POCl_3$ 1550 $\pm$150 CC/MIN N_2 CARRIER GAS 62.5 $\pm$6.0 CC/MIN O_2 CARRIER GAS TEMPERATURE = 850 +5/-10°C TIME = 35 $\pm$10 MIN COOLING RATE = 5 $\pm$1°C/MIN FROM T = 850°C TO T $\leq$ 700°C
OUTPUT:	N+PP+ FORMED WEB WITH 50 $\pm$5 $\Omega/\square$ SHEET RESISTANCE
VALUE ADDED:	\$0.023/PEAK WATT (1980 \$, 25 MW/YEAR PRODUCTION)
ALTERNATIVE:	ION IMPLANTATION

C-2

Antireflective Coating Application

PURPOSE:	APPLY AR COATING AND PLATING MASK TO SURFACE OF WEB
PROCESS:	DIP AND WITHDRAW WEB FROM TiO_2/SiO_2 METAL/ORGANIC SOLUTION AIR BAKE TO FORM GLASS AR COATING
INPUT:	17" LENGTHS OF WEB WITH N + PP + STRUCTURE
CONTROLS:	3.5 ± .5% OXIDE MIXTURE IN ALCOHOL OXIDE MIXTURE – 88 ±2% TiO_2/12 ± 2% SiO_2 WITHDRAWAL RATE = 30 ±3 CM/MIN HEAT IN AIR FOR 15 ±1 MIN AT 400 ±10°C
OUTPUT:	WEB WITH 750 ± 30 Å AR COATED SURFACES
VALUE ADDED:	$0.005/PEAK WATT, 25 MW/YR PRODUCTION
ALTERNATIVE:	NONE AS COST EFFECTIVE

Photoresist Coating Application

PURPOSE:	APPLY PR LAYER TO SURFACE OF WEB FOR GRID DELINEATION
PROCESS:	DIP AND WITHDRAW WEB FROM POSITIVE PR SOLUTION AIR BAKE TO CURE PR
INPUT:	17" LENGTHS OF AR COATED WEB
CONTROLS:	50 ± 5% SOLUTION OF PR AND PR THINNER WITHDRAWAL RATE = 25 ±5 CM/MIN HEAT IN AIR 90 ±3°C FOR 25 ±3 MIN
OUTPUT:	WEB COATED WITH 1.0 ±.2 μM OF CURED POSITIVE PR
VALUE ADDED:	$0.011/PEAK WATT, 25 MW/YR PRODUCTION
ALTERNATIVE:	NONE IDENTIFIED COMPATIBLE WITH BASELINE SEQUENCE

Grid Delineation

PURPOSE: DEFINE GRID PATTERN ON FRONT SURFACE OF CELLS

PROCESS: EXPOSE PR; DEVELOP PR; ETCH EXPOSED AR

CONTROLS:
- NEGATIVE MASK LOCATED BETWEEN DENDRITES, SUN SIDE
- EXPOSE PHOTORESIST AT 55 $\pm$10 MJ/CM^2 (BOTH SIDES)
- DEVELOP EXPOSED PR; 60 $\pm$5 SEC AT 20 $\pm$5°C
- RINSE IN DI H_2O
- AR ETCH: 3:1/H_2O:HF FOR 5 $\pm$1 SEC
- RINSE IN DI H_2O AND DRY

OUTPUT: 17" LENGTHS OF WEB WITH SI EXPOSED GRID PATTERN HAVING LESS THAN 5% CELL AREA COVERAGE

VALUE ADDED: \$0.020/PEAK WATT, 25 MW/YR PRODUCTION

Metallization

PURPOSE: APPLICATION OF BASE METAL SUB-STRATE CONTACTS

PROCESS: EVAPORATE Ti/Pd/Cu METALS ON FRONT AND REAR WEB SURFACES

INPUT: WEB WITH DELINEATED GRID (FRONT) AND EXPOSED SI BACK SURFACE

CONTROLS:
- PRESSURE $\lesssim 10^{-6}$ TORR
- E-BEAM METAL EVAPORATION
- COMPUTER POWER CONTROL/CRYSTAL DEPOSITION RATE SENSOR
- DEPOSITION RATES = 2-5 Å/SEC

OUTPUT: WEB WITH 300 $\pm$ 50 Å Ti/Pd/Cu FILMS ON FRONT AND BACK

VALUE ADDED: \$0.032/PEAK WATT, 25 MW/YR PRODUCTION

ALTERNATIVE: OTHER METALLIZATION CONFIGURATIONS

Rejection of Excess Metal

PURPOSE:	REMOVE EXCESS METALS FROM CELL FRONT SURFACES
PROCESS:	DISSOLVE UNEXPOSED PR REMOVE METAL COATED ON PR
INPUT:	17" LENGTHS OF WEB WITH Ti/Pd FILMS DEPOSITED ON ENTIRE SURFACE
CONTROLS:	ACETONE IMMERSION OF WEB ULTRASONIC AGITATION MEOH/H_2O RINSE; DRY
OUTPUT:	17" LENGTHS OF WEB WITH Ti/Pd FILMS DEPOSITED ONLY ON SILICON
VALUE ADDED:	$0.010/PEAK WATT, 25 MW/YR PRODUCTION

Copper Electroplating

PURPOSE:	DEPOSIT CURRENT CARRYING CONTACTS ON CELLS
PROCESS:	ELECTROPLATE COPPER OVER EXPOSED Cu SURFACES
INPUT:	17" LENGTHS OF WEB WITH DEPOSITED Ti/Pd/Cu SUB-STRATE
CONTROLS:	ACIDIC COPPER PLATING SOLUTION CURRENT DENSITY = 15 ±5 MA/CM^2 FOR 10 ±1 MIN RINSE IN DI H_2O/DRY
OUTPUT	17" LENGTHS OF WEB WITH 6-8 μM THICK COPPER PLATING
VALUE ADDED:	$0.031/PEAK WATT, 25 MW/YR PRODUCTION
ALTERNATIVE:	SILVER ELECTROPLATING

Cell Separation

PURPOSE: SEPARATE CELLS FROM DENDRITE/WEB MATRIX

PROCESS:
- OPTICALLY ALIGN WEB IN LASER SCRIBE
- LASER SCRIBE CELL PATTERN ON SCRIBE
- MECHANICALLY FRACTURE/SEPARATE CELLS FROM MATRIX

INPUT: 17" LENGTH OF COPPER PLATED WEB

CONTROLS:
- SCRIBE DEPTH = 50 ± 5 μM (REAR SCRIBE)
- MECHANICAL FRACTURE/SEPARATION

OUTPUT: FOUR 2.5 x 10 CM FINISHED CELLS

VALUE ADDED: $0.015/PEAK WATT (INCLUDING CELL TEST); 25 MW/YR PRODUCTION

Interconnect

PURPOSE: INTERCONNECT INDIVIDUAL CELLS IN SERIES/PARALLEL MODULE MATRIX

PROCESS: ULTRASONICALLY BOND ELECTRICAL INTERCONNECT TABS TO ADJACENT CELLS

POSITION INDIVIDUAL CELLS IN REQUIRED MODULE MATRIX

INPUT:
- 180 PROCESSED CELLS LOADED INTO CASSETTES
- .0015" ALUMINUM INTERCONNECT TABS

CONTROLS: MICROPROCESSOR CONTROLLED ULTRASONIC BONDING PARAMETERS (POWER, FORCE, AND SPEED) AND CELL HANDLING STATION

OUTPUT: FOUR SERIES CONNECTED STRINGS OF 45 CELLS POSITIONED FOR LAMINATION

VALUE ADDED: $0.018/PEAK WATT, 25 MW/YR PRODUCTION

ALTERNATIVES:
1. ULTRASONIC SPOT BONDING OF INTERCONNECTS
2. SOLDER REFLOW BONDING

Module Lamination and Assembly

PURPOSE:	ENCAPSULATE INTERCONNECTED CELLS INTO LAMINATED MODULE ASSEMBLY
PROCESS	LAMINATE MODULE LAYUP INSTALL LAMINATED ASSEMBLY INTO FRAME
INPUT:	TEMPERED FLOAT GLASS, INTERCONNECTED CELL ASSEMBLY, EVA, CRANE GLASS, KORAD, RUBBER GASKETS, AND FRAME COMPONENTS
CONTROLS:	LAMINATION TEMPERATURE = 200 ±4°C LAMINATE VACUUM = (1 ±.5) x 10^{-2} TORR
OUTPUT:	16" x 48" SOLAR MODULE MEETING JPL 5101-138 ENVIRONMENTAL SPECIFICATION
VALUE ADDED:	\$0.205/PEAK WATT (INCLUDING TEST AND CRATING), 25 MW/YR PRODUCTION

Process Sequence Status

- BASELINE MEPSDU PROCESS SEQUENCE SELECTED
- ALL BASELINE PROCESS SEQUENCE STEPS SUCCESSFULLY DEMONSTRATED
- COMPATIBILITY OF STEPS WITHIN SEQUENCE DEMONSTRATED
- ALTERNATE STEPS UNDER INVESTIGATION

SAMICS Analysis: Conceptual Factory

- 25 MW/YR PRODUCTION, BALANCED LINE
- ALL AUTOMATED PROCESSES
- CELLS: 2.5 CM X 40 CM (NOM)
- MODULES: 40 CM X 120 CM
- 12% MODULE EFFICIENCY AT 28°C
- 345 DAYS/YR OPERATION (3 SHIFT)
- DENDRITIC WEB SHEET MATERIAL COST $.24/WATT (1980 $)
- 86% OVERALL YIELD

MEPSDU Module Mechanical Design

- OVERALL SIZE OF 40 cm X 120 cm (OPEN APERTURE 38 cm X 118 cm)
- LAMINATED TEMPERED FLOAT GLASS SUPERSTRATE
- LAMINATION LAYUP: EVA, CRANE GLASS, MOISTURE BARRIER
- COR-TEN STEEL USED FOR FRAME AND MOUNTING
- DESIGNED TO PASS JPL 5101-138

MEPSDU Module Electrical Design

- 180 CELLS/MODULE; 2.5 cm X 10.0 cm CELLS
- 4 PARALLED STRINGS OF 4.5 SERIES CONNECTED CELLS
- ALL CONNECTIONS INSIDE MODULE TO BE ULTRASONICALLY WELDED
- INTERCELL SPACING - 0.03 cm
- PACKING FACTOR - 92%
- TEN ELECTRICAL INTERCONNECTS/CELL
- CELL ASPECT RATIO IMPROVES RELIABILITY

MEPSDU Module Operation

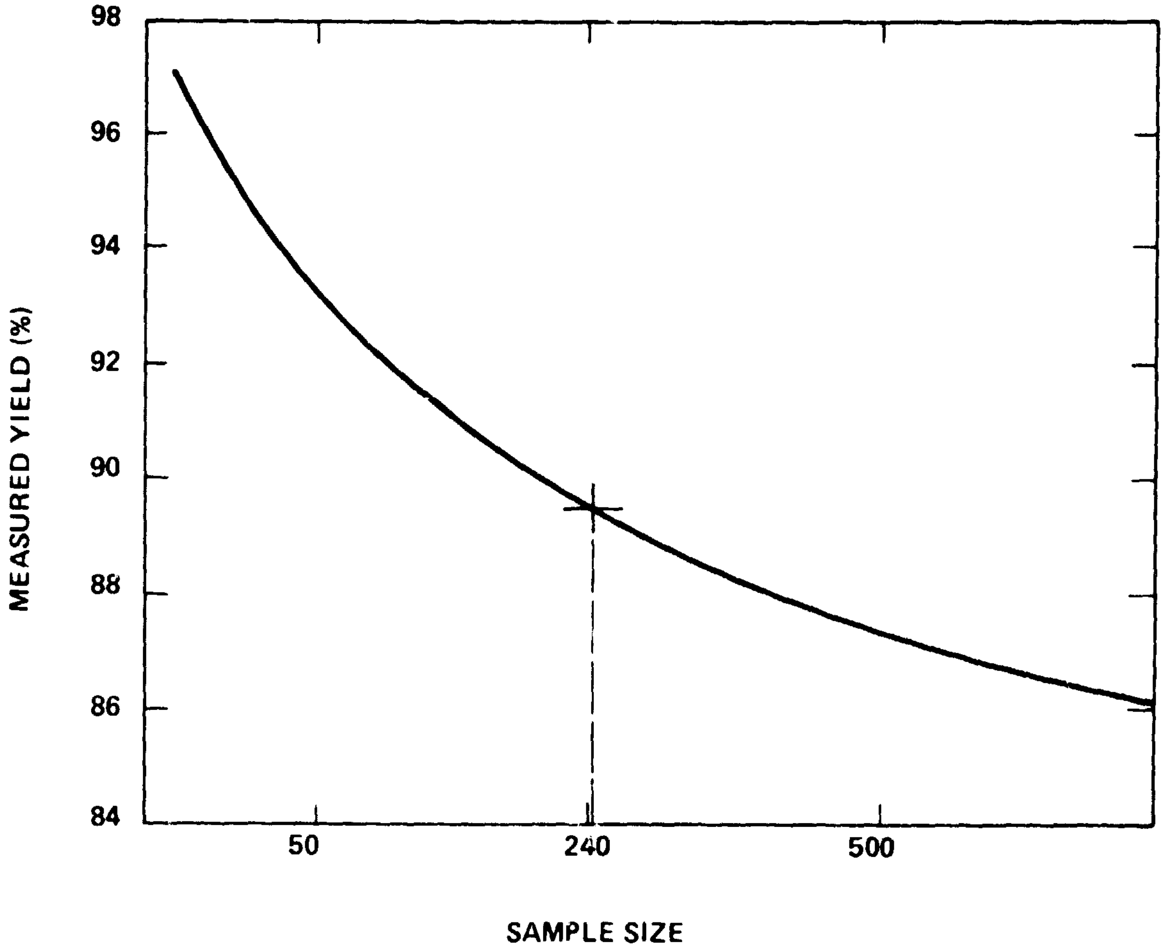
- **THERMAL ANALYSIS UNDERWAY**
- **ASSUMING NOCT OF 40°C MODULE OUTPUT AT 80 MW/cm^2:**

VOLTAGE	- 19.1 V	SOC
CURRENT	- 2.39 A	
POWER	- 45.6 WATTS	
MODULE EFFICIENCY	- 11.9%	

- **ASSUMING AT 25°C AND 100 MW/cm^2**

VOLTAGE	- 20.4 V
CURRENT	- 2.95 A
POWER	- 61 WATTS
MODULE EFFICIENCY	- 12.7%

Measured Yield Required to Demonstrate 0.95 Confidence That Large Production Yield Will Be 86%



Data Collection During Technical Readiness Demo Runs

- OVERALL INPUT
- OVERALL OUTPUT
- OPERATIONAL COST FACTORS
  - OPERATOR TIME
  - EXPENDABLE CONSUMPTION RATES
  - ENERGY CONSUMPTION RATE

Approach to Demonstration of Technical Readiness

- DESIGN, BUILD AND OPERATE A BALANCED 1 MW/YR MEPSDU LINE
- EXPLOIT ADVANTAGES OF DENDRITIC WEB SILICON
- EMPHASIS PLACED ON MAXIMIZING EFFICIENCY
- INCORPORATE ONLY QUALIFIED PROCESS STEPS
- INCORPORATE ONLY AUTOMATABLE PROCESS STEPS
- UPDATE SAMICS CONTINUALLY TO VERIFY THAT PROCESS SEQUENCE WILL MEET COST GOALS OF $.70/WATT IN 1986 (1980 $)
- SPECIFY MEPSDU EQUIPMENT WITH DEMONSTRATED RELIABILITY RECORD

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

TECHNOLOGY SESSION

Ralph Lutwack, Chairman

Seven contractors reported on progress in developing Si production processes and in supporting activities.

Having summarized the status of their programs at the plenary session, Union Carbide Corp. and the Massachusetts Institute of Technology reviewed progress in more detail. The free-space reactor R&D program was successfully completed by UCC. Design and procurement of the Si powder melting and consolidation equipment were completed, and installation and checkout are in progress. In MIT's study of the hydrochlorination of metallurgical-grade Si and $SiCl_4$ to $SiHCl_3$, a prolonged test (238-hour duration) was carried out to study the life of the Si bed in the fluidized-bed reactor. No significant change in the reaction rate was observed, indicating good bed life.

Hemlock Semiconductor Corp. started construction of the dichlorosilane (SiH_2Cl_2) PDU, after making changes in its design and location as a result of finding that SiH_2Cl_2 is more hazardous to handle than previously thought. The PDU will be used to study the preparation of SiH_2Cl_2, and to make feedstock for Siemens-type reactors to investigate the Si deposition process. Hemlock described the safety-related tests that were conducted on SiH_2Cl_2 and its mixtures with hydrogen and air.

Battelle Columbus Laboratories reported on efforts to operate a PDU consisting of the critical components required for their process (zinc reduction of $SiCl_4$). Battelle described the numerous modifications that were made to the PDU to improve operability and stated that in 10 tests made after the modifications, Si deposition was achieved in seven. Efforts to operate for eight hours failed; the longest test was 41 minutes. The experimental phase of the Battelle contract was completed at the end of January.

In the area of impurity studies, Westinghouse reported on its spectral response measurements made on polycrystalline solar cells, indicating that both impurities and grain boundaries reduce carrier lifetime, causing decreased red response and cell efficiency. Information was also presented on accelerated aging tests and other studies. Progress was reported by C. T. Sah Associates on the program to determine the maximum concentrations of certain metallic impurities that can be allowed in Si solar cells to maintain a given efficiency.

Experimental results were reported by AeroChem Research Laboratories in a study on the formation and growth of Si particles produced by the decomposition of silane at high temperatures. Representative data indicate that: (1) particles formed from silane decomposition have a narrow size distribution and are spherical in shape at a given time in the decomposition-growth process; (2) the decomposition-growth process is dominated by heterogeneous gas-particle interactions for sizes greater than 0.05 μm radius; (3) rates of particle growth and silane decomposition are consistent with diffusion-limited kinetics in the 50 to 550 torr pressure range studies; (4) tentatively, particles larger than 0.05 μm radius do not grow by agglomeration; and (5) particles larger than 0.05 μm radius have a cellular structure.

Material presented by the contractors is summarized in the following pages.

SILICON PARTICLE FORMATION AND GROWTH

AEROCHEM RESEARCH LABORATORIES

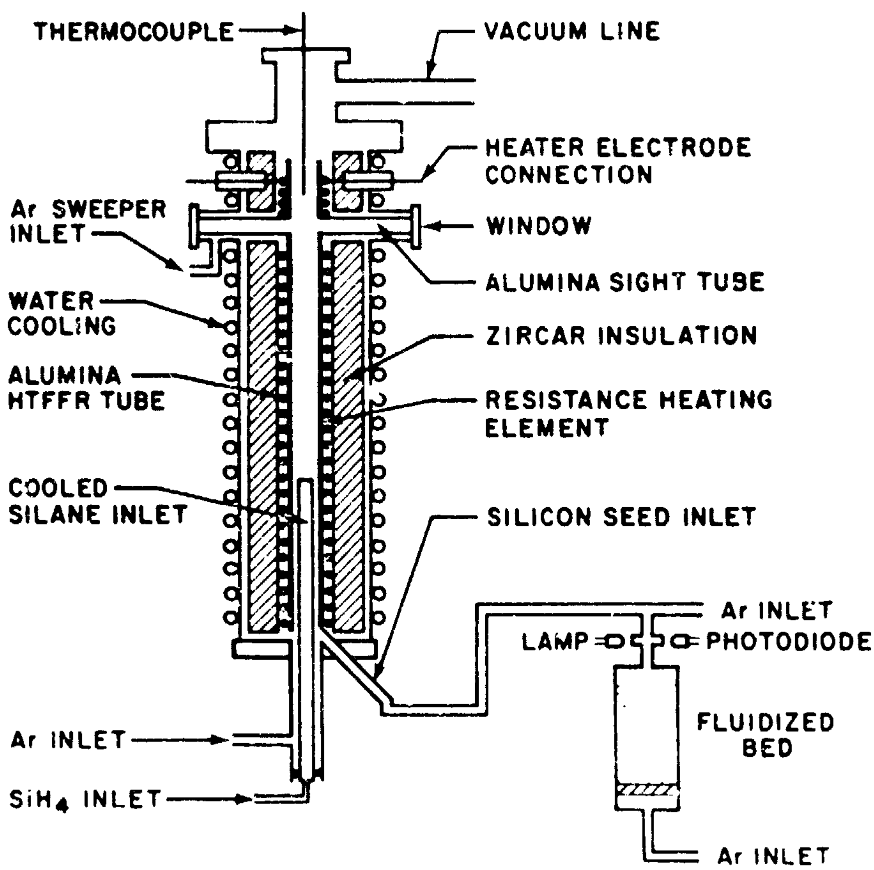
TECHNOLOGY Production of solar grade silicon	**REPORT DATE** February 4, 1981
APPROACH High-temperature fast-flow reactor studies of kinetics of silane decomposition and silicon particle formation and growth. **CONTRACTOR** AeroChem Research Laboratories, Inc. **GOALS** Assemble reactor and diagnostics. Study Si particle formation and growth Monitor precursor species Utilize data in silane to silicon process	**STATUS** ●● Apparatus and diagnostic equipment ●● Particle formation studies ●● Particle growth studies ● Decomposition studies ● Data utilization

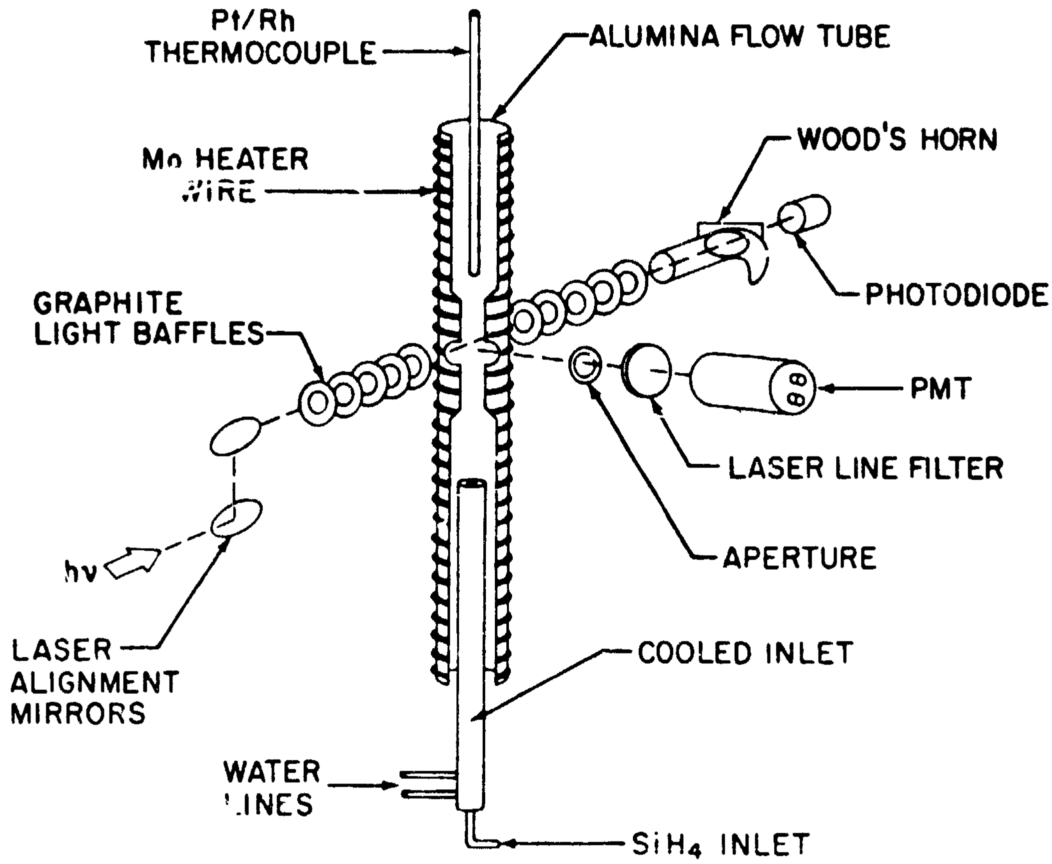
Particle Formation and Growth Studies

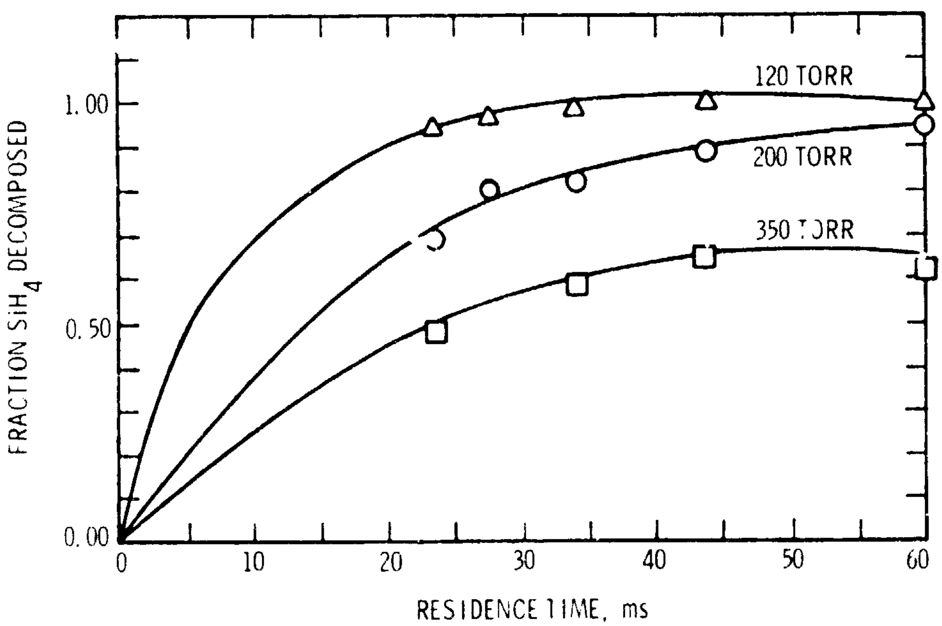
- **LIGHT SCATTERING DATA**
- **SIZE CALIBRATION**
- **PARTICLE GROWTH RATES**
- **PARTICLE SEEDING**
- **PARTICLE COLLECTION**

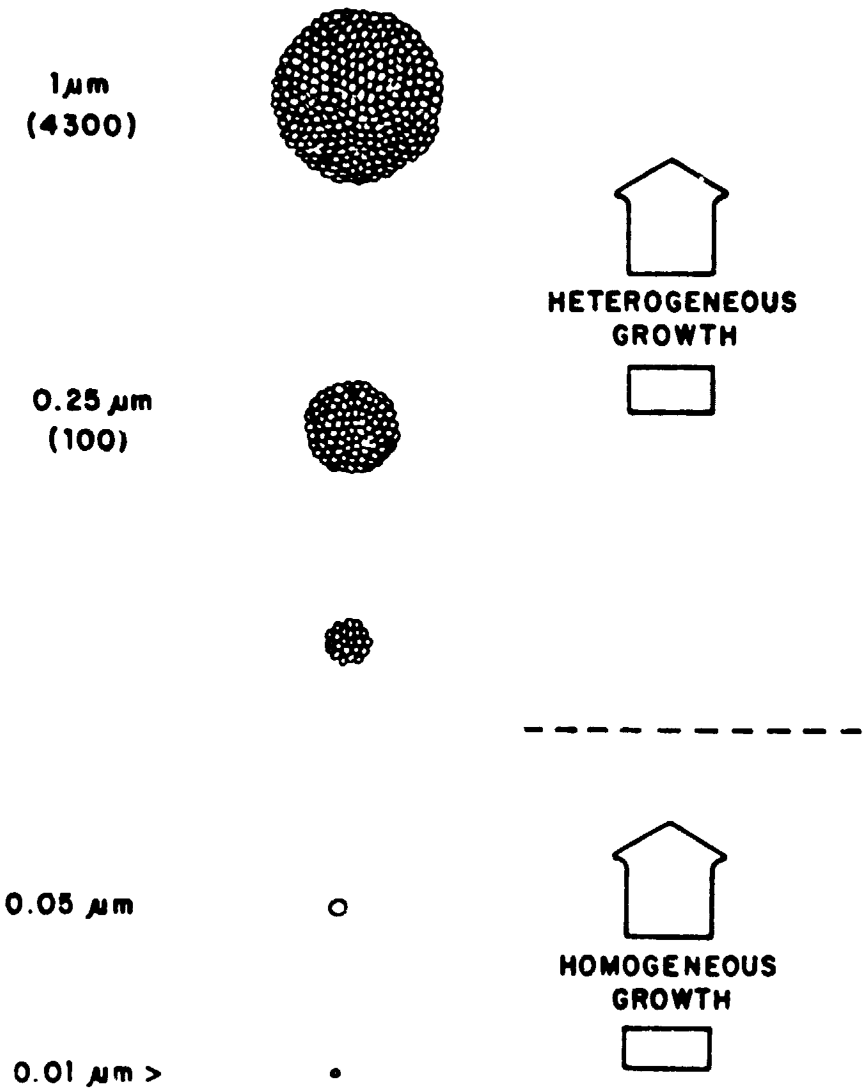
Apparatus Construction

- **HTFFR**
- **LIGHT SCATTERING DIAGNOSTICS**
- **LONG PATH IR CELL**
- **FLUIDIZED BED**




Pt/Rh THERMOCOUPLE
ALUMINA FLOW TUBE
Mo HEATER WIRE
WOOD'S HORN
PHOTODIODE
GRAPHITE LIGHT BAFFLES
PMT
LASER LINE FILTER
APERTURE
hν
LASER ALIGNMENT MIRRORS
COOLED INLET
WATER LINES
SiH4 INLET


120 TORR
200 TORR
350 TORR
1.00
0.50
0.00
FRACTION SiH4 DECOMPOSED
0
10
20
30
40
50
60
RESIDENCE TIME, ms


1μm
(4300)
HETEROGENEOUS
GROWTH
0.25 μm
(100)
0.05 μm
HOMOGENEOUS
GROWTH
0.01 μm >

Problems and Concerns

MORE WORK NEEDED

- **PARTICLE CONCENTRATION BY FORWARD SCATTERING**
- **EXPERIMENTS CLOSE TO PROCESS CONDITIONS**
- **ADDITIONAL COMPUTER WORK**
- **IMPROVE Si, SiH, SiH_2 MEASUREMENTS**

SILANE-TO-SILICON PROCESS

UNION CARBIDE CORP.

CONTRACTOR: UNION CARBIDE CORPORATION
PRICE PROJECTION (1980$, 1000-MT/YR, 20% ROI)

ASSUMPTIONS:	PLANT SIZE:	1000 MT/YR SEMICONDUCTOR-GRADE LIQUID SILICON PRODUCT*
	TOTAL PLANT COST:	$9.66 MM
	START-UP COST:	$1.74 MM
	WORKING CAPITAL:	$0.72 MM
	ANNUAL OPERATING COST:	$5.88 MM
	FEDERAL INCOME TAX:	46%
	CONSTRUCTION TIME:	2.5 - 3 YRS
	DEPRECIATION:	10 YEARS SUM OF YEARS DIGITS
	PROJECT LIFE:	15 YEARS

PROJECTION

ROI RATE, %	PRODUCT PRICE, $/KG
10	8.77
15	9.77
20	10.90

* INCREMENTAL PRODUCT PRICE INCREASE GOING FROM LIQUID SILICON TO POLYCRYSTALLINE SILICON SHOT HAS NOT BEEN DETERMINED. ONE TO TWO DOLLAR/KG INCREASE IS ANTICIPATED.

Problems and Concerns

EPSDU ENGINEERING & INSTALLATION

- A SAFETY REVIEW MEETING WAS HELD IN NOVEMBER 1980, AND POSSIBLE PROBLEMS WERE IDENTIFIED. DESIGN CHANGES ARE BEING MADE WHICH ADDRESS THESE POTENTIAL PROBLEMS.
- A PORTION OF THE WASTE TREATMENT SYSTEM DESIGN IS RELATIVELY NOVEL, AND SOME FIELD ADJUSTMENT MAY BE NEEDED FOR PROPER OPERATION.

SILANE PYROLYSIS R & D

- A SUCCESSFUL OPERATION OF THE SILICON POWDER MELTING/SHOTTING SYSTEM MUST BE DEMONSTRATED.
- A RELIABLE SILICON POWDER TRANSFER SYSTEM FROM THE FREE-SPACE REACTOR TO THE MELTER/SHOTTER MUST BE DESIGNED.

Engineering Summary

A. M. G. SILICON - TO - SILANE

- PROCESS DESIGN COMPLETE
- FACILITY DESIGN COMPLETE
- ALL MAJOR EQUIPMENT ORDERED
- INSTALLATION DESIGN -- COMPLETE IN APRIL
- INSTALLATION SUBCONTRACTS -- ONGOING THRU 1981
- SHAKEDOWN/STARTUP -- EARLY 1982

B. SILANE - TO - POLYSILICON

- PROCESS DESIGN -- COMPLETE IN MAY
- INSTALLATION DESIGN -- COMPLETE IN 1981
- SHAKEDOWN/STARTUP -- MID 1982

Free-Space Reactor Summary

- THREE 12-HR. RUNS & SEVERAL SHORT DURATION RUNS CONFIRMED REACTOR OPERATILIRY.
- POLYCRYSTALLINE BOULE PULLED FROM MELTED POWDER SHOWED RESISTIVITY OF 55 ΩCM, P TYPE.
- PDU OPERATION WAS SUCCESSFULLY COMPLETED AND ALL ITS OBJECTIVES WERE MET.
- EPSDU PYROLYSIS REACTOR DESIGN WAS INITIATED.

Fluid-Bed Reactor Summary

- PDU DESIGN & FABRICATION COMPLETED.
- INSTALLATION & CHECKOUT IN PROGRESS.
- OPERATING PROCEDURES PREPARED.
- STARTUP WITH HYDROGEN PLANNED FOR APRIL.

Quality-Control Activities Summary

- PHOSPHINE DOPANT PROFILE COMPLETED IN EPITAXY REACTOR.
  - PROVIDES CONFIRMATION OF ANALYTICAL METHOD AND CALIBRATION FOR RAPID GO/NO GO SPOT EVALUATION OF SILANE.
- POLYSILICON RODS GROWN WITH CONTROLLED DIBORANE OR PHOSPHINE DOPANT LEVEL IN SILANE FEED GAS.
  - PROVIDES CONFIRMATION OF ANALYTICAL METHOD AND CALIBRATION FOR ON-LINE SILANE QUALITY MONITORING.
- DIBORANE/SILANE VAPOR-LIQUID EQUILIBRIUM MEASURED AT EPSDU OPERATING CONDITIONS.
  - NEAR IDEAL BEHAVIOR CONFIRMS EPSDU DESIGN BASIS.
- EPSDU Q/C LABORATORY FACILITY ORDERED.
- ON-LINE SAMPLING DEVICES DESIGNED.

Melting and Consolidation Summary

- SILICON SHOTTER DESIGN & PROCUREMENT COMPLETED.
- INSTALLATION & CHECKOUT IN PROGRESS.
- PRELIMINARY TESTS USING CHUNK SILICON TO START SOON.

ZINC REDUCTION OF SILICON TETRACHLORIDE

BATTELLE COLUMBUS LABORATORIES

CONTRACTOR: BATTELLE COLUMBUS LABORATORIES (BCL)
PRICE PROJECTION (1980$, 1000-MT/YR, 20% ROI)

ASSUMPTIONS:

FLUIDIZED-BED REACTORS: TWO 29-INCH DIAMETER OR ONE 41-INCH DIAMETER

ELECTROLYSIS CELLS FOR ZINC AND CHLORINE RECYCLE: ONE, TWO, SIX, OR TWELVE

PROJECTION DOLLARS PER KILOGRAM:

	2 REACTORS 12 CELLS	2 REACTORS 6 CELLS	1 REACTOR 2 CELLS	1 REACTOR 1 CELL
BCL	$18.59			$14.80
LAMAR U.		$19.75	$17.19	

Progress Since 16th PIM

- PDU OPERATING EXPERIENCE REVIEWED TO DEFINE NEEDS FOR IMPROVEMENT OF DESIGN AND PROCEDURE
- MODIFICATIONS OF DESIGN AND PROCEDURE MADE, RESULTING IN IMPROVED PDU OPERATION
- OUTGASSING OF RESIDUAL ZINC FROM 400μm-DIA MINIPLANT PRODUCT GRANULES MODELLED TO PERMIT EXTRAPOLATION TO EXPECTED 800μm PRODUCT

PDU Activities Since 16th PIM: Overview

- REVIEW OF OPERATING EXPERIENCE TO IDENTIFY NEEDED SYSTEM IMPROVEMENTS
- UPGRADING OF PDU SYSTEM
- RESUMPTION OF PDU OPERATION
- SUMMARY OF EXPERIENCE

PDU Improvements

- REDESIGNED REACTOR INLET AND OUTLET CONNECTIONS
- CORRECTED REACTOR SHELL WARPAGE
- MODIFIED QUARTZ DELIVERY TABLE
- IMPROVED $ZnCl_2$ RECIRCULATION IN CONDENSER
- IMPROVED ZINC FEED SYSTEM
- MODIFIED REACTOR DISTRIBUTOR PLATE

PDU Operation

- TEN RUNS CONDUCTED
- SILICON PRODUCTION ACHIEVED IN SEVEN RUNS

Summary of PDU Experience

- SYSTEM OPERABILITY IMPROVED
- PRESENT GRAPHITE-LINED STAINLESS STEEL REACTOR REQUIRES BASIC REDESIGN TO BE COMMERCIALLY PRACTICAL
- ZINC REDUCTION PROCESS STILL TECHNICALLY AND ECONOMICALLY VIABLE WITH APPROPRIATE DESIGN OF FLUIDIZED-BED REACTOR

Zinc Removal

OBJECTIVE

- TO STUDY THE REMOVAL OF AN EXPECTED ~100 ppmw RESIDUAL ZINC FROM THE GRANULAR PRODUCT OF THE ZINC VAPOR REDUCTION OF $SiCl_4$ IN A FLUIDIZED BED OF SEED PARTICLES.

APPROACH

1. CONSIDER OPTIONS.
2. STUDY VACUUM OUTGASSING OF MINIPLANT PRODUCTS CONTAINING ~160 ppmw AND ~2300 ppmw ZINC.
3. DEVELOP MODEL FOR EXTRAPOLATION OF MINIPLANT-PRODUCT RESULTS TO LARGER SIZE.
4. REVIEW OPTIONS AND DATA, AND RECOMMEND PROCEDURE.

OPTIONS

1. POST-PROCESS FUSION OF ZINC GRANULES (REJECTED BECAUSE OF LOSS OF CONVENIENT FREE-FLOWING PRODUCT FORM).
2. POST-PROCESS HEAT TREATMENT OF GRANULES IN VACUUM OR INERT GAS, AT E.G., 1100 C (TEMPERATURE LIMITED BY SINTERING AND LOSS OF FREE-FLOWING FORM).
3. POSTPONE ZINC REMOVAL UNTIL FUSION IN INGOT FORMATION OR SHEET FORMING PROCESS.

Conclusions From Outgassing Data

(1) MODEL A (DIFFUSION OF ZINC THROUGH SOLID SILICON SPHERE) IS INCONSISTENT WITH DATA AT DIFFERENT CONCENTRATION LEVELS.

(2) MODEL C (ZINC VAPOR PERMEATION OF MICROPORES ORIGINALLY OCCUPIED BY ZINC) RESOLVES BEHAVIOR AT DIFFERENT CONCENTRATIONS, BUT RATIO OF INITIAL TO LATER OUTGASSING RATE IS TOO LOW FOR SPHERICAL PARTICLES (ALSO TRUE FOR MODEL A).

(3) MODEL B (DIFFUSION OF ZINC THROUGH SOLID SILICON TO CONNECTED ZERO-IMPEDANCE MICROPORES) RESOLVES DATA WITH ASSUMPTION THAT PORE SIZE OR DEGREE OF POROSITY IS A FUNCTION OF ZINC CONCENTRATION. RATIO OF INITIAL TO LATER OUTGASSING RATE IS TOO HIGH FOR UNIFORM POROSITY. CAN BE RESOLVED BY ASSUMING RANGE OF PORE SIZES.

(4) NO CORRELATION IS COMPLETELY SATISFACTORY, BUT EFFORT TO RESOLVE IS NOT JUSTIFIABLE.

(5) WORST-CASE SCENARIO (MODEL C) PREDICTS HUNDREDS OF HOURS OUTGASSING TIME FOR 800-μm-DIAMETER GRANULES AT 1100 C. IF CONNECTED POROSITY IS CONFIRMED (MODEL B) ONLY TENS OF HOURS MAY BE NEEDED.

(6) AS OUTGASSING ADDS TO COST, IMPLICATIONS OF REMOVING ZINC IN INGOT- OR SHEET-GROWTH PROCESS SHOULD BE SERIOUSLY CONSIDERED.

Volumetric Ratio of Zn Condensate to SiO Condensate in Cz Ingot Growth

- RATE OF ATTACK OF SiO_2 BY Si(l) = 1×10^{-5} cm min^{-1} [CHANEY & VARKER, J. CRYSTAL GROWTH 33, 188 (1976)]
- Si(l) SATURATED WITH O AT 30 ppma

$$V_{Zn}/V_{SiO} = \frac{0.0074\ w}{0.335t\ (1/h + 4/d) \cdot 1}$$

V_{Zn} = Zn CONDENSATE VOLUME, cm^3

V_{SiO} = SiO CONDENSATE VOLUME, cm^3

w = ZINC CONCENTRATION, ppmw

t = Si/SiO_2 EXPOSURE TIME, minutes

h = INITIAL SILICON DEPTH, cm

d = CRUCIBLE DIAMETER, cm

PREDICTION FOR d = 18 cm, h = 19 cm and t = 180 min:

w, ppmw	V_{Zn}/V_{SiO}
10	0.005
50	0.024
100	0.048
500	0.238
1000	0.475

CONCLUSION

AT $\leq$ 100 ppmw ZINC IN SILICON, ZINC CONDENSATE SHOULD NOT BE NOTICED IN SiO CONDENSATE.

Project Summary

- TECHNICAL AND ECONOMIC FEASIBILITY OF THE ZINC REDUCTION PROCESS REMAINS PROMISING
- 13%-EFFICIENT CELLS (WITH AR COATING) ATTEST TO UTILITY OF THE PRODUCT
- UNDERSTANDING OF PROCESS ENHANCED BY PDU OPERATION
- BASICALLY NEW FLUIDIZED-BED REACTOR DESIGN NEEDED FOR COMMERCIAL OPERATION

HYDROCHLORINATION PROCESS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	FEBRUARY 4, 1981 17TH PIM

APPROACH HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLROSILANE FOR PRODUCING SILICON **CONTRACTOR** MASSACHUSETTS INSTITUTE OF TECHNOLOGY **GOALS** TO SUPPORT THE UNION CARBIDE SILANE-TO-SILICON PROCESS BY CONDUCTING EXPERIMENTAL AND THEORETICAL STUDIES, ● ESTABLISH FUNDAMENTAL UNDERSTANDING OF HYDROCHLORINATION OF METALLURGICAL GRADE SILICON IN TERMS OF REACTION KINETICS AND ROLE OF CATALYST ● OPTIMIZE THE REACTION CONDITION FOR THE HYDROCHLORINATION STEP	**STATUS** I REACTION KINETICS MEASUREMENT ● TEMPERATURE ● PRESSURE ● $H_2/SiCl_4$ FEED RATIO ● COPPER CATALYST CONCENTRATION ● PARTICLE SIZE DISTRIBUTION ● EFFECT OF IMPURITIES IN SILICON II MASS LIFE STUDY ● NO CHANGE IN REACTION RATE AFTER 238 HOURS - LONG MASS LIFE III CORROSION STUDY ● NO CORROSION OF THE METAL REACTOR MADE OF INCOLOY 800 ● STABLE SILICIDE PROTECTIVE FILM ON REACTOR WALL

Summary of Progress

- REACTION RATE AT 500 PSIG, 500°C REINFORCES THE UNION CARBIDE ENGINEERING DESIGN
- COPPER CATALYST INCREASES REACTION RATE BY 100%
- REACTION RATE INDEPENDENT OF Si PARTICLE SIZE
- IMPURITIES IN M.G. SILICON INCREASE REACTION RATE
- LONG MASS LIFE MEANS REACTION CAN BE RUN FOR LONG PERIODS OF TIME WITH NO INTERRUPTION
- CORROSION OF THE METAL REACTOR IS NOT A PROBLEM
- INCOLOY 800 IS A GOOD CHOICE AS THE MATERIAL OF CONSTRUCTION OF THE HYDROCHLORINATION REACTOR

What Has Been Done

HYDROCHLORINATION REACTOR DEVELOPMENT AT
THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

I	ENGINEERING DATA	● REACTION KINETICS, YIELD, CONVERSION ● CATALYST, IMPURITIES ● SILICON PARTICLE SIZE, MASS LIFE ● CORROSION STUDY
II	CONCLUSIONS	● EFFICIENT REACTION, HIGH YIELD AND CONVERSION ● COPPER CATALYST DOUBLES REACTION RATE ● LONG PERIODS OF CONTINUOUS OPERATION ● CONVENTIONAL METAL ALLOYS FOR REACTOR
III	RECOMMENDATION	● MAXIMIZE REACTOR PRESSURE 500 PSIG ● ADD COPPER CATALYST TO INCREASE RATE ● INCOLOY 800 AS MATERIAL OF CONSTRUCTION FOR THE REACTOR

Potential Application to Polycrystalline Silicon Technology

I THE CURRENT SIEMENS TECHNOLOGY FOR POLY SILICON

$$SiHCl_3 + H_2 \xrightarrow{1000°C} Si,\ SiCl_4,\ HCl,\ \text{LITES, HEAVIES}$$

II THE HYDROCHLORINATION OF $SiCl_4$

$$3\ SiCl_4 + 2\ H_2 + Si \rightleftarrows 4\ SiHCl_3$$

- IT PRODUCES THE STARTING $SiHCl_3$ FOR THE SIEMENS TYPE REACTOR AT ESSENTIALLY 100% EFFICIENCY
- IT CONSUMES THE BY-PRODUCT $SiCl_4$
- IT CAN ALSO CONVERT HCl AND OTHER BY-PRODUCTS TO $SiHCl_3$
- IT FITS PERFECTLY INTO THE SIEMENS PRODUCTION SCHEME TO FORM A CLOSED LOOP PROCESS
- SUBSTANTIAL SAVINGS ON RAW MATERIAL COST CAN BE REALIZED

SILICON MATERIAL TASK

DICHLOROSILANE CVD PROCESS

HEMLOCK SEMICONDUCTOR CORP.

TECHNOLOGY

POLYCRYSTALLINE SILICON

REPORT DATE

FEBRUARY, 1981

APPROACH

CHEMICAL VAPOR DEPOSITION OF SILICON FROM DICHLOROSILANE (DCS)

CONTRACTOR

HEMLOCK SEMICONDUCTOR CORPORATION

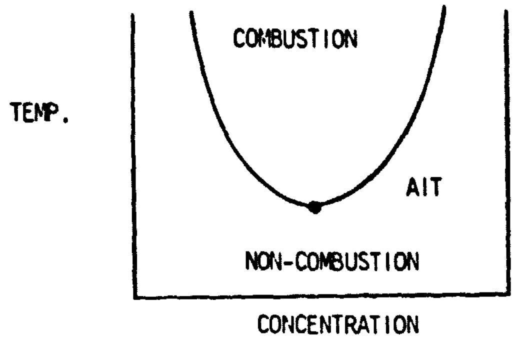
GOALS

- DEMONSTRATE PROCESS FEASIBILITY
- ESTABLISH TECHNICAL READINESS BY OPERATION OF EPSDU SIZED TO ABOUT 150-MT/YR
- SILICON PRICE OF LESS THAN $21/KG (1980$, 1000-MT/YR, 20% ROI) IN LOW-RISK PROGRAM
- DEFINE PROCESS ECONOMICS

STATUS

- SAFETY RELATED REDESIGN OF PDU, INTERMEDIATE REACTOR FEED PROGRAMS COMPLETE
- PDU, INTERMEDIATE REACTOR SYSTEMS UNDER CONSTRUCTION
- SILICON PURITY FROM DCS OR REDISTRIBUTED TCS EXCELLENT (ZONE REFINING, SOLAR CELLS)

Autoignition Temperature

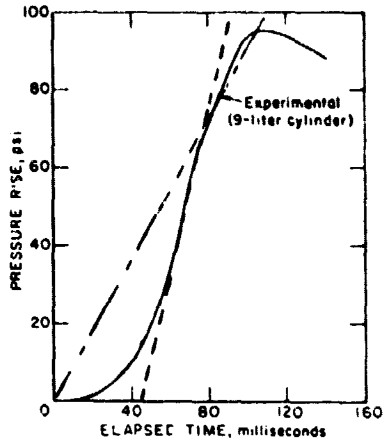


- RESULTS

DCS	58 °C ± 5 °C
DCS/H_2 10/90	255 °C ± 5 °C
EQUILIBRATED TCS DCS/TCS/STC 10/80/10	130 °C ± 5 °C
TCS LITERATURE	215 °C

Explosion Severity

- PRESSURE - TIME BEHAVIOR CHARACTERISTIC OF COMBUSTION IN A CLOSED VESSEL



CH_4/AIR

--- - --- AVERAGE = 900 PSI/SEC

--------- MAXIMUM = 2700 PSI/SEC

SYSTEM COMPOSITION	PSI/SEC AVG.	PSI/SEC MAX.
DCS	$6. \times 10^4$	1×10^6 DETONATION
DCS/H_2 10/90	3.2×10^4	5.4×10^4
H2 (LITERATURE)		2.4×10^4
EQUILIBRATED TCS DCS/TCS/STC 10/80/10		2.4×10^4
TCS (17, 23% IN AIR)		1.2×10^3

DCS Hazards Summary

- LOW AIT FOR DCS

  ==> IGNITION OF DCS IS EXTREMELY FACILE, AND CAN BE UNPREDICTABLE

- HYDROLYSIS PRODUCTS ARE COMBUSTIBLE

- DCS/AIR MIXTURES HAVE HIGH EXPLOSION SEVERITY POTENTIAL

  ==> REMOTE OR PROTECTED LOCATION FOR EQUIPMENT SHOULD BE USED

- EXPLOSIVE OUTPUT TRIALS INDICATED DEFLAGRATION RATHER THAN DETONATION

- DILUTION OF DCS WITH H_2 ATTENUATES HAZARDS

PDU Revised Design Features

- REMOTE LOCATION
- NO DCS STORAGE
- MINIMAL DCS HOLDUP IN EQUIPMENT
- DCS DILUTED WITH H_2 BEFORE TRANSPORT
- REMOTE OPERATION

Purity of Si Grown From Laboratory Rearranger-Supplied Chlorosilanes

TCS SOURCE	CATALYST	BORON (PPBA)	DONOR (PPBA)	AL (PPBA)	CARBON (PPMA)
CONTROL	---	0.19	1.1	0.30	0.5
A	DOWEX (24 °C)	0.48	1.4	0.09	0.5
CONTROL	---	0.15	1.7	0.18	0.3
A	DOWEX (77 °C)	0.69	1.2	0.06	0.4
CONTROL	---	0.11	0.84	0.26	
B	DOWEX (77 °C)	0.24	1.0	0.17	
A	DOWEX (77 °C)	0.41	1.7	0.51	

CONCLUSIONS:

- SILICON PURITY GREATLY EXCEEDS SOLAR REQUIREMENTS
- DOWEX RESIN IS NOT A DIRECT SOURCE OF IMPURITIES
- DOWEX RESIN MAY SERVE AS INDIRECT SOURCE OF BORON IN SOME SITUATIONS

Intermediate Reactor Task

OBJECTIVES

- DEMONSTRATE SAFE AND EFFICIENT PRODUCTION OF SILICON FROM COMMERCIAL DCS IN AN INTERMEDIATE SIZED REACTOR
- FOCUS ON SYSTEM OPERABILITY, ESPECIALLY AT LARGE ROD DIAMETERS

STATUS

- PROJECT DELAYED FOR SAFETY REASONS
- FEED SYSTEM COMPLETELY REDESIGNED
- CONSTRUCTION UNDERWAY
- STARTUP SCHEDULED FOR MARCH, 1981

HSC Low-Cost Si Process Cost-Capital Summary

FOR A 1000 METRIC TONNE PLANT:

	(1980)$/KG SILICON
MANUFACTURING COST	15.47
PROFIT (20% ROI)	4.38
PRODUCT COST	19.85*

MANUFACTURING CAPITAL: $21.9 M̄

*NOTE: IN PIM HANDOUT, PRICE OF Si PRODUCT WAS ERRONEOUSLY GIVEN AS $18.95/KG.

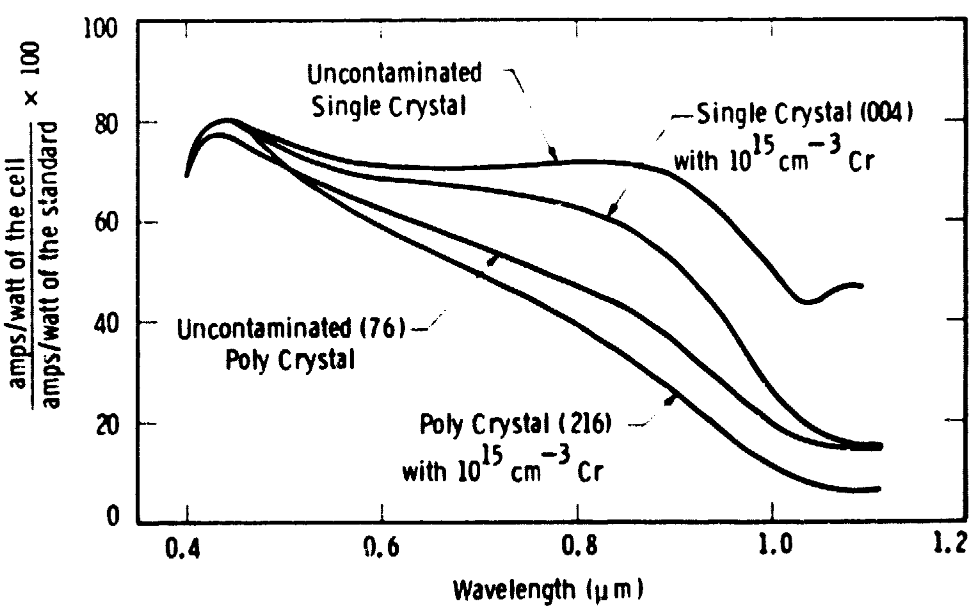
Problems and Concerns

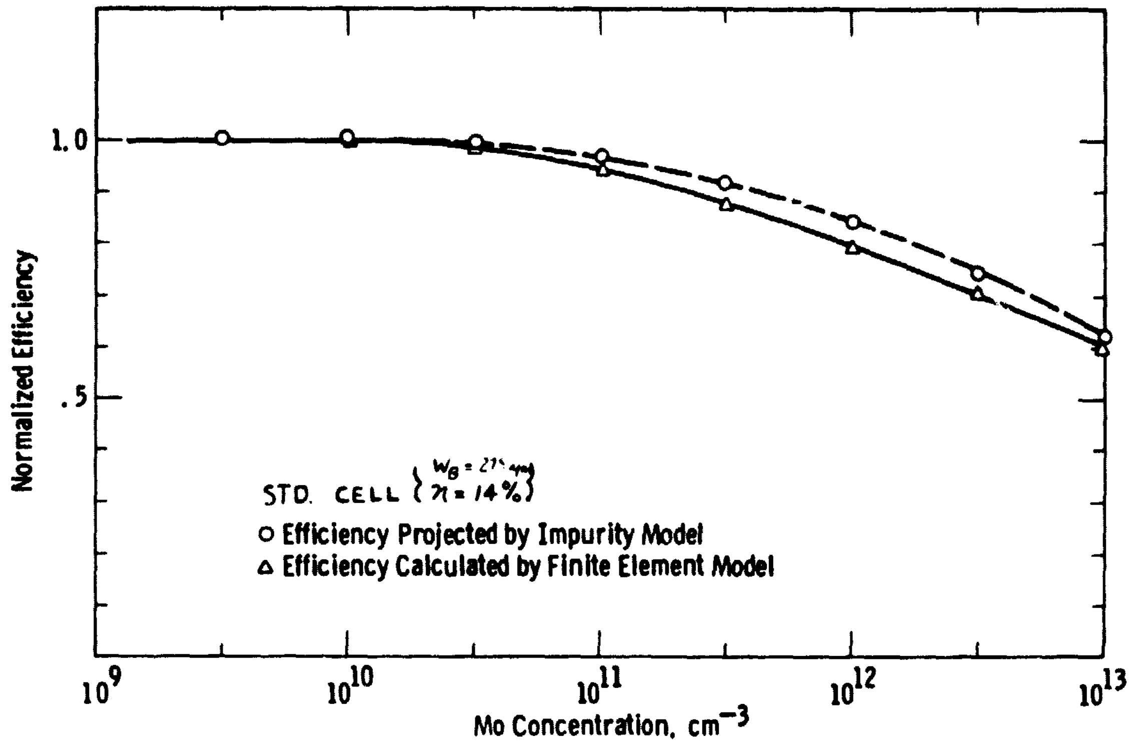
- PROJECT DELAY DUE TO SAFETY CONSIDERATIONS

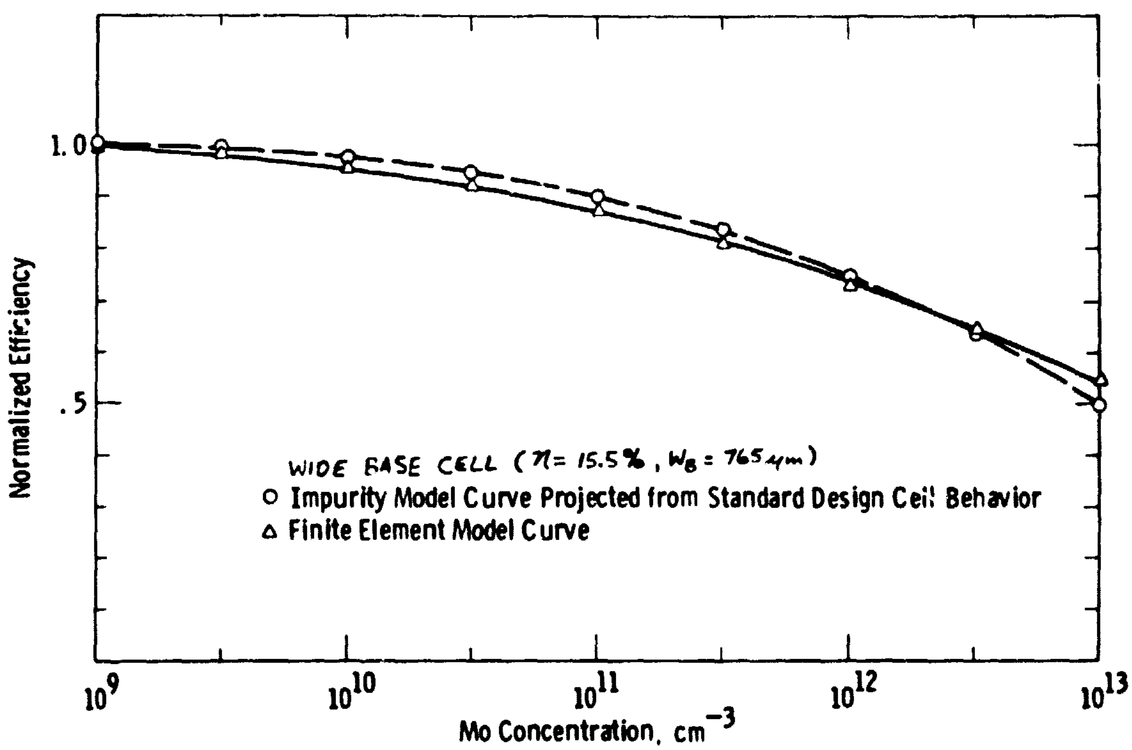
DEFINITION OF PURITY REQUIREMENTS

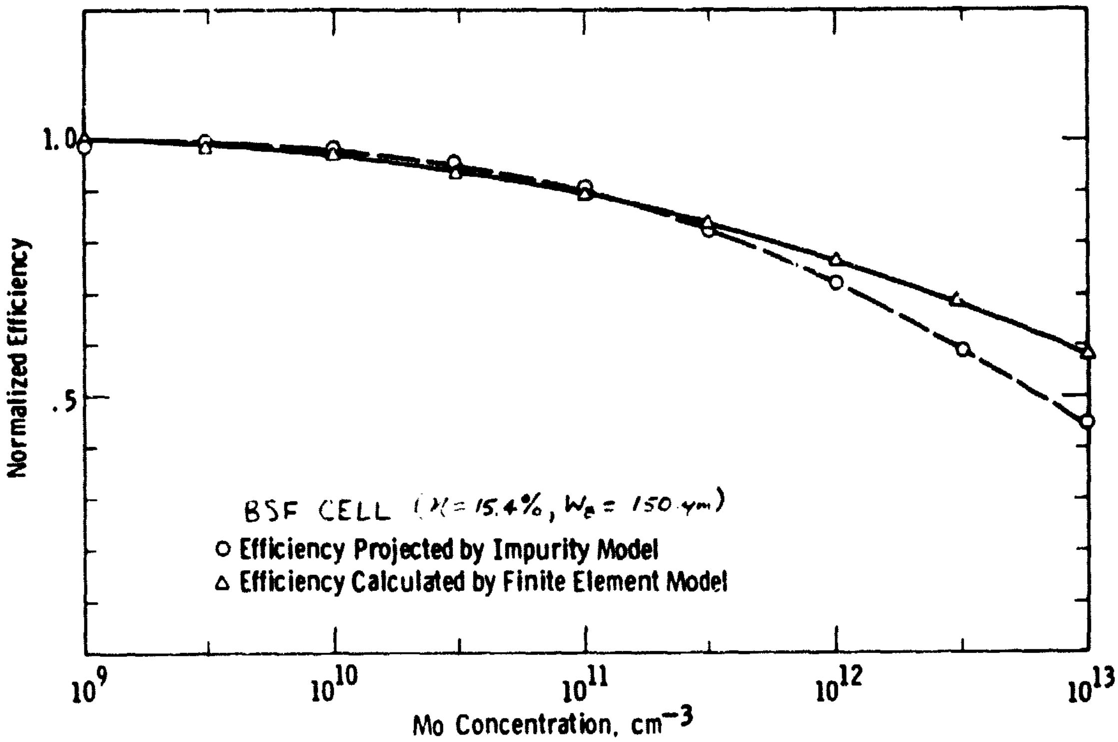
WESTINGHOUSE ELECTRIC CORP.

Technology Impurity effects in silicon	**Report Date** 2/4/81
Approach Analysis of silicon material and solar cells with controlled impurity additions **Contractor** Westinghouse Electric Corp., R&D Center	**Status** Phase IV experimental program approximately 70% completed **Recent Results:** • Spectral response data indicate both impurities and grain boundaries reduce carrier lifetime in polycrystal cells. • Accelerated aging of Ni-doped cells projects time to failure over 20 years • Combined electrical bias/temperature stress show no effect for seven impurties up to 205°C • Impurity model for narrow base, BSF and wide base, ohmic contact high efficiency devices completed.
Phase IV **Goals** Evaluate impurity effects in: • Polycrystalline silicon • High efficiency cells • Experimental silicon material • Cells subjected to processing e.g. gettering • Cells treated to simulate long term behavior	




1.0
.5
Normalized Efficiency
STD. CELL
η = 14%
○ Efficiency Projected by Impurity Model
△ Efficiency Calculated by Finite Element Model
10^9
10^{10}
10^{11}
10^{12}
10^{13}
Mo Concentration, cm^{-3}


1.0
.5
Normalized Efficiency
WIDE BASE CELL (η = 15.5%, W_B = 765 μm)
○ Impurity Model Curve Projected from Standard Design Cell Behavior
△ Finite Element Model Curve
10^9
10^{10}
10^{11}
10^{12}
10^{13}
Mo Concentration, cm^{-3}


1.0
.5
Normalized Efficiency
BSF CELL (η = 15.4%, W_B = 150 μm)
○ Efficiency Projected by Impurity Model
△ Efficiency Calculated by Finite Element Model
10^9
10^{10}
10^{11}
10^{12}
10^{13}
Mo Concentration, cm^{-3}

EFFECTS OF IMPURITIES ON SOLAR CELL PERFORMANCE

C.T. SAH ASSOCIATES

TECHNOLOGY	REPORT DATE
IMPURITY EFFECTS IN SILICON SOLAR CELLS	81/02/05
APPROACH CAPACITANCE TRANSIENT SPECTROSCOPY AND P/N JUNCTION DIODE REVERSE SWITCHING CURRENT TRANSIENT ARE USED TO DETERMINE THE THERMAL CAPTURE RATES OF ELECTRONS AND HOLES AT THE IMPURITY RECOMBINATION LEVELS IN SILICON. **CONTRACTOR** C. T. SAH ASSOCIATES **GOALS** TO DETERMINE THE CAPTURE RATES ACCURATELY SO THAT THE MAXIMUM ALLOWABLE RECOMBINATION IMPURITY CONCENTRATION AT A GIVEN AM1 EFFICIENCY CAN BE PREDICTED.	**STATUS** LARGE SERIES RESISTANCE HAVE BEEN OBSERVED FROM LOW TEMPERATURE D.C. CURRENT-VOLTAGE CHARACTERISTICS OF BOTH SCHOTTKY AND P/N JUNCTION DIODES DOPED WITH TI, V, CR AND MO. THE LARGE RC TIME CONSTANT MAKES THE PUBLISHED ELECTRON CAPTURE RATE AT THE E_C-228 MV TI LEVEL UNRELIABLE DUE TO THE VERY SHORT ELECTRON FILLING TIME ($<$10 NS). A 30-60 OHM-CM N-SI DOPED WITH TI IS GROWN TO GIVE LARGER ELECTRON CAPTURE TIME AT THE TI LEVEL.

TECHNOLOGY DEVELOPMENT AREA

Large-Area Silicon Sheet Task

TECHNOLOGY SESSION

J. Liu, Chairman

Shaped-Sheet Technology

Mobil Tyco Solar Energy Corp. (EFG)

Several temperature profiles of cartridges #2 and #3 (the two cartridges furthest away from the melt replenishment port) in the multiple-ribbon-growth machine (Machine 16) have been made. The data indicate a temperature variation of about 20 to 30° across the die tops. This cannot be corrected with adjustments of the present cartridge end heaters and is attributable to undue influence of the main furnace heaters. It is apparent that this condition is adversely affecting the optimum growth throughput of the EFG ribbons in the multiple-ribbon machine. Five to six different modifications of the main furnace heaters were made to assess a proper direction toward solving this poor thermal symmetry. Several subsequent multiple-ribbon growth runs were attempted.

One hour and 49 minutes of simultaneous three-ribbon growth was demonstrated as part of a 5-hour, 20-minute run. The run was terminated due to a shortage of starting material in the necessary rod form. A total of 19 meters of 10-cm-wide ribbon was grown from the three cartridges at an average rate of 3.3 cm/min.

Several high-growth-rate runs were made in Machine 17 using CO_2 ambient and a new die-shield configuration.

Runs made in Machine 18 with CO and CO_2 ambient and improved gas purging in the vicinity of the die top resulted in production of 7 to 8 meters of 10-cm-wide ribbon material.

Westinghouse Electric Corp. (Web)

Westinghouse is now in the design phase of a web ESGU. This includes some redesign of the present web grower configuration.

Engineering drawings of the dendritic web ESGU mechanical system were received at JPL for review and a preliminary design review was held with Westinghouse at JPL.

Work continues on the design of the low-cost modifications of the web-growth system. Electronic developments include: redesign of the closed-loop melt-level controller; a re-specified custom temperature controller for a reduction in the component cost; installation for testing of the start-up programmer, and identification of a supplier for the web-thickness sensor-controller. Mechanical design developments include: identification of a lower-cost stainless-steel pipe for the furnace chamber wall and design of an inexpensive web take-up reel.

Advanced web throughput runs have begun and faster growth rates have been achieved while maintaining thickness (Westinghouse relates stress to ribbon thickness, not pull speed or width). This development, like the planned web width-control study, depends upon passive heat-shield design development.

Honeywell Corp. (SOC)

Both the SCIM II and dip-coat machines were operated during this period; 10-cm-wide slotted substrates were coated by SCIM II at speeds of 3 to 5 cm/min. Areas of uniform thickness, 100 μm, were deposited on the substrate.

Problems encountered and overcome included the continuous formation of dendrites along the center of the sheet, the freezing of silicon between the crucible and the coating trough, mullite substrate cracking and non-uniformity of temperature along the furnace tunnel. The best SCIM-coated cell showed an efficiency of 7.5% AM1.

SOC material dip-coated at speeds of 3 to 5 cm/min continues to provide cells of 10-10.5% AM1 efficiencies.

The latest contract expired December, 1980. Further work in this technology will be funded by SERI, and will be managed jointly by JPL and SERI.

Ingot Technology

Kayex Corp. (Advanced Cz)

A design review of the Advanced Cz ESGU was held at JPL in October. The ESGU will be a prototype of equipment suitable for high-volume silicon ingot production (150 kg of ingots from a single crucible, 2.5 kg/h throughput, 90% yield). The review consisted of presentation and discussion of design and assembly drawings, system diagrams and machine and process specifications together with appropriate technical justifications.

Kayex has commenced modification of a CG 2000 (to be called CG 6000) for the Cz ESGU. All of the long-lead-time items are in, and the chamber, framework, and crucible-lift mechanism are assembled; 15-in-dia crucibles are in and are being analyzed for impurities. Testing and debugging has begun on the console electronics. Growth-parameter sensors and microprocessor test and definition continue for automated growth.

Siltec Corp. (Advanced Cz)

Siltec's Advanced Cz contract expired in September, 1980; nogotiations are under way for continuation of the program into the next phase, ESCU development. Siltec presently is working with in-house funding on two major problem areas. These center mainly on the transfer-tube heater system and the automatic ingot-diameter control. Using a new modified diameter controller, Siltec has successfully demonstrated the growth of a large ingot (weighing approximately 60 kg) from the CLF furnance with a uniform 13.8-cm diameter along the entire length.

Crystal Systems, Inc. (HEM)

A redirection of program goals for the HEM casting technology was made during this reporting period. The new goal calls for the growth of HEM ingots to yield 35 kg (30 x 30 x 15 cm) in a 56-hour cycle time. The other goals of the original contract remain the same.

Several growth runs aimed at improving the quality of the ingot material have been completed. These are tests with various growth parameters; such runs will continue in coming months.

Successful growth of several 35-kg ingots was reported by CSI. A growth rate of 28 hours per 35-kg ingot with a total cycle time of 56 hours has been achieved. No further attempt to improve the cycle time was made in this period. Emphasis at this point is on optimization of the growth process to improve material quality. CSI has noted a substantial increase in the amount of single-crystal material across the bottom of the ingots for these runs.

Preliminary results from a material analysis of the HEM material showed a large amount of precipitates, presumably the source of carbon impurities in the material. These precipitates are also the source of the high concentration of dislocations in this material. The impurities observed in this material are undoubtedly due to the graphite heaters in the HEM furnace.

Semix Inc. (Semicrystalline Casting)

Terms of a confidentiality agreement have been established and the first meaningful technical review took place during this reporting period. Technical and economic data that were received at and after the PIM are now being analyzed to ascertain the validity of Semix's process claims.

Hardware design and fabrication continues on the casting, wafering and test subsystems. In the wafering area, Semix is planning to evaluate high-speed multi-blade slicing and ID wafering by various manufacturers. Data collection for a SAMICS analysis report has been completed. A review draft of this report, entitled "Definition of Present Technology and Economic Considerations," has been received by DOE/JPL; a final version illustrating 1982 and 1986 sheet costs will be made based on comments and suggestions from JPL and DOE.

Silicon Technology Corp. (Advanced ID Sawing)

STC has replaced the hollow spindle of the prototype R&D slicing machine with a solid ball-bearing spindle. This successfully reduced the excessive blade vibrations observed with the hollow spindle. Some feed-column-related vibration remains. Nevertheless, 15-cm-dia wafers are now being successfully plunge-cut at rates up to 4.5 cm/min with slice and kerf thickness (d and k) each equal to 12.5 mils at >90% yield. Edge chipping remains the major fault with rotary slicing, but slow rates (3.8 cm/hr) and high slice thickness (d = 20 mils, k = 11 mils) are also problems.

For the 10 x 10-cm ingot wafering, both single-crystal material from Crystal Systems, Inc., and polycrystalline material were used. The minimum thickness of the poly wafers was 6.5 mils and the kerf loss was 11 mils. (The d + k value for the desired goal of 25 wafers/cm is 16 mils.) The average yield for these runs was greater than 90%, the material being sliced at an average rate of 2.5 cm/min (0.25 wafer/min). One observation made by STC was that polycrystalline material was easier to slice than single-crystal and had greater yields. Also, STC noted that the 6.5-mil wafers were very difficult to handle.

The use of thin core material for the saw blades (4.8 mil or 120 μm thick) resulted in some blade deflection causing a blade-rubbing problem with the wafers. This problem does not occur with the thicker (6-mil) core material. More 4.8-mil core material of different steel composition has been ordered and will be used in subsequent experiments.

Siltec Corp. (Enhanced ID Slicing)

Slicing experiments with the 42-cm (16 5/8-in.) blade head have resulted in the production of 250-μm (10-mil)-thick wafers with 200-μm (8-mil) kerf thickness from 10-cm-dia silicon ingots. These experiments were done with ingot rotation and yields of 85-90% have been achieved. Blade life, however, has been much less than expected (about 200 cuts as opposed to 800-1000 expected). Wafer throughput in these demonstrations averaged 0.25 wafers/min.

Crystal Systems, Inc. (FAST)

An attempt at slicing a 10-cm dia ingot at 25 wafers/cm was successfully completed at CSI during this period. The yield was <30%. The slicing rate was a moderate 2.9 mils/min; slice and kerf thickness, d + k, was 7 mils + 9 mils. CSI also tried to slice a 15-cm-dia ingot but aborted the run after approximately 13 cm. The reason for the failure was given as a combination of wire and roller degradation.

One significant achievement during this period was that one wire pack electroplated in house was able to slice through three ingots with yield of 85%, 80% and 38%, respectively. The last run might have also had an 80% yield, but the epoxy holding the ingot in place loosened and the ingot shifted during the last 20% of slicing.

Material Evaluation

Applied Solar Energy Corp. (Cell Fabrication)

Cells fabricated on vertically sliced HEM wafers (Ingot No. 41-41C) show that the material in some places is as good as Cz material. An average taken over one entire slice indicates that the HEM efficiency is 92% of that of the Cz controls (HEM average: 10.2% AM1, Cz average: 11.1% AM1). No definite pattern of cell efficiency was obtained over the cross-section of the ingot although there is a trend toward lower efficiency for cells from the seed area. Horizontal sections of the same ingot (41-41C) have been fabricated into cells and tested. The results will be correlated with the results for the vertical sections. Material from the same ingot will also be tested for dislocation densities and oxygen and carbon concentrations.

Gettering experiments on HEM ingot material were also performed during this period. The results are similar to those in earlier gettering experiments, i.e., cells made from material at the top of the ingot improve substantially with gettering whereas those from material at the bottom of the ingot showed little improvement. DLTS measurements reveal a wide band of trapping levels in this material indicating a large number of impurities.

Data from dislocation-etch experiments on the HEM and EFG material revealed that dislocations are evenly distributed throughout the HEM ingot, while the EFG ribbons showed a significant drop in dislocation density on ribbon grown in a CO atmosphere.

A two-step diffusion process on polycrystalline EFG, Wacker and Hamco Cz materials did not improve the Wacker or Hamco Cz cell performances and degraded the performance of the EFG cell. A 9-hour, 750° pre-diffusion step has shown a 10% improvement in the short-circuit current on Wacker Silso material.

University of Missouri, Rolla (Reactant Gas Studies)

UMR visited three Task II sheet growth contractors to measure oxygen partial pressures in their silicon growth systems during this reporting period. The three contractors are Westinghouse, Honeywell and Crystal Systems, Inc.

At Westinghouse, the web growth system proved to be very stable, with little change in the partial pressure of oxygen with varying gas flow rates. There also was no evidence of back diffusion of oxygen into the system. These findings were of particular interest to Westinghouse in that they indicate that some cost savings can be made by reducing gas flow rates.

Cornell University (Silicon Sheet Characterization)

HEM samples were investigated by a combination of EBIC and optical microscopy-etching. It is found that high-angle grain boundaries in HEM are only weakly electrically active. Centers of electrical activity are due to boundary dislocations. Many grain boundaries that appear macroscopically to be high-angle boundaries are really made up of alternating sections of coherent twin or low-angle boundaries, or both.

Materials Research, Inc. (Silicon Microstructure)

MRI is currently characterizing the defect structure of both the surface and cross-section areas of web material from Westinghouse. The through-the-thickness defect density may or may not be similar to the surface density; this is to be investigated. Two web samples have been mounted edge-on and are presently being prepared for defects and image characterization.

Honeywell's SOC material has been difficult to section. The entire width of the mullite substrate has had to be bonded to an aluminum support plate during cutting.

In-House Activities

MBS Slurry Tests: Four additional types of corrosion inhibitors for a water-based slurry to be used in MBS wafering were evaluated. The evaluations consisted of fatigue testing of the 1095 carbon steel MBS blades in a water solution of the corrosion inhibitors. The fatigue lives of blades tested in three of the four types of inhibitors evaluated were greater than the fatigue lives of such blades tested in the standard PC oil used in MBS slurries. These water-based corrosion inhibitors would provide a large cost savings for MBS wafering.

MBS Blade Tests: Lateral deflection and twist tests were made on 1095 high-carbon steel and three types of metallic glass (Metglas) ribbons for the MBS wafering technology. The lateral deflection tests are used to compare flexibility of metallic glass ribbon with that of 1095 carbon blades under equivalent tensile forces in MBS wafering and the lateral twist test results indicate that a very small force can produce an appreciable twisting of the metallic glass ribbons.

Crystal Growth: Two runs were made with the in-house Czochralski crystal growth system using a new flexible seed holder in attempts to grow and evaluate crystals from Battelle-produced polysilicon starting material. In the first effort, melting as-received poly resulted in clouds of vapor that obscured the operator's view and made growth difficult. For the second run the poly was leached for 20 minutes in HF, rinsed and dried before melting. It produced much less vapor. In both cases, small single crystals were grown and are being evaluated.

Characterization: A preliminary measurement of oxygen content in HEM material using an IR spectrophotometer on material adjacent to that used for the solar cells indicate a correlation between cell efficiency and oxygen content in the material. The lower-efficieny cells were made from material that exhibited high oxygen content.

Preliminary experiments on silicon grain boundaries using a light-induced deep-level transient spectroscopy (DLTS) method has shown some signals from the minority carrier trapping levels. More investigations are under way to improve the resolution of this technique. This technique can provide information concerning minority carrier trapping levels at the grain boundaries that a convential DLTS measurement cannot give.

Economic Analysis: A Monte-Carlo simulation model program has been improved to include the consideration of ingot technology alternatives. Several runs were made with current data and the results indicate that there is need for further improvement of the model for an equitable comparison of results from different sheet technologies. A program to examine the sensitivity of various parameters has been developed for the EFG, HEM and SOC processes. This will compute the add-on price of silicon as a function of sheet thicknesses, throughput rates and other parameters of the processes.

Other: A Cameca IMS-3f ion microanalysis probe was delivered and installed in JPL. This instrument provides the capabilities of elemental analysis with coherent spatial resolutions of less than 1 μm depth resolutions of 100A, and detection limits of 10^{13} to 10^{16} atoms/cm^2 (depending on element) and will greatly enhance the capability of the Task in evaluating silicon-sheet material.

SILICON WEB PROCESS DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

<table>
<tr><td>Technology
Single crystal ribbon growth</td><td>Completion Date 10/30/80
Report Date 2/4/81</td></tr>
<tr><td>Approach
Silicon dendritic web growth
Contractor
Westinghouse Electric Corp.
Research & Development Center
JPL Contract 954654</td><td rowspan="2">Status
• 27 Square centimeters per minute growth demonstrated
• One-day manually-controlled melt replenished growth cycle demonstrated
• Solar cell efficiency of 15.5% AM1 demonstrated. Average efficiency = 13.5% AM1
• Semi-automated growth demonstrated - 8 hours
• Thickness routinely 100-200 μm
• Dislocation density routinely < 10⁴/cm²</td></tr>
<tr><td>Goals
• Area rate of growth 25 cm²/minute
• Continuous melt replenishment
• Cell efficiency > 15% AM1
• Semi-automatic growth cycle
• Thickness 100-200 μm
• Dislocation density < 10⁴/cm²</td></tr>
</table>

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ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

Technology	Report Date
Single crystal ribbon growth	02/04/81
Approach Silicon dendritic web growth **Contractor** Westinghouse Electric Corp. Research & Development Center JPL Contract 955843 **Goals** Demonstrate Technology Readiness • Automated melt-replenished growth period to 65 hours • Area rate of growth 25 cm^2/min • Length of web crystal >10 meters • Dislocation density $<10^4/cm^2$ • Resistivity 1 to 3 ohm-cm p-type • Terrestrial solar cell efficiency >15% Demonstrate Advanced Throughput • 30-35 cm^2/min area growth rate	**Status** • Advanced throughput development in progress • Design of prototype web growth machine in progress, on schedule • Verification of automation concepts in progress • Preliminary design review at JPL 11/16/80

Chronology of Key Development Goals

	Process Development 954654	Technology Readiness 955843
Area Throughput Rate, cm^2/min	Demonstrate 25	Routinely 25
Cell Efficiency, AM1%	Demonstrate 15	Average 15
Continuous Melt Replenishment	1 Day Cycle	3 Day Cycle
Growth Mode	Semi-Automatic	Automatic

1986 Cost Projection per SAMICS/IPEG (1980 $)

Assumptions:

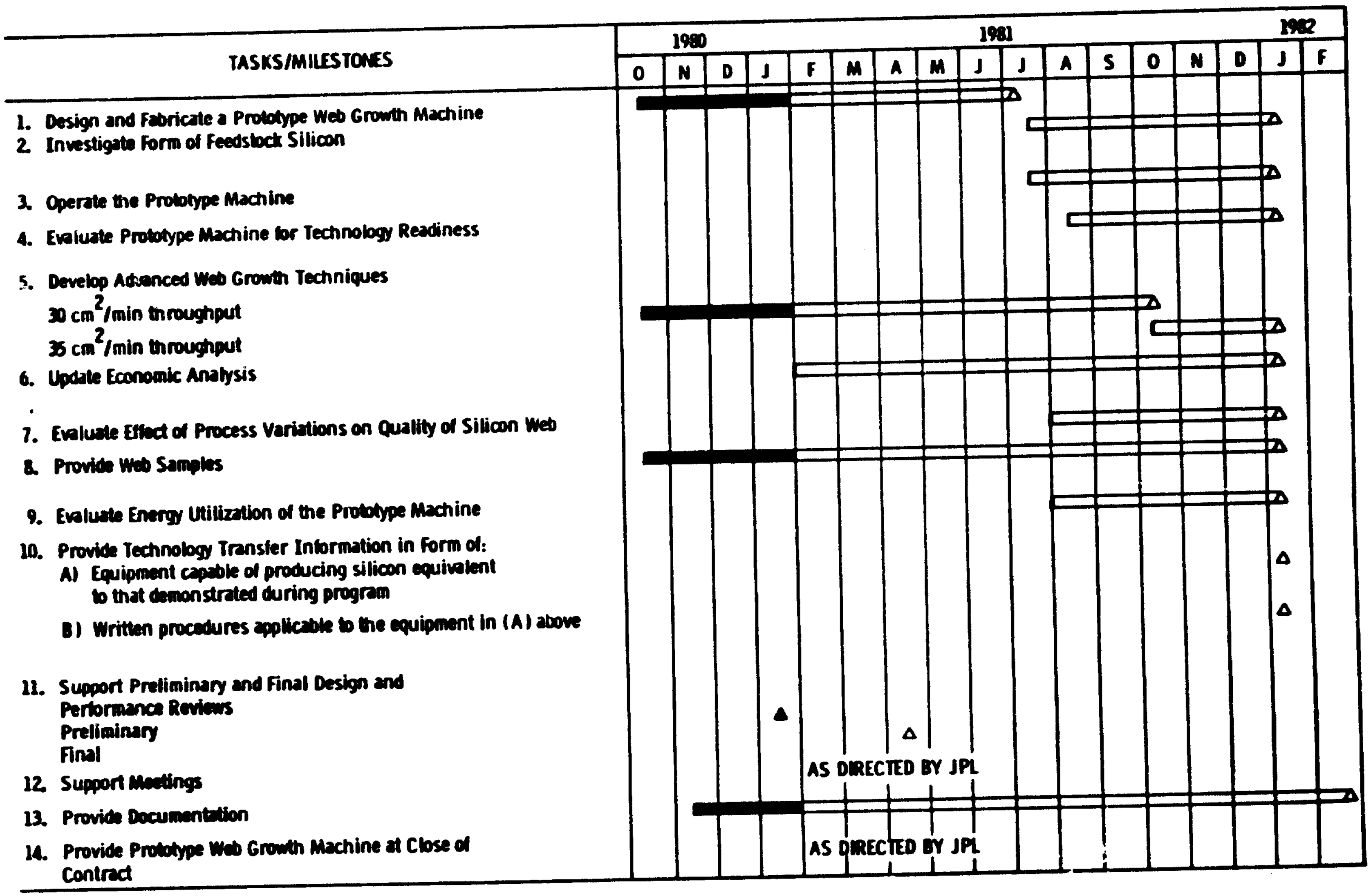
Area throughput rate 25 cm^2/minute
Terrestrial Cell efficiency 15%
Continuously melt-replenished 3 day growth cycle
Automated growth
Solar grade polysilicon price $14/kg
Thickness 150 μm

	Projected Cost, $/$W_{pk}$
Value-Added Sheet Cost	.134
Polysilicon Cost	.039
Total Sheet Cost	.173
DOE/JPL 1986 Goal	.224

Overview of Approach

- Overall objective is to achieve the Low Cost Solar Array Project technology readiness goal for silicon sheet growth
- Program combines the demonstrated key elements of silicon web growth shown by economic analysis to be capable of satisfying the DOE/JPL 1986 cost goal
- Major program tasks to achieve technology readiness are:
  - Design and build prototype web growth machine having features to satisfy 1986 goal
  - Operate prototype machine to demonstrate technology readiness
  - Provide full information for transfer of technology
- Develop advanced web growth techniques and demonstrate higher area throughput rates

Milestone Chart



Work in Progress

- **Design of prototype web growth machine**
- **Development of advanced web growth techniques for high throughput**

Development Plan: Advanced Web Growth Techniques for High Throughput

High Speed Growth Increase dissipation of latent heat. Maximize coefficients in equation $V = C + D/\sqrt{t}$

- Modify lid design*
- Modify shield configuration*
- Control melt height (continuous melt replenishment)*
- Manage gas flow

Wide Web Growth Management of melt profile and thermal stress

- Growth slot/susceptor shield design to control melt profile
- Control of thermal stress (elastic)
  - Develop criterion for critical buckling stress*
  - Identify required thermal profile in web
  - Design lid/shield system to generate required profile

Combine Speed and Width Designs

* Current Activity

Design Status: Prototype Web Growth Machine

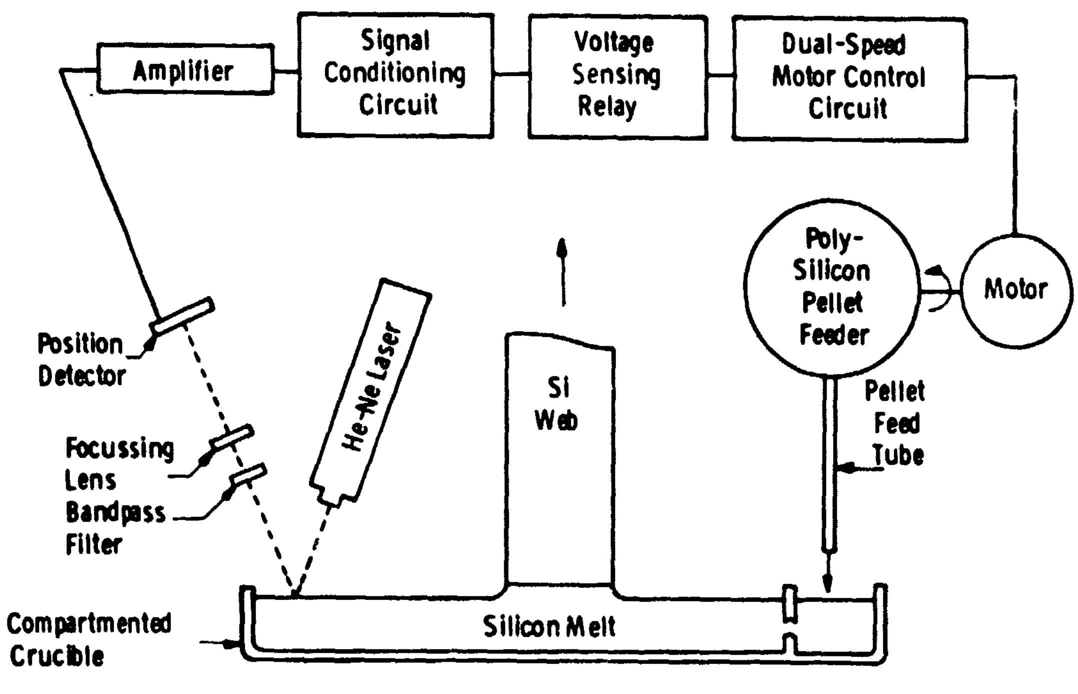
Mechanical Design

- Functional design completed
- Design refinement for equipment cost reduction in progress

Electronic Design

- Functional design near completion
- Unverified control circuits undergoing evaluation
- Design refinement for equipment cost reduction in progress

Closed-Loop Circuit for Melt-Level Control



Current Problems

- **Long delivery time for electronic components**
- **Availability of low-cost pellet-form polysilicon**

Summary

All Tasks On Schedule Per Contract Requirement

- **Prototype design**
- **Development of techniques for higher throughput**

MULTIPLE SILICON RIBBON GROWTH BY EFG

MOBIL TYCO SOLAR ENERGY CORP.

1980 Goals

1. DEMONSTRATE ON A SMALL CELL (MINIMUM 4 CM^2) THAT 13% EFFICIENCY CAN BE OBTAINED FROM ANY RIBBON GROWN IN RESISTANCE-HEATED EQUIPMENT: ACHIEVED.

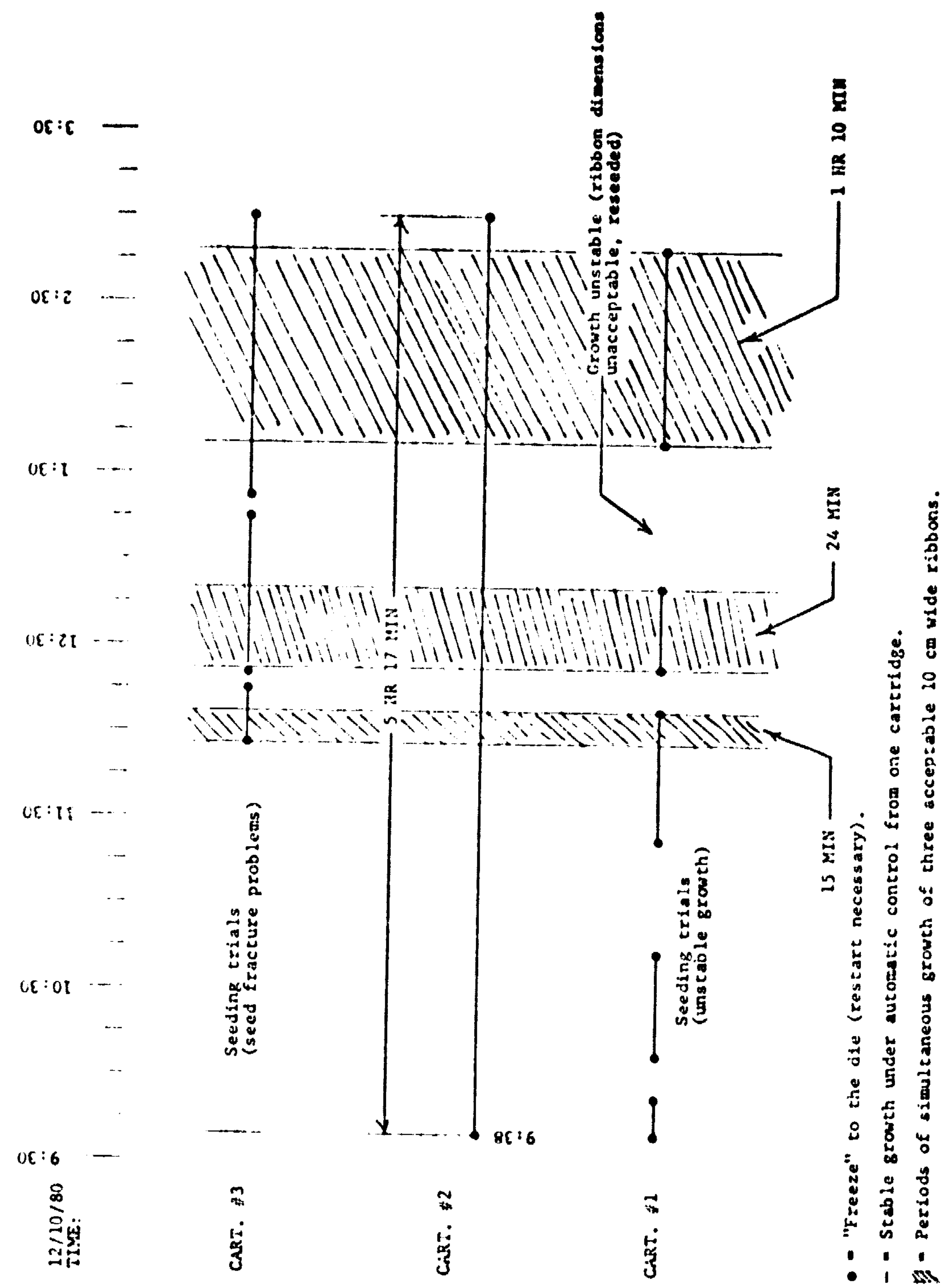
2. SHOW RIBBON GROWTH AT 10 CM WIDTH TO BE POSSIBLE AT 4 CM/MINUTE: ACHIEVED.

3. DEMONSTRATE CELL EFFICIENCIES OF 10+% ON CELLS OF 50 CM^2 AREA PREPARED FROM 10 CM WIDE RIBBON GROWN AT ~4 CM/MINUTE: ACHIEVED.

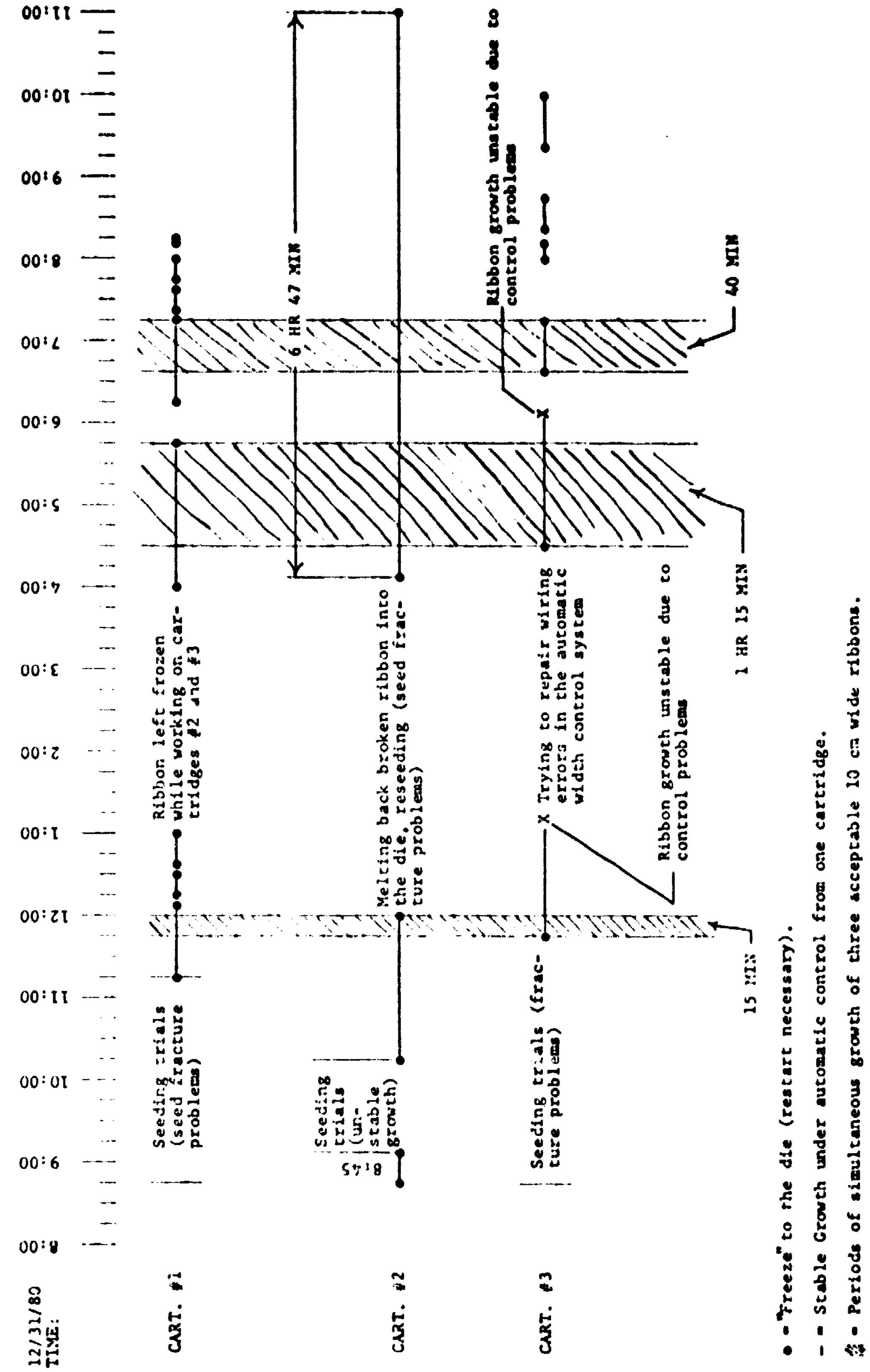
4. TECHNICAL FEATURES DEMONSTRATION, MULTIPLE RIBBON GROWTH: THREE RIBBONS, 10 CM WIDE AT 4 CM/MINUTE FOR EIGHT HOURS UNDER CONTINUOUS MELT REPLENISHMENT; MEAN CELL EFFICIENCY ON A 10% SAMPLE = 10.2%:
FIRST SCHEDULED FOR JULY 1980: NOT ACHIEVED.
RESCHEDULED FOR DECEMBER 1980: NOT ACHIEVED.

5. DESIGN EXPERIMENTAL SHEET GROWTH UNIT: POSTPONED, PENDING ACHIEVEMENT OF (4).

Run 16-248


12/10/80
TIME:
9:30
10:30
11:30
12:30
1:30
2:30
3:30
CART. #3
CART. #2
CART. #1
Seeding trials
(seed fracture problems)
9:38
5 HR 17 MIN
Growth unstable (ribbon dimensions
unacceptable, reseeded)
1 HR 10 MIN
24 MIN
15 MIN
Seeding trials
(unstable growth)
● = "Freeze" to the die (restart necessary).
— = Stable growth under automatic control from one cartridge.
= Periods of simultaneous growth of three acceptable 10 cm wide ribbons.

Run 16-250


12/31/80
TIME:
8:00
9:00
10:00
11:00
12:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
CART. #1
Seeding trials (seed fracture problems)
Ribbon left frozen while working on cartridges #2 and #3
CART. #2
8:45
Seeding trials (un-stable growth)
Melting back broken ribbon into the die, reseeding (seed fracture problems)
6 HR 47 MIN
CART. #3
Seeding trials (fracture problems)
X Trying to repair wiring errors in the automatic width control system
Ribbon growth unstable due to control problems
Ribbon growth unstable due to control problems
15 MIN
1 HR 15 MIN
40 MIN
• = "Freeze" to the die (restart necessary).
— = Stable Growth under automatic control from one cartridge.
= Periods of simultaneous growth of three acceptable 10 cm wide ribbons.

1. THE HOT-ZONE TEMPERATURE PROFILE PROBLEMS WHICH PREVIOUSLY PREVENTED SATISFACTORY GROWTH IN CARTRIDGE POSITIONS 2 AND 3 HAVE BEEN SOLVED.

2. THE AUTOMATIC WIDTH CONTROL SYSTEM HAS BEEN SHOWN TO FUNCTION WELL TO SUSTAIN GROWTH FOR LONG PERIODS WITHOUT ATTENTION. CARTRIDGE POSITION 2 OPERATED FOR 5¼ HOURS IN RUN 248 AND 6 3/4 HOURS IN RUN 250. IN BOTH THESE CASES, STEADY-STATE GROWTH APPEARED LIKELY TO CONTINUE MUCH LONGER, BUT THE RUNS HAD TO BE ENDED AT THE END OF THE WORKDAY.

3. THE AUTOMATIC CONTROL SYSTEM CANNOT RELIABLY COMPENSATE FOR THE LARGE TEMPERATURE EXCURSIONS INDUCED IN THE LEFT SIDE OF CARTRIDGE 1 BY THE LOWERING OF SILICON RODS INTO THE MELT REPLENISHMENT UNIT. THIS PROBLEM MAY BE PARTIALLY SOLVED BY OPERATING THE RIBBON-EDGE CONTROL LOOP AT HIGHER GAIN, BUT WILL BE MORE COMPLETELY SOLVED BY THE INCLUSION, IN FUTURE FURNACE HOT ZONE DESIGNS, OF SOMEWHAT GREATER SEPARATION BETWEEN THE MELT REPLENISHMENT UNIT AND THE GROWTH CARTRIDGES.

4. THE COOLING PROFILE IN THE CARTRIDGE NEEDS TO BE CHANGED TO REDUCE THE MAGNITUDE OF THERMAL STRESSES IMPOSED ON THE RIBBON. THE CARTRIDGE/PULLER MOUNTING HARDWARE ALSO NEEDS TO BE REDESIGNED TO ENSURE A MORE PRECISE ALIGNMENT BETWEEN THESE TWO UNITS.

5. THE EXISTING MELT REPLENISHMENT SYSTEM CANNOT SUPPLY SILICON AT A RATE SUFFICIENT TO SUSTAIN THE GROWTH OF THREE RELATIVELY THICK 11-cm WIDE RIBBONS. A NEW REPLENISHMENT UNIT IS BEING DESIGNED* WHICH USES SILICON IN THE FORM OF CHUNKS AND WHICH, WHEN BUILT, WILL BE DEVELOPED TO OBTAIN AN ADEQUATE MELTING RATE TO FEED THE FOUR CARTRIDGES OF FUTURE MULTIPLE RIBBON FURNACES.

6. DESIGN MODIFICATIONS NEED TO BE MADE TO THE CARTRIDGE AND HOT ZONE SO THAT GAS FLOWS AND COMPOSITIONS IN THE MULTIPLE FURNACE CAN BE MORE PRECISELY CONTROLLED. IT WILL THEN BE POSSIBLE TO DETERMINE THE CONDITIONS NECESSARY FOR LOW-CARBIDE RIBBON AS IS PRODUCED BY FURNACES 17 AND 18.

7. THE CARTRIDGE POWER SUPPLIES NEED TO BE REVISED TO PROVIDE GREATER IMMUNITY TO FALSE TRIGGERING AND POWER SURGES CAUSED BY POWER-LINE TRANSIENTS. THE USE OF POWER CONTROLLERS WITH PROPERLY APPLIED SCR'S RATHER THAN TRIACS, AND CAREFUL SELECTION OF THE OUTPUT VOLTAGE OF THE STEP-DOWN TRANSFORMERS, APPEAR LIKELY TO SOLVE THIS PROBLEM.

*THIS IS DESIGN WORK UNDERTAKEN FOR OUR INTERNAL MULTIPLE GROWTH PROGRAM.

Ambient Studies in Furnace 17

- USE OF HOLLOW DIE SHIELD HAS IMPROVED GAS DISTRIBUTION AT INTERFACE.

- AMBIENT MANIPULATION SHOWN TO HAVE INFLUENCE ON QUALITY OF RIBBON GROWN WITH COLD SHOE SYSTEM.

- SOLAR CELLS OF 10 TO 11% AM1 EFFICIENCY PRODUCED AT SPEEDS OF 3.5 TO 4 CM/MINUTE.

- OPTIMIZATION STUDIES IN PROGRESS TO INVESTIGATE AMBIENT/SPEED/COOLING PROFILE/COLD SHOE EFFECTS.

Machine 17

Date	Run No.	Growth	Thickness (cm)	Speed (cm/minute)	Process	Average Resistivity (Ω-cm)	Cell Results J_{sc}	V_{oc}	FF	η	Notes
02/30/80	17-139	CO_2 off CO_2 on	0.019 - 0.033	3.5	PH_3, 1" x 2", no AR	5	15.5 19.0	0.470 0.513	0.734 0.753	5.35 7.33	
12/16/80	17-136	CO_2 off CO_2 on	0.030	3.1	PH_3, 2" x 4", no AR	5.9	15.8 18.5	0.472 0.511	0.681 0.706	5.03 6.66	
12/16/80	17-134	CO_2 off CO_2 on	0.027	3.1	PH_3, 2" x 4", no AR	6.2	14.1 16.3	0.459 0.479	0.680 0.666	4.40 5.21	furnace problem
11/05/80	17-131	reduced ambient, SOP	0.029	3.6	PH_3, 2" x 4", no AR	5	16.7	0.483	0.621	5.0	graphite-like
					CVD, 2" x 4", no AR		17.8	0.503	0.714	6.40	
10/26/80	17-126	reduced ambient, SOP	0.025	3.4	PH_3, 2" x 4", no AR	5.2	15.7	0.476	0.708	5.29	graphite-like
					CVD, 2" x 4", no AR		16.8	0.501	0.709	5.96	

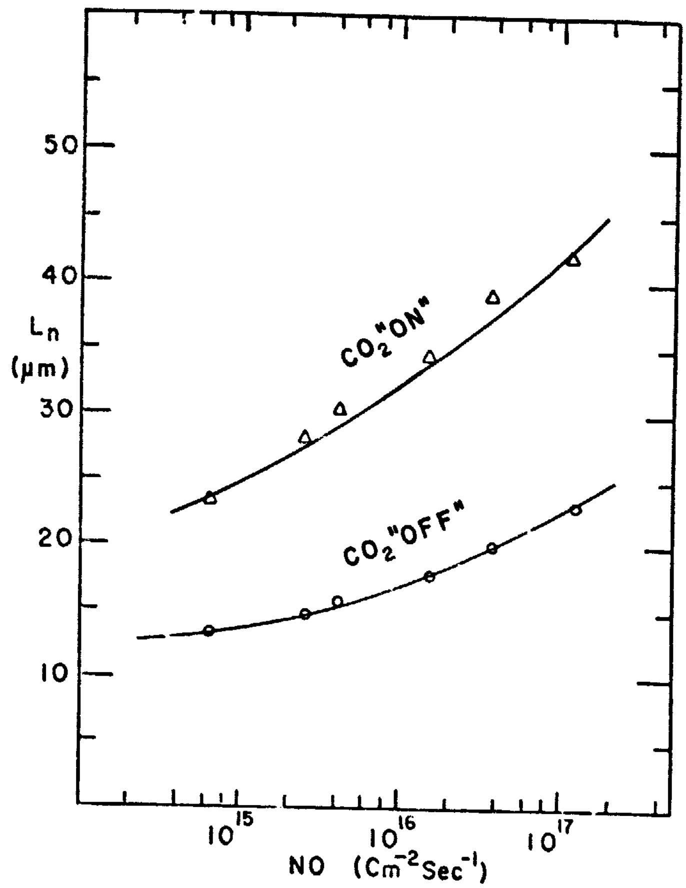
Evaluation

SOLAR CELL EVALUATION OF MATERIAL GROWN
IN JPL GROWTH MACHINE NO. 1.
ALL CELLS WERE FABRICATED WITH THE PH_3 DIFFUSION PROCESS.

ELH LIGHT, 100 mW/cm^2, 28°C, AR COATED, CELL AREA = 13 cm^2

Run No.	Growth Conditions	Cell Parameters J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
17-139 ρ = 5 Ω-cm 3.5 cm/min	CO_2 "off"	22.6	.483	.71	7.8
		21.6	.476	.73	7.5
		22.2	.478	.74	7.8
		24.2	.502	.72	8.8
	CO_2 "on"	26.6	.521	.75	10.4
		26.0	.514	.74	9.9
		28.0	.528	.76	11.2
		27.7	.533	.72	10.6
		27.9	.527	.75	11.1

Run 17-139



Cartridge-Furnace Interaction in JPL No. 1

- INCREASED POWER DEMAND OF 10 CM CARTRIDGE HAS NECESSITATED COMPLETE REBUILDING OF FURNACE POWER SUPPLIES:

  MAIN ZONE

  - INSULATION RECONFIGURED.
  - HEATER POSTS REDESIGNED FROM MOLYBDENUM TO GRAPHITE TO IMPROVE HANDLING OF HIGHER CURRENTS.

  AFTERHEATER

  - POWER DEMAND COUPLED TO MAIN ZONE INSULATION EFFECTIVENESS.
  - AVAILABLE TRANSFORMER POWER INADEQUATE FOR HEATING LARGER CROSS SECTION LINEAR COOLING PLATES.

  FACE HEATER

  - POWER DEMAND COUPLED TO COLD SHOE/AFTERHEATER CONFIGURATION.
  - HEAVY DUTY CONTROLLERS INSTALLED.

- GROWTH CONDITIONS CLOSELY RELATED TO BALANCE OF MAIN ZONE, AFTERHEATER, FACE HEATER POWER LEVELS.

SILICON ON CERAMIC

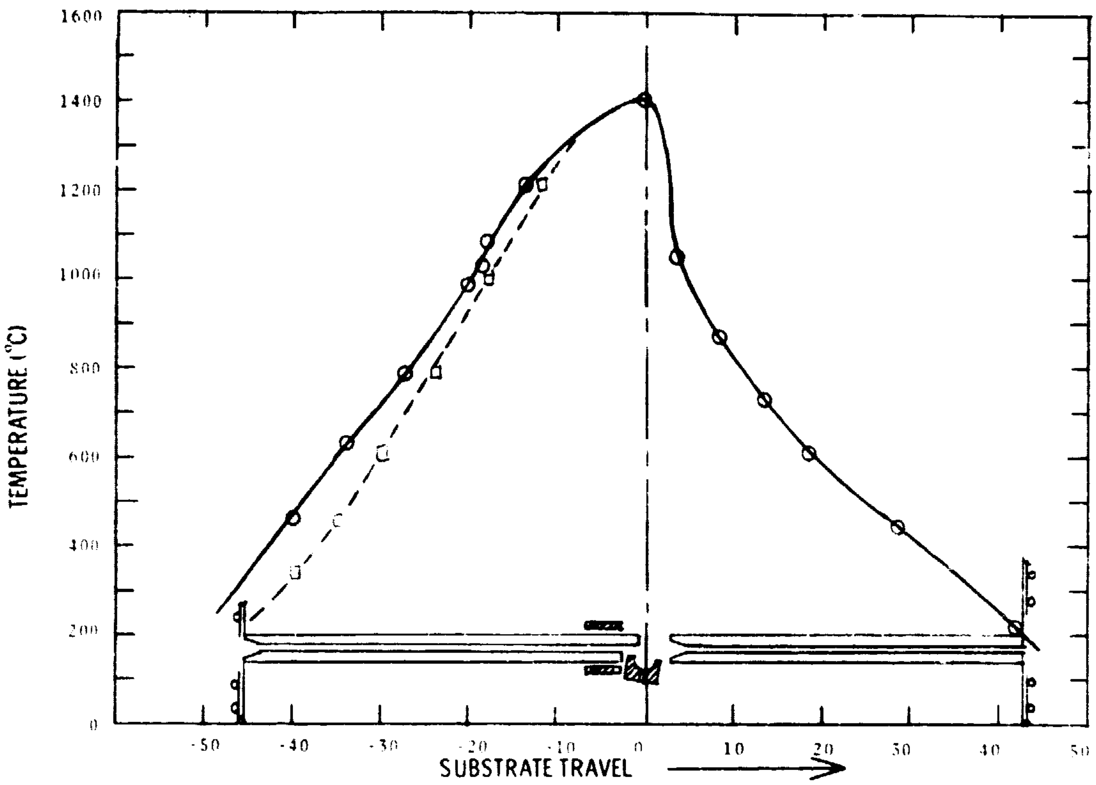
HONEYWELL CORP.

TECHNOLOGY SILICON ON CERAMIC	**REPORT DATE** FEBRUARY 4, 1981
APPROACH SCIM-COATED SOC 12 x 100 cm SLOTTED CERAMIC **CONTRACTOR** HONEYWELL INC. **GOALS** 12 cm WIDE x 100 cm LONG 15 cm/min PULL SPEED 350 cm^2/min THROUGHPUT 11% CELL EFFICIENCY 9.8% AVERAGE EFFICIENCY	**STATUS** • SCIM-COATING 10 cm x 100 cm FULLY SLOTTED SUBSTRATES ROUTINELY • 15 cm/min DEMONSTRATED (DIPCOATING) • 30 cm/min THIN LAYERS SCIM-COATED. • 10.54% CELL EFFICIENCY (DIPCOATED) • 7.64% ON SCIM-COATED SOC • 9.6 $\pm$ .5% AVERAGE EFFICIENCY FOR 74 RECENT DIP-COATED CELLS.

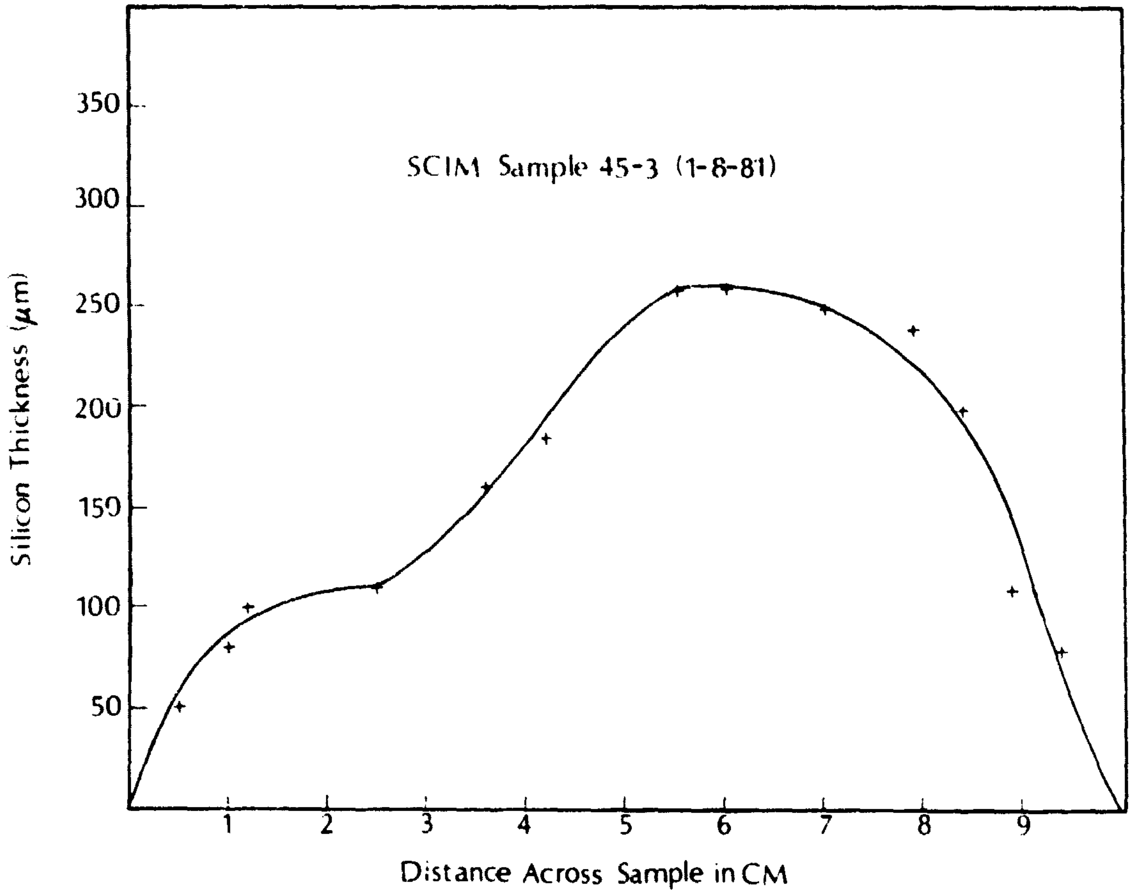
Growth Activities and Status

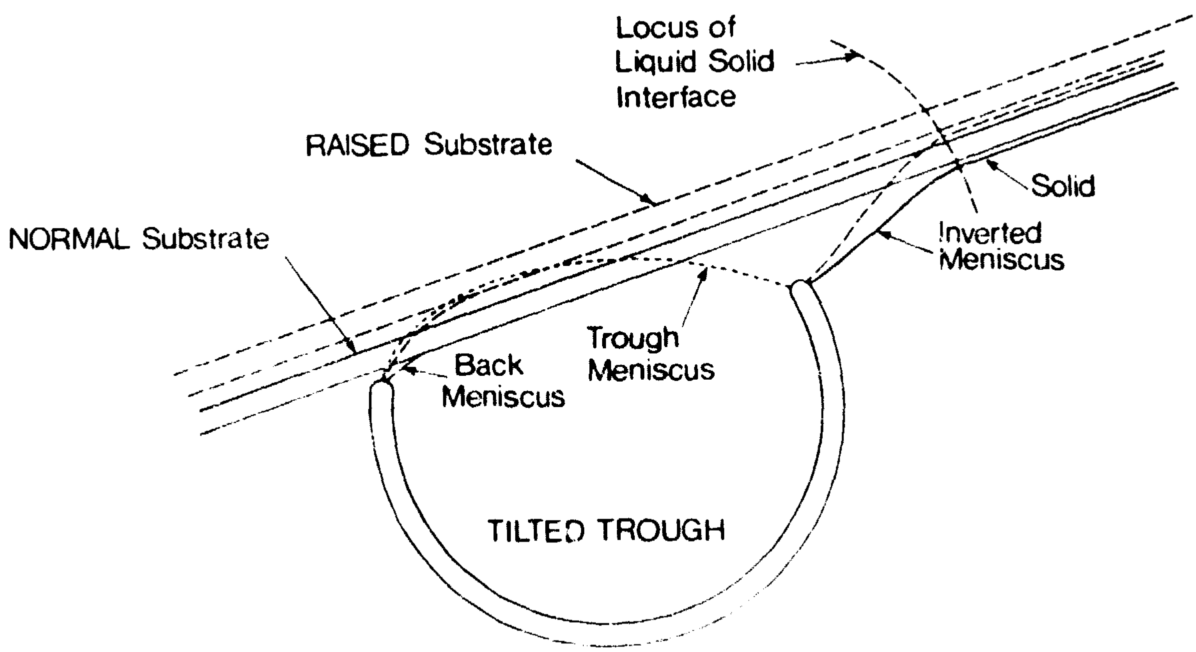
- ALL SCIM-II RUNS NOW USE 10 cm x 100 cm SUBSTRATES FULLY SLOTTED
- MANUAL MELT REPLENISHMENT USED WITH EACH RUN.
- HEAVY BORON DOPING ROUTINELY USED IF DESIRED.
- LONGITUDINAL TEMP. PROFILE HAS BEEN SPECIFIED.
- TRANSVERSE TROUGH TEMPERATURE GRADIENTS SIGNIFICANTLY IMPROVED.
- EFFECTS OF CHANGES IN CRUCIBLE, TROUGH, PREHEATER, TEMPERATURES INVESTIGATED.
- EFFECTS OF LIQUID-SOLID INTERFACE POSITION INVESTIGATED.
- EFFECTS OF GAS BLOWING, GAS PURITY INVESTIGATED.
- SCIM-III DESIGN COMPLETE, CONSTRUCTION BEGUN.
- MATERIAL PRODUCTION BASED ON DIPCOATING.
- SCIM-I NOT IN OPERATION

Longitudinal Thermal Profile, SCIM II

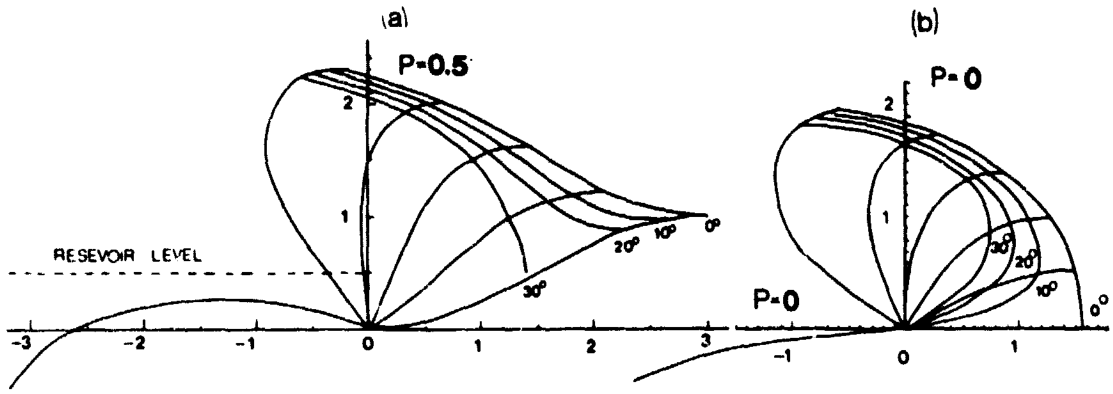


SCIM Sample 45-3 (1-8-81)





Calculated Meniscus Shapes And Loci of Constant Slope



Liquid-Solid Interface (LSI) Effects

- LSI CLEARLY VISIBLE BECAUSE OF NON-ZERO CONTACT ANGLE.
- WHEN DENDRITES FORM, LSI ROUGHENS: SOLID POINTS PROJECT INTO LIQUID, AS VIEWED FROM BACK.
- COATING OCCURS OVER A WIDE RANGE OF MENISCUS PRESSURES, BUT THICKNESS VARIES
- LSI POSITION ALONG HORIZONTAL AXIS CONTROLLED BY MENISCUS PRESSURE; SUBSTRATE ANGLE AND HEIGHT HAVE MUCH LESS EFFECT.
- FOR GIVEN THERMAL CONDITIONS, THERE IS A PREFERRED LSI POSITION ALONG HORIZONTAL AXIS. TOO CLOSE PRODUCES THIN LAYERS. TOO FAR PRODUCES DENDRITES.
- BLOWING ARGON ON MENISCUS MOVES LSI AWAY FROM TROUGH. NON-DENDRITIC GROWTH CAN BE OBTAINED WITH HIGHER MENISCUS PRESSURES.

Dendrites

TYPES OF DENDRITES IN SOC GROWTH

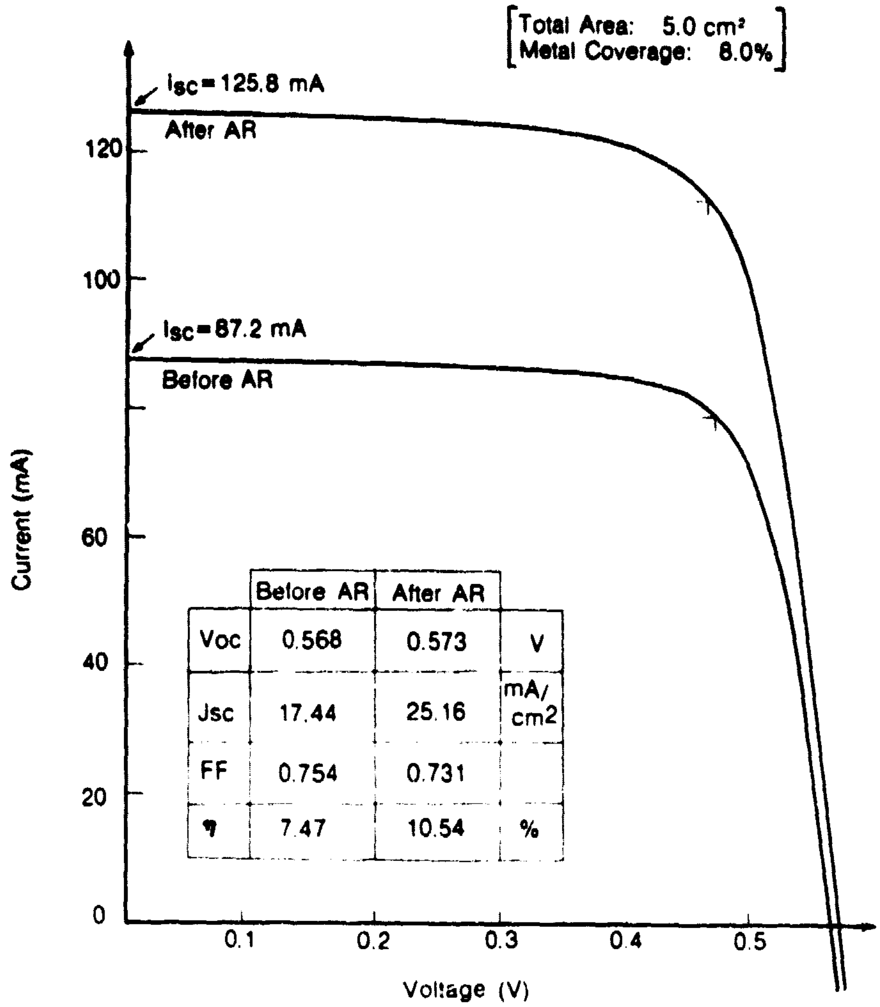
A. LARGE, THICK REGIONS
B. SMALL, ISOLATED REGIONS
C. SINGLE ISOLATED PEAKS
D. THIN, FINE STRUCTURE; LARGE REGIONS
E. FINE STRUCTURE, LONG NARROW REGIONS (SCIM-II ONLY)

KNOWN CAUSES OF DENDRITES	TYPE
1. MELT TOO COOL	A
2. SPEED TOO FAST	D
3. CARBON, SILICON IN SLOTS	B

POSSIBLE CAUSES OF DENDRITES	
1. IMPURITIES IN MELT - CONSTITUTION SUPERCOOLING	D, E
2. SURFACE ROUGHNESS OF CERAMIC	B, C
3. SiO ON CARBON SURFACE	
4. VIBRATION OF MELT	E
5. THICKNESS TEMPERATURE GRADIENT (PREHEATER LOCATION)	E
6. MENISCUS GEOMETRY AND PRESSURE	

Slotted SOC Cell

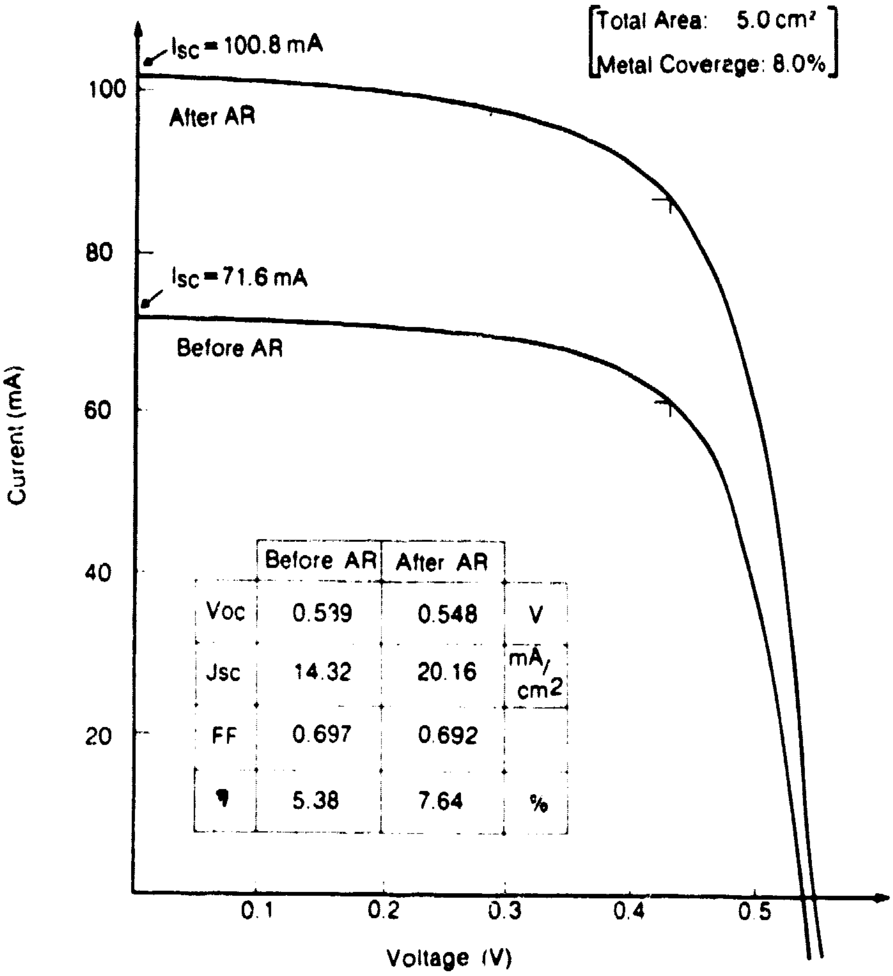
No: 485-4-211



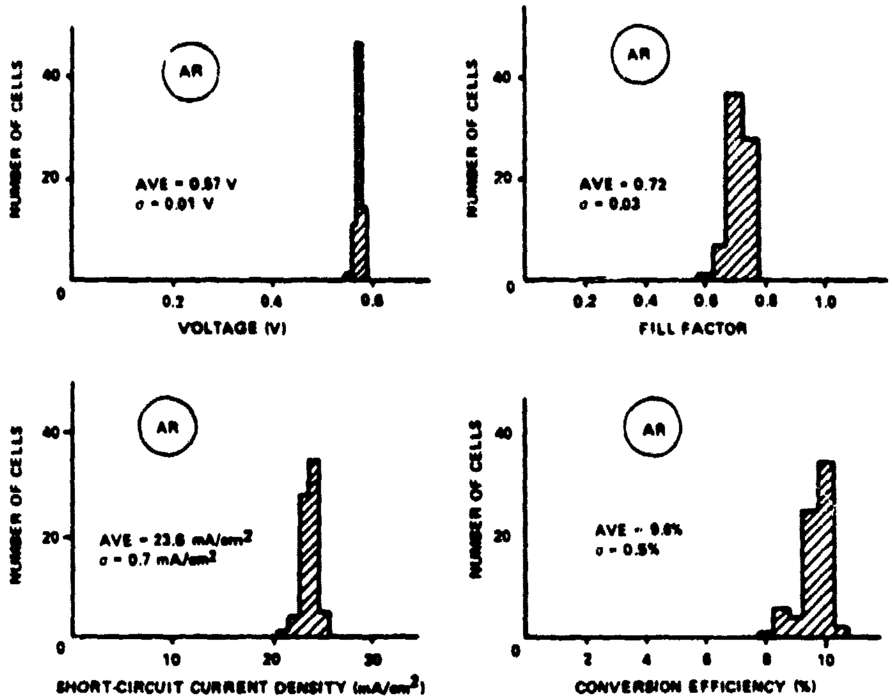
	Before AR	After AR	
Voc	0.568	0.573	V
Jsc	17.44	25.16	mA/cm2
FF	0.754	0.731	
η	7.47	10.54	%

SCIM-Coated Slotted SOC Cell

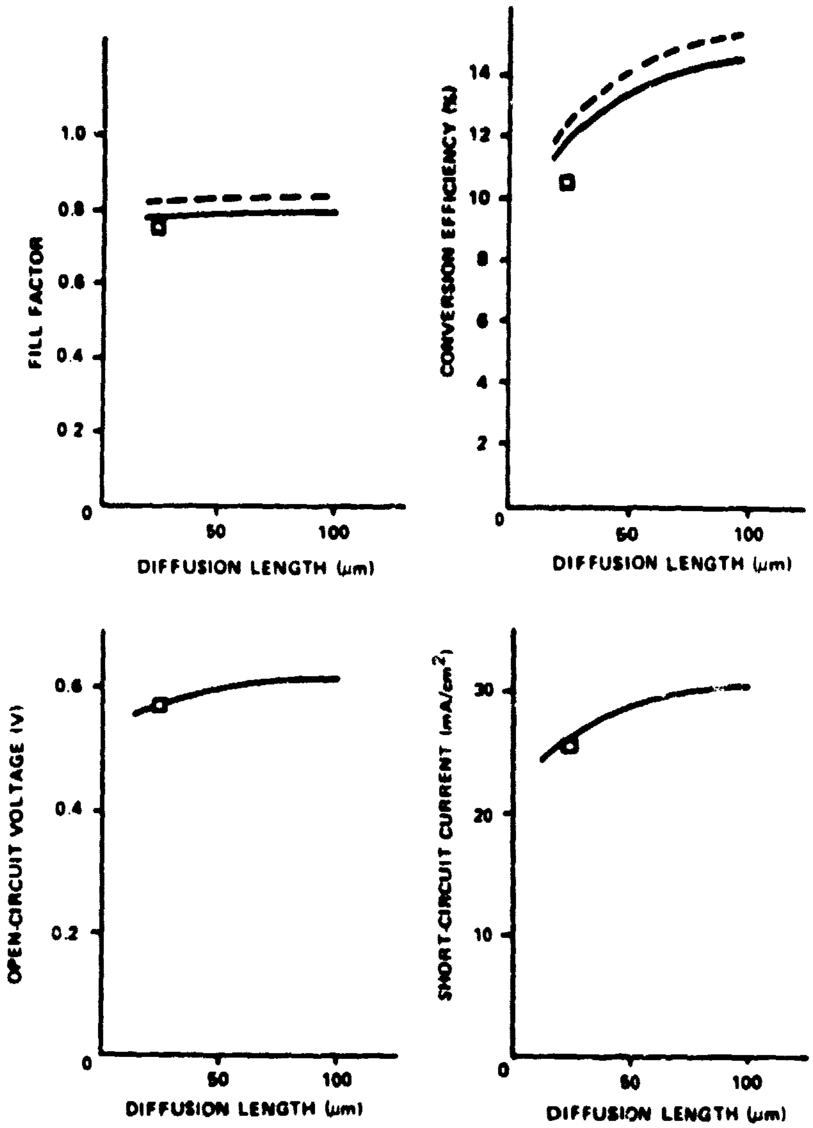
No: 38-4-35-111



	Before AR	After AR	
Voc	0.539	0.548	V
Jsc	14.32	20.16	mA/cm2
FF	0.697	0.692	
η	5.38	7.64	%



AR
NUMBER OF CELLS
AVE = 0.57 V
σ = 0.01 V
VOLTAGE (V)
AR
AVE = 0.72
σ = 0.03
FILL FACTOR
AR
AVE = 23.6 mA/cm²
σ = 0.7 mA/cm²
SHORT-CIRCUIT CURRENT DENSITY (mA/cm²)
AR
σ = 0.5%
CONVERSION EFFICIENCY (%)


FILL FACTOR
1.0
0.8
0.6
0.4
0 2
0
50
100
DIFFUSION LENGTH (μm)
CONVERSION EFFICIENCY (%)
14
12
10
8
6
4
2
0
50
100
DIFFUSION LENGTH (μm)
OPEN-CIRCUIT VOLTAGE (V)
0.6
0.4
0.2
0
50
100
DIFFUSION LENGTH (μm)
SHORT-CIRCUIT CURRENT (mA/cm²)
30
20
10
0
50
100
DIFFUSION LENGTH (μm)

Summary of JPL Cell Results

- BEST DIP-COATED CELL: = 10.54%
- BEST SCIM-COATED CELL: = 7.64%
- 1980 BASELINE CELLS:

$$\left.\begin{array}{ll} \eta & = 9.6\% \ (\pm\ 0.5) \\ J_{sc} & = 23.6\ \dfrac{mA}{cm^2}\ (\pm\ 0.7) \end{array}\right\}\ \text{TOTAL AREA}$$

V_{oc} = 0.57 V ($\pm$ 0.01)

FF = 0.72 ($\pm$ 0.03)

A = 5 cm^2 FOR ALL CELLS

AM1 WITH AR COATING

Major Assumptions

- 2.5 MILLION m^2 PRODUCTION
- 0.25-cm/sec PULL SPEED.
- TWO 12.5-cm TRACKS PER COATING MACHINE
- $50,800 COST FOR SILICON COATING MACHINE
- 1/12 OPERATOR PER COATING MACHINE; 4.7 SHIFTS
- OPERATOR LABOR $13.150/YEAR WITHOUT FRINGE BENEFITS
- COATING MACHINES STACKED SIX HIGH (24 ft^2 PROPRATED FLOOR SPACE PER MACHINE)
- $5.78/$m^2$ CERAMIC COST
- 85% PLANT EFFICIENCY
- 92% PROCESS YIELD

Projected Technology Costs by IPEG2 ($\$/m^2$)

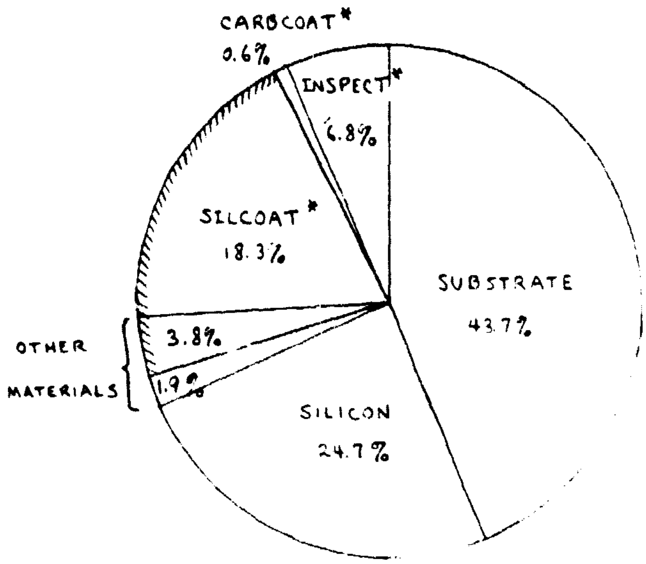
TASK	EQPT	SQFT	DLAB	MATS	UTIL	TOTAL
CARBON COATING	0.0078	0.0283	0.0692	0.330[a]	0.00678	7.981
				7.539[b]		
SILICON COATING	1.917	0.1731	0.954	0.662[c]	0.12154	3.828[e]
				4.263[d]		8.091[f]
INSPECT	0.104	0.1045	0.966	---	0.00352	1.178
TOTALS	2.029	0.306	1.98[illegible]	8.531[e]	0.132	12.987[e]
				12.791[f]		17.250[f]

(a) CARBON, (b) SUBSTRATES, (c) ARGON, CRUCIBLES, FURNACES, INSULATION,
(d) POLYSILICON, (e) EXCLUDING SILICON, (f) INCLUDING SILICON

IPEG2 Projected Cost Breakdown

ADDED VALUE $12.99 / M^2

INCLUDING SI $17.25 / M^2



* PROCESSING COSTS EXCLUDING MATERIALS

SHADED SECTORS ARE SENSITIVE TO SILCOAT THRUPUT RATE

Problems and Concerns

- ADEQUATE SILICON THICKNESS AT HIGH SPEEDS NOT DEMONSTRATED
- DENDRITIC GROWTH IN SCIM-II
- CELL EFFICIENCY OF SOC GROWN AT HIGH SPEEDS NOT DEMONSTRATED

OXYGEN ANALYSIS

UNIVERSITY OF MISSOURI, ROLLA

P.D. Ownby
H.V. Romero

Introduction

AN OXYGEN PARTIAL PRESSURE MAINTAINED HIGHER THAN 10^{-19} ATM. IN THE PRESENCE OF MOLTEN SILICON IS OBSERVED TO ENHANCE THE INTERACTION BETWEEN THE SILICON AND THE CONTAINER MATERIAL. THUS IT IS DESIRABLE TO KNOW THE pO_2 OVER MOLTEN SILICON IN ACTUAL PRODUCTION FACILITIES.

pO_2 MEASUREMENTS WERE MADE IN:

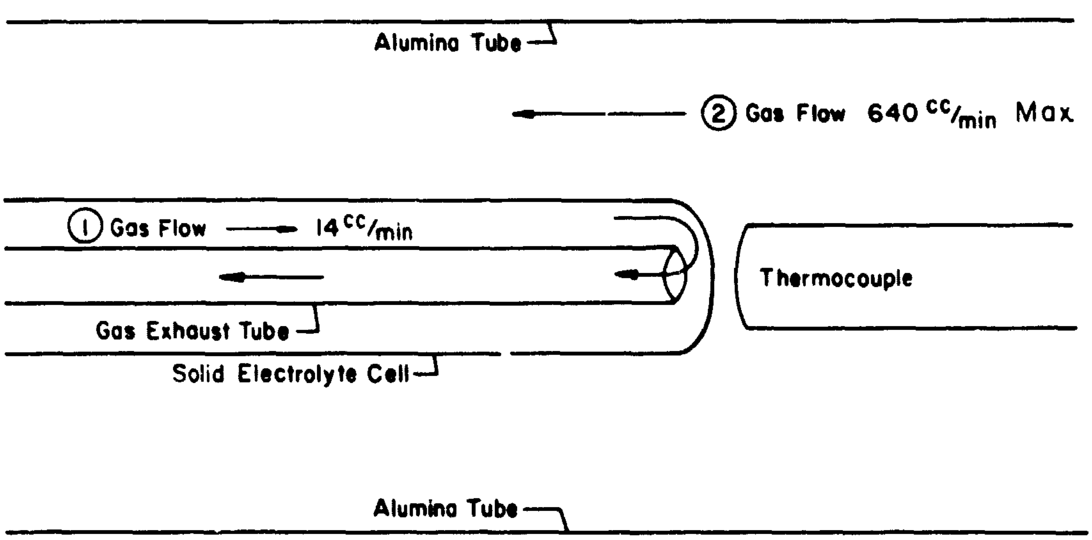
- WESTINGHOUSE SILICON WEB FURNACES
- HONEYWELL SCIM COATER FURNACE
- HONEYWELL DIP COATER FURNACE

TO DETERMINE: pO_2 OF PURGE GAS
pO_2 OF FURNACE ATMOSPHERE AT OPERATING TEMPERATURE

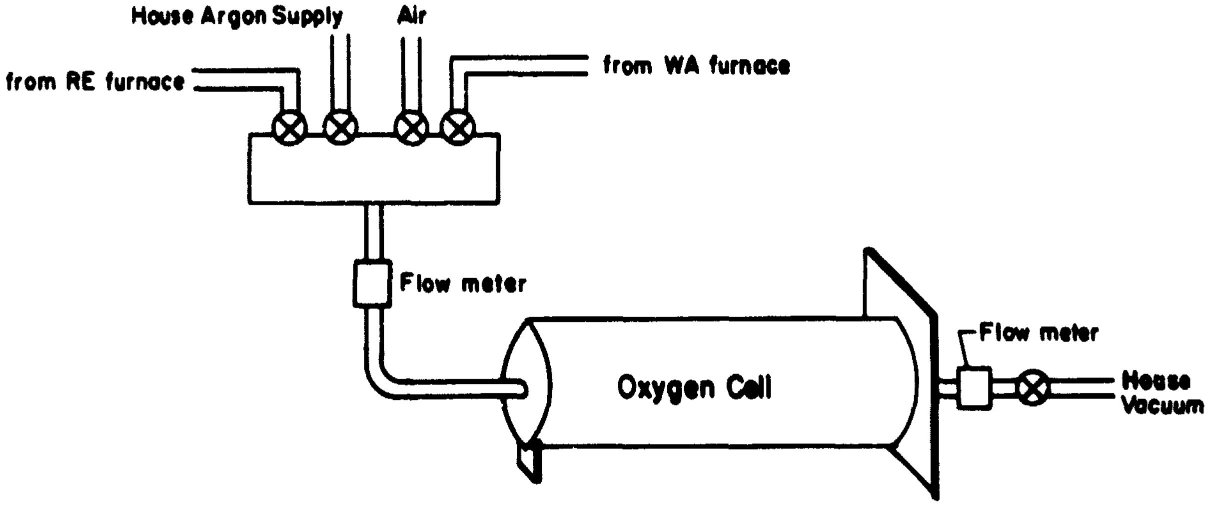
Conditions for Westinghouse Runs

- THORIA-YTTRIA OXYGEN CELL USED WITH A CO/CO_2 REFERENCE GAS HAVING A pO_2 OF 10^{-14} ATM.
- LONG SAMPLE LINE FROM FURNACE TO CELL
- SLOW SAMPLE RATE (14. CC/MIN) DRAWN THROUGH CELL WITH HOUSE VACUUM--GAS FLOW PATH(1)
- THORIA TUBE DESTROYED BY THERMAL SHOCK ON INITIAL HEAT-UP--CELL REBUILT WITH NEW THORIA TUBE
- LESS THAN 0.5 VARIATION IN LOG pO_2 OVER DURATION OF RUNS EXCEPT WHEN AIR WAS INTRODUCED INTO THE SAMPLE LINE
- HOUSE ARGON $pO_2 = 10^{-12}$ ATM.

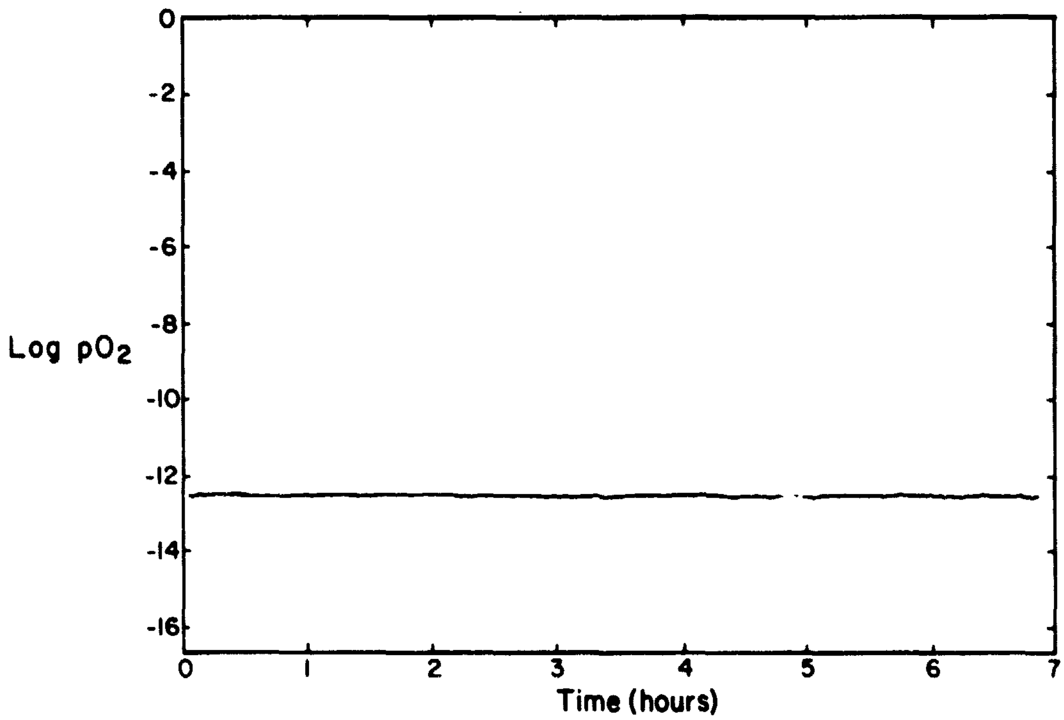
Gas Flow in Oxygen Cell



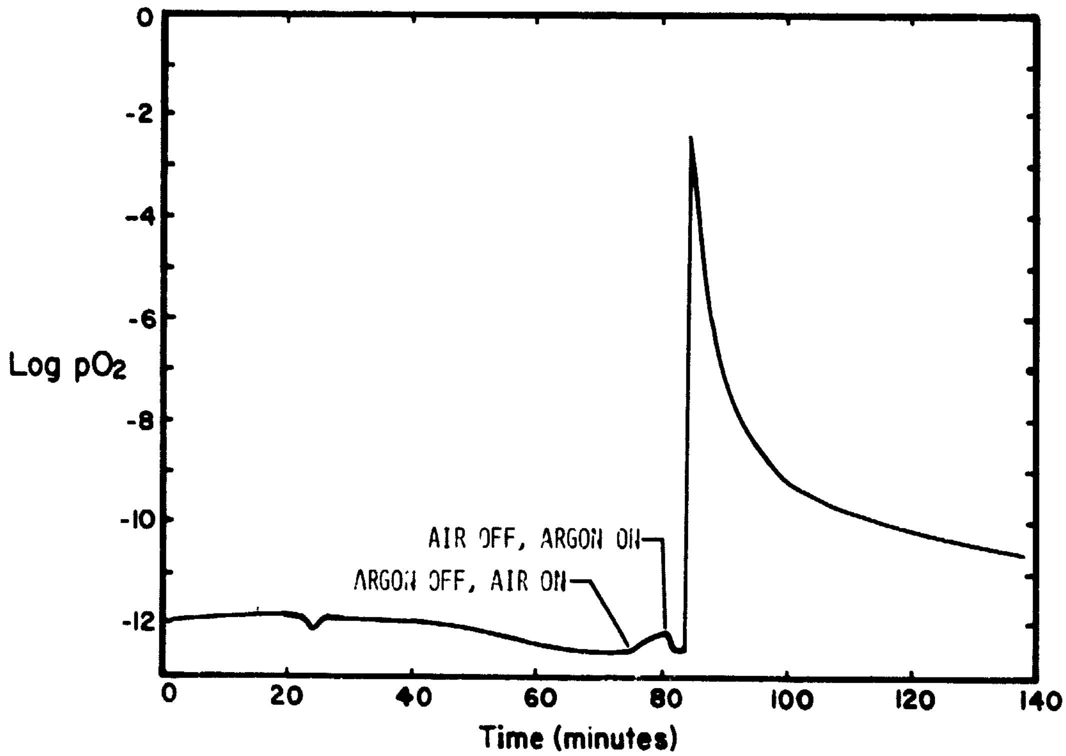
Gas Supply to Oxygen Cell



Log pO_2 vs Time for Westinghouse Web Furnace



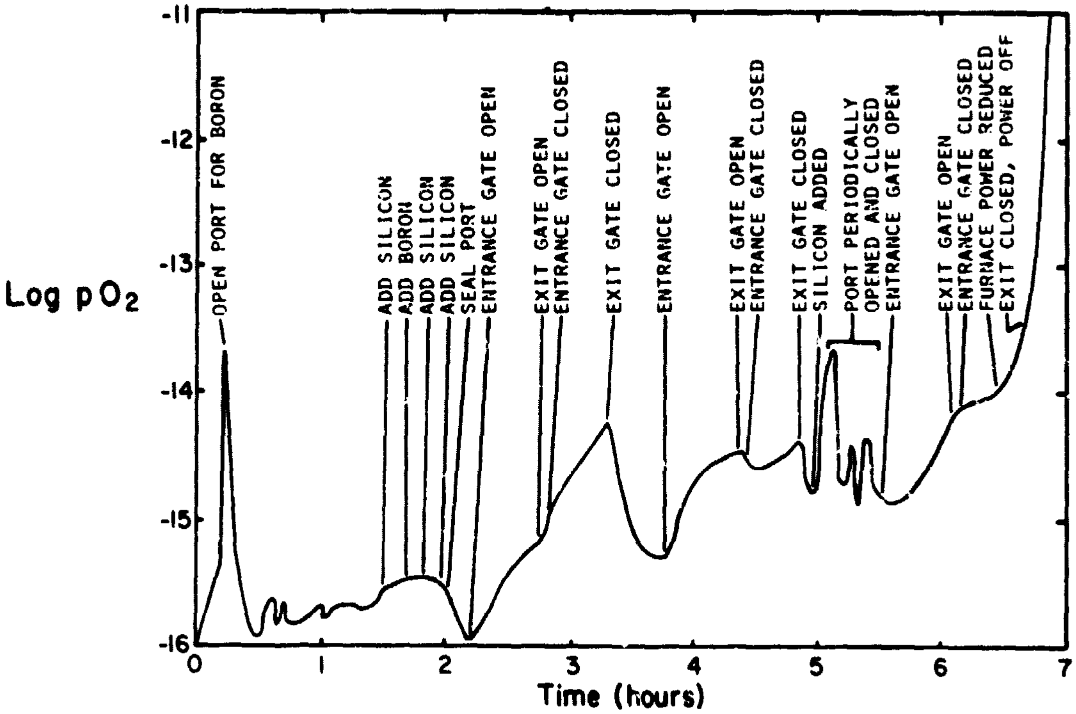
Response of Oxygen Cell to Introduction of Air
(While Monitoring House Argon)



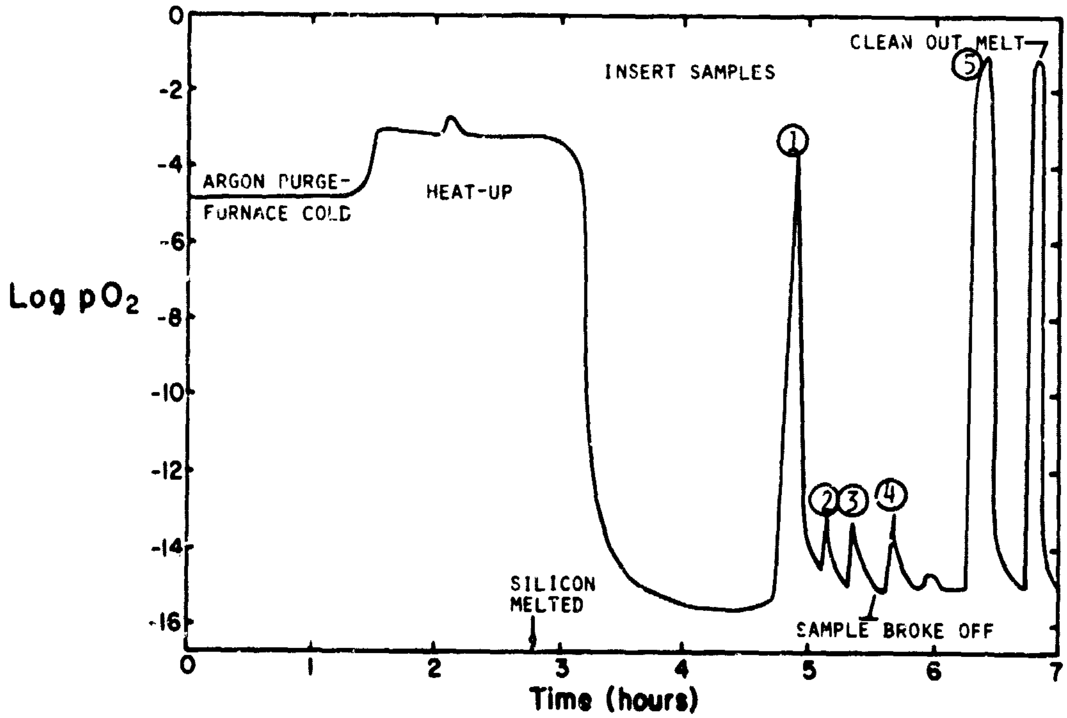
Conditions for Honeywell Runs

- ZIRCONIA-YTTRIA OXYGEN CELL WITH 1 ATM. OF OXYGEN FOR REFERENCE
- HIGH SAMPLE RATE (200 CC/MIN)--GAS FLOW PATH (2)
- pO_2 OF HOUSE ARGON FOR DIP FURNACE WAS $10^{-4.8}$ ATM
- pO_2 OF HOUSE ARGON FOR SCIM FURNACE WAS $10^{-6.0}$ ATM.
- pO_2 OF SCIM FURNACE ATMOSPHERE VARIED BETWEEN $10^{-16.0}$ AND $10^{-14.3}$ ATM DURING COATING
- pO_2 OF DIP FURNACE ATMOSPHERE VARIED BETWEEN $10^{-14.8}$ AND $10^{-13.0}$ ATM DURING COATING

pO_2 vs Time for Honeywell SCIM Coater



pO_2 vs Time for Honeywell Dip Coater



Summary of Results

BASELINE OXYGEN PARTIAL PRESSURE AS MEASURED
AT 1000°C WITH SOLID ELECTROLYTE CELL

1 FROM WESTINGHOUSE WEB FURNACE:

$$pO_2 = 10^{-12.5} \text{ ATM}$$

2 FROM HONEYWELL SOC FURNACES:

A) SCIM COATER:

$$pO_2 = 10^{-16.0} \text{ ATM}$$

B) DIP COATER:

$$pO_2 = 10^{-15.5} \text{ ATM}$$

3 FROM MOBIL-TYCO EFG FURNACE:

$$pO_2 = 10^{-12.1} \text{ ATM}$$

ADVANCED CZOCHRALSKI INGOT GROWTH

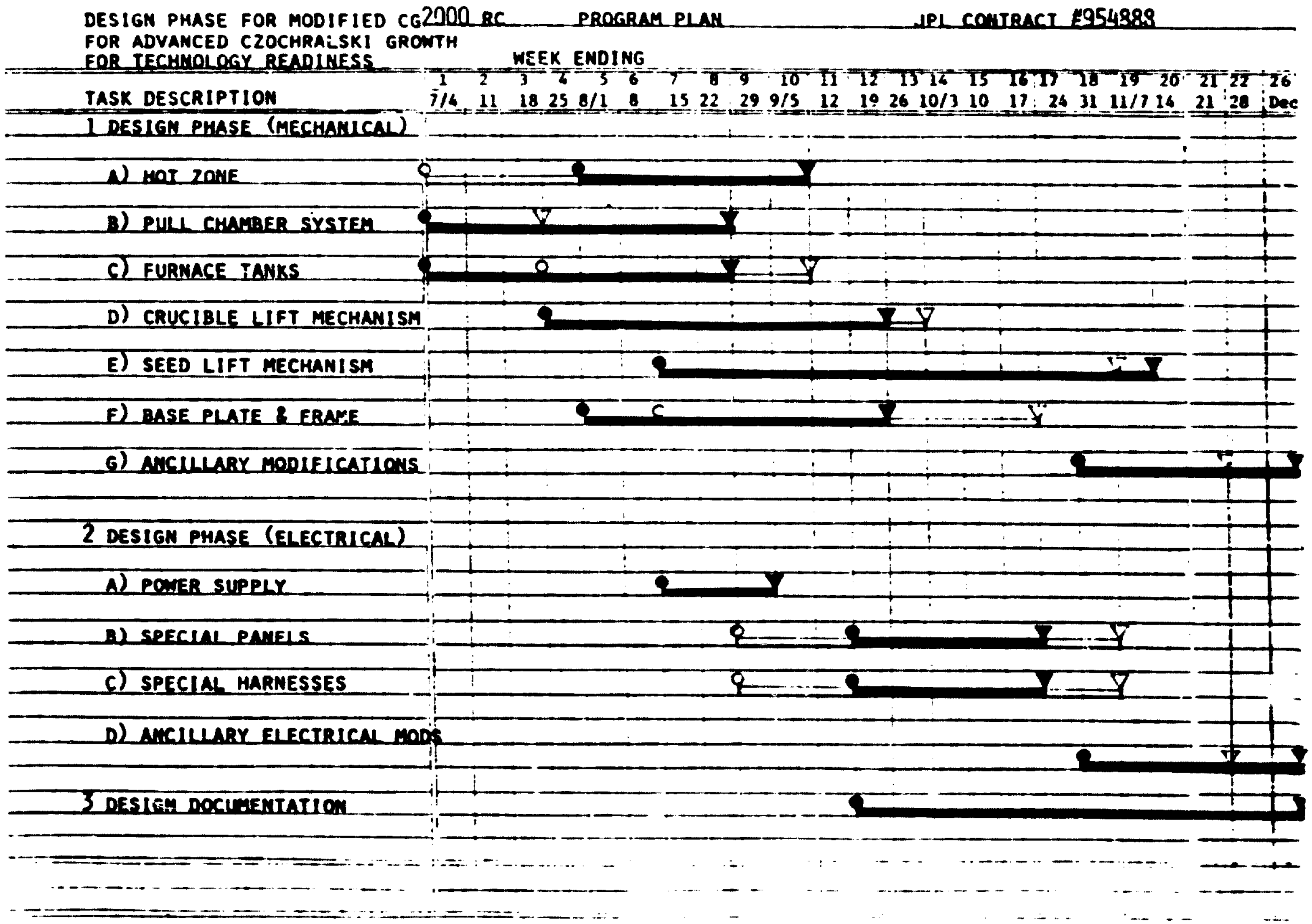
KAYEX CORP.

Design Program Requirements

TECHNOLOGY - INGOT GROWTH	REPORT DATE: DECEMBER 31, 1980 START DATE: JULY 1, 1980
APPROACH. DESIGN OF A MODIFIED CG 2000 RC CRYSTAL GROWER FOR ADVANCED CZOCHRALSKI GROWTH FOR TECHNICAL READINESS. GOALS. EQUIPMENT TO BE CAPABLE OF PULLING FIVE CRYSTALS, EACH OF 30 KG WEIGHT, 150 MMS DIAMETER FROM A SINGLE 16" DIAMETER CRUCIBLE.	MODIFICATIONS. A. OVERALL EQUIPMENT DESIGN. B. PROCESS AUTOMATION WITH M.P.U. C. SENSOR DEVELOPMENT: MELT LEVEL, MELT TEMPERATURE; CRYSTAL DIAMETER. D. RADIATION SHIELD TO ACCELERATE GROWTH. E. RECHARGE MELTING RATE OF 25 KG/HR USING SILICON CHUNKS OF GRANULAR SILICON UTILIZING A RECHARGE HOPPER. F. MODIFIED GROWTH CHAMBER SUITABLE FOR USE AS A PRODUCTION FACILITY. G. THROUGHPUT CAPABILITY OF 2.5 KG/HR.

Equipment Design CG 6000 RC

GOALS	IMPLEMENTATION
1. OVERALL EQUIPMENT DESIGN.	A). 2000 RC AS BASIC CONCEPT B). INCREASED CHAMBER SIZE. C). IMPROVED RELIABILITY: - SEALS, WELDS, VIEWPORTS, ARGON SUPPLY, GRAPHITE. D). INCREASED CAPACITY: - 15" x 12" AND 16" x 12" HOT ZONES. SEED MOTION MECHANISM. 10" ADDED TO PULL CHAMBER HEIGHT 150 KW POWER SUPPLY. E). IMPROVED SERVICEABILITY.
2. PROCESS AUTOMATION.	A). MPU SYSTEM - PLUG COMPATIBLE FOR REPLACING ANALOG SYSTEM. B). SENSOR DEVELOPMENT FOR MELT LEVEL, MELT TEMP. CRYSTAL DIAMETER.
3. ACCELERATED GROWTH.	SUITABLE RADIATION SHIELD.
4. RECHARGE MELTING RATE OF 25 KG/HR.	RECHARGE HOPPER UPRATED (150 KW) POWER SUPPLY.
5. THROUGHPUT RATE OF 2.5 KG/ HR	INCORPORATE ABOVE MODS. AND DEVELOPMENT WORK.



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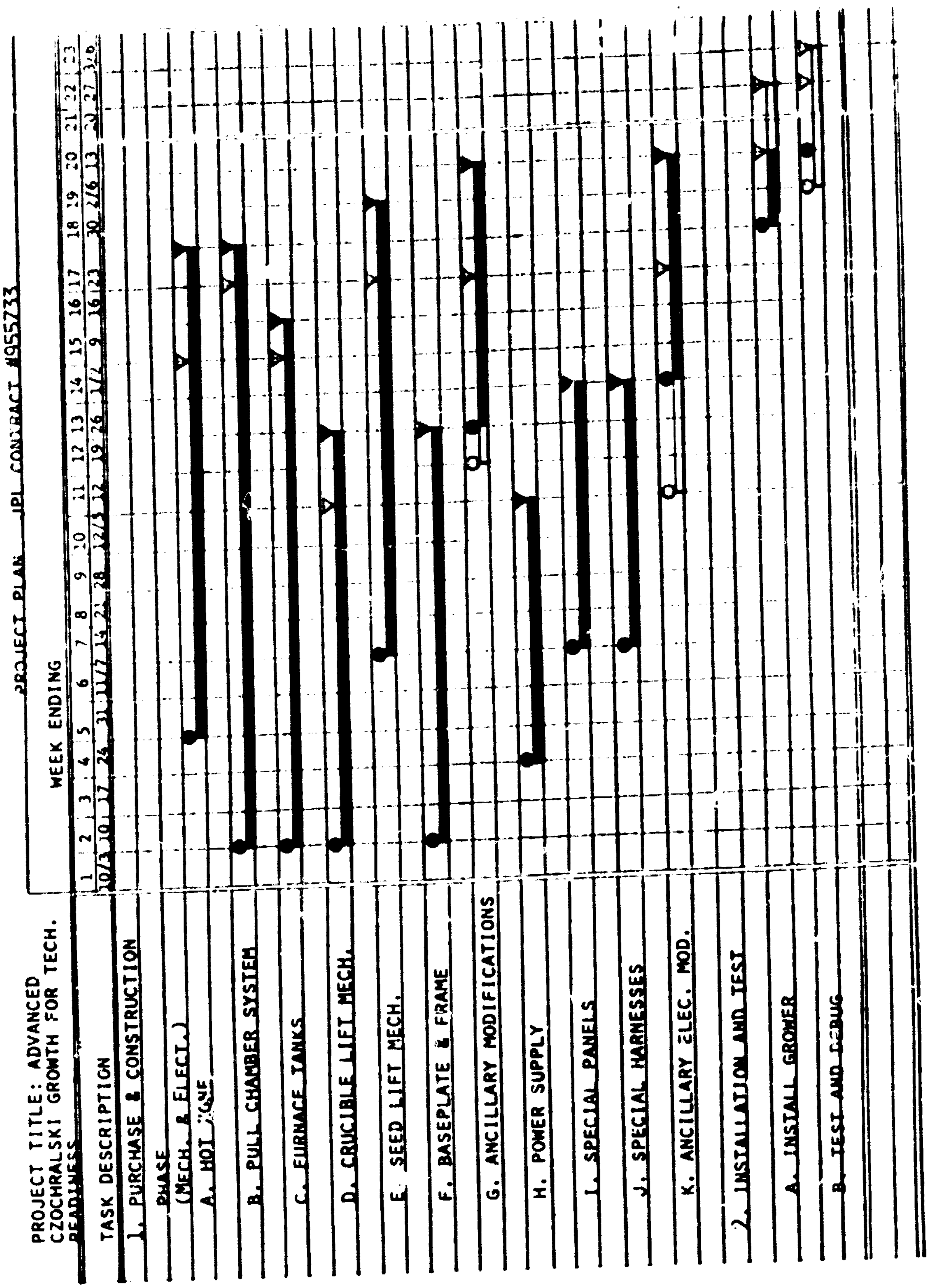
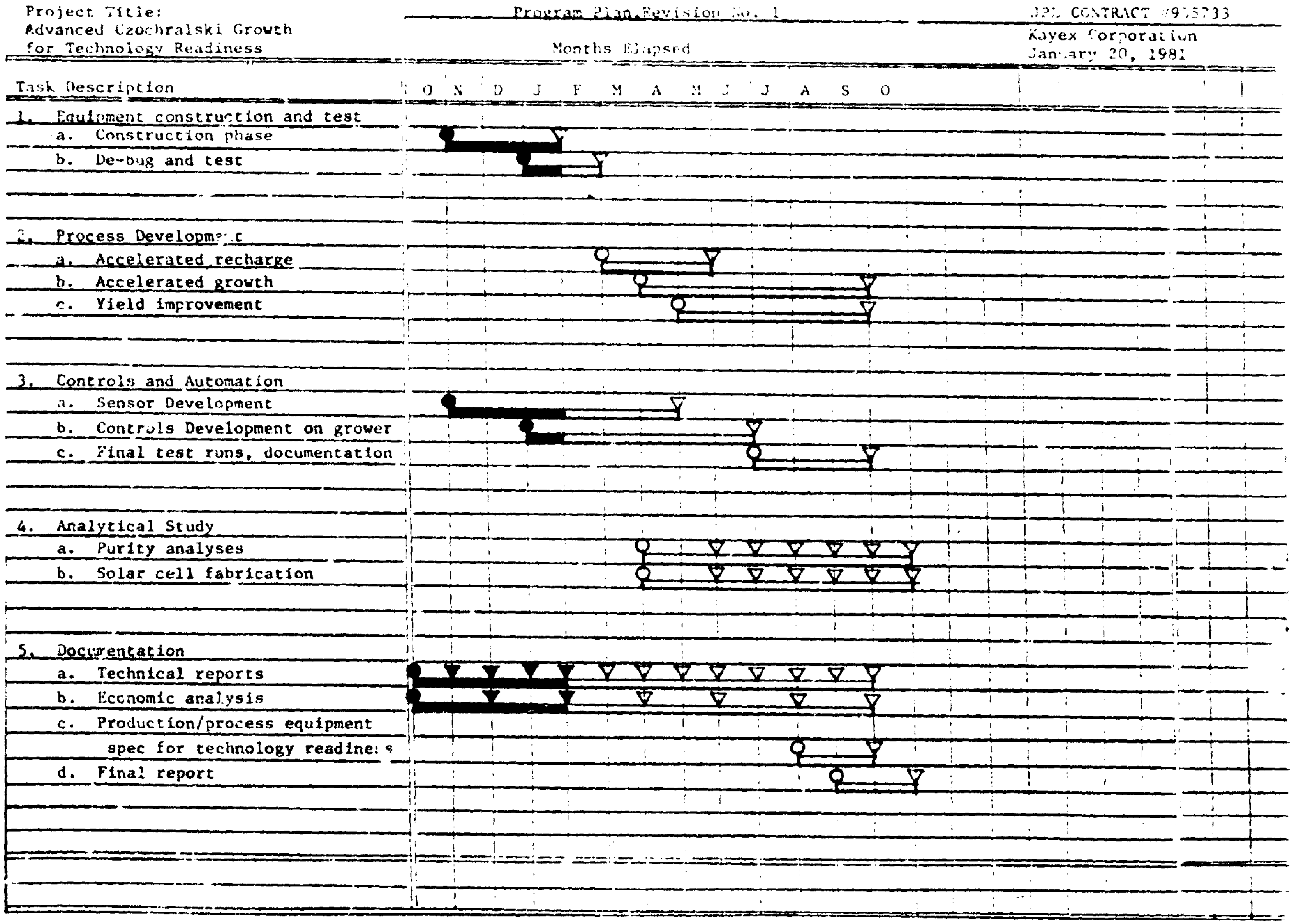
Equipment and Process Goals

TECHNOLOGY INGOT GROWTH	REPORT DATE: FEBRUARY 5, 1981 START DATE: SEPTEMBER 26, 1980
APPROACH. CONSTRUCTION AND DEVELOPMENT EQUIPMENT TO DEMONSTRATE AN ADVANCED CZOCHRALSKI GROWTH PROCESS TO PRODUCE LOW COST SILICON INGOTS FROM A SINGLE CRUCIBLE FOR TECHNOLOGY READINESS.	GOALS. 1. CONTINUOUS GROWTH OF 150 KG OR MORE OF MULTIPLE INGOTS FROM ONE CRUCIBLE USING MELT REPLENISHMENT. 2. DIAMETER OF 15 CMS E.P.D. 10^4 PER CM^2 3. GROWTH THROUGHPUT 2.5 KG PER HOUR USING A RADIATION SHIELD. 4. AFTER GROWTH YIELD 90%. 5. RECHARGE MELTING RATE OF 25 KG/HR USING HOPPER RECHARGING TECHNIQUES. 6. MICROPROCESSOR CONTROLS PLUS IMPROVED SENSORS FOR MELT LEVEL, MELT TEMPERATURE AND CRYSTAL DIAMETER. 7. PROTOTYPE EQUIPMENT SUITABLE FOR HIGH VOLUME SILICON PRODUCTION TRANSFERABLE DIRECTLY TO INDUSTRY.

Overall Program

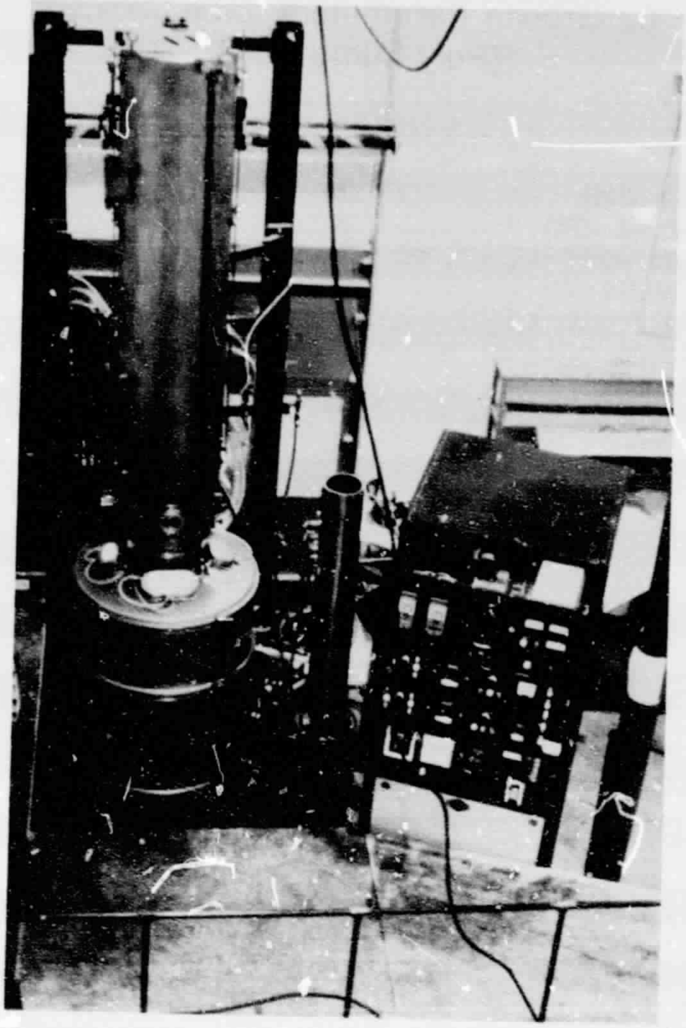
TECHNOLOGY - INGOT GROWTH	REPORT DATE: FEBRUARY 5, 1981 START DATE: SEPTEMBER 26, 1980
PROGRAM.	PROGRAM GOAL.
1. EQUIPMENT CONSTRUCTION AND TEST.	1. CONSTRUCT/DEBUG/TEST CG 6000 RC CRYSTAL PULLER.
2. PROCESS DEVELOPMENT.	2. A. ACCELERATED RECHARGE. B. ACCELERATED GROWTH. C. YIELD AND COST IMPROVEMENT.
3. AUTOMATION AND CONTROLS.	3. MPU INCORPORATING MELT LEVEL, MELT TEMPERATURE, DIAMETER CONTROL SENSORS.
4. ANALYTICAL STUDY.	4. A. PURITY ANALYSIS. B. SOLAR CELL FABRICATION.
5. DOCUMENTATION	5. A. TECHNICAL REPORTS. B. ECONOMIC ANALYSIS. C. PRODUCTION/PROCESS EQUIPMENT SPEC. FOR TECHNOLOGY READINESS. D. FINAL REPORT.


PROJECT TITLE: ADVANCED CZOCHRALSKI GROWTH FOR TECH. READINESS
PROJECT PLAN JPL CONTRACT #955733
WEEK ENDING
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
TASK DESCRIPTION
1. PURCHASE & CONSTRUCTION PHASE (MECH. & ELECT.)
A. HOT ZONE
B. PULL CHAMBER SYSTEM
C. FURNACE TANKS
D. CRUCIBLE LIFT MECH.
E. SEED LIFT MECH.
F. BASEPLATE & FRAME
G. ANCILLARY MODIFICATIONS
H. POWER SUPPLY
I. SPECIAL PANELS
J. SPECIAL HARNESSES
K. ANCILLARY ELEC. MOD.
2. INSTALLATION AND TEST
A. INSTALL GROWER
B. TEST AND DEBUG


Project Title:
Advanced Czochralski Growth
for Technology Readiness
Program Plan Revision No. 1
JPL CONTRACT #955733
Kayex Corporation
January 20, 1981
Months Elapsed
Task Description
O N D J F M A M J J A S O
1. Equipment construction and test
a. Construction phase
b. De-bug and test
2. Process Development
a. Accelerated recharge
b. Accelerated growth
c. Yield improvement
3. Controls and Automation
a. Sensor Development
b. Controls Development on grower
c. Final test runs, documentation
4. Analytical Study
a. Purity analyses
b. Solar cell fabrication
5. Documentation
a. Technical reports
b. Economic analysis
c. Production/process equipment
spec for technology readiness
d. Final report

Overall Program Status

TECHNOLOGY - INGOT GROWTH	REPORT DATE: FEBRUARY 5, 1981 START DATE: SEPTEMBER 21, 1980
<u>TASK</u>	<u>STATUS</u>
1. CONSTRUCTION AND TEST	1. CONSTRUCTION ALMOST COMPLETE. TESTING UNDERWAY.
2. PROCESS DEVELOPMENT A. RAW MATERIALS.	2. A. ALL PURCHASE ORDERS PLACED FOR SILICON, CRUCIBLES, GRAPHITE.
B. ACCELERATED GROWTH.	B. RADIATION SHIELD DESIGN COMPLETE QUOTATIONS AWAITED.
C. ACCELERATED RECHARGE.	C. 150 KW POWER SUPPLY RECEIVED.
D. YIELD AND COST IMPROVEMENT.	D. ONGOING.
3. AUTOMATION AND CONTROLS.	3. SYSTEMS UNDER EVALUATION. EXPERIMENTAL RUNS COMMENCED.
4. PURITY ANALYSIS AND SOLAR CELL FAB.	4. EVALUATION OF METHODS ONGOING.
5. DOCUMENTATION. A. DESIGN REVIEW.	5. A. COMPLETE.
B. ECONOMIC ANALYSIS.	B. ONGOING.
C. TECHNOLOGY TRANSFER INFORMATION.	C. COMMENCE, JUNE 1981.



Overall View of Kayex CG 6000 RC Crystal Puller (JPL's LASS Task ESGU)

Cz Growth Parameters, Low-Cost Cz (Poly Lump Feed)

CONDITIONS	5 CRYSTALS x 30 KG	3 CRYSTALS x 50 KG
CRUCIBLE SIZE (INS)	16	16
CRYSTAL DIAMETER (CMS)	15	15
AVG. STRAIGHT GROWTH RATE (CMS/HR)	11.40	8.56
TOTAL POLY MELTED (KG)	160	160
TOTAL CRYSTAL PULLED (KG)	150	150
PULLED YIELD (%)	93.75	93.75
YIELD AFTER CG(%)	82.5 (18 KG LOSS)	86.25 (12 KG LOSS)
NO. OF CRYSTALS/CRUCIBLE	5	3
CYCLE TIME (HRS)	60	60

Process Time Cycle

OPERATION	LOW COST CZ		LOW COST CZ	
1. PREPARATION		150 MINS		165 MINS
LOAD POLY	20		25	
CLOSE FURNACE	5		5	
PUMP DOWN	20		10	
MELT	105		125	
2. GROWTH CYCLE (INITIAL)		508 MINS		962 MINS
LOWER SEED *	15*		15*	
STABILIZE TEMP.	30		30	
SEED GROWTH	20		20	
CROWN GROWTH	55		55	
STRAIGHT GROWTH	343		797	
TAPER END	60		60	
3. RECHARGE/GROWTH CYCLE		2792 MINS		2324 MINS
COOL CRYSTAL	30	(4 CYCLES)	30	(2 CYCLES)
REMOVE CRYSTAL	10		10	
LOAD HOPPER & VAC DOWN (2)	60		60	
LOWER HOPPER (2)	10		10	
MELT POLY LUMP	80		90	
LOWER SEED *	15*		15*	
STABILIZE TEMP.	30		30	
SEED GROWTH	20		20	
CROWN GROWTH	55		55	
STRAIGHT GROWTH	343		797	
TAPER END	60		60	

* COMPLETED DURING STABILIZATION OF MELT TEMPERATURE.

OPERATION	LOW COST CZ		LOW COST CZ	
SHUT DOWN CYCLE		140 MINS		140 MINS
COOL FURNACE	80		80	
REMOVE CRYSTAL **	10**		10**	
CLEAN, SET UP	60		60	

** COMPLETED DURING FURNACE COOLING TIME

TOTAL TIME =	60 HRS	60 HRS

GROWTH RATE CALCULATION:

AVERAGE STRAIGHT GROWTH FOR 27 KG	AVERAGE STRAIGHT GROWTH FOR 47 KG
343 MINS = 4.72 KG/HR	797 MINS = 3.54 KG/HR
AT 1050 GMS/INCH: = 4.49"/HR GROWTH RATE	= 3.37"/HR GROWTH RATE

SAMICS-IPEG Input Data and Cost Calculation

CONDITIONS (PER CYCLE)		
TOTAL Si MELTED (KG)	160	160
CRYSTAL WT (KG)	30	50
NO CRYSTALS/CRUCIBLE	5	3
DIAMETER OF CRYSTAL (CMS)	15	15
AVG. STR. GROWTH RATE (CMS/HR)	11.4	8.56
CYCLE TIME (HRS)	60	60
CRUCIBLE SIZE (INS)	16 x 12	16 x 12

INPUT DATA ($1980)		
CAPITAL EQUIP COST (EQPT)	$ 266900	266900
MANUFACTURING FLOOR SPACE (SQFT)	100	100
ANNUAL DIRECT SALARIES		
PROD. OPERATOR (0.65 PERSONS/YR)	$ 8554	8554
ELECT. TECHNICIAN (0.3 PERSONS/YR)	$ 5082	5082
INSPECTOR (0.1 PERSONS/YR)	$ 1155	1155
TOTAL D/LAB	$ 14791	14791

DIRECT USED MATERIALS & SUPPLIES 85% USAGE PER YEAR	LOW COST CZ	LOW COST CZ
CYCLES/YR HRS/CYCLE	138/60	138/60
POLY KG/YR CHARGED	22080	22080
SEED ($20 EA)	1380	1380
DOPANT (NOT COSTED)		
ARGON (150 FT^3/CYCLE HR @ $0.02/$FT^3$)	24840	24840
CRUCIBLES (16" x 12" = $375 EA.)	51750	51750
MISCELLANEOUS (4 SETS OF 16" GRAPHITE/ YR AT $8889 PER SET)	35556	35556
MATERIALS TOTAL (MATS)	$ 113526	$ 113526
UTILITIES (PROCESS)		
ELECTRICITY (90 KW @ $0.035/KW) (CYCLE TIME - 3 HRS) (# OF CYCLES)	$ 24778	$ 24778
COOLING WATER (90 KW @ $0.0074/KW)(CYCLE TIME - 2 HRS)(# OF CYCLES)	$ 5331	$ 5331
UTILITIES TOTAL (UTIL)	$ 30109	$ 30109

IPEG PRICE	LOW COST CZ (5 x 30KG CRYSTALS)	LOW COST CZ (3 x 50KG CRYSTALS)
C1 EQPT = $0.57/YR = $ EQPT	152133	152133
C2 SQFT = $1.09/YR = $ SQFT	10900	10900
C3 DLAB = $2.1/YR = $ DLAB	31061	31061
C4 MATS = $1.2/YR = $ MATS	136231	136231
C5 UTIL = $1.2/YR = $ UTIL	36131	36131
ANNUAL COST	$ 366456	$ 366456
QUAN.(TOTAL CHARGE x % YIELD) (KG)=	18216 KG	19044
THROUGHPUT =	2.2 KG/HR	2.3 KG/HR
ADD ON COST ($KG OR $$M^2$) (ASSUME 1 KG = 1$M^2$) =	$ 20.12	$ 19.24
=	14.19¢/PEAK WATT	13.57¢/PEAK WATT

$$\text{PEAK WATT CALCULATION} = \frac{\$/M^2}{1000W/M^2 \times \text{CELL EFF.} \times \text{CELL YIELD} \times \text{MANUF. YIELD}}$$

(15%) 95%) (99.5%)

CONDITIONS	3 x 50 KG CRYSTAL GROWTH
CRUCIBLE SIZE (INS)	16" x 12"
CRYSTAL DIAMETER (CMS)	15
GROWTH RATE (CMS/HR)	11.40
TOTAL POLY MELTED (KG)	160
TOTAL CRYSTAL PULLED (KG)	150
PULLED YIELD (%)	93.75
YIELD AFTER CG (%)	86.25
NO OF CRYSTALS/CRUCIBLE	3
CYCLE TIME (HRS)	49.85

Process Time Cycle

	OPERATION	MINS	
1.	PREPARATION		165 MINS
	LOAD POLY	25	
	CLOSE FURNACE	5	
	PUMP DOWN	10	
	MELT	125	
2.	GROWTH CYCLE (INITIAL)		762 MINS
	LOWER SEED *	15*	
	STABILIZE TEMPERATURE	30	
	SEED GROWTH	20	
	CROWN GROWTH	55	
	STRAIGHT GROWTH	597	(SEE CALCULATION)
	TAPER END	60	
3.	RECHARGE/GROWTH CYCLE		1924 MINS (2 CYCLES)
	COOL CRYSTAL	30	
	REMOVE CRYSTAL	10	
	LOAD HOPPER & VAC DOWN (2)	60	
	LOWER HOPPER (2)	10	
	MELT POLY LUMP	90	
	LOWER SEED *	15*	
	STABILIZE TEMP.	30	
	SEED GROWTH	20	
	CROWN GROWTH	55	
	STRAIGHT GROWTH	597	
	TAPER END	60	

* COMPLETED DURING STABILIZATION OF MELT TEMPERATURE

	OPERATION		
4.	SHUT DOWN CYCLE		140 MINS
	COOL FURNACE	80	
	REMOVE CRYSTAL **	10**	
	CLEAN, SET UP	60	
	TOTAL TIME (HRS	49.85	

** COMPLETED DURING FURNACE COOLING TIME

AVERAGE STRAIGHT GROWTH FOR 47 KG

597 MINS = 4.72 KG/HR
AT 1050 GMS/INCH = 4.49"/HR AV. GROWTH RATE REQUIRED

SAMICS-IPEG Input Data and Cost Calculation For 3 x 50-kg Crystal Growth

CONDITIONS(PER CYCLE)	
TOTAL SI MELTED(KG)	160
CRYSTAL WEIGHT (KG)	50
NO CRYSTALS/CRUCIBLE	3
DIAMETER OF CRYSTAL (CMS)	15
GROWTH RATE (CMS/HR)	11.40
CYCLE TIME (HRS)	49.85
CRUCIBLE SIZE (INS)	16" x 12"

INPUT DATA ($1980)	
CAPITAL EQUIP COST (EQPT)	$ 266900
MANUFACTURING FLOOR SPACE (SQFT)	100
ANNUAL DIRECT SALARIES	
PROD. OPERATOR (0.65 PERSONS/YR)	$ 8554
ELECT. TECH. (0.3 PERSONS/YR)	$ 5082
INSPECTOR (0.1 PERSONS/YR)	$ 1155
TOTAL D/LAB	$ 14791

DIRECT USED MATERIALS & SUPPLIES 85% USAGE PER YEAR	
CYCLES/YR HRS/CYCLE	166/49.85
POLY KG/YR CHARGED	26560
SEED ($20 EA)	$ 1660
DOPANT (NOT COSTED)	
ARGON 150 FT^3/CYCLE HR @ $0.02/$FT^3$)	$ 24825
CRUCIBLES (16" x 12" = $375 EA.)	$ 62250
MISCELLANEOUS (4 SETS OF 16" GRAPHITE/ YR @ $8889 PER SET)	$ 35556
MATERIALS TOTAL (MATS)	$ 124291
UTILITIES (PROCESS)	
ELECTRICITY (90 KW @ $ 0.035/KW)(CYCLE TIME - 3 HRS)(# OF CYCLES)	24498
COOLING WATER (90 KW @ 0.0074/KW)(CYCLE TIME - 2 HRS)(# OF CYCLES)	5290
UTILITIES TOTAL (UTIL)	29788

IPEG PRICE	LOW COST CZ 3 x 50 KG CRYSTAL GROWTH
C1 EQPT = $ 0.57/YR = $EQPT	152133
C2 SQFT = $ 1.09/YR = $SQFT	10900
C3 DLAB = $ 2.1/YR = $DLAB	31061
C4 MATS = $ 1.2/YR = $MATS	149149
C5 UTIL = $ 1.2/YR = $UTIL	35746
ANNUAL COST	$ 378989

QUAN.(TOTAL CHARGE x % YIELDING)(KG)	= 22908 KG
THROUGHPUT	= 2.77 KG/HR
ADD ON COST ($KG OR $$M^2$) (ASSUME 1 KG - $1M^2$)	= $ 16.54
	= 11.66¢/PEAK WATT

CONTINUOUS LIQUID-FEED Cz GROWTH

SILTEC CORP.

SUMMARY OF WORK AND RESULTS:

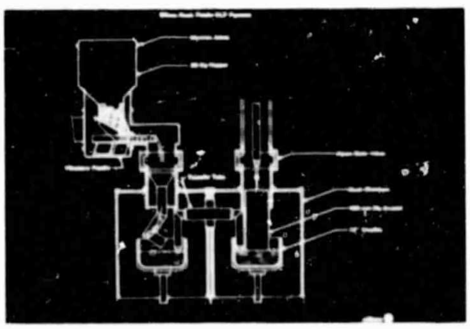
Recent efforts centered on identification and control of process variables to achieve optimum monocrystalline yields.

Automatic diameter control of ingots of 125 dia can now hold diameter variations to 380 μm. Ingots of 75 kg (150 μm dia.) have been grown. Better control of thermal convection currents in melt resulted in significant increases in monocrystalline yield.

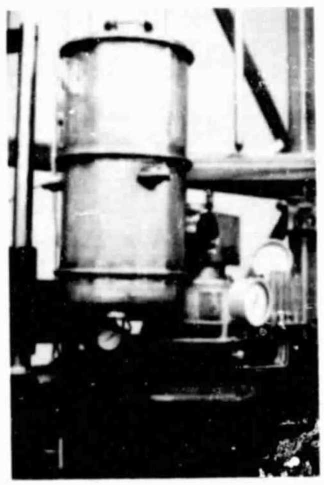
The melt transfer system was simplified, with improved insulation and better temperature control of the replenishing melt stream.

Preliminary material analysis shows greater consistency in impurity levels (i.e. carbon, oxygen and others) in ingot material grown from the CLF furnace.

An overall design for a production prototype CLF-Cz furnace has been begun, incorporating Siltec's new microprocessor-controlled AG660-Cz growth furnace.

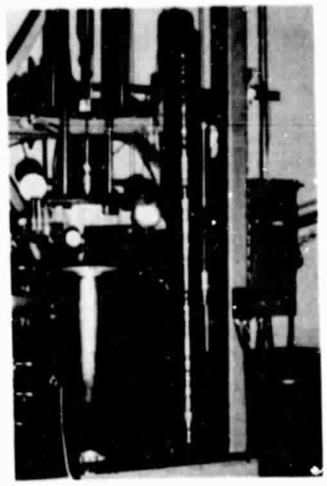


Schematic of Silicon "Rock" Feeder for the Continuous Liquid-Feed Furnace

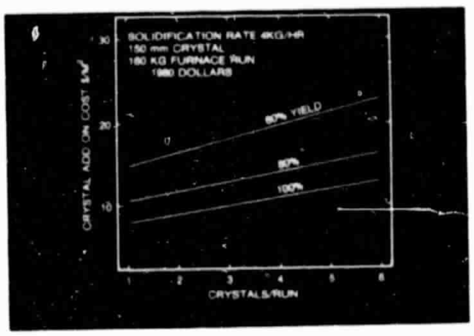


Constructed Hopper Chamber for Si Particles (50 kg Capacity)

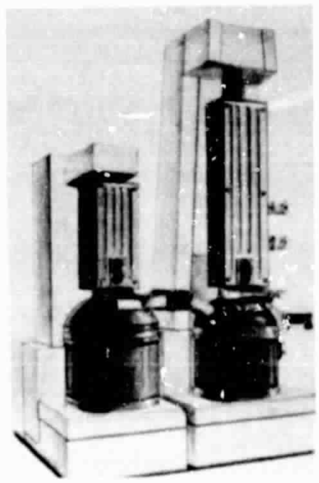
Bench Test of Silicon Particle Feeder



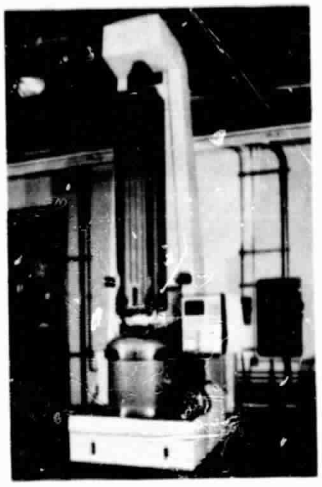
-kg 150-mm-dia Si Ingot



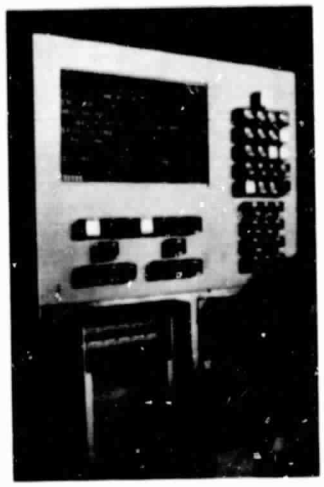
Effect of Crystal Size on CLF-Cz Add-On Cost



Artist's Conception of CLF Cz ESGU



Siltec's AG660 Cz Furnace



Control Panel for Microprocessor-Controlled AG660

SEMICRYSTALLINE CASTING PROCESS

SEMIX INC.

Basic Terms of Cooperative Agreement

- ESTABLISHED AGREEMENT FORMAT - INTEGRATED INTO JPL/LSA PROJECT
- 3 YEAR PRO RAM
- FINANCIAL
  COST SHARING AGREEMENT - 77.8% D.O.E. - $7.7M
  22.2% SEMIX - $2.2M
  PAYBACK - 1% OF NET SALES AFTER PROGRAM SUCCESSFULLY COMPLETED
- PATENT AND TECHNICAL DATA RIGHTS
  GOVERNMENT WAIVES PATENT RIGHTS
  RESTRICTION OF PROPRIETARY INFORMATION

Agreement Objectives

- DEVELOP AND DEMONSTRATE THE KEY ELEMENTS OF SI SHEET TECHNOLOGY NEEDED BY SEMIX TO ACHIEVE COMMERCIAL READINESS TO MEET 1982 PRICE GOALS AT 10MW/YEAR OUTPUT
  $1.66/WP* (SHEET) • $56/KG SILICON COSTS FOR $2.80/WP (MODULE)
- DEVELOP AND DEMONSTRATE TECHNOLOGY READINESS TO MEET 1986 PRICE GOALS
  $.37/WP* (SHEET) • $14/KG SILICON COSTS FOR $.70/WP (MODULE)
- SEMIX INTENDS TO FULLY COMMERCIALIZE TECHNOLOGY WITH PRIVATE FUNDS, TO MEET OR EXCEED PHOTOVOLTAIC PROGRAM GOALS
- SEMIX INTENDS TO SELL SHEET TO PHOTOVOLTAIC INDUSTRY AT PRICE GOALS IF PROJECT IS SUCCESSFUL (PROJECTED BY FY 83)

* ALLOCATION BASED UPON JPL PRICE GUIDELINES

Program Status

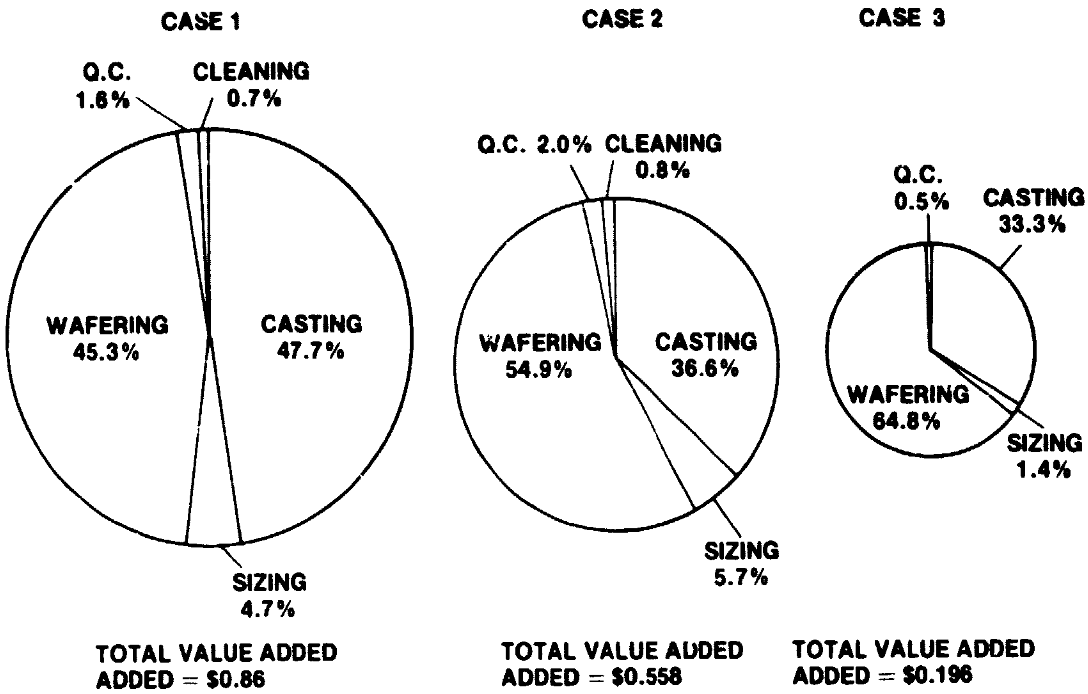
PHASE I — JUNE 1980 — JUNE 1981	% COMPLETE
TASK 1 — ECONOMIC AND TECHNICAL PERFORMANCE ANALYSIS OF CURRENT SEMICRYSTALLINE PROCESS	80%
TASK 2 — DEMONSTRATE PROOF OF CONCEPT	25%
TASK 3 — PRELIMINARY DESIGN, ANALYSIS AND PROTOTYPE EVALUATION	60%
TASK 4 — CRITICAL SUBSYSTEM DESIGN, ASSEMBLY AND TEST	50%
TASK 5 — PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION FOR 1986 GOALS	90%

- 2 REVIEW MEETINGS — DOE/JPL/SEMIX
- DELIVERABLES ON SCHEDULE — SEVERAL CELLS DELIVERED AHEAD OF SCHEDULE FOR EARLY VERIFICATION

Summary of Ubiquitous Crystallization Process (UCP) SAMICS Analyses (1980 $/W$_p$)

PROCESS	CASE 1 1982 TECHNOLOGY SILICON PRICE $56/KILOGRAM	CASE 2 1982 TECHNOLOGY SILICON PRICE $14/KILOGRAM	CASE 3 1986 TECHNOLOGY SILICON PRICE $14/KILOGRAM
CASTING	0.41	0.20	0.065
SIZING	0.04	0.032	0.003
WAFERING	0.39	0.31	0.127
CLEANING	0.006	0.005	N/A
QUALITY CONTROL	0.014	0.011	0.001
TOTAL VALUE ADDED FOR PROCESSES	0.86	0.558	0.196
JPL PRICE ALLOCATION	1.00	N/A	0.26
FEEDSTOCK SILICON COST	0.789	0.158	0.130
TOTAL SHEET COST	1.649	0.716	0.326
CELL EFFICIENCY	12%	15%	15%

UCP SAMICS Analyses
(Not Including Cost of Si Feedstock)
(1980 $\$/W_p$)



UCP Semicrystalline Cell Measurements

- 11% AM1 AVERAGE 10 X 10 CM CELL EFFICIENCY — MEASURED BY SEMIX
- >12% AM1 AVERAGE 2 X 2 CM CELL EFFICIENCY — MEASURED BY SEMIX

C-3

SILICON INGOT CASTING: HEAT EXCHANGER METHOD (HEM)

CRYSTAL SYSTEMS INC.

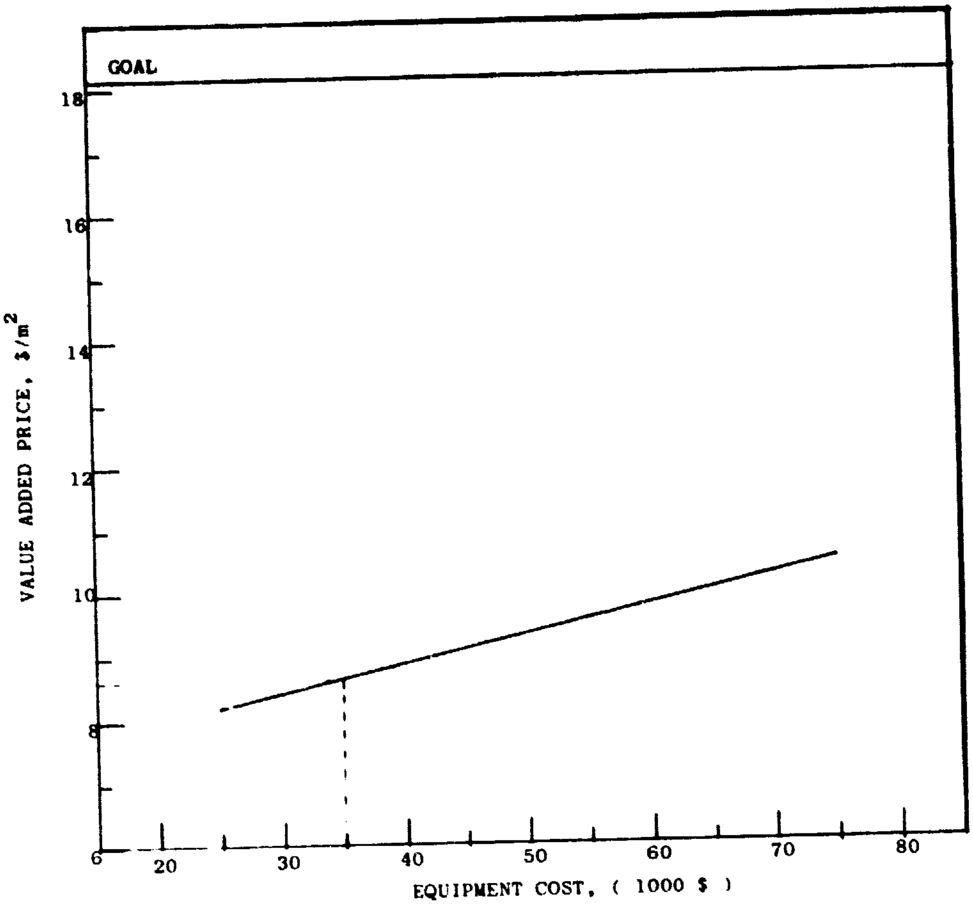
F. Schmid
C.P. Khattak

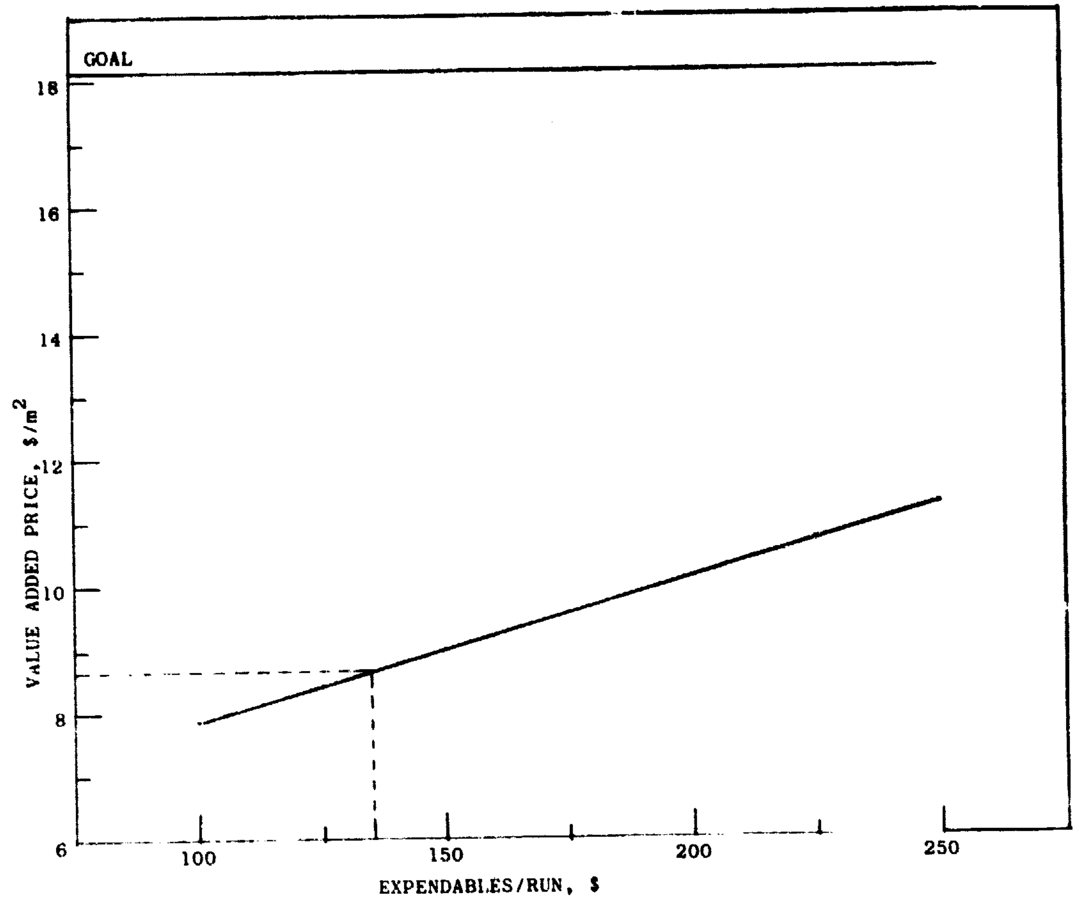
IPEG Analysis Assumptions for HEM Casting

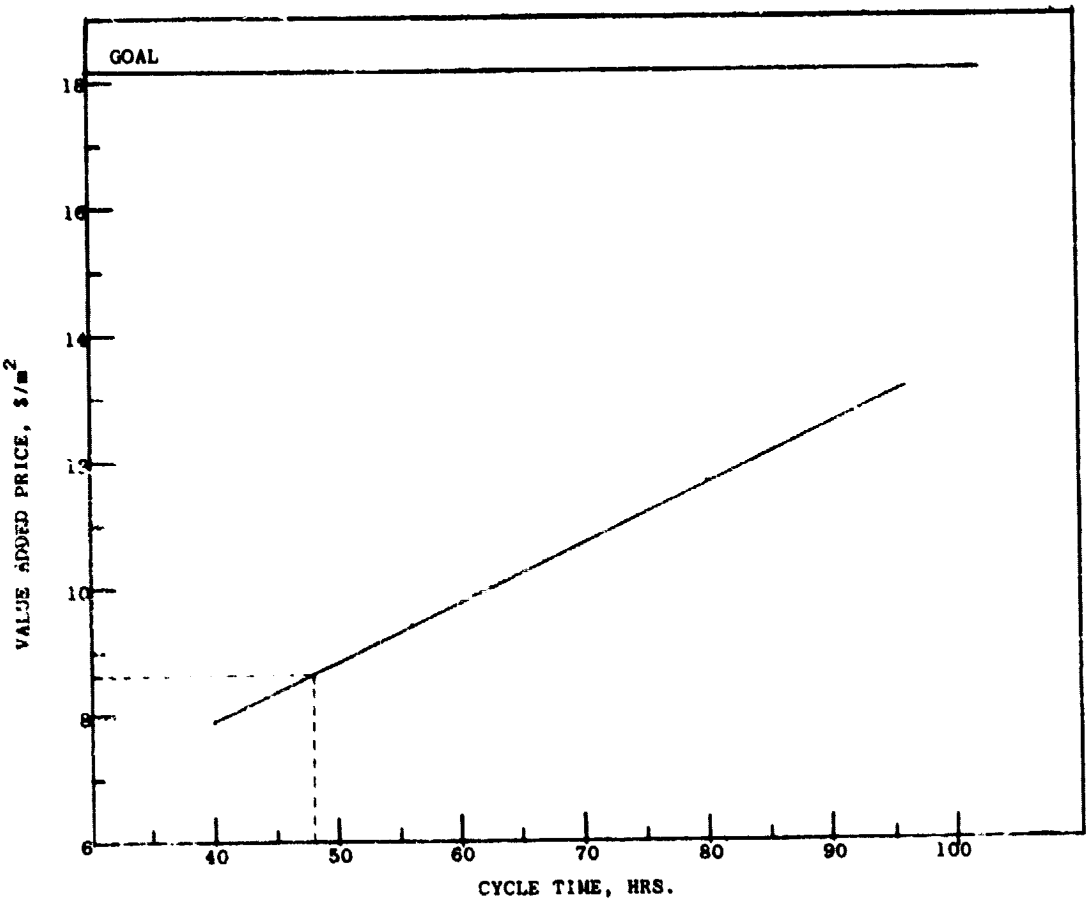
EQUIPMENT COST PER UNIT, $	35,000
FLOOR SPACE PER UNIT, SQ.FT.	60
LABOR, UNITS/OPERATOR	10
CYCLE TIME, HRS.	48
EXPENDABLES/RUN, $	135
CONVERSION RATIO, M^2/KG	1

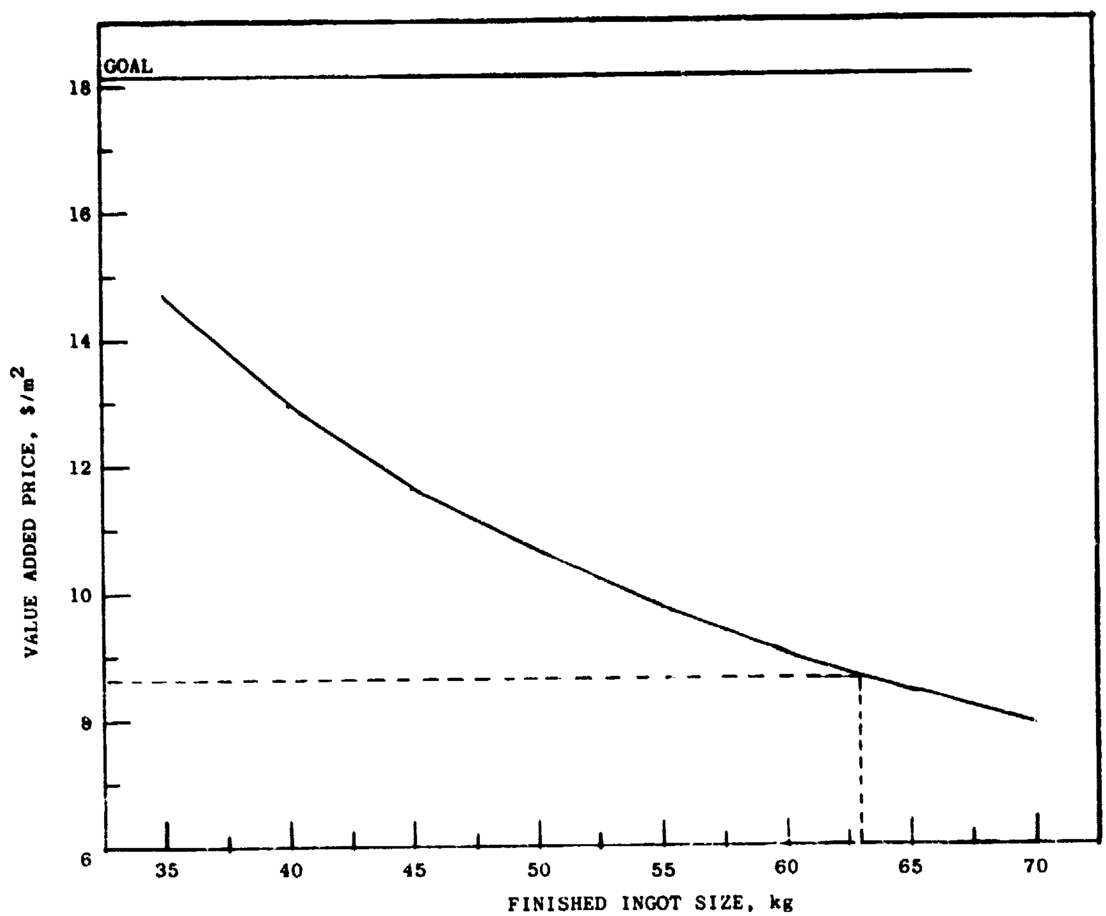
INGOTS ARE CAST BY HEM AND SECTIONED INTO NINE BARS OF 10 CM x 10 CM x 30 CM SIZE.

VALUE ADDED PRICE	$8.65/$M^2$
GOAL	$18.15/$M^2$


GOAL
18
16
14
12
10
8
6
VALUE ADDED PRICE, $/m²
20
30
40
50
60
70
80
EQUIPMENT COST, (1000 $)


GOAL
18
16
14
12
10
8
6
VALUE ADDED PRICE, $/m²
100
150
200
250
EXPENDABLES/RUN, $


GOAL
18
16
14
12
10
8
6
40
50
60
70
80
90
100
VALUE ADDED PRICE, $/m2
CYCLE TIME, HRS.


GOAL
18
16
14
12
10
8
6
VALUE ADDED PRICE, $/m²
35
40
45
50
55
60
65
70
FINISHED INGOT SIZE, kg

Revised IPEG Analysis Assumptions For HEM Casting

EQUIPMENT COST PER UNIT, $	35,000
FLOOR SPACE PER UNIT, SQ.FT.	60
LABOR, UNITS/OPERATOR	10
CYCLE TIME, HRS.	48
EXPENDABLES/RUN, $	135
CONVERSION RATIO, M^2/KG	1

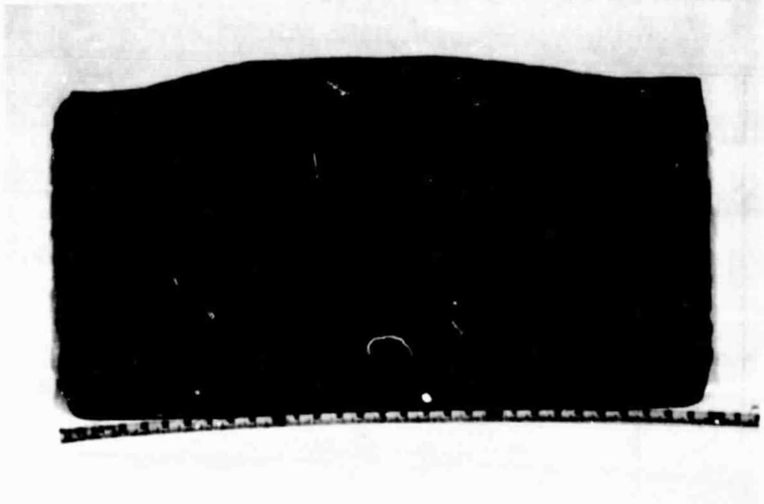
INGOTS ARE CAST BY HEM AND SECTIONED INTO NINE BARS OF 10 CM X 10 CM X 15 CM SIZE.

VALUE ADDED PRICE	$15.59/$M^2$
GOAL	$18.15/$M^2$

Heat Exchanger and Furnace Temperatures

RUN	PURPOSE	SEEDING	GROWTH CYCLE		REMARKS
		FURN.TEMP. ABOVE M.P. °C	DECREASE OF FURN.TEMP. °C	GROWTH TIME IN HRS.	
41-37	Improve crystallinity	-	-	-	Run aborted during meltdown due to problem at heat exchanger fitting
41-38	Improve crystallinity	24	42	25	Good crystallinity
41-39	Improve crystallinity	8	24	25	No seed meltback on top of seed
41-40	Improve crystallinity	6	22	27	No seed meltback
41-41	Cast 32 x 32 cm^2 35 kg ingot	15	33	40	Crucible leaked at crack on wall. Final weight was 30.8 kg. Ingot sent to JPL.
41-42	Improve crystallinity at bottom	37	29	24	Spurious nucleation restricted to area of melted back seed in contact with crucible
41-43	Improve crystallinity at bottom	48	48	32	Spurious nucleation restricted to area of melted back seed in contact with crucible
41-44	Improve crystallinity at bottom	62	64	31.5	Spurious nucleation restricted to area of melted back seed in contact with crucible

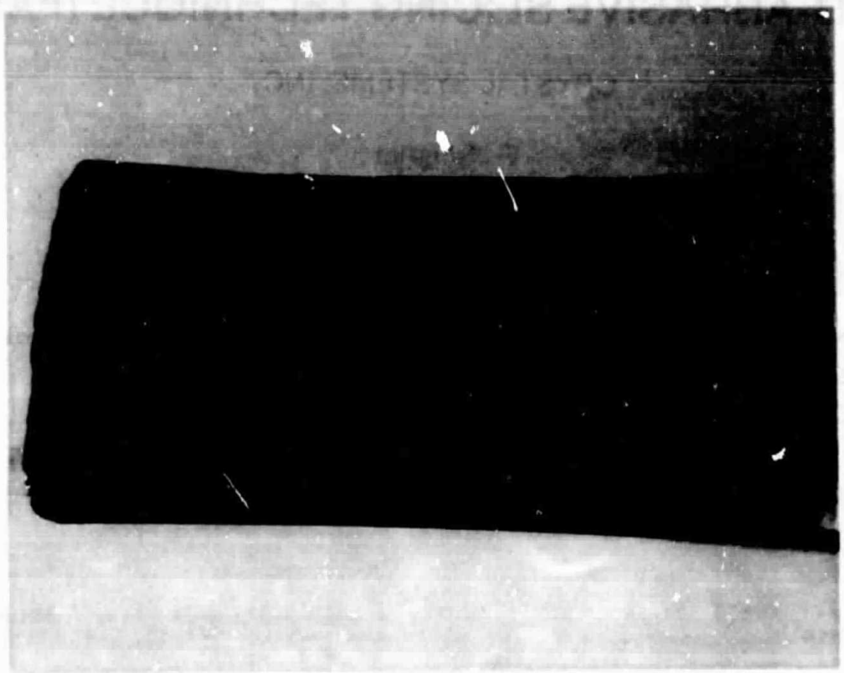
RUN	PURPOSE	SEEDING: FURN. TEMP. ABOVE M.P. °C	GROWTH CYCLE: DECREASE OF FURN. TEMP. °C	GROWTH CYCLE: GROWTH TIME IN HRS.	REMARKS
41-45	Improve crystal-linity at bottom	39	39	23	
41-46	Cast 32 x 32 cm^2 35 kg ingot	-	-	-	Run aborted after 17 hrs. of growth time due to crucible breakage.
41-47	Study heat flow	33	33	22	
41-48	Cast 32 x 32 cm^2 35 kg ingot	14	14	28.5	Ingot sent to JPL
41-49	Study heat flow	33	33	14	
41-50	Study heat flow	20	20	21	



Grid Pattern on Cross Section of Ingot Cast in Run 41-41, Corresponding to Positions for Resistivity Values Shown Below

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
(a)				1.31	1.17	1.18	1.28	1.27			
(b)	1.66	1.20	1.19	1.17	1.34	1.29	1.23	1.25	1.24	1.20	1.40
(c)	1.36	1.29	1.34	1.40	1.39	1.46	1.49	1.38	1.29	1.38	1.25
(d)	1.45	1.44	1.45	1.47	1.48	1.58	1.53	1.40	1.48	1.44	1.37
(e)	1.60	1.44	1.49	1.53	1.58	1.57	1.60	1.52	1.62	1.44	1.55
(f)	1.55	1.47	1.55	1.59	1.50	1.52	1.51	1.58	1.59	1.56	1.63
(g)		1.45	1.58	1.47	1.55	8.55	1.66	1.69	1.75	1.57	1.55

Resistivity data in Ω-cm



Cross Section of Ingot Cast in Run 41-48

ORIGINAL PAGE IS
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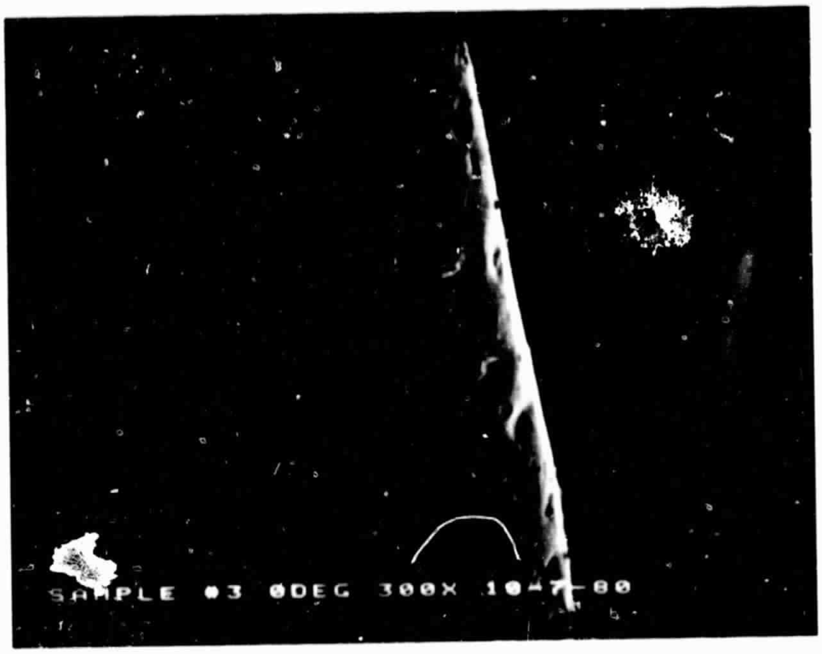
FIXED-ABRASIVE SLICING TECHNIQUE (FAST)

CRYSTAL SYSTEMS, INC.

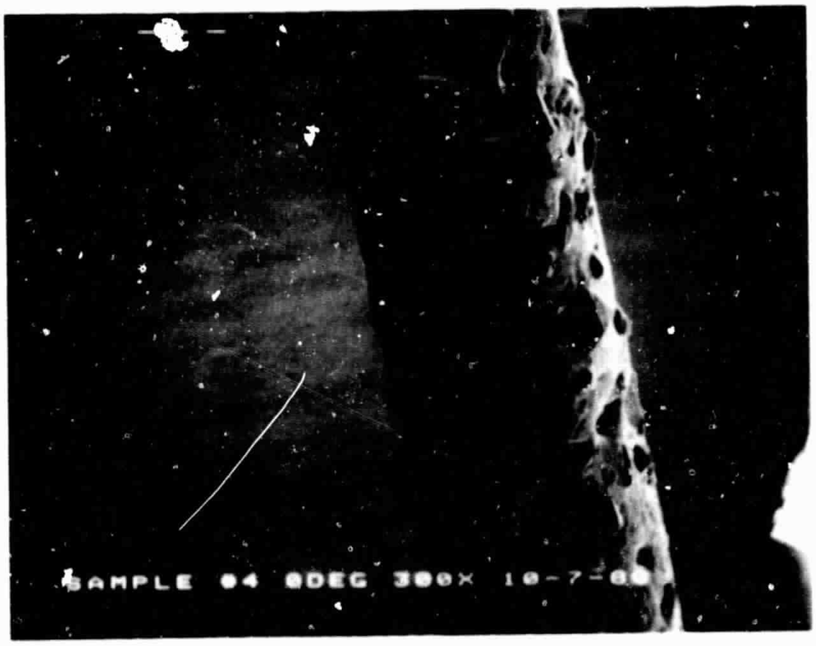
F. Schmid
C.P. Khattak

Silicon Slicing Summary

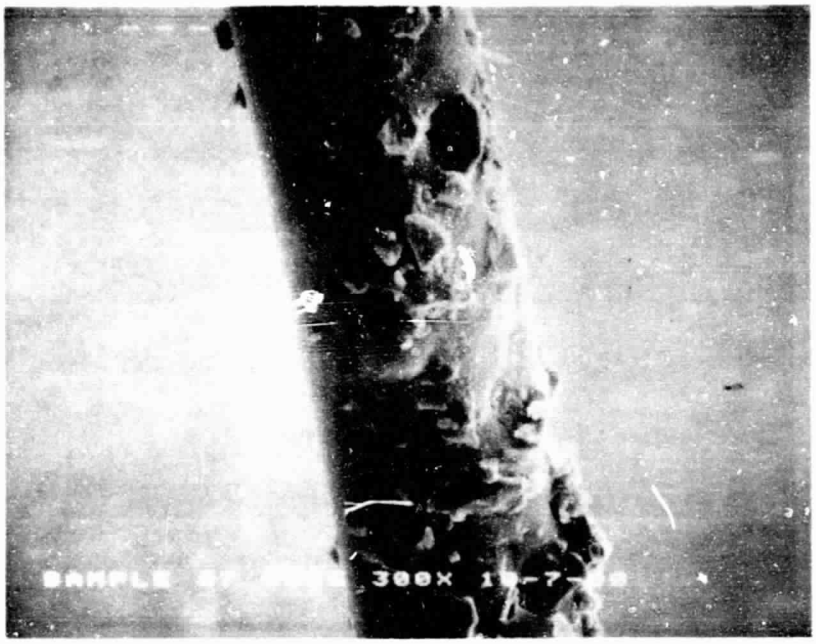
RUN	PURPOSE	FEED FORCE/BLADE lb	FEED FORCE/BLADE gm	AVERAGE CUTTING RATE mil/min	AVERAGE CUTTING RATE mm/min	WIRE TYPE	REMARKS
441-SX	Test codeposited bladepack	0.069	31.60	3.7	0.092	5 mil, 0.125 mm W wire, codeposited with 45, 30 μm diamonds	48% yield. Diamond pull-out caused blade wander.
442-SX	Test codeposited bladepack	0.066	30.01	3.4	0.085	5 mil, 0.125 mm W wire, codeposited with 45, 30 μm diamonds	55% yield. Loss of wafers during last inch of cut.
443-SX	Test codeposited bladepack	0.070	32.14	3.5	0.087	5 mil, 0.125 mm W wire, codeposited with 45, 30 μm diamonds	38% yield.
444-SX	Test codeposited bladepack (25/cm)	0.044	19.9	-	-	5 mil, 0.125 mm stainless steel core; 0.1 mil, 2.5 μm Cu sheath; codeposited with 45, 30 μm diamonds	Run aborted due to wires jumping from the grooves of support rollers and diamond pullout
445-SX	Test codeposited bladepack	0.072	32.7	2.9	0.074	5 mil, 0.125 mm W core, codeposited with 45, 30 μm diamonds	48% yield; diamond pullout reduced cutting effectiveness
446-SX	Test CSI codeposited bladepack	0.070	31.6	3.8	0.096	5 mil, 0.125 mm W wire, codeposited on one side with 45 μm diamonds	49% yield.
447-SX	Test CSI codeposited bladepack	0.072	32.5	2.6	0.066	5 mil, 0.125 mm W wire, codeposited on both sides with 45 μm diamonds	91% yield.
448-SX	Test CSI codeposited bladepack	0.072	32.5	3.7	0.094	5 mil, 0.125 mm W wire, codeposited on both sides with 45 μm diamonds	80% yield.
449-SX	Life test (2nd run)	0.079	35.8	2.8	0.071	5 mil, 0.125 mm W wire, codeposited on both sides with 45 μm diamonds	74% yield.
450-SX	Life test (3rd run)	0.082	37.0	2.4	0.061	5 mil, 0.125 mm W wire, codeposited on both sides with 45 μm diamonds	38% yield. Sudden breakage of wafers due to loosening of workpiece.
451-SX	Test CSI codeposited 25/cm bladepack	0.063	28.5	2.15	0.055	5 mil, 0.125 mm W wire codeposited on both sides with 45 μm diamonds	Run aborted due to loss of water coolant system which caused wafer breakage.
452-SX	Life test (2nd run) 25/cm	0.062	28.3	2.9	0.0[illegible]	5 mil, 0.125 mm W wire codeposited on both sides with 45 μm diamonds	18% yield. Some breakage during handling.
453-SX	Slice 15 cm diameter crystal	0.071	32.4	1.9	0.048	5 mil, 0.125 mm W wire codeposited on both sides with 45 μm diamonds	Run aborted after 4.5 inch of cut.

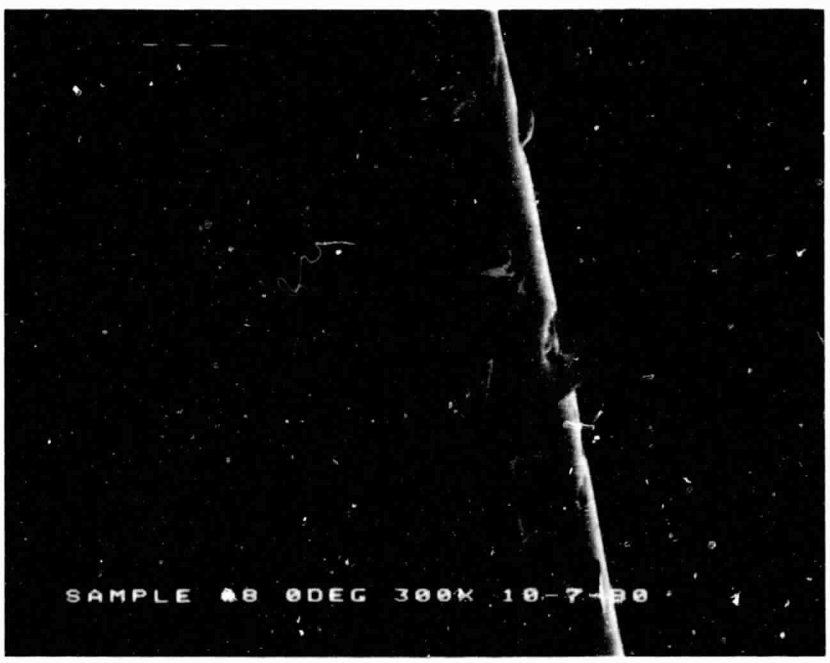


SEM Photograph of Electroplated Wire Before Use in Runs 437-SX and 438-SX, Showing Diamonds Buried in Nickel

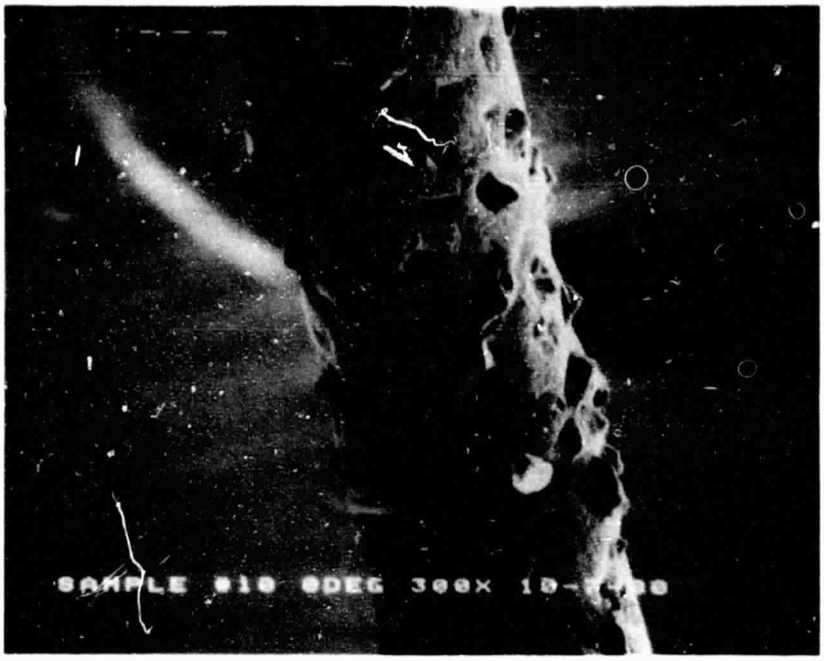


SEM Photograph of Wire Used in Run 437-SX Showing High Diamond Concentration and Even Diamond Distribution

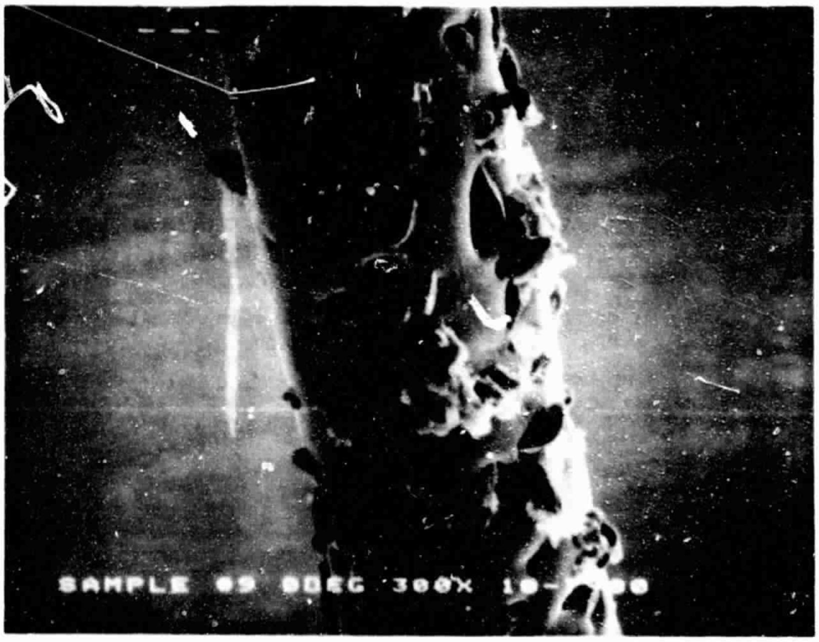




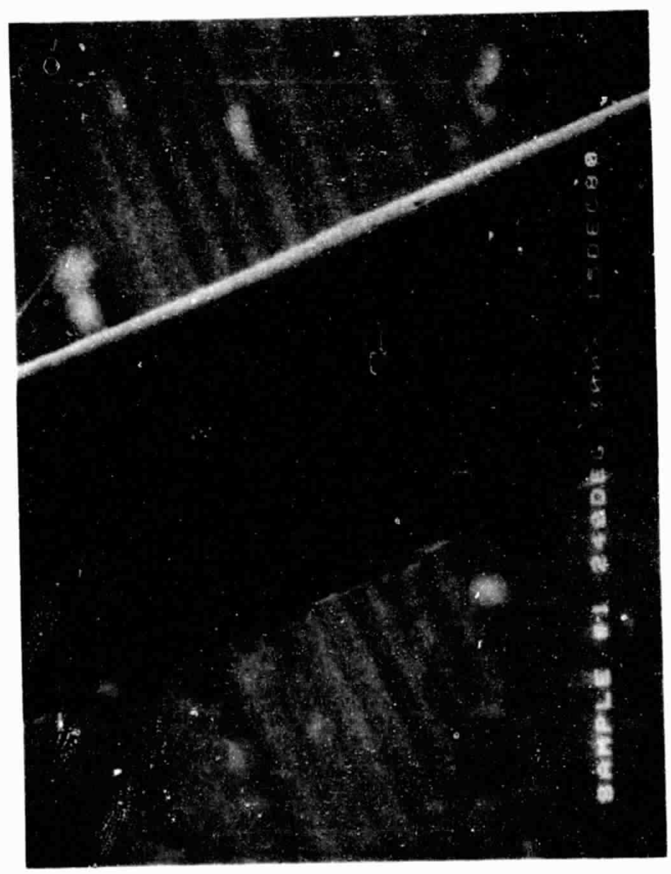
SEM Photos of Electroplated Wires
Showing No Diamonds on the Sides



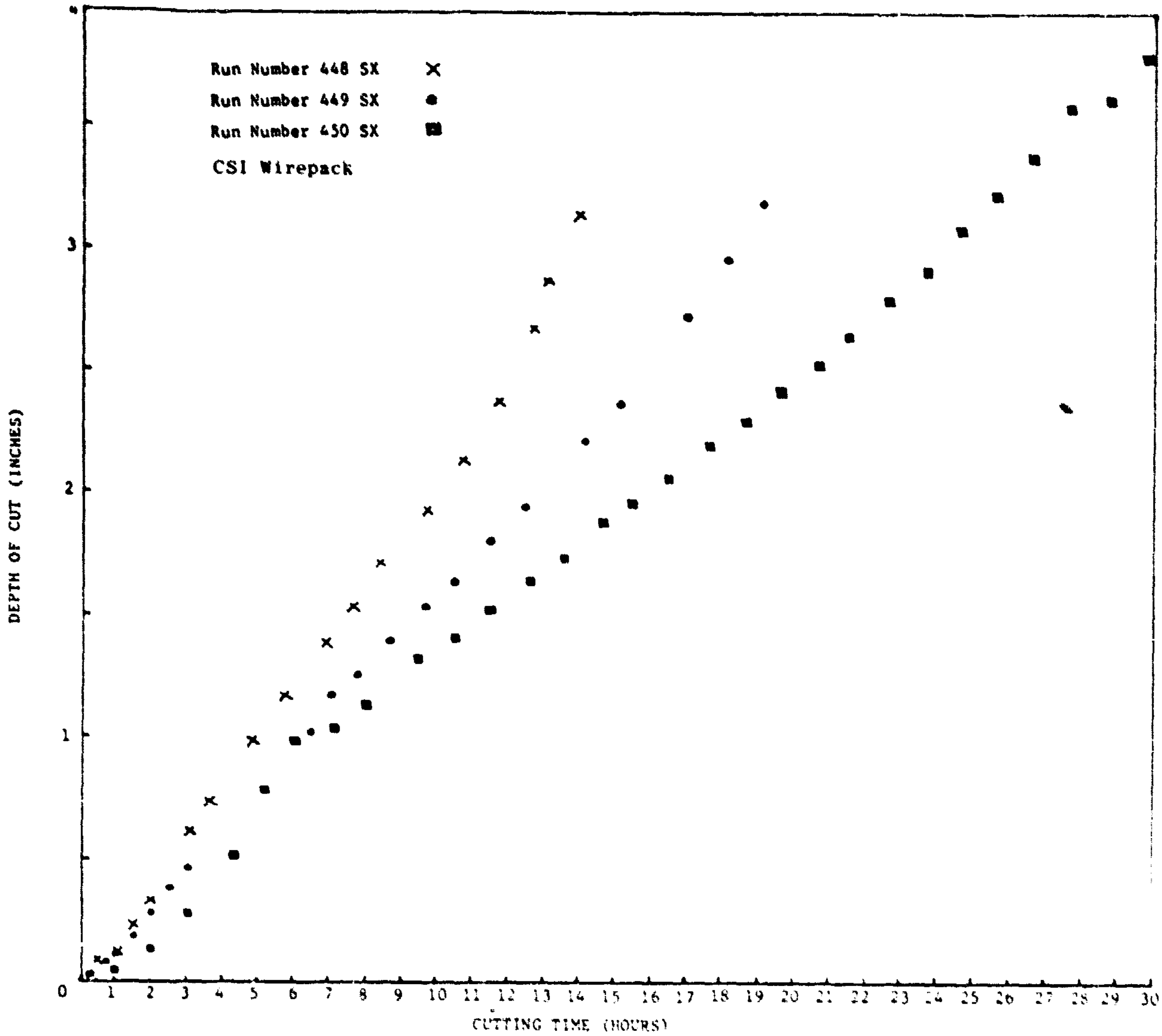
SEM Photograph of Wire After Use
In Runs 433-SX Through 435-SX

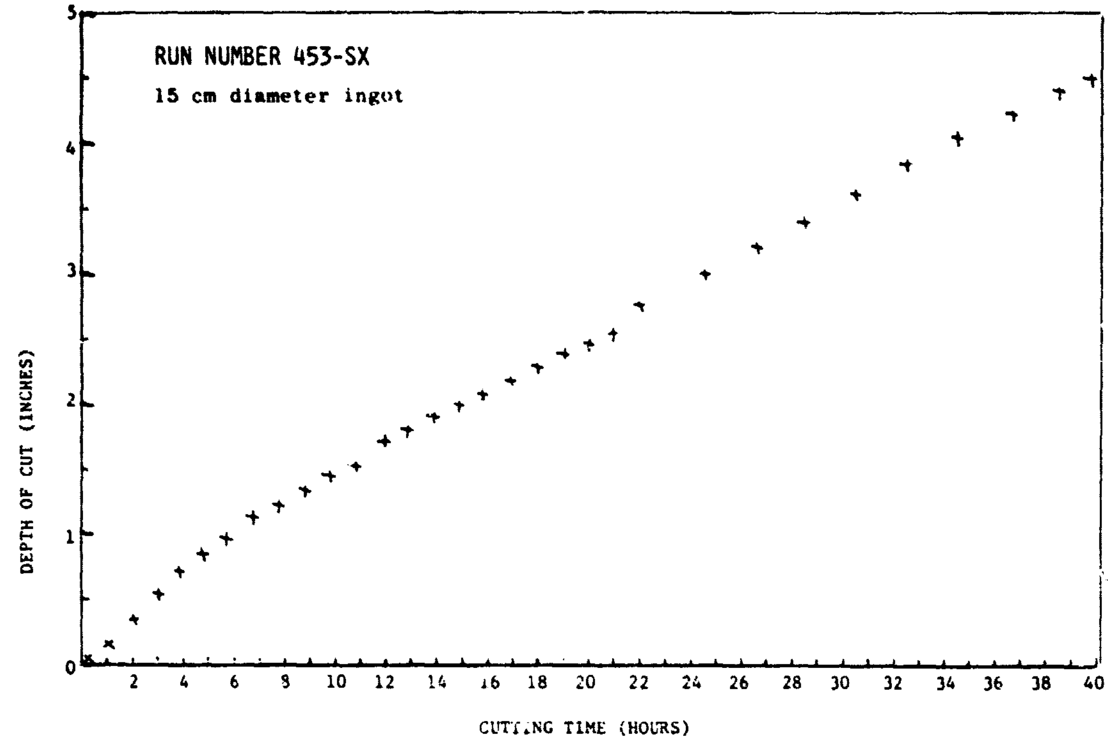


Wire Shown Above, Before Use

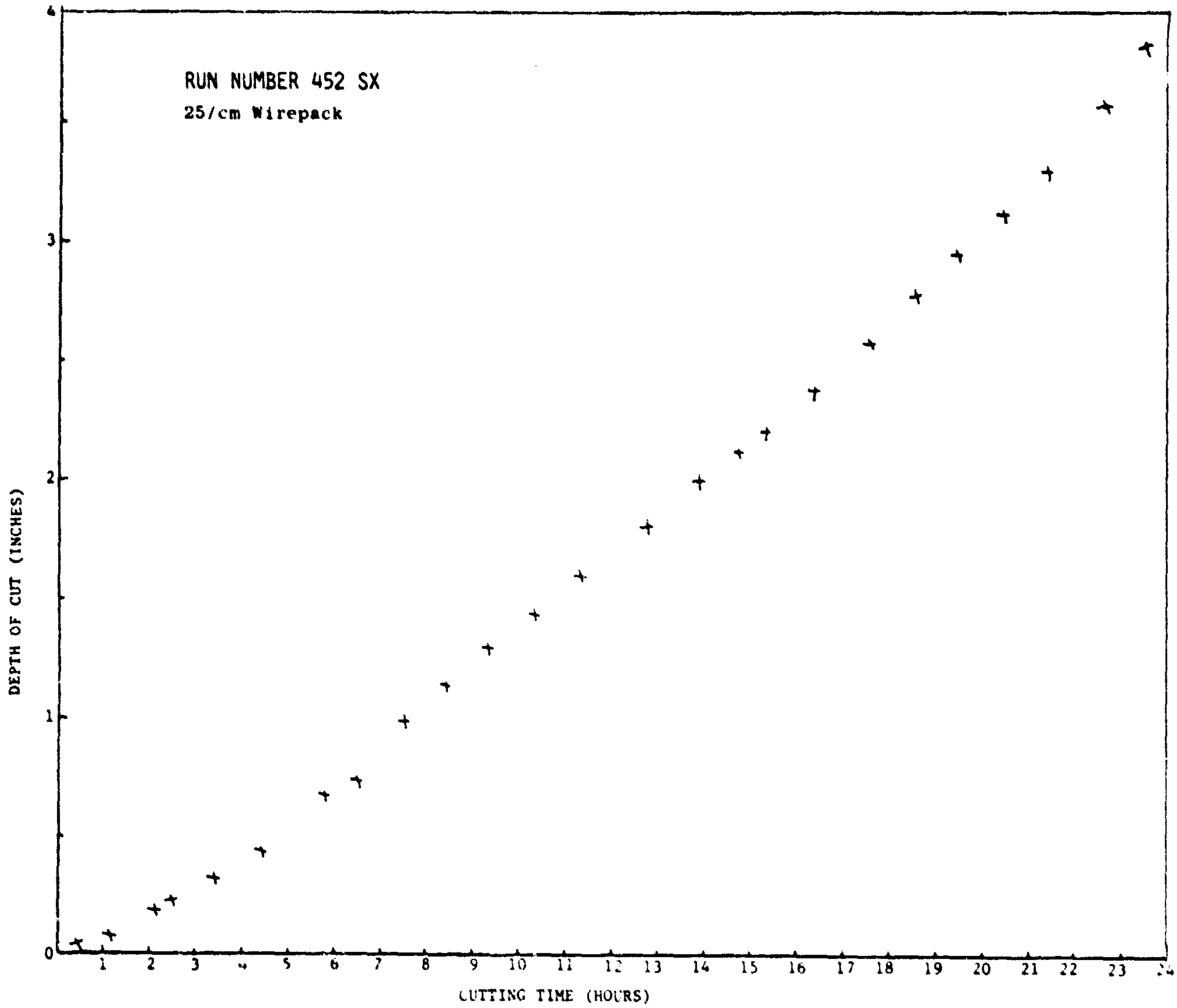


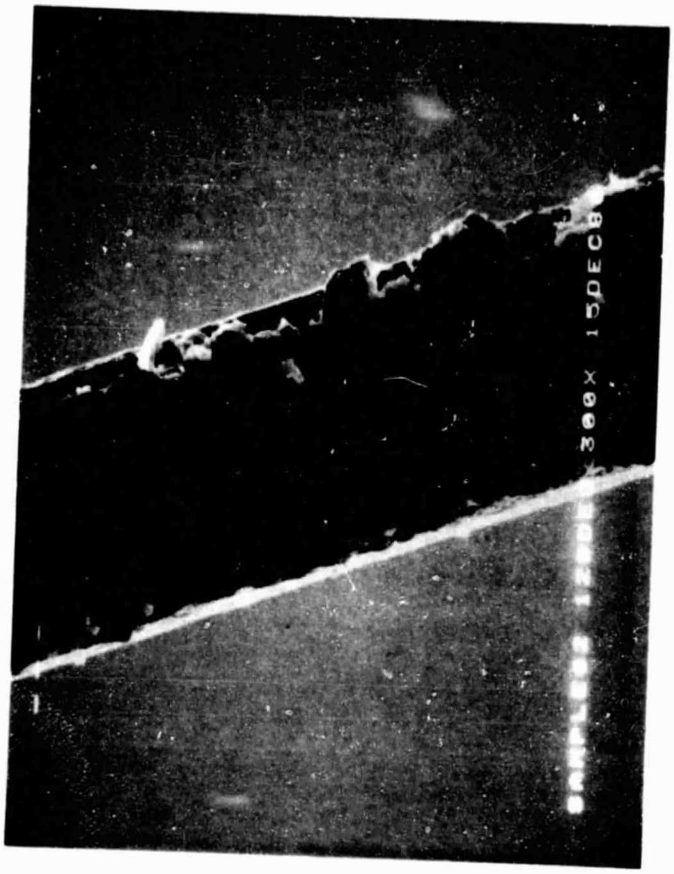
Sample No. 1. CSI Electroplated Wire, With Diamond on One Side

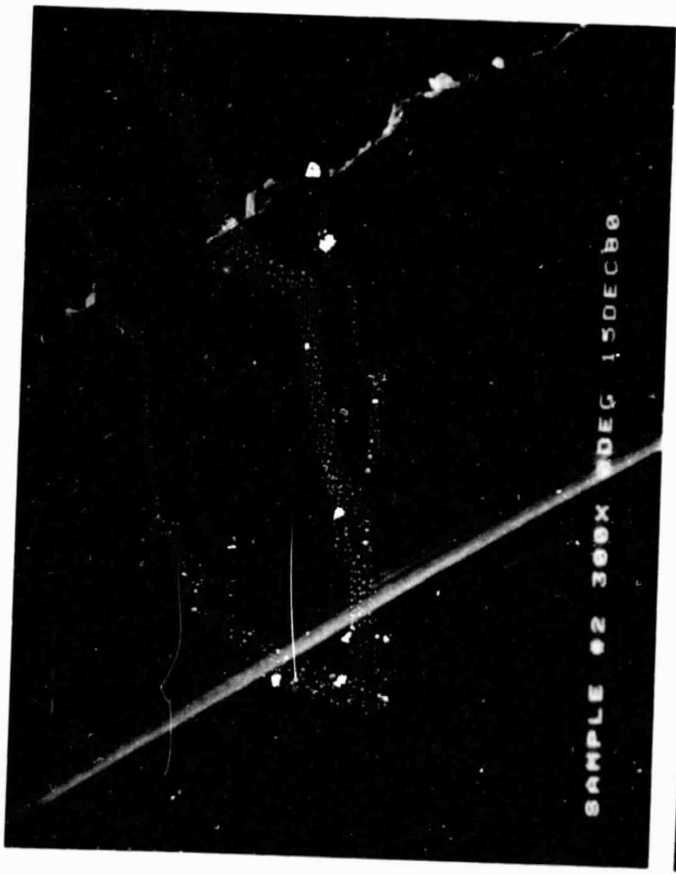

Run Number 448 SX
Run Number 449 SX
Run Number 450 SX
CSI Wirepack
DEPTH OF CUT (INCHES)
CUTTING TIME (HOURS)

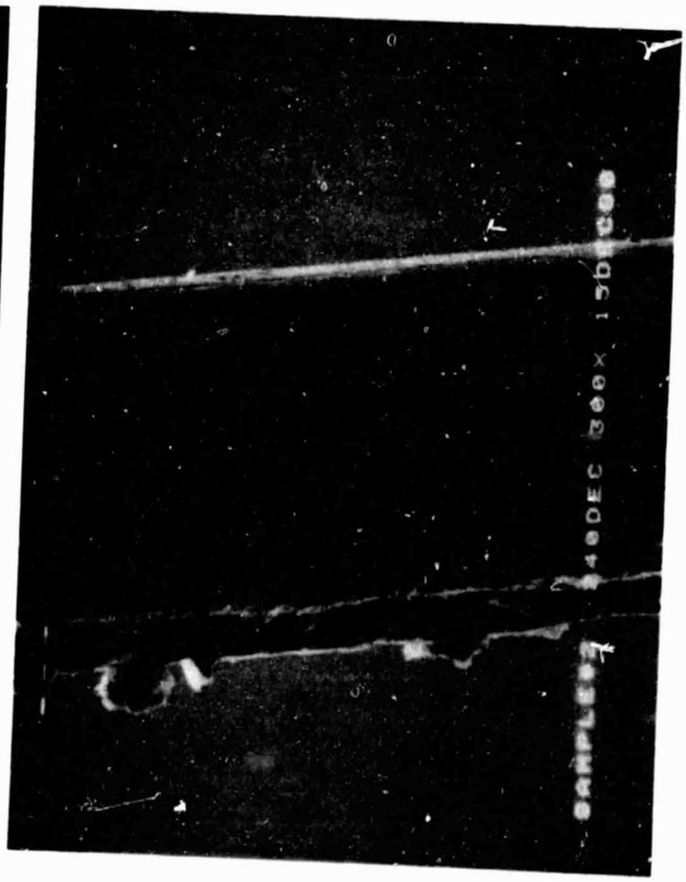


RUN NUMBER 453-SX
15 cm diameter ingot
DEPTH OF CUT (INCHES)
0
1
2
3
4
5
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
CUTTING TIME (HOURS)


RUN NUMBER 452 SX
25/cm Wirepack
DEPTH OF CUT (INCHES)
CUTTING TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24







Sample No. 2. CSI Electroforming Technique to Produce Predetermined Kerf

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ID WAFERING

SILICON TECHNOLOGY CORP.

1. Contract Goals

The contract goals are aimed at demonstrating the state-of-the-art capability of ID slicing for producing wafers suitable for solar cells.

This contract is aimed at demonstrating reduced-kerf slicing of silicon, and slicing throughput is of secondary consideration.

The two slicing methods used for slicing 6-in. dia silicon are aimed at producing wafers with thickness greater than 10 mils with a total material usage at 17 to 18 wafers/cm. This translates to approximately 23 mils for slice thickness plus kerf.

Plunge cutting of 4-in.-dia round and 4-in. square ingots and rotational cutting of 4-in.-dia round ingots are aimed at producing 25 wafers/cm, which translates to about 16 mils for slice thickness plus kerf.

2. Equipment and Blades.

The plunge cutting of 6-in.-dia ingots is being done exclusively on the RD-140 prototypes machine due to its large capacity. The RD-140 saw has a 32-in.-dia blade mount that can slice ingots up to 8-in diameter.

The design of the RD-140 is different from the pivot arm concept. The blade mount and spindle are kept stationary while the ingot is moved vertically by linear air bearing pads on a granite block

There were three spindles used for the saw. They are:

1) Air-bearing spindle.
2) Hollow conventional-bearing spindle.
3) Solid conventional-bearing spindle.

The solid mechanical spindle has provided the best results. Chief advantages of the mechanical spindle are low vibration, trueness of the rotational plane and high reliability.

The air bearing pads on the granite block were the cause of some vibration which affected the quality of the wafers during the cutting stroke. By adjusting air pressure, the problem has been resolved and the air bearing surface provides an accuracy of 1 μm over a 10-in cutting stroke. The smooth action of the air pads evidences itself by exceptionally good surface quality of wafers cut on the RD-140 saw.

The blade mount used on the RD-140 is a hydraulic Dyna-Head design which does not permit the fine tuning of the ID runout. Typically, the ID of a 32-in. blade had a 2- to 3-mil runout. We are in the process of building a mechanical mount that will allow a much truer ID, thereby allowing faster cutting rates and thinner wafers.

The 32-in.-dia blades had 6-mil cores, which provided good results. We are able to slice satisfactory with about 13 mils of kerf. We plan to experiment with 4- and 5-in. cores which will reduce kerf by 1 or 2 mils; however, the thinner cores may be more successful on smaller-diameter blades. Since we do not need the full capacity of the 32-inch blade, we plan to make a 27-inch blade mount that will amply accomodate 6-in.-dia crystals.

Rotational slicing of 6-in. and 4-in. round crystals and plunge slicing of 4-in. square crystals were done on a standard 22-inch STC saw equipped with crystal rotation and programmed feed rate. The programmable feed is of a new design that allows feed rates up to 6 in./min. Programming is done through a cam that moves a linear potentiometer.

All slicing was programmed for the rotational slicing and slicing of 4-in.-square wafers.

The 22-inch blades had 6-mil cores, which gave kerf losses from 11 to 12 mils. We tried some 22-inch blades with 5-mil cores, but they were not very successful. We think that the problem was with the material and we have ordered some new 5-mil sheet material. We also plan to test 4-mil cores, which will reduce kerf below 10 mils.

3. Slicing Runs.

3.1 Six-in-Dia Plunge Cutting

Average kerf for the 32-in.-dia blades was 13 mils. We were able to cut wafers down to 12 mils thick with yield greater than 85%. Throughout the 6-in. plunge runs, we were able to maintain cutting speeds at 1.5 in./min. The kerf plus slice thickness yielded about 16 wafers/cm; our goal is 17 wafers per cm.

The greatest area for improving wafers/cm will come from reduction of kerf losses. A 27-inch OD can amply accommodate 6-in.-dia wafers. Kerf should be reduced to 11.5 mils for the 27-in.-dia blades. With the present slice thickness of 12 mils, we should achieve 17 wafers per cm.

3.2 Six-in. Dia Rotational Slicing

Rotational slicing of 6-in.-dia wafers was less successful than plunge cutting. Although kerf was reduced to 11.5 mils on the 22-inch blade, it was difficult to get whole wafers less than 18 mils thick. Even at 20 mils, yield was only about 50%. Cutting rates were about .3 in./min. It was much more difficult to slice 6-in. dia ingots rotationally than 4-dia.-dia ingots. The problem may be due to alignment of the rotational axis and larger deviations at the larger diameter.

3.3 Rotational Slicing of 4-in. Dia Ingots

We were able to cut wafers down to 9 mils thick with about 9.5 mils kerf. Rotational slicing of 4-in.-dia wafers yielded the lowest kerf due to the use of smaller 16-in blades. Average cutting rates were about .4 in./min for plunge cutting. The feed was programmed from 0.080 to 0.600 in./min and the rotation from 9 to 20 rpm.

3.4 Plunge Cutting of 4-in. Squares

We achieved best results on 4-in. square polycrystalline silicon with a fine-grain structure (1 to 5-mm grain sizes.) With 11 mils kerf, we were able consistantly to cut 5 to 6-mil wafers at 1 in. per minute. Yield was better than 90%. When the thickness was doubled to 10 or 12 mils we were able to increase cutting rates to 2.5/min with the same yield. This type of material seems to slice much better than single-crystal or larger-grain polycrystalline silicon.

We tested other 4-in.-square material but were not able to reduce slice thickness below 10 mils with the same yields.

4. Conclusions

The best results are achieved by plunge cutting 6-in.-dia single-crystal silicon and 4-in.-square fine-grain polycrystalline silicon. Although rotational slicing allows for use of smaller blades, ease of set-up, lower equipment cost and faster cutting rates seem to favor conventional plunge cutting. Of course, square ingots must be plunge cut.

We still intent to pursue rotational slicing of 6-in.-dia silicon because the problems we are encountering may be due to the equipment being used rather than inherent deficiencies in rotational slicing. The biggest problem we are seeing is the difficulty in aligning the rotational axis, which may be resolved by better equipment and techniques.

In terms of achieving the stated goals of material usage, we have already demonstrated 25 wafers/cm with 4-in.-square material and we should be able to demonstrate 17 to 18 wafers/cm with 6-in. material within a short time with the 27-inch blade mount.

Production capability with desired add-on costs is very easily attainable with some more development in terms of automation using present state-of-the-art ID technology.

5. Recommendations for Future Work

We plan to continue plunge cutting and rotational cutting of 6- and 4-in. ingots.

The RD-140 and the STC 22-inch machines will be modified to improve results. Both machines will be changed to mechanical blade mounts to allow less run-out of the ID.

The blade mount enclosure on the RD-140 will be modified to reduce turbulence, which will allow thinner wafers.

A 27-inch blade mount will be used to slice 6-in. material. We will experiment with 4-mil and 5-mil core material on the 22- and 27-inch blade mounts to reduce kerf losses.

Contract Goals

6-INCH DIAMETER -	17-18 WAFERS/CM (23 MILS T + K)
4-INCH SQUARE 4-INCH ROUND	25 WAFERS/CM (16 MILS T + K)

SLICING METHODS

PLUNGE CUTTING	6" Ø ROUND 4" Ø ROUND 4" SQUARE
ROTATIONAL CUTTING	6" Ø ROUND 4" Ø ROUND

Equipment

- RD-140 PROTOTYPE 32-INCH SAW

- STANDARD STC 22-INCH SAW

MODIFICATIONS:

- PROGRAMMABLE FEED RATE
- CRYSTAL ROTATION
- MONITORING DEVICES

- BLADES

32-INCH - 13 MILS KERF

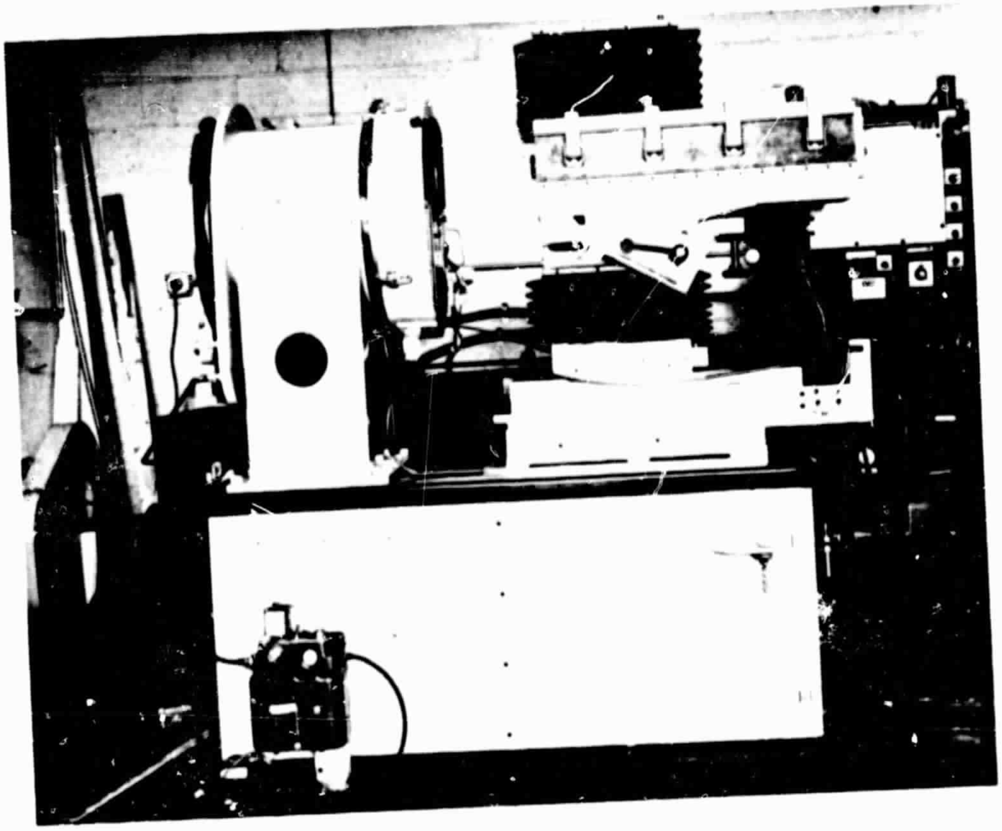
22-INCH - 11 MILS KERF

22-INCH - 10 MILS KERF

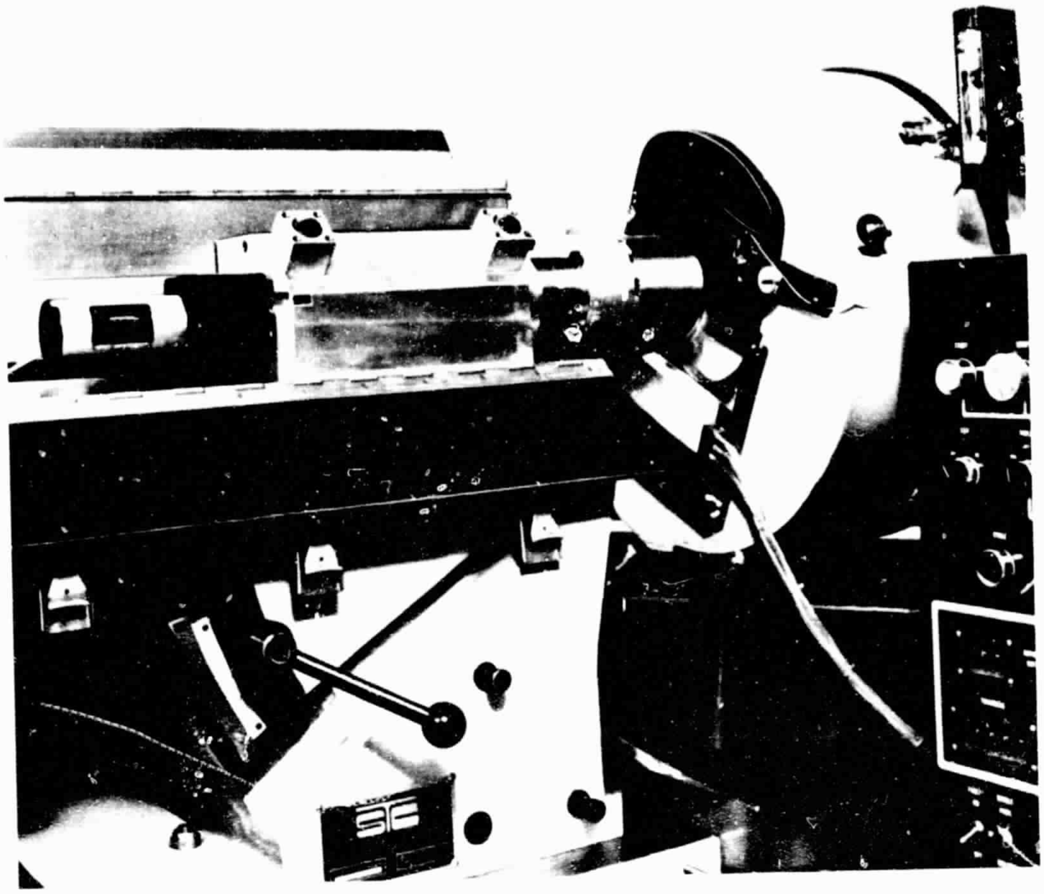
16-INCH - 9 MILS KERF

Slicing Results

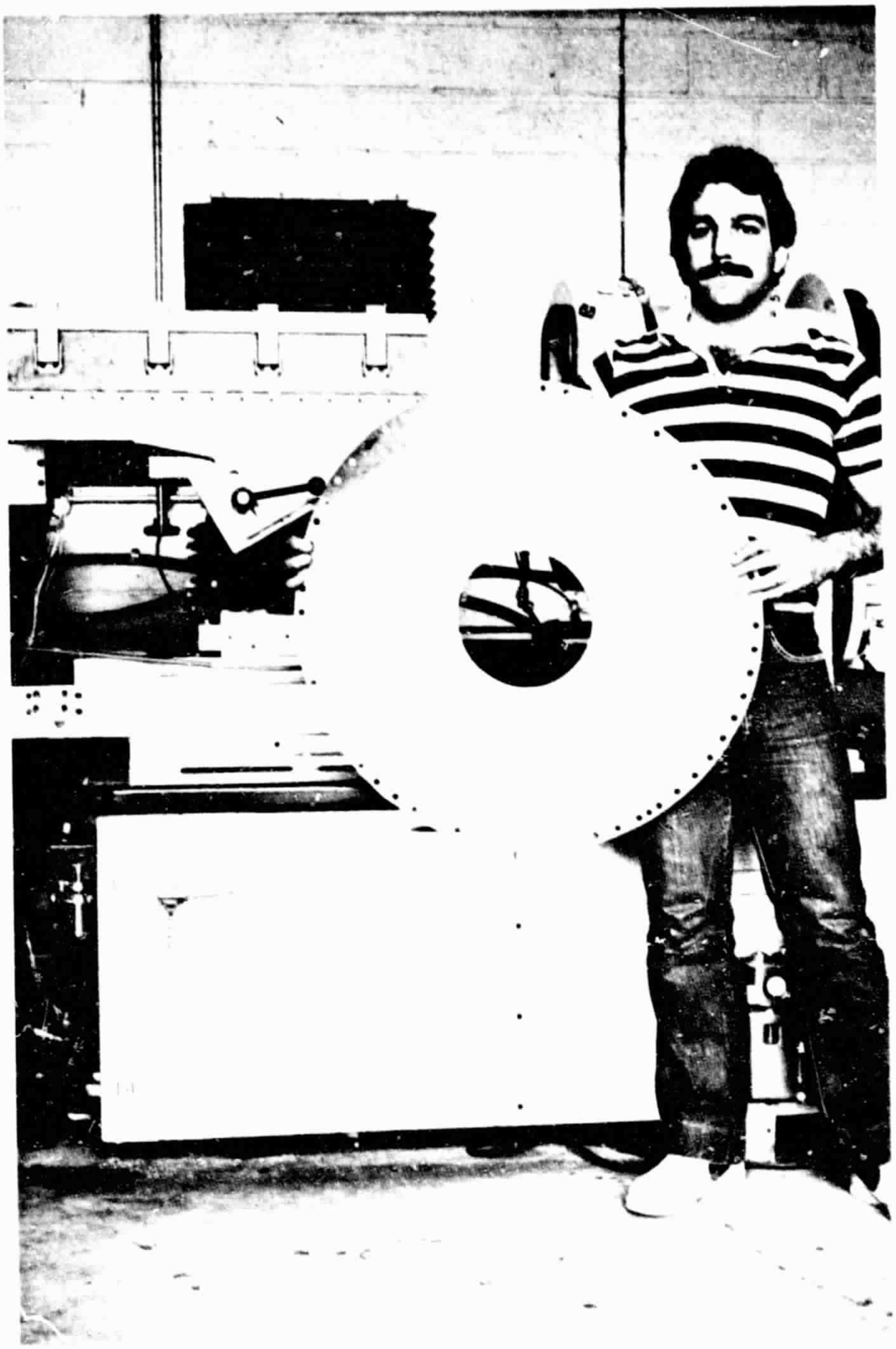
	KERF	SLICE THICKNESS	WAFERS/ CM	CUTTING SPEED	YIELD
6" Ø PLUNGE	13 MILS	12 MILS	16	1.5 IN/MIN	85%
6" Ø ROTARY	11.5 MILS	18 MILS	13	.6 IN/MIN	50%
4" Ø ROTARY	9.5 MILS	9 MILS	21	.8 IN/MIN	85%
4" PLUNG	11 MILS	5 MILS	25	1 IN/MIN	90%



Side View of Silicon Technology Corp. RD-140 Prototype 32-in. ID Saw
(Note Fixed Saw Head and Movable Ingot Feed Fixtures)



Close-Up View of Ingot Rotating Fixture as Mounted in Standard STC 22-in. ID Saw



32-in. ID Blade for STC RD-140 Prototype ID Saw in Background

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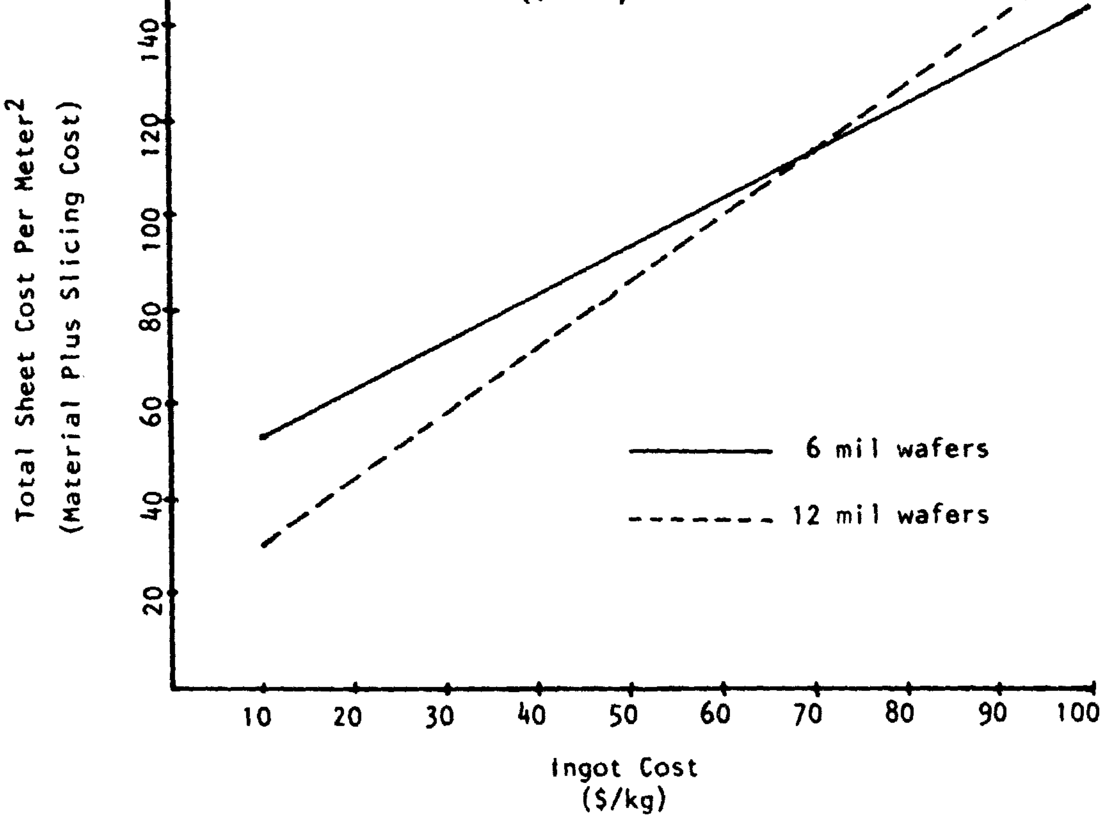
IPEG Assumptions With Present Technology (1980 $)

Ingot Size	6 in-round	4 in-square	4 in-square
Wafer Thickness	12 mils	6 mils	12 mils
Cutting Speed	1.5"/min.	1"/min.	2.5"/min.
Equipment Cost	$45,000.00	$40,000.00	$40,000.00
Machine Area	84 $ft.^2$	80 $ft.^2$	80 $ft.^2$
No. of Machines/Operator	10	10	10
Blade life	4,000 slices	4000 slices	4000 slices
Blade Cost	100	80	80
Other Materials/Year	1800	1800	1800
Power Consumption	2000 watts	2000 watts	2000 watts
Add-on Cost/$Meter^2$	25.79	42.50	17.02

Sheet Cost Comparison: 4-in. Square Wafers ($/m²)



Plans for ID Technology

NEAR TERM -

27-INCH BLADE MOUNT

MECHANICAL BLADE MOUNT

REDESIGNED WHEEL GUARD

THINNER CORE 22- AND 27-INCH BLADES

PROGRAMS FOR FEED RATES

LONG TERM -

EQUIPMENT DESIGN

- HIGHER THROUGHPUT
- AUTOMATION

BLADE DESIGN

SYSTEMS APPROACH TO FACTORY DESIGN

ENHANCED ID SLICING TECHNOLOGY

SILTEC CORP.

SUMMARY OF WORK AND RESULTS:

Severe limitations were experienced in slicing thin wafers with ID rotation because of anisotropic material characteristics of single-crystal silicon.

Reduction of ingot feed eliminated fracturing problems but resulted in less than cost-effective wafer-throughput levels.

Best results achieved consistently with ID rotation are 250 μm-thick, 100-μm-dia wafers with kerfs of 200 m sliced at a feed rate of 15 μm/min.

Results were improved by increasing cutting head size, thereby reducing high-frequency vibrations during slicing.

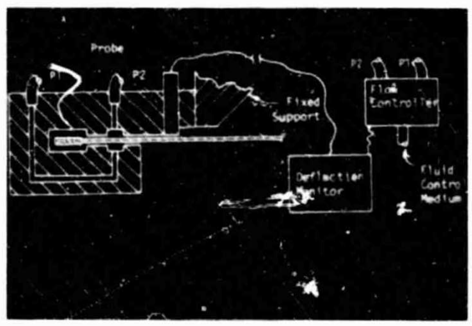
Cutting-edge position control was effective in all experiments, particularly when cutting with low-kerf (152-200 μm) blades.

Prefabricated blade inserts for ID blade show great potential but require further work in bonding of insert to core to become an effective production tool.

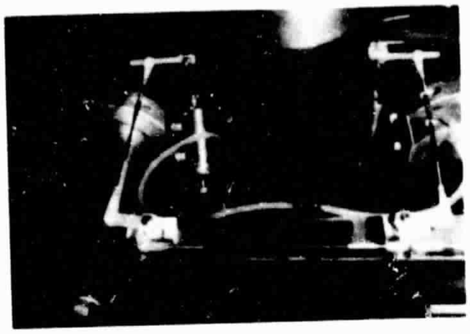
Alternative solution of etched blade core construction has shown good results.

Comparison of ID plunge and rotation cutting results indicate that a multiple-ingot ID plunge technique will improve slicing production significantly.

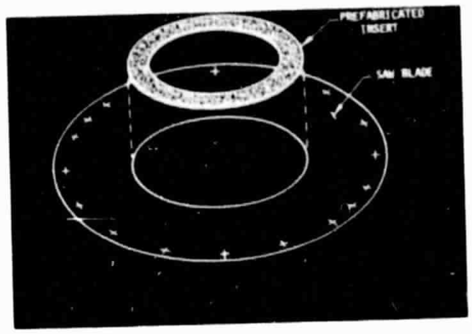
Oriented Fractures Due to ID Rotation Wafering



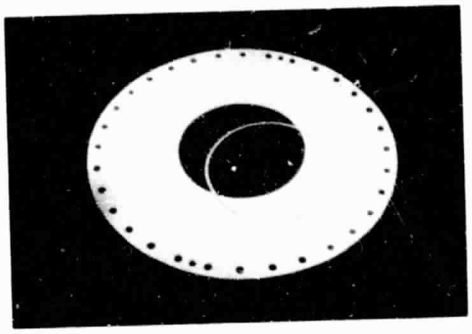
Closed-Loop Blade Position Control System



Close-Up of Blade Position Control System With Ingot in Position for Wafering

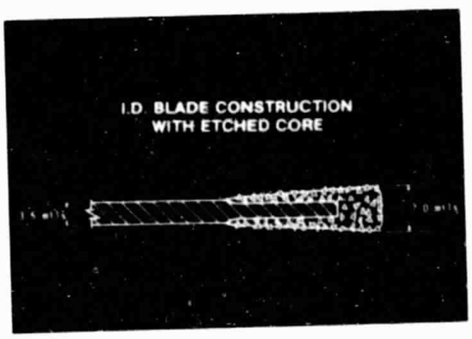


Perspective View of Prefabricated Insert Blade

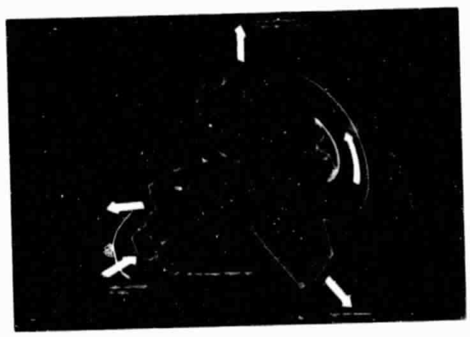


ID Blade With Core Ingot

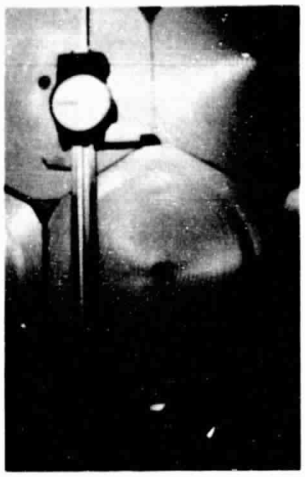
Close-Up View of Insert-Core Bone Showing Distortion at Weld



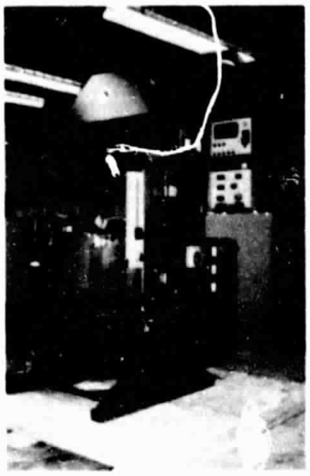
ID Blade Construction With Etched Core



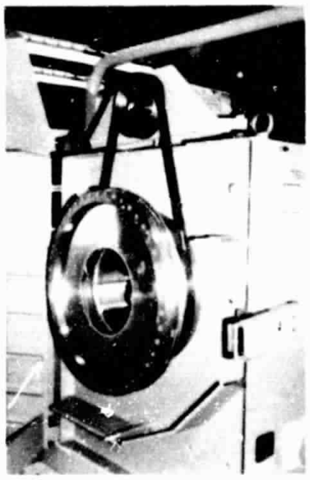
Conceptual Drawing of Multiple Ingot Feed for ID Wafering



150- m-dia Wafers Trimmed to Show Packing Improvement With Hexagonal Shape



Meyer & Burger TS-23 ID Saw



Close View of Meyer & Burger TS-23 27-in. Blade Head

CHARACTERIZATION

APPLIED SOLAR ENERGY CORP.

Material Evaluation

1. EFG (MOBIL - TYCO):

   A. COMPARISON OF EFG MATERIALS WITH AND WITHOUT A CO ENVIRONMENT IN THE SAME FURNACE.

   B. LOW TEMPERATURE ANNEALING (600°C, 30 hr.)

   C. GRAIN BOUNDARIES PASSIVATION WITH TWO STEP DIFFUSION (ALSO INCLUDE POLY HAMCO CZ AND SILSO)

2. DENDRITIC WEB (WESTINGHOUSE)

   A. BASELINE PROCESS

   B. ADVANCE PROCESSES

3. HEM (CRYSTAL SYSTEM) - MAPPING OF A CRYSTAL:

   HEM I.D. 41-41C

EFG Materials With and Without CO In Ambient of Same Furnace

	Voc, mV	Jsc, mA/cm2	CFF %	η %
Without CO	540	22.9	70	8.6
With CO	567	25.1	76	10.7
CZ Control	582	28.2	78	12.7

BASELINE PROCESS ON 2 x 2 CELLS WITH SiO AR MEASURED AT 28°C AM1.

EFG Material With Low-Temperature Annealing ($600^{o}C$, 30 h)

	Voc, mV	Jsc mA/cm 2	CFF %	η %
Not Annealed	493	13.2	74	4.8
Annealed	493	13.3	73	4.7
Cz Control	568	20.1	74	8.5

BASELINE PROCESS ON 2x2 CELLS WITHOUT AR MEASURED AT AM1 AT $28^{o}C$. (EFG MATERIAL WITHOUT CO IN THEIR GROWTH)

Average Short-Circuit Current Density (J_{SC} mA/cm^2) for Two-Step Diffusion Process ($750^{o}C$, 9 h in $POCl_3$)

	EFG	Poly Hamco	SILSO
No 2 Step Diffusion	17.9	22.1	22.4
2 Step Diffusion	15.3	22.1	22.3

Jsc of Control : 23.4

Baseline Process on 2 x 2 cells without AR, measured at AM0, $28^{o}C$. (EFG Material without CO in growth)

Dendritic Web Solar Cell from Baseline Process

		WEB ID. NO.			CZ CONTROL
		17-1373 ρ=3.5Ωcm	17-1377 ρ=3.4Ω-cm	17-1390 ρ=9.4Ω-cm	
Voc (mV)	AV.	532	534	515	588
	S.D.	530~534	532~536	512~513	584~590
	R	2	2	3	3
Jsc (mA/cm^2)	AV.	28.8	28.1	28.6	29.8
	S.D.	0.5	0.3	0.5	0.5
	R	28.3~25.4	27.8~28.4	27.4~29.0	29.3~30.0
CFF (%)	AV.	76	76	75	74
	S.D.	1	1	1	3
	R	75~76	75~76	74~77	70~7[illegible]
η (%)	AV.	11.6	11.4	11.[illegible]	13.0
	S.D.	0.1	0.1	0.2	0.6
	R	11.4~11.7	11.3~11.5	10.6~11.3	12.2~13.5

NOTE. 1) 2x2 cm cells under AM1 measured at 28°C test block temperature.

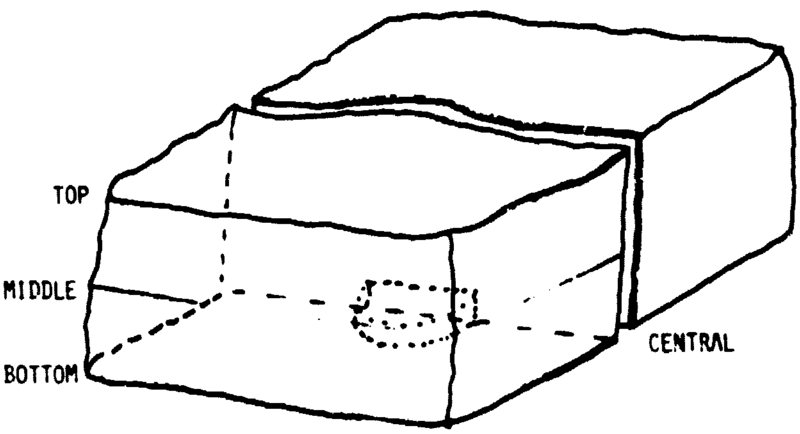
Dendritic Web Solar Cells From Advanced Process

			CONTROL CELLS (NO BSF)	
		WEB	WEB	CZ
Voc (mV)	AV.	545	531	581
	S.D.	14	11	-
	R	528-558	514~546	578-582
Jsc (mA/cm^2)	AV.	29.2	28.1	29.9
	S.D.	0.6	0.5	-
	R	28.5-29.8	27.4-28.8	29.3-30.4
CFF (%)	AV.	79	78	78
	S.D.	1	2	-
	R	78-80	75-79	77-79
η (%)	AV.	12.5	11.7	13.5
	S.D.	0.6	0.5	-
	R	11.8-13.0	10.9-12.2	13.2-13.7

NOTE: 1) Measured under AM1 at 28°C test block temperature.

2) Advanced process; SJ+BSF+MLAR

HEM ID 41-41C



SIZE: 12" x 12" x 6"

WT. ~ 35 kg

Summary of Results for HEM (ID 41-41C)

Average Parameters for Horizontally Cut Layers
(Values Normalized to Control are in Parenthesis)

	Voc,mV	Jsc mA/cm2	CFF %	η %
Top	557 (.97)	26.1(.93)	69(.91)	10 (.82)
Middle	566 (.98)	27.0(.96)	73(.96)	11.1(.90)
Bottom	550 (.95)	25.1(.89)	73(.96)	10.0(.81)
Cz Control	577	28.2	76	12.3

Average Parameters for Vertically Cut Layer
(Values Normalized to Control are in Parenthesis)

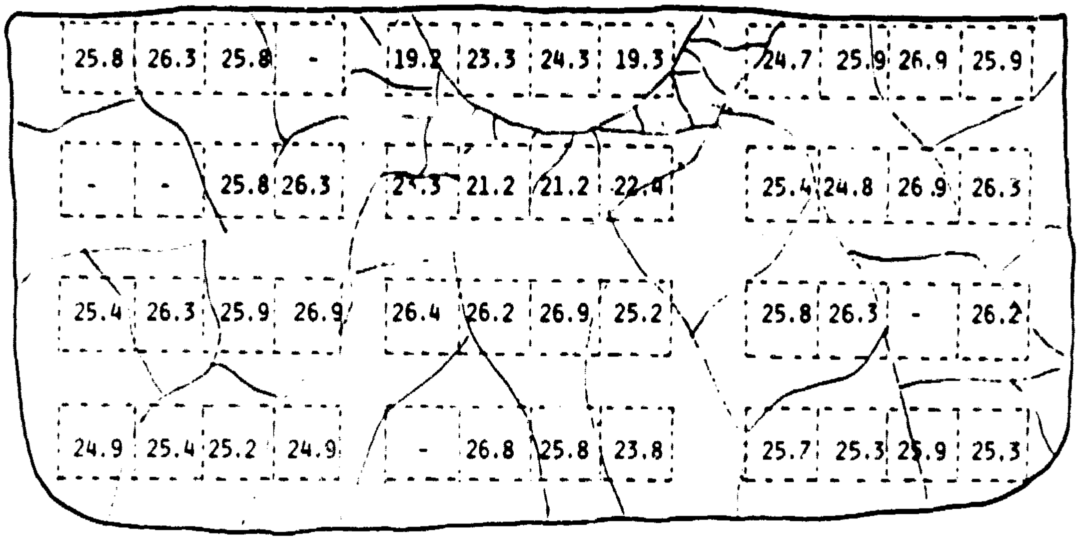
	Voc,mV	Jsc mA/cm2	CFF %	η %
CENTRAL	559(.97)	25.8(.95)	72(.93)	10.4(.85)
Cz Control	577	27.3	77	12.2

All values were measured in AM1, 28°C. Cells were fabricated by baseline process with SiO AR coating.

Cell Size: 2x2cm

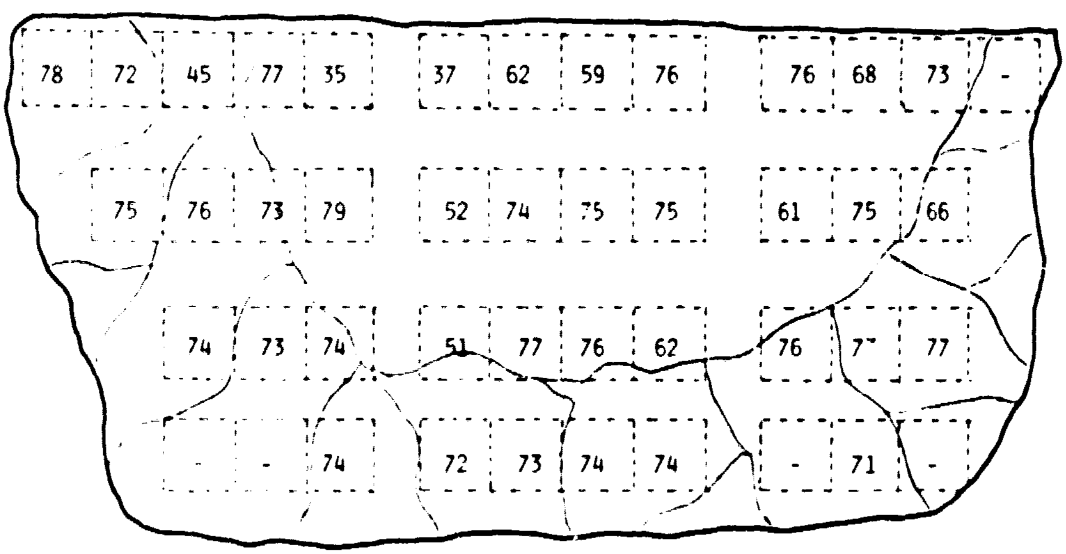
HORIZONTALLY CUT HEM ID 41-41C

J_{sc}(mA/cm^2) for Bottom Layer



Ave 25.1 (892)
Control Ave 28.2

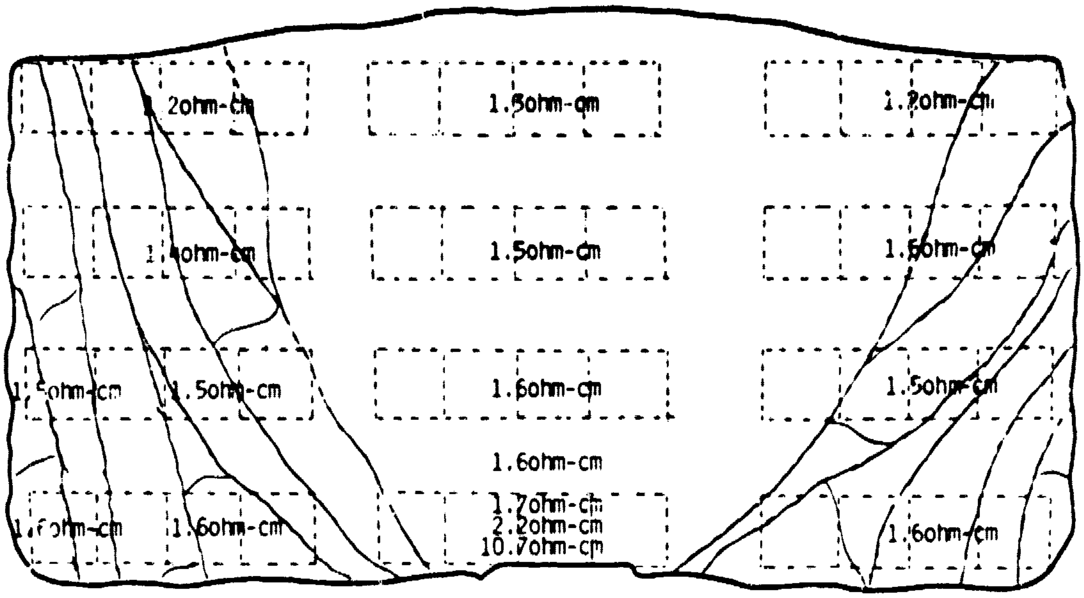
CFF (%) for Top Layer



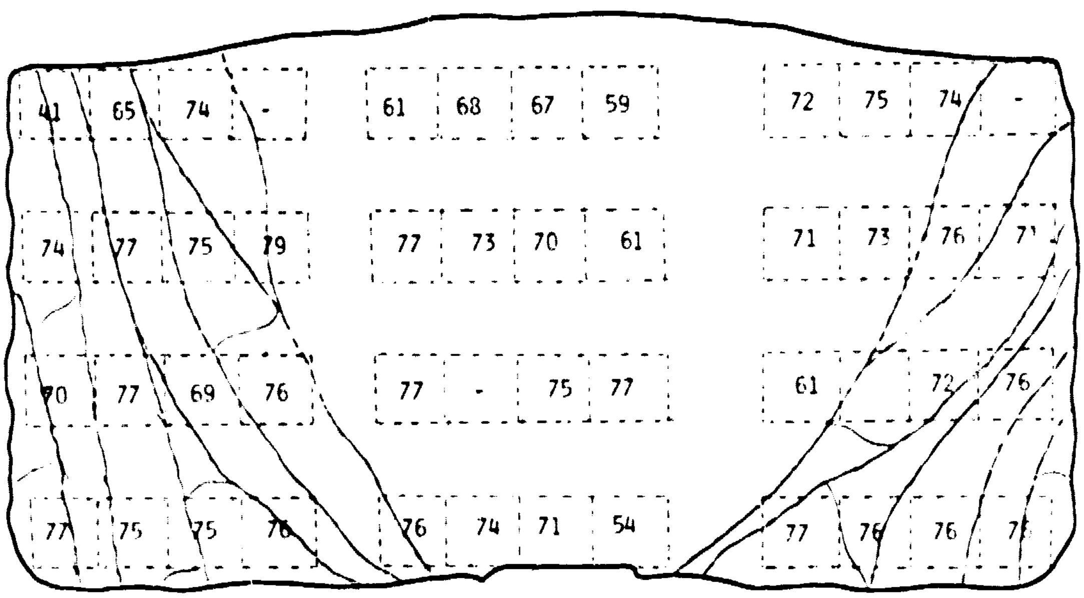
Ave 68% (50[illegible])
Control Ave 7[illegible]%

VERTICALLY CUT HEM ID 41-41C

Resistivity Distribution

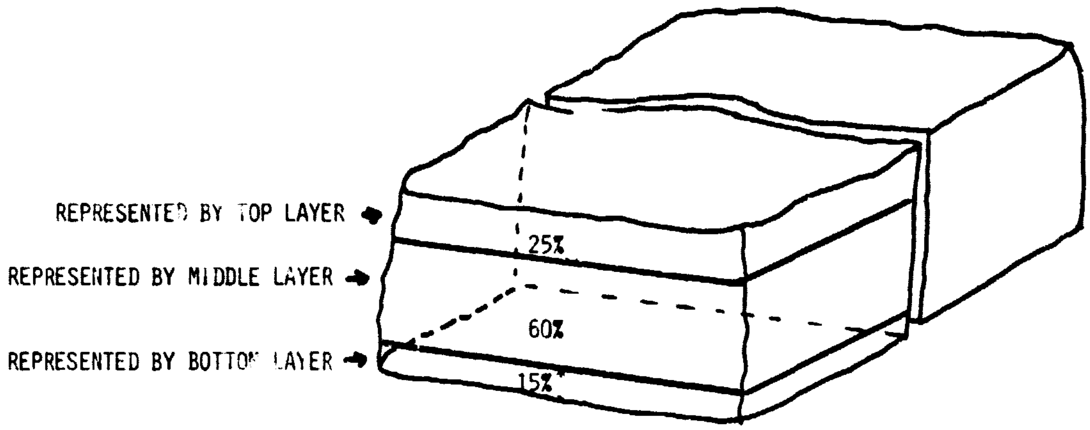


CFF (%)



AVE. 72% (93%)
CONTROL AVE. 76%

HEM ID 41-41C



AVERAGE η FOR THE WHOLE CRYSTAL: 10.7% AM1

NORMALIZED TO Cz CONTROL: 87% (IN USABLE AREA)

TECHNOLOGY DEVELOPMENT AREA

Encapsulation Task

TECHNOLOGY SESSION

C.D. Coulbert, Chairman

Encapsulation Materials and Design Principles

Encapsulation Task progress and status were reported in three major PIM sessions. A general overview and summary of module encapsulation technology and design guidelines was presented by Ed Cuddihy in the Wednesday-morning plenary session, with a follow-up discussion session on Thursday afternoon. Individual contractor reports were presented during contract reviews on Wednesday afternoon and Thursday morning.

A major goal of the Encapsulation Task is to compile and publish this year an encapsulation-design report that will document the encapsulant material system performance requirements and the status and characteristics of available encapsulant materials and fabrication processes. The report is being organized to be of maximum usefulness to module manufacturers and to the material-supply industry. This is being achieved through discussions at the PIMs and continuing technical contracts between LSA and industry. It is expected that this encapsulation-design report will be updated in subsequent years. Ed Cuddihy presented at this PIM the current technology status and the general content of the evolving encapsulant material specifications and performance requirements. Selected figures from the presentation are included in these Proceedings (see p. 59).

The following highlights are summarized from the LSA contract review session, which also covered JPL in-house efforts on module-life assessment and photothermal aging. Selected figures from the presentations are included.

Springborn Laboratories: EVA formulated specifically for PV module lamination is now being made available to module manufacturers for module production evaluation. Alternative pottant materials being intensively developed and evaluated include EMA for lamination and PnBA for a casting pottant. One low-cost edge-gasket material, under evaluation for module mounting, that appears to meet the LSA goals is EPDM (ethylene propylene diene monomer) rubber, which comes in a variety of compositions and molded forms. The EPDM edge gasket may be supplied either as a continuous extruded shape and cut to fit the module edges or as a complete molded one-piece "picture frame."

Spire Corp.: Small solar modules with cells electrostatically bonded (ESB) to a borosilicate glass superstrate and encapsulated on the back side with a conventional pottant and cover film have been produced routinely, and these modules are currently undergoing durability testing. These modules have also been produced with preformed mesh front metallization applied during the ESB process.

The ESB process has also been demonstrated as a lower-temperature approach to bonding Si wafers to larger glass sheets and processing the cells with interdigitated back-contact metallization.

Illinois Tool Works: Ion plating of front metallization has been used on 4-in.-dia wafers with boron-doped junctions in n-type base Si to produce cells as good as production cells. Low-cost materials and high deposition rates are the potential advantages of this approach.

Rockwell Science Center: The measurement of module or cell ac impedance has been demonstrated as a potentially sensitive non-destructive field or laboratory evaluation technique for assessing changes in solar cell series and shunt resistance. The technique will be applied to a set of Block II modules now undergoing accelerated life testing at JPL.

JPL In-House: Photothermal degradation 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, PnBA, polyurethane, and acrylic films. Additional materials will be characterized during the coming year. Failure mechanisms and critial temperature limits associated with module hot-cell experience are being identified for use in establishing module circuit design and diode protection criteria.

Modeling of the photodegradation of UV screening acrylic outer cover films has yielded rates of degradation of the material constituents and of the total system. These data have been used to provide material composition criteria for the achievement of optimum low-cost long-life cover films.

Encapsulation Task Highlights Summary: Candidate encapsulant material systems and configurations that meet the LSA cost and performance goals and have the potential for meeting the life and durability goals have been identified and demonstrated. Recognizing that module manufacturers may prefer different module assembly methods (e.g., casting vs laminating pottants), candidate pottants for each process have been identified. Furthermore, it is expected that future module designs will be optimized for specific applications and for specific geographic or climatic areas. In consideration of these different requirements, candidate design approaches within the cost guidelines include both the glass superstrate designs and the steel or wood hardboard substrate panel designs. Each design approach has its advantages and disadvantages, depending on application and deployment site. The lowest potential cost resides with the hardboard substrate design.

Validation of the 20-year module life potential is still the focus of intensive LSA studies on photothermal degradation at JPL with contracted support from organizations that include Case Western Reserve University, University of Toronto, Colorado State University, Rockwell Science Center and the California Institute of Technology.

Specific life-limiting module failure modes that have been observed and related to the characteristics of the encapsulation material systems include cell cracking due to gas evolution under hot-spot cells and cell cracking and interconnect fatigue due to expansion and contraction of organic substrate panels with varying humidity and temperature. Candidate solutions to these failure modes have been identified and are in the process of evaluation. Solution approaches include optimizing the module circuit design to limit hot-spot temperatures, controlling the substrate expansion stresses by material selection and packaging design and by ranking and selecting encapsulants for the greatest photothermal stability.

Encapsulation Task Technical Readiness

I. ENCAPSULANT MATERIALS, PROCESSES, & DESIGNS WHICH MEET THE LSA COST, PERFORMANCE, & LIFE GOALS
- FABRICATION OF PROTOTYPE MODULES WITH SELECTED MATERIALS AND PRODUCTION METHODS
- PASS JPL QUALIFICATION TESTS
- A DESIGN SPECIFICATION HANDBOOK FOR INDUSTRY (MATERIAL SUPPLIERS AND MODULE BUILDERS)
- OPTIMIZE DESIGNS FOR MINIMUM LIFE CYCLE ENERGY COST

II. ASSESS 20-YEAR LIFE POTENTIAL BY ACCELERATED AND OUTDOOR TESTING
- IDENTIFY AND ELIMINATE OR MINIMIZE LONG TERM MATERIAL DEGRADATION MODES
- ACCUMULATE MAXIMUM OPERATING EXPERIENCE
- PROVIDE LIFE PREDICTION RELATIONSHIPS BASED ON MODELS AND ACCELERATED TESTS

LOW-COST ENCAPSULATION SYSTEMS

SPRINGBORN LABORATORIES, INC.

Ethylene Vinyl Acetate (EVA) Pottant

NOW PRODUCED BY SPRINGBORN LABORATORIES-
"CRANEGLASS" SPACER

ADVANTAGES:

- GLASS MAT AVAILABLE IN ROLL FORM
- EFFECTIVE ANTI-BLOCKING SURFACE
- POSITIVE SPACER FOR MODULE COMPONENTS
- AIDS DEGASSING IN LAMINATION
- PROVIDES INSULATION RESISTANCE
- TOTAL INTEGRATED TRANSMISSION 91% *
- ADD ON COST, 0.78¢/FT^2

* PRODUCT IMPROVEMENT WITH NO LOSS OF POWER

Candidate Pottant Under Development
Ethylene Methyl Acrylate*

- COST, $0.59 / LB
- VERY HIGH THERMAL STABILITY
- EXCELLENT ADHESION PROPERTIES
- NON-HYDROPHILIC
- AVAILABLE WITH ANTI-BLOCKING ADDITIVE
- VACUUM BAG LAMINATION DEMONSTRATED
- TOTAL INTEGRATED TRANSMISSION: 91.5 %
- EXTRUDABLE IN THIN FILMS

* GULF OIL CHEMICALS

ETHYLENE/METHYL ACRYLATE

FORMULA NO. A11877

	PARTS
EMA TD 938 BASE RESIN	100.0
LUPERSOL 231 (CURING AGENT)	3.0
CYASORB UV-531 (STABILIZER)	0.3
TINUVIN 770	0.1
NAUGARD - P (ANTIOXIDANT)	0.2

- INGREDIENTS TUMBLE BLENDED PRIOR TO EXTRUSION - NO SEPARATE COMPOUNDING STEP REQUIRED
- NO RELEASE PAPER REQUIRED DURING ROLL WINDUP
- SAME CURE REQUIREMENTS AS EVA POTTANT
- SAMPLES AVAILABLE FOR INDUSTRIAL EVALUATION BY MARCH, 1981

Butyl Acrylate Casting Syrup

CURRENT FORMULATION:

- BUTYL ACRYLATE POLYMER 35%
- BUTYL ACRYLATE MONOMER 60%
- HEXANEDIOLDIACRYLATE (CROSSLINKING AGENT) 5%

CURE CHARACTERISTICS:

- APPX. 5 MINUTES AT 45°C

  INITIATOR: LUPERSOL - 11, 0.5% BY WEIGHT
- POT LIFE APPX. 8 HOURS AT ROOM TEMPERATURE

SAMPLES WILL BE AVAILABLE FOR INDUSTRIAL EVALUATION BY MAY, 1981

PROPERTIES:

SYRUP : WATER WHITE, CLEAR
VISCOSITY APPX. 10,000 CENTIPOISE
SPECIFIC GRAVITY APPX. 0.94

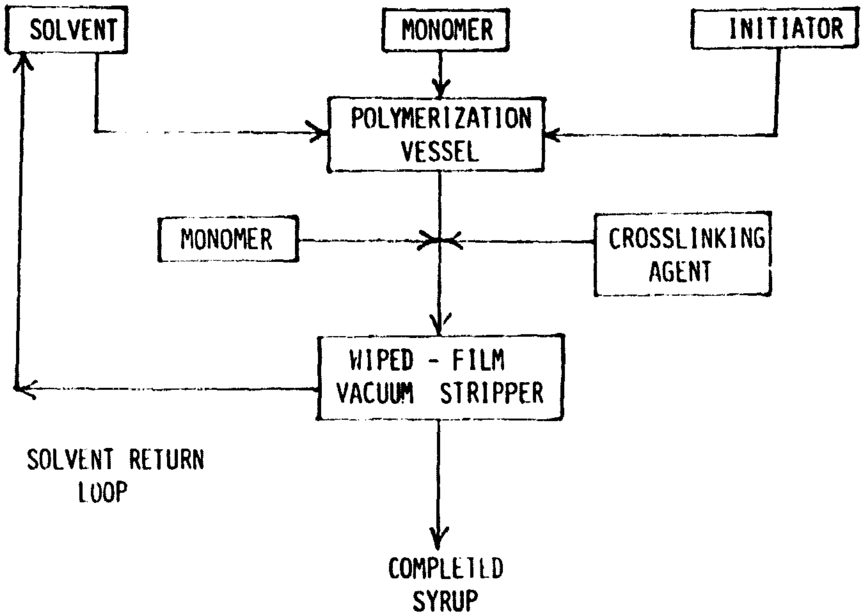
CURED PROPERTIES:

TENSILE STRENGTH (D638)	200 PSI
100% MODULUS (D-638)	300 PSI
ULTIMATE ELONGATION (D638)	100 %
HARDNESS (SHORE A)	44
GEL CONTENT	84 %
ODOR: ACCEPTABLE LOW	

- MAY BECOME ACCEPTABLE REPLACEMENT FOR RTV SILICONES

BUTYL ACRYLATE CASTING SYRUP

NEW METHOD OF PRODUCTION:



ELIMINATES THE RECOVERY OF DRY POLYMER AND PROCEEDS DIRECTLY TO SYRUP FORMULATION

Gasket Compounds

COMPOUNDED ELASTOMER	COST $/LB	COMPRESSION SET RECOVERY	COST/SET[A.] RECOVERY INDEX $/%
SILICONE	$2.53	65 - 90%	2.81 - 3.89
ETHYLENE/VINYL ACETATE	$0.85	65 - 80%	1.06 - 1.31
NEOPRENE	$0.87	75 - 85%	1.02 - 1.16
EPDM	$0.58	70 - 90%	0.64 - 0.83

EPDM COMPOUNDS, ADVANTAGES:

- BEST COMPRESSION SET/COST RATIO
- LOW COST
- EASY EXTRUSION - COMPLEX PROFILES
- DEMONSTRATED WEATHERABILITY
- HISTORY OF SUCCESSFUL USE IN RELATED APPLICATION (AUTOMOTIVE WINDSHIELDS)

A. FOR COMPARATIVE PURPOSES ONLY

RS/4 Sunlamp Exposure

MATERIAL	HOURS	PROPERTY RETAINED (ASTM D-638) TENSILE	ELONGATION
3M ACRYLIC FILM X-22417	3,000	54%	100%
EMA BASE RESIN (UNCOMPOUNDED)	5,000	10%	10%
EMA A11877 (COMPOUNDED)	5,000	100%	100%
DUPONT TEDLAR 100 BG 30 UT	3,000	100%	100%
BUTYL ACRYLATE BASE FORMULATION	4,000	N/A	N/A

EVA POTTANT

(NO COVER FILM)

CLEAR STABILIZED EVA EXPOSED 17,600 HOURS
NO OBSERVABLE CHANGE

	TOTAL INTEGRATED TRANSMISSION (%)	ULTIMATE* ELONGATION (%)	TENSILE * STRENGTH (PSI)
CONTROL	91	510	1830
EXPOSED 17,600 HRS	90	560	1870

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

* ASTM D-638

ELECTROSTATIC BONDING

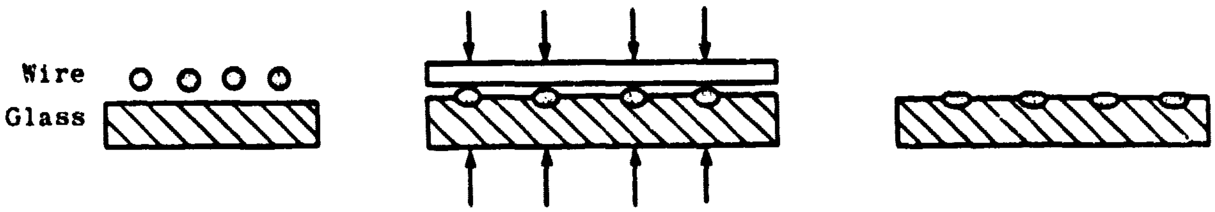
SPIRE CORP.

Phase III Summary

- INTEGRAL FRONT MODULE FABRICATION IS ROUTINE
  - --- Efficiency to 13%
  - --- Yield in Non-Production Bonder > 80%
- PREFORMED CONTACT BONDING
  - --- Process Routine with Skilled Operators
  - --- Efficiency Nearly as Good as Conventional Cells
- LOW TEMPERATURE MODULE FABRICATION
  - --- 12" x 16" Modules Fabricated on Hot Plate
  - --- Good Results with Proper Glass Surface
  - --- Continue Work to Lower Bond Temperature
- LARGE AREA BONDER ENGINEERING
  - --- Conceptual Design Complete

Low-Temperature Preformed Contact Process

1. Press Preform into Glass at High Temperature



Starting Material

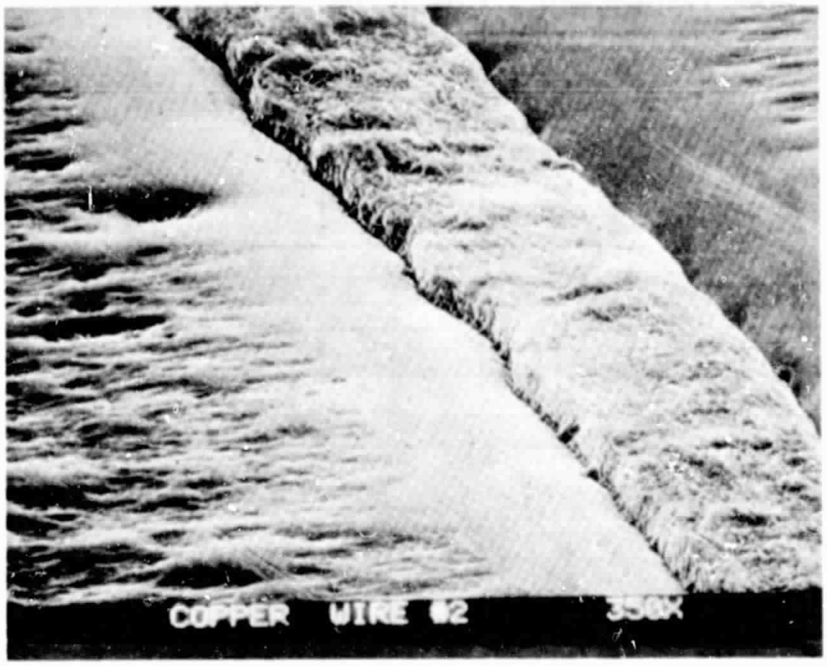
Heat and Pressure

Glass Containing Contact Wire

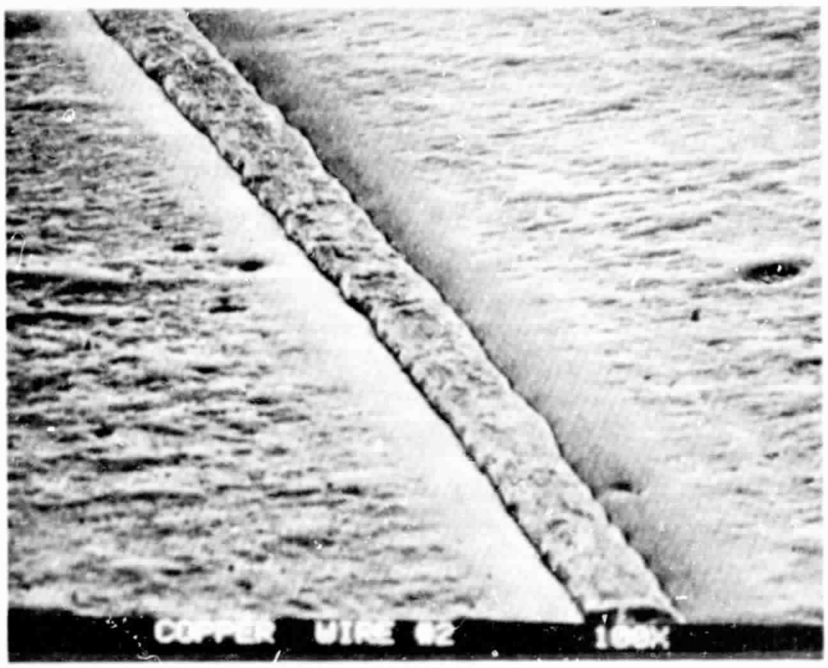
2. Electrostatically Bond Bare Cell to Glass/Wire Structure at Low Temperature

Heat and High Voltage

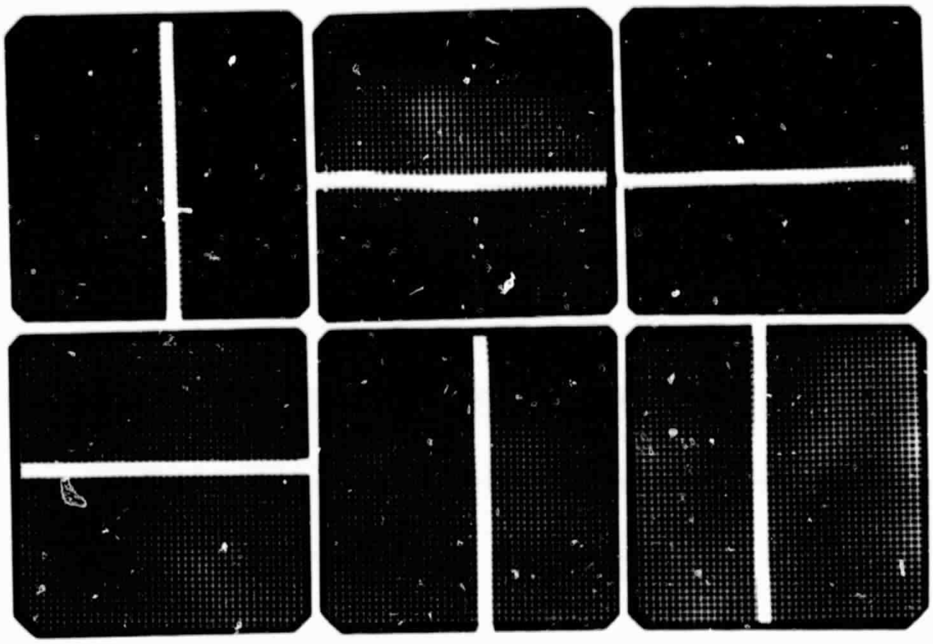
Finished Cell Assembly with Integral Cover



SEM Photo of Cu Wire Hot Pressed
Into Glass Cover Slip (350x)



SEM Photo of Cu Wire Hot Pressed
Into Glass Cover Slip (100x)

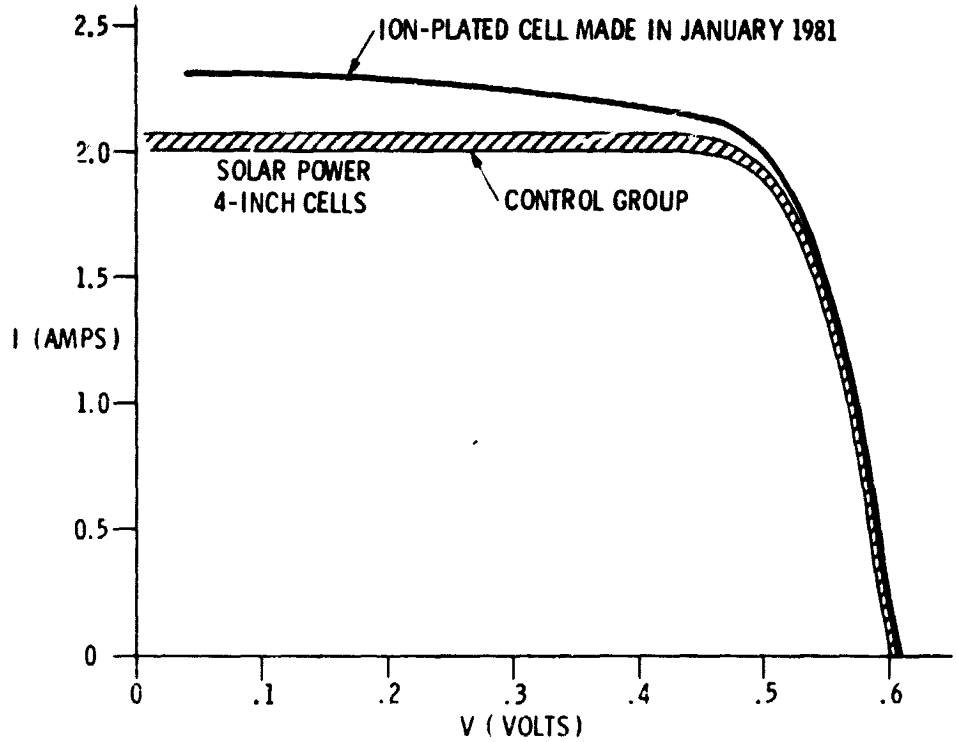


ION PLATING

ILLINOIS TOOL WORKS

ITW-Endurex Cell No. 101

Front: Ni, Sn With Bus Bars and Solder Dip
Back: Ti, Cu



Proposed Low-Cost Metallization Systems For p on n and n on p Solar Cells

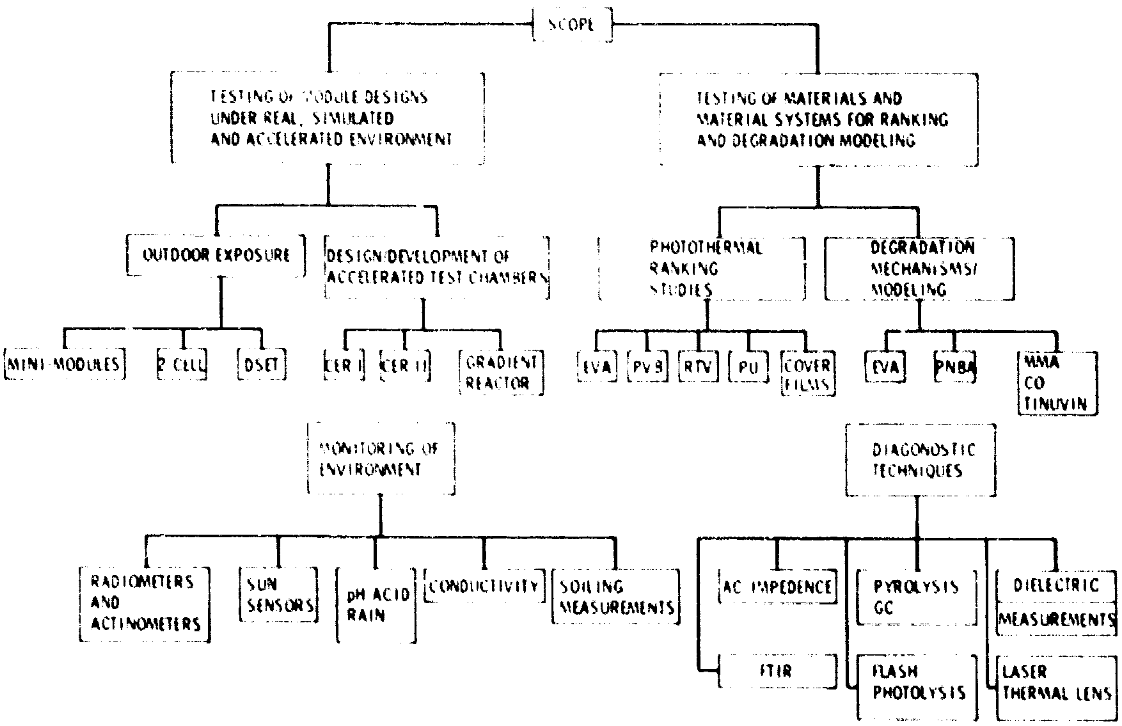
	P ON N TYPE WAFERS (SOLAR POWER CORP.)	N ON P TYPE WAFERS (SPECTROLAB)
FRONT		
1ST LAYER	NICKEL, CHROMIUM	NICKEL, CHROMIUM, TITANIUM
2ND LAYER	COPPER	COPPER
BACK		
1ST LAYER	TITANIUM	TITANIUM-ALUMINUM ALLOY
2ND LAYER	COPPER ($.124\ \Omega\cdot cm^2$)	COPPER ($.091\ \Omega\cdot cm^2$)

--COPPER IS USED FOR EASE OF CONNECTING

--ADDITIONAL LAYERS FOR CORROSION PROTECTION, ETC. MAY BE USED

MATERIAL DEGRADATION AND LIFE PREDICTION

JET PROPULSION LABORATORY



Long-Term Degradation Modeling

EVA : UNIVERSITY OF TORONTO

STATUS : DEVELOPED COMPUTER MODEL OF PHOTODEGRADATION

PNBA : CASE WESTERN RESERVE U.

STATUS : DEVELOPED MECHANISM OF PHOTODEGRADATION OF UNCROSSLINKED PNBA

UV SCREENING COVERS: IN-HOUSE

STATUS : DEVELOPED PHOTODEGRADATION MODEL AND ACCELERATED TESTING CRITERIA

PHOTOTHERMAL DEGRADATION OF EVA FILMS

LOADS AND STRESSES

- UV LEVEL: 6-10 SUNS/DARK
- TEMPERATURE: 25°C, 70°C, 85°C, 105°C
- OXYGEN LEVEL: FULL ACCESS, NO EDGE SEAL, CLOSED OVEN

PROPERTIES MEASURED

- WEIGHT LOSS
- CHANGE IN ABSORBANCE: UV/VISIBLE/IR
- STRESS-STRAIN
- EXTRACTION/GPC/SWELLING STUDIES

OBJECTIVE

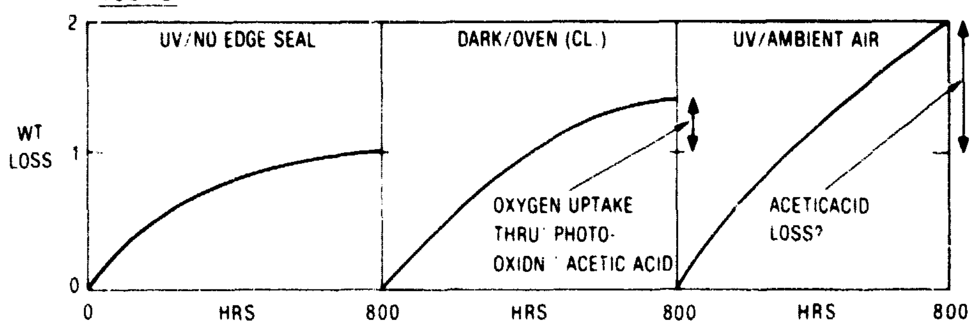
- DETERMINE DEGRADATION RATES

WEIGHT LOSS DATA

70°C
GRADUAL WEIGHT LOSS UP TO 0.5 WT% AFTER 500 HRS OF AGING

85°C
GRADUAL WEIGHT LOSS UP TO 1% AFTER 800 HRS OF AGING

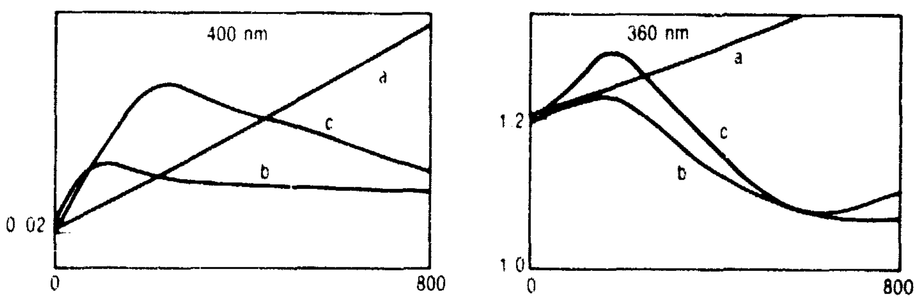
105°C



UV-VISIBLE TRANSMISSION ANALYSIS OF EVA FILMS

- TESTS CARRIED OUT AT 70°C, 85°C, 105°C. SIMILAR FEATURES AT ALL TEMPERATURES RATES DIFFERENT

105°C a: CLOSED OVEN; b: NO EDGE SEAL, UV; c: UV/AIR



TRANSMISSION ANALYSIS ON EVA FILMS

RESULTS

- LOSS OF ADDITIVES (800 HR TEST)

	CLOSED	NO EDGE SEAL	OPEN
85°C	0	11%	19%
105°C	0	14%	24%

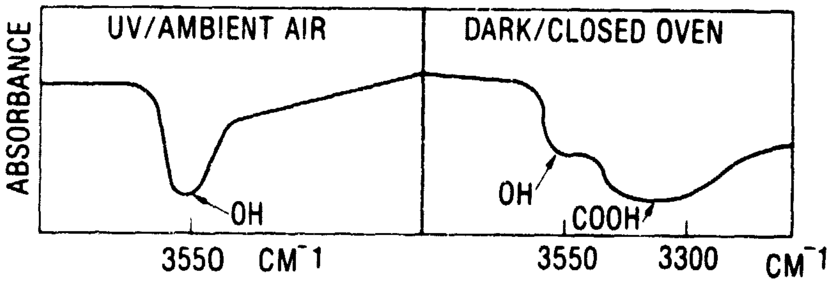
- YELLOWING: (ΔABSORBANCE AT 400 nm)

	CLOSED, NO UV	UV + NO EDGE SEAL	UV + AIR
85°C	0.01	0.005	0.005
105°C	0.02	0.01	0.01

FT — IR ANALYSIS OF EVA FILMS

- 25°C
  SLOW PHOTOOXIDATION INDICATED BY HYDROXYLS FORMATION (OLD DATA)

- 105°C



- FASTER PHOTOOXIDATIVE FORMATION OF HYDROXYLS IN PRESENCE OF UV AND O_2

- BUILD UP OF ACETIC ACID IN CLOSED OVEN

EXTRACTION OF IRRADIATED EVA FILMS

- PERCENT EXTRACTIBLE ~30% UNDER ALL EXPERIMENTAL CONDITIONS AFTER 800 HRS
- MOLECULAR WEIGHT ANALYSIS OF EXTRACTIBLES

105°C, 800 HRS

SAMPLE	$\bar{M}n$
CONTROL	200,000
OVEN (CLOSED)	170,000
UV/AIR	91,000
UV/NO EDGE SEAL	44,000

- SWELLING STUDIES: IN PROGRESS

PHOTOTHERMAL TESTING OF PVB FILMS

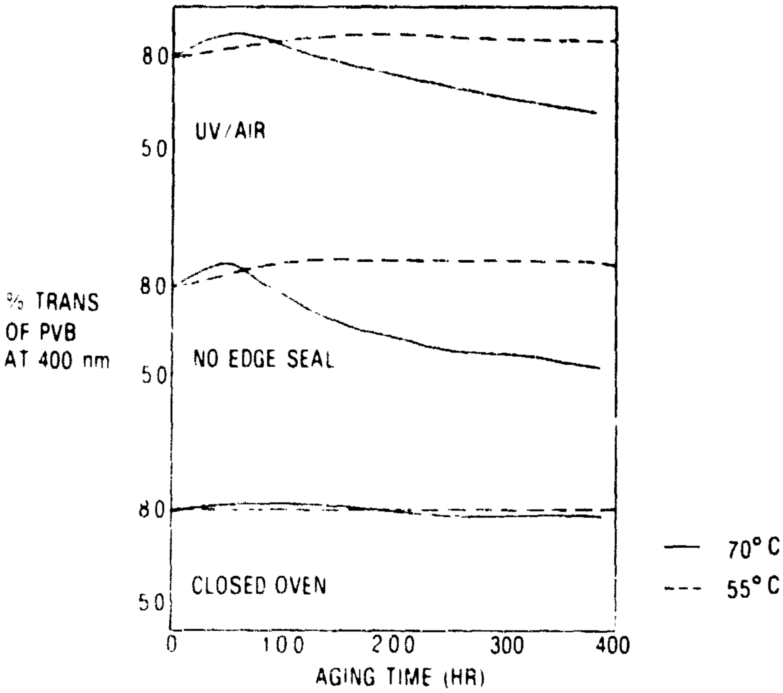
LOADS AND STRESSES

- TEMP 55°C, 70°C
- O_2 LEVELS: CLOSED OVEN, AMBIENT AIR

  NO EDGE SEAL (3'' X 1/2'')
- UV LEVELS: 6-10 SUNS, DARK

PROPERTIES MEASURED

- WEIGHT LOSS
- EXTRACTION, MOL. WT.
- TRANSMISSION



RESULTS

WEIGHT LOSS AT 70°C

	WT. LOSS	ACTIVATION ENERGY 55-70°C
CLOSED OVEN	<0.5%	
UV/AIR	6%	~10K CAL/MOLE
NO EDGE SEAL	9%	~10K CAL/MOLE

EXTRACTION AT 70°C

	% SOLUBLE
CONTROL	100
CLOSED OVEN	100
UV/AIR	54
NO EDGE SEAL	59

RESULTS

FT-IR SPECTROSCOPIC ANALYSIS

- CLOSED OVEN, 105°C: Si—H STRETCH DISAPPEARING, NO CARBONYL FORMATION, TRACE HYDROXYL
- UV/AIR AT 105°C, 800 HRS: LOSS OF Si—H LARGE HYDROXYL PEAK, FORMATION OF CARBONYL

EXTRACTION

- PERCENT EXTRACTIBLES UNCHANGED= 0.4%
- NO CHANGE IN MOL. WT. OF EXTRACTIBLES

WEIGHT LOSS DATA

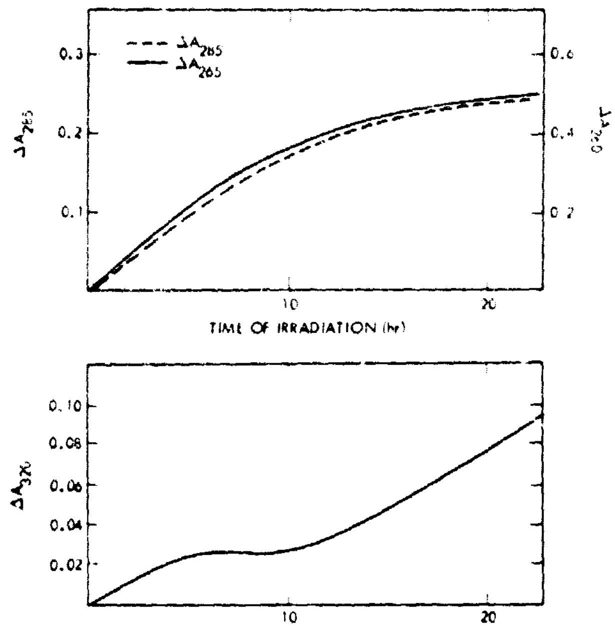
- CLOSED OVEN AT 105°C: 0.3% AT 800 HRS
- UV/AIR AT 105°C: 0.5% AT 800 HRS

TRANSMISSION CHANGE

- YELLOWING IN CLOSED OVEN, ACCELERATED UNDER UV/AIR E (ACTIVATION) 85° — 105° = 20K cal/MOLE

Photodegradation of PnBA

RATE OF ABSORBANCE CHANGE OF P-NBA AS
A FUNCTION OF IRRADIATING TIME



Development of Accelerated Test Chambers

- TESTS CONDUCTED ON WOOD SUBSTRATE MODULES: PREDICTED CELL CRACKING WITH CURRENT DESIGN
- IDENTIFIED NEW FAILURE MODE: CORROSION AT CRACK SITES: MAY BE RADIATION DRIVEN
- TWO TEST CHAMBERS CONSTRUCTED, TESTED, SHIPPED AND INSTALLED AT SPRINGBORN LABS

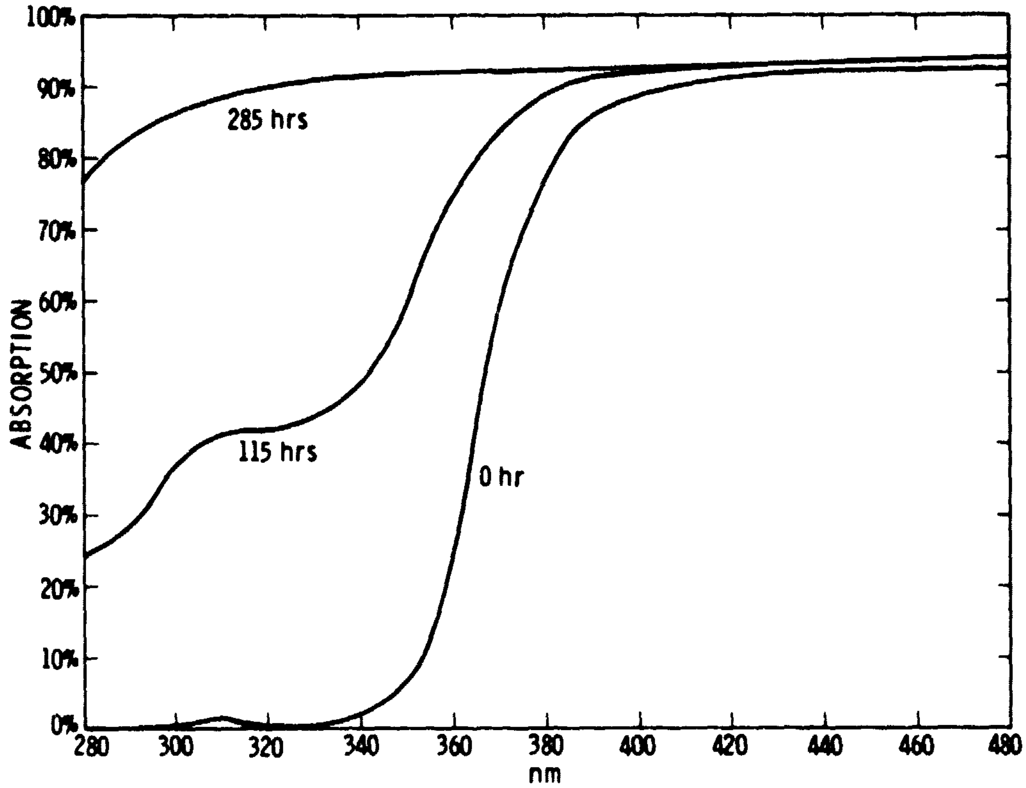
Photothermal and Photodegradation Of UV-Stabilized Front-Cover Films

PHOTOTHERMAL STUDIES OF 3M — ACRYLIC FILM

- AT ROOM TEMP STRAIN AT YIELD POINT WAS MEASURED TO BE 4.5 — 10% DEPENDING ON ORIENTATION

- AFTER 800 HRS. AT 85°C, SLIGHT TRANSMISSION GAIN (< 1%) AT 400 nm

Loss of UV Absorber From Korad at 85°C

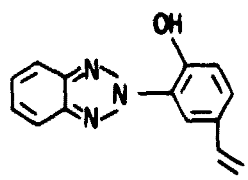


Material Modification Concepts

- CUT DOWN SYNERGISM (SENSITIZATION) THRU MORE RAPID DEACTIVATION OF UV ENERGY
- ATTACH UV ABSORBERS CHEMICALLY ON POLYMER CHAIN

NEW CANDIDATE

COPOLYMER OF MMA AND 5 VINYL TINUVIN



5 VINYL TINUVIN

PRODUCTION PROCESS AND EQUIPMENT AREA

TECHNOLOGY SESSION

Don Bickler, Chairman

MEPSDU planned activities presented by Solarex and Westinghouse (contracts awarded November, 1980) were critiqued by senior industry representatives. MEPSDU efforts are to demonstrate technology capable of manufacturing modules for $\$0.70/W_p$.

> The Solarex process uses 10 x 10-cm Semix polycrystalline wafers with spray-on front-junction formation, back-surface junction, spray-on AR coating, and electroless Ni contacts dipped in solder. The modules will be an EVA-laminated glass superstrate design.
>
> Westinghouse process uses 2.5 x 10-cm dendritic-web ribbons with diffused front junction, diffused back-surface junction, dip AR coating, and evaporated Ti/Pd/Cu-plated Cu contacts. Aluminum electrical interconnections will be ultrasonically welded to the cells. The modules will be an EVA-laminated glass superstrate design.
>
> Critiques indicated that backup activities should be implemented to offset potential problem areas when any are identified.

The near-term cost-reduction contracts resulted in the timely identification and demonstration of cost-effective process improvements, especially in automated cell interconnections and module assembly.

A computer program for cell metallization grid trade-off analyses is available. The program calculates cell power losses from series resistance and shading effects for various cell grid designs.

Analysis of non-mass-analyzed ion implantation indicates that it can be cost-competitive with gaseous diffused junction formation.

MEPSDU STATUS

JET PROPULSION LABORATORY

D.B. Bickler

- OPEN MINDED APPROACH USING PROCESSES FROM SEVERAL SOURCES
- BOTH USING CASSETTES WITH RECTANGULAR WAFERS
- BOTH REASONABLY WELL BALANCED PRODUCTION
- DEMONSTRATION AT RELATIVELY SMALL RATES (1 MW & 5 MW)
- BOTH HAVE EXPERIENCE WITH PROPOSED PROCESSES, MOSTLY LOW VOLUME
- PRELIMINARY DESIGN REVIEWS DUE IN MARCH 1981

Near-Term Cost-Reduction Contracts

- TIMELY IDENTIFICATION OF COST EFFECTIVE PROCESS IMPROVEMENTS
- AUTOMATED CELL INTERCONNECTING MOST COST EFFECTIVE
- SOME PROMISING TECHNOLOGIES IDENTIFIED WHICH ARE NOT YET FULLY DEVELOPED

Junction Formation

- PULSED ELECTRON BEAM ANNEALING MACHINE CONSTRUCTED AND READY FOR TESTING
- LASER ANNEALING DATA INDICATES THAT WITH DEVELOPMENT IT CAN BE EQUIVALENT TO PULSED ELECTRON ANNEALING.
- NON-MASS ANALYZED ION IMPLANTATION NOT ONLY FEASIBLE BUT PRACTICAL

Metallization

- MIDFILM PROCESSES DEVELOPED USING Ag; SAMPLES BEING PREPARED FOR ENVIRONMENTAL TEST
- BERND ROSS ASSOCIATES Cu BASED PRINTED METALLIZATION SHIFTING EMPHASIS FROM AgF FLUX TO TEFLON
- JPL COMPUTER PROGRAM FOR PARALLEL GRID TRADE OFFS IS AVAILABLE
- MOTOROLA GRID PATTERN ANALYSES USE "ACTUAL" METAL CROSS SECTION

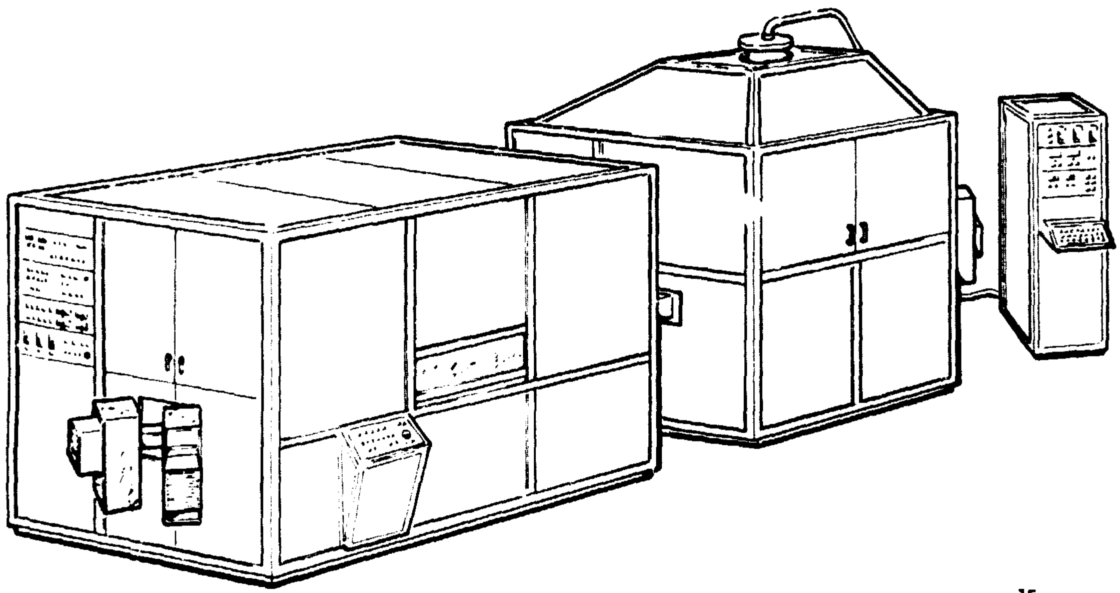
Assembly

- MB ASSOCIATES LAMINATION STATION IN FINAL STAGES OF ASSEMBLY
- JPL IN-HOUSE ASSESSING MEPSDU's FOR AUTOMATED MECHANICAL HANDLING
- SCIENCE APPLICATIONS DIFFUSE REFLECTION ANALYSIS INDICATES APPROXIMATELY 6% GAIN USING WHITE BACKGROUND ON STATE-OF-THE-ART MODULES

SOLAR CELL JUNCTION PROCESSING SYSTEM

SPIRE CORP.

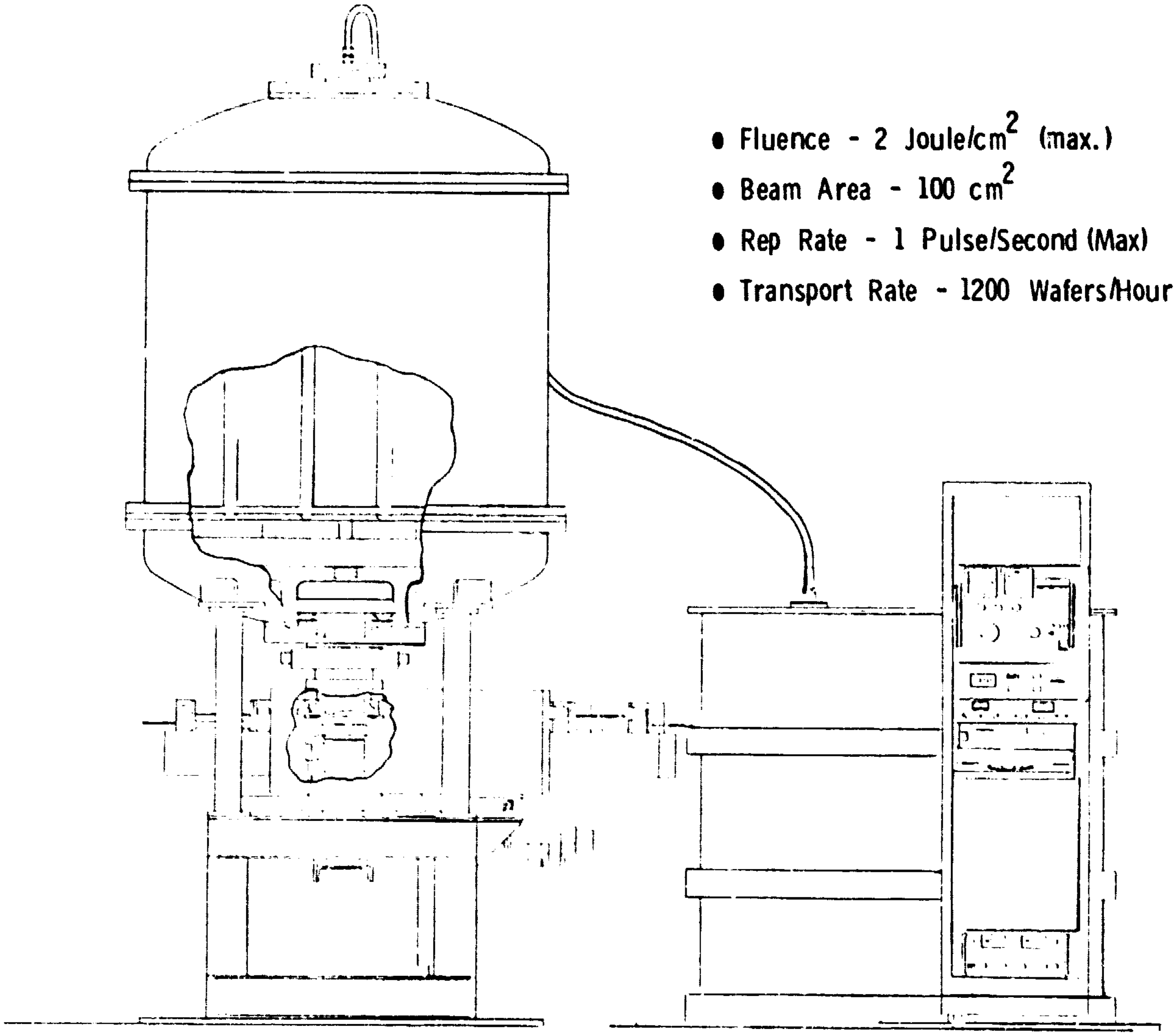
Solar Cell Junction Processor



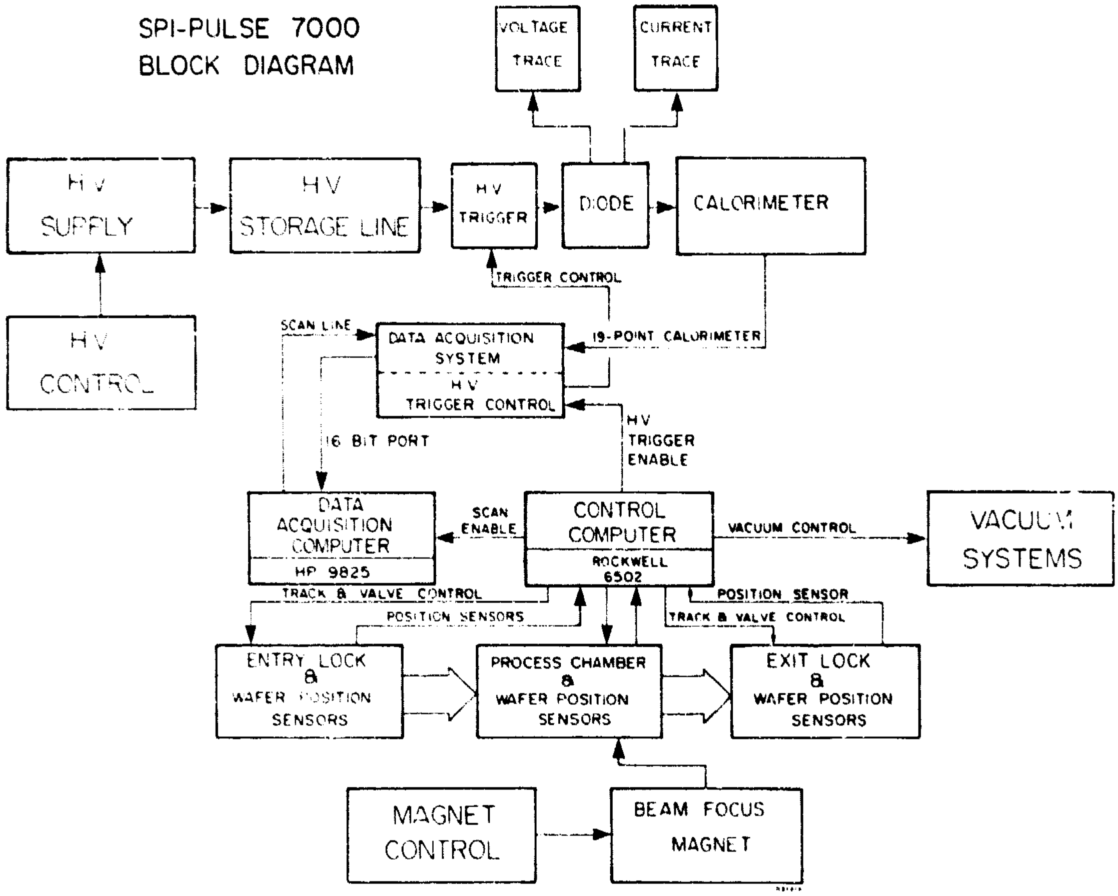
- P_{31} Implant @ 2.5×10^{15} - 1200 4" Wafers/Hour
- Pulse Anneal - Liquid Phase Epitaxy
- Cassette-to-Cassette

SPI-PULSE 7000 Pulse Annealer

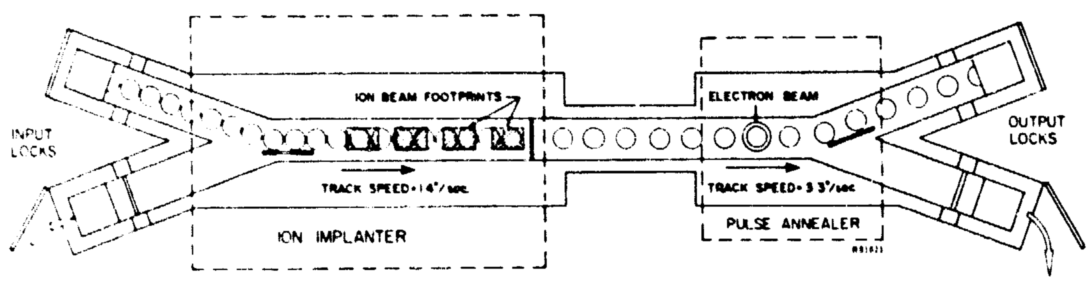
- Fluence - 2 Joule/cm^2 (max.)
- Beam Area - 100 cm^2
- Rep Rate - 1 Pulse/Second (Max)
- Transport Rate - 1200 Wafers/Hour



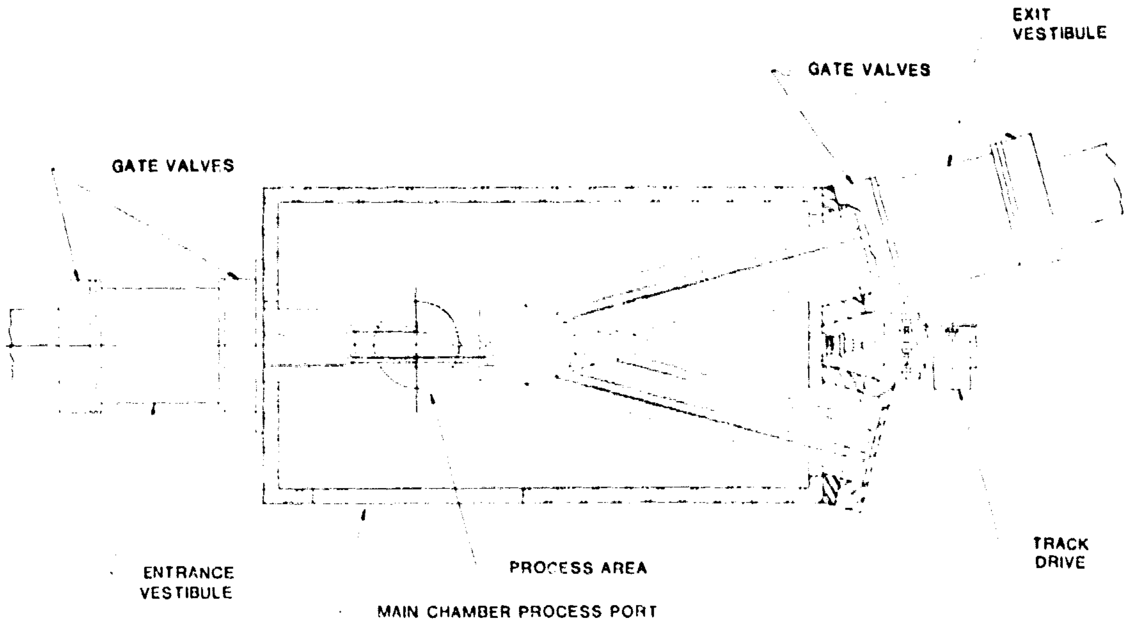
SPI-PULSE 7000 Block Diagram



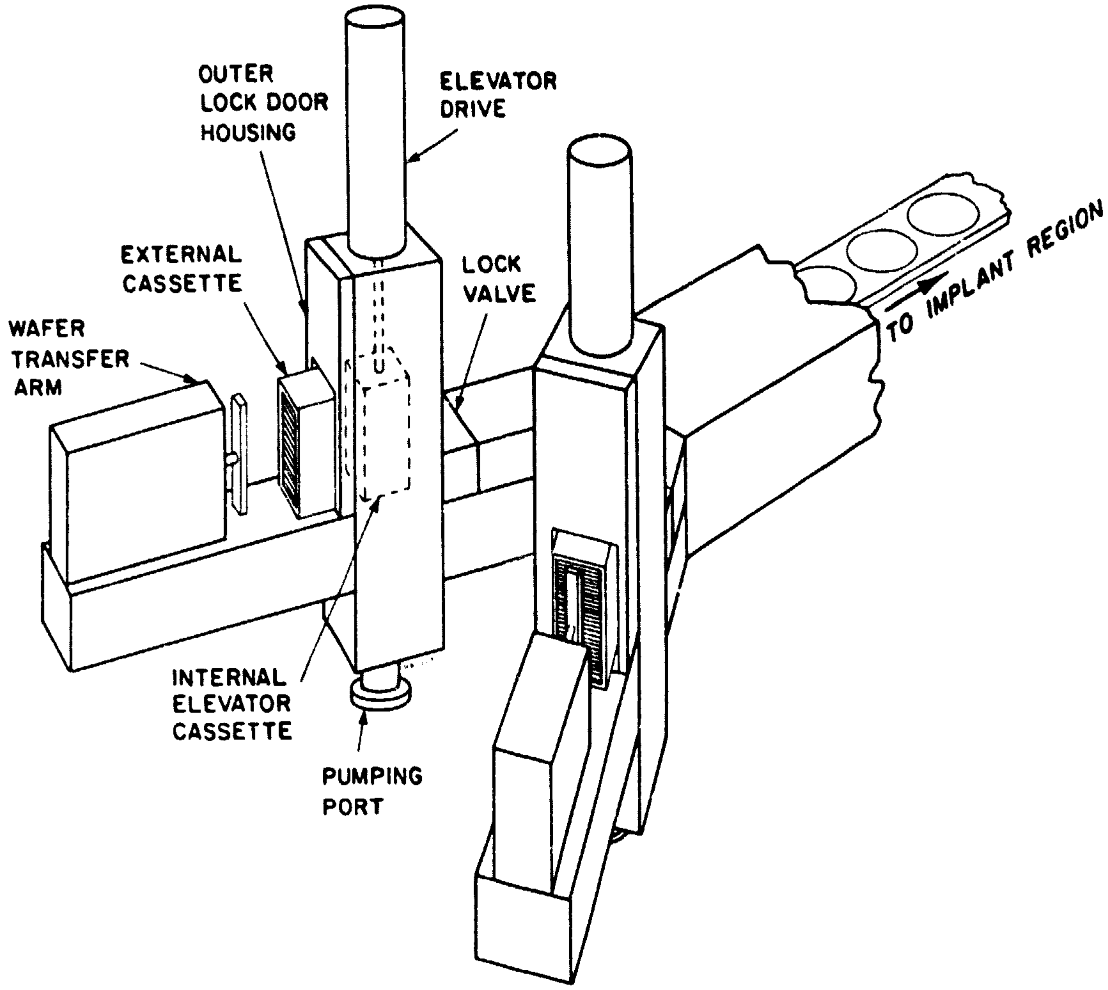
Layout of High-Speed Vacuum Transport



Process Chamber: Top View



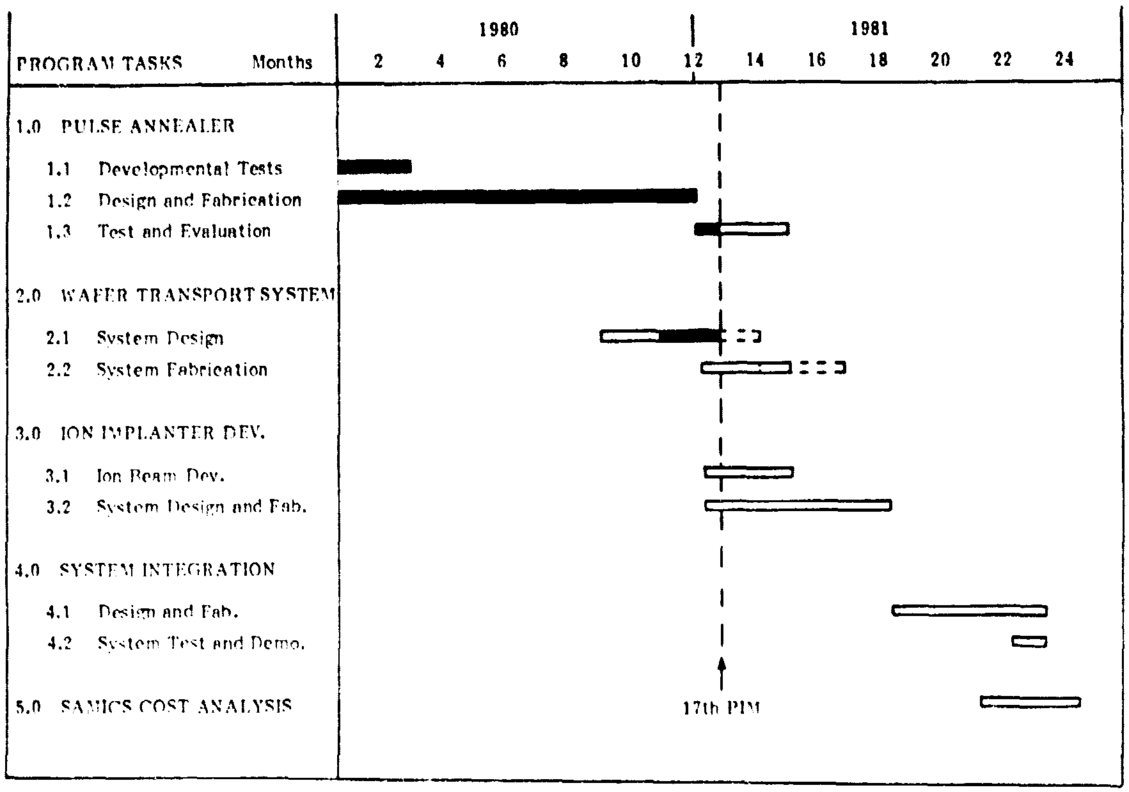
Y Track Cassette Input Locks



Junction Processor: Hardware Status

1. ELECTRON BEAM PULSER
   - All Hardware Fabricated
   - Assembly Almost Completed
   - Control/Transport System Operational
   - HV Checkout Next Week
   - Anneal Development in March
2. WAFER TRANSPORT SYSTEM
   - Pulser Portion Completed
   - Ion Implanter Track Being Designed
   - Cassette Elevators Design Complete
3. ION IMPLANTER
   - Concept Determined
   - Design to Begin in 1-2 Months

Development of Junction Processing Equipment



LASER ANNEALING FOR ION-IMPLANTED JUNCTIONS

LOCKHEED MISSILES & SPACE CO. INC.

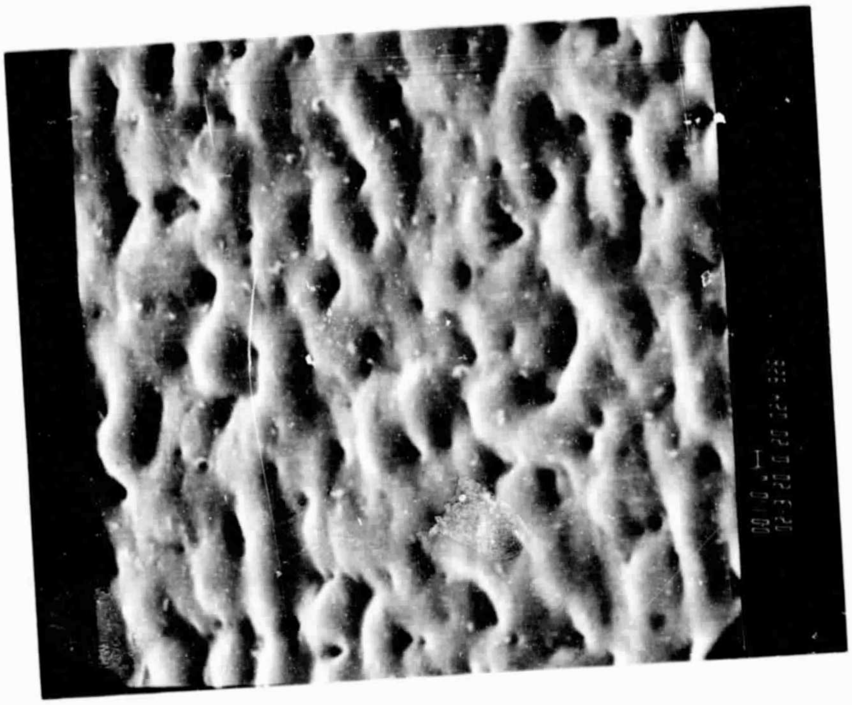
2 x 4 cm Cell Processing Variations and Results

WAFER SURFACE CONDITIONS	ION IMPLANTATION LEVELS		SCREEN AL BSF	LASER ENERGY DENSITY (J/cm^2)		QTY CELLS	MEAN VALUES			
	FRONT - ^{31}P	BACK - ^{11}B ①/BF_2 ②		FRONT	BACK		Voc(mV)	Isc(mA)	CFF(%)	η(%)
CHEM-POLISHED PO-5	5 KEV, 2.5×10^{15}	–	–	1.2	–	5	499	267	72.5	12.2
CHEM-POLISHED PO-5	5 KEV, 2.5×10^{15}	–	–	1.5	–	3	538	256	73.0	12.6
CHEM-POLISHED PO-10	10 KEV, 2.5×10^{15}	–	–	1.2	–	6	539	253	77.4	13.2
CHEM-POLISHED PO-10	10 KEV, 2.5×10^{15}	–	–	1.5	–	3	546	258	78.4	13.8
FLASH-ETCHED FE-5	5 KEV, 2.5×10^{15}	–	–	1.2	–	4	474	262	71.9	11.2
FLASH-ETCHED FE-5	5 KEV, 2.5×10^{15}	–	–	1.5	–	4	520	265	70.2	12.2
FLASH-ETCHED FE-10	10 KEV, 2.5×10^{15}	–	–	1.2	–	2	518	247	76.2	12.1
FLASH-ETCHED FE-10	10 KEV, 2.5×10^{15}	–	–	1.5	–	2	536	253	73.9	12.6
TEXTURE ETCHED TE 10	10 KEV, 4×10^{15}	–	–	1.2	–	6	463	257	60.7	9.0
TEXTURE ETCHED TE 10	10 KEV, 4×10^{15}	–	–	1.5	–	7	512	246	68.3	10.8
WITH BSF:										
CHEM-POLISHED PO5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.2	PEBA	5	497	265	71.3	11.8
CHEM-POLISHED PO5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA	4	542	264	76.6	13.8
CHEM-POLISHED PO5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA + LASER 1.9	4	567	276	73.9	14.5
CHEM-POLISHED PO10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.2	PEBA	5	541	255	76.6	13.2
CHEM-POLISHED PO10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA	2	553	251	78.1	13.5
CHEM-POLISHED PO10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA + LASER 1.9	4	562	259	74.6	13.6
FLASH-ETCHED FE5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.2	PEBA ONLY	3	472	265	68.3	10.7
FLASH-ETCHED FE5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.5	PEBA ONLY	5	529	264	73.[illegible]	12.8
FLASH-ETCHED FE5-BSF	5 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.5	PEBA + LASER 1.9	3	539	270	73.3	13.3
FLASH-ETCHED FE10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.2	PEBA ONLY	5	541	255	76.6	13.2
FLASH-ETCHED FE10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.5	PEBA ONLY	2	553	251	78.1	13.5
FLASH-ETCHED FE10-BSF	10 KEV, 2.5×10^{15}	25 KEV, 5×10^{15}, ①+②	–	1.5	PEBA + LASER 1.9	4	563	259	74.6	13.6
TEXTURE ETCHED TE10-BSF	10 KEV, 4×10^{15}	25 KEV, 5×10^{15}, ②	–	1.2	PEBA ONLY	4	483	247	66.2	9.9
TEXTURE ETCHED TE10-BSF	10 KEV, 4×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA ONLY	2	538	239	76.8	12.4
TEXTURE ETCHED TE10-BSF	10 KEV, 4×10^{15}	25 KEV, 5×10^{15}, ②	–	1.5	PEBA + LASER 1.9	4	532	242	72.5	11.7
CHEM-POLISHED PO5-BSF	5 KEV, 2.5×10^{15}	–	✓	1.5	–	2	583	281	75.1	15.4
CHEM-POLISHED PO10-BSF	10 KEV, 2.5×10^{15}	–	✓	1.5	–	5	577	270	76.2	14.8
FLASH-ETCHED FE5-BSF	5 KEV, 2.5×10^{15}	–	✓	1.5	–	2	553	272	70.5	13.3
FLASH-ETCHED FE10-BSF	10 KEV, 2.5×10^{15}	–	✓	1.5	–	3	574	276	73.0	14.4

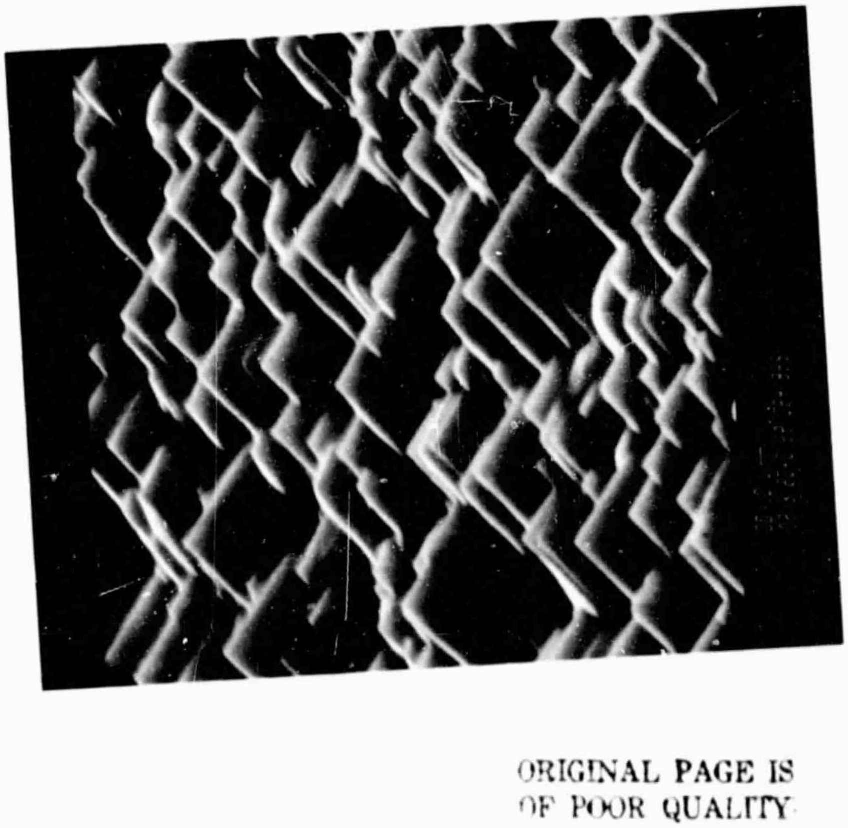
2 x 4 cm Cells Ranked by Conversion Efficiencies

Rank	Conversion Eff. Grouping		Cell Process Configuration
1	15%	15.4	Chem-Pol, 5 KeV, LA*@1.5J, AL-BSF
2	14%	14.8	Chem-Pol, 10 KeV, LA @ 1.5J, AL-BSF
		14.5	Chem-Pol, 5 KeV, LA@1.5J, BSF w/PEBA + Laser
		14.4	Flash Etch, 10 KeV, LA@1.5J, AL-BSF
3	13%	13.8	Chem-Pol, 10 KeV, LA@1.5J, No BSF
		13.8	Chem-Pol, 5 KeV, LA@1.5J, BSF w/PEBA only
		13.6	Flash Etch, 10 KeV, LA@1.5J, BSF w/PEBA + Laser
		13.6	Chem-Pol, 10 KeV, LA@1.5J, BSF w/PEBA + Laser
		13.5	Chem-Pol, 10 KeV, LA@1.5J, BSF w/PEBA only
		13.5	Flash Etch, 10 KeV, LA@1.5J, BSF w/PEBA only
		13.3	Flash Etch, 5 KeV, LA@1.5J, AL-BSF
		13.3	Flash Etch, 5 KeV, LA@1.5J, BSF w/PEBA + Laser
		13.2	Flash Etch, 10 KeV, LA@1.2J, BSF w/PEBA only
		13.2	Chem-Pol, 10 KeV, LA@1.2J, No BSF
		13.2	Chem-Pol, 10 KeV, LA@1.2J, BSF w/PEBA only
4	12%	12.8	Flash Etch, 5 KeV, LA@1.5J, BSF w/PEBA only
		12.6	Chem-Pol, 5 KeV, LA@1.5J, No BSF
		12.6	Flash Etch, 10 KeV, LA@1.5J, No BSF
		12.4	Text Etch, 10 KeV, LA@1.5J, No BSF
		12.2	Chem-Pol, 5 KeV, LA@1.2J, No BSF
		12.2	Flash Etch, 5 KeV, LA@1.5J, No BSF
		12.1	Flash Etch, 10 KeV, LA@1.2J, No BSF
5	11%	11.8	Chem-Pol, 5 KeV, LA@1.2J, BSF w/PEBA only
		11.7	Text Etch, 10 KeV, LA@1.5J, BSF w/PEBA + Laser
		11.2	Flash Etch, 5 KeV, LA@1.2J, No BSF
6	9 & 10%	10.8	Text Etch, 10 KeV, LA@1.5J, No BSF
		10.7	Flash Etch, 5 KeV, LA@1.2J, BSF w/PEBA
		9.9	Text Etch, 10 KeV, LA@1.2J, BSF w/PEBA
		9.0	Text Etch, 10 KeV, LA@1.2J, No BSF

* Laser Annealed

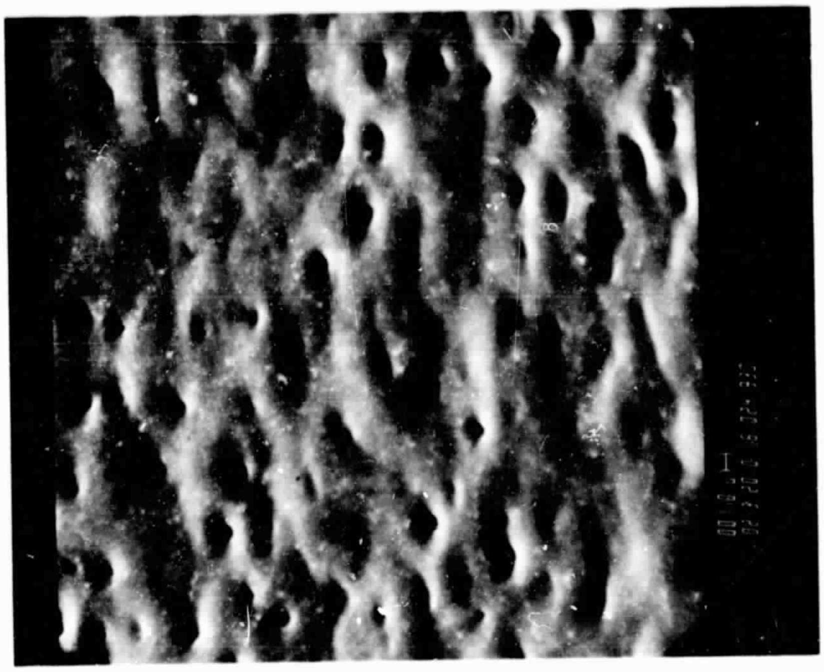


Pulsed Laser Annealed 1.2 J/cm^2

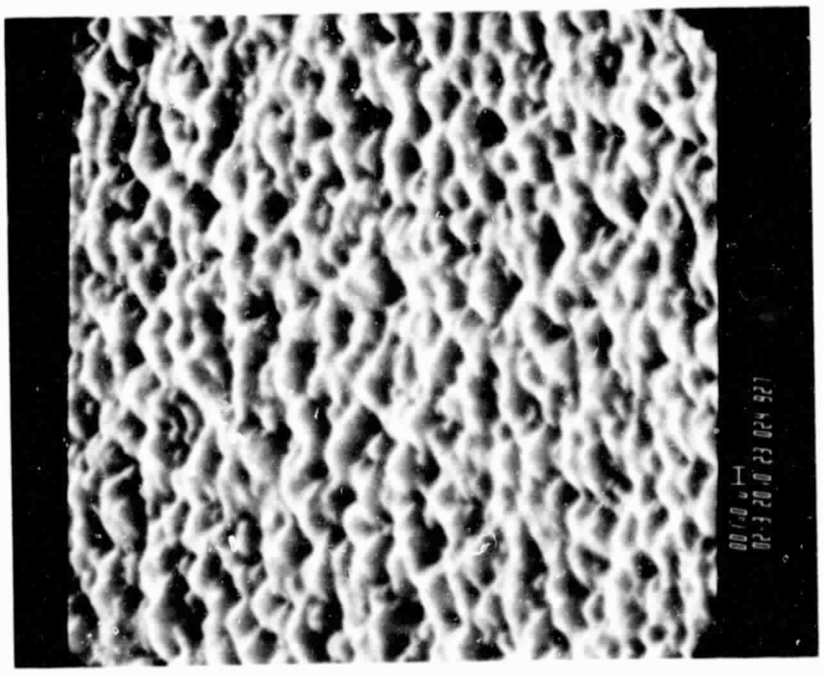


As Implanted, ^{31}P

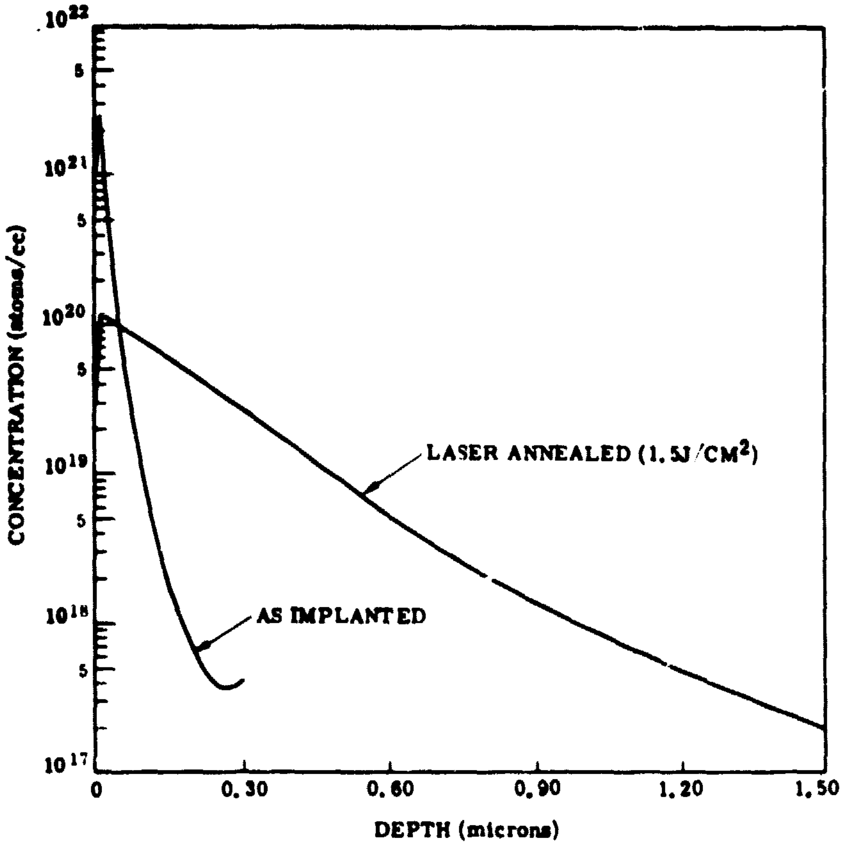
Ion-Implanted BF_2 BSF-PEBA/Laser



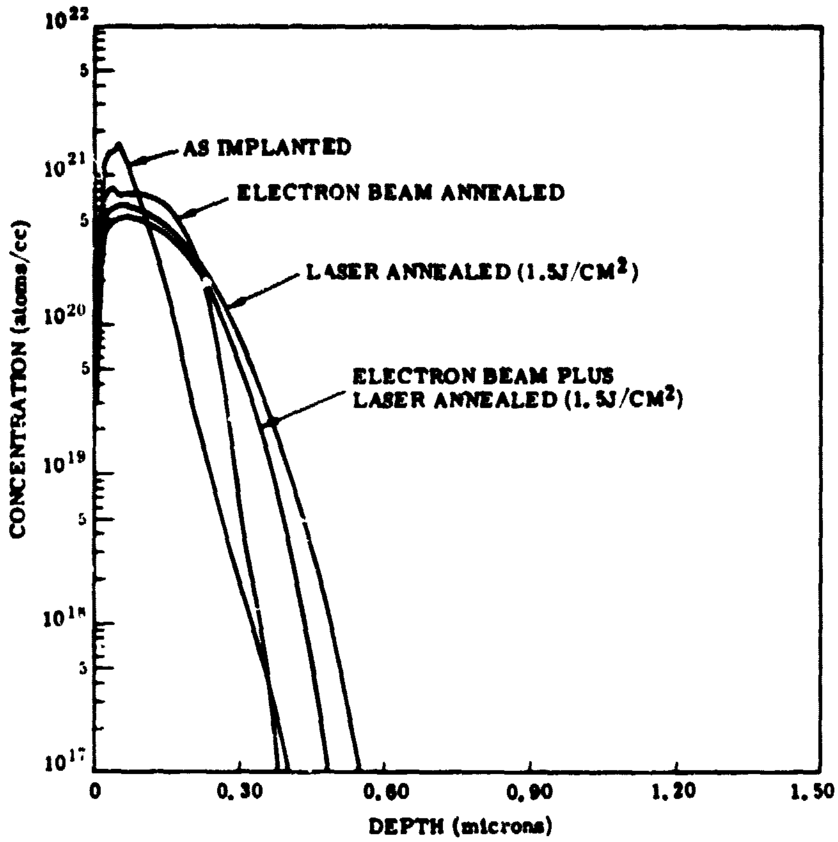
Ion-Implanted BF_2 BSF-PEBA



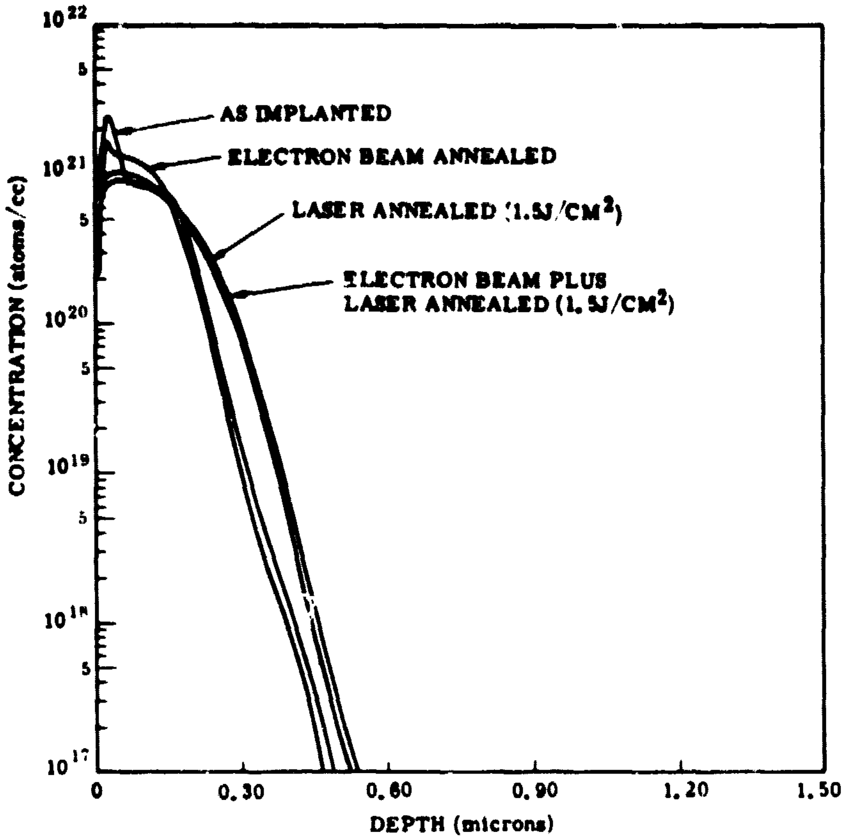
SIMS Profile of Phosphorus in Texture-Etched Silicon



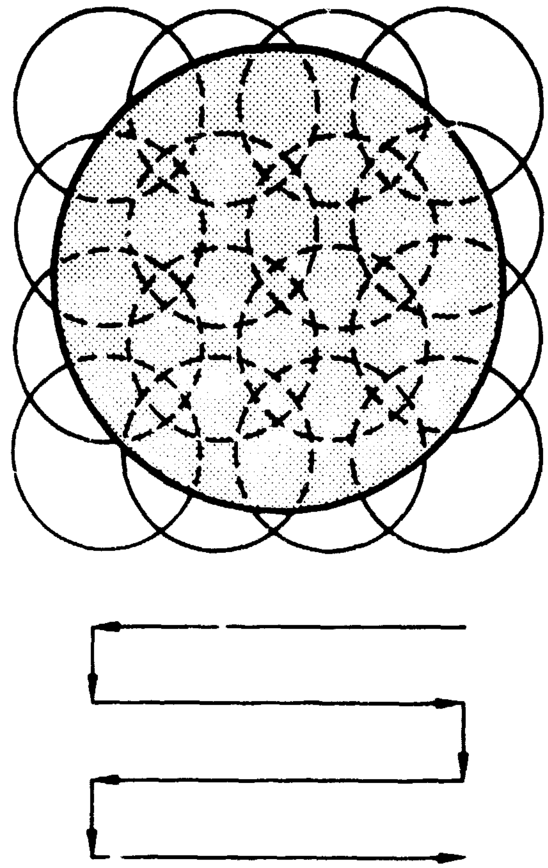
SIMS Profile of Boron in Chem-Polished Silicon



SIMS Profile of Boron in Flash-Etched Silicon



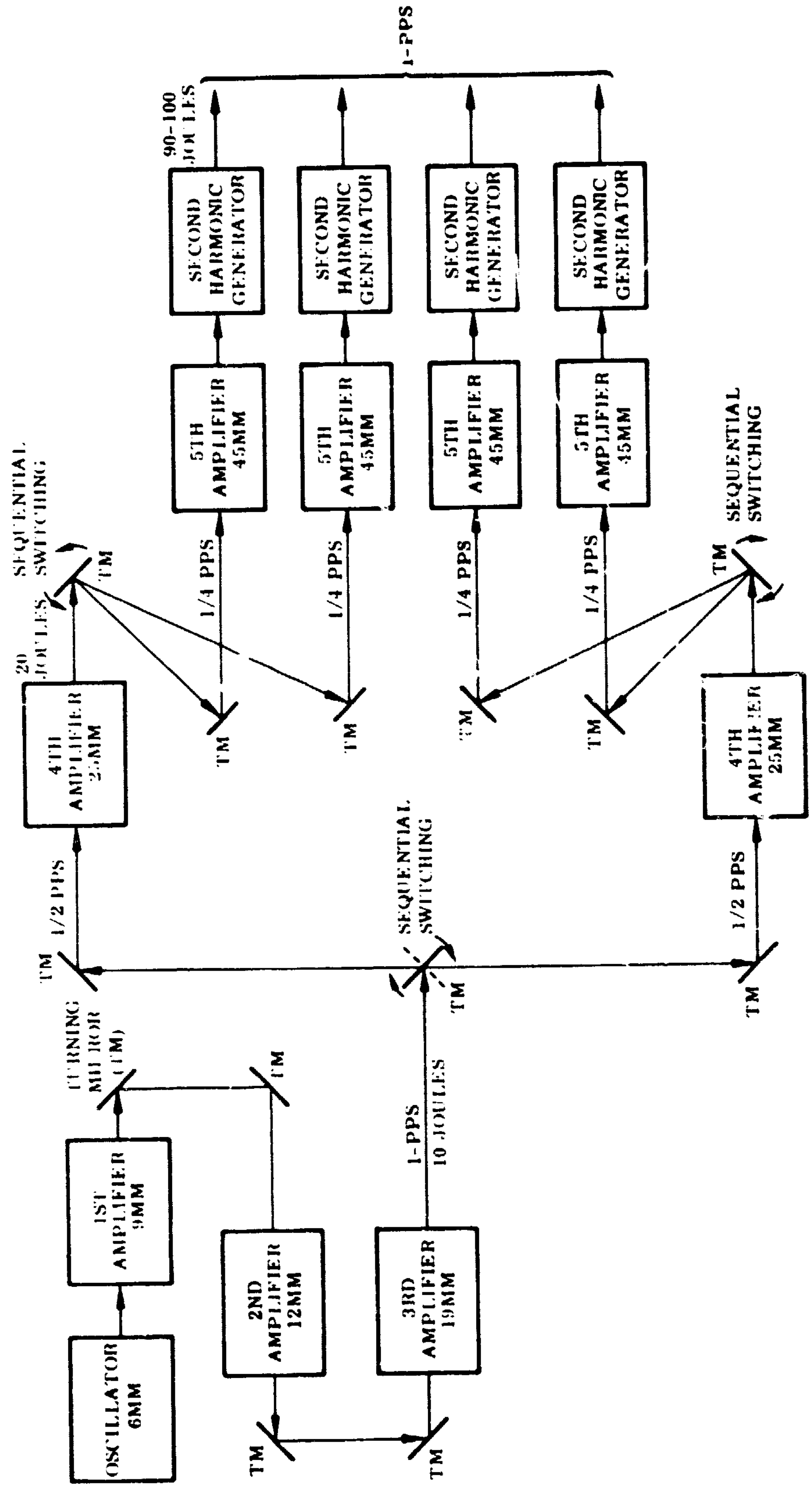
Scan Pattern for Annealing 3-in.-dia Wafer



Process Verification: 2 x 2 cm Cells

Cell Type	BSF	Laser Pulse 1.5J/cm^2	Best Values				Qty.
			Voc (mV)	Isc (mA)	CFF (%)	η (%)	
Chem Polished, 5 KeV, 2.5 x 10^{15}/cm^2	-	Single	550	133	77	14.3	16
	-	Multi	550	135	77	14.2	8
	X	Single	588	143	73	15.4	19
	X	Multi	584	141	73	15.1	6
Chem Polished, 10 KeV, 2.5 x 10^{15}/cm^2	-	Single	546	131	79	14.3	12
	-	Multi	546	126	76	13.2	5
	X	Single	584	134	74	14.6	11
	X	Multi	584	133	74	14.5	4
Flash Etched, 5 KeV, 2.5 x 10^{15}/cm^2	-	Single	544	133	77	14.1	11
	-	Multi	544	132	75	13.5	4
	X	Single	578	139	71	14.4	14
	X	Multi	576	135	74	14.5	3
Flash Etched, 10 KeV, 2.5 x 10^{15}/cm^2	-	Single	550	131	78	14.1	13
	-	Multi	546	128	76	13.5	4
	X	Single	584	137	75	15.3	12
	X	Multi	580	137	71	14.6	4
Re-implanted:							
5 KeV, 2.5 x 10^{15}/cm^2	-	Single	546	129	76	13.2	7
	-	Multi	548	128	76	13.3	4
10 KeV, 2.5 x 10^{15}/cm^2	-	Single	554	127	77	13.9	7
	-	Multi	554	127	74	13.2	6
Furnace Annealed:							
5 KeV, 2.5 x 10^{15}/cm^2	-	---	546	135	78	13.9	5
	-	---	582	137	74	14.9	5

Nd: Glass Laser for 1-PPS Application



Conclusions

- TEXTURE ETCHED SILICON SURFACES ARE NOT COMPATIBLE WITH PULSED LASER ANNEALING PROCESSING.
- IMPLANTATION/PULSE ANNEALING PARAMETERS FOR A BACK SURFACE FIELD FORMATION REQUIRE FURTHER DEVELOPMENT TO OPTIMIZE PERFORMANCE.
- SCREENED AND FIRED ALUMINUM PASTE FOR A BACK SURFACE FIELD FORMATION YIELD ACCEPTABLE PERFORMANCE IN COMBINATION WITH FRONT IMPLANT/LASER ANNEALED DEVICES.
- A HIGH THROUGHPUT PULSED LASER SYSTEM TO ACCOMMODATE SINGLE PULSE ANNEALING OF THREE (3) INCH DIAMETER WAFERS AT A RATE OF ONE (1) PER SECOND APPEARS FEASIBLE.

NON-MASS-ANALYZED ION IMPLANTS

CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

D.J. Fitzgerald

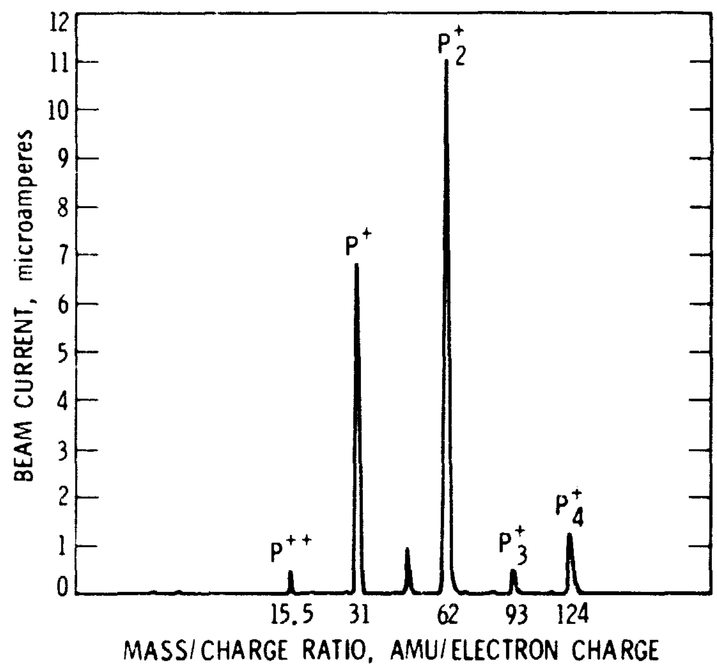
PURPOSE

- INCREASE THROUGHPUT (BEAM CURRENT)
- REDUCE COMPLEXITY (COST)
- IMPROVE PRODUCTION EFFICIENCY (POWER/MASS FLOW)

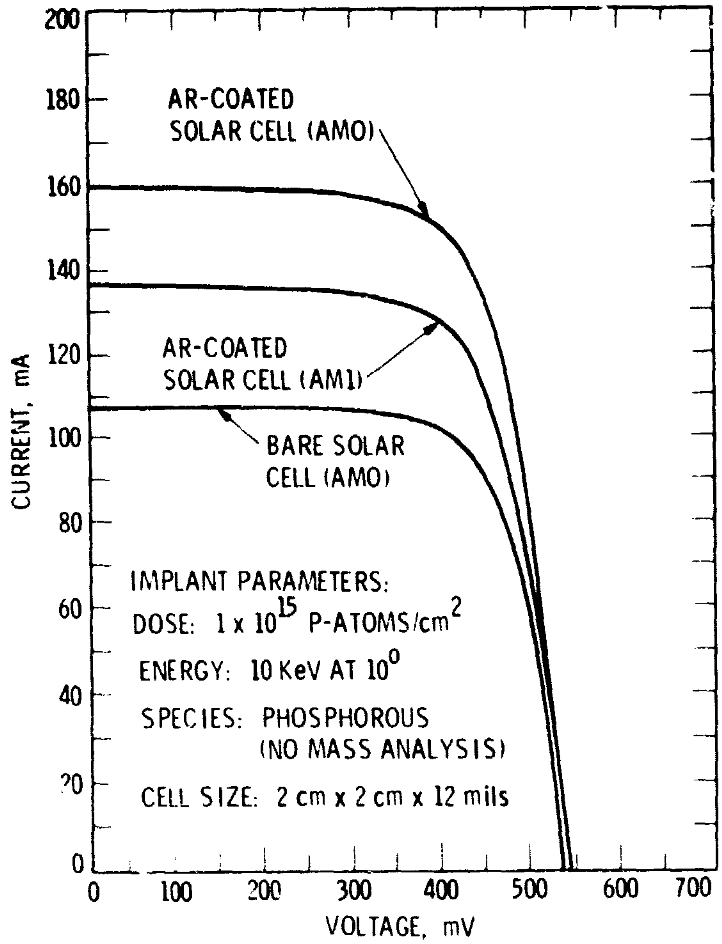
APPROACH

- STUDY MOLECULAR PHOSPHOROUS/CONTAMINANT EFFECTS WITH MASS ANALYSIS (CALTECH)
- PERFORM DIRECT IMPLANTS WITHOUT MASS ANALYSIS (JPL)

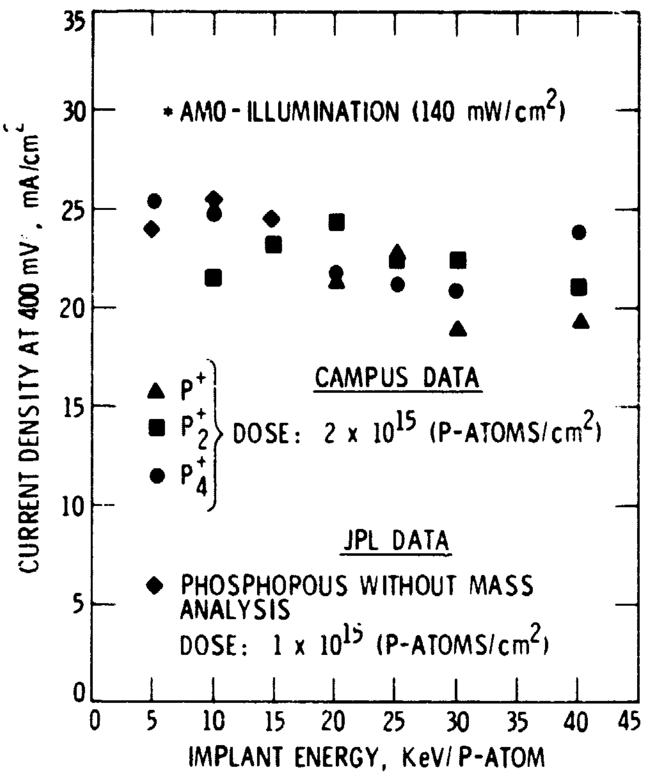
Mass Spectrum From Solid Red Phosphorus Source



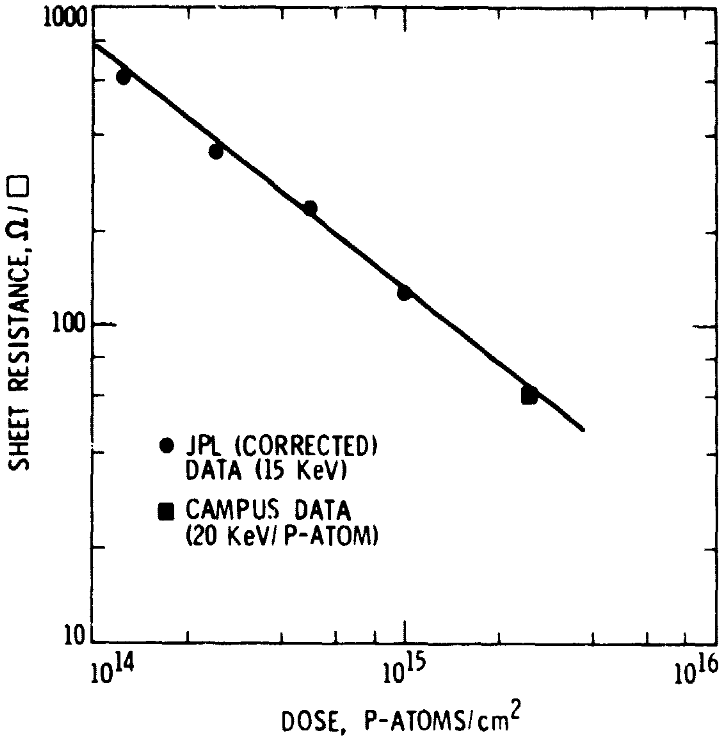
I-V Characteristics



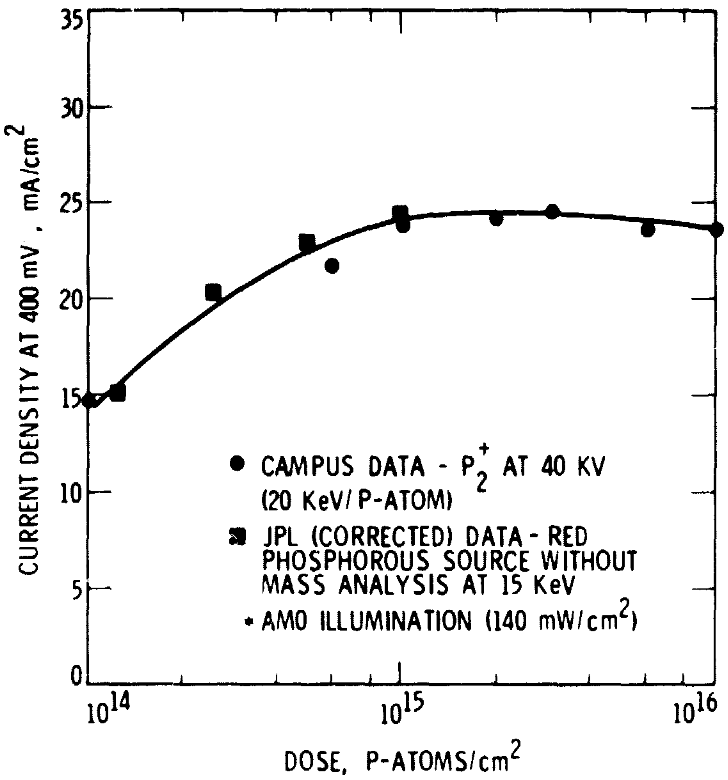
Effect of Implant Energy and Molecular Species on Power Output



Effect of Dose on Sheet Resistance



Effect of Dose on Power Output



Results

- SOLAR CELL JUNCTIONS MADE WITH PHOSPHOROUS W/O MASS ANALYSIS
- NON-MASS-ANALYZED IMPLANT HAVE COMPARABLE PERFORMANCE
- POWER OUTPUT INSENSITIVE TO DOSE >2.5 (10^{15}) ATOMS/CM^2
- SMALL INCREASE IN POWER OUTPUT AT LOWER IMPLANT ENERGY

Conclusions

- ION IMPLANTED JUNCTIONS W/O MASS ANALYSIS IS FEASIBLE
- DOSE UNIFORMITY REQUIREMENTS MAY BE RELAXED ABOVE 2.5 (10^{15}) ATOMS/CM^2
- RELATIVELY LOW VOLTAGE IMPLANTS DESIREABLE $\leq$ 5 KV
- ION THRUSTER/MILLING TECHNOLOGY USABLE FOR CELL IMPLANTS

HIGH-RESOLUTION, LOW-COST CONTACT DEVELOPMENT (MIDFILM)

SPECTROLAB INC.
Alec Garcia

Program Tasks

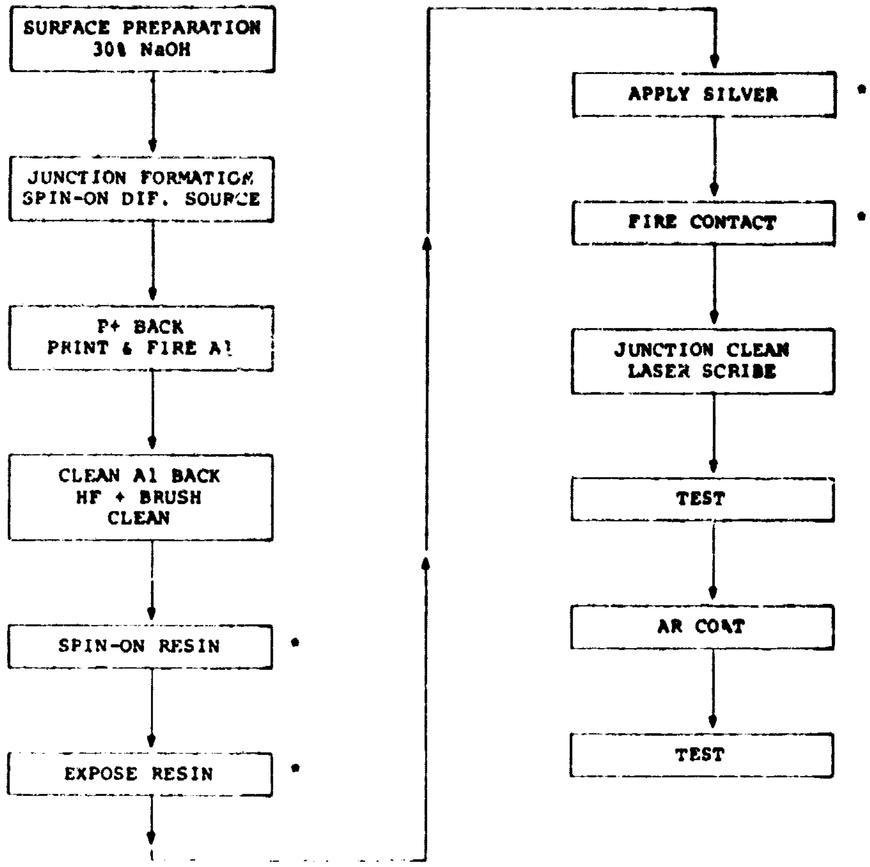
I. ESTABLISH MIDFILM PROCESS AT SPECTROLAB

II. FABRICATION OF MODULES

III. ENVIRONMENTAL TEST

IV. ALTERNATE MATERIALS

Midfilm Process Sequence



*These steps are the MIDFILM photolithographic technique for producing front contacts.

Exposure System

- Mercury Vapor Lamp ~ 1000 Watts
- Collimating Lens
- 10 Seconds Exposure

Powder Firing Parameters

- No Dry

- Pre-Fire at 575°C, 24"/Min., 18"

  -- Remove Organics

- Fire at 675°C, 36"/Min., 18"

  -- Sinter Silver

24 in. per min., No AR Coating

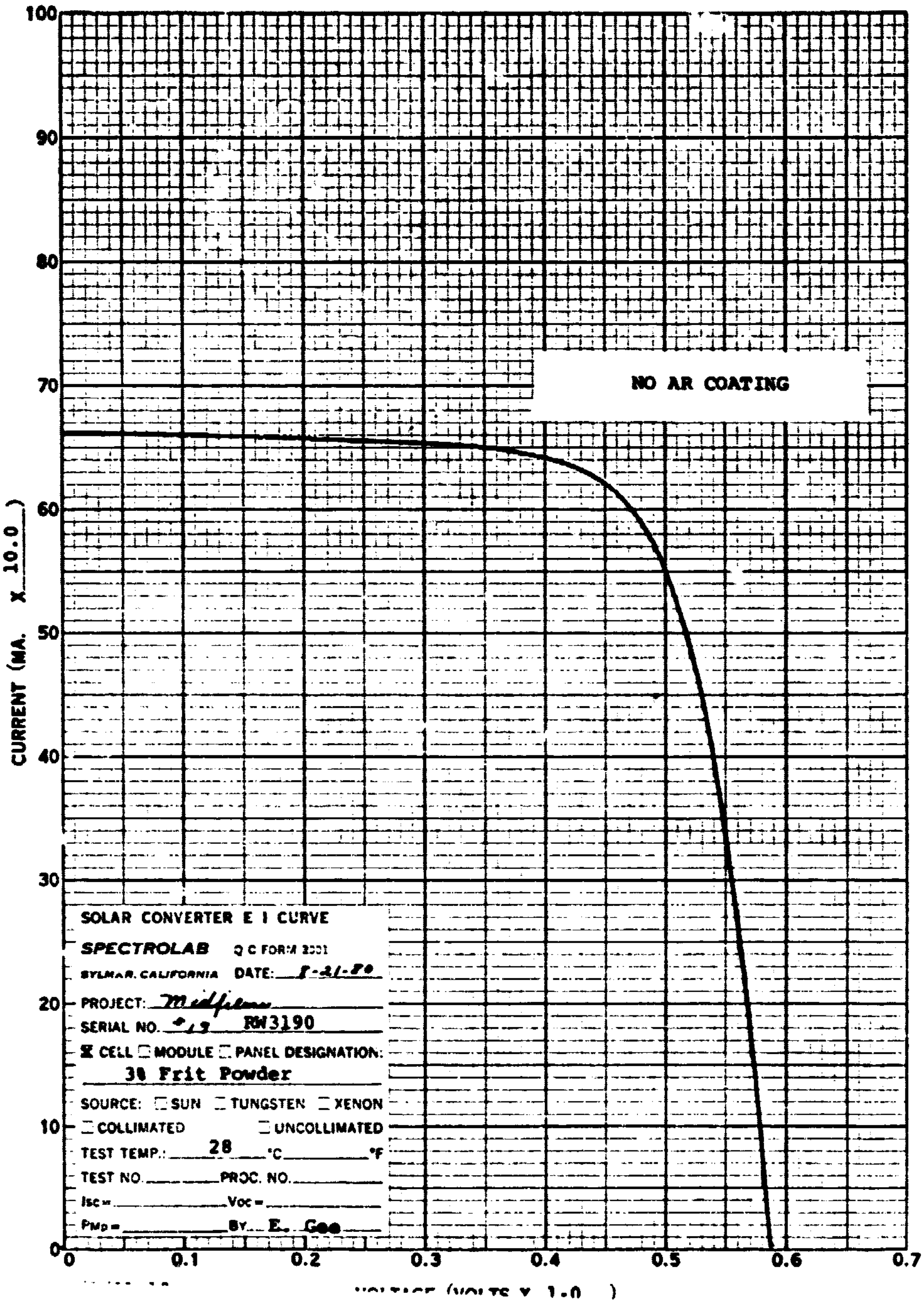
Cell #	V_{oc}	I_{sc}	I_{500}	η_{500}
2	596	639	559	10.0
22	596	628	534	9.5
21	593	621	545	9.7
36	597	642	574	10.3
24	595	626	543	9.7
13	594	633	553	9.9
23	596	615	528	9.4
14	594	610	525	9.4
17	596	623	552	9.9
15	596	639	567	10.1
16	598	647	581	10.4
19	597	633	547	9.8
27	597	644	552	9.9
20	595	613	541	9.7
34	596	625	563	10.1
18	595	640	472	8.4
33	599	661	592	10.6
26	594	612	526	9.4
32	595	635	538	9.6
30	596	628	553	9.9
25	596	614	544	9.7
35	600	661	570	10.2
28	598	660	581	10.4
Average	596	632.6	549.6	9.8
Standard Deviation	1.7	15.5	20.9	

Yield: 23 of 25 - 92%

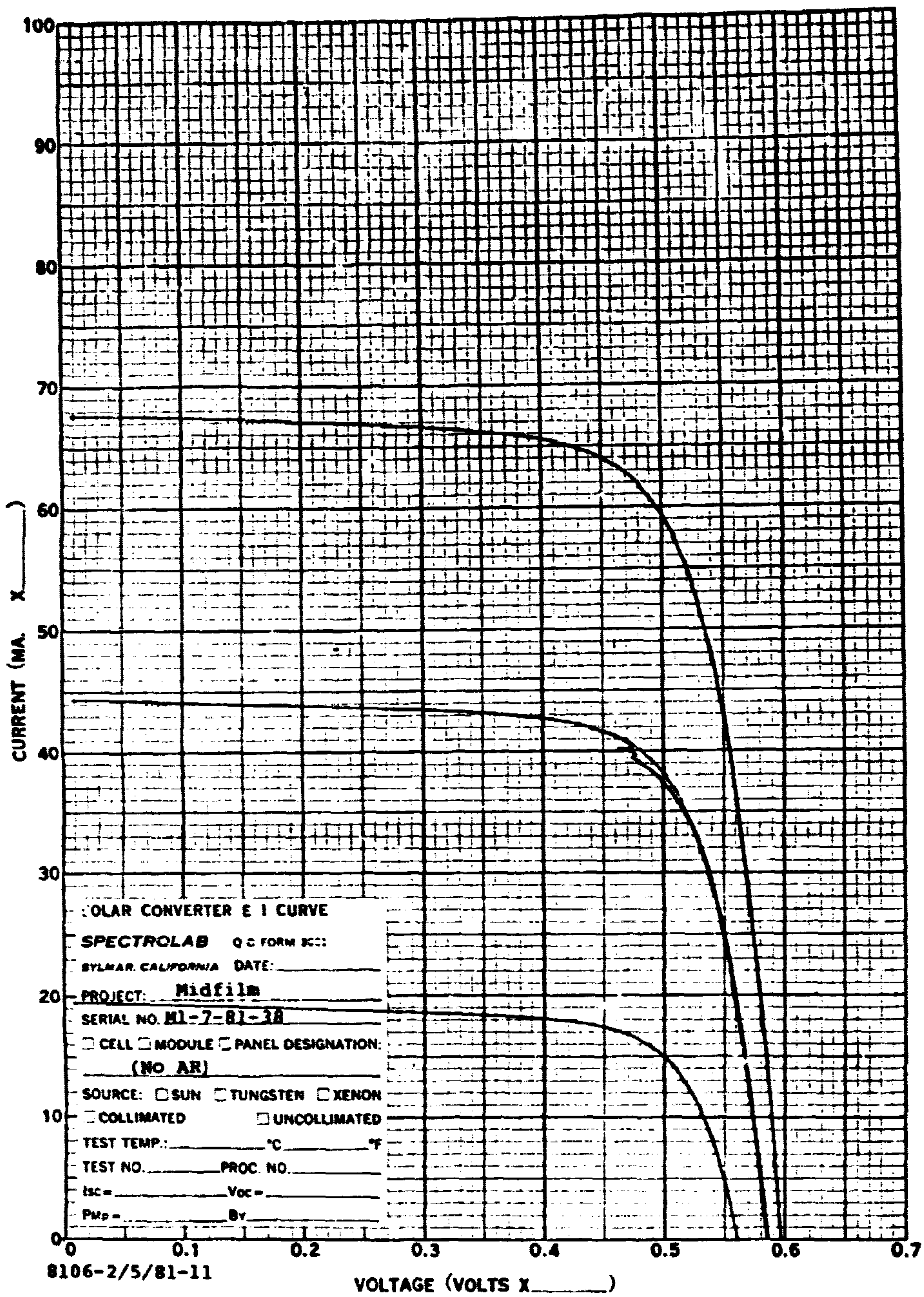
Soldering Results: 45° Pull Test

PARAMETER	AVERAGE PULL STRENGTH	NOTES
1 SEC., 340°C	283 GRAMS	ONE CELL TAB HAD NO STRENGTH
1 SEC., 370°C	643 GRAMS	ALL CELLS AT LEAST 500 GRAMS
1 SEC., 400°C	531 GRAMS	ALL CELLS AT LEAST 375 GRAMS

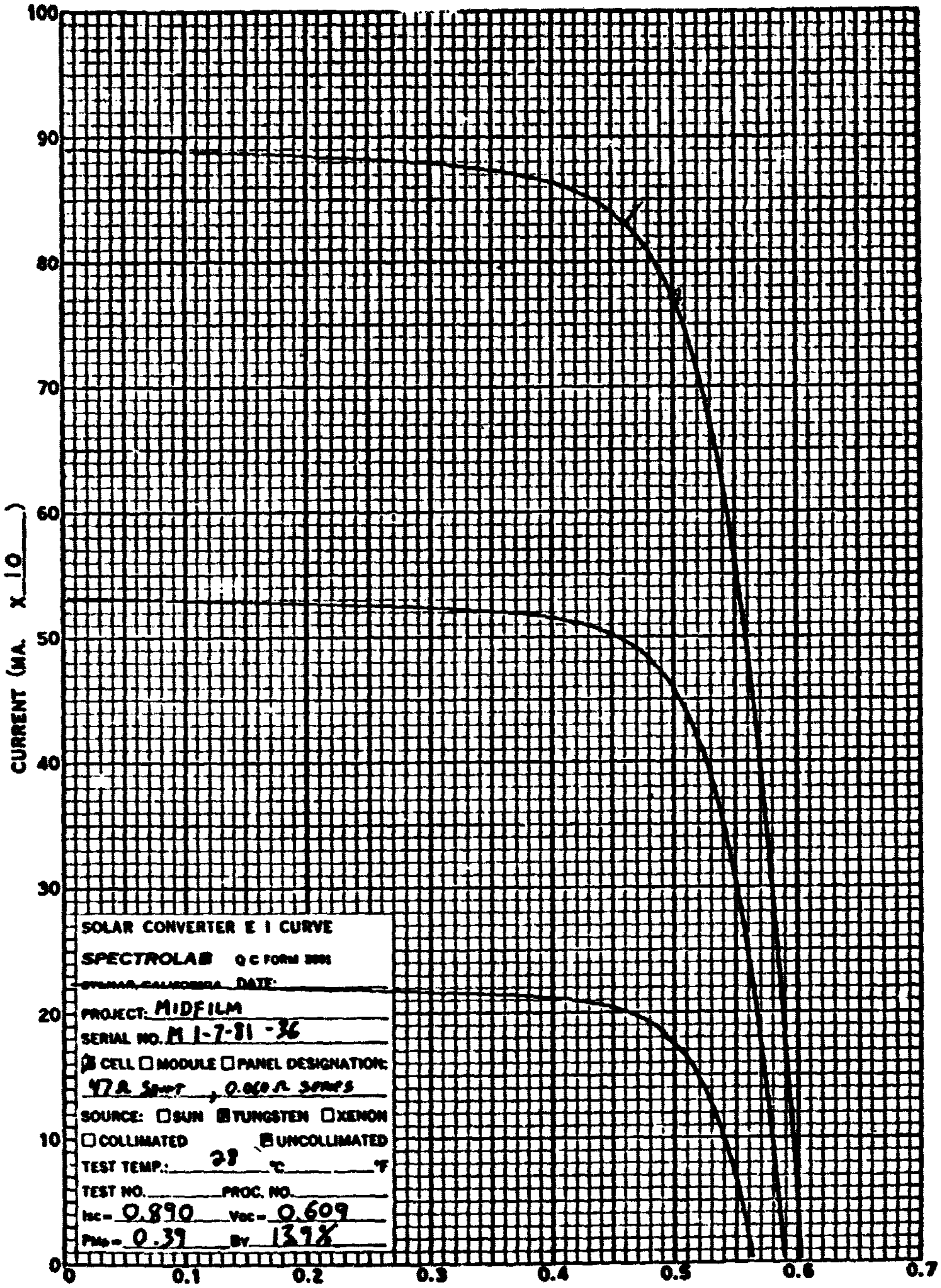
5 CELLS WERE TESTED IN EACH GROUP.


NO AR COATING
CURRENT (MA. X 10.0)
VOLTAGE (VOLTS X 1.0)
SOLAR CONVERTER E I CURVE
SPECTROLAB Q C FORM 2001
SYLMAR, CALIFORNIA DATE: 8-21-80
PROJECT: Midfilms
SERIAL NO. #19 RW3190
CELL MODULE PANEL DESIGNATION:
3# Frit Powder
SOURCE: SUN TUNGSTEN XENON
COLLIMATED UNCOLLIMATED
TEST TEMP.: 28 °C °F
TEST NO. PROC. NO.
Isc = Voc =
PMP = BY E. Gee

C-4



100
90
80
70
60
50
40
30
20
10
0
CURRENT (MA. X_____)
:OLAR CONVERTER E I CURVE
SPECTROLAB Q C FORM
SYLMAR, CALIFORNIA DATE:
PROJECT: Midfilm
SERIAL NO. M1-7-81-38
CELL MODULE PANEL DESIGNATION:
(NO AR)
SOURCE: SUN TUNGSTEN XENON
COLLIMATED UNCOLLIMATED
TEST TEMP.: °C °F
TEST NO. PROC. NO.
Isc = Voc =
PMP = BY
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
8106-2/5/81-11
VOLTAGE (VOLTS X_____)


CURRENT (mA. x 10)
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
SOLAR CONVERTER E I CURVE
SPECTROLAB Q C FORM
DATE:
PROJECT: MIDFILM
SERIAL NO. M 1-7-81 -36
CELL MODULE PANEL DESIGNATION:
SOURCE: SUN TUNGSTEN XENON
COLLIMATED UNCOLLIMATED
TEST TEMP.: 28 °C °F
TEST NO. PROC. NO.
Isc- 0.890 Voc- 0.609
BY 13.9%

8106-2/5/81-12

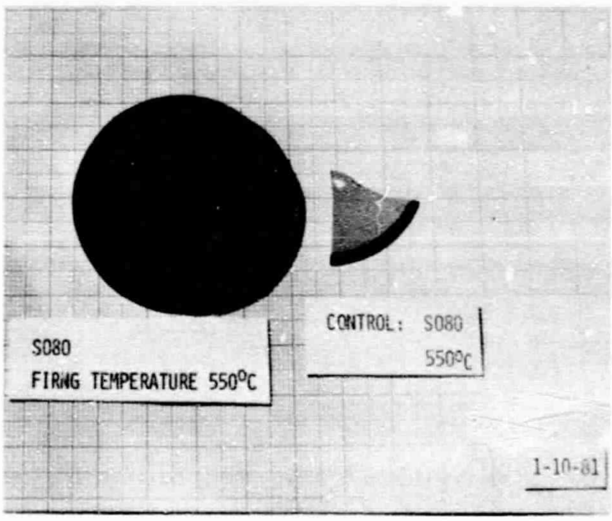
DEVELOPMENT OF ALL-METAL THICK-FILM COST-EFFECTIVE METALLIZATION SYSTEM

BERND ROSS ASSOCIATES

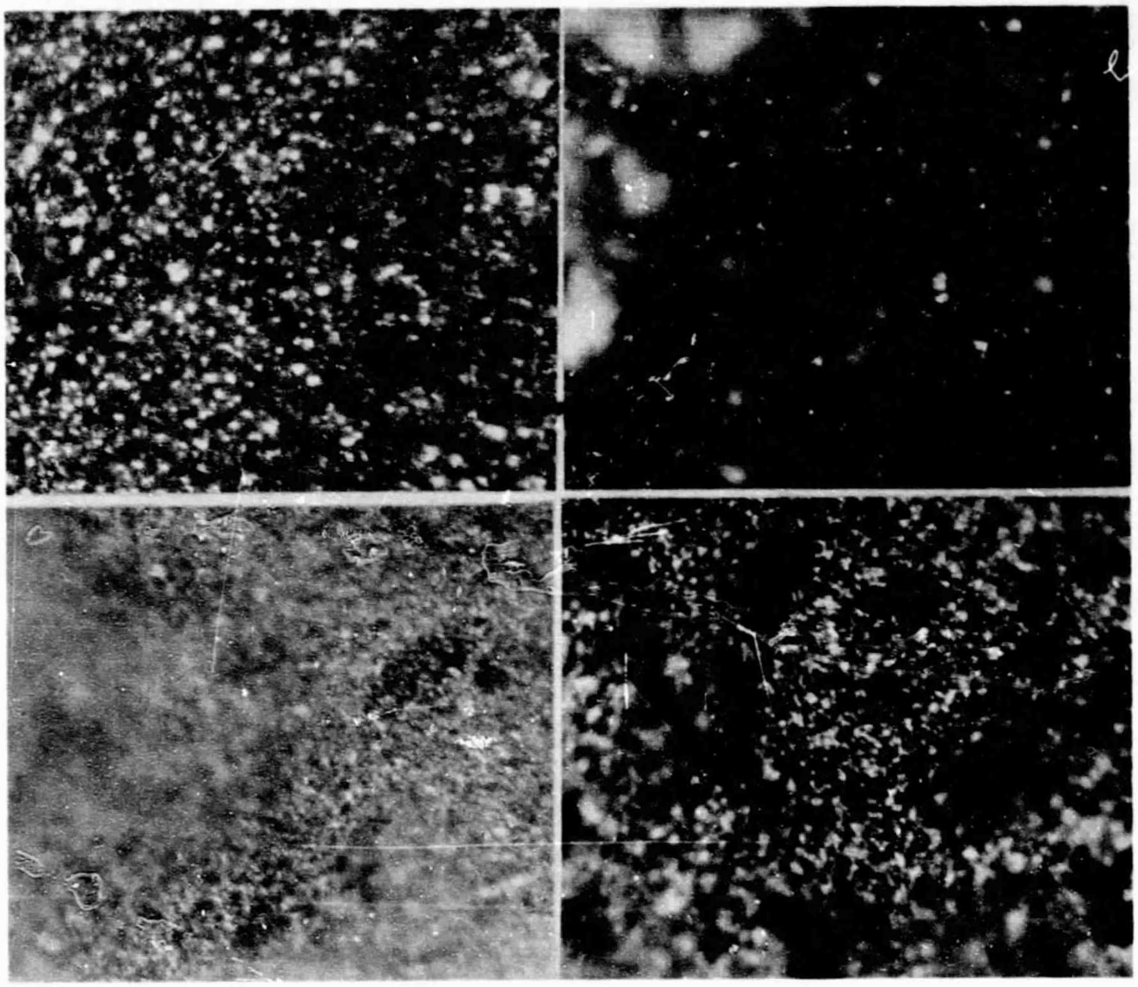
Bernd Ross

Progress to Date

NEW SOURCE OF ELECTRONIC PASTES IDENTIFIED. SOLAR CELL EXPERIMENT COMPLETED AND ANALYZED. ANALYSIS INDICATES SOME POTENTIAL SOURCES OF PROBLEM. FRONT CONTACT EXPERIMENT UNSUCCESSFUL DUE TO ADHESION PROBLEMS OF RECENT PASTE BATCHES.



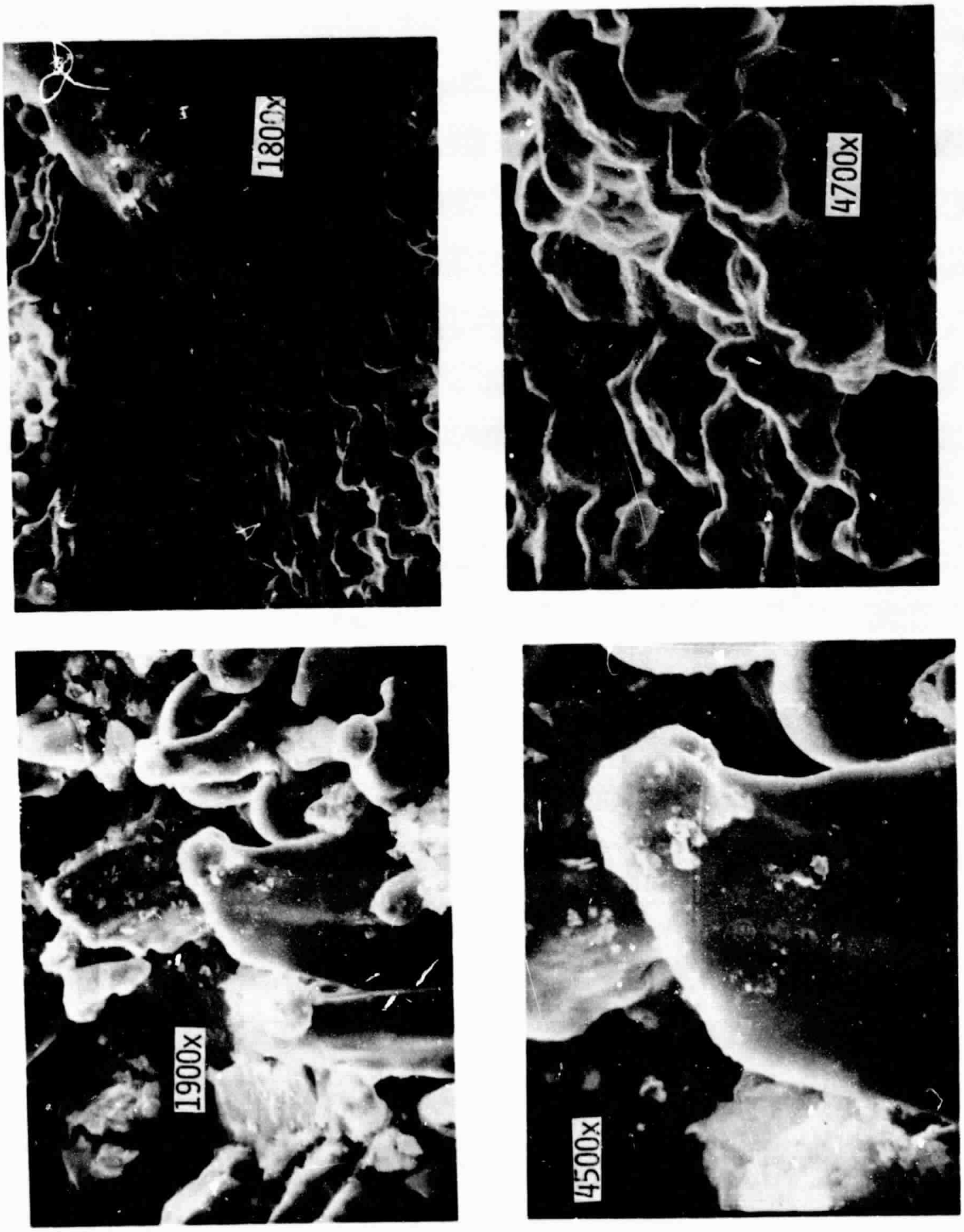
MACROSCOPIC COMPARISON OF SUCCESSFUL AND UNSUCCESSFUL BATCHES OF S080. THE FIRED PRINT (LEFT) SPONTANEOUSLY SEPARATED FROM THE SOLAR CELL. DARK BROWN APPEARANCE IS PROBABLY DUE TO OXIDATION DURING REMOVAL FROM FURNACE TUBE WHILE PASSING THROUGH FLAME CURTAIN. THE FRAGMENT LABELED CONTROL TO THE RIGHT IS BRIGHT COPPERY IN APPEARANCE, HAS GOOD ADHERENCE AND ELECTRICAL CHARACTERISTICS.



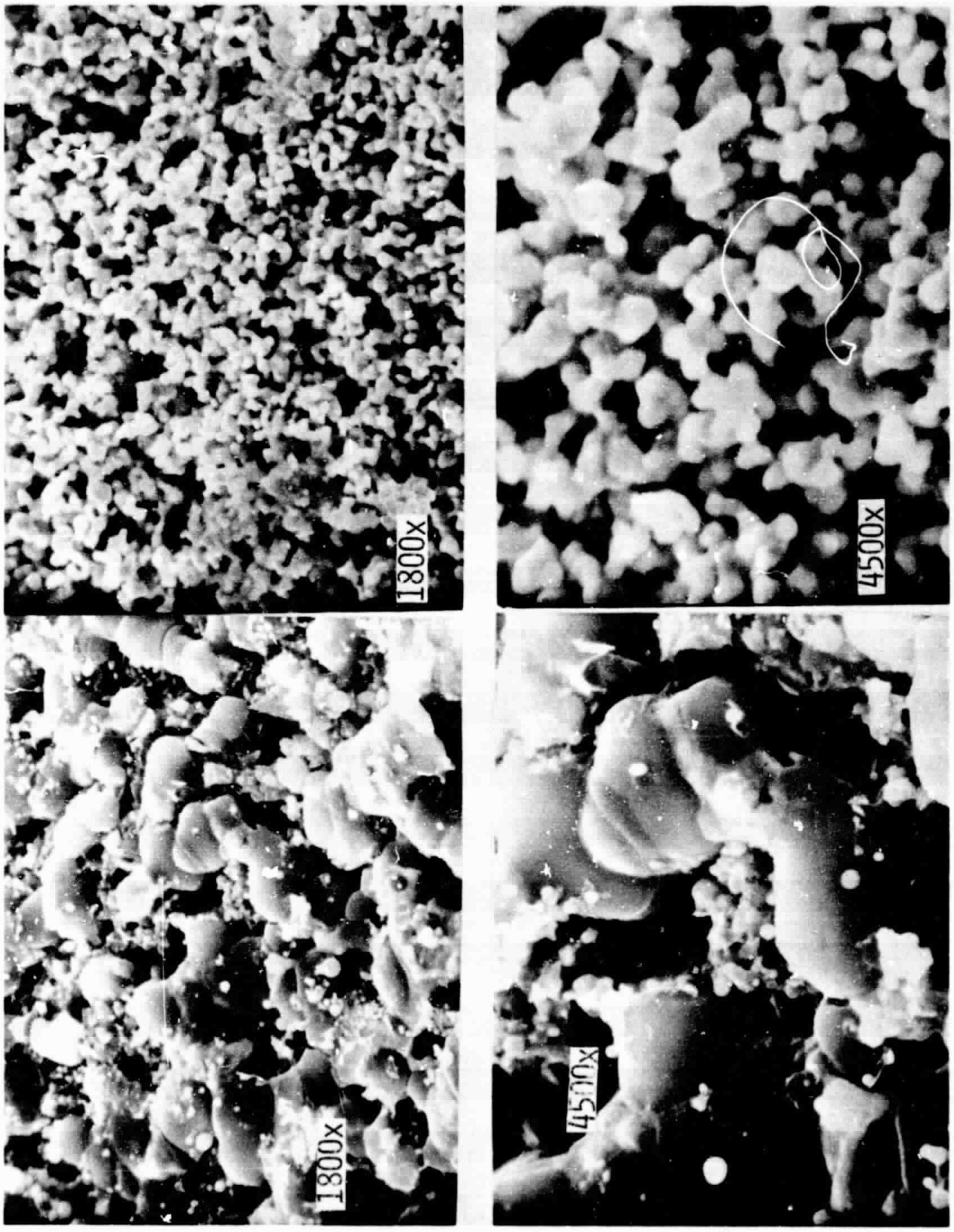
OPTICAL MICROGRAPHS OF S080 SUCCESSFUL AND S079 UNSUCCESSFUL SCREENED PRINTS WITH EXPERIMENTAL COPPER PASTES.
LEFT SIDE, TOP: SILICON SUBSTRATE UNDER GOOD S080 PRINT (ELECTRODE REMOVED BY ETCHING IN CONCENTRATED NITRIC ACID).
BOTTOM: SILICON SUBSTRATE OF S079 PRINT (ELECTRODE PEELED SPONTANEOUSLY).
RIGHT SIDE, TOP: S080 SUCCESSFUL ELECTRODE PRINT.
BOTTOM: S079 UNSUCCESSFUL ELECTRODE PRINT.

MAGNIFICATION 400x

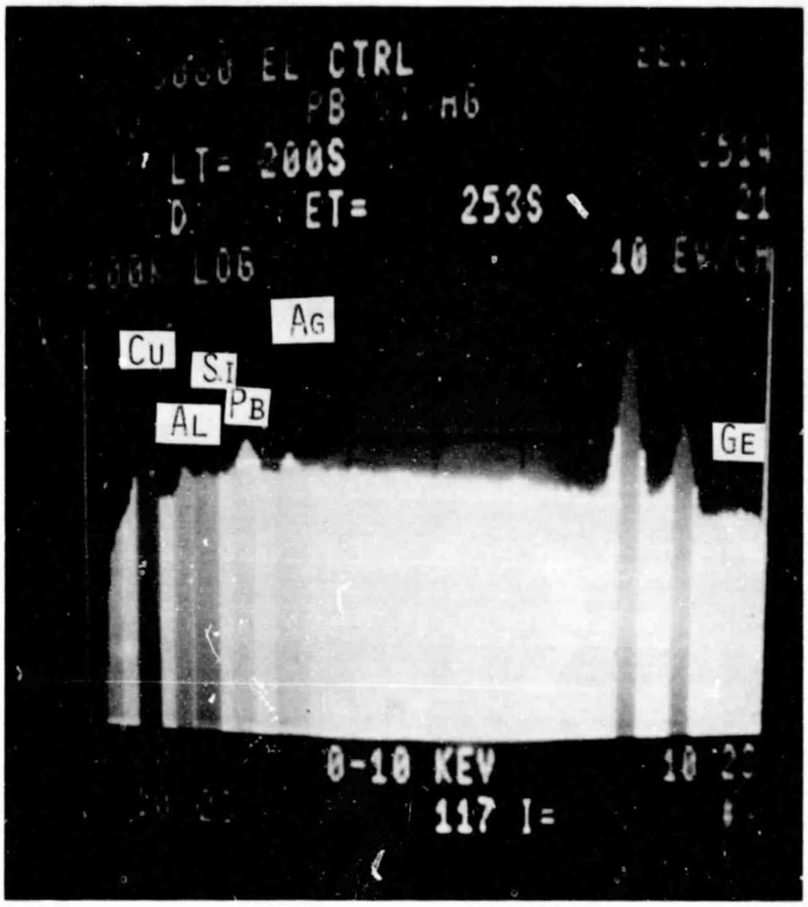
ORIGINAL PAGE IS
OF POOR QUALITY



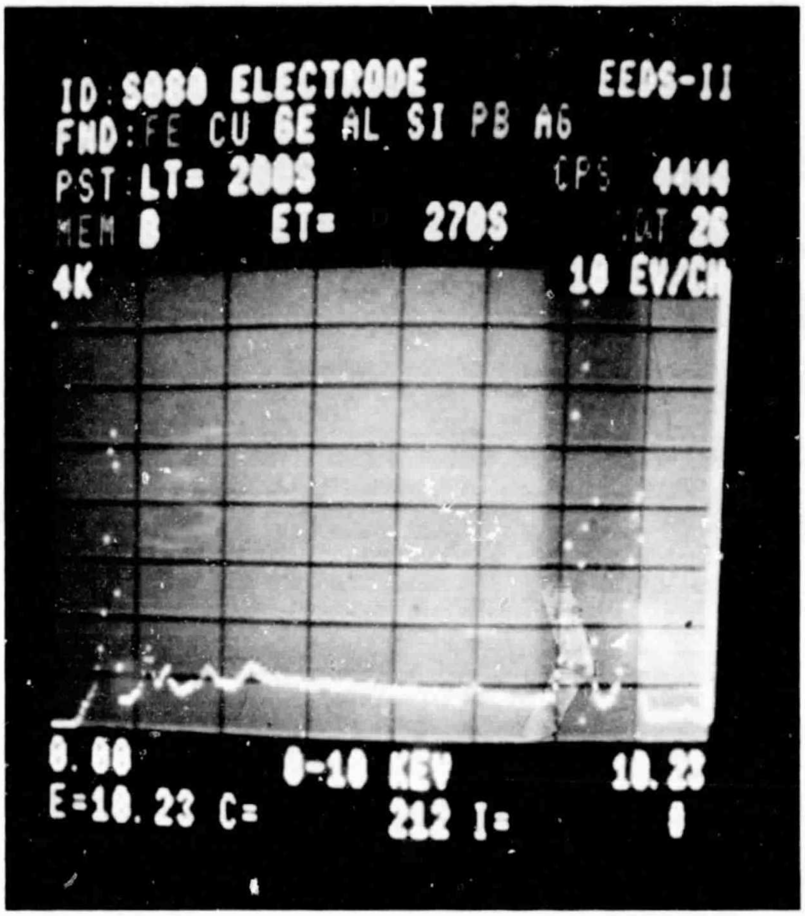
SEM MICROGRAPHS OF S080 CONTROL SUCCESSFUL SCREEN PRINT.
LEFT SIDE: SILICON SUBSTRATE. RIGHT SIDE: ELECTRODE



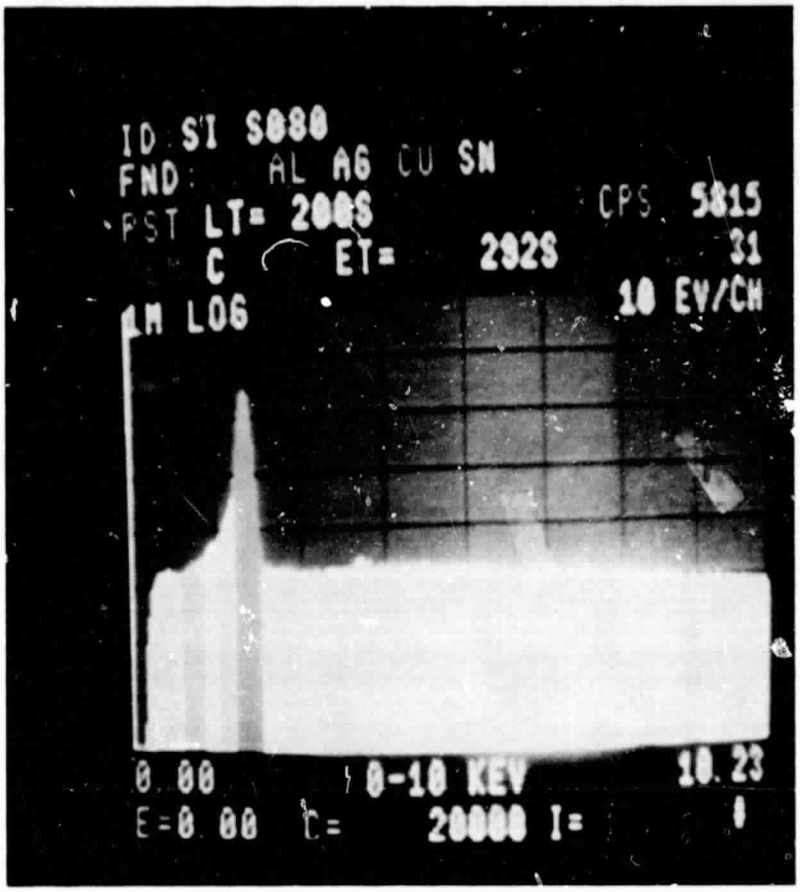
SEM MICROGRAPHS OF S080 UNSUCCESSFUL ELECTRODING EXPERIMENT.
LEFT SIDE: SUBSTRATE. RIGHT SIDE: ELECTRODE.



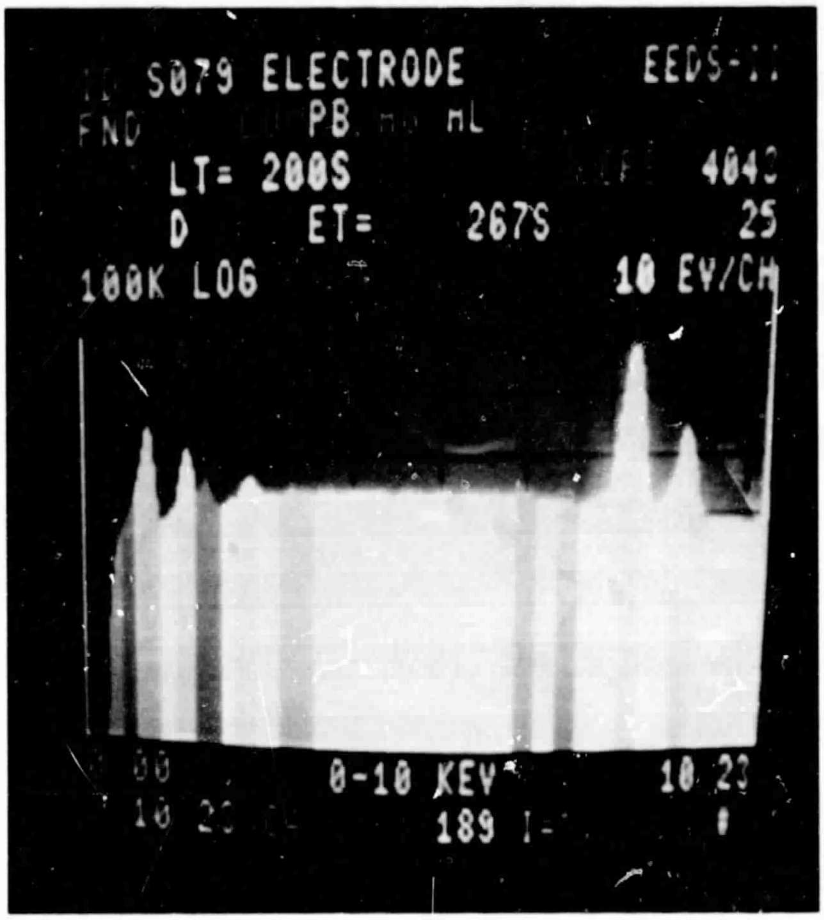
ENERGY DISPERSIVE XRAY SPECTRUM OF ORIGINAL S080 SCREENED PRINT WITH LOG ORDINATE



ENERGY DISPERSIVE XRAY SPECTRUM OF RECENT ATTEMPT TO REPRODUCE S080 (LINEAR ORDINATE)



ENERGY DISPERSIVE XRAY SPECTRUM OF SILICON SUBSTRATE FROM WHICH UNSUCCESSFUL S080 ELECTRODE WAS REMOVED BY PEELING (LINEAR ORDINATE)



ENERGY DISPERSIVE XRAY SPECTRUM OF S079 SCREENED PRINT WITH LOG ORDINATE

Conclusions and Problems

1. PASTE MANUFACTURE OF EXPERIMENTAL PASTES REINITIATED.
2. SPECIAL ANALYSIS SHOWS ESSENTIAL COMPOSITIONAL COMPONENTS BUT POTENTIALLY INADEQUATE SiO_2 REMOVAL BY DECOMPOSING SILVER FLUORIDE.
3. INADEQUATE ADHESION OF PREVIOUSLY MANUFACTURED PASTES PREVENTED ELECTRICAL EVALUATION OF FRONT CONTACT EXPERIMENT.
4. ESCALATING COST OF SILVER FLUORIDE (AgF) MAKES SUBSTITUTE SCAVENGING AGENT DESIRABLE.

AUTOMATED SOLAR MODULE ASSEMBLY (ASMA)

TRACOR MBASSOCIATES

I. PHASE ONE – IMPROVE EXISTING LAYUP AND INTERCONNECT SYSTEM. PROGRESS SINCE LAST PIM:

- **PHASE COMPLETED AS PER CONTRACTUAL REQUIREMENTS**
- **PREPARATION CYCLE TIME REDUCED 40% (15 Sec to 8½ Sec)**
- **MANIFOLD TYPE DISPENSER FOR IMPROVED SOLDER PASTE DISPENSING**
- **IMPROVE LAYDOWN ACCURACY TO ROBOT MAXIMUM (± 0.050")**
- **SOLDERING TIME REDUCED ON ORDER OF MAGNITUDE (30 Sec to 3 Sec)**
- **NEW SOLDER TECHNIQUE TO ELIMINATE SOLDER AND FLUX SMEAR**
- **SYSTEM INSTALLED IN NEW ENCLOSURE**

Automated Laminating and Encapsulation Station

II. PHASE THREE — AUTOMATED MODULE ENCAPSULATION.
PROGRESS SINCE LAST PIM:

- **DETAILED LAYOUT DRAWINGS COMPLETED**
- **FRAME FABRICATED**
- **COMPONENT DRAWINGS 75% COMPLETE**
- **COMPONENT FABRICATION 50% COMPLETE**
- **COMPONENT ASSEMBLY (ONTO FRAME) 30% COMPLETE**

IN-HOUSE ROBOTICS

JET PROPULSION LABORATORY

R. Cunningham
E. Saund
D. Varney
C. Ruoff

Objective

APPLICATION OF ADVANCED ROBOTICS AND MACHINE PERCEPTION TECHNIQUES TO SOLAR CELL MODULE PRODUCTION.

Plan

- AUTOMATION EVALUATION STUDY TO IDENTIFY POTENTIAL APPLICATIONS OF MACHINE INTELLIGENCE
  - INITIAL STRAWMAN BASED ON 1978 JPL PROCESS SEQUENCE
  - MEPSDU BASED STRAWMEN (IN PROCESS)
- LAB DEMONSTRATION OF SELECTED DEVELOPMENT TASK(S)

Automation Issues

- WHAT IS THE PROCESS SEQUENCE?
- CONTINUOUS VS. BATCH PROCESSING
- INTER-STEP TRANSFER
- BUFFERING
- MODULE FABRICATION
- INSPECTION AND TESTING FOR QUALITY CONTROL FEEDBACK
- PROCESS CONTROL
- COMPUTERIZATION

Process Sequence

- THE MEPSDU PROPOSALS FROM SOLAREX AND WESTINGHOUSE ARE CURRENTLY BEING EVALUATED
- A PRODUCTION STRAWMAN WILL BE PROPOSED FOR EACH MEPSDU

Continuous vs Batch Processing

CONTINUOUS

- CONVEYOR BELT OPERATIONS
  FURNACES, SPRAY-ON COATINGS, DIFFUSION, SILK SCREEN
- K & S CELL STRINGING MACHINE
- CELL TEST
- LASER SCRIBING

BATCH

- DIP COATING
- CLEANING/ETCHING
- METAL PLATING

Interstep Transfer

- BETWEEN FIXTURES (CASSETTES, ETC.)
- CELL ORIENTATION
- INVERTING CELLS
- CONVERGENT/DIVERGENT PROCESSES

Buffering

- LINE BALANCING
- MACHINE DOWN TIME
- MORE FLEXIBLE WHEN DONE ON INDIVIDUAL CELL BASIS

Inspection and Testing

- INSPECTION FOR BROKEN CELLS
- VERIFICATION THAT CELL IS PRESENT
- ELECTRICAL TESTS
- CELL ORIENTATION

Process Control

- MAINTAIN PROCESS PARAMETER SUCH AS CHEMICAL CONCENTRATIONS, TEMPERATURE, AND PROCESSING TIME
- COULD POSSIBLY ADJUST ONE PARAMETER ON THE BASIS OF DEVIATIONS OF ONE OF THE OTHERS
- STATUS MONITORED BY CENTRAL COMPUTER

Computerization

- DISTRIBUTION OF CONTROL
- INTER-STEP COMMUNICATION
- HUMAN INTERFACE

Candidate Development Tasks

1. CELL HANDLING
   - INTERSTEP TRANSFER
   - BUFFERING
   - INSPECTION
2. MODULE FABRICATION
   - BUS BARS
   - PARALLEL INTERCONNECTIONS
   - BYPASS DIODES
   - TERMINALS

Development Task Selection Considerations

- SHOW COST BENEFIT USING SAMICS METHODOLOGY
- ALTHOUGH A PUMA ROBOT WILL BE USED FOR DEMONSTRATION PURPOSES, IT IS RECOGNIZED THAT A SOMEWHAT SIMPLER DEVICE MAY ALSO BE SUITED TO THE TASK.

Westinghouse Process Sequence

1. PRE-DIFFUSION CLEAN - PLASMA ETCH
2. $POCl_3$ DIFFUSION - DIFFUSION FURNACE
3. OXIDE ETCH
4. BSF FORMATION - PLASMA SPRAY, DRIVE FURNACE
5. AR COATING - DIP TANKS, FURNACES
6. PHOTORESIST COATING - DIP TANKS, FURNACES
7. EXPOSE/DEVELOP/ETCH - LIGHT SOURCE, DIP TANKS
8. METALLIZATION - BOX COATER
9. REJECTION/PLATING - PLATING LINE
10. CELL SEPARATION - LASER SCRIBE
11. CELL TEST
12. INTERCONNECT - ULTRASONIC WELDER
13. LAMINATION/ASSEMBLY
14. MODULE TEST

Solarex Process Sequence

1. SURFACE PREPARATION - NaOH ETCH
2. FRONT JUNCTION FORMATION - SPRAY-ON DOPANT, BELT DIFFUSION
3. BACK JUNCTION FORMATION - AL PASTE, BELT FIRE
4. AR COATING - SPRAY-ON, BELT DRY
5. METALLIZATION - NEGATIVE SCREEN PRINT, ELECTROLESS Ni PLATE, SOLDER DIP
6. EDGING - LASER SCRIBE
7. CELL TEST
8. TAB AND STRING - SOLDER CONTACTS
9. ENCAPSULATE MODULE
10. MODULE TEST

Computer Vision Demonstration

- INSPECTION AND VERIFICATION IN THE CONTEXT OF A SIMULATED CELL STRINGING OPERATION
- ESTIMATE POSITION ERRORS
- CORRECTLY IDENTIFY SITUATIONS WHERE TWO OR THREE CELLS OVERLAP
- DETECT BROKEN CELLS, MISSING CELLS

Other Applications

- INTERSTEP TRANSFER
  - MISSING CELLS
  - BROKEN CELLS
- CONVEYOR BELTS
  - OVERLAPPING CELLS
- LASER SCRIBING
  - BROKEN CELLS
  - VERIFY SIZE

Vision System Features

- ADAPTS TO CHANGES IN THE ABSOLUTE LOCATION OF THE TASK
- ABSOLUTE CELL POSITION IS DETERMINED TO AVOID PROPAGATION OF ERRORS
- EASILY PROGRAMMED TO HANDLE DIFFERENT CELL SIZES AND LAYUP PATTERNS

Improvements

- INCREASED IMAGE RESOLUTION
- HARDWARE IMAGE FEATURE EXTRACTION FOR INCREASED SPEED
- EXTEND IMAGE ANALYSIS TO HANDLE INTERCONNECTS
- MODIFY TO HANDLE DIFFERENT CELL SHAPES

PROCESSING EXPERIMENTS ON NON-CZOCHRALSKI SI SHEET

MOTOROLA, INC.

Major Areas of Investigation

1. PROCESS TECHNOLOGY
   - SUBSTRATE SURFACE PREPARATION
     - SURFACE ETCHING
     - SURFACE TEXTURING
     - SURFACE CLEANING
   - PROCESS UNIFORMITY CONSIDERATIONS
   - HANDLING RECTANGULAR SHAPES
2. CELL DESIGN
   - METALLIZATION PATTERN OPTIMIZATION FOR RECTANGULAR CELLS
3. METALLIZATION
   - PLATED METALLIZATION ADVANCEMENTS
4. COST ANALYSIS
   - DOCUMENTATION OF MOTOROLA APPROACH AND COMPARISON WITH SAMIS

Process Technology: Baseline Process Sequence

1. BLANKET PHOSPHORUS DIFFUSION, PH_3 AT 900°C.
2. MESA JUNCTION ETCH, PHOTORESIST WITH A PLASMA ETCH FOR SILICON.
3. SILICON NITRIDE COAT, LPCVD Si_3N_4 AT 780°C.
4. OHMIC PATTERN, PLASMA ETCH NITRIDE.
5. METAL PLATE, NICKEL-COPPER OR PALLADIUM-NICKEL-COPPER.

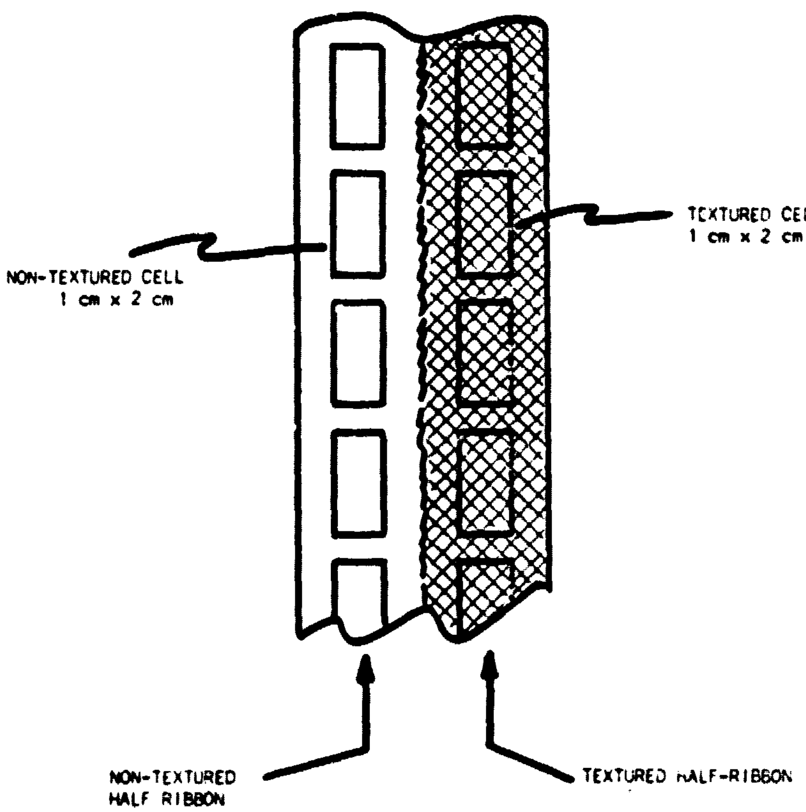
Process Technology: Surface Preparation Experiment

1. DESIRED STRUCTURE: SIDE-BY-SIDE COMPARISON OF TEXTURED AND NON-TEXTURED (FRONT SURFACE) CELLS.

2. PROCEDURE: USE SILICON NITRIDE COATING TO MASK TEXTURED SURFACE PREPARATION ON ENTIRE BACK SIDE AND HALF OF FRONT SIDE (LENGTHWISE) FOR 10 RIBBON SAMPLES.

3. SOLAR CELL STRUCTURE: FORM PAIRS OF SIDE-BY-SIDE 1 cm BY 2 cm SOLAR CELLS, ONE CELL OF THE PAIR ON TEXTURED SIDE AND THE OTHER ON SMOOTH SIDE OF THE RIBBON. (USE BASELINE PROCESS.)

Substrates Used for Texture-Etch And Surface-Etch Studies



Process Technology: Surface Preparation Experiments

RESULTS

1. 10 RIBBONS PROCESSED, UP TO 11 CELL PAIRS PER RIBBON.
2. 48 PAIRS USED FOR ANALYSIS.
3. 32 PAIRS INDICATED IMPROVEMENT IN SHORT CIRCUIT CURRENT, I_{SC}, WITH TEXTURING.
   AVERAGE I_{SC} INCREASE 2.1 mA OR 4.3%.
4. 15 PAIRS INDICATED DECREASE IN I_{SC} WITH TEXTURING.
   AVERAGE I_{SC} DECREASE 1.6 mA OR 3.2%.
5. TOTAL AVERAGE INCREASE WITH TEXTURING (FOR ALL 48) WAS 0.9 mA OR 1.9%.

Cell Design: Metal Pattern Optimization Procedure

EXPRESSION FOR EFFICIENCY:

$$\eta = \eta^0 T (1-F) - (P_\Omega / P_I)$$
$$= \eta^0 T - \Delta\eta$$

WHERE η = OVERALL EFFICIENCY

η^0 = INHERENT SUBSTRATE CONVERSION EFFICIENCY

T = OPTICAL TRANSMISSION COEFFICIENT OF EXPOSED FRONT SURFACE

F = METAL SHADOWING FRACTION

P_Ω = OHMIC POWER LOSS

P_I = TOTAL INPUT POWER OVER USEFUL SPECTRUM

NOTE: $\Delta\eta = \eta^0 TF + P_\Omega/P_I$
$= \Delta\eta_{SHADOW} + \Delta\eta_{OHMIC}$

CELL DESIGN - METAL PATTERN OPTIMIZATION PROCEDURE

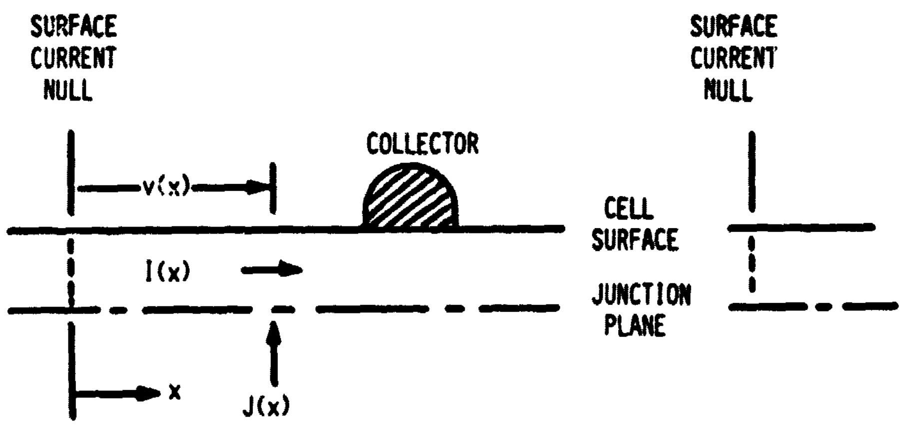
NECESSARY OPTIMIZATION CONDITION

$$\frac{\partial}{\partial F} \Delta\eta = 0$$

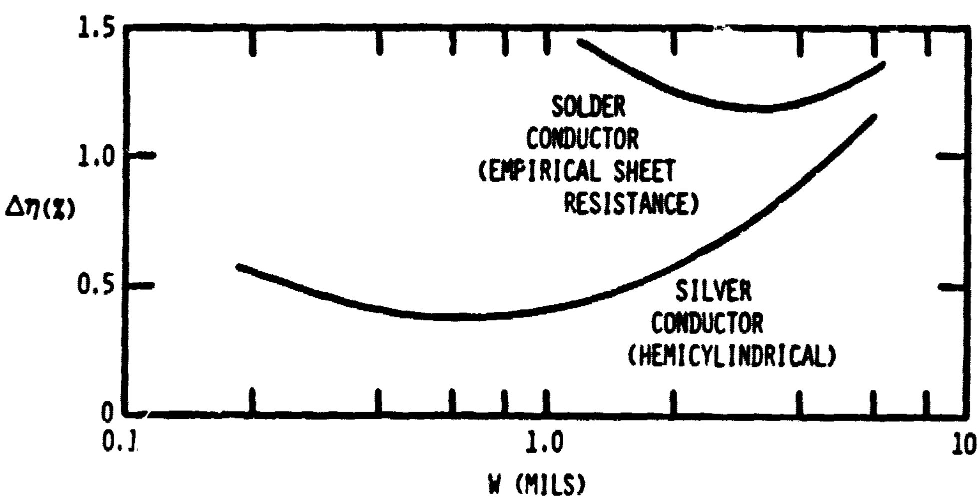
HENCE $$\frac{\partial}{\partial F} (P\Omega / P_I) = -\eta^0 T$$

THIS CONDITION, ALONG WITH OTHER SPECIFIC CONSTRAINTS RELATED TO THE DESIRED CELL DESIGN, RESULTS IN EQUATIONS TO DETERMINE OPTIMUM LINE WIDTHS, SPACING, ETC.

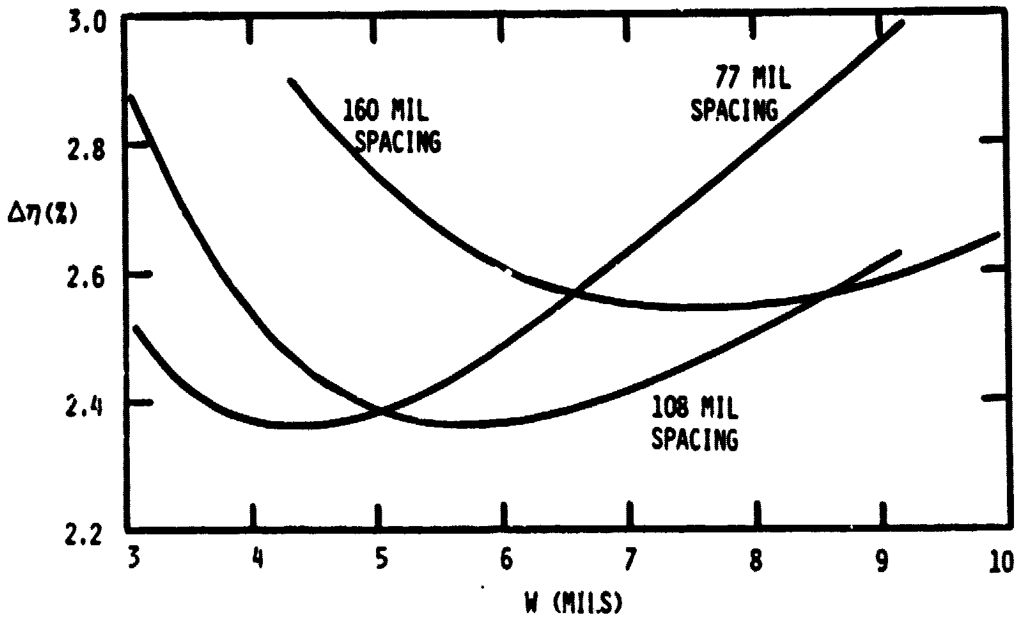
Surface Current and Potential Distributions At a Zone Element



Optimized Performance vs Line Width (Spacing Variable) for 1 x 2-in. Cell With Side Buses



Performance vs Line Width
(Fixed Spacings) for 4-in.-Square Cell With 3 Buses



Metallization: Electroless Nickel Plating

FORMULA CURRENTLY BEING INVESTIGATED:

REAGENT	CONCENTRATION
NICKEL SULFATE $NiSO_4 \cdot 6H_2O$	25 G/l
SODIUM PYROPHOSPHATE $Na_4P_2O_7 \cdot 10H_2O$	50 G/l
AMMONIUM HYDROXIDE 58% NH_4OH	66 Ml/l
SODIUM HYPOPHOSPHITE $NaH_2PO_2 \cdot H_2O$	25 G/l

REFERENCE: N. FELDSTEIN, RCA REVIEW, JUNE 1970, P. 317.

Cost Analysis: Motorola Costing Program

REQUIRED INPUT FILES:

1. PROCESS NAME FILE
2. CELL DIMENSION FILE
3. PROCESS DATA FILE
4. VARIABLE DATA

Cost Analysis: Input File Contents

1. PROCESS NAME FILE

   PROCESS NAME
   NUMBER OF PROCESS STEPS
   PROCESS SEQUENCE
   PROCESS CATEGORIES

2. CELL DIMENSION FILE

   DIMENSION IDENTIFYING NAME
   CELL AREA
   DIMENSION FILE NAME
   SILICON CONSUMPTION

COST ANALYSIS - INPUT FILE CONTENTS

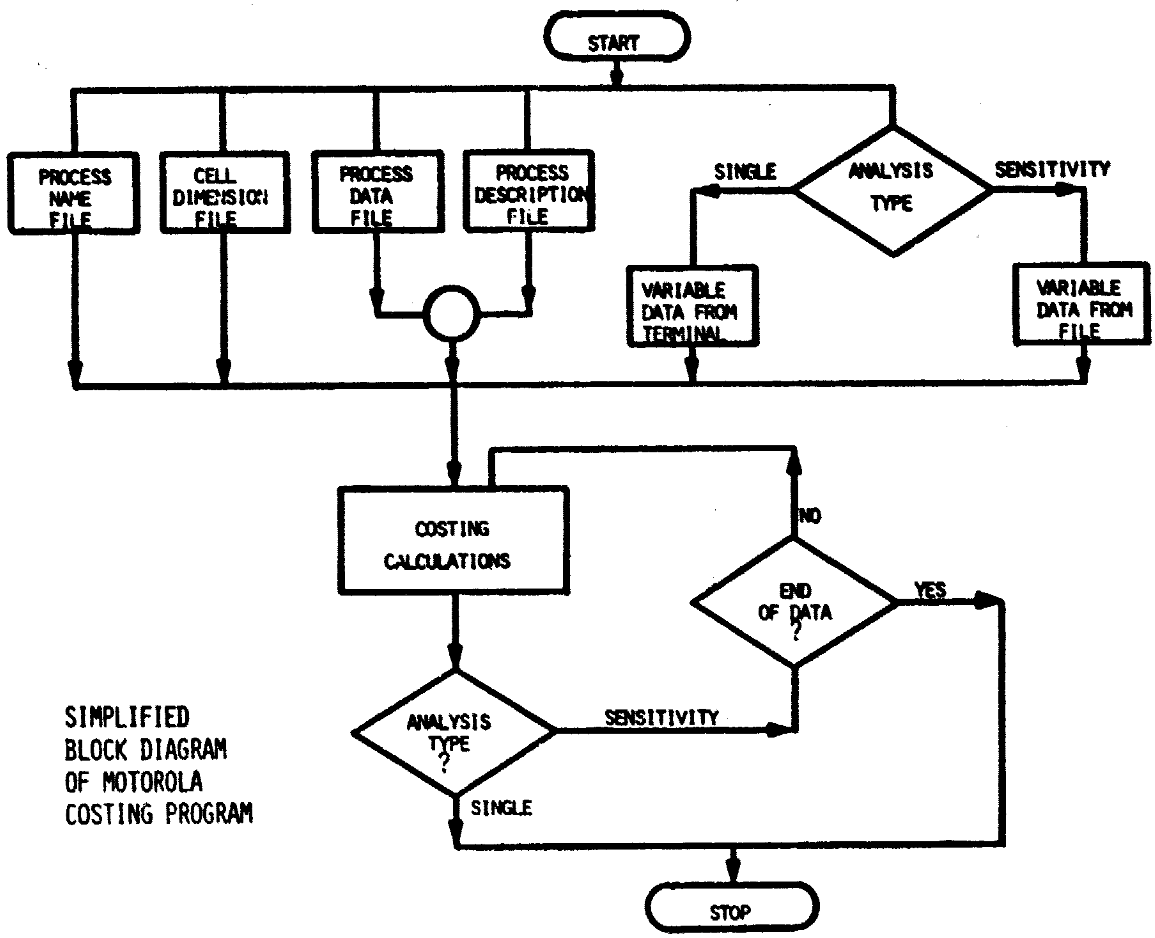
3. PROCESS DATA FILE

- PROCESS YIELD (%)
- MACHINE EFFICIENCY
- MACHINE CAPACITY
- MACHINE COST
- DIRECT LABOR
- FLOOR SPACE
- ELECTRICAL POWER
- VENTILATION
- DE-IONIZED WATER
- PROCESS EXPENSES
- MACHINE EXPENSES (CONSTANT)
- MACHINE EXPENSES (VARIABLE)
- PROCESS MATERIALS
- FACILITY REQUIREMENT CODE
- EQUIPMENT MAINTENANCE PERSONNEL

4. VARIABLE DATA

- ANNUAL PRODUCTION VOLUME (MW)
- CELL EFFICIENCY (%)
- SOLAR CONCENTRATION (SUNS)
- SILICON COST ($/KG)
- FACTORY LIFE (MONTHS)
- INTEREST RATE (%)
- ELECTRICAL POWER RATE (¢/KWH)
- DIRECT LABOR RATE ($/HOUR)
- SILICON THICKNESS (MICRONS)

Motorola Costing Program



SIMPLIFIED
BLOCK DIAGRAM
OF MOTOROLA
COSTING PROGRAM

OPTICAL DESIGN GUIDE FOR LIGHT TRAPPING

SCIENCE APPLICATIONS, INC.
T.M. Knasel

Organization of Design Guide

- BACKGROUND - MATERIAL TO FAMILIARIZE AUDIENCE WITH BASIC PHYSICAL CONCEPTS, GOALS AND PURPOSES OF THIS GUIDE
- SIMPLIFIED DESIGN TECHNIQUES - TO ALLOW A DESIGN ENGINEER TO DEVELOP EFFECTIVE OPTIONS AND STUDY TRADE-OFFS
- EXAMPLES - TO ILLUSTRATE THE TECHNIQUES PRESENTED
- CONCLUSIONS AND REFERENCES - FOR FOLLOW UP IN MORE DETAIL ON FACTS PRESENTED HERE

Acknowledgments

- SCIENCE APPLICATIONS, INC. APPRECIATES THE ASSISTANCE OF THE LOW COST SOLAR ARRAY PROJECT OF THE JET PROPULSION LABORATORY, PARTICULARLY DON BICKLER AND PAUL ALEXANDER OF PPE AND ED CUDDIHY OF THE ENCAPSULATION TASK.

- THE DESIGN GUIDE WAS PREPARED BY C.N. BAIN, BRUCE GORDON, BOB MALINOWSKI, AND T. MICHAEL KNASEL (PROJECT MANAGER) OF SAI McLEAN, VIRGINIA.

Table of Contents

EXAMPLES

SYSTEM CONCEPTS THAT EXPLOIT LIGHT TRAPPING

GROWTH SYSTEM
WALL INTEGRATED SYSTEMS

FUTURE PROSPECT

GOALS OF COST/BENEFIT STUDY
INFORMATION REQUIRED

CONCLUSIONS

REFERENCES

Introduction

- CONTRACT DETAILS
- GOALS OF DESIGN GUIDE
- DEFINITIONS

Contract Details

TITLE: ANALYSIS OF COST-EFFECTIVE PHOTOVOLTAIC PANEL DESIGN CONCEPTS USING LIGHT TRAPPING

SPONSOR: JET PROPULSION LABORATORY

CONTRACT NO: 955787

OBJECTIVES:

1. DEVELOP OPTICAL DESIGN RULES FOR EFFICIENT USE OF LIGHT TRAPPING IN FLAT PANEL PHOTOVOLTAIC MODULES

2. PERFORM A COST BENEFIT STUDY OF OPTIMUM DESIGNS TO DETERMINE ECONOMIC VALUE OF LIGHT TRAPPING

Goals of Design Guide

TAKING THE POINT OF VIEW THAT A PHOTOVOLTAIC MODULE IS A OPTICAL THICK FILM - THREE DIMENSIONAL OPTICAL SYSTEM IN WHICH TRAPPING OF LIGHT CAN AND DOES TAKE PLACE:

- DEVELOP GRAPHICAL RELATIONSHIPS BETWEEN CELL/MODULE EFFICIENCIES AND OPTICAL VARIABLES
- VARIABLES SHALL INCLUDE:
  - CELL SPACING
  - COVER PLATE MATERIALS
  - ENCAPSULATION THICKNESS
  - INDEX OF REFRACTION OF ALL OPTICAL MATERIALS
  - REFLECTIVITY (ANGULAR PATTERN) OF BACK LAYER
- MODLING EFFORT SHALL ADDRESS SINGLE AND MULTIPLE TRAPPING LAYERS
- SIMPLIFIED EQUATIONS SHALL BE DEVELOPED AS APPROXIMATIONS TO FULLY DETAILED CALCULATIONS
- PICTORIAL DISPLAYS AND CROSS-SECTIONING OF OPTICAL MATERIALS SHALL BE USED AS APPROPRIATE

THE DESIGN GUIDE WILL ENABLE THE ENGINEER TO USE LIGHT TRAPPING EFFECTIVELY IN PV PANEL DESIGN.

Definitions

- <u>THIN FILM</u> OPTICAL SYSTEMS - TWO DIMENSIONAL STRUCTURES THAT REFLECT, REFRACT OR TRANSMIT LIGHT DEPENDENT ON THE WAVELENGTH AND THE OPTICAL PROPERTIES OF THE MATERIALS - OPTICAL RADIATION GOES FORWARD OR BACKWARD ONLY.

- <u>THICK FILM</u> OPTICAL SYSTEMS - THREE DIMENSIONAL STRUCTURES THAT REFLECT AND TRANSMIT OPTICAL RADIATION FORWARD OR BACKWARD, WITH PROPAGATION POSSIBLE TRANSVERSE TO LAYER STRUCTURE.

- <u>LIGHT TRAPPING</u> REFERS TO PROPAGATION IN THICK FILMS WHERE LIGHT IS TRAPPED IN HIGH INDEX MATERIALS BY TOTAL INTERNAL REFLECTION. LIGHT IS NOT NORMALLY TRAPPED UNLESS IT IS SCATTERED IN A DIFFUSE (I.E., NON-SPECULAR) MANNER.

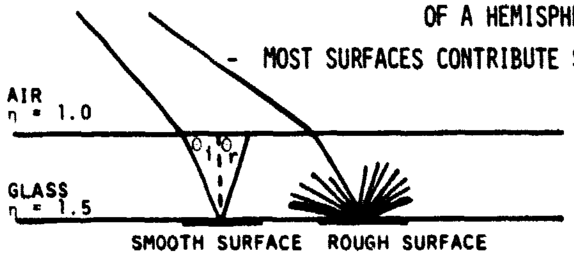
Optical Principles

- REFRACTION, REFLECTION IN THICK FILMS
- LIGHT TRAPPING CONCEPT
- THICK FILMS FOR OPTICAL CONCENTRATION
- CLOSED FORM APPROXIMATE SOLUTION
- COMPUTER MODELING
- SIMPLIFIED DESIGN EQUATIONS

Refraction, Reflection in Thick Films

REFRACTION AND REFLECTION ARE THE PRINCIPAL OPTICAL INTERACTIONS IN THICK FILMS:

- REFRACTION: BENDING OF OBLIQUE RAYS AS THEY PASS FROM ONE MEDIUM TO ANOTHER HAVING A DIFFERENT REFRACTIVE INDEX
- REFLECTION: THE RETURN OF RADIATION BY A SURFACE WITHOUT CHANGE IN WAVELENGTH
  - SPECULAR - FROM A SMOOTH SURFACE
    - ANGLE OF INCIDENCE (Θ_i) EQUAL ANGLE OF REFLECTION (Θ_r)
  - DIFFUSE - FROM A ROUGH SURFACE
    - INTO MANY (SOMETIMES ALL) DIRECTIONS OF A HEMISPHERE
  - MOST SURFACES CONTRIBUTE SPECULAR AND DIFFUSE COMPONENTS.



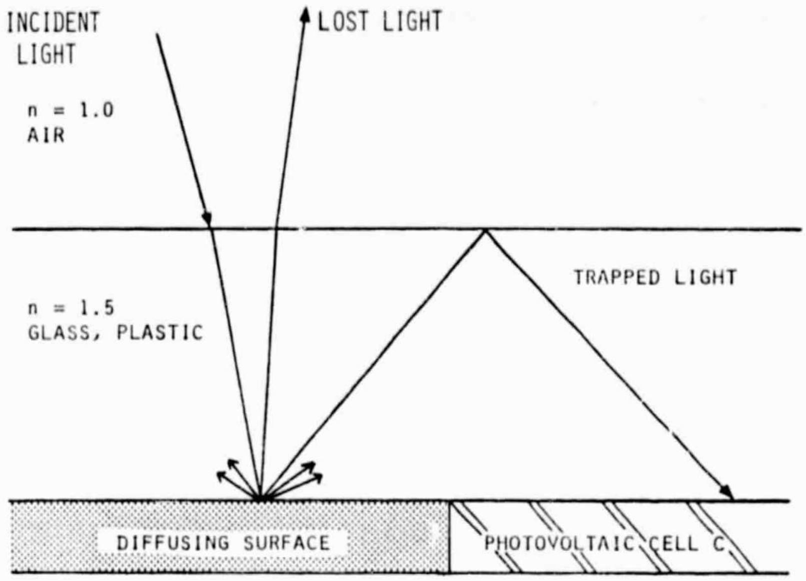
Thick Films as Optical Concentrators

THE ABILITY OF THICK FILMS TO PROPAGATE OPTICAL RADIATION IN A TRANSVERSE DIRECTION RAISES THE POSSIBILITY THAT OPTICAL CONCENTRATION (CALLED GAIN) CAN BE ACHIEVED. SUCH SYSTEMS WOULD HAVE THE FOLLOWING PROPERTIES:

- MAXIMUM THEORETICAL GAIN FOR ANY RECEIVING ELEMENT WOULD BE LIMITED TO THE SQUARE OF THE RATIO OF INDICIES, $(\eta_{HIGH}/\eta_{LOW})^2$
- MAXIMUM GAIN FOR AN ARRAY OF ELEMENTS THAT TRAP WOULD BE LIMITED TO THE RATIO OF THE TOTAL AREA TO AREA OF RECEIVER, A_{TOTAL}/A_{RCVR}
- THE GAIN WILL BE LIMITED ALSO BY THE ABSORPTION OF THE THICK FILM

Light-Trapping Concept

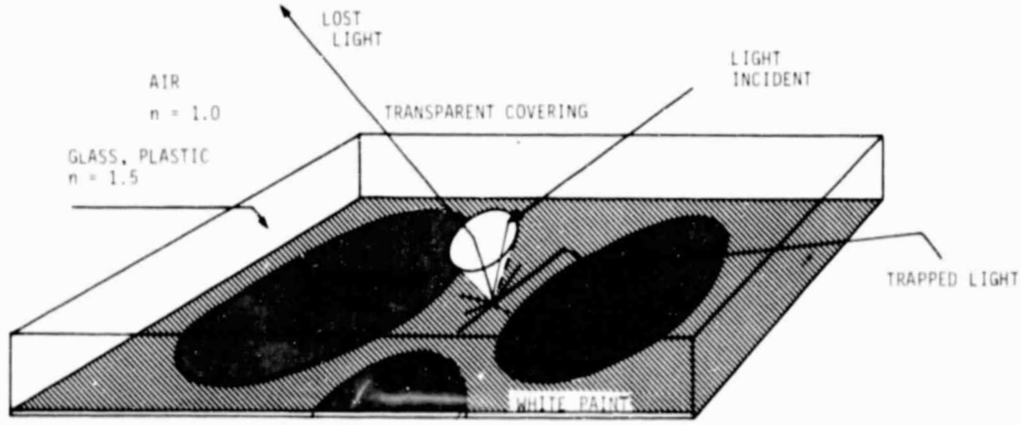
- USE OF HIGH INDEX OF REFRACTION MATERIALS
- DIFFUSELY REFLECTING INTERCELL AREA



Light Trapping by Diffuse Reflection in Thick Film

DIFFUSE LIGHT TRAPPING IS ACCOMPLISHED WHEN AN INCIDENT RAY ENTERS A HIGHER INDEX TRANSPARENT LAYER AND IS SCATTERED.

AN EXAMPLE RELATED TO PHOTOVOLTAIC MODULES IS SHOWN BELOW:



Closed-Form Approximate Solution

- ASSUMPTIONS:
  - SINGLE TRAPPING LAYER, INDEX η_2; PLACED IN AIR, INDEX η_1.
  - NO ABSORPTION IN LAYER
  - NO FRESNEL REFLECTIONS
  - HOMOGENEOUS MIXTURE OF DIFFUSING LAYER AND CELLS
  - PERFECT DIFFUSE (LAMBERTIAN) REFLECTION BETWEEN CELLS

- METHOD—SERIES SOLUTION TO RAY PROPAGATION

$$G_0(N_1) = 1/(C+L - LC)$$

$N_1 = \eta_2/\eta_1$

C = CELL PACKING FACTOR

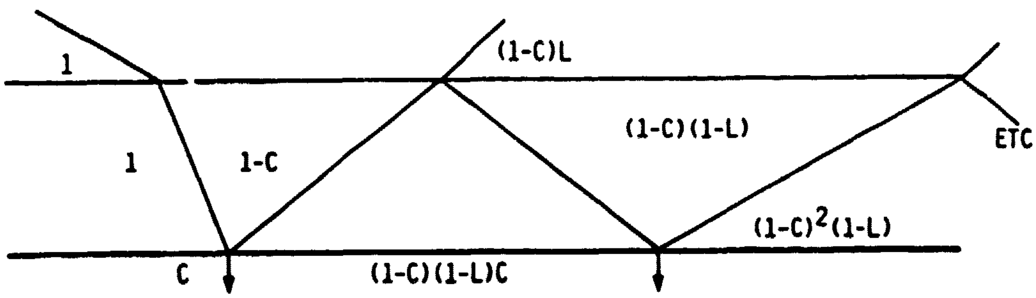
L = LOSS DUE TO LESS THAN CRITICAL ANGLE REFLECTION

$$L = \sin^2\theta_C = \left(\frac{\eta_1}{\eta_2}\right)^2 \equiv (N_1)^2$$

- FOR THE CASE WHERE THE PACKING FACTOR IS SMALL THE EXPRESSION REACHES THE OPTICAL LIMIT FOR GAIN

$$G_0(N_1) = 1/(N_1)^2;\ C \longrightarrow 0$$
$$= (\eta_2/\eta_1)^2$$

Derivation of Closed-Form Solution



$$G = \left[1 + \underbrace{(1-C)(1-L)}_{1-C-L+LC} + (1-C)^2(1-L)^2 \cdots\right]$$

$$G = \sum_{n=0}^{\infty} (1-C-L+LC)^n = \sum_{n=0}^{\infty} X^n = \frac{1}{1-X} = \frac{1}{C+L-LC}$$

Simplified Design Equations

1) GAIN WITH NO FRESNEL REFLECTIONS

$$G_0 = 1/(C+L-LC)$$

2) GAIN WITH FRESNEL REFLECTION AT TOP LAYER

$$G_0 = 1/(C+L-LC-LF+LCF)$$

3) GAIN WITH FINITE REFLECTIVITY $R \leq 1.0$

$$G(R) = 1/\left[1-R(1-C-L+LC+LF-LCF)\right]$$

4) GAIN FOR LESS THAN OPTIMUM THICKNESS $\tau/\ell < 0.3$

$$G(T) = 1 + \left[G_0 - 1\right]\left(1-(1-3.33\tau/\ell)^3\right)$$

5) EFFECTS OF ADDITIONAL LAYERS ARE MULTIPLICITIVE

$$G(N_1, N_2 \cdots, = 1 + \left[G(N_1)\ G(N_2) \cdots - 1\right]$$

6) EFFECTS OF R,T CAN BE ALSO INCLUDED

$$G(N_1, N_2 \cdots, R_1 \cdots, T_1 \cdots,) = 1 + \left[G(N_1, R_1, T_1)\ G(N_2, R_2, T_2) \cdots - 1\right]$$

Computer Model for Simulation of Light Propagation And Diffusion by Monte Carlo Methods

IN ORDER TO CHECK THE CLOSED FORM SOLUTION AND TO PROVIDE MORE DESIGN DETAIL A COMPUTER CODE WAS WRITTEN WITH THESE FEATURES:

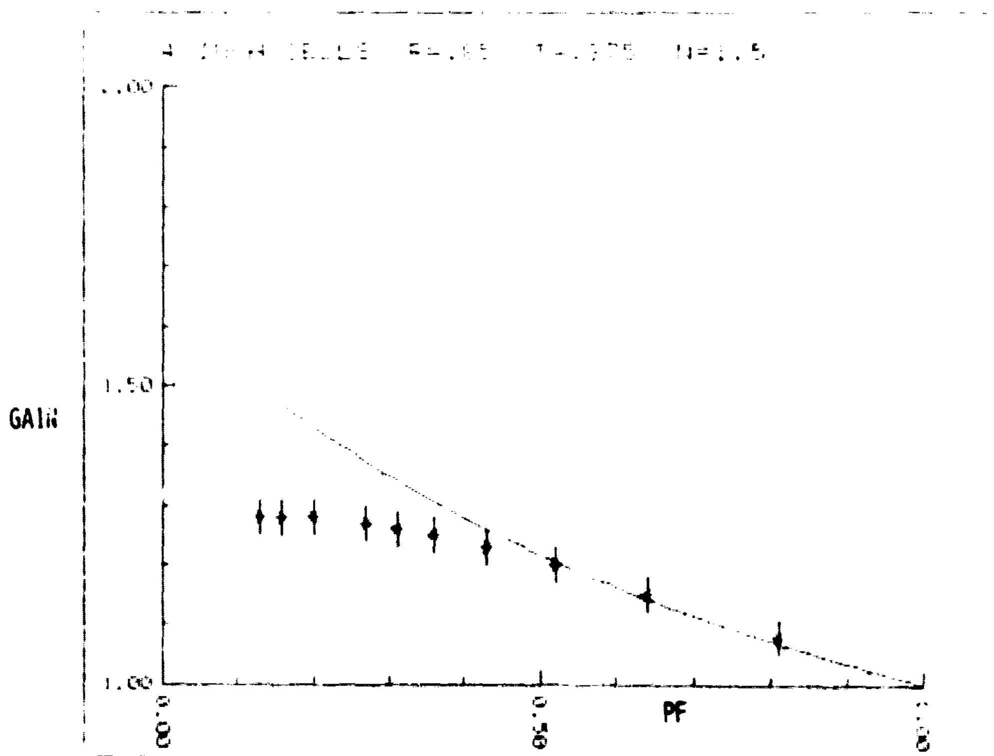
- PROPAGATION OF LIGHT IN THREE DIMENSIONS INCLUDES FRESNEL LOSSES, ABSORPTION LOSSES, AND DIFFUSION LOSSES
- DIFFUSED RAYS GIVEN ANGLES WHICH EFFECTIVELY SAMPLE THE REAL DISTRIBUTION OF DIFFUSED LIGHT - A MONTE CARLO TECHNIQUE IS USED
- VARIOUS DIFFUSION PATTERNS INCLUDING LAMBERTIAN DISTRIBUTION ARE AVAILABLE AS INPUT
- A TWENTY BY TWENTY BOX MATRIX IS USED TO DEFINE CELL AND DIFFUSING AREAS

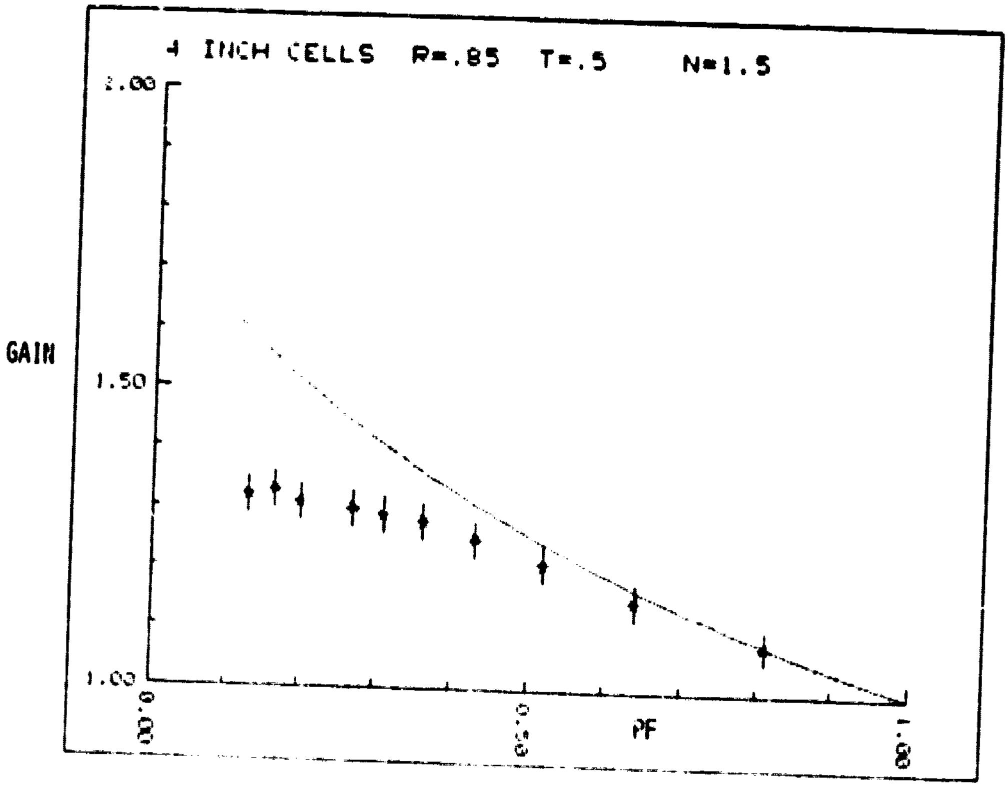
THE ACCURATE COMPUTER PREDICTIONS WERE THEN COMPARED TO THE CLOSED FORM SOLUTIONS.

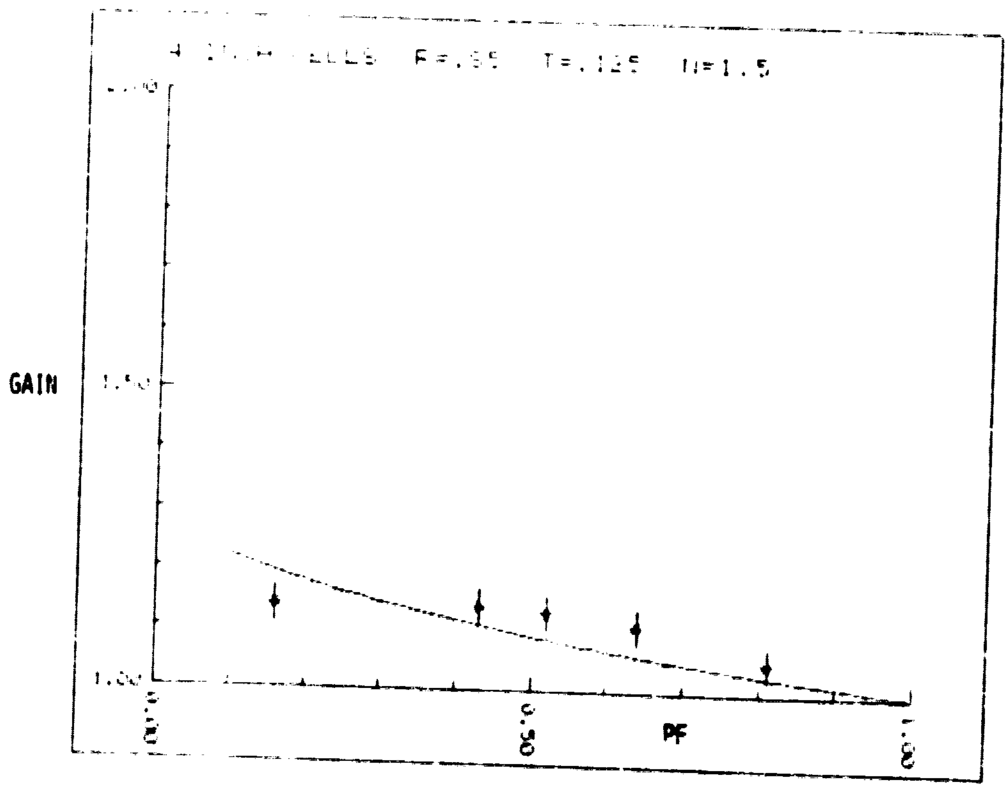
Closed-Form Equation vs Computer Calculation Comparison Format

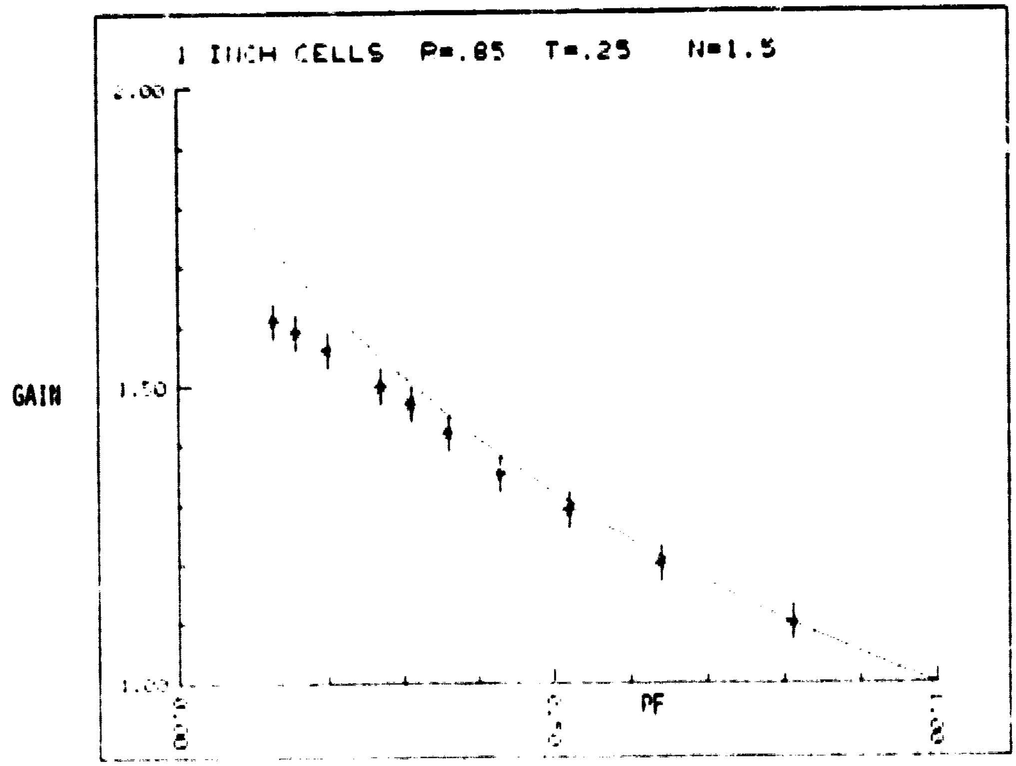
- LABELS
  - CELL DIAMETER (INCHES) OR SIDE IF SQUARE
  - REFLECTIVITY OF WHITE DIFFUSING LAYER, R
  - TOTAL THICKNESS ABOVE CELL, T
  - INDEX OF REFRACTION ABOVE CELL, N
- AXES
  - Y AXIS, GAIN ON CELL, G
  - X AXIS, PACKING FACTOR, PF
- LINE
  - CLOSED FORM EQUATION
  - POINTS, MONTE-CARLO MEAN (X) AND ERROR (BAR)

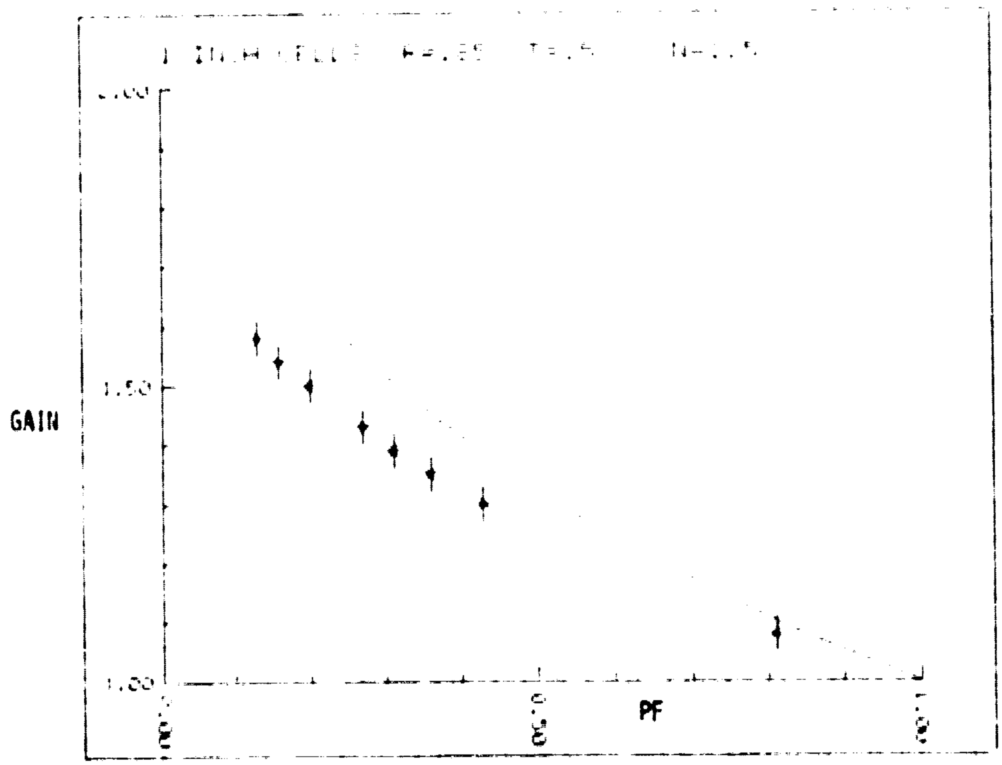
Closed-Form Equation vs Computer Calculation




4 INCH CELLS R=.85 T=.5 N=1.5
GAIN
2.00
1.50
1.00
0.00
0.50
PF
1.00


4
T=.125
N=1.5
GAIN
0.00
0.50
PF
1.00


1 INCH CELLS P=.85 T=.25 N=1.5
2.00
GAIN
1.50
1.00
0.00
0.50
PF
1.00


GAIN
1.50
1.00
0.00
0.50
PF
1.00

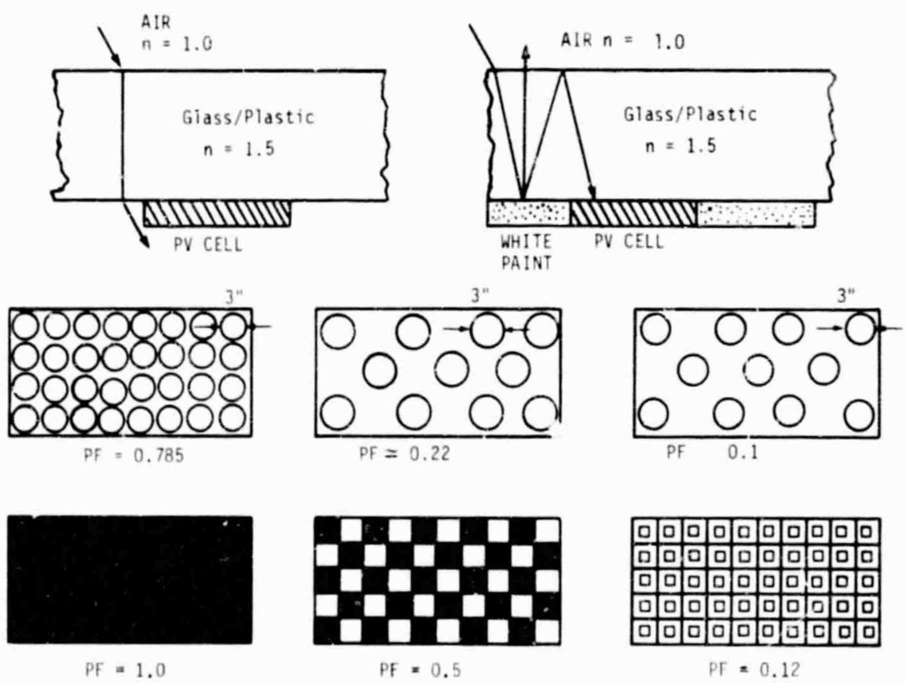
Baseline Module Design

- MODULE LAYOUT, CELL SPACING GEOMETRY
- BASELINE PERFORMANCE ESTIMATES
- EXPERIMENTAL CONFIRMATION

Light-Trapping Concentration for PV: Concept Description

- LIGHT TRAPPED BY DIFFUSE BACK REFLECTION FROM THE REGION BETWEEN CELLS CAN CONTRIBUTE TO SYSTEM PERFORMANCE
- SYSTEM TRADE-OFF IS BETWEEN CELL SPACING, COVER THICKNESS AND INDEX OF REFRACTION
- LIGHT TRAPPING WORKS OVER THE ENTIRE HEMISPHERE THUS, PROVIDING CONCENTRATION OF SOLAR DIFFUSE RADIATION AS WELL AS DIRECT

Module Layout; Cell-Spacing Geometry



Definition of Layers in Baseline Module Cross Section*

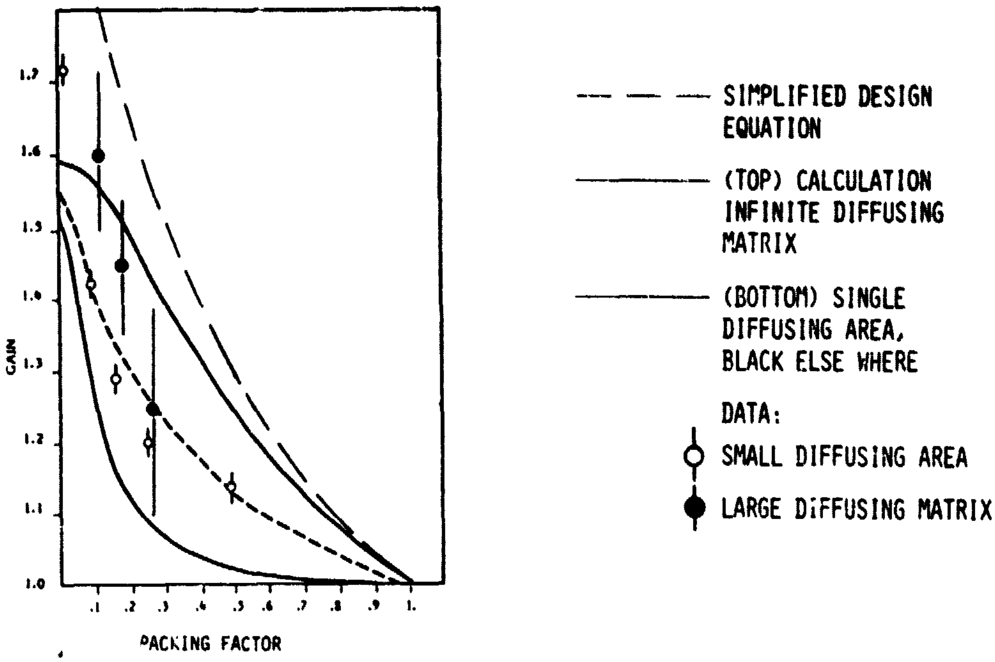
OPTICALLY IMPORTANT MODULE LAYERS FROM SUN SIDE DOWN	PREFERRED MATERIAL CHOICES AND NOMINAL THICKNESS: LAMINATION	CASTING
SUPERSTRATE DESIGN:		
TOP COVER	LOW IRON, TEMPERED SODA-LIME GLASS, 125 MIL MINIMUM	SAME
POTTANT	ETHYLENE VINYL ACETATE (EVA) OR ETHYLENE METHLYACRYLATE (EMA), 5 MIL MINIMUM	POLY-N-BUTYL ACRYLATE, OR ALIPHATIC POLYETHER URETHANE, OR GE SILICONE 534-044, 5 MIL MINIMUM
SPACER	NON-WOVEN GLASS MAT TO ACHIEVE MINIMUM POTTANT THICKNESS - CRANEGLAS	MAY NOT BE REQUIRED
SUBSTRATE DESIGN:		
TOP COVER	BIAXIALLY ORIENTED POLYMETHYLMETH - ACRYLATE (PMMA) OR TEDLAR, 3 MIL	SAME
POTTANT	NONE RECUIRED ON SUN SIDE	SAME
FOR EITHER MODULE:		
CELLS	FOUR INCH ROUND OR FOUR BY ONE INCH RECTANGULAR, PACKING FACTOR 0.6 TO 0.85	SAME

*SOURCE: JPL LETTER TO SAI OCTOBER 1, 1980.

Variation in Module Thickness

- THE THICKNESS OF A PHOTOVOLTAIC MODULE IS A FUNCTION OF MODULE SIZE, MATERIALS USED, WIND AND ENVIRONMENTAL LOADS ON THE MODULE AND THE ARRAY STRUCTURE.
- IN MODULES WHERE THE ENCAPSULATING MATERIALS PROVIDE MOST OF THE MODULE STRENGTH, SUPERSTRATE LAYER THICKNESSES MAY INCREASE OPTICAL PERFORMANCE AND STRENGTH.
- IN LIGHT TRAPPING PV MODULES, THE IMPORTANT DESIGN PARAMETERS ARE:
  - MATERIAL INDEX AND TRANSMISSION
  - LENGTH OF TRANSMISSION PATHS
  - NUMBER OF REFLECTIONS, ENERGY ABSORBED
  - TRAPPING LAYER MATERIAL HEAT CAPACITANCE
- MATERIAL(S), THICKNESS OF TRAPPING LAYER(S), CELL SIZE AND PF CAN BE CONTROLLED TO MAXIMIZE GAIN, OR TO MINIMIZE MODULE COST PER WATT.
- THESE PARAMETERS AND COSTS CAN BE TRADED OFF AGAINST LAND, STRUCTURE, AND OPERATION AND MAINTENANCE COSTS TO MINIMIZE SYSTEM COST PER WATT.

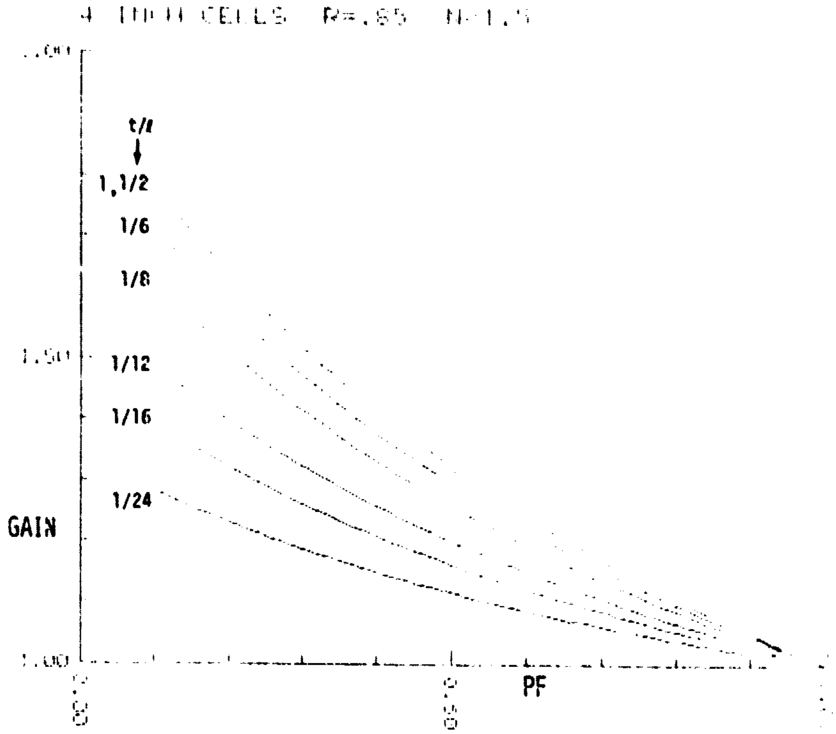
Experimental Confirmation

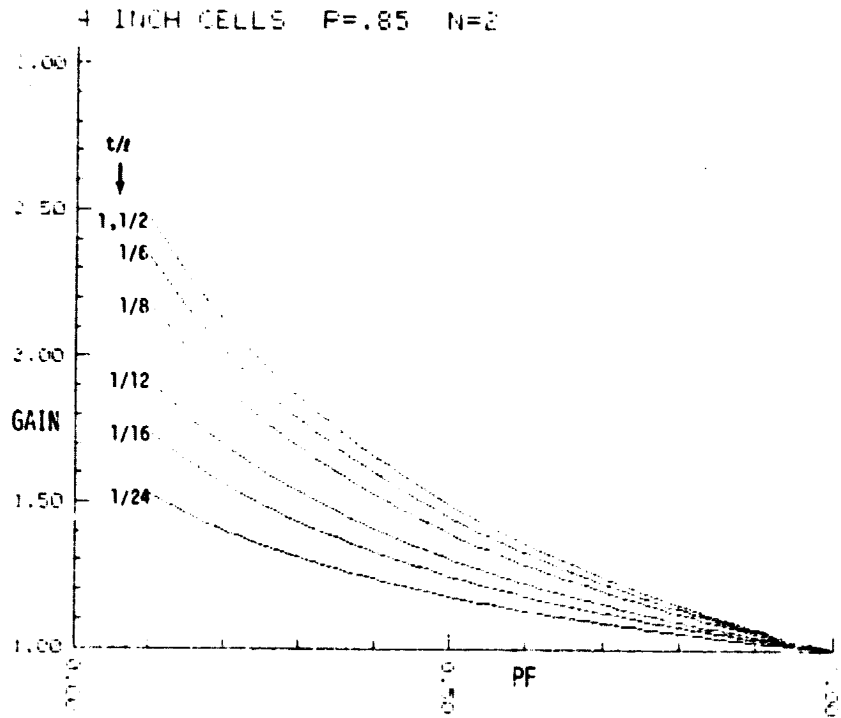


Design Rules

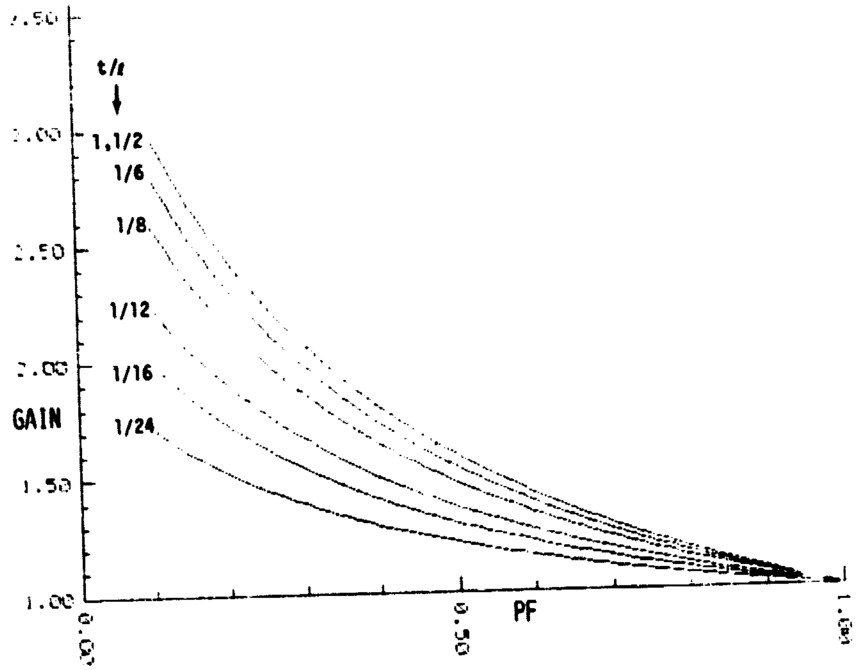
- VARIATION IN MODULE THICKNESS/MATERIAL INDEX OF REFRACTION
- TRAPPING GAIN AS A FUNCTION OF PACKING FACTOR AND LAYER THICKNESS

Design Equations for Various Indexes of Encapsulant, Thickness and Packing Factor

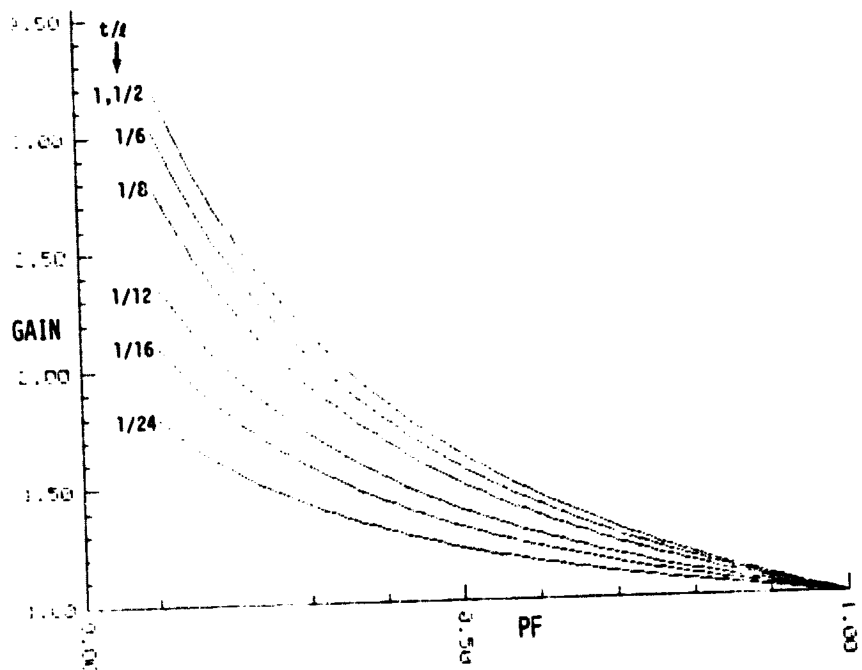




4 INCH CELLS P=.85 N=2.5



4 INCH CELLS P=.85 N=2.8



Typical Gains for Block III Modules Using Simplified Design Equations

SUPPLIER	AS CONFIGURED	WITH T = 1/2"
ARCO	1.08	1.17
MOTOROLA	1.10	1.20
SENSOR TECHNOLOGY	1.12	1.24
SOLAR POWER	1.06	1.13
SOLAREX	1.13	1.26

Module Design

- MODIFICATIONS FOR LIGHT TRAPPING
- MAXIMIZING GAIN IN A DENSELY PACKED MODULE
- MULTIPLE LAYERS
- INTER-CELL/INTRA-CELL TRAPPING

Maximizing Gain in Densely Packed Module

THESE STEPS WILL PRODUCE AN OPTICALLY EFFICIENT PV MODULE:

- AR COATING
- ADD DIFFUSE REFLECTOR
- OPTIMIZE SUPERSTRATE THICKNESS BASED ON CELL SIZE
- UTILIZE TWO OR MORE TRAPPING LAYERS
- USE DIFFUSING LAYER ON CELL GRIDS
- ADD REFLECTORS TO SUPER- AND SUB-STRATE EDGES
- OPTIMIZE LOAD

Modifications for Light Trapping

Design Options to be Considered

MATRIX OF STUDY CASES	PANEL PERFORMANCE IMPROVEMENT DUE TO TRAPPING FROM	
COMPLEXITY OF TRAPPING LAYER	INTER-CELL REGION	INTRA-CELL REGION
Single Layer	(BASELINE CASE)	
• Existing Design	Use Commercial Module Design	Use Commercial Cell Design
• Optimal Design	Design is a Function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout
Multiple Layers		
• Existing Design	Use Commercial Module Design	Use Commercial Cell Design
• Optimal Design	Design is a function of Time as Cell Costs Decline with Time	Optimize Cell Grid Layout

Intercell-Intracell Trapping

- INTER-CELL TRAPPING TRAPS LIGHT BY DIFFUSE BACK REFLECTION FROM THE REGIONS BETWEEN CELLS
- INTRA-CELL TRAPPING USES A DIFFUSING LAYER ON THE CELL GRID ITSELF TO RECOVER A LARGE PART OF GRID BLOCKAGE LOSSES
- IN BOTH CASES LIGHT TRAPPING WORKS OVER THE ENTIRE HEMISPHERE THUS PROVIDING CONCENTRATION OF THE SKY DIFFUSED COMPONENT OF SOLAR RADIATION

System Concepts That Exploit Light Trapping

- GROWTH SYSTEM
- WALL INTEGRATED SYSTEMS

Growth System

- DESIGNING A PHOTOVOLTAIC SYSTEM TO ALLOW FOR THE OPTIMUM PACKING FACTOR WITH TODAY'S PRICES, CAN ALSO ALLOW A MORE EFFECTIVE SYSTEM WHEN THE DOE COST GOALS ARE MET OR EXCEEDED, SINCE THE INFLATION SENSITIVE MATERIAL AND LABOR ITEMS ARE PRODUCED EARLY.

ECONOMIC MODEL

REQUIRED AREA OF SOLAR CELLS $A_S = \frac{P_{OUT}}{\eta I G}$

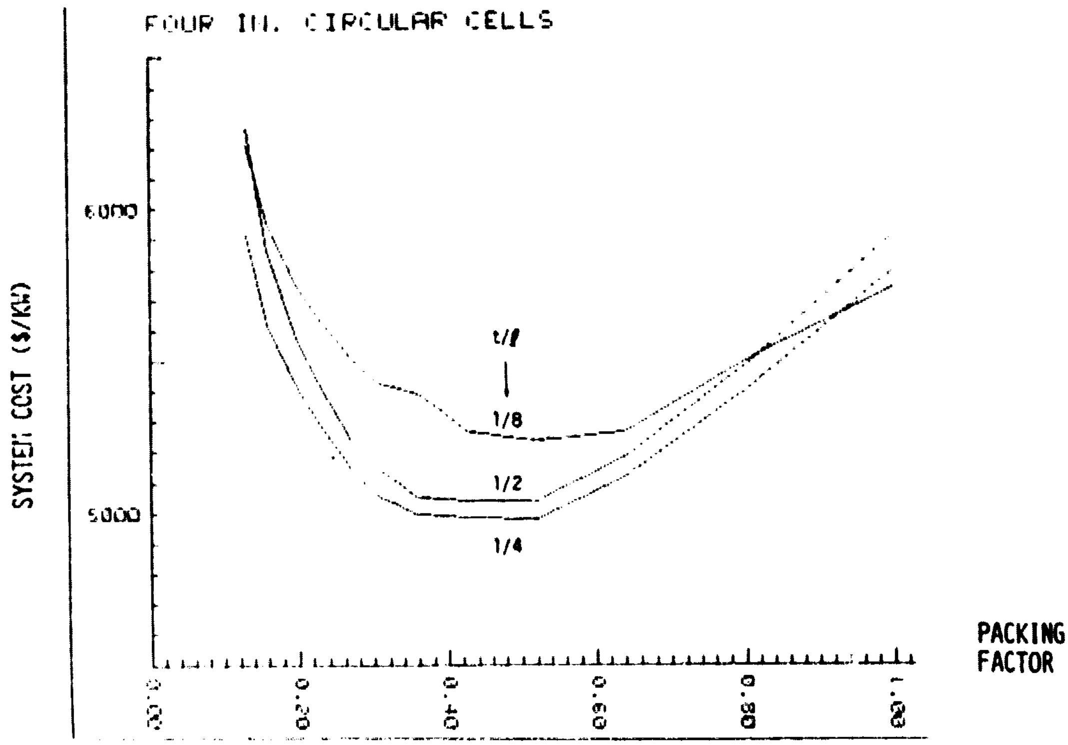
REQUIRED TOTAL AREA $A_T = \frac{A_S}{P.F.}$

TOTAL COST $= C_T = A_S C_S + A_T [C_C + C_F + C_L]$

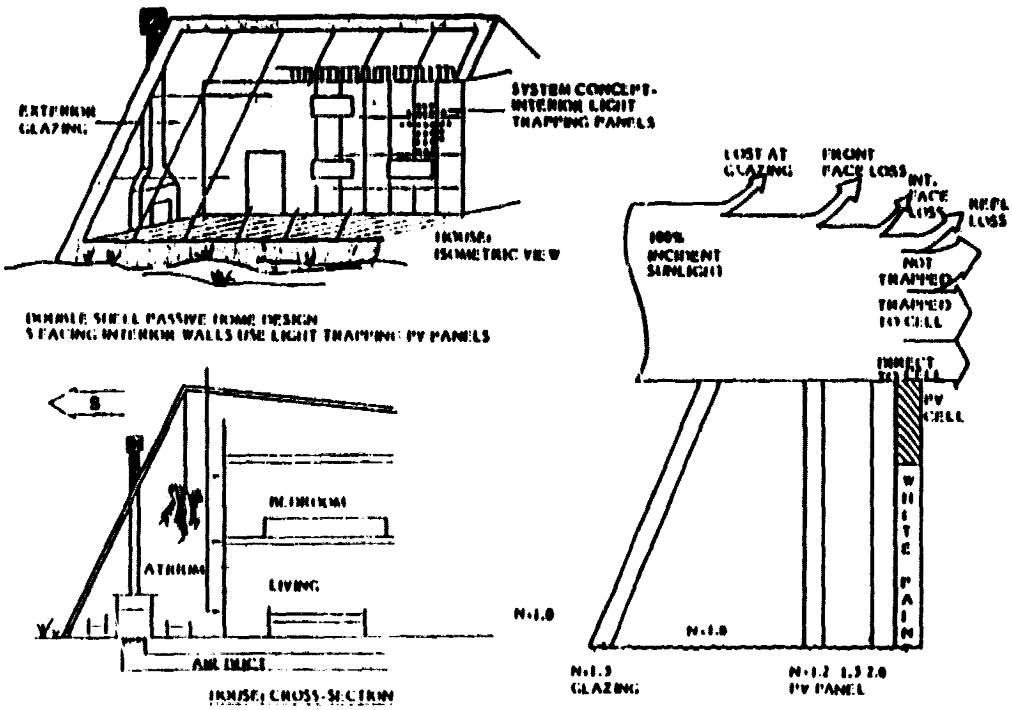
COST/M² OF:	SOLAR CELLS	TRAPPING LAYER	STRUCTURE	LAND

$$C_T = \frac{P_{OUT}}{\eta I G} [C_S + \frac{1}{P.F.} (C_C + C_F + C_L)]$$

Example: 1980 Cell Prices, Three Encapsulant Thickness



Wall Integrated System



Future Prospect

- GOALS OF COST/BENEFIT STUDY
- INFORMATION NEEDED

Goals of Cost-Benefit Study

AS A FOLLOW-UP TO THE DESIGN GUIDE A COST/BENEFIT STUDY WAS PERFORMED

- USES SIMPLIFIED DESIGN EQUATION FOR PV MODULE PERFORMANCE
- SIMPLIFIED COSTING EQUATIONS TO RELATE COST OF CELLS, ENCAPSULANT, ARRAY STRUCTURES AND LAND AT A CONSTANT POWER LEVEL, WERE DEVELOPED
- THE GOAL IS TO DETERMINE THE OPTIMUM COST/BENEFIT POINT FOR OPTICAL DESIGN OF PHOTOVOLTAIC PANELS.

Information Required

IN ORDER TO PERFORM THE COST/BENEFIT STUDY THE FOLLOWING DATA IS REQUIRED:

- MODULE
  OPTICAL MATERIALS, INDEX, ABSORPTION, VOLUMETRIC COST OF MATERIALS, COST OF LABOR FOR MANUFACTURER

  COST OF CELLS, AND EFFICIENCY
- ARRAY
  AREA RELATED COST OF ARRAY STRUCTURE,

  COST OF LAND

PROCEDURE IS TO TRADE-OFF PACKING FACTOR, AND/OR MODULE THICKNESS VERSUS COST FOR THE SAME LEVEL OF DELIVERED ELECTRICAL POWER.

Conclusions

- OPTICAL DESIGNS OF PV PANELS USING LIGHT TRAPPING INTRODUCE A HOST OF NEW PARAMETERS THAT MUST BE CONSIDERED IN PV MODULE DESIGN AND NEW RESEARCH AND DEVELOPMENT AVENUES THAT PROMISE TO PROVIDE EARLY DIVIDENDS.
- LIGHT TRAPPING CAN BE USED TO:
  - IMPROVE EFFICIENCY IN STANDARD PV MODULES
  - OPTIMIZE PV MODULE DESIGNS BASED ON COST USING CURRENT AND PROJECTED MATERIAL, LABOR, MONEY AND REAL ESTATE
  - IMPROVE THE EFFICIENCY OF SOLAR SYSTEMS ARCHITECTURALLY INTEGRATED INTO BUILDINGS TO PROVIDE PV ELECTRIC POWER GENERATION, SPACE HEATING AND DIFFUSE LIGHTING.
- LIGHT TRAPPING PV MODULES USING TRAPPING LAYERS MADE OF CURRENTLY AVAILABLE MATERIALS IS ALREADY A VIABLE PROPOSITION. THE DEVELOPMENT OF HIGHER INDEX MATERIALS CAN IMPROVE THIS SITUATION EVEN AS CELL COSTS DECLINE.

Design Method

- FAMILIARIZATION WITH CONCEPTS - EXAMPLES
- OBTAIN DATA ON MATERIALS: OPTICAL PROPERTIES AND COSTS TO AUGMENT DATA ON MODULE
- USE DESIGN NOMOGRAPHS OR SIMPLFIED DESIGN EQUATION TO OBTAIN GAIN AS A FUNCTION OF PACKING FACTOR AND THICKNESS OF ENCAPSULANT ABOVE CELL
- USE COSTING NOMOGRAPH OR SIMPLIFIED COSTING EQUATIONS TO DETERMINE GAIN FOR VARIOUS PACKING FACTOR AND THICKNESS VALUES, FIND A COST MINIMUM
- ESTIMATE COST SAVINGS OBTAINED AT MINIMUM AND COMPARE WITH STANDARD DESIGN
- REPEAT WITH OTHER MATERIAL CHOICES

Recommended Applications

BASED ON THIS STUDY IT IS RECOMMENDED THAT DESIGNERS CONSIDER LIGHT TRAPPING DESIGNS IN SITUATIONS WHERE

- ROUND CELLS (FULL OR PARTIAL) ARE TO BE UTILIZED
- SILICON IS COSTLY AND/OR IN SHORT SUPPLY
- CELLS ARE ROOF AND/OR WALL INTEGRATED (RESIDENTIAL)
- MODULE THICKNESS IS IMPORTANT - (HAIL AREAS IS AN EXAMPLE)
- RAPID POWER REQUIREMENT GROWTH IS ANTICIPATED AT SITE
- THIN OR SHARP SHADOWS FALL ON ARRAY
- ARRAY AREA COSTS ARE LOW

References

1. T.M. KNASEL, SYSTEM DESIGNS FOR LOW COST-LOW RATIO SOLAR CONCENTRATORS SPIE VOL. 161, OPTICS APPLIED TO SOLAR ENERGY IV (1978).

2. UNITED STATES PATENT NO. 4,162,928, "SOLAR CELL MODULE", NEAL F. SHEPARD, JR., JULY 31, 1979, (ASSIGNED TO NASA).

3. UNITED STATES PATENT NO. 4,116,718, "PHOTOVOLTAIC ARRAY INCLUDING LIGHT DIFFUSER", J.W. YERKES AND J.E. AVERY, SEPTEMBER 26, 1978 (ASSIGNED TO ATLANTIC RICHFIELD CO.).

4. N.F. SHEPARD, "DEVELOPMENT AND TESTING OF SHINGLE-TYPE SOLAR CELL MODULES-FINAL REPORT" DOE/JPL-954607-79/4, FEBRUARY 28, 1979.

5. J.G. MARK AND C.H. VOLK, "THE ZERO DEPTH CONCENTRATOR PHENOMENON", JPL 5101-13B.

6. UNITED STATES PATENT APPLICATION "FIXED SOLAR ENERGY CONCENTRATOR" (ASSIGNED TO SCIENCE APPLICATIONS, INC.).

ANALYSIS AND EVALUATION OF PROCESS AND EQUIPMENT

UNIVERSITY OF PENNSYLVANIA

M. Wolf

Design Rules for Front Metallization Of Large-Area Solar Cells

1. Observe: Careless metallization design is costly.

2. Select conductor metal of the highest practical conductivity.

3. Select deposition processes which approach bulk conductivity as closely as practical.

4. Each higher level in the hierarchy of conductors needs a much lower sheet resistance than the preceding level. This leads to the "sky scraper rule" for the bus lines: Build high rather than wide.

5. If the bus lines cannot have a sheet resistance small compared to the grid lines, omit the bus lines. Proceed directly to 10.

6. Select the bus line spacing, for bus lines of round wire, according to:

$$2W = \left(\frac{3}{\pi^2}\,\frac{\rho_{BL}^{\;2}}{R_{sh,GL}^{\;3}\;{}_{GL}^{\;3}}\,\frac{V_{mp}}{|j_{mp}|}\right)^{1/8} L_1^{\;1/2}$$

7. Select bus line wire diameter according to:

$$T_{BL} = \left(\frac{32}{3\pi}\,\frac{|j_{mp}|\,\rho_{BL}}{V_{mp}}\,L_1^{\;2}\,W^2\right)^{1/3}$$

8. For rectangular bus wires of height-to-width ratio k, multiply each π by $4k/\pi$.

9. For bus lines of constant sheet resistance $R_{sh,BL}$, rather than thickness directly proportional to width, as in round or rectangular wires, the relationship:

$$\frac{T_{BL}}{2W} = L_1 \left(\frac{|j_{mp}|}{3\ V_{mp}} R_{sh,BL}\ \delta_{BL} \right)^{1/2}$$

applies, instead of 6.) and 7.). Choose W then as small as practical, considering 13.) and 14.).

10. Arrange grid lines normal to bus lines, and parallel to each other.

11. Select grid line width as small as practical, commensurate with acceptable production costs and yields and solar cell value differences resulting from the consequent efficiency differences.

12. Select grid line spacing S according to:

$$S = \left(\frac{6\ V_{mp}}{|j_{mp}|} \frac{T_{GL}}{R_{sh,FL}} \right)^{1/3} - \frac{2^{\ 4/3}}{3} \frac{R_{sh,GL}\ \delta_{GL}}{R_{sh,FL}} \frac{W^2}{T_{GL}}$$

13. Check that

$$\frac{T_{GL}}{S} \approx \left(\frac{1}{3} R_{sh,GL}\ \delta_{GL} \frac{|j_{mp}|}{V_{mp}} \right)^{1/2} W$$

14. Check that

$$S \leq 2 \cdot \left[\frac{\left(R_{sh,GL}\ \delta_{GL}\right)^{1/2}}{R_{sh,FL}} \left(\frac{3\ V_{mp}}{|j_{mp}|} \right)^{1/2} W \right]^{1/2}$$

15. If checks 13.) and 14.) are negative, select S as small as possible in view of 11.), but not significantly larger than given by 14.). If T_{GL}/S is large compared to right hand side of 13.), use the smallest practical value for T_{GL}, if pattern resolution is limiting. If grid line width-to-thickness ratio is limiting, reduce thickness (increase $R_{sh,GL}$), to find T_{GL} and $R_{sh,GL}$ values for least power loss.

16. The "shape factor" δ varies from 0.75 for fully tapered grid lines to unity for uniform width lines of equal shading.

Back Metallization

3 LAYERS IN PARALLEL:

$$R_{SH,P} = \frac{1\ \Omega\ \text{CM}}{2 \cdot 10^{-2}\ \text{CM THICK}} = 50\ \Omega\ ;$$

$$R_{SH,P+} = \frac{0.02\ \Omega\ \text{CM}}{2 \cdot 10^{-3}\ \text{CM THICK}} = 10\ \Omega\ ; \quad (N_A = 2 \cdot 10^{18}\ \text{CM}^{-3}\ ;\ \mu_P = 160\ \text{CM}^2\ V^{-1}\ s^{-1}.)$$

$$R_{SH,Cu} = \frac{1.7 \cdot 10^{-6}\ \Omega\ \text{CM}}{1 \cdot 10^{-4}\ \text{CM THICK}} = 1.7 \cdot 10^{-2}\ \Omega\ ;$$

COMPOSITE SHEET RESISTANCE:

$$R_{SH,COMP} = \frac{R_{SH,P} \cdot R_{SH,P+} \cdot R_{SH,Cu}}{R_{SH,P+}\ R_{SH,Cu} + R_{SH,P}\ R_{SH,Cu} + R_{SH,P}\ R_{SH,P+}}$$

$$= \frac{50 \cdot 10 \cdot 1.7 \cdot 10^{-2}}{1.7 \cdot 10^{-1} + 8.5 \cdot 10^{-1} + 50 \cdot 10} = 1.7 \cdot 10^{-2} \quad (-0.2\%)$$

CONCLUSIONS:

1. METAL DOMINATES SHEET FLOW, EVEN IN 0.1 μM THICKNESS.
2. CURRENT FLOW THROUGH SEMICONDUCTING BASE (P AND P+) IS NORMAL.

BUT:

3. BUS WIRES ON BACK PERMIT LAYER-METAL SAVINGS FOR EQUAL PERFORMANCE. (IMPORTANT FOR TF Ag WITH Cu BUS WIRES.)

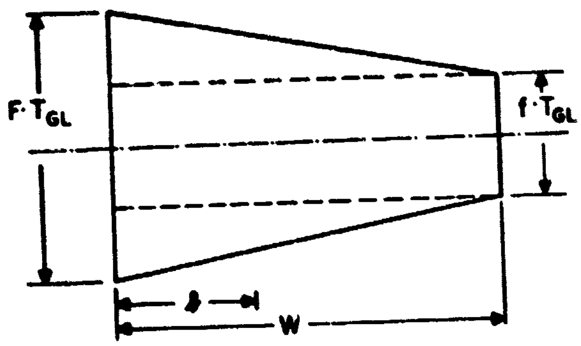
GENERAL:

4. GRID STRUCTURE ON BACK DOES NOT PROVIDE METAL SAVING, REQUIRES PROPORTIONALLY GREATER THICKNESS FOR EQUAL PERFORMANCE.

Optimization Constraints

1. WHERE SHEET RESISTANCE (OR CONDUCTOR THICKNESS) IS FIXED, AN OPTIMIZATION OF INDIVIDUAL DIMENSIONS IS NOT POSSIBLE. OPTIMUM WOULD BE SPACING $\cdot$ 0. HOWEVER, THE SHADING RATIOS $\frac{T_{GL}}{S}$ AND $\frac{T_{BL}}{2W}$ CAN BE OPTIMIZED. (DESIGN RULES 9 AND 13.)
2. WHERE CONDUCTOR THICKNESS IS PROPORTIONAL TO WIDTH, INDIVIDUAL DIMENSIONS CAN BE OPTIMIZED. (DESIGN RULES 6 AND 7.)
3. WHEN TECHNOLOGICAL CONSTRAINTS DETERMINE THE LINE WIDTH, AN OPTIMUM SPACING CAN BE DETERMINED. (DESIGN RULE 12.)
4. REDUCING LINE SPACING, WHILE KEEPING THE LINE WIDTH TO SPACING RATIO CONSTANT, REDUCES THE VOLTAGE DROP IN THE NEXT LOWER LEVEL OF CONDUCTOR (V_{FL} $\cdot$ 0, WHEN S $\cdot$ 0). HOWEVER, IT DOES NOT MAKE SENSE TO REDUCE THE SPACING FURTHER, WHEN THE NEXT LOWER LEVEL VOLTAGE DROP IS ALREADY NEGLIGIBLE COMPARED TO THE HIGHER LEVEL CONDUCTOR VOLTAGE DROP AND SHADING LOSS. (DESIGN RULES 14 AND 15.)

Tapered Grid Lines



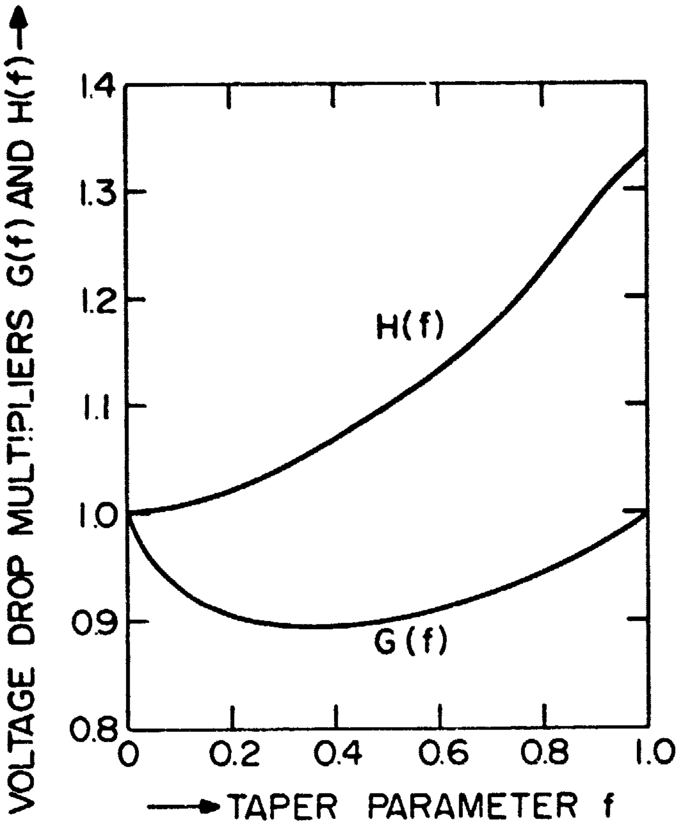
S = CLEAR SPACING BETWEEN GRID LINES

$$V(W) = R_{SH} J_{MP} \frac{S\,W^2}{2\,T_{GL}} \cdot G(F) \;;$$

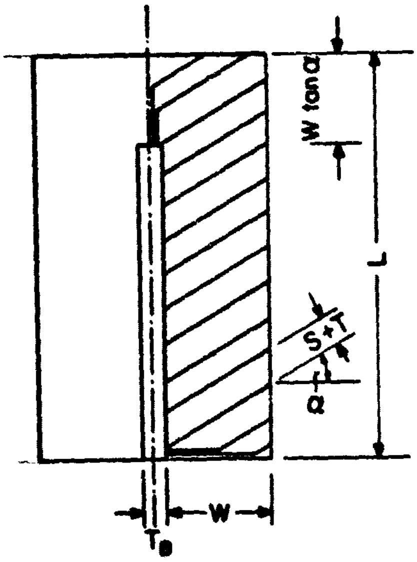
$$P = J_{MP}\, S\, W\, V_{EFF}(F) \;;$$

$$V_{EFF} = V(W) \cdot \frac{1}{2} \cdot H(F) \;;$$

	F	G(F)	V_{EFF}
Uniform Width	1	1	$\frac{2}{3}$ V(W)
Fully Tapered	0	1	$\frac{1}{2}$ V(W)


VOLTAGE DROP MULTIPLIERS G(f) AND H(f)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
0.2
0.4
0.6
0.8
1.0
H(f)
G(f)
TAPER PARAMETER f

Oblique Grid Lines



$$V_{OBL}(W) = \frac{V_{NORM}(W)}{\cos^2 \alpha} ;$$

$\alpha = 30°$: $V_{OBL}(W) = 1.33\ V_{NORM}(W)$;

OR: $T_{GL,OBL} = 1.33\ T_{GL,NORM}$;

TO OBTAIN $V_{OBL}(W) = V_{NORM}(W)$

	$\alpha = 0°$	$\alpha = 30°$
Grid Shading	0.3 cm^2	1.066 cm^2
Bus Shading	0.36 cm^2	0.30 cm^2
Add'l Connections	-	0.035 cm^2
Total Shading	1.16 cm^2	1.40 cm^2
Rel. Power Loss	0	-0.6%
[illegible]	0	-0.1%

Hierarchy of Conductors: Decreasing Sheet Resistance

SEMICONDUCTING FRONT LAYER: $R_{SH,FL}$ 35 Ω

GRID LINES (10 μM THICK CU): $R_{SH,GL} = 1.7 \cdot 10^{-3}$ Ω

BUS LINES (30 GA CU WIRE, 0.255 MM DIA.): $R_{SH,BL}$(EQUIV.) $= 8.5 \cdot 10^{-5}$ Ω

> IF $R_{SH,BL} = R_{SH,GL}$: DO NOT USE BUS LINES!

MINIMUM LOSS WITH GRID LINES ONLY, S→0, 10 CM x 10 CM CELL: $\frac{\Delta P_{FRONT}}{P_{IDEAL}} = 11.7\%$

EXAMPLES FOR 10 CM x 10 CM CELLS:

A.) 65 GRID LINES, 10 μM THICK CU, 85 μM WIDE $\frac{\Delta P_{FRONT}}{P_{IDEAL}} = 12.0\%$

B.) 65 GRID LINES, 10 μM THICK CU, 25 μM WIDE
7 BUS LINES, 10 μM THICK CU, 750 μM WIDE $\frac{\Delta P_{FRONT}}{P_{IDEAL}} = 12.1\%$

C.) 65 GRID LINES, 10 μM THICK CU, 25 μM WIDE
7 BUS LINES, 255 μM DIA CU WIRE $\frac{\Delta P_{FRONT}}{P_{IDEAL}} = 4.9\%$

Effect of Metal Mass on Cell and Its Price

METALLIZATION OPTION	GRID LINES NO	T_{GL}	THICK	MASS 1)	BUS LINES NO	T_{BL}	THICK	MASS 1)	BACK METAL BUSSES	THICK	MASS 1)	TOTAL MASS 1)	METAL PRICE	METAL COST	POWER LOSS
	-	μM	μM	MG		μM	μM	G	-	μM	MG	G	\$/G	\$/M^2	%
TF AG	40	127	20 2)	52.5	4	271	20 2)	10.6	0	20 2)	1060	1.1	0.50	55	9.1
TF AG	DTO				DTO				4	0.4	21	0.034	0.50	4.2	9.1
BULK CU	65	25	10	146	7	255 DIA		324	0	10	900	1.25	0.002	0.25	5.3

1) *PER 10 CM x 20 CM CELL

2) 50% OF VOLUME IS AG

ENGINEERING AREA
OPERATIONS AREA

JOINT TECHNOLOGY SESSION

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

At the Wednesday-afternoon session of the PIM devoted to Block IV Module Production, contractors commented on the efficacy of that initiative by addressing design and performance requirements, environments, SAMICS-SAMIS, and general topics. Discussion was candid and, not surprisingly, there were both positive and negative comments on the contract content. A summary of these comments is given below.

Under the topic Design and Performance Requirements, these remarks stand out as subjects for consideration and concern:

1. Standardizing on a module terminal voltage is not necessary, and when coupled with dimensional constraints and the requirement to specify power at NOCT, becomes an important cost driver.

2. Redundant terminals serve no crucial purpose and raise the cost, but redundant interconnects are of significant value.

3. Efficiency was characterized both as being of critical importance and of secondary importance.

4. The need for shunt diode protection when arrays are used with maximum power tracking electronics in highly paralleled arrays was challenged. The case for diodes located external to the modules was advocated. The hot-spot endurance of modules should be verified (as planned for Block V).

5. The focus on residential and intermediate-load modules was said to be out of step with the market, which now is oriented toward remote applications.

6. The documentation required by JPL in support of a design program is unreasonable.

7. The quality assurance program demanded by JPL is too rigorous, given recent improvements in module yield and reliability. QA imposed is not what contractors use for commercial product line.

"Environmental Requirements" also elicited a wide range of comments:

1. Thermal and humidity testing was characterized both as valid and as inadequate. Recommendations were received both for more severe and for less severe testing. Constant, longer-term humidity testing at lower temperature rather than cycling was suggested. Thermal cycling both before and after humidity testing was proposed. Less severe thermal cycling but with increased number and rate of cycles was recommended.

2. Environmental design and testing should be site specific.

3. Tests such as hail and twist should be deleted when prior testing or analysis shows that design is satisfactory.

4. Wind loading should be a panel requirement, not a module requirement. That is, structural capability of modules should be evaluated as installed (rack or roof, as applicable).

5. Pass-fail should be determined on a performance basis, not on cosmetic criteria; a 5% performance degradation limit is too small.

6. In qualifying modules there is no need to run tests by both the contractor and JPL. Substantial costs to contractors for duplicate tests were identified.

7. Environmental testing is not a substitute for life testing.

8. Increased emphasis should be placed on reliability and durability requirement.

The use of SAMICS-SAMIS elicited considerable spirited discussion; comments ran the gamut from favorable to unfavorable, as follows:

1. Program is easy to use; program is difficult to use. The consensus was that it is difficult to use, particularly for new users who lack computer experience.

2. The high cost of running the program is a nearly universal objection.

3. Their usefulness is generally held to be dubious, primarily because of the imprecision of the Block IV input data, but there were also complaints that SAMIS overhead is too high and that some catalog prices are not correct.

4. Some contractors preferred to omit SAMIS (Solar Power) or do their own cost projection (Motorola).

5. Since the results can be manipulated, the program is valuable only in a relative sense; however, there was fairly good agreement between SAMIS results and prior contractor bids in several cases.

In the area of general comments, the need for more rapid feedback from JPL was mentioned, and the desirability of having large prototype runs was also expressed.

In the open discussion that followed the contractors' presentations, cognizant JPL personnel responded to these comments. It is expected that some -- but not all -- of the recommendations can be incorporated in the Block V contracts.

In the Thursday-morning session, John Griffith, LSA Environmental Test Director, presented the results of comparative environmental testing of candidate foreign and domestic modules for water-pumping applications. The U.S. modules compared favorably with their foreign competitors. In exploratory testing of 11 modules in the proposed new Block V humidity-freeze cycle, this was seen to be more effective than the Block IV sequence in inducing corrosion, delamination, and some forms of power degradation.

Steve Forman of MIT-LL gave an update of applications experiments experience and a status report on residential experiments under development. Residential sites in the Northeast are nearing completion, and the Southwest Residential Experiment station (RES) is approaching the hardware phase. Array performance at the various MIT-LL sites continues to be excellent, with some concern about the increasing frequency of interconnect failures and discoloration of PVB-encapsulated cells.

Charles Cox of MIT-LL reported on their recently developed I-V meter for field use. The meter uses a capacitor-charging method of I-V curve tracing and is capable of handling high-power (multiple-module) measurements.

Steve Sollock and Alex Shumka of the JPL Failure Analysis Laboratory gave a joint presentation on module cell string shorts to ground. Sollock presented a historical overview that showed the problem to be prevalent and persistent, and he characterized the various types of shorts that have been encountered. Shumka detailed the causes of each type, and described the experimental tools available for analysis. It was concluded that the problems seen to date can be prevented through attention to design and workmanship.

R.G. Ross, Jr., Engineering Area manager, presented a summary of Engineering Area activities since the 16th PIM. Recently published reports by Engineering Area contractors include the Phase I report on Product Liability Assessment by Carnegie-Mellon University and the Third Annual Report of the Clemson University cell-reliability testing contract.

In the area of requirements development, two new module design and test specification drafts prepared by LSA Engineering were distributed to the PV industry for review and comment, along with a preliminary draft of a module and array safety requirements document, jointly developed by JPL and Underwriters Laboratories.

An industry workshop on module and array safety was conducted in conjunction with the 17th PIM on February 3, 1981.

ENGINEERING AND OPERATIONS AREAS

As part of the Array Subsystem Development activities, a design data package for the LSA-developed Low-Cost Array Structure was made available to industry participants.

Contract awards were made during this reporting period to General Electric Co. and the American Institute of Architects Research Corp. for integrated residential PV array development. In the area of Module Engineering and Reliability, reports were issued covering in-house soiling studies and the proceedings of the Cell Reliability Workshop that was sponsored jointly by JPL and Clemson University. A number of ongoing tasks were described briefly in the areas of requirement development, array subsystem development, module engineering and reliability studies, and standards activities. The status of a number of these activities was described in a technical session held jointly with the Operations Area.

Due to a schedule conflict, Dr. Weinstein of Carnegie-Mellon University was unable to present his discussion of Module Product Liability as planned during the joint session; however, participants in the Safety Workshop did hear his presentation covering methodology for assessment of product safety and liability.

A presentation by J. Oster and R. Rittelmann of Burt Hill Kosar Rittelmann Associates described the results of their study of commercial and industrial PV module and array requirements based on a review of building codes and regulations. Important findings were related to module sizing and modularity, material selection restrictions, and wiring and interconnection concerns, especially with regard to the National Electric Code.

A defect design approach to sizing terrestrial photovoltaic electrical insulation systems was presented by C. R. Mon. The approach consists of gathering quantitative data characterizing voltage breakdown statistics of thin insulating films. For a designated failure density the number of layers of film of a particular thickness can be selected. Typical flaws that can enhance the likelihood of breakdown were discussed and design procedures to minimize their effects presented.

The method realizes its full power when failure rate data is available. This technique was discussed and preliminary results were presented.

Clemson University offered a presentation covering exploratory testing of several different types of photovoltaic cells for the purpose of investigating possible correlation between cell electrical characteristic degradation and losses and/or removal of antireflective (AR) coating. The initial impetus to study this problem came from reports on field observations made by MIT-LL on modules taken from photovoltaic field application sites. When MIT-LL personnel learned of the availability of special equipment at Clemson University, i.e. an IBM 7400 Spectrophotometer, it was suggested to the JPL Engineering Area that quantitative tests using color spectrum analyses might provide useful reliability data.

From the tests performed, plots were generated of percentage decrease in electrical output vs percentage missing AR coating from the cell. The color-spectrum analysis data gathered was taken using strict controls on orientation and alignment, observation angle and spectrual reflectance. Data derived from use of IBM 7400 spectral reflectance measurements included chromasticity tristimultus, etc.

Module hot-spot endurance test development was addressed in presentations prepared jointly by J. Arnett and C. Gonzalez. Details of the new Block V Hot-Spot Endurance Test Procedure and its rationale for development were presented at the Safety Workshop on February 3. As a follow-up, specific testing results and preliminary design information were presented at the joint technology session.

In presentations by R. Whitaker and E. Zerlaut of DSET Laboratories, Phoenix, Arizona, the current status of two LSA Engineering Area contracts was described. The results of a total of 1.7×10^6 langleys of exposure of Block III Modules (approximately equivalent to 8.5 years of weathering) during the preceding 18 months was described along with examples of typical before-and-after I-V measurements. Completion of the computer software and instrument calibration for the DSET Scanning Spectroradiometer was reported along with sample solar spectral curves as part of the Natural Sunlight Measurements contract.

BLOCK IV CONTRACTOR EXPERIENCE

APPLIED SOLAR ENERGY CORP.
Bill Sampson

Design and Performance Requirements

- REQUIRED OUTPUT VOLTAGE WITHIN A RANGE (15V-60V) NOT FIXED.
- REDUNDANT CIRCUIT THROUGHOUT NOT ONLY AT TERMINATION
- BYPASS DIODES EXTERNAL TO MODULE.
- MODULE INTERCHANGEABILITY SHOULD END WITH PHYSICAL DIMENSIONS ONLY NOT ELECTRICAL PERFORMANCE

Effect of Design Requirement

- FIXED VOLTAGE REQUIREMENT

  1. NONSTANDARD CELL SIZE (3.05" DIAMETER)
  2. LOWER PACKING FACTOR
  3. ADDITIONAL ENGINEERING TIME
  4. INCREASED COSTS

- FIXED ENVELOPE DIMENSIONS AND INCREMENTAL DIMENSION RESTRICTIONS

  1. LOWER PACKING FACTOR
  2. DETERMINED CELL SIZE AND QUANTITY
  3. DOES NOT FIT ANY COMMERCIAL OR ARCHITECTURAL STANDARD

Module Efficiency

- EFFICIENCY SHOULD NOT BE A FACTOR IF IT IS NOT ECONOMICAL.

Knowledge Gained During This Contract

- TEMPERED GLASS
- REDUCTION OF HOT SPOTS
- LOW COST FRAME ASSEMBLY
- BYPASS DIODES
- TEDLAR SUBSTRATE
- SAMICS PROGRAM

Environmental Test Requirements

- SEVERITY
  1. COVERS EXTREME ENVIRONMENTAL CONDITION
  2. CYCLE TIME FASTER THAN ACTUAL IN MANY CASES

- RESULTS
  1. PASS/FAILURE BASED ON ELECTRICAL PERFORMANCE AND SAFETY.
  2. 5% POWER DEGRADATION SEEMS EXTREME WHEN COMPARED TO OTHER 20 YEAR LIFETIME PRODUCTS

- TEST DATA
  1. DATA IS VERY HELPFUL IN ISOLATING PROBLEM AREAS

- IN-HOUSE TESTING
  1. WITHOUT JPL TESTING WE WOULD CONDUCT OUR OWN SELECTED TESTS ON A RANDOM SAMPLE BASIS.

SAMICS and SAMIS

- THE PROGRAM
  1. VERY WELL DONE
  2. EASY TO USE AND ACCURATE
  3. EXPERT HELP FROM JPL STAFF
  4. COSTS TOO MUCH TO RUN

- TEST RESULTS
  1. ACCURACY IS DOUBTFUL
     A. INPUT DATA ACCURACY
     B. INTENT OF OUTPUT
     C. CONSIDERED TO BE TODAYS COST - NOT PILOT PLANT COST

Suggestions

- CHECK LIST IN USERS GUIDE
- TROUBLE SHOOTING SECTION IN USERS GUIDE
- EXPLAIN IMPORTANT FUNCTIONS (SAVE/STOP)
- ADD COST SAVING SECTION (TEXT EDITOR, IPEG, STACKING, ETC.)
- SPECIFY EXACT REPORTS REQUIRED BY NAME AND NUMBER
- REVIEW ALL INPUT (FORMAT A,B,C, AND CURRENT TECHNOLOGY)
- SPECIFY IF "PROOF COPY" IS REQUIRED

General Comments

FEEDBACK:

- ADEQUATE
- HELPFUL
- SUFFICIENT

DESIGN AND PRODUCTION NEEDS:

- QUOTE HIGH EFFICIENCY/HIGH TECHNOLOGY MODULES
- QUOTE LOW COST MODULES
- LARGER PROTOTYPE RUNS

ARCO SOLAR, INC.

W.R. Bottenberg

Introduction

At this time, as PV technology faces new markets, the primary general concerns are the balance of cost reduction versus reliability requirements and the need to meet immediate and near-term market demands while developing technology for the long term. ARCO Solar's involvement in Block IV is with two designs for two applications: (1) an intermediate-load module, and (2) a residential module. Module (1) is related to our mainline product and the Block III product, while module (2) is a new departure. Our goal in these developments, like JPL's in Block IV, has been to go for product quality and cost reduction in that order. The tendency in Block IV to emphasize reliability is certainly an advantage for long-term market development, even where it increases cost in the near term.

A. Design and Performance Requirements

To a certain extent we found the Block IV design requirements incompatible with commercial market requirements. The specification of both voltage and module demensions (especially the 1.2 meter dimension) potentially required a costly redesign and a more costly product, without any improvement in reliability.

For the present world market. with a large number of different applications, module dimensions need not and should not be standardized, and voltage is not standardizable for all applications. Therefore, Block IV designs may not be compatible with customer requirements. These concerns apply to Module (1) not Module (2). Further, at a time when the majority of sales are for applications of 1-10 modules for battery charging, array dimensioning is not critical for efficiency. We are on the threshold of penetrating some markets where area and area-related costs become important and module efficiency more critical to the buyer.

ARCO Solar has improved the design of both module types more rapidly than might have happened otherwise, as a result of these requirements and our interaction with JPL. The intermediate-load module is based on a commercial product that had previously been modified to incorporate a metal-foil back as a moisture barrier to meet world market requirements for hermeticity. This had to be grounded when Block IV hi-pot testing revealed capacitive coupling from the circuit to the foil, which discharged to the frame.

The residential module was developed at this time partly because of the stimulus of Block IV. Improvements in termination and diode design resulted from interaction with JPL and the design requirements. More important, our choice of EVA instead of PVB for this module resulted from these requirements.

As shown in the table, we found sample modules using EVA to be clearly superior in maintaining performance parameters after 15-year simulated exposure at DSET Laboratories in Phoenix.

PLASTIC ENCAPSULANT SYSTEM PERFORMANCE
RATIO OF PERFORMANCE PARAMETERS BEFORE & AFTER TEST
15-YEAR EQUIVALENT EXPOSURE AT DSET
RATIO: FINAL/INITIAL

POTTANT	COVER	V_{oc}	V_{pm}	I_{sc}	I_{pm}
EVA	TEDLAR	1.00 $\pm$.02	1.02 $\pm$.05	1.02 $\pm$.03	1.00 $\pm$.05
EVA	KORAD	1.01 $\pm$.01	.099 $\pm$.05	1.01 $\pm$.05	1.00 $\pm$.08
PVB	TEDLAR	0.72 $\pm$.22	0.71 $\pm$.27	0.70 $\pm$.16	0.58 $\pm$.24
PVB	KORAD	0.99 $\pm$.03	1.11 $\pm$.08	0.86 $\pm$.12	0.79 $\pm$.15

B. Environmental Test Requirements

These requirements are about right for this stage of development. A key to JPL's success in assisting development is the coupling of progressively stiffer requirements in the successive Block procurements with experience in accelerated testing and in the field. The common experimental data base for lifetime testing and evaluation is a key benefit from JPL's program to the developing PV industry.

The test results are meaningful as indicators of what we should be doing in design. However, the relationship of these test requirements to probable module lifetime remains to be established. European environmental specifications are much stiffer. JPL and industry need to balance carefully the roles of cost and reliability in design and to determine what environmental requirements are needed to achieve optimally balanced designs.

C. SAMICS-SAMIS

The investment of engineering time for estimating cost elements for this rather complex program is high, considering the reliability of input data that can be obtained before production starts. For near-term production, current operational data are much more useful for estimating cost. For far-off production, back-of-envelope calculation is adequate for development program justification until economic analysis methods of the type required for internal planning may be used. These methods of analysis are very company-specific and depend on company strategic goals. Thus SAMICS is not useful to the individual contractor for estimating future costs. This is not to say that SAMICS may not be very useful at the program level, comparing processes or technologies across the industry, if some imprecision can be tolerated in the estimated input data.

D. GENERAL

Data feedback from JPL is good: we found the personnel very cooperative, and the failure analysis work is excellent.

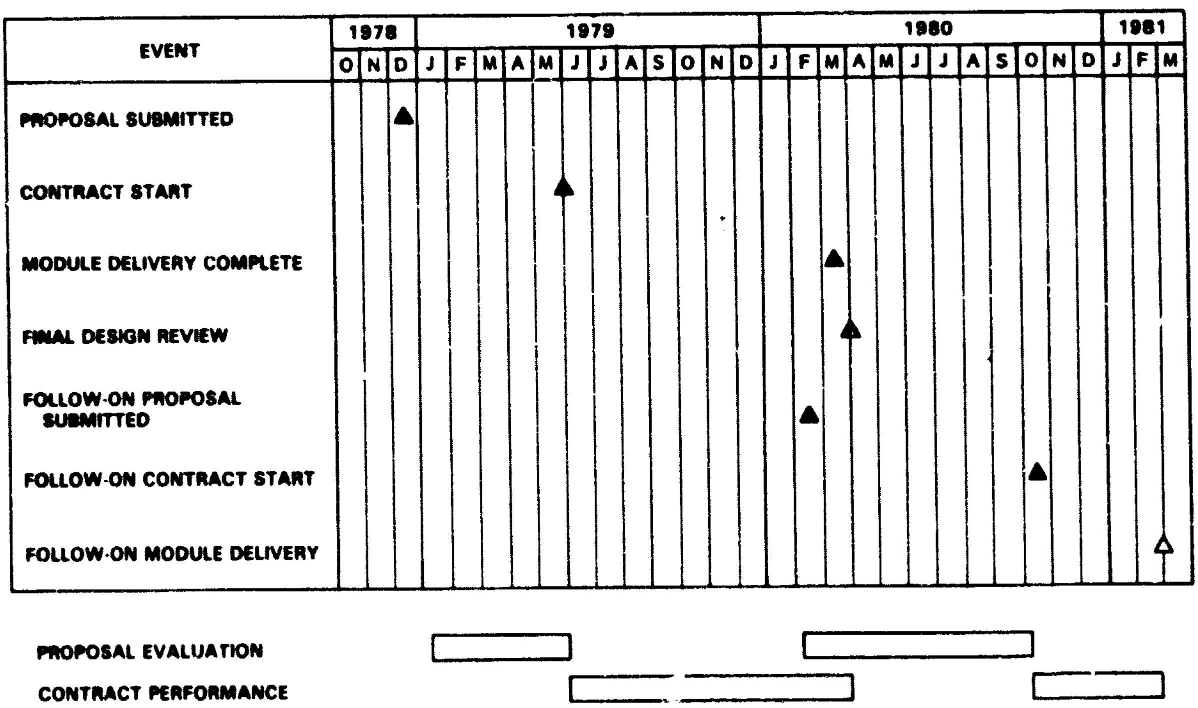
Technology development activities should focus on such things as developing environmental and life-history performance data, and not so much on defining voltage and dimensional characteristics, which are market-directed.

GENERAL ELECTRIC CO.
Neal Shepard

Topics of Concern

- PROCUREMENT DURATION
- DESIGN CHANGES
- ENVIRONMENTAL TESTING

Procurement Duration



Scheduling Implications

- 26 MONTHS FROM BLOCK IV DESIGN INCEPTION UNTIL COMPLETION OF STAGED PROCUREMENT
- TOO LONG TO "FREEZE" DESIGN
- SHORTENED SCHEDULE POSSIBLE WITH ONE CONTRACT FOR ENTIRE BLOCK IV PROCUREMENT

Design Changes

	BLOCK IV	BLOCK IV-A
SOLAR CELL SUPPLIER	ARCO - SOLAR	SOLEC INTERNATIONAL
MODULE-TO-MODULE INTERCONNECTION	INTEGRAL WIRING WITH SCREW/WASHER	INTEGRAL AMP INC. UNDER CARPET FCC WITH CRIMP CONNECTIONS

Environmental Testing

- DUPLICATE TESTING (BY JPL AND THE CONTRACTOR) IS EXPENSIVE
  - 50 CYCLE THERMAL CYCLING TEST $3500.00
  - 7 DAY HUMIDITY TEMPERATURE TEST $2050.00

PHOTOWATT INTERNATIONAL, INC.
Mike Keeling

JPL Solar Module Development Effort

STRUCTURE: GOOD

- o EMPHASIS ON SOLID TECHNOLOGY
- o THIRD-PARTY INPUT
- o EVALUATION SUPPORT

INTENT:

- o RELIABLE, LOW-COST RESIDENTIAL AND INTERMEDIATE LOAD MODULES
- o SOMEWHAT OUT-OF-STEP WITH PRESENT COMMERCIAL MARKETS, I.E., LOW-VOLTAGE, REMOTE SYSTEMS

APPROACH:

- o ITERATIVE
- o INDUSTRY AND USER FEEDBACK
- o DESIRE TO IDENTIFY APPROPRIATE SOLUTIONS

Solar Module Design and Test Specifications

TEST SPECIFICATIONS:

- o QUALIFICATION - GOOD, COMPLETE, NECESSARY
- o LIFE TESTING - LACK OF LIFE TESTING TENDS TO SKEW MODULE DESIGNS TOWARDS PASSING QUAL REQUIREMENTS WITH POTENTIALLY REDUCED LIFE AS A CONSEQUENCE, E.G., METALLIC BACKSKIN OF LAMINATED MODULES
- o SUGGEST: BALANCE OF QUAL AND LIFE TEST REQUIREMENTS WHICH SHOULD BRING ABOUT BALANCE PRODUCT DESIGNS

DESIGN CRITERIA:

- o ORIENTION TOWARD RESIDENTIAL/INTERMEDIATE LOAD APPLICATIONS OUT-OF-STEP WITH TODAY'S COMMERCIAL MARKETS, I.E., LOW VOLTAGE, REMOTE SYSTEMS

SAMICS

VALUE

- o COMPARE PROCESSES WITHIN FRAMEWORK OF FIXED BURDEN COMPANY
- o ALL LABOR SUPPLIES AND COMPONENTS ARE AT SAME PRICE FOR EVERYONE
- o PROGRAM IS "UPDATEABLE" FOR NEW ITEMS

DRAWBACKS

- o CAN BE INTERPRETED AS TRUE COSTS WHICH IS NOT NECESSARILY SO
- o CAN BE MANIPULATED
- o DOES NOT ALLOW FOR MANAGEMENT INFLUENCE
- o HAS LOADING IN INDIRECTS THAT ARE NOT NECESSARILY VALID

SOLAREX CORP.
John Wohlgemuth

Design and Performance Requirements

IS THE DESIGN AND PERFORMANCE SPECIFICATION RESPONSIVE TO YOUR PERCEPTION OF THE NEED FOR MODULES?

BY PLACING A LIMITATION ON SIZE AND REQUIREMENT FOR AN INTEGRAL VOLTAGE, JPL HAS RESTRICTED THE MODULE DESIGN IN REGARD TO CELL SIZE.

THIS RESTRICTION BECOMES MORE SEVERE AS THE CELL SIZE INCREASES.

WHAT HAS BEEN THE EFFECT OF THE DESIGN REQUIREMENTS ON YOUR DESIGN?

FORCED SOLAREX TO USE A 9.5 CM X 9.5 CM CELL INSTEAD OF A 10 CM X 10 CM CELL. THIS HAD A SIGNIFICANT IMPACT ON MODULE COST SINCE A 9.5 CM X 9.5 CM CELL COSTS THE SAME AS A 10 CM X 10 CM CELL.

HOW CRITICAL IS MODULE EFFICIENCY?

PEOPLE SHOULD NOT BUY MODULES BY EFFICIENCY BUT BY AVERAGE POWER KNOWING THE MODULE SIZE AND THE MEASUREMENT CONDITIONS.

THE IMPORTANCE OF MODULE EFFICIENCY DEPENDS ON CONDITIONS OF THE USE INCLUDING:

- LAND AVAILABILITY AND COST
- SUPPORT STRUCTURE AND INTERARRAY WIRING COSTS
- MAINTENANCE REQUIREMENTS AND COST

ONLY AFTER THIS SYSTEMS ANALYSIS CAN ONE DETERMINE IF A LOWER-COST-PER-WATT, LOWER EFFICIENCY MODULE IS A BETTER VALUE THAN A HIGHER-COST-PER-WATT, HIGHER EFFICIENCY MODULE.

IN THE PROCESS OF DESIGNING TO COMPLY WITH THE SPECIFICATION, DID YOU LEARN ANYTHING USEFULL ABOUT MODULE DESIGN?

NO MORE SO THAN DESIGNING A MODULE TO ANY SPECIFICATION FOR A CUSTOMER.

Environmental Test Requirements

ARE THE TESTS TOO STIFF OR TOO LENIENT?

WE PREFER A HIGHER TEMPERATURE HUMIDITY TEST WITH NO CYCLING 70°C AND 90% RELATIVE HUMIDITY. PROBLEMS SHOW UP FASTER.

SHOULD DO THERMAL CYCLE TESTS BOTH BEFORE AND AFTER HUMIDITY.

50 THERMAL CYCLES TOO SHORT TO REALLY INDICATE EXPECTED FIELD PERFORMANCE.

+90°C TO -40°C IS TOO SEVERE TO ACTUALLY SIMULATE PERFORMANCE.

RECOMMEND LESS SEVERE CYCLE, MUCH SHORTER CYCLE, BUT MANY MORE CYCLES.

ARE THE RESULTS OF THE TESTS MEANINGFUL?

IN GENERAL THERMAL CYCLE AND HUMIDITY ARE VERY USEFUL.

DON'T REALLY UNDERSTAND THE RESULTS OF THE HAIL TEST AND WHY SOME MODULES ARE TESTED TO FAILURE.

AS MORE MODULES ARE PROVIDED WITHOUT FRAMES A REDEFINITION OF THE MECHANICAL LOADING TEST MAY BE REQUIRED.

TWIST TEST APPEARS MEANINGLESS ESPECIALLY AFTER THE MECHANICAL LOADING TEST.

WOULD YOU PERFORM THE TESTING IF JPL DID NOT REQUIRE IT?

WE DO THERMAL CYCLE AND HUMIDITY TESTING ROUTINELY.

PROBABLY WOULD NOT DO THE MECHANICAL LOADING AND TWIST TESTS SINCE THESE PROPERTIES ARE WELL KNOWN FOR GLASS.

SAMICS and SAMIS

DO YOU BELIEVE THE RESULTS OF THIS ANALYSIS?

OUR QUOTE FOR SMALL QUANTITIES (100 KW) WAS ACTUALLY LESS THAN SAMICS RESULTS DUE TO THE HIGH OVERHEAD RATE IN SAMICS. WE BELIEVE THAT THE HIGH OVERHEAD IS DUE TO AN ARTIFICIAL ENVIRONMENT WHERE THE FACTORY ONLY MAKES MODULES. AN INTEGRATED CELL-MODULE LINE BETTER DISTRIBUTES OVERHEAD AND YIELDS A LOWER COST.

WE IDENTIFIED A NUMBER OF AREAS WHERE MATERIALS COST WAS EITHER MUCH HIGHER OR MUCH LOWER THAN WE NOW PAY.

HOW COULD THE SYSTEM BE IMPROVED?

THE FORMAL SAMICS PROCEDURE DOESN'T PROVIDE A FORMAT THAT IS EASY TO USE FOR IDENTIFICATION OF COST COMPONENTS AND COST DRIVERS.

WOULD RATHER JPL STRESS A LESS COMPLICATED TECHNIQUE THAT THE CONTRACTOR CAN USE TO UNDERSTAND THE COST COMPONENTS AND COST DRIVERS.

General

IS THE FEEDBACK OF DATA FROM JPL ADEQUATE FOR OUR NEEDS?

GENERALLY, THE FEEDBACK IS VERY GOOD BUT SLOW.

IN WHAT WAYS COULD THE TECHNOLOGY DEVELOPMENT ACTIVITIES OF THE PROJECT BE BETTER FOCUSED ON YOUR MODULE DESIGN AND PRODUCTION NEEDS?

I BELIEVE THAT THE JPL PROCUREMENT GROUP NEEDS MORE SUPPORT AND INTERACTION WITH THE ENCAPSULATION AND PP&E GROUPS TO BETTER INCORPORATE RESULTS FROM OTHER JPL PROGRAMS.

Other

WHY DOES JPL PUT OUT A SPECIFICATION ENTITLED "DESIGN AND TEST SPECIFICATION FOR INTERMEDIATE LOAD MODULES" AND LIMIT THE SIZE AND VOLTAGES OF THE MODULE? SUCH DECISION SHOULD BE LEFT UP TO THE MODULE MANUFACTURER AND THE SYSTEM DESIGNER.

SPIRE CORP.
Peter R. Younger

Design and Performance Requirements

- SPECIFICATIONS
  - --- Cost Drivers
    - Redundant output terminations
    - Dimensional tolerances
    - High voltage isolation
- PERFORMANCE REQUIREMENTS
  - --- Generally Well Stated
  - --- Referenced to NOCT
    - Difficult to establish
- DESIGN REQUIREMENTS
  - --- Obvious Interpretation Is To Design A High Reliability Module
- MODULE EFFICIENCY
  - --- Critical
- MEETING OF SPECIFICATIONS
  - --- Useful Learning Process
  - --- Thanks To Engineering Area Personnel

Environmental Test Requirements

- LEVEL OF REQUIREMENTS IS APPROPRIATE
- NEED FOR CONTINUOUS UPDATE
  - --- e.g. Hot Spot Test
- FOR CONSISTENCY JPL SHOULD DO ALL TESTING AND REPORT IN DETAIL
- ULTIMATELY REQUIREMENTS SHOULD BE SITE SPECIFIC

SAMICS and SAMIS

- SAMIS IS EXPENSIVE
- RESULTS ARE REPRESENTATIVE BUT INTERPRETATION DIFFICULT FOR THE UNINITATED
- USE IPEG FOR WORKING SYSTEM
- RESERVE SAMICS FOR FINAL DETERMINATION

General

- JPL DATA FEEDBACK
  - --- Information Available Informally
  - --- Formal Structure Inadequate
- PROJECT ACTIVITIES
  - --- Establish Independent Certification of Modules
  - --- JPL Specifications Often Quoted
    - Only comprehensive documents
    - Not always representative of customer needs
- BLOCK PROCUREMENT PROGRAM
  - --- Represents and Demonstrates Technology Advancement
  - --- Should Insure Establishment of Reliable Industry Standards
  - --- It is Difficult to Make Significant Technological Advancements and Cost Reductions Simultaneously and at Low Volume

ENVIRONMENTAL TESTING

JET PROPULSION LABORATORY
John S. Griffith

Contents

- RESULTS OF TESTING WORLD BANK MODULES
- NEW BLOCK V HUMIDITY TEST - TRIAL RUN ON 11 DIFFERENT TYPES OF MODULES

WORLD BANK MODULES
UNDP Project GLO/78/004

• TITLE:	TESTING AND DEMONSTRATION OF SMALL SCALE SOLAR POWERED PUMPING SYSTEMS
• PURPOSE:	DEVELOPMENT AND DEMONSTRATION OF IRRIGATION PUMPING IN DEVELOPING COUNTRIES
• FINANCED BY:	UNITED NATIONS DEVELOPMENT PROGRAMME
• EXECUTED BY:	WORLD BANK
• A&E:	SIR WILLIAM HALCROW AND PARTNERS, CONSULTING ENGINEERS AND ARCHITECTS, LONDON, IN ASSOCIATION WITH THE INTERMEDIATE TECHNOLOGY DEVELOPMENT GROUP LTD
• LOCATIONS:	SUDAN, MALI (AFRICA), PHILLIPINES

Test Requirements

• U.V. IRRADIATION:	AT ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH, ENGLAND, 2 MODULES
• BLOCK IV TEST: (JPL5101-16A)	AT JPL, 4 MODULES

Test Results for F1 Modules

- CONSTRUCTION — GLASS TOP COVER, 0.13 mm AIRSPACE, CELLS IN SILICONE RUBBER ENCAPSULANT, ANODIZED ALUMINUM SUBSTRATE
- TEST RESULTS
  - UV — AMBER DISCOLORATION OF ENCAPSULANT NEAR EDGE SEAL
  - HIPOT — FAILED PRETEST AND POSTTEST HIPOT
  - TEMPERATURE CYCLING — ONE OF FOUR MODULES OPEN CIRCUITED DUE TO MULTIPLE FRACTURED INTERCONNECTS. DIFFUSION OF EDGE SEALANT INTO ENCAPSULANT (1 MODULE)
  - HUMIDITY CYCLING — THE TWO UV IRRADIATED MODULES SHOWED FURTHER DISCOLORATION. DELAMINATION NEAR TERMINALS ON ONE. MILKY ENCAPSULANT IN THE OTHER
  - WIND — NOT DONE. NO MOUNTING PROVISIONS.
  - TWIST — ONE MODULE SHORTED TO FRAME
- COMMENTS — DESIGN DEFICIENCIES INCLUDE AIRGAP UNDER GLASS, NO STRESS RELIEF LOOPS, SINGLE (NON-REDUNDANT) INTERCONNECTS, INADEQUATE ENCAPSULANT UNDER CELLS (0.03 TO 0.15 mm).

Test Results for F2 Modules

- CONSTRUCTION — GLASS TOP, ENCAPSULATED CELLS, GLASS
- TEST RESULTS
  - HIPOT — ALL FOUR MODULES FAILED PRETEST HIPOT, PASSED POSTTEST HIPOT
  - WIND — ONE MODULE HAD INTERMITTENT OPEN DURING TEST. A LOOSE TERMINAL SCREW WAS FOUND
- COMMENTS — RESULTS ARE SOMEWHAT AMBIGUOUS SINCE ISOLATION WAS RESTORED AND THE LOOSE SCREW PROBABLY CAUSED THE INTERMITTENT OPEN

Test Results for U1 Modules

- CONSTRUCTION — GLASS TOP, CELLS IN PVB, TEDLAR, PVB, KORAD/ STEEL BACK SURFACE. BUTYL EDGE SEALANT
- TEST RESULTS
  - HIPOT — TWO MODULES FAILED PRETEST, 3 FAILED POSTTEST
  - TEMPERATURE CYCLING — FRAME SEALANT EXTRUDED OUT OF FRAMES, (4 MODULES) AND IN TOWARD CELLS (2 MODULES)
  - HUMIDITY CYCLING — ONE MODULE HAD BACK SURFACE DELAMINATION (BLISTER)
- COMMENTS — SOME REDESIGN AND PROCESSING IMPROVEMENTS NEEDED

Test Results for U2 Modules

- CONSTRUCTION — GLASS TOP, ENCAPSULATED CELLS, FIBERGLASS/ POLYESTER SUBSTRATE
- TEST RESULTS (5 MODULES)
  - HIPOT — UV IRRADIATED MODULES FAILED PRETEST HIPOT, PASSED POSTTEST HIPOT
  - HUMIDITY CYCLING — ONE CELL CRACKED; NO ELECTRICAL DEGRADATION
  - TWIST — INCREASE IN SERIES RESISTANCE OBSERVED, ONE MODULE
- COMMENTS — RESULTS GENERALLY VERY GOOD. CAUSES OF HIPOT AND TWIST TEST PROBLEMS UNKNOWN

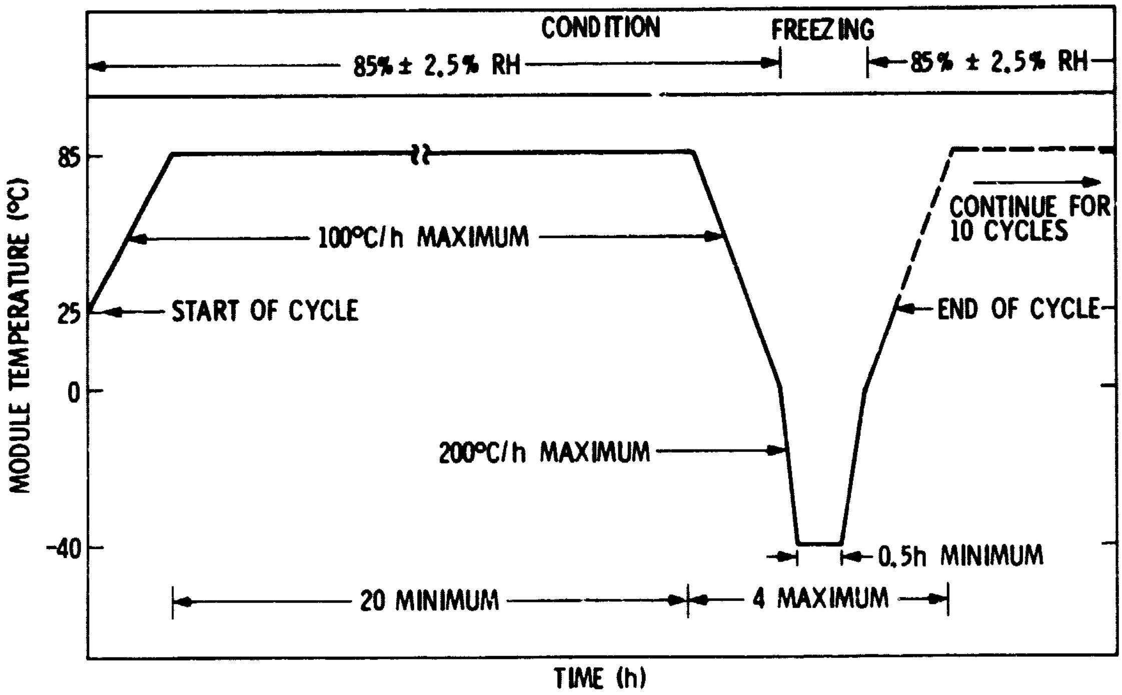
Conclusions

- ONE U.S. AND ONE FOREIGN MODULE APPEAR TO BE SATISFACTORY AFTER CORRECTING SOME MINOR DEFICIENCIES
- ANOTHER U.S. MODULE REQUIRES MORE EXTENSIVE IMPROVEMENTS
- THE SECOND FOREIGN MODULE IS UNSATISFACTORY ON SEVERAL COUNTS

PROPOSED NEW ENVIRONMENTAL TESTS FOR BLOCK V MODULES

- QUALIFICATION TESTS HAVE NOT BEEN EFFECTIVE IN REVEALING SOME MODULE WEAKNESSES
- EXAMPLES
  - BROKEN INTERCONNECTS IN < 2 yrs AT SCHUCHULI, UPPER VOLTA
  - HOT CELL PROBLEM AT MT. LAGUNA AND OTHER SITES
  - DELAMINATION, DISCOLORATION, CORROSION, ELECTRICAL DEGRADATION
- NEW TESTS PROPOSED
  - INTERCONNECT FATIGUE - 200 TEMPERATURE CYCLES
  - HOT CELLS - BACK BIAS SEVERAL CELLS TO WORST CONDITIONS
  - DELAMINATION, ETC - MORE SEVERE HUMIDITY TEST WITH FREEZING

New Humidity-Freezing Cycle Test
(To Follow 50 Temperature Cycles)



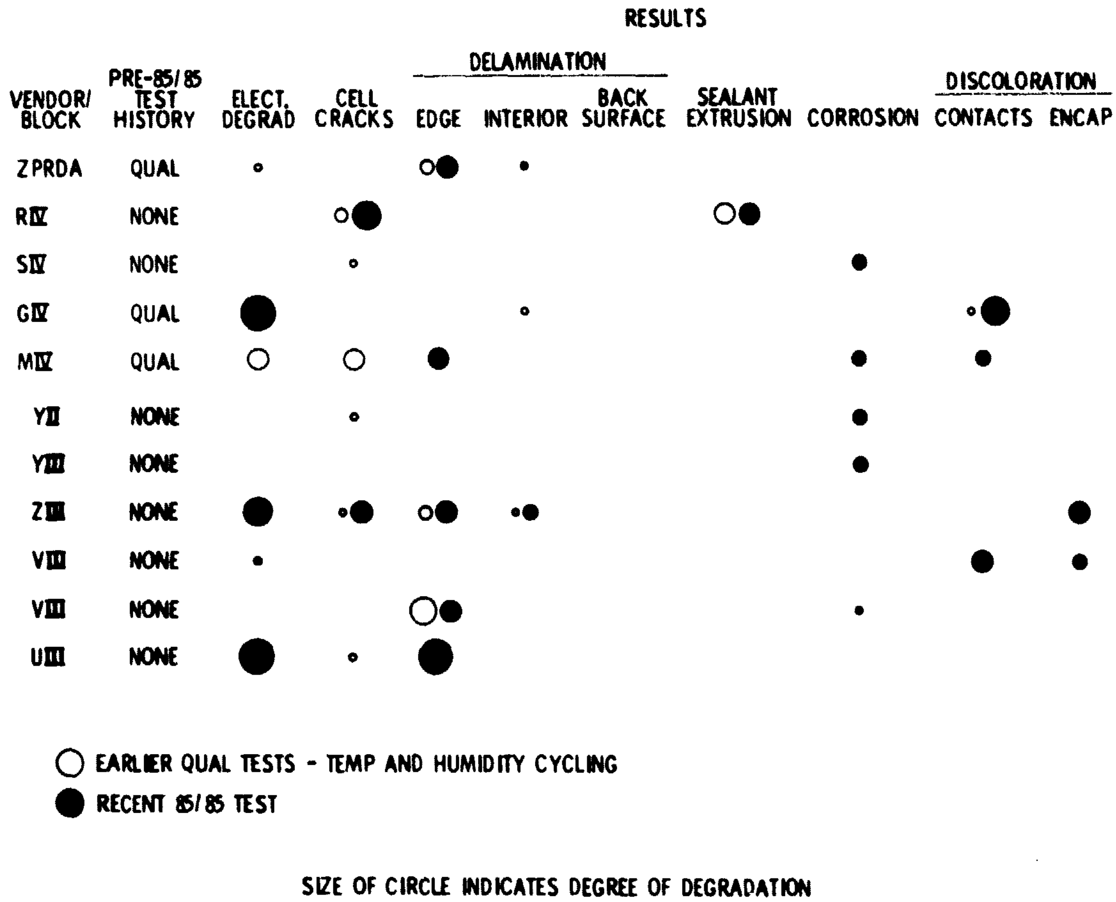
Results of 85° - 85% Test

VENDOR/ BLOCK	PRE-85/85 TEST HISTORY	CONSTRUCTION	RESULTS
YII	NONE	RTV, F/P*	J-BOX CORROSION
YIII	NONE	RTV, F/P	J-BOX CORROSION
ZIII	NONE	SILICONE, F/P	6% ELECT. DEGRAD, YELLOWED ENCAP, DELAM AT ICs, CELLS, FRAME SEAL, 1 CELL CRACK
VIII	NONE	RTV, PVC SCREEN, ALUM PAN	YELLOWED ENCAP, GRAY METALLIZATION
VIII	NONE	GLASS, RTV, SCREEN ALUM PAN	GROUND TERM. RUST, FRAME SEAL DELAM
UIII	NONE	GLASS, PVB, TEDLAR, ALUM FRAME	19% ELECT. DEGRAD, 98% FRAME SEAL DELAM, END CAPS DISTORTED

*F/P, FIBERGLASS POLYESTER SUBSTRATE

VENDOR/ BLOCK	PRE-85/85 TEST HISTORY	CONSTRUCTION	RESULTS
ZPRDA	QUAL	GLASS, RTV, MYLAR, ALUM FRAME	FRAME SEAL DELAM, CELL DELAM
RIV	NONE	GLASS, PVB, TEDLAR/ALUM/TEDLAR BACK, SS FRAME	(2) CELLS CR., FRAME SEALANT EXTRUDED
SIV	NONE	GLASS, EVA, RIPSTOP, MYLAR/ALUM, BACKSPRAY	CORROSION OF RIVETS AND GROUND CLIP
GIV	QUAL	SHINGLE - GLASS, SILICONE, CARDBOARD	29% ELECT. DEGRAD, CORROSION OF ICs, COLLECTORS
MIV	QUAL	GLASS, PVB, TEDLAR, ALUM FRAME	60% FRAME SEAL DELAMINATION, GRAY ICs, RUSTED RIVETS

Comparison: Earlier Qualification Tests vs New 85° - 85%



CONCLUSIONS

- WORLD BANK MODULES
    - TWO FOREIGN AND TWO U. S. TYPES OF MODULES WERE TESTED FOR APPLICATION TO PUMPING SYSTEMS IN DEVELOPING COUNTRIES
    - TWO MODULES WERE SATISFACTORY, 1 FOREIGN AND 1 U. S.; 1 U. S. WAS MARGINAL; ONE FOREIGN WAS UNSATISFACTORY

- PROPOSED NEW HUMIDITY-FREEZE TEST
    - THE NEW TEST IS 85°C, 85% R.H. FOR 10 days EXCEPT FOR 10 SHORT EXCURSIONS TO -40°C
    - A TRIAL RUN WAS MADE ON 11 TYPES OF MODULES
    - RESULTS SHOW THE NEW TEST TO BE MORE EFFECTIVE IN REVEALING PROBLEMS WITH CORROSION, DELAMINATION, AND SOME FORMS OF POWER DEGRADATION

MIT-LL PV TEST FACILITIES STATUS REPORT

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

S.E. Forman

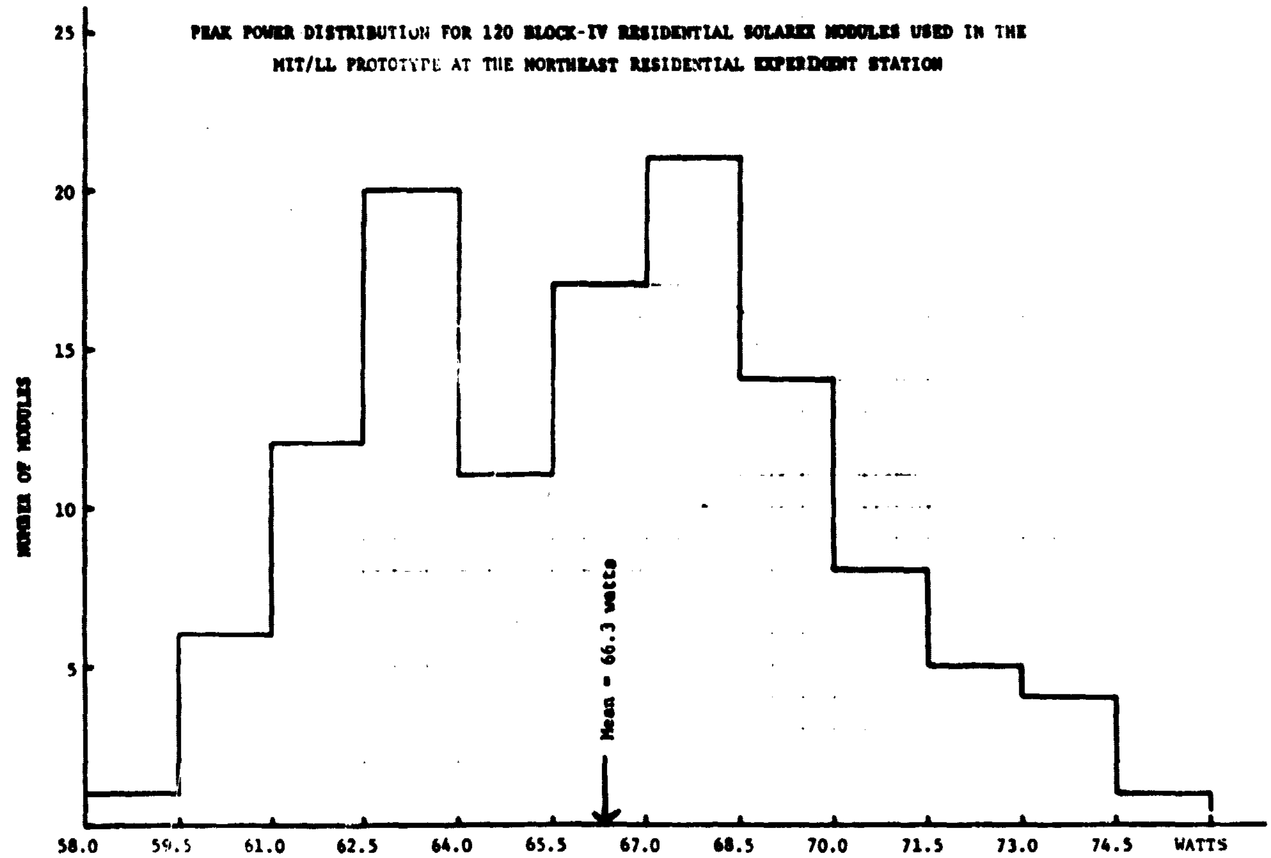
MIT-LL Residential PV Test Facilities

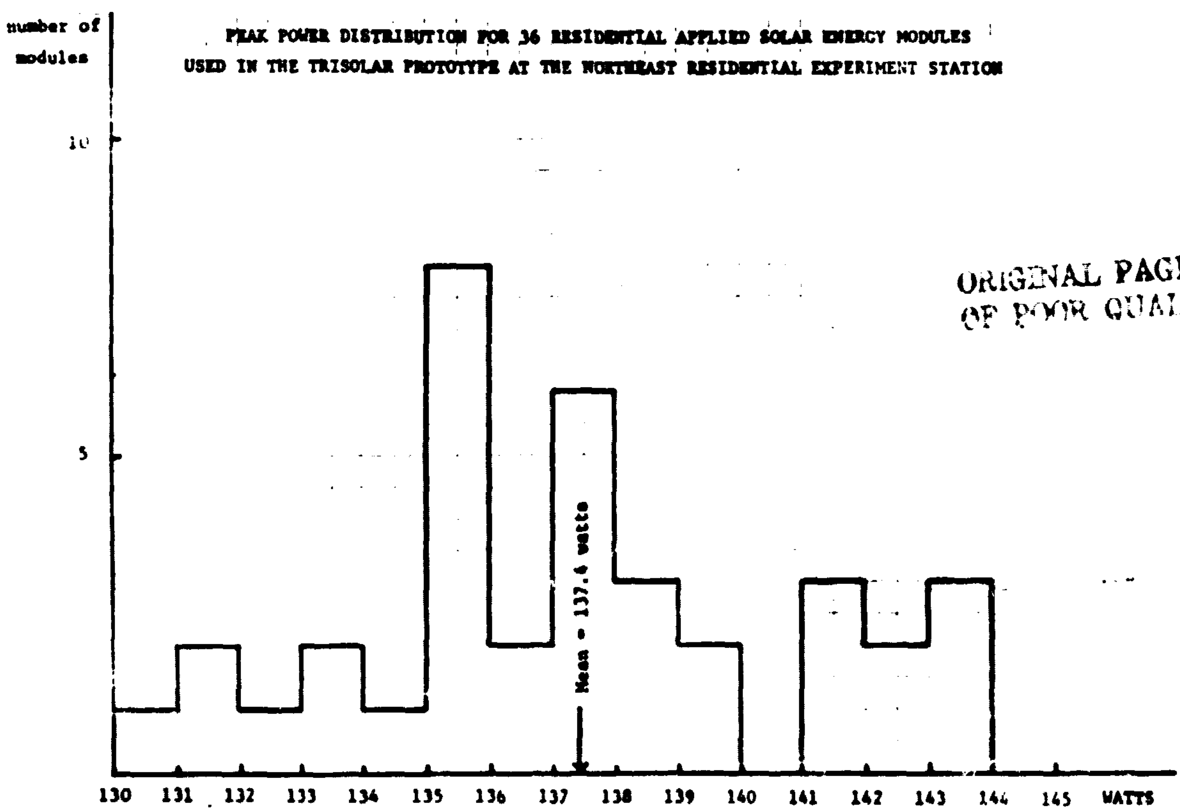
1. NE RESIDENTIAL TEST STATION
   5 PROTOTYPES IN CONCORD, MA
   1 ISEE IN CARLISLE, MA
2. SW RESIDENTIAL TEST STATION
   8 PROTOTYPES IN LAS CRUCES, NM
3. INNOVATIVE PV APPLICATIONS FOR RESIDENCES
   ARIZONA, FLORIDA, HAWAII (3)
4. SE RESIDENTIAL TEST STATION
   RFQ FOR SITE OPERATOR ISSUED 19 DECEMBER 1981

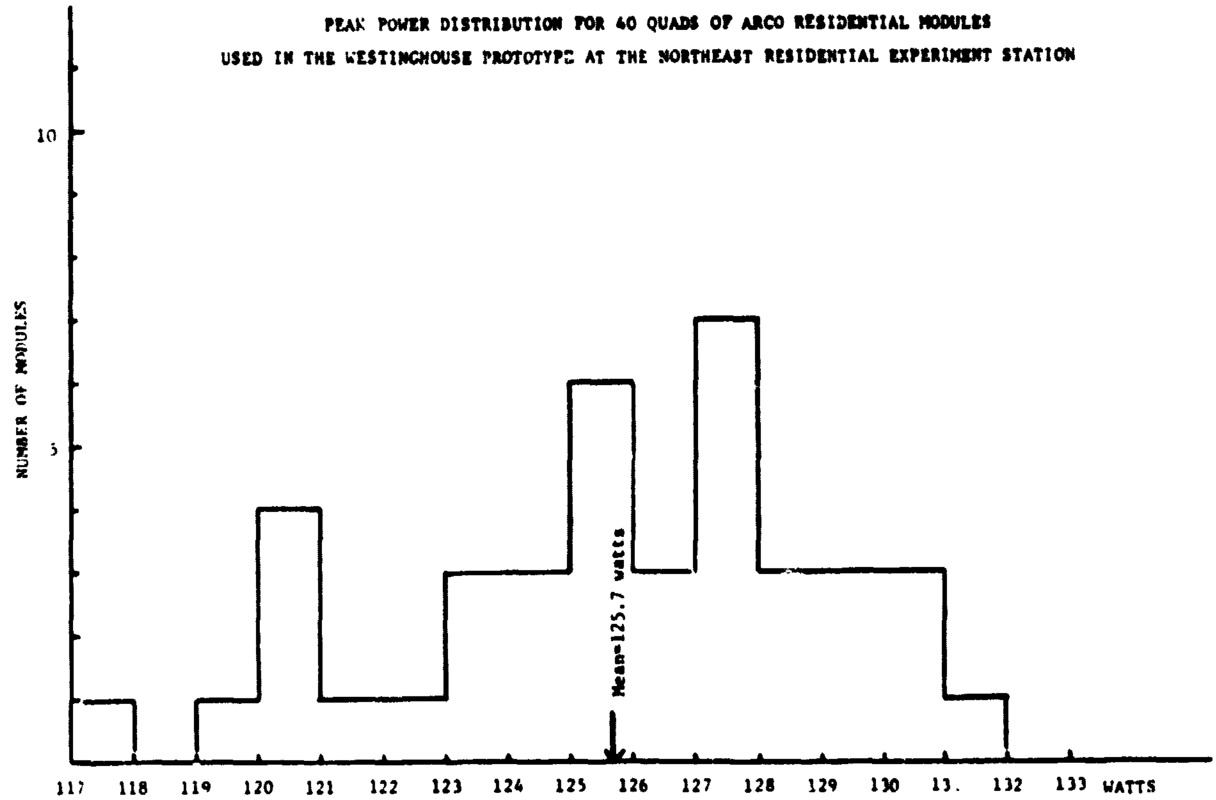
Northeast Residential Test Station, Concord MA

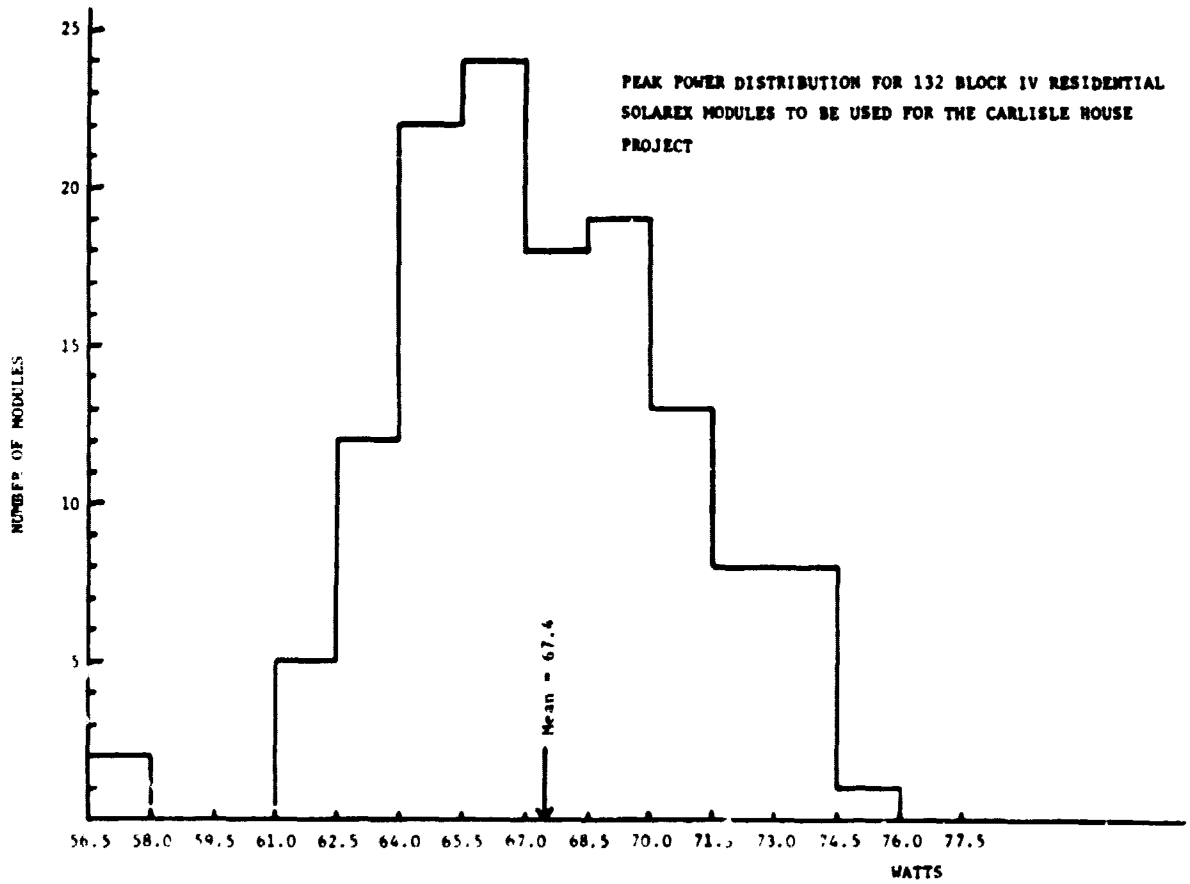
SITE OPERATOR: MIT LL

PRIME CONTRACTOR	NO. OF MODULES	PV ARRAY DETAILS SIZE - M^2	TILT ANGLE	PEAK POWER - kW
TRISOLAR	36 ASEC INTEGRAL	47.6	45^o	4.8
GENERAL ELECTRIC	375 GE SHINGLE	73.3	33.7^o	5.6
SOLAREX	80 SX STANDOFF	74.3	40^o	6.2
WESTINGHOUSE	160 ARCO INTEGRAL	59.5	45^o	5.4
MIT LL	120 SX STANDOFF	93.6	45^o	7


PEAK POWER DISTRIBUTION FOR 120 BLOCK-IV RESIDENTIAL SOLAREX MODULES USED IN THE MIT/LL PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
NUMBER OF MODULES
25
20
15
10
5
Mean = 66.3 watts
58.0
59.5
61.0
62.5
64.0
65.5
67.0
68.5
70.0
71.5
73.0
74.5
WATTS


number of modules
PEAK POWER DISTRIBUTION FOR 36 RESIDENTIAL APPLIED SOLAR ENERGY MODULES USED IN THE TRISOLAR PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
10
5
Mean = 137.4 watts
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
WATTS


PEAK POWER DISTRIBUTION FOR 40 QUADS OF ARCO RESIDENTIAL MODULES
USED IN THE WESTINGHOUSE PROTOTYPE AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION
NUMBER OF MODULES
10
5
Mean=125.7 watts
117 118 119 120 121 122 123 124 125 126 127 128 129 130 13. 132 133 WATTS


PEAK POWER DISTRIBUTION FOR 132 BLOCK IV RESIDENTIAL SOLAREX MODULES TO BE USED FOR THE CARLISLE HOUSE PROJECT
NUMBER OF MODULES
25
20
15
10
5
Mean = 67.4
56.5 58.0 59.5 61.0 62.5 64.0 65.5 67.0 68.5 70.0 71.5 73.0 74.5 76.0 77.5
WATTS

Southwest Residential Test Station, Las Cruces NM

SITE OPERATOR: NMSEI

PV ARRAY DETAILS

PRIME CONTRACTOR	NO. OF MODULES	SIZE - M^2	TILT ANGLE	PEAK POWER - kW
BDM	117 MOT STANDOFF	43.9	35°	4.7
TEA	112 MOT RACK MOUNTED	48.6	29.7°	4.5
SOLAREX	80 SX STANDOFF	70.6	26°	5.2
TRISOLAR	44 ASEC INTEGRAL	58.1	30°	5.1
ARTU	168 ARCO STANDOFF	62.5	45°	6.2
ARCO	126 ARCO BATTEN-SEAM	80	26°	6.6
GE	375 GE SHINGLE	73.3	26.6°	5.0
WESTINGHOUSE	160 ARCO INTEGRAL	59.5	30.2°	5.8

Innovative PV Applications for Residences

I. J. F. LONG HOUSE - PHOENIX, ARIZONA
120 ARCO BATTEN-SEAM MODULES, 4.6 kW

II. FLORIDA SOLAR ENERGY CENTER, CAPE CANAVERAL, FLORIDA
152 ARCO STANDOFF MODULES, 5 kW

III. HAWAII NATURAL ENERGY INSTITUTE, HONOLULU, HAWAII
THREE SITES: KALIHI, PEARL CITY, MOLOKAI
ALL SITES USE ARCO MODULES

PV Module Performance at Various MIT-LL Test Sites

I. **SYSTEM TEST FACILITIES**
- NBNM, UTAH 100 KW
- MEAD, NEBRASKA 25 KW
- RESIDENTIAL TEST BED, MASSACHUSETTS 25 KW
- AM RADIO STATION, BRYAN, OHIO 15 KW
- ROOFTOP TEST BED, MASSACHUSETTS 10 KW
- UNIVERSITY OF TEXAS, ARLINGTON 7.5 KW
- CHICAGO MUSEUM 1.5 KW

II. **ENVIRONMENTAL TEST SITES**
- NEW YORK UNIVERSITY - (23 MODULES)
- COLUMBIA UNIVERSITY - (10 MODS)
- MASSACHUSETTS INSTITUTE OF TECHNOLOGY - (18 MODS)
- MT. WASHINGTON, NEW HAMPSHIRE WEATHER STATION - (5 MODS)

PV Module Failures at MIT-LL Test Sites

DATA UP TO 1/81

MFC. START	NEB (7/77)	RES STF (11/78)	ROOF STF (5/77)	UTA (8/78)	CHIC (7/77)	WBNO (8/79)	NBNM (1/80)	TOTALS
A (I)	-	-	15/945	-	0/288	-	-	15/1233
A (II)	-	-	-	-	-	-	0/720**	0
B (II)	-	-	5/64	65/240	-	-	-	70,
C (II)	61/1512	15/700	0/36	-	-	-	-	76/2248
C (III)	-	8/372	-	5/640*	-	-	-	13/1012
D (II)	35/728	-	-	-	-	-	-	35/728
D (III)	-	5/194	1/74	-	-	4/800	-	9/1068
E (III)	-	-	-	-	-	-	1/1740	1/1740
F (III)	-	-	-	-	-	-	31/2064	31/2064
	4.28%	2.21%	1.9%	27% 0.8%	0%	0.5%	0.7%	250/11117 2.25%

* ARRAY START DATE 4/80

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

ORIGINAL PAGE IS OF POOR QUALITY

PV MODULE FAILURES AT MIT LL TEST SITES
DATA UP TO 1/81

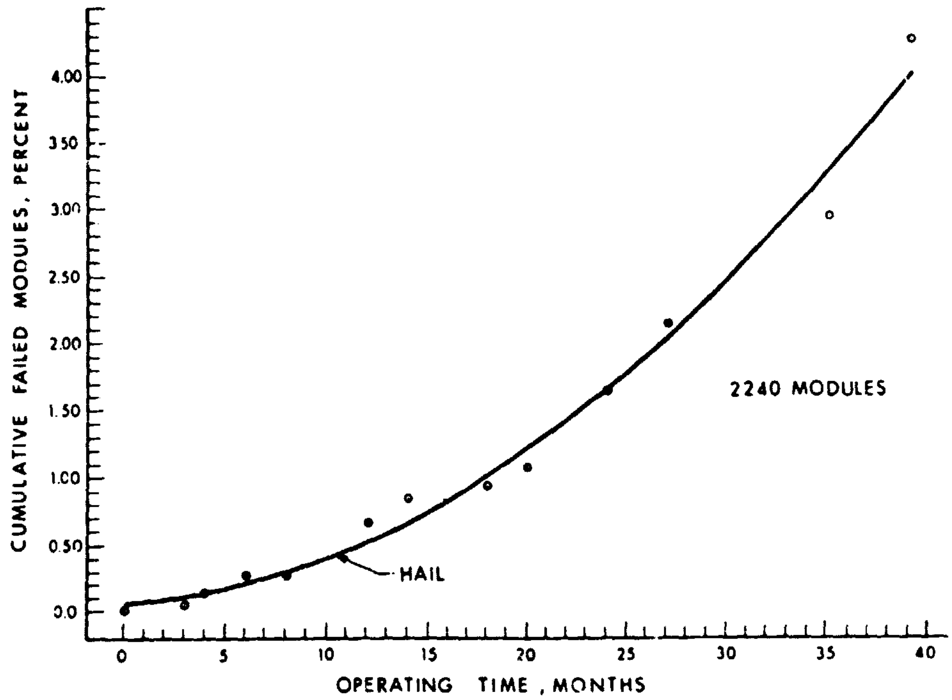
SITE	STARTING DATE	No. OF FAILURES/TOTAL BLOCK I	BLOCK II	BLOCK III
NEB	7/77	--	96/2240	--
RES STF	11/78	--	15/700	13/556
ROOF STF	5/77	15/945	5/100	1/74
UTA	8/78-4/80	--	65/240	--
UTA	4/80	--	--	5/640
CHIC	8/79	0/288	--	--
WBNO	8/79	--	--	4/800
NBNM	1/80	--	0/720**	32/3804
TOTALS		15/1233 (1.22%)	180/4000 (4.50%)	55/5884 (0.93%)

**NOTE: 52 MODULES HAVE BEEN FOUND WITH CRACKED GLASS COVER SHEETS.

Principal Causes of Module Failures

1. CELLS CRACKED DUE TO WEATHERING OR INTERNAL MODULE STRESSES.
2. FAILED SOLDER JOINTS.
3. INTERCONNECTS NOT SOLDERED TO REAR SIDES OF CELLS AT ASSEMBLY.
4. CELL STRING SHORTED TO SUBSTRATE.
5. BROKEN OR SPLIT INTERCONNECTS.

In-Service Performance of Nebraska PV Modules



C-5

Module Failures at Mead Test Site

FRONT ROW = 728 MODULES
BACK ROW = 1512 MODULES

STARTING DATE = JULY 1977

DATE OF SEARCH	NUMBER OF FAILURES FOUND FRONT ROW	NUMBER OF FAILURES FOUND BACK ROW
OCTOBER 1977	0	1
NOVEMBER 1977	1	1
FEBRUARY 1978	0	3
MARCH 1978	0	0
JULY 1978	6	3
SEPTEMBER 1978	3	1
FEBRUARY 1979	2	0
MARCH 1979	1	2
JULY 1979	6	7
OCTOBER 1979	1	10
JULY 1980	11	7
OCTOBER 1980	4	26
TOTALS	35	61

Failed Modules With Broken Interconnects

SITE (MFG)	TOTAL NO. OF MODULES	TOTAL NO. OF FAILURES	FAILURES WITH BROKEN INTER-CONNECTS	TIME
NEB (D-II)	728	35	4	3-1/4 YRS.
OHIO (D-III)	800	4	2	9 MOS.
RES STF (D-III)	194	5	5	2 YRS.
ROOF STF (D-III)	74	1	1	2 YRS.
(B-II)	64	5	1	3-1/4 YRS.

E-5

I-V CURVE TRACER EMPLOYING A CAPACITIVE LOAD

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

C.H. Cox III
T.H. Warner

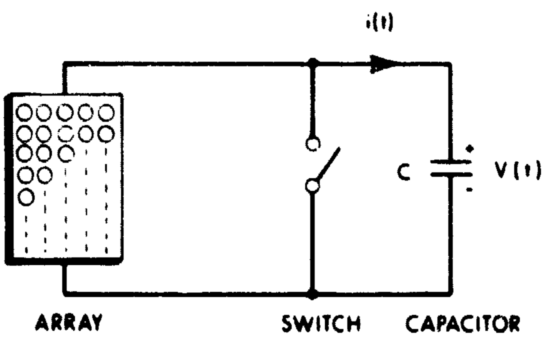
Functions and Requirements

Operations
- Display
- Analysis
- Storage

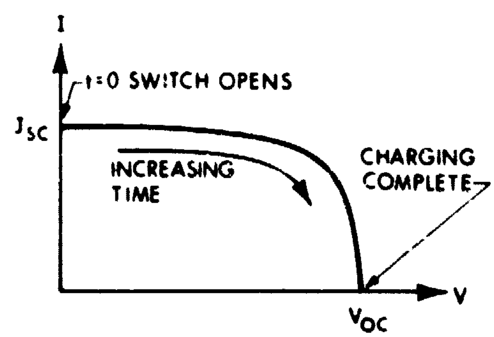
Interface
- IEEE Bus

Packaging
- Portable
- AC Available

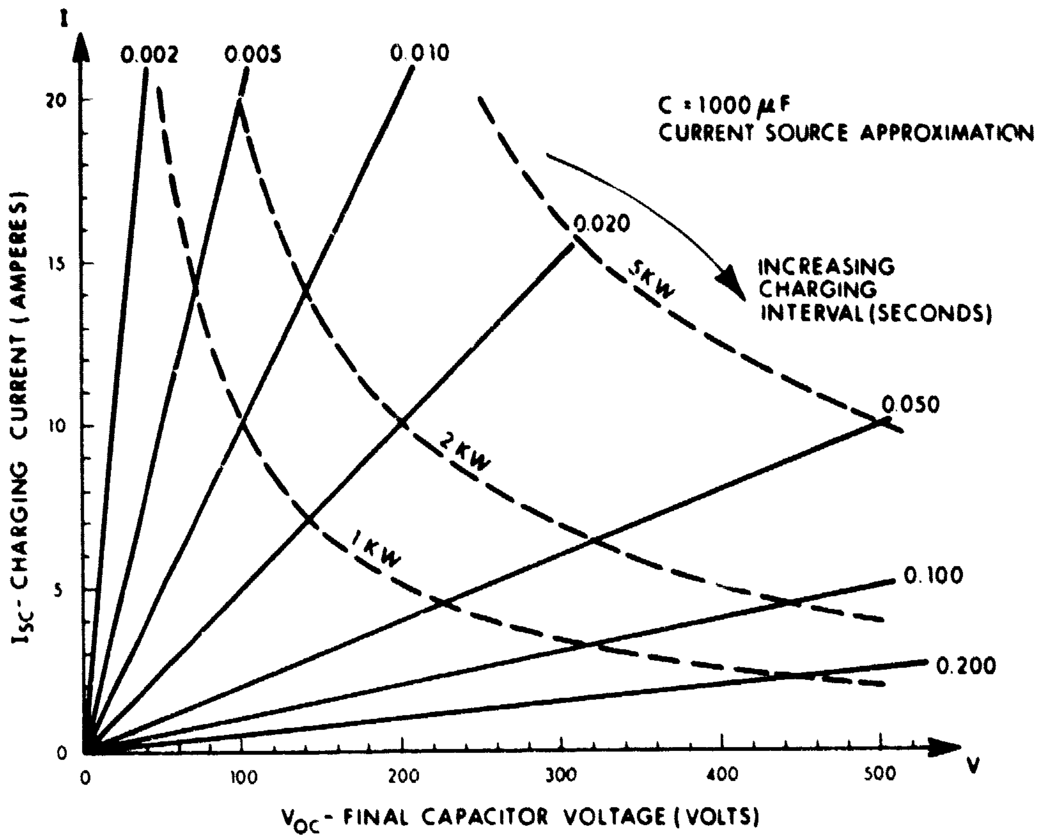
Basic Capacitive-Charging Method



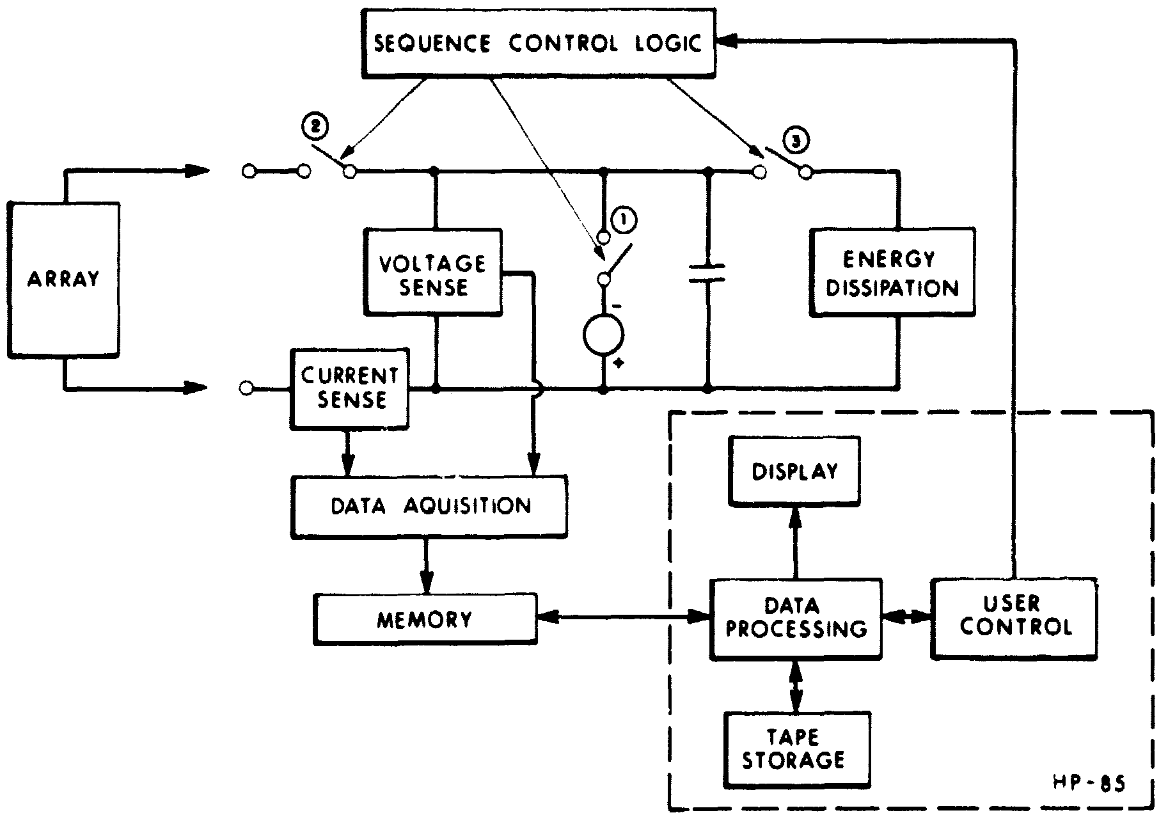
Resultant I-V Curve



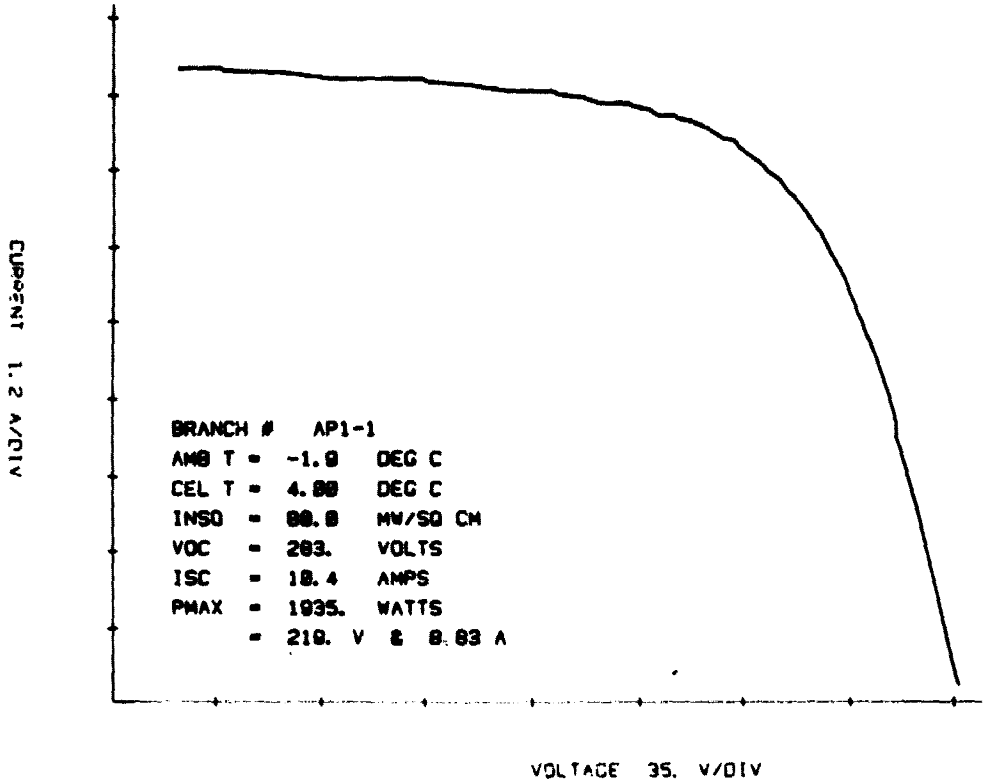
$$V(t) = \frac{1}{C}\int_0^t i(\tau)\,d\tau$$

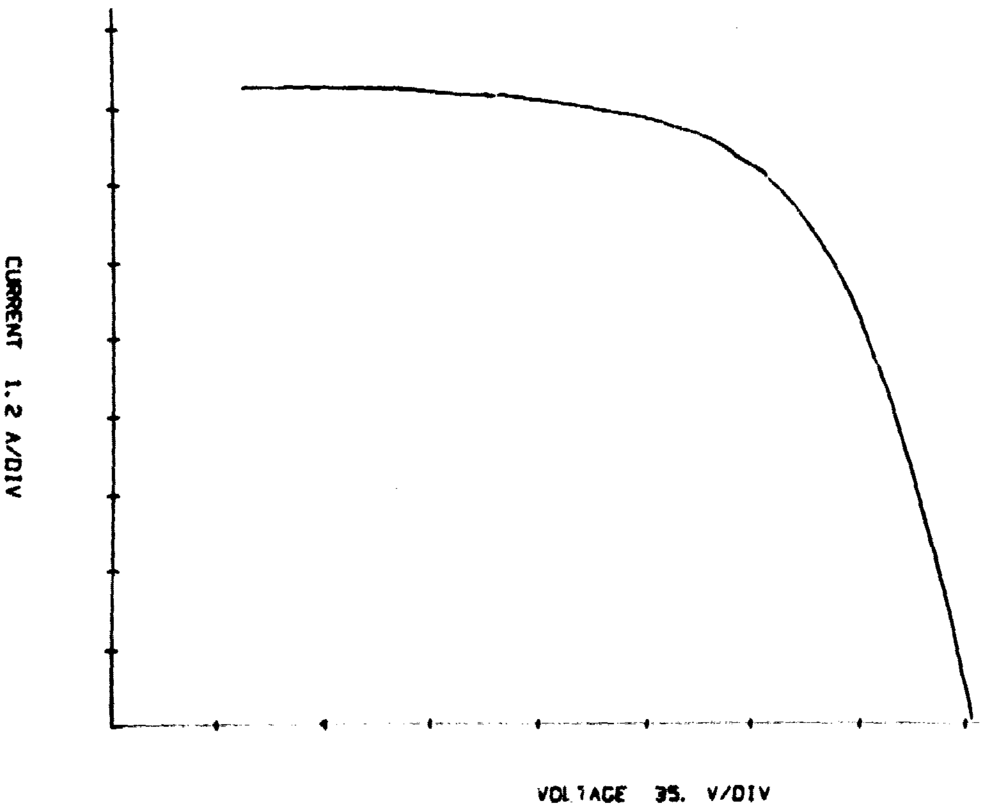

I
0.002
0.005
0.010
20
15
10
5
0
C = 1000 μF
CURRENT SOURCE APPROXIMATION
0.020
5KW
INCREASING
CHARGING
INTERVAL (SECONDS)
0.050
2KW
1KW
0.100
0.200
I_{SC} - CHARGING CURRENT (AMPERES)
0
100
200
300
400
500
V
V_{OC} - FINAL CAPACITOR VOLTAGE (VOLTS)

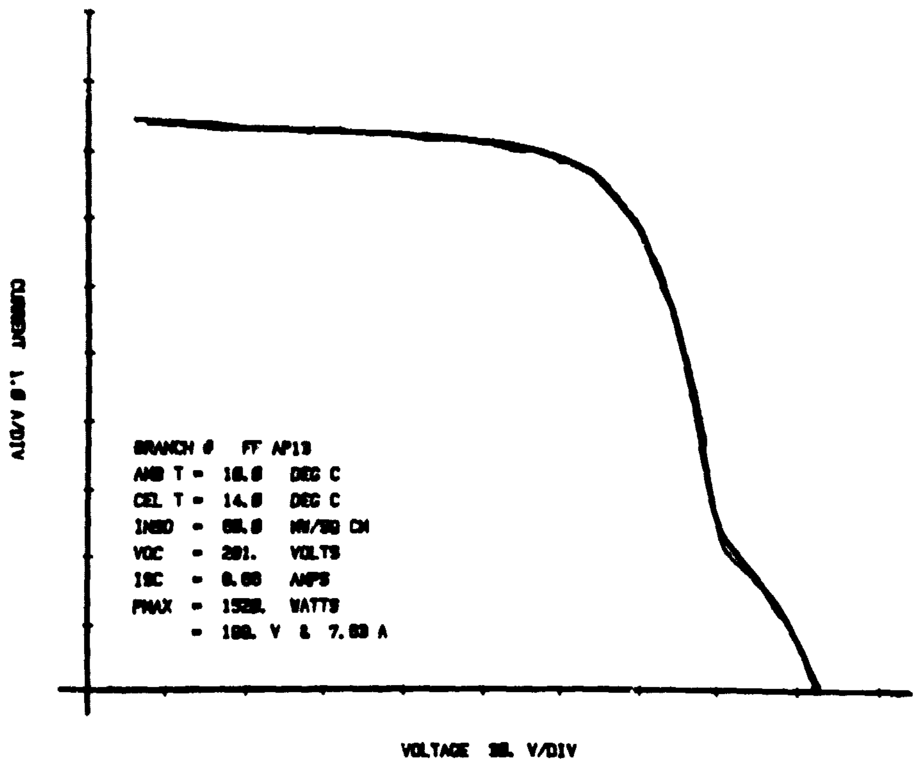
I-V Curve Tracer

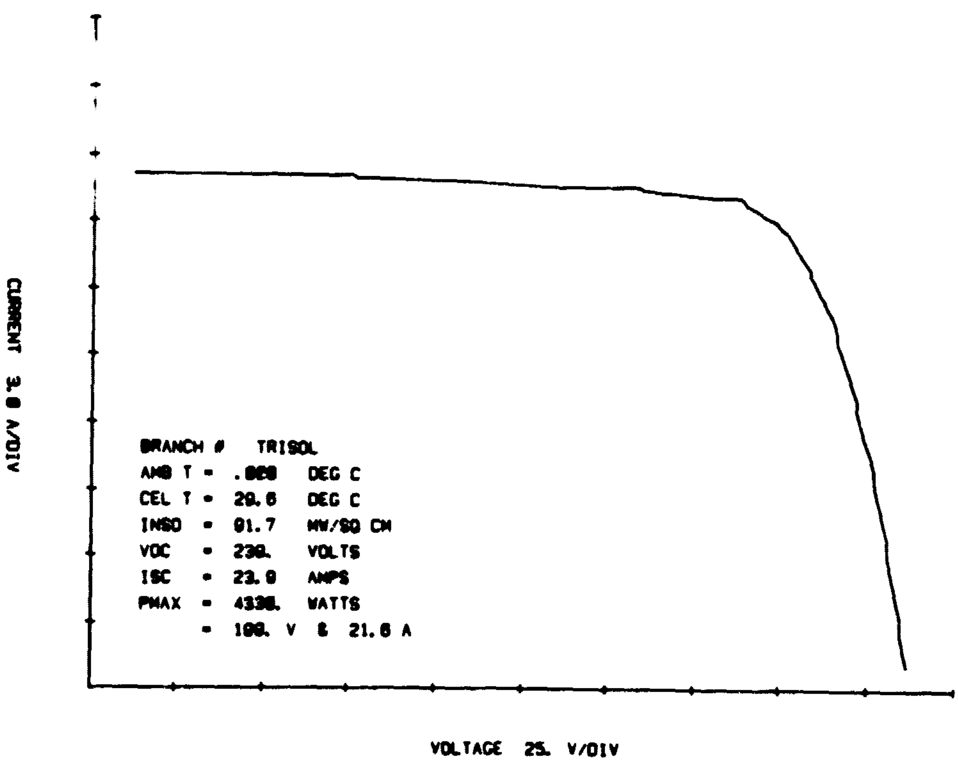


Comparison of 10-kW Curve Tracers






CURRENT 1.0 A/DIV
BRANCH # FF AP13
CEL T = 14.0 DEG C
VOC = 201. VOLTS
PMAX = 1520. WATTS
VOLTAGE V/DIV


CURRENT 3.0 A/DIV
BRANCH # TRISOL
AMB T = .000 DEG C
CEL T = 20.6 DEG C
INSO = 91.7 MW/SQ CM
VOC = 230. VOLTS
ISC = 23.0 AMPS
PMAX = 4330. WATTS
= 200. V & 21.6 A
VOLTAGE 25. V/DIV

	Resistor Load	Capacitor Load		
		Power Head	HP	Total
Weight (lbs)	125	13	20	33
Size (cu ft)	4.3	0.5	1.08	1.58
Cost ($)	10,000	2500	3200	5700
Power Consumption (W)	240	20	30	50

PROBLEM-FAILURE ANALYSIS

JET PROPULSION LABORATORY
Steve Sollock

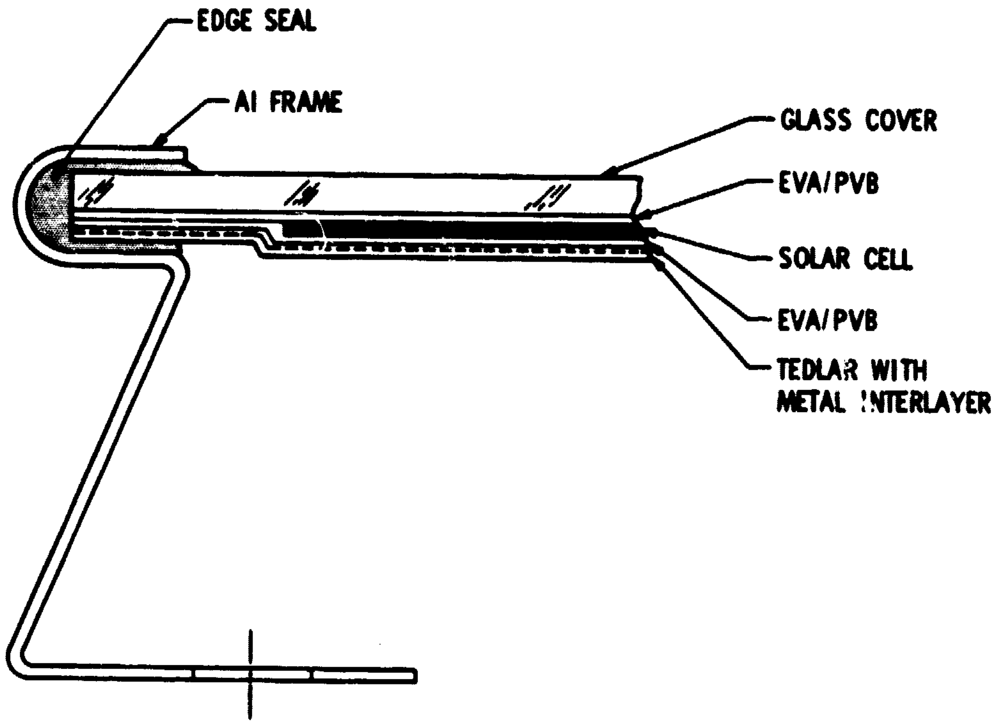
Problem-Failure Reporting System
Short-to-Ground History

VENDER	PROCUREMENT					
	BLOCK I	BLOCK II	BLOCK III	BLOCK IV	OTHER	PRDA
V	1	1				
W	2	3				
Y		2				3
Z						
U					3	3
R			14	3		
S						
K						
M				2	1	16
COM AND DEVEL					8	5

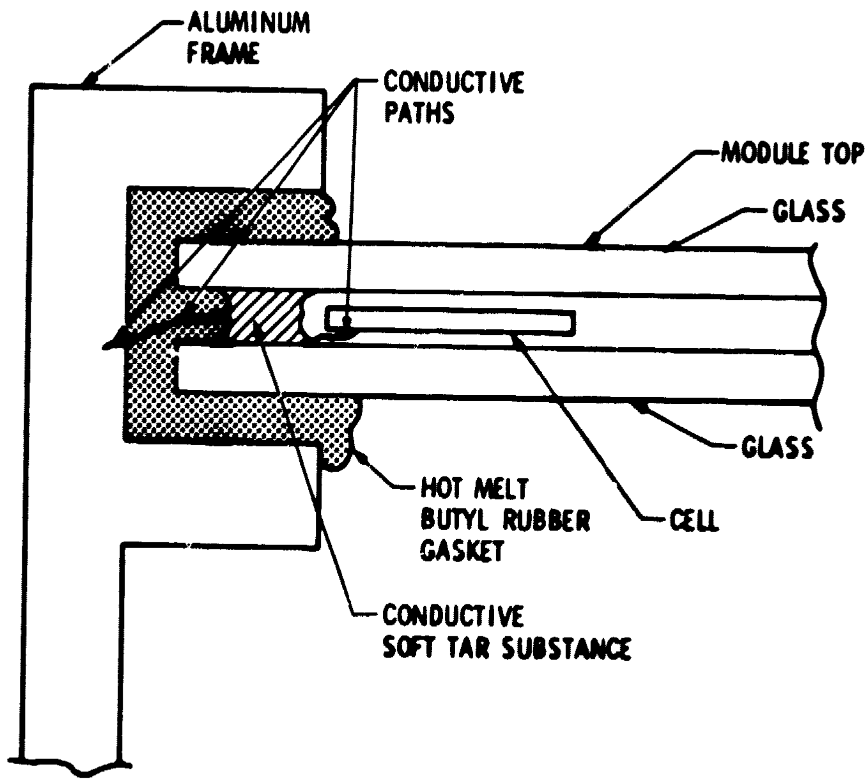
Short to Ground

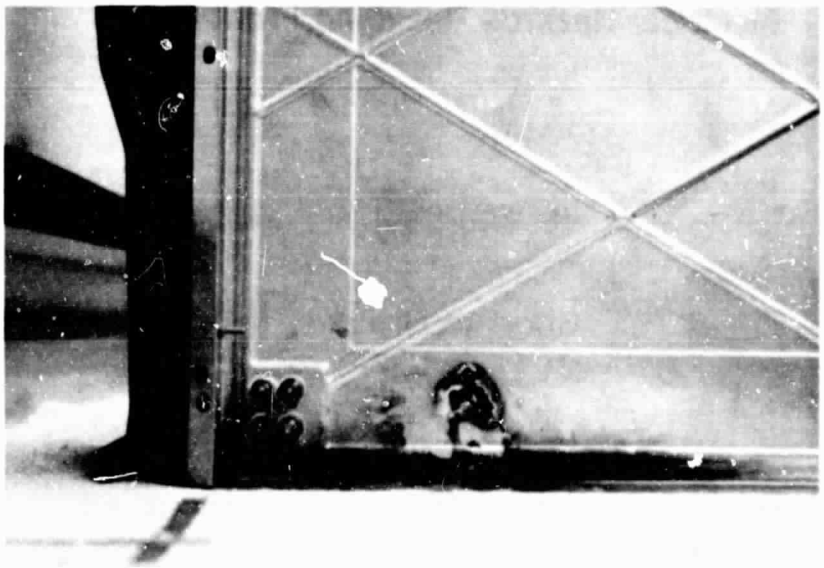
- PROBLEM CLASSIFICATION
  - DESIGN
    - PROBLEMS RELATING TO PROCESS AND MATERIALS
  - WORKMANSHIP
    - PROBLEMS RELATING TO PROCEDURE AND ASSEMBLY

Sample Module Laminate



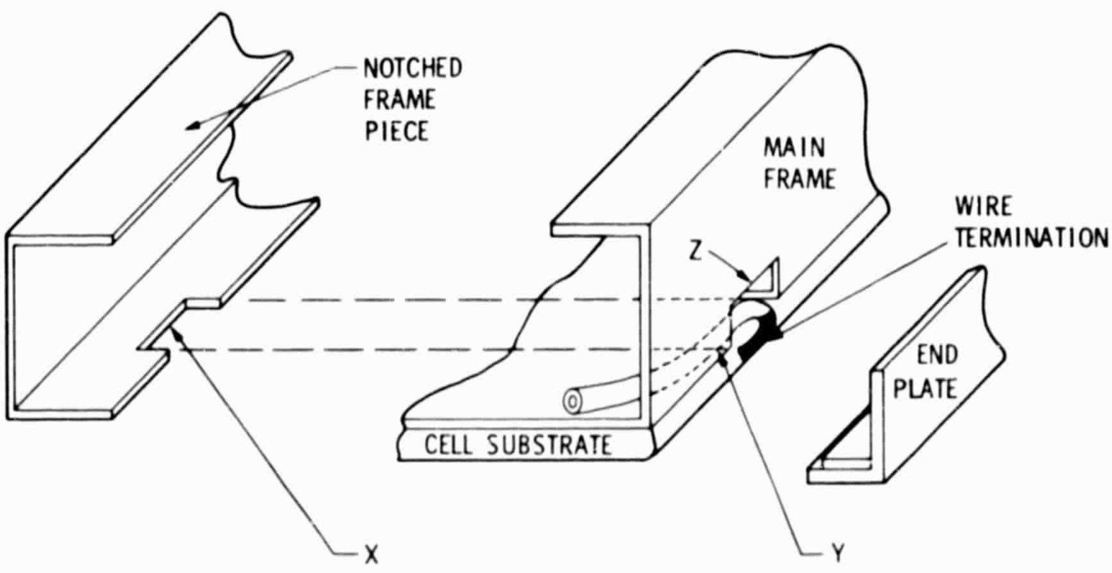
Shorts Due to a Conductive Sealant





Substrate Burnthrough Caused by Interconnect Foil Short to Substrate Pan Assembly

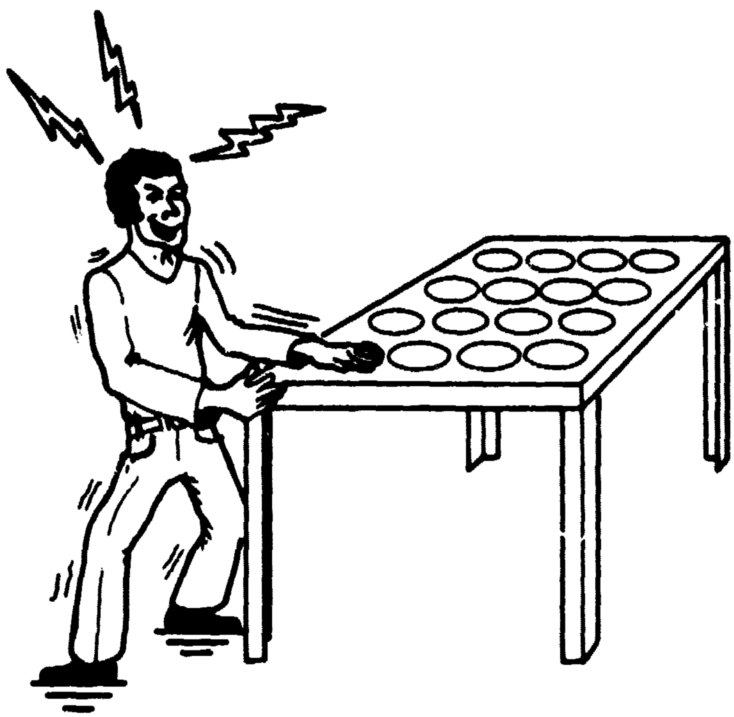
Sample Module Laminate



Electrical Hazards Resulting From Shorts

- TO EQUIPMENT
- PERSONNEL

Short to Ground



PROBLEM-FAILURE ANALYSIS

JET PROPULSION LABORATORY
Alex Shumka

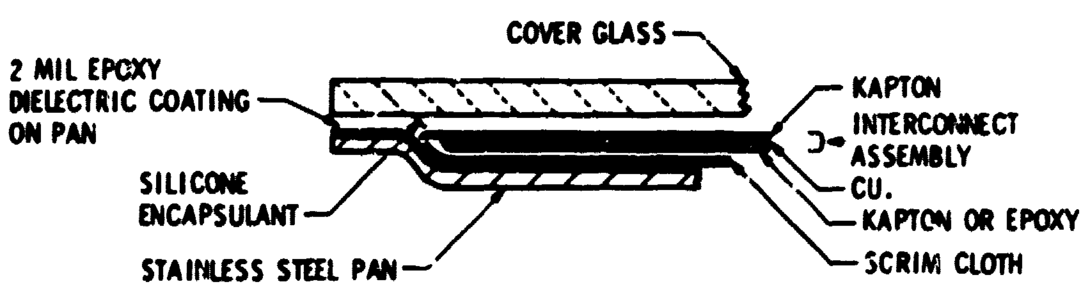
Objective

- PRESENT FAILURE ANALYSIS RESULTS ON SHORTS TO GROUND
- DISCUSS PROBABLE FAILURE CAUSE
- DESCRIBE MEASUREMENT TECHNIQUES ON DIELECTRIC MATERIALS USEFUL FOR DESIGN EVALUATION, QUALITY CONTROL AND FAILURE ANALYSIS

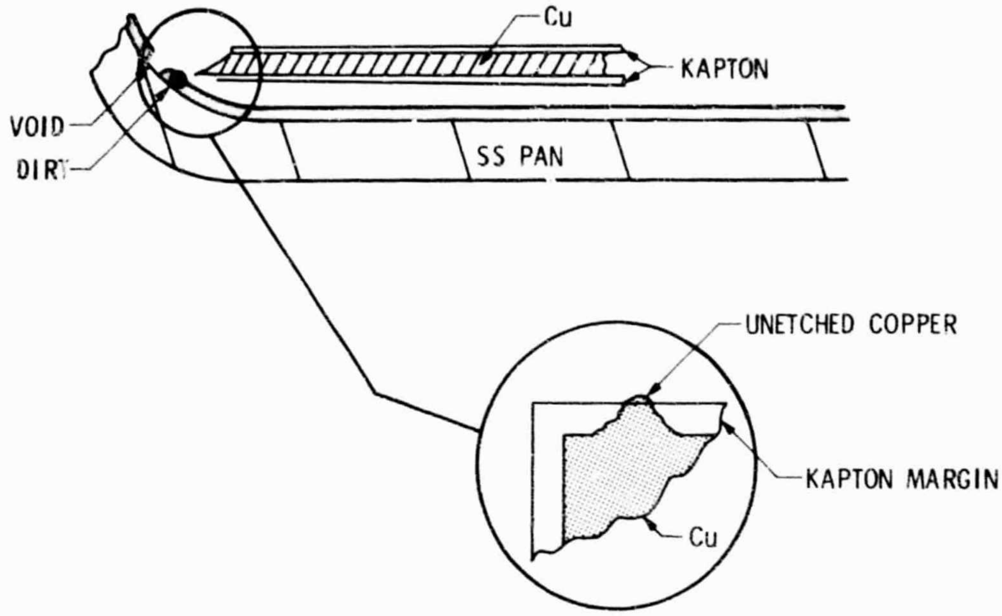
Shorts to Ground

- MODULE FRAME TO CELL STRING
- MODULE FRAME TO MODULE TERMINALS
- ARRAY STRUCTURE/MODULE FRAME TO MODULE INTERCONNECT WIRES
- FRAME TO FLOATING METALLIC MOISTURE BARRIER
- CELL STRING TO FLOATING/GROUNDED METALLIC MOISTURE BARRIER

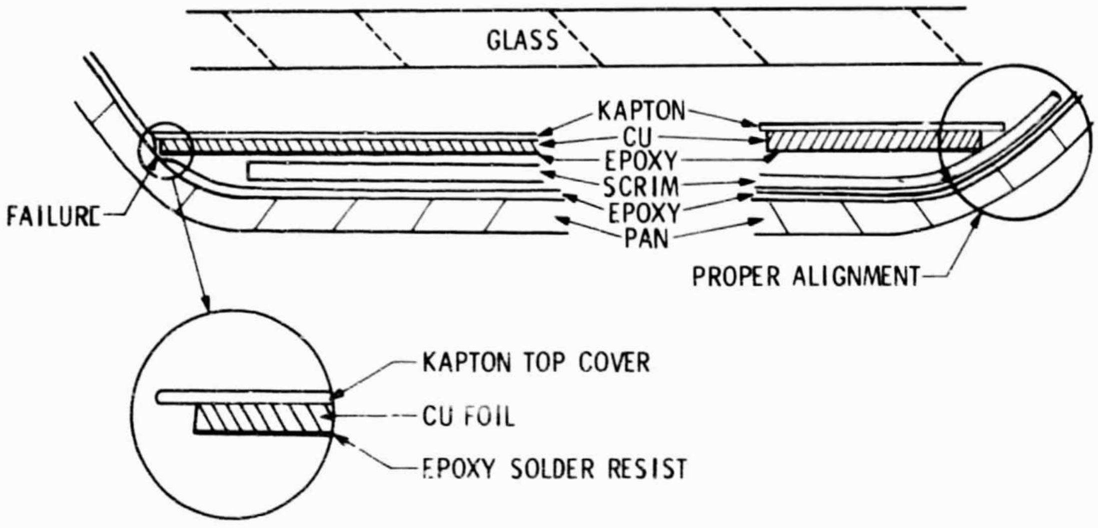
General Construction



Improperly Etched Margin; Poor Dielectric Coating Application

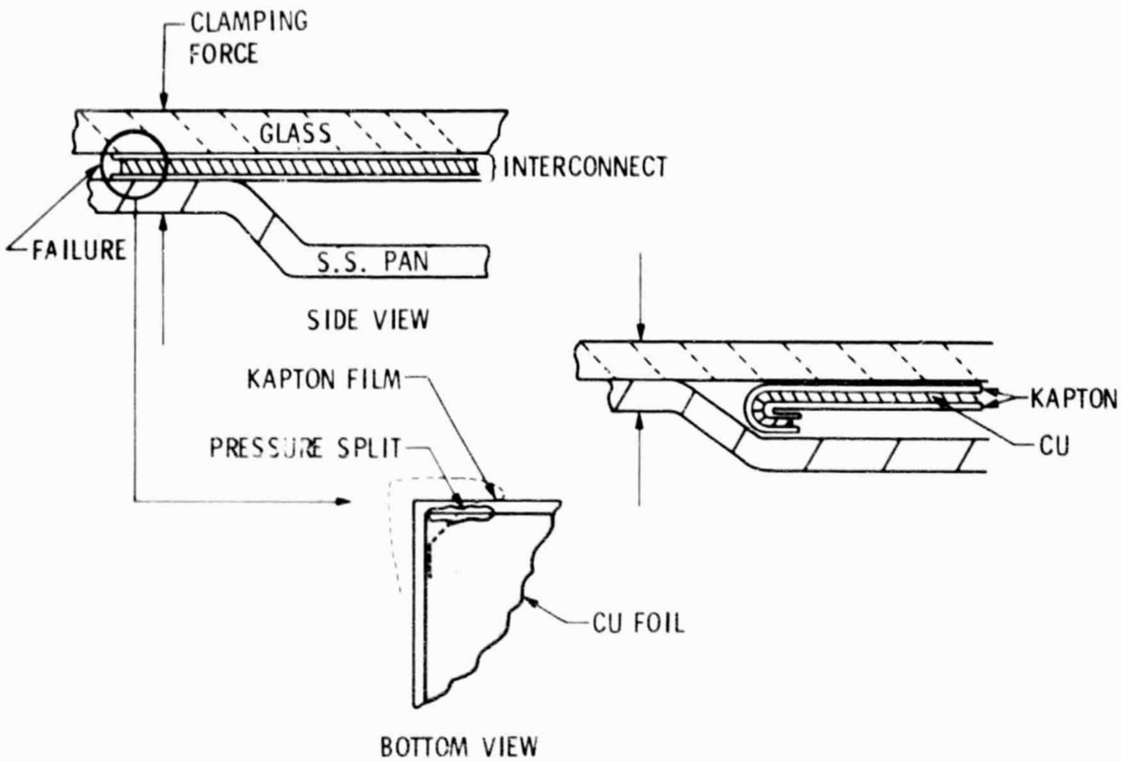


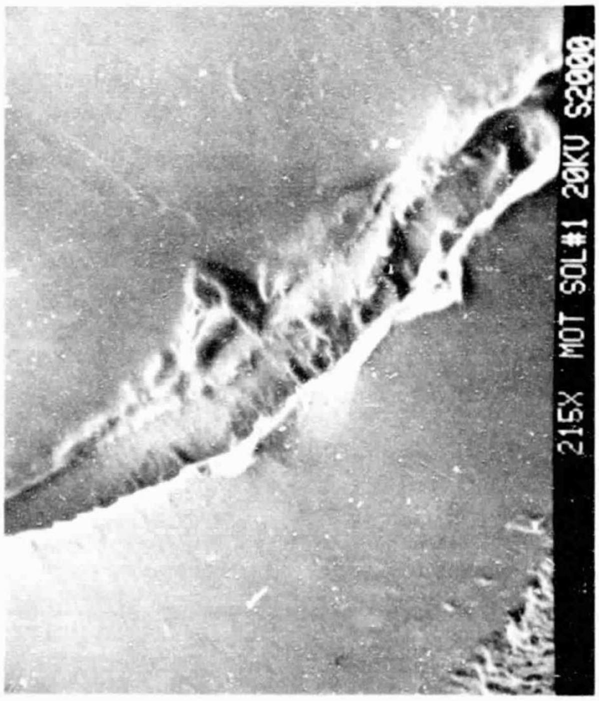
Misaligned Scrim Cloth; Dielectric Coating Cut Through



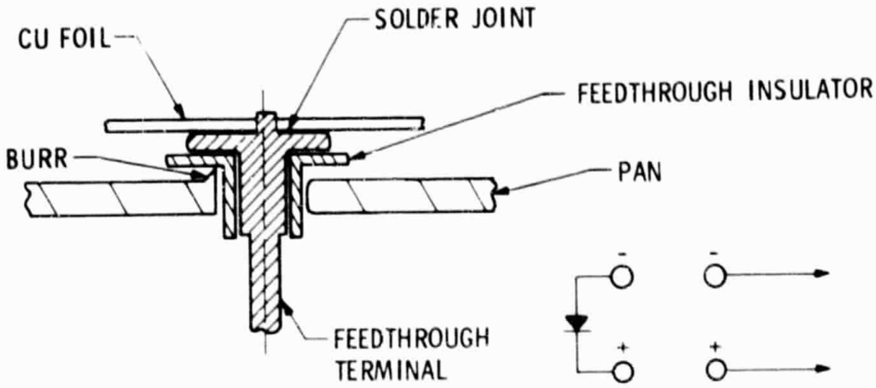
ORIGINAL PAGE IS
OF POOR QUALITY

Pressure-Induced Kapton Failure



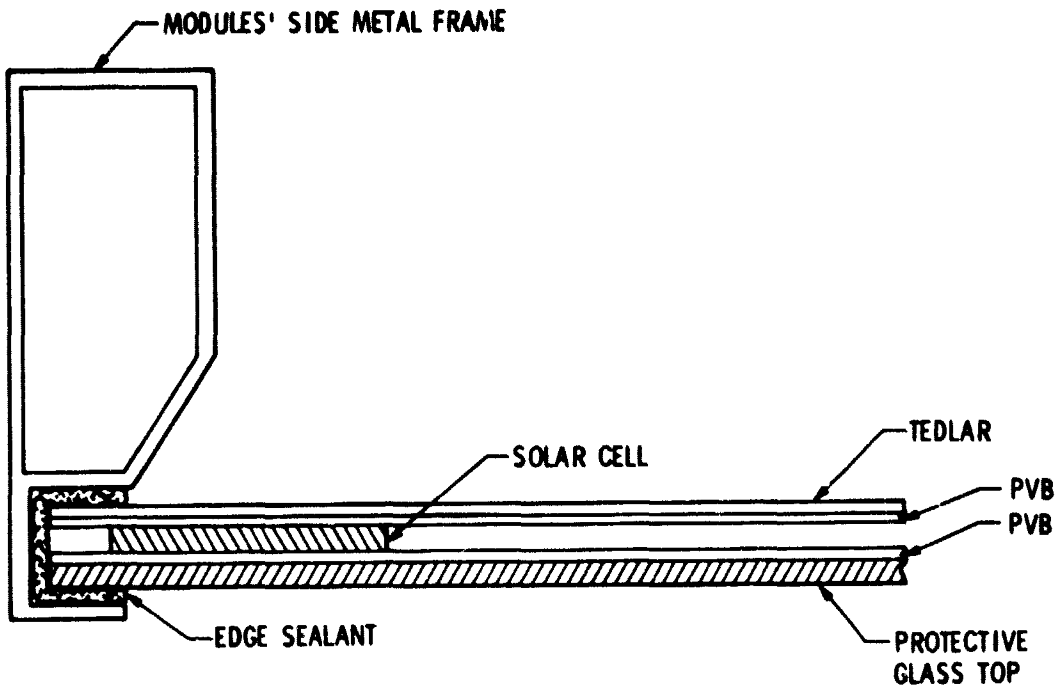


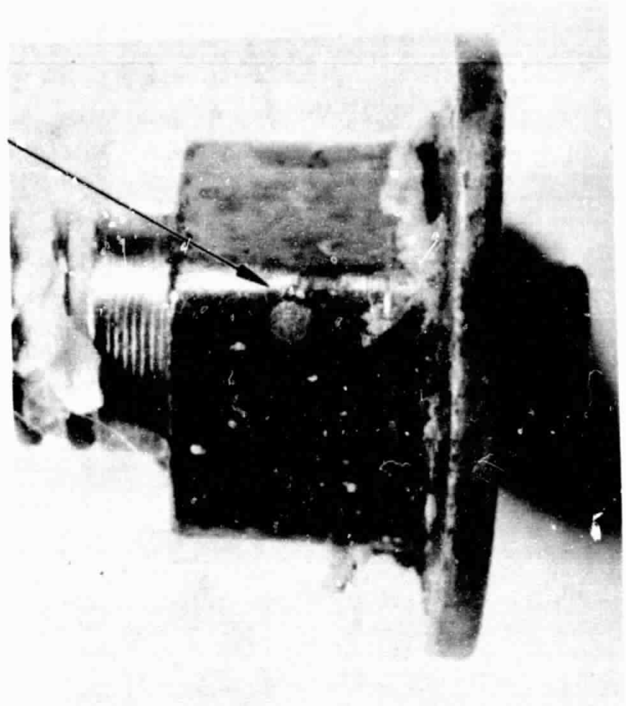
Burr-Induced Insulation Failure; Power Overstress at Solder Joint

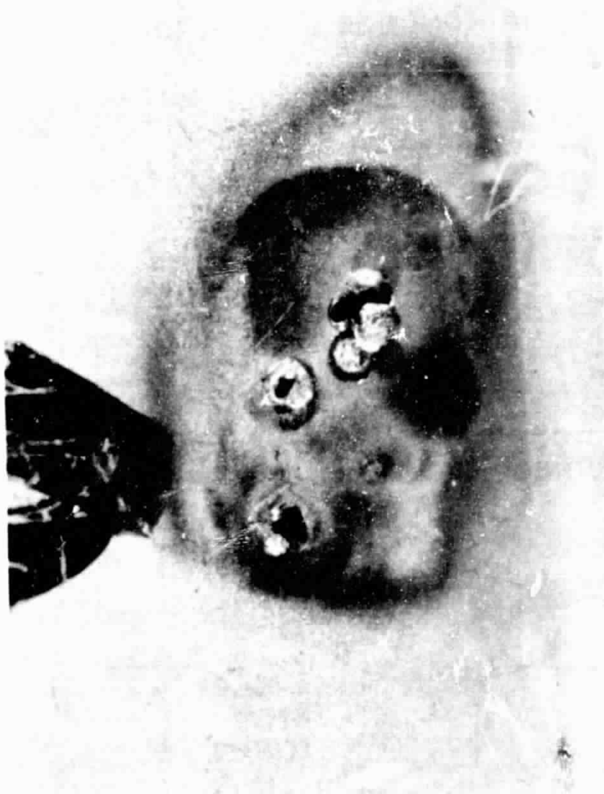


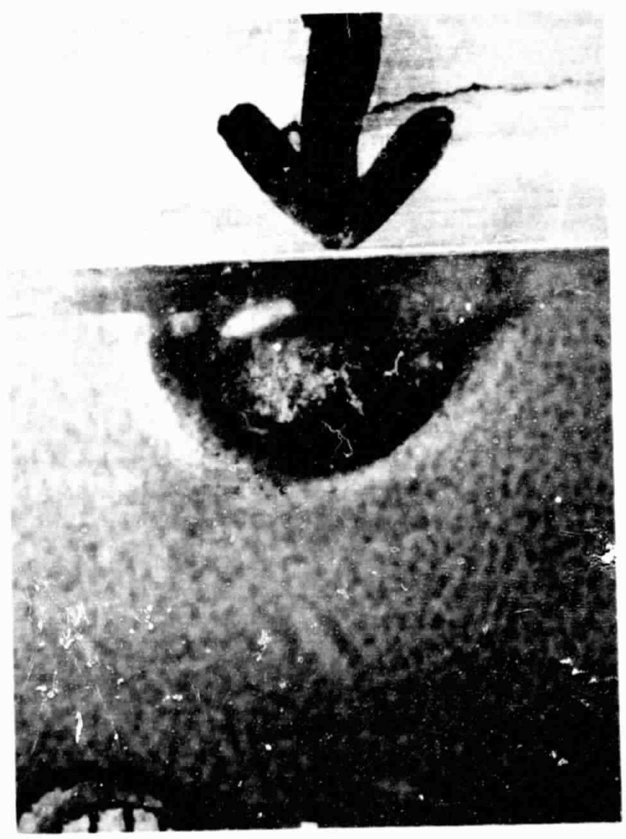
INSULATOR FAILURE

Insufficient Spacing Between Cells and Frame

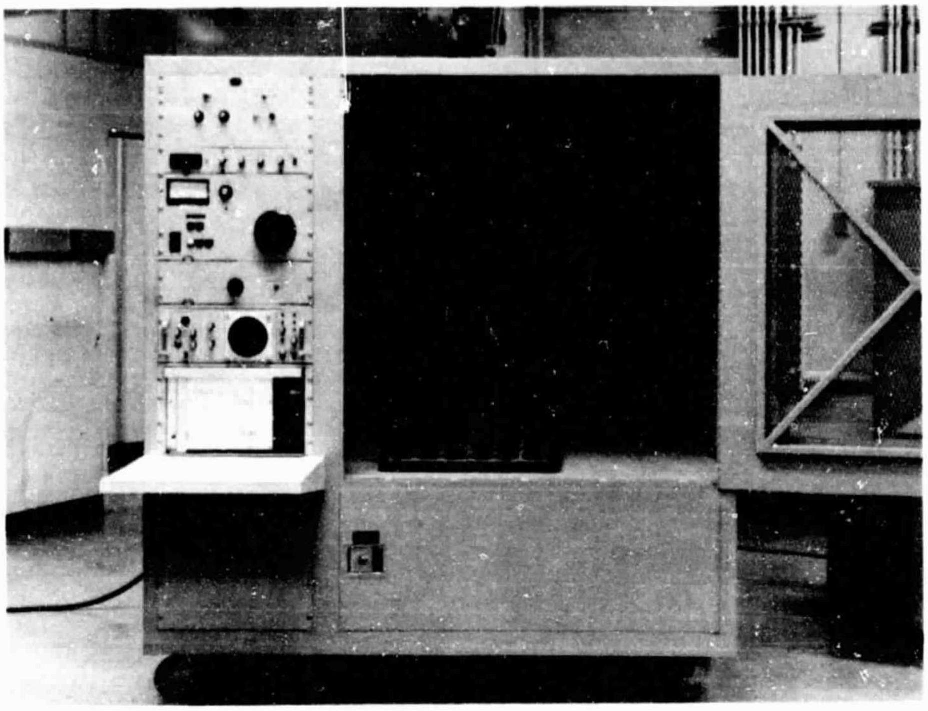




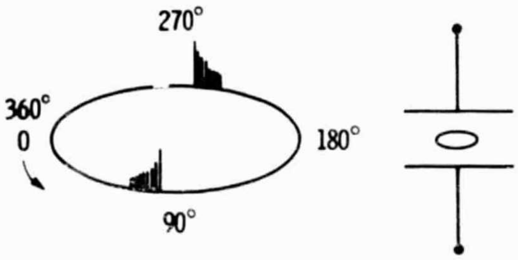




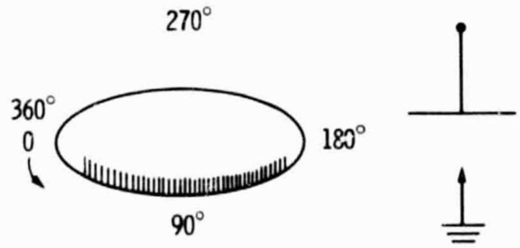
Partial Discharge Tester



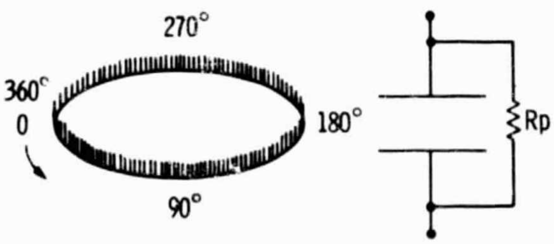
Discharges Due to Voids



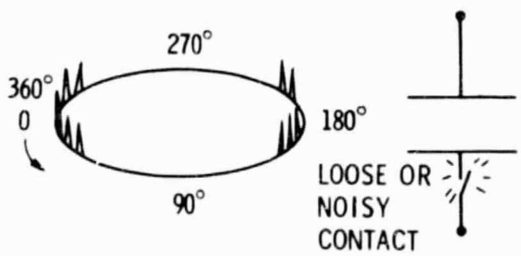
Point-to-Plane Discharges

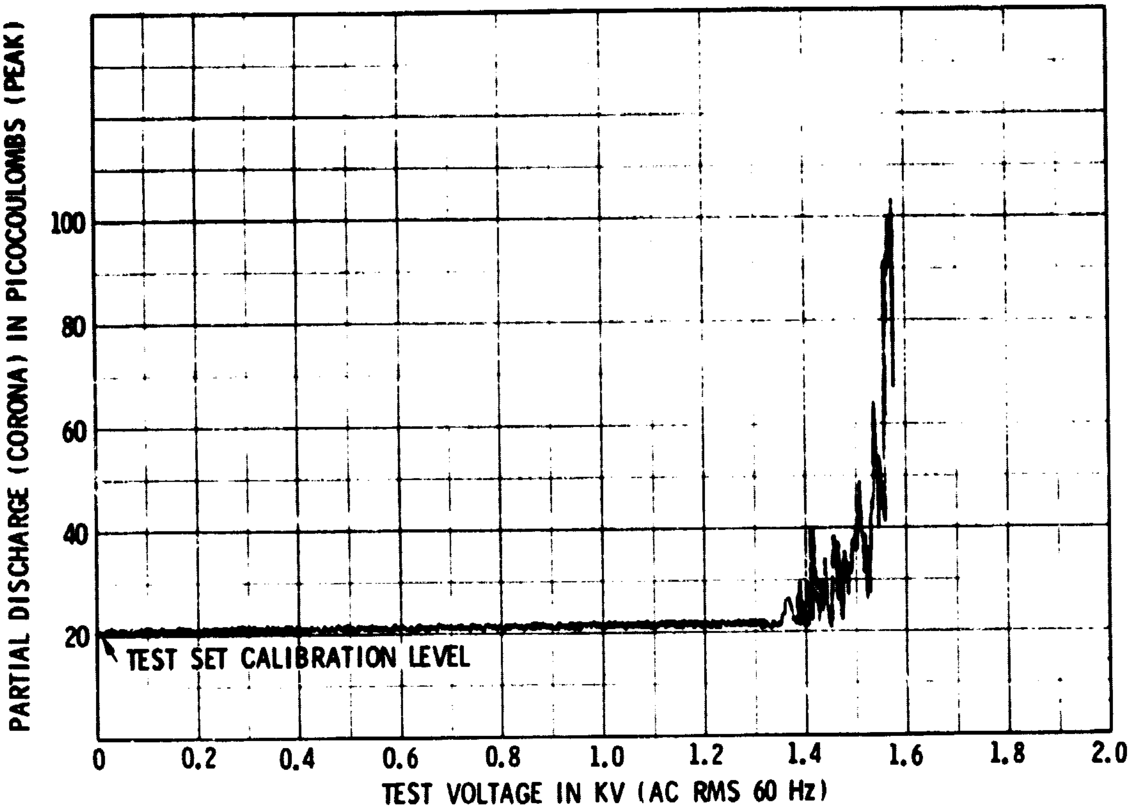


Surface Discharges



Contact Resistance Discharges




PARTIAL DISCHARGE (CORONA) IN PICOCOULOMBS (PEAK)
100
80
60
40
20
TEST SET CALIBRATION LEVEL
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
TEST VOLTAGE IN KV (AC RMS 60 Hz)

Failure Analysis Module Dielectric Tests

TEST	Q/C EVALUATION	DESIGN EVALUATION	DEGRADATION	
			QUAL TEST	FIELD
CAPACITANCE	X	√ X	√ X	√ X
DISSIPATION FACTOR (R/X)	X	√ X	√ X	√ X
PARTIAL DISCHARGE (CORONA)	X	√ X	√ X	√ X
HI-POT	X	√ X	√ X	√ X
DC I_L OR IR	X	√ X	√ X	√ X

NOTE: √ = TESTS PERFORMED BY JPL/FA

X = TESTS RECOMMENDED BY JPL/FA

Summary

SOME FAILURE CAUSES

DESIGN: INADEQUATE INSULATION MARGIN; UNDESIRABLE DEFORMATION OF INSULATION DUE TO COMPRESSIVE FORCES/ USE OF CONDUCTIVE SEALANT MATERIAL

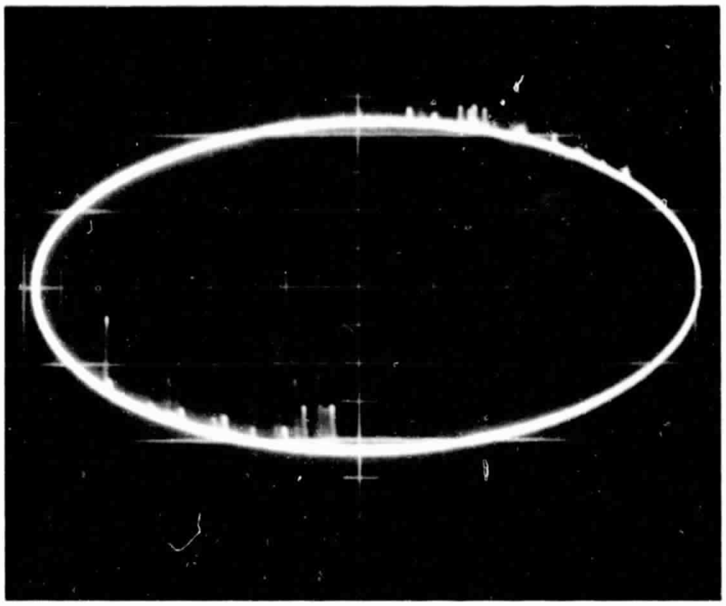
WORKMANSHIP: METALLIC BURRS; SHARP POINTS ON INTERCONNECTS; MISALIGNMENT OF INSULATORS AND/OR CELLS

HANDLING: MECHANICAL DAMAGE OF TERMINALS AND FRAME

Discharges Due to Voids

270°

360°
0°



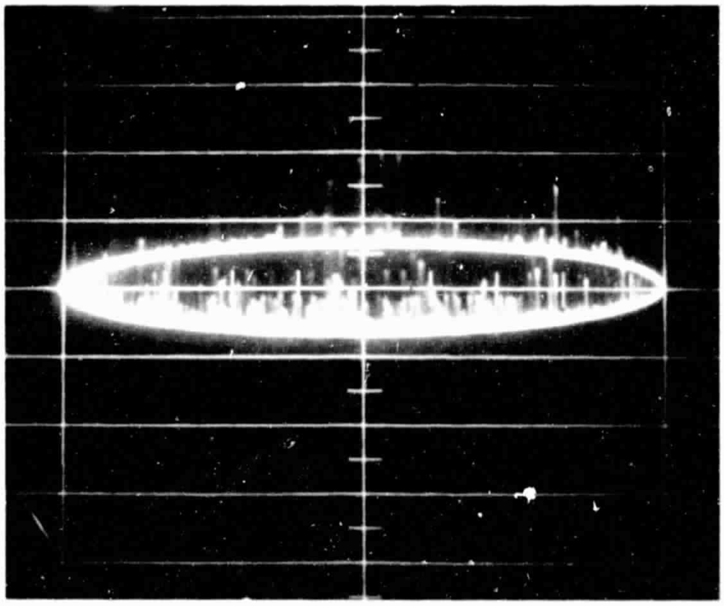
180°

90°

Surface Discharges

270°

360°
0°



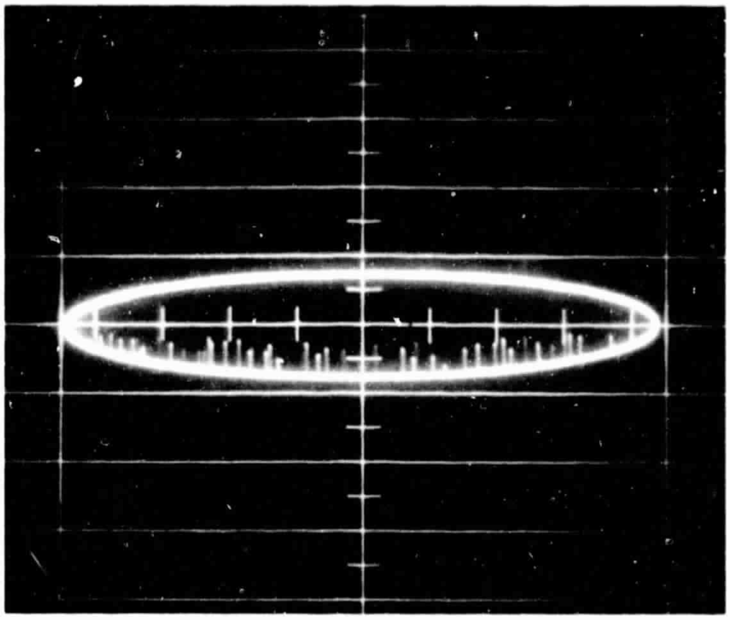
180°

90°

Point-to-Point Discharges

270°

360° 0°



180°

90°

ENGINEERING AREA STATUS (February 1981)

JET PROPULSION LABORATORY

R.G. Ross Jr.

Recent Accomplishments

- REQUIREMENT DEVELOPMENT
  - FLAT-PLATE MODULE SAFETY STANDARD (5101-164)
  - FLAT-PLATE ARRAY SAFETY WORKSHOP (FEB. 3)
  - BLOCK V MODULE DESIGN SPECIFICATIONS (5101-161, 5101-162)
  - PRODUCT LIABILITY PHASE 1 REPORT (CMU)
- ARRAY SUBSYSTEM DEVELOPMENT
  - GROUND-MOUNTED ARRAY STRUCTURE DESIGN PACKAGE
  - RESIDENTIAL ARRAY STRUCTURE CONTRACT INITIATION (GE, AIA/RC)
- MODULE ENGINEERING/RELIABILITY
  - MODULE SOILING REPORT (5101-131)
  - CELL RELIABILITY TESTING ANNUAL REPORT (CLEMSON)
  - CELL RELIABILITY WORKSHOP PROCEEDINGS (5101-163)
  - INTERCONNECT FATIGUE PROBABILITY ANALYSIS
  - HOT-SPOT ENDURANCE TEST PROCEDURE/RESULTS
- PERFORMANCE CRITERIA AND STANDARDS
  - FLAT-PLATE PV-T TEST METHOD
  - ACTIVELY COOLED CONCENTRATOR TEST METHOD

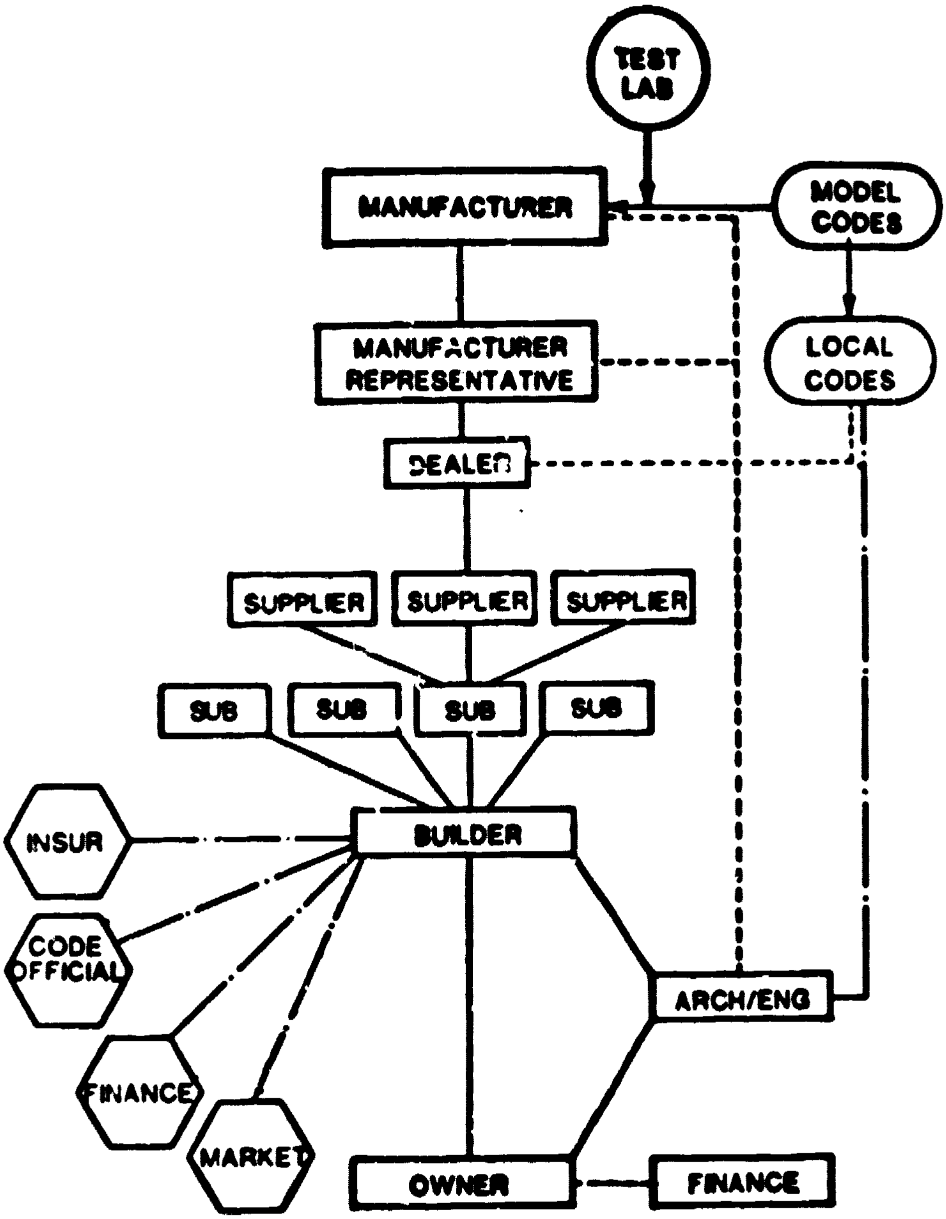
Ongoing Activities

- REQUIREMENT DEVELOPMENT STUDIES
  - SAFETY DESIGN REQUIREMENTS (UL)
  - PRODUCT LIABILITY REQ. (CARNEGIE-MELLON)
  - COMMERCIAL BUILDING CODES (BURT-HILL)
  - WIND LOADING (BOEING/CSU)
- ARRAY SUBSYSTEM DEVELOPMENT
  - LARGE GROUND MOUNTED ARRAYS (JPL)
  - INTEGRATED RESIDENTIAL ARRAYS (GE AND AIA)
- MODULE ENGINEERING/RELIABILITY STUDIES
  - OVERALL RELIABILITY ANALYSIS (JPL/IITRI)
  - ELECTRICAL INSULATION (JPL)
  - GLASS BREAKAGE (JPL)
  - INTERCONNECT FATIGUE (JPL)
  - HOT-SPOT ENDURANCE (JPL)
  - CELL RELIABILITY TESTING (CLEMSON)
  - CELL FRACTURE MECHANICS (JPL)
  - ACCELERATED SUNLIGHT TESTING (DSET)
  - LONG-TERM HUMIDITY TESTING (WYLE)
  - CORROSION ENDURANCE (WYLE)
  - SOILING (JPL)
- STANDARDS ACTIVITIES
  - ARRAY TASK GROUP MANAGEMENT (FOR SERI)
  - PV-T PERFORMANCE TEST DEVELOPMENT (JPL)
  - CONCENTRATOR PERFORMANCE TEST DEVEL (ASU)

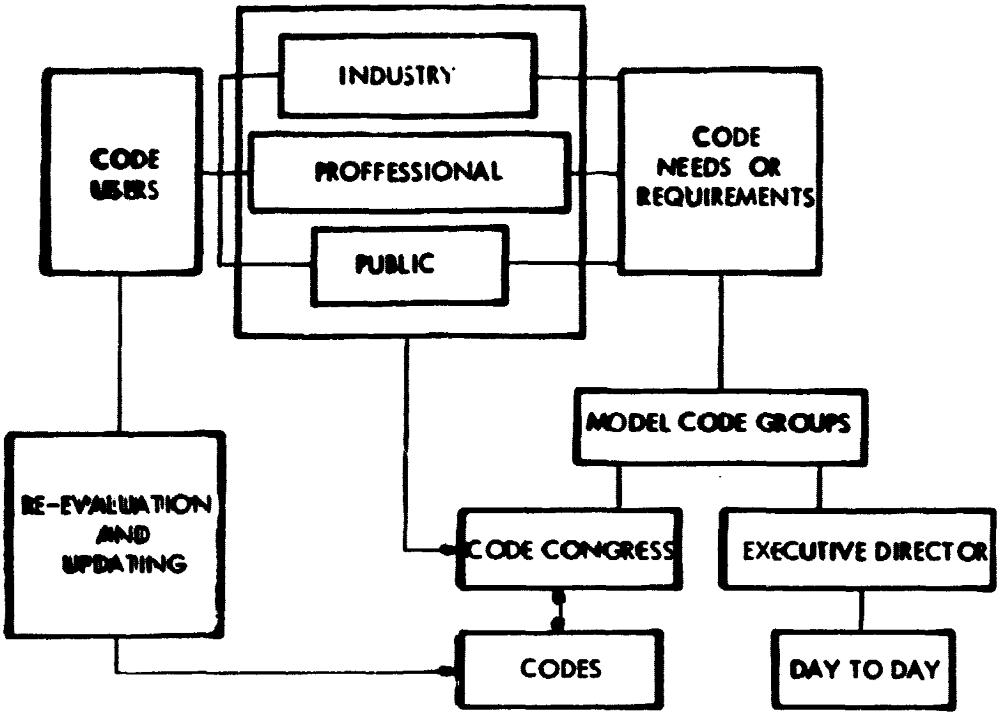
COMMERCIAL AND INDUSTRIAL PV MODULE CODE REQUIREMENTS

BURT HILL KOSAR RITTELMANN ASSOCIATES

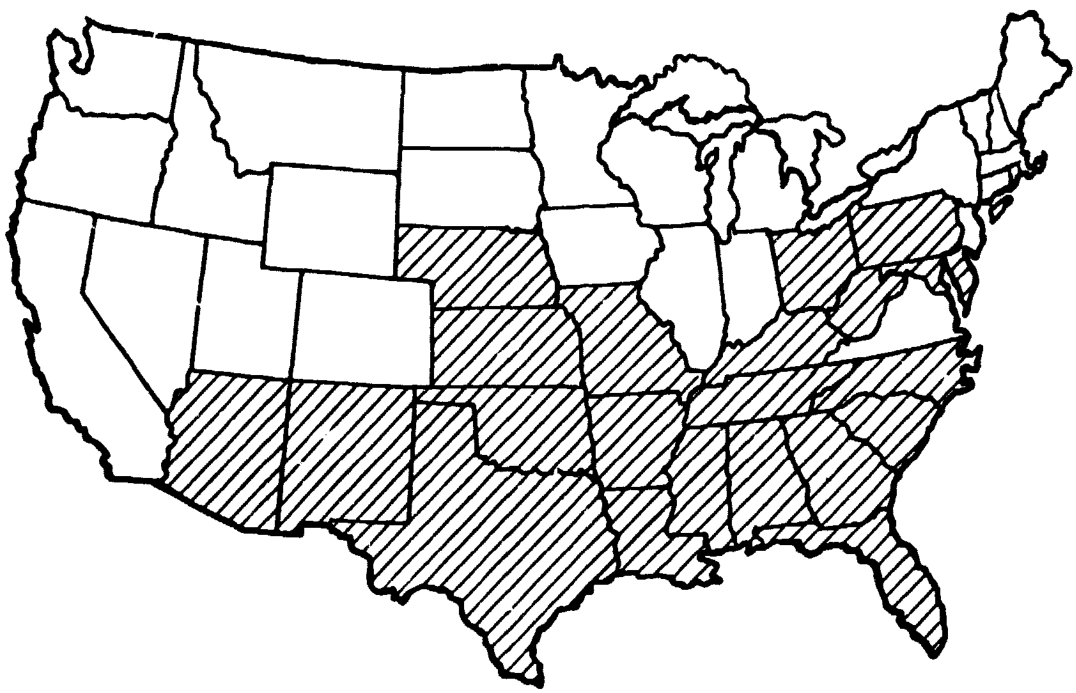
J. Oster
R. Rittelmann



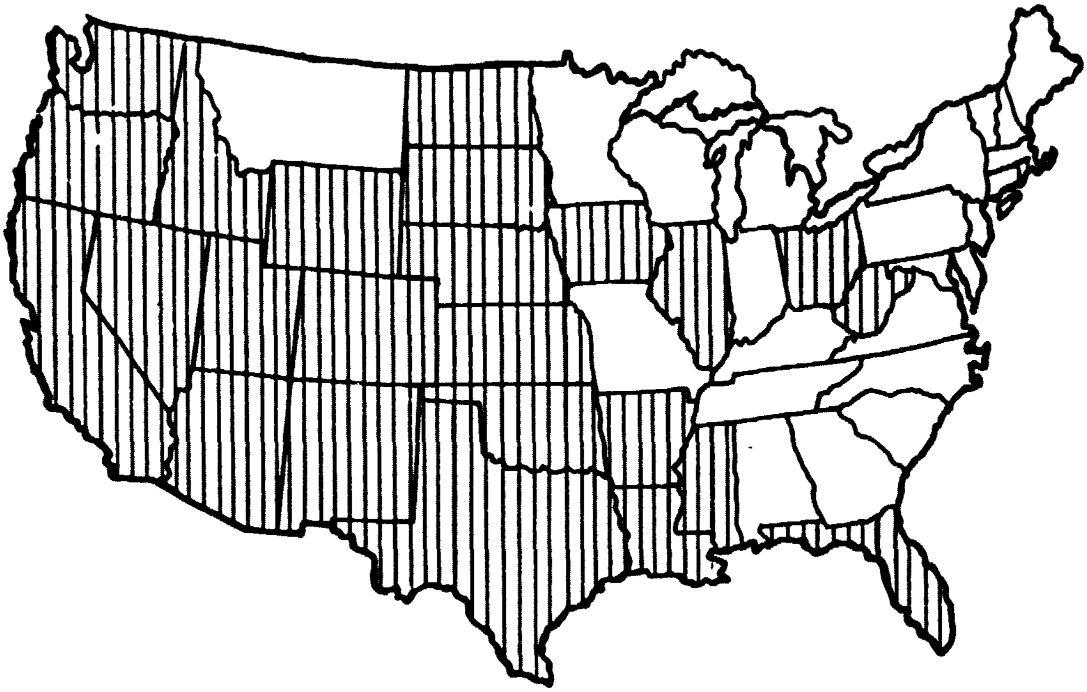
Code Development and Usage



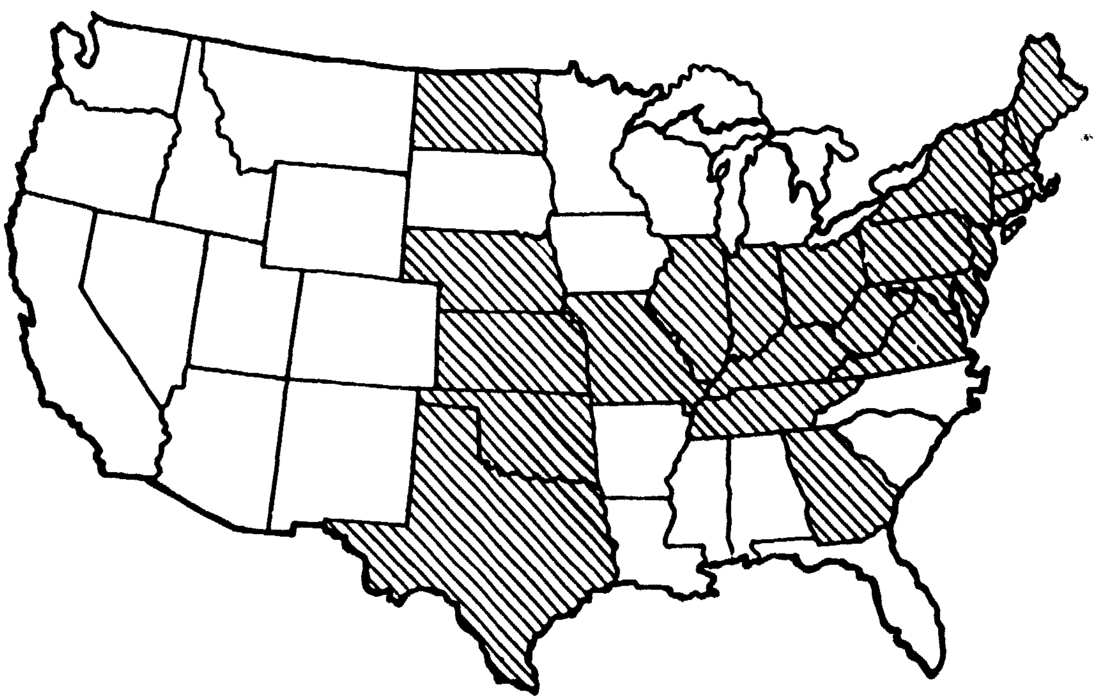
Southern Building Code Congress (SBCC)



International Conference of Building Officials



Building Officials and Code Administrators Int. Inc. (BOCA)



BOCA BASIC BUILDING CODE 1981 EDITION

SECTION 101.3: MATTERS NOT PROVIDED FOR:

ANY REQUIREMENT ESSENTIAL FOR STRUCTURAL, FIRE OR SANITARY SAFETY OF AN EXISTING OR PROPOSED BUILDING OR STRUCTURE, OR ESSENTIAL FOR THE SAFETY OF THE OCCUPANTS THEREOF, AND WHICH IS NOT SPECIFICALLY COVERED BY THIS CODE, SHALL BE DETERMINED BY THE BUILDING OFFICIAL.

SECTION 107.4: ALTERNATIVE MATERIALS AND EQUIPMENT

THE PROVISIONS OF THIS CODE ARE NOT INTENDED TO PREVENT THE USE OF ANY MATERIAL OR METHOD OF CONSTRUCTION NOT SPECIFICALLY PRESCRIBED BY THIS CODE, PROVIDED ANY SUCH ALTERNATIVE HAS BEEN APPROVED. THE BUILDING OFFICIAL MAY APPROVE ANY SUCH ALTERNATIVE PROVIDED THE BUILDING OFFICIAL FINDS THAT THE PROPOSED DESIGN IS SATISFACTORY AND COMPLIES WITH THE INTENT OF THE PROVISIONS OF THIS CODE, AND THAT THE MATERIAL, METHOD OR WORK OFFERED IS, FOR THE PURPOSE INTENDED, AT LEAST THE EQUIVALENT OF THAT PRESCRIBED IN THIS CODE IN QUALITY, STRENGTH, EFFECTIVENESS, FIRERESISTANCE, DURABILITY AND SAFETY.

ENGINEERING AND OPERATIONS AREAS

BUILDING AREA SQUARE FEET	CONSTRUCTION TYPE									
	TYPE 1 FIREPROOF		TYPE 2 NON-COMBUSTIBLE			TYPE 3 EXTERIOR MASONRY WALLS			TYPE 4 FRAME	
			PRO-TECTED	PRO-TECTED	UNPRO-TECTED	TIMBER	ORDINARY		PRO-TECTED	UNPRO-TECTED
CLASSIFICATION	1A	1B	2A	2B	2C	3A	3B	3C	4A	4B
A4 ASSEMBLY SCHOOL EXAMPLE CITED: SECONDARY SCHOOL	NO LIM.	NO LIM.	34200	22500	14400	21600	19800	14400	15300	7200
B BUSINESS OFFICE EXAMPLE CITED: DENTAL CLINIC REAL ESTATE OFFICE	NO LIM.	NO LIM.	34200	22500	14400	21600	19800	14400	15300	7200
F FACTORY/INDUSTRY EXAMPLE CITED: MACHINERY MANUFACTURER	NO LIM.	NO LIM.	22800	15000	9600	14400	13200	9600	10200	4800
I INSTITUTIONAL/ INCAPACITATED	NO LIM.	21600	17100	11250	7200	10800	9900	7200	7650	
M MERCANTILE EXAMPLE CITED: SHOPPING CENTER	NO LIM.	NO LIM.	22800	15000	9600	14400	13200	9600	10200	4800
A ASSEMBLY OTHER	NO LIM.	NO LIM.	19950	13125	8400	12600	11550	8400	8925	4200
H HAZARD	16800	14400	11400	7500	4800	7200	6600	4800	5100	
R RESIDENTIAL NON-HOUSEKEEPING	NO LIM.	NO LIM.	22800	15000	9600	14400	13200	9600	10200	4800
S STORAGE	NO LIM.	NO LIM.	19950	13125	8400	12600	11550	8400	8925	4200

BUILDING HEIGHT STORIES AND FEET	CONSTRUCTION TYPE: TYPE 1 FIREPROOF		TYPE 2 NON-COMBUSTIBLE			TYPE 3 EXTERIOR MASONRY WALLS			TYPE 4 FRAME	
CLASSIFICATION	1A	1B	PRO-TECTED 2A	PRO-TECTED 2B	UNPRO-TECTED 2C	TIMBER 3A	ORDINARY 3B	ORDINARY 3C	PRO-TECTED 4A	UNPRO-TECTED 4B
A4 ASSEMBLY SCHOOL EXAMPLE CITED: SECONDARY SCHOOL	NO LIM.	NO LIM.	5 ST 65'	3 ST 40'	2 ST 30'	3 ST 40'	3 ST 40'	2 ST 30'	1 ST 20'	1 ST 20'
B BUSINESS OFFICE EXAMPLE CITED: DENTAL CLINIC REAL ESTATE OFFICE	NO LIM.	NO LIM.	7 ST 85'	5 ST 65'	3 ST 40'	5 ST 65'	4 ST 50'	3 ST 40'	3 ST 40'	2 ST 30'
F FACTORY/INDUSTRY EXAMPLE CITED: MACHINERY MANUFACTURER	NO LIM.	NO LIM.	6 ST 75'	4 ST 50'	2 ST 30'	4 ST 5'	3 ST 40'	2 ST 30'	2 ST 30'	1 ST 20'
I INSTITUTIONAL/ INCAPACITATED	NO LIM.	8 ST 90'	4 ST 50'	2 ST 30'	1 ST 20'	2 ST 30'	2 ST 30'	1 ST 20'	1 ST 20'	
M MERCANTILE EXAMPLE CITED: SHOPPING CENTER	NO LIM.	NO LIM.	6 ST 75'	4 ST 50'	2 ST 30'	4 ST 50'	3 ST 40'	2 ST 30'	2 ST 30'	1 ST 20'
A ASSEMBLY OTHER	NO LIM.	NO LIM.	5 ST 65'	3 ST 40'	2 ST 30'	3 ST 40'	3 ST 40'	2 ST 30'	1 ST 20'	1 ST 20'
H HAZARD	5 ST 65'	3 ST 40'	3 ST 40'	2 S 30'	1 ST 20'	2 ST 30'	2 ST 30'	1 ST 20'	1 ST 20'	
R RESIDENTIAL NON-HOUSEKEEPING	NO LIM.	NO LIM.	9 ST 100'	4 ST 50'	3 ST 40'	4 ST 50'	4 ST 50'	3 ST 40'	3 ST 40'	3.5 ST 35'
S STORAGE	NO LIM.	NO LIM.	5 ST 65'	4 ST 50'	2 ST 30'	4 ST 50'	3 ST 40'	2 ST 30'	2 ST 30'	1 ST 20

POTENTIAL FOR PHOTOVOLTAIC APPLICATION	CONSTRUCTION TYPE									
	TYPE 1 FIREPROOF		TYPE 2 NON-COMBUSTIBLE			TYPE 3 EXTERIOR MASONRY WALLS			TYPE 4 FRAME	
			PRO-TECTED	PRO-TECTED	UNPRO-TECTED	TIMBER	ORDINARY		PRO-TECTED	UNPRO-TECTED
CLASSIFICATION	1A	1B	2A	2B	2C	3A	3B	3C	4A	4B
A4 ASSEMBLY SCHOOL EXAMPLE CITED: SECONDARY SCHOOL										
B BUSINESS OFFICE EXAMPLE CITED: DENTAL CLINIC REAL ESTATE OFFICE										
F FACTORY/INDUSTRY EXAMPLE CITED: MACHINERY MANUFACTURER										
I INSTITUTIONAL INCAPACITATED										N.P.
M MERCANTILE EXAMPLE CITED: SHOPPING CENTER										
A ASSEMBLY OTHER										
H HAZARD										N.P.
R RESIDENTIAL NON-HOUSEKEEPING										
S STORAGE										

KEY				
		PROBABLE		IMPROBABLE
		POSSIBLE	N.P.	NOT PERMITTED

Building Codes Reviewed

SOUTHERN BUILDING CODE CONFERENCE (SBCC)
STANDARD BUILDING CODE

BUILDING OFFICIAL CONFERENCE OF AMERICA (BOCA)
BASIC BUILDING CODE

INTERNATIONAL CONFERENCE OF BUILDING OFFICIALS (ICBO)
UNIFORM BUILDING CODE

PITTSBURGH BUILDING CODE

LOS ANGELES BUILDING CODE

Standards and Testing Agencies Reviewed

AMERICAN SOCIETY OF TESTING AND MATERIALS (ASTM)

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

NATIONAL BURUEAU OF STANDARDS (NBS)

FEDERAL STANDARDS AND SPECIFICATIONS

NATIONAL FIRE PROTECTION ASSOCIATES (NFPA)

UNDERWRITERS LABORATORIES (UL)

Present Potential Barriers to the Development Of Photovoltaic Arrays in Model Codes

- Roof covering materials must achieve a Class A or B rating for many applications when tested according to ASTM E108, The Standard Methods of Fire Tests of Roof Coverings.

- Plastic materials must achieve an approved status of CC1 or CC2 according to ASTM D635, Rate or Burning and/or Extent and Time of Burning of Self-Supporting Plastics in a Horizontal Position, to be Utilized. Even then, restrictions can be severe.

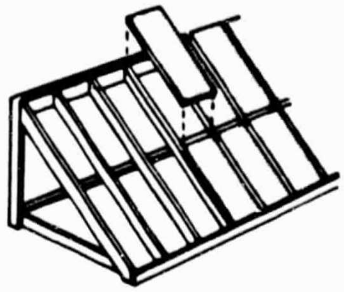
PLASTIC ROOF PANELS

CLASSIFICATION	MAX. PANEL AREA (Individual Unit)	TOTAL AREA OF PLASTIC ON ROOF (% of Floor Area)
SBCC and BOCA		
Class CC1	300 S.F.	30%
Class CC2	100 S.F.	25%

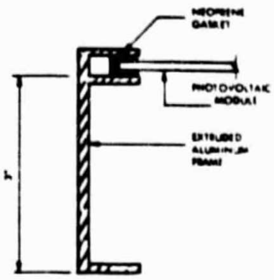
- Photovoltaic Modules which become part of a bearing wall section or roof section must be rated according to ASTM E119 Standard Methods of Fire Tests of Building Construction and Materials for hours of fire containment with structural retention.

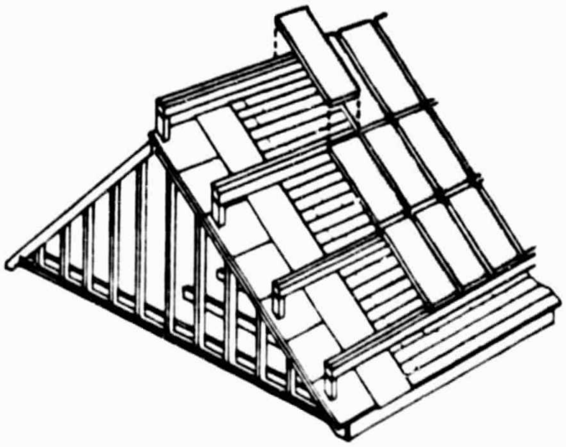
CONSTRUCTION TYPE

Mounting Application	Type 1 Fireproof		Type 2 Non-combustible			Type 3			Type 4 Frame	
			Protected	Protected	Unprotected	Exterior Timber	Masonry Walls Ordinary		Protected	Unprotected
	1A	1B	2A	2B	2C	3A	3B	3C	4A	4B
Non-Bearing Exterior Walls	4 or 0	4 or 0	1 or 0	1 or 0	0	4 or 0	1 or 0	0	1 or 0	0
Exterior Bearing Walls	4	3	2	1	0	2	2	2	1	0
Roof Construction	2	1-1/2	1	1	0	Var.	1	0	1	0

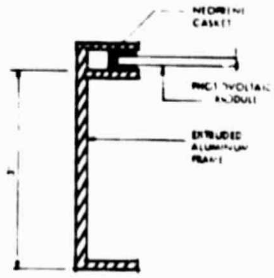


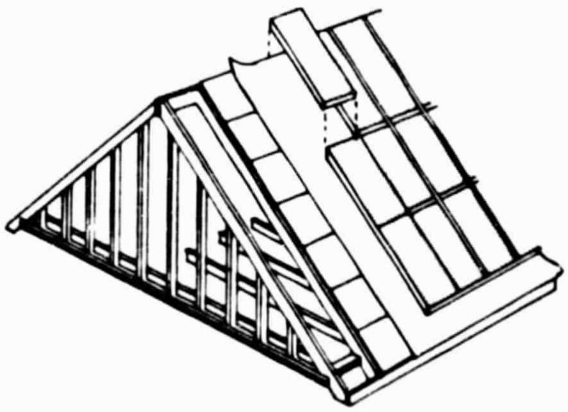
Rack



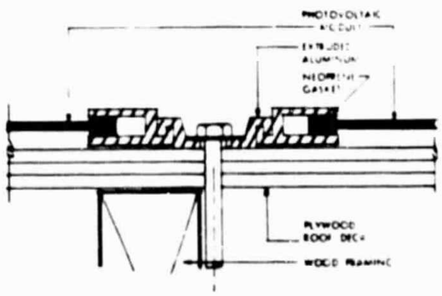


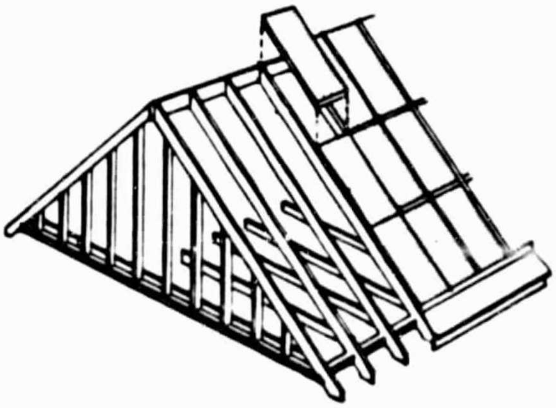
Standoff



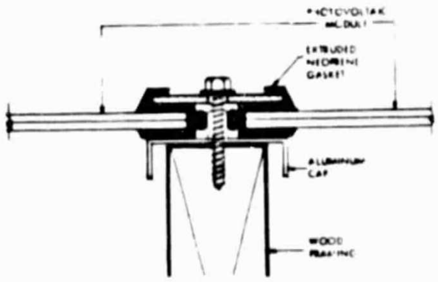


Direct





Integral



Preliminary Conclusions

- PV NOT ADDRESSED IN NEC
- POSSIBLE INCLUSION IN NEC 1984 EDITION. DRAFT REQUIRED BY MID - 1982
- PREMANUFACTURED WIRING SYSTEMS ADVANTAGEOUS
- VOLTAGE LEVEL 110 - 220 V (BASED ON COST OF WIRING)
- UL TESTING AND APPROVAL NECESSARY
- FURTHER WORK REQUIRED ON OPTIMUM SIZE
- NO MAJOR OR INSURMOUNTABLE PROBLEMS
- STANDARD INVESTIGATION IS ANTICIPATORY AND CURRENTLY UNDERWAY BY SERI AND ANSI
- CODE INVESTIGATION REQUIRED FOR EACH APPLICATION

National Electric Code Summary

GENERAL

THE PURPOSE OF THE CODE IS PRACTICAL SAFEGUARDING OF PERSONS AND PROPERTY.

SAFETY

LIVE PARTS OPERATING AT 50 VOLTS OR MORE SHALL BE GUARDED AGAINST ACCIDENTIAL CONTACT DURING INSTALLATION. THIS MAY BE NECESSARY AT ALL VOLTAGE LEVELS.

NATIONAL ELECTRICAL CODE SUMMARY

GROUNDING

NEC GROUNDING REQUIREMENTS FOR D.C. SYSTEMS DO NOT APPLY TO PV SYSTEMS IN GENERAL. THE AREAS OF NONAPPLICABILITY INCLUDE:

- QUALIFICATION FOR CIRCUIT AND SYSTEM GROUNDING BASED ON VOLTAGE LEVEL
- POINT OF GROUNDING CONNECTION FOR D.C. SYSTEMS
- GROUNDING OF CONDUCTOR ENCLOSURES
- GROUNDING OF SOME NONCURRENT-CARRYING METAL PARTS OF EQUIPMENT

PV GROUNDING SHOULD COMPLY WITH THE NEC IN CERTAIN AREAS:

- EFFECTIVE GROUNDING PATH
- GROUNDING ELECTRICAL CONDUCTOR REQUIREMENTS (E.G. SIZE AND MATERIAL)

PV SYSTEMS GROUNDING PHILOSOPHY SHOULD BE CHARACTERIZED BY:

- GROUNDING OF CONDUCTIVE ENCLOSURE OF ANY EQUIPMENT THAT IS INTERFACED WITH GROUNDED AC SYSTEM (DUE TO NEC REQUIREMENTS)
- GROUNDING OF ARRAY FRAME CONDUCTIVE MEMBERS
- METALLIC CONDUIT (IF USED) AND NON-UTILITY INTERFACING EQUIPMENT BE ISOLATED FROM GROUND
- UNGROUNDED CONDUIT ONLY ACCESSIBLE BY QUALIFIED PERSONNEL USING GROUND DETECTOR
- ISOLATION TRANSFORMER USED TO SEPARATE AC AND DC CIRCUITS

NATIONAL ELECTRICAL CODE SUMMARY

WIRING

MAJOR DIFFERENCE BETWEEN RESIDENTIAL AND COMMERCIAL/INDUSTRIAL SECTORS IS THE USE OF CONDUCTOR PROTECTIVE ENCLOSURE, E.G., CONDUIT. THIS IS DUE TO PROPENSITY FOR MECHANICAL DAMAGE OF UNPROTECTED CONDUCTORS.

FACTORY INSTALLED INTERNAL WIRING OF EQUIPMENT THAT IS LISTED BY AN ELECTRICAL TESTING LABORATORY IS ACCEPTED FOR USE BY THE NEC WITHOUT NEEDING TO MEET FURTHER NEC REQUIREMENTS. PV WIRING DESIGN SHOULD CONSIDER THIS APPROACH TO ACCELERATE ACCEPTANCE, AS THE BURDEN OF INTERPRETATION IS ESSENTIALLY REMOVED FROM THE CODE OFFICIAL.

DEFINITE NEC REQUIREMENTS WILL APPLY IF THE WIRING QUALIFIES AS A "SERVICE ENTRANCE CONDUCTOR".

CONDUCTOR SIZING SHOULD BE BASED ON INDIVIDUAL SYSTEM CHARACTERISTICS AS WELL AS RELATED NEC REQUIREMENTS. THIS SIZING CRITERIA SHOULD INCLUDE:

- AMPERAGE OF SHORT-CIRCUIT "SYSTEM" CURRENT @ MAXIMUM INSOLATION
- NUMBER OF CONDUCTORS IN A RACEWAY OR CABLE (NEC)
- AMBIENT TEMPERATURE OF CONDUCTOR ENVIRONMENT
- MATERIAL(S) OF CONDUCTORS
- TOTAL SYSTEM VOLTAGE DROP (5% - NEC)
- COST

SYSTEMS WITH VOLTAGES IN EXCESS OF 600 VOLTS WILL NEED TO MEET CERTAIN NEC REQUIREMENTS FOR:

- SERVICE CONDUCTORS ENTERING A BUILDING (AWG NO. 6 OR NO. 8 MINIMUM)
- LIMITED ACCESS

NATIONAL ELECTRICAL CODE SUMMARY

LIGHTNING

IN GENERAL THE NEED FOR LIGHTNING PROTECTION IS BASED ON THE FOLLOWING FACTORS:

- OCCUPANT SAFETY
- NATURE OF BUILDING AND CONTENTS
- RELATIVE EXPOSURE
- THUNDERSTORM FREQUENCY AND SEVERITY
- INDIRECT LOSSES
- AVAILABILITY OF FIREFIGHTING APPARATUS

TWO MAJOR CONSIDERATIONS FOR LIGHTNING PROTECTION FOR PV ARRAYS INVOLVE INDIRECT LOSSES RESULTING FROM VOLTAGE SURGES CAUSED EITHER BY DIRECT STRIKE OR INDUCTION:

- FIRE RESULTING FROM ELECTRICAL EQUIPMENT OR CONDUCTOR INSULTION FAILURE
- SHOCK RESULTING FROM CONTACT WITH "HOT" EQUIPMENT ENCLOSURE OR UNINSULATED CONDUCTOR

THE TWO TECHNIQUES USED IN LIGHTNING PROTECTION SYSTEMS ARE "SHIELDING" AND "ARRESTING". THE SHIELDING METHOD INTERCEPTS THE STRIKE WHILE THE ARRESTING IS USED TO DRAIN DAMAGING HIGH POTENTIAL CURRENT TO GROUND. BOTH SHOULD BE USED ON PV SYSTESM.

SPACING OF THE PV SYSTEM FROM LIGHTNING TERMINALS DICTATES BONDING TO LIGHTNING SHIELD SYSTESM.

- NEC 250-46
- NFC SECTION 78 PARAGRAPH 3-24

LIGHTNING ROD CONDUCTORS CANNOT BE USED FOR PV SYSTEM GROUNDING

- NEC 250-86

NFC VOLUME 7 SECTION 78 ADDRESSES LIGHTNING PROTECTION SYSTEMS REQUIREMENTS.

NATIONAL ELECTRICAL CODE SUMMARY

TERMINATION

WIRING TERMINATION REQUIREMENTS ARE NOT EXTENSIVELY ADDRESSED BY THE NEC.

CERTIFICATION BY A RECOGNIZED ELECTRICAL TESTING LABORATORY WOULD SUFFICE FOR ACCEPTANCE BY THE NEC. (IN MOST JURISDICTIONS)

FUNDAMENTAL TERMINATION REQUIREMENTS ARE:

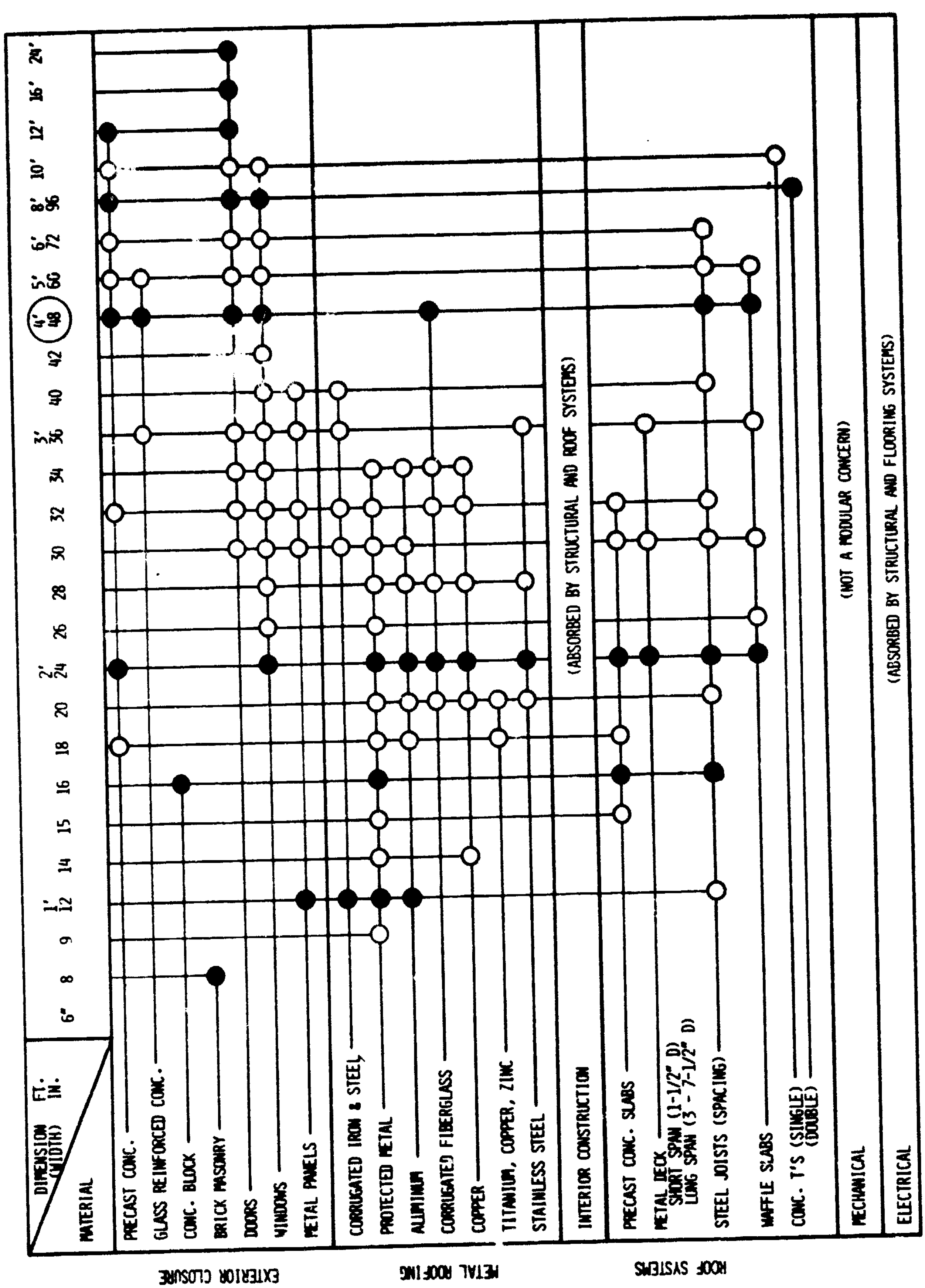
- ADEQUATE CURRENT CAPACITY
- ADEQUATE ELECTRICAL INSULATION (VOLTAGE REQUIREMENT)
- LOW OHMIC CONTACT
- ADEQUATE WEATHERIZATION
- LOW LIFE-CYCLE COST

AT THIS POINT IN TIME, TESTING AND MAINTENANCE ACCESS IS IMPORTANT. WHEN RELIABILITY IS IMPROVED, AND IT IS FOUND THAT MEAN TIME BETWEEN FAILURE EXCEEDS MODULE LIFE, THEN THESE REQUIREMENTS SHOULD BE RECONSIDERED.

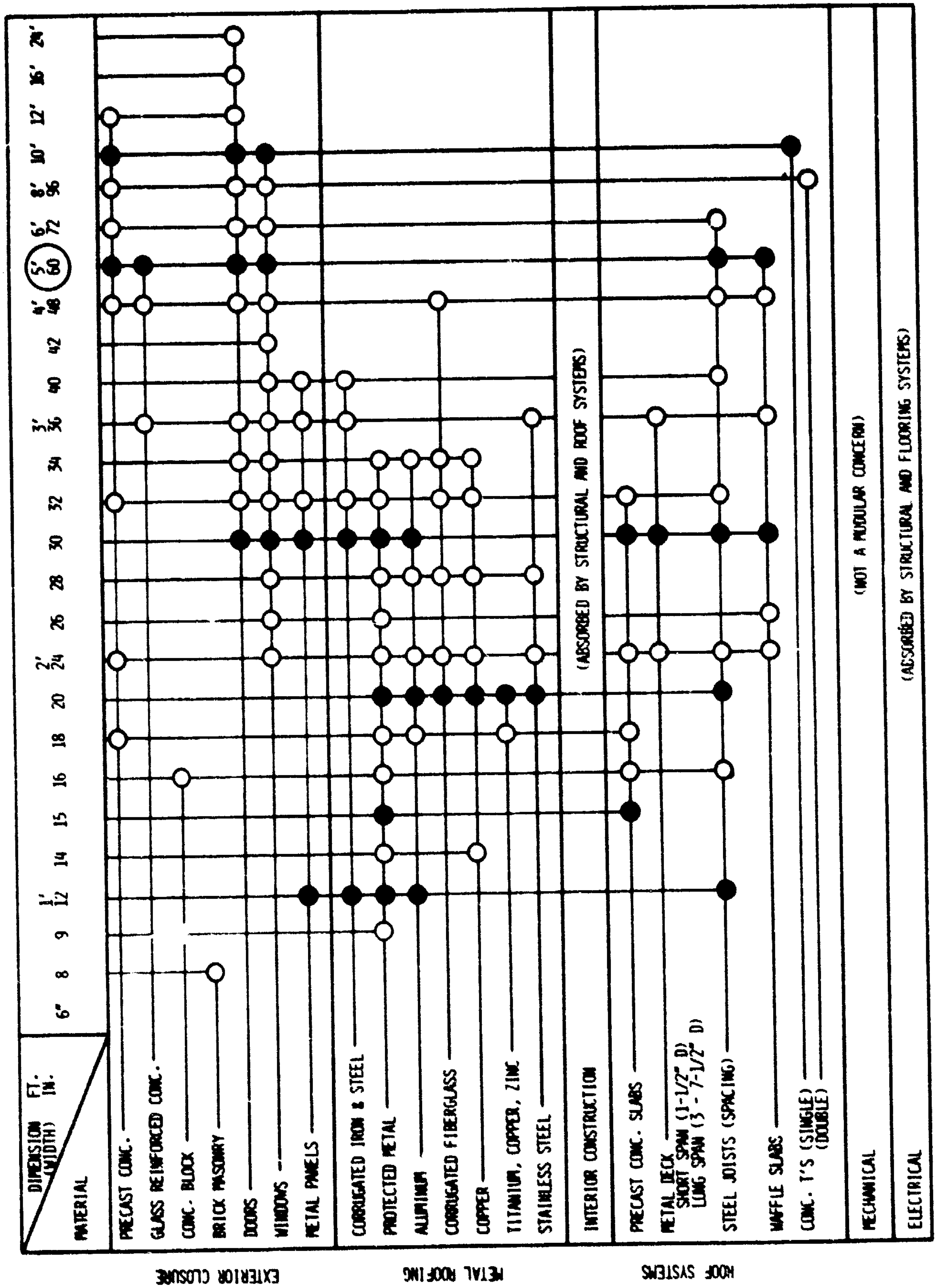
PERTINENT TEST STANDARDS PRESENTLY AVAILABLE FOR CONNECTORS:

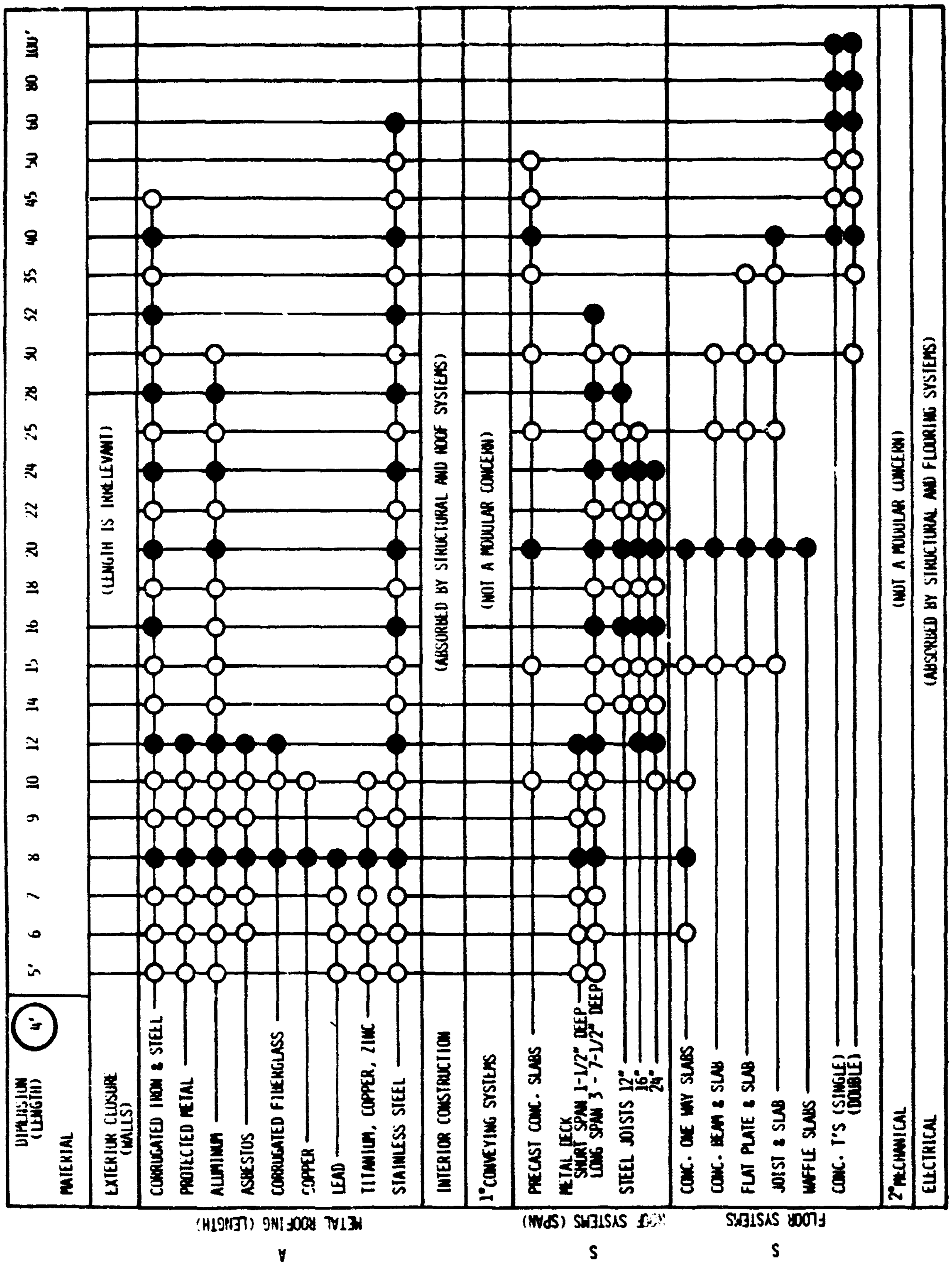
- UL310 QUICK CONNECT TERMINALS
- UL486 WIRE CONNECTORS AND SOLDERING LUGS
- UL514 OUTLET BOXES AND FITTINGS
- MIL-STD-810-C ENVIRONMENTAL TEST METHODS
- MIL-STD-202, METHOD 107 ACCELERATED TEMPERATURE CYCLING
- ASTM D-1435-65 RECOMMENDED PRACTICE FOR OUTDOOR WEATHERING OF PLASTIC

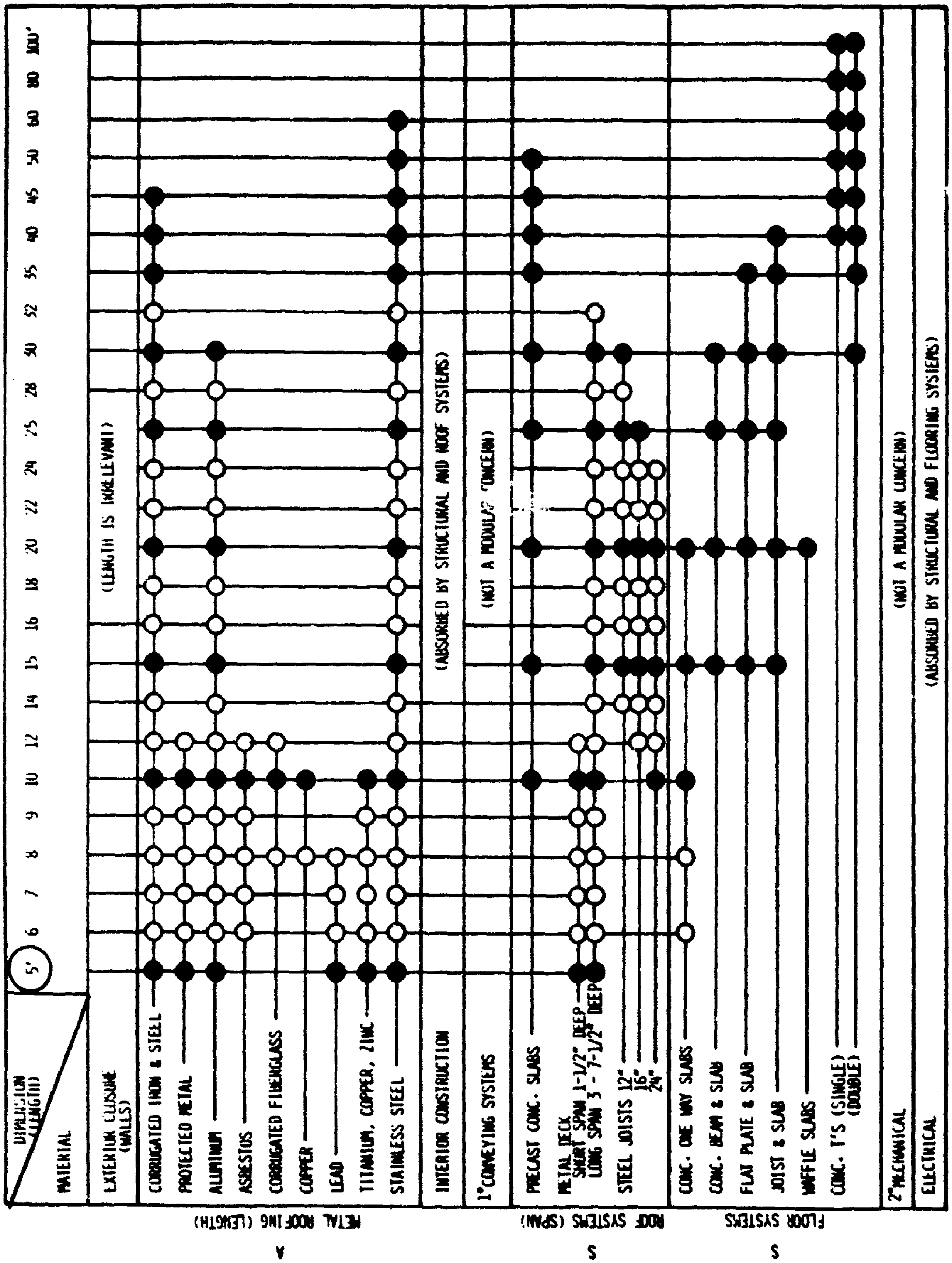
QUICK CONNECT TERMINALS, ALTHOUGH NOT SPECIFICALLY MENTIONED IN THE CODE, ARE A RECOGNIZED METHOD FOR MAKING ELECTRICAL CONNECTIONS. INDIVIDUAL QUICK CONNECTS MUST BE TESTED AND APPROVED BY A RECOGNIZED TESTING LAB. SOME MUNICIPALITY CODES DO NOT RECOGNIZE QUICK CONNECTS WHERE INSTALLATIONS ARE CONSIDERED TO BE PERMANENT.



DIMENSION (WIDTH) FT: IN.
MATERIAL
6" 8 9 1' 12 14 15 16 18 20 2' 24 26 28 30 32 34 3' 36 40 42 4' 48 5' 60 6' 72 8' 96 10' 12' 16' 24'
EXTERIOR CLOSURE
PRECAST CONC.
GLASS REINFORCED CONC.
CONC. BLOCK
BRICK MASONRY
DOORS
WINDOWS
METAL PANELS
METAL ROOFING
CORRUGATED IRON & STEEL
PROTECTED METAL
ALUMINUM
CORRUGATED FIBERGLASS
COPPER
TITANIUM, COPPER, ZINC
STAINLESS STEEL
INTERIOR CONSTRUCTION
(ABSORBED BY STRUCTURAL AND ROOF SYSTEMS)
ROOF SYSTEMS
PRECAST CONC. SLABS
METAL DECK SHORT SPAN (1-1/2" D) LONG SPAN (3" - 7-1/2" D)
STEEL JOISTS (SPACING)
WAFFLE SLABS
CONC. T'S (SINGLE) (DOUBLE)
MECHANICAL
(NOT A MODULAR CONCERN)
ELECTRICAL
(ABSORBED BY STRUCTURAL AND FLOORING SYSTEMS)


DIMENSION (WIDTH) FT. IN.
MATERIAL
6" 8 9 1' 12 14 15 16 18 20 2' 24 26 28 30 32 34 3' 36 40 42 4' 48 5' 60 6' 72 8' 96 10' 12' 16' 20'
PRECAST CONC.
GLASS REINFORCED CONC.
CONC. BLOCK
BRICK MASONRY
DOORS
WINDOWS
METAL PANELS
CORRUGATED IRON & STEEL
PROTECTED METAL
ALUMINUM
CORRUGATED FIBERGLASS
COPPER
TITANIUM, COPPER, ZINC
STAINLESS STEEL
INTERIOR CONSTRUCTION
(ABSORBED BY STRUCTURAL AND ROOF SYSTEMS)
PRECAST CONC. SLABS
METAL DECK
SHORT SPAN (1-1/2" D)
LONG SPAN (3 - 7-1/2" D)
STEEL JOISTS (SPACING)
WAFFLE SLABS
CONC. T'S (SINGLE)
(DOUBLE)
MECHANICAL
(NOT A MODULAR CONCERN)
ELECTRICAL
(ABSORBED BY STRUCTURAL AND FLOORING SYSTEMS)
EXTERIOR CLOSURE
METAL ROOFING
ROOF SYSTEMS


DIMENSION (LENGTH)
4'
5' 6 7 8 9 10 12 14 15 16 18 20 22 24 25 28 30 32 35 40 45 50 60 80 100'
MATERIAL
EXTERIOR CLOSURE (WALLS)
(LENGTH IS IRRELEVANT)
CORRUGATED IRON & STEEL
PROTECTED METAL
ALUMINUM
ASBESTOS
CORRUGATED FIBERGLASS
COPPER
LEAD
TITANIUM, COPPER, ZINC
STAINLESS STEEL
METAL ROOFING (LENGTH)
A
INTERIOR CONSTRUCTION
(ABSORBED BY STRUCTURAL AND ROOF SYSTEMS)
1° CONVEYING SYSTEMS
(NOT A MODULAR CONCERN)
PRECAST CONC. SLABS
METAL DECK
SHORT SPAN 1-1/2" DEEP
LONG SPAN 3 - 7-1/2" DEEP
STEEL JOISTS 12"
16"
24"
SYSTEMS (SPAN)
S
CONC. ONE WAY SLABS
CONC. BEAM & SLAB
FLAT PLATE & SLAB
JOIST & SLAB
WAFFLE SLABS
CONC. T'S (SINGLE)
(DOUBLE)
FLOOR SYSTEMS
S
2° MECHANICAL
(NOT A MODULAR CONCERN)
ELECTRICAL
(ABSORBED BY STRUCTURAL AND FLOORING SYSTEMS)


DIMENSION (LENGTH)
MATERIAL
5'
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40
45
50
60
80
100'
EXTERIOR CLOSURE (WALLS)
(LENGTH IS IRRELEVANT)
CORRUGATED IRON & STEEL
PROTECTED METAL
ALUMINUM
ASBESTOS
CORRUGATED FIBERGLASS
COPPER
LEAD
TITANIUM, COPPER, ZINC
STAINLESS STEEL
METAL ROOFING (LENGTH)
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INTERIOR CONSTRUCTION
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CONC. ONE WAY SLABS
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WAFFLE SLABS
CONC. T'S (SINGLE)
(DOUBLE)
FLOOR SYSTEMS
S
2° MECHANICAL
(NOT A MODULAR CONCERN)
ELECTRICAL
(ABSORBED BY STRUCTURAL AND FLOORING SYSTEMS)

LEAST LIFE-CYCLE ENERGY COST INTERCONNECT RELIABILITY DESIGN

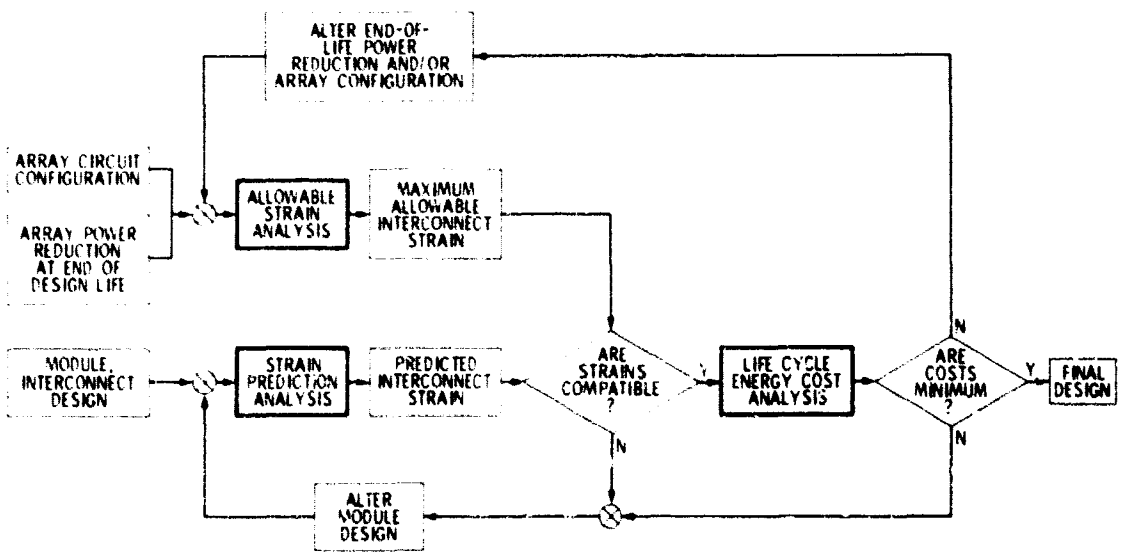
JET PROPULSION LABORATORY

G.R. Mon

Overview

- PROBLEM: DIURNAL THERMAL CYCLES STRAIN INTERCONNECTS, WHICH MAY LEAD TO THEIR EVENTUAL RUPTURE AND LOSS OF ARRAY POWER OUTPUT
- GOAL: DESIGN MODULES AND INTERCONNECTS NOT TO EXCEED COST-OPTIMAL ARRAY POWER REDUCTION AFTER A SPECIFIED NUMBER OF YEARS
- APPROACH: USE DESIGN ALGORITHM, PRESENTED HERE, INCORPORATING:
  - MINIMUM LIFE-CYCLE COST ANALYSIS
  - INTERCONNECT STRUCTURAL ANALYSIS
  - INTERCONNECT FAILURE STATISTICS

Cost-Optimal Interconnect Reliability Design Algorithm



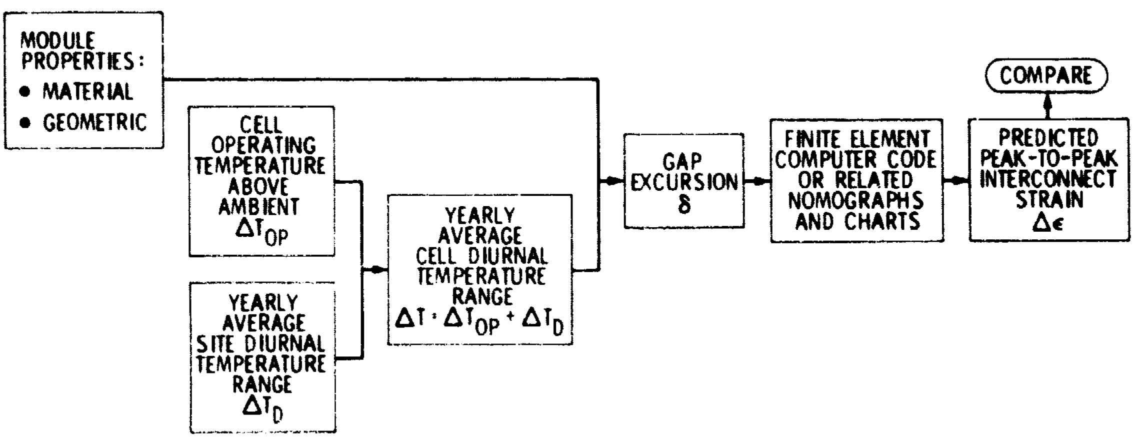
Life-Cycle Energy Cost Analysis

- EQUATION

$$\begin{pmatrix}\text{ENERGY}\\ \text{COST,}\\ \text{\$/kWh}\end{pmatrix} = \frac{\begin{pmatrix}\text{BALANCE}\\ \text{OF PLANT}\\ \text{COST, \$/kW}\end{pmatrix} + \left(\begin{matrix}\text{INITIAL}\\ \text{ARRAY}\\ \text{COST,}\\ \text{\$/}m^2\end{matrix} + \begin{matrix}\text{ARRAY}\\ \text{L-C O\&M}\\ \text{COST,}\\ \text{\$/}m^2\end{matrix}\right) \bigg/ \begin{pmatrix}\text{PLANT EFFICIENCY}\\ 100\ \text{mW/cm}^2\text{, NOCT}\end{pmatrix}}{\left(\begin{matrix}\text{ANNUAL}\\ \text{INSOLATION}\\ \text{kWh/m}^2\text{/yr}\end{matrix} \times \begin{matrix}\text{L-C ENERGY}\\ \text{FRACTION}\end{matrix}\right)}$$

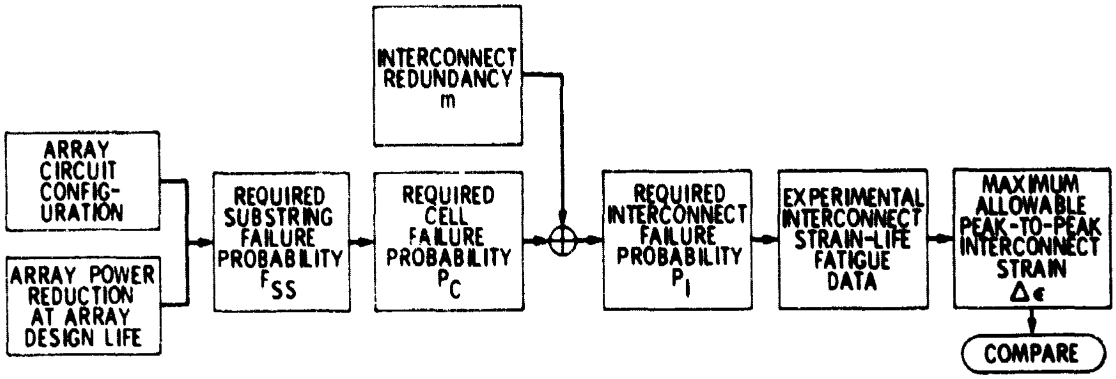
- METHOD
  - DETERMINE ENERGY COSTS FOR VARIOUS 20-YEAR ARRAY POWER LOSS FRACTIONS AND INTERCONNECT REDUNDANCIES
  - MINIMUM ENERGY COST DETERMINES DESIGN SELECTION

Strain Prediction Analysis

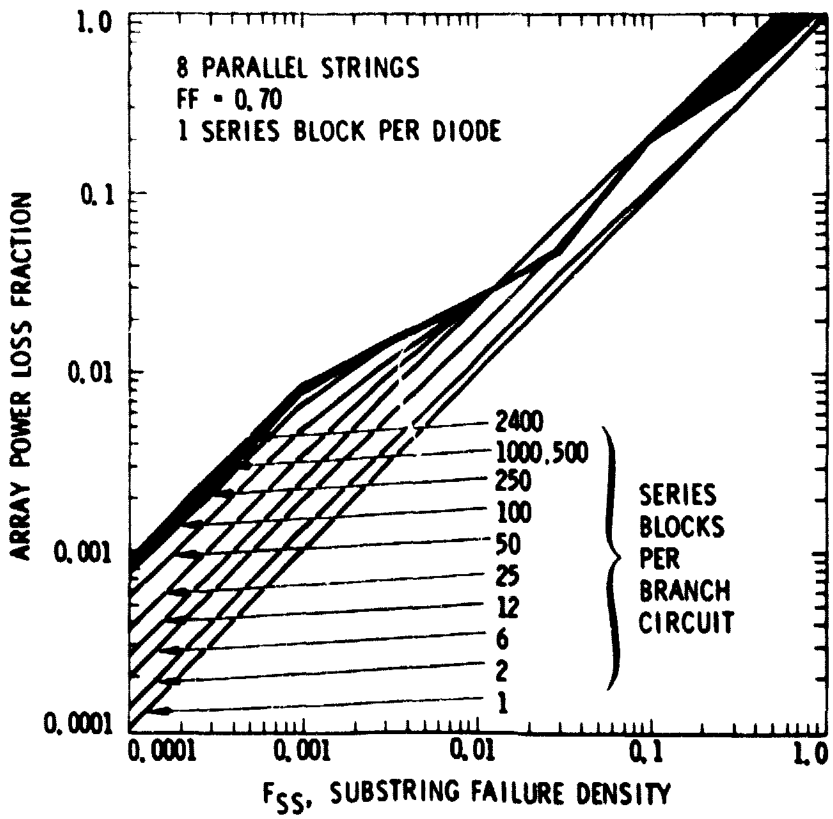


- SEE D. MOORE'S PRESENTATION, THE "TIN CAN LID" PHENOMENON, AT THE 16th PIM
- CHARTS AND NOMOGRAPHS TO DETERMINE PREDICTED INTERCONNECT STRAIN ARE IN PREPARATION

Allowable Strain Analysis



Array Power Loss



FROM 5101-167, SERIES/PARALLEL DESIGN WORKSHOP PROCEEDINGS

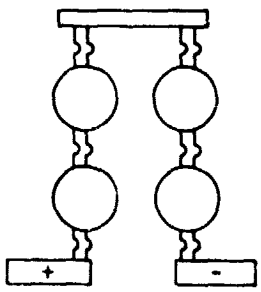
Cell Failure Probability Formula

$$P_C = 1 - (1 - F_{SS})^{\frac{1}{n}}$$

P_C = CELL FAILURE PROBABILITY

F_{SS} = SUBSTRING FAILURE PROBABILITY

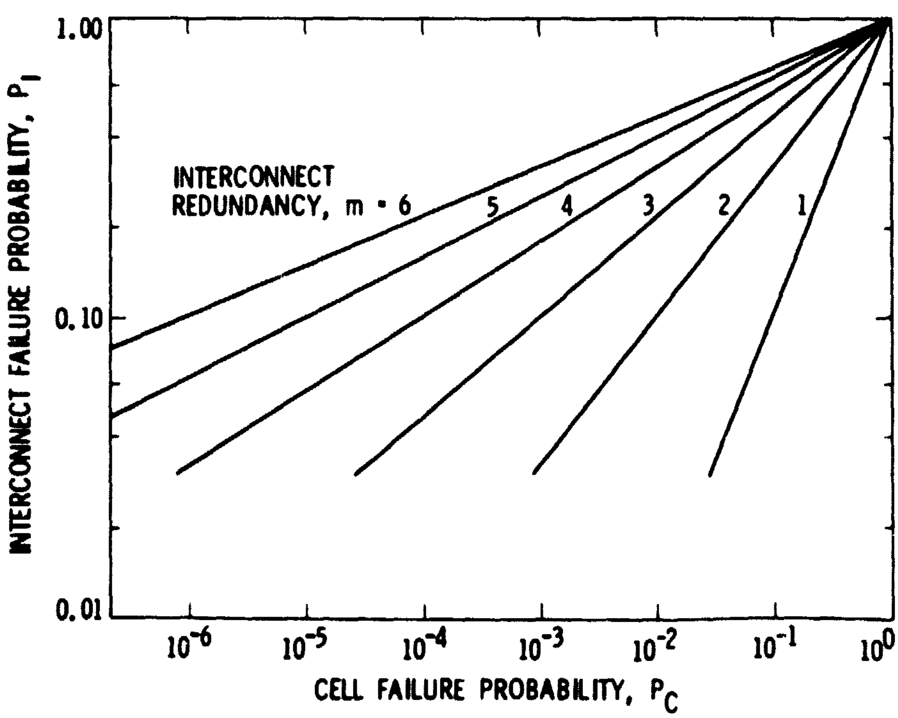
n = NUMBER OF PARALLEL INTERCONNECT GROUPS PER SUBSTRING (APPROXIMATELY EQUAL TO NUMBER OF CELLS PER SUBSTRING)



EXAMPLE: 4 CELLS, n = 6

Interconnect vs Cell Failure Probability With Redundancy m as Parameter

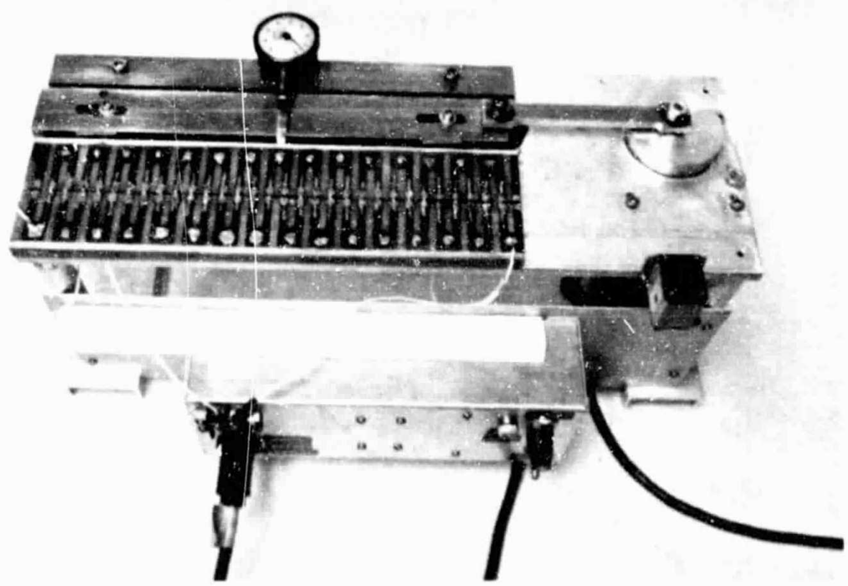
$$P_I = P_C^{1/m}$$



Interconnect Fatigue: Experimental Study

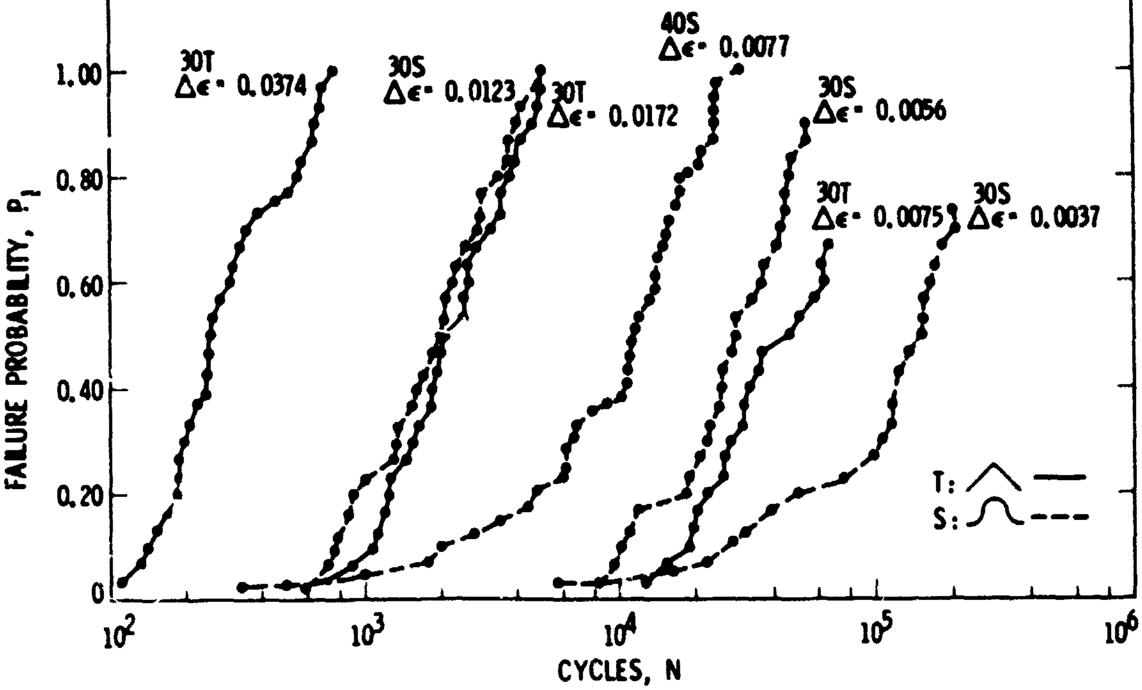
- OBJECTIVES
  - UNDERSTAND INTERCONNECT FAILURE PROBABILITY BEHAVIOR
  - RELATE INTERCONNECT FAILURE PROBABILITIES, STRAIN LEVELS, AND ARRAY LIFE
- APPROACH
  - DEVELOP APPARATUS TO MECHANICALLY SIMULATE FIELD THERMAL CYCLES (ACCELERATED TEST)
  - GATHER STATISTICAL FAILURE DATA FOR SEVERAL OFHC COPPER INTERCONNECT CONFIGURATIONS
  - DEVELOP STRAIN-LIFE (FATIGUE) CURVES FOR INTERCONNECTS. USE STRAIN PREDICTION ANALYSIS TO COMPUTE STRAIN

Interconnect Strain-Cycle Apparatus

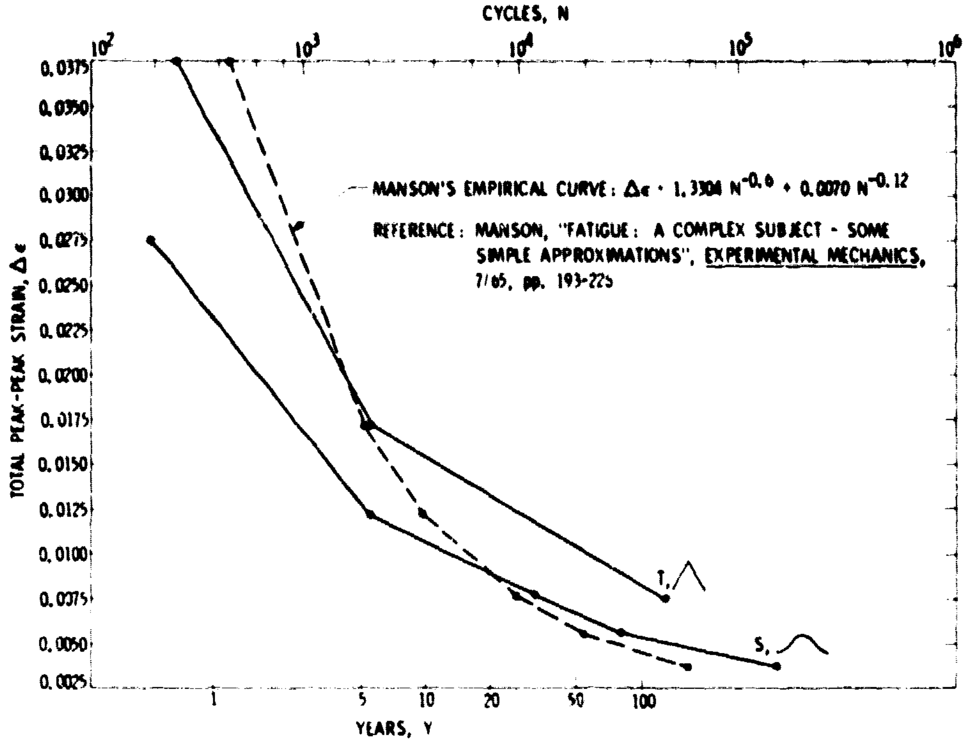


Interconnect Configurations Tested to Date

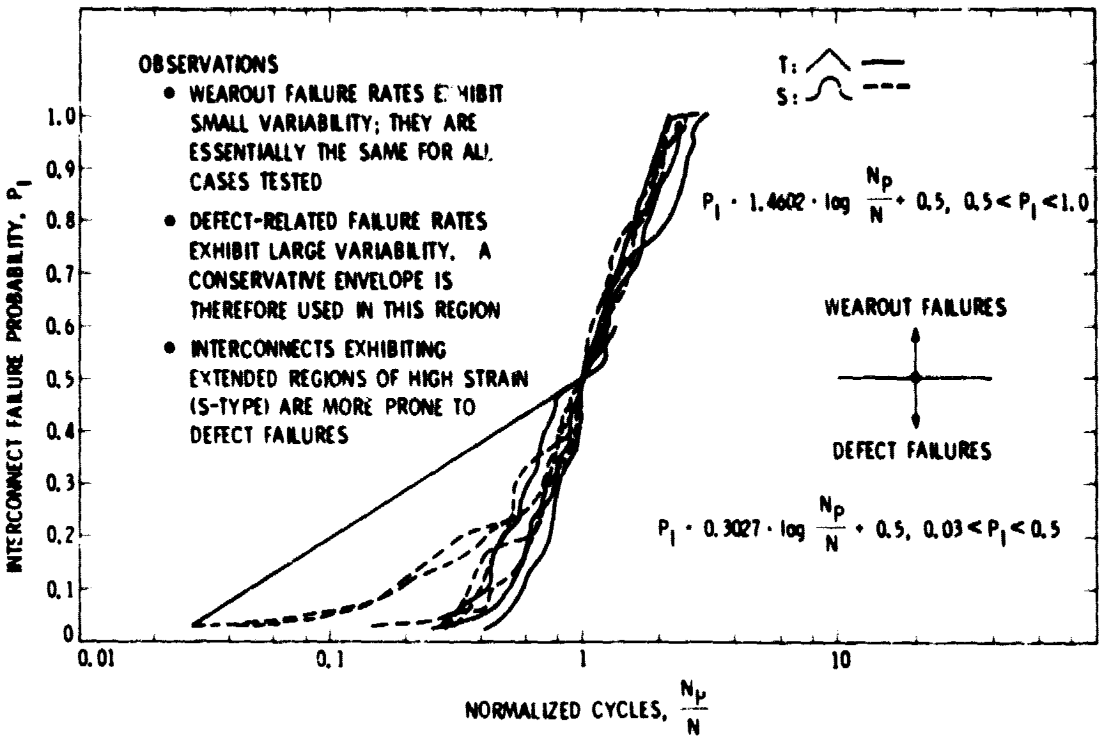
Interconnect Strain-Cycle Test Data



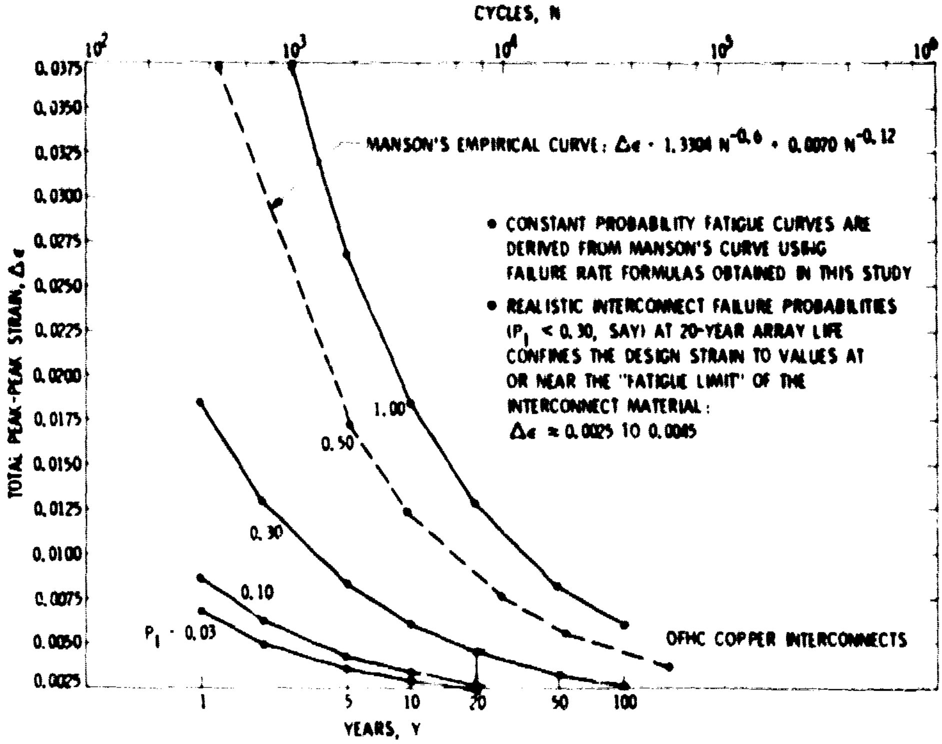
OFHC Copper Strain-Cycle (Fatigue) Curves



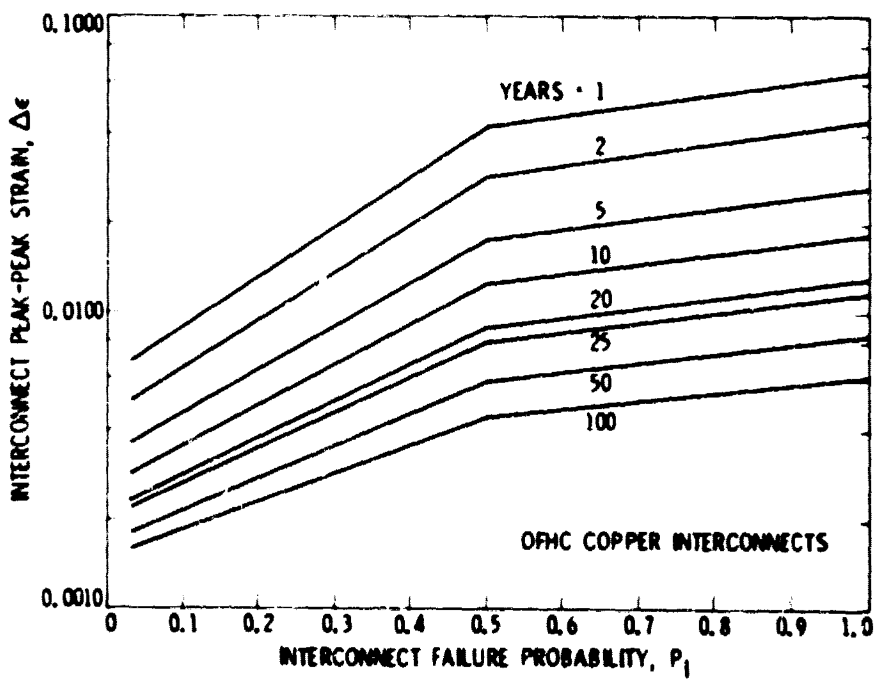
Superposition of Test Data Curves And Failure Rate Determination



Interconnect Fatigue Curves With Failure Probability as Parameter



Interconnect Strain $\Delta\epsilon$ vs Failure Probability P_I With Array Life (Years) as Parameter



Design Example: 1982 MTR Strawman

- ARRAY CONFIGURATION
  - OFHC COPPER INTERCONNECTS
  - 8 PARALLEL BY 11 SERIES CELLS PER SERIES BLOCK
  - 57 SERIES BLOCKS PER BRANCH CIRCUIT
  - 1 SERIES BLOCK PER DIODE
  - V_{ARRAY} · 250 VOLTS
- DESIGN OBJECTIVES
  - 20-YEAR ARRAY POWER REDUCTION YIELDING MINIMUM LIFE-CYCLE ENERGY COSTS
  - REQUIRED INTERCONNECT REDUNDANCY

- ALLOWABLE STRAIN ANALYSIS

20-YEAR ARRAY POWER REDUCTION f	SUBSTRING FAILURE PROBABILITY F_{SS}	CELL FAILURE PROBABILITY P_C	INTERCONNECT FAILURE PROBABILITY, P_I, FOR REDUNDANCY m			MAXIMUM ALLOWABLE STRAIN, $\Delta\epsilon$, FOR INTER-CONNECT REDUNDANCY m		
			2	3	4	2	3	4
0.20	0.092	0.008735	0.0935	0.2059	0.3057	0.0027	0.0035	0.0047
0.10	0.055	0.005130	0.0716	0.1725	0.2676	0.0025	0.0032	0.0042
0.05	0.029	0.002672	0.0517	0.1388	0.2274	0.0024	0.0030	0.0037
0.01	0.0022	0.000200	0.0141	0.0585	0.1189	0.0022	0.0025	0.0028
0.001	0.00009	0.000008	0.0028	0.0200	0.0532	0.0022	0.0023	0.0024

- OBSERVATIONS
  - FOR A GIVEN INTERCONNECT REDUNDANCY, STRAIN LEVEL IS RELATIVELY INSENSITIVE TO ARRAY POWER REDUCTION, BUT SENSITIVITY INCREASES WITH INCREASING REDUNDANCY
  - FOR A GIVEN POWER REDUCTION, GREATER REDUNDANCY PERMITS HIGHER DESIGN STRAIN LEVELS; THE EFFECT IS MORE PRONOUNCED AT LARGER POWER REDUCTIONS, AT WHICH COST TRADE-OFFS BETWEEN STRAIN LEVEL AND REDUNDANCY CAN BE MADE

- LIFE-CYCLE ENERGY COST ANALYSIS

$$\bullet\ \begin{pmatrix}\text{ENERGY}\\ \text{COST,}\\ \$/\text{kWh}\end{pmatrix} = \frac{\begin{pmatrix}\text{BALANCE}\\ \text{OF PLANT}\\ \text{COST, }\$/\text{kW}\end{pmatrix} + \left(\begin{matrix}\text{INITIAL}\\ \text{ARRAY}\\ \text{COST, A}\\ \$/\text{m}^2\end{matrix} + \begin{matrix}\text{ARRAY}\\ \text{L-C O\&M}\\ \text{COST,}\\ \$/\text{m}^2\end{matrix}\right) \Big/ \begin{pmatrix}\text{PLANT EFFICIENCY}\\ 100\ \text{mW/cm}^2\text{, NOCT}\end{pmatrix}}{\begin{pmatrix}\text{ANNUAL}\\ \text{INSOLATION}\\ \text{kWh/m}^2\text{/yr}\end{pmatrix} \times \begin{pmatrix}\text{L-C ENERGY}\\ \text{FRACTION, } \epsilon_{LC}\end{pmatrix}}$$

$$= \frac{(250) + \dfrac{A + 0}{0.092}}{(2000 \times \epsilon_{LC})}$$

- COST ALLOCATIONS: R. ROSS, "QUANTIFYING FLAT-PLATE ARRAY RELIABILITY/DURABILITY GOALS", 9/23/80

- ASSUMPTIONS
  - ▲ 0% DISCOUNT RATE
  - ▲ ARRAY COST LESS INTERCONNECTS: 113 $\$/m^2$
  - ▲ CONSTANT ARRAY POWER LOSS RATE: $\epsilon_{LC} = \sum_{n=1}^{20} \left(1 - \frac{n}{20} \cdot f\right)$

    f = 20-YEAR ARRAY POWER LOSS FRACTION

- CALCULATIONS

20-YEAR ARRAY POWER REDUCTION f	INTERCONNECT REDUNDANCY m	ESTIMATED COSTS FOR INTERCONNECTS $\$/m^2$	TOTAL INITIAL ARRAY COST $\$/m^2$	LIFE-CYCLE ENERGY FRACTION ϵ_{LC}	LIFE-CYCLE ENERGY COST $/kWh
0.20	2	4.22	117.22	17.9000	0.043
0.10	2	4.22	117.22	18.9500	0.040
0.05	2	4.22	117.22	19.4750	0.039
0.01	3	5.05	118.05	19.8950	0.038
0.0001	4	6.18	119.18	19.9895	0.039
0	∞	∞	∞	20.0000	∞

- COST-OPTIMAL DESIGN SELECTION
  - DESIGN FOR A POWER REDUCTION OF 1% AND AN INTERCONNECT REDUNDANCY OF 3

PHOTOVOLTAIC MODULE CAPACITANCE AND PERSONAL SAFETY

JET PROPULSION LABORATORY
G.R. Mon

- OBJECTIVE
  - DETERMINE LIMITS ON MODULE CAPACITANCE TO GUARANTEE PERSONAL SAFETY DURING ROUTINE OPERATION AND MAINTENANCE FIELD REMOVALS AND REPLACEMENTS
- APPROACH
  - GATHER DATA ON HUMAN TOLERANCE TO ELECTRICAL SHOCK BY CAPACITIVE DISCHARGE
  - DETERMINE MAXIMUM ALLOWABLE MODULE UNIT CAPACITANCE AS A FUNCTION OF ARRAY OPERATING VOLTAGE

Factors Affecting Severity of Shock

- VOLTAGE
  - TYPE
    - AC
    - DC - CONTINUOUS OR INTERRUPTED
    - EXPONENTIAL DECAY
  - MAGNITUDE
- CURRENT
  - TYPE
  - MAGNITUDE
  - DURATION
- BODY IMPEDANCE
  - CURRENT PATH
  - PRESENCE OF MOISTURE

Human Physiological Response to Electric Shock

- AC - 60 Hz, 120 V (UL, USDL)

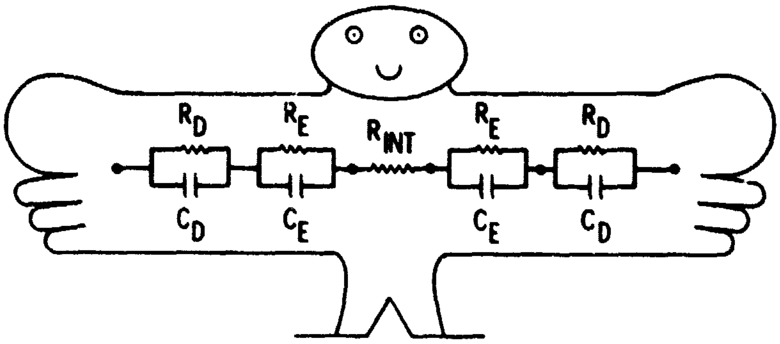
I, mA	PHYSIOLOGICAL RESPONSE
< 0.5	NO SENSATION
0.5 - 2	THRESHOLD OF PERCEPTION
1 - 5	REACTION
2 - 10	MUSCULAR CONTRACTION
5 - 25	CAN'T LET GO
> 15	STOPPAGE OF BREATHING
> 25	SEVERE MUSCULAR CONTRACTION
30 - 200	VENTRICULAR FIBRILLATION

- DC

DOES NOT PRODUCE SEVERE MUSCULAR CONTRACTIONS AS DOES AC.
HIGHER DC LEVELS CAN BE TOLERATED

Electrical Impedance of the Human Body

- MEASUREMENT - 50 Hz, 125 V



D → DERMIS
E → EPIDERMIS
INT → INTERNAL

$R_D + R_E = 1456\Omega$

$C_D + C_E = 0.65\ \mu F.$

$R_{INT} = 711\Omega$

- SUGGESTED WORKING VALUES

DAMP: $R_{HUMAN} = 500\Omega$

DRY: $R_{HUMAN} = 1500\Omega$

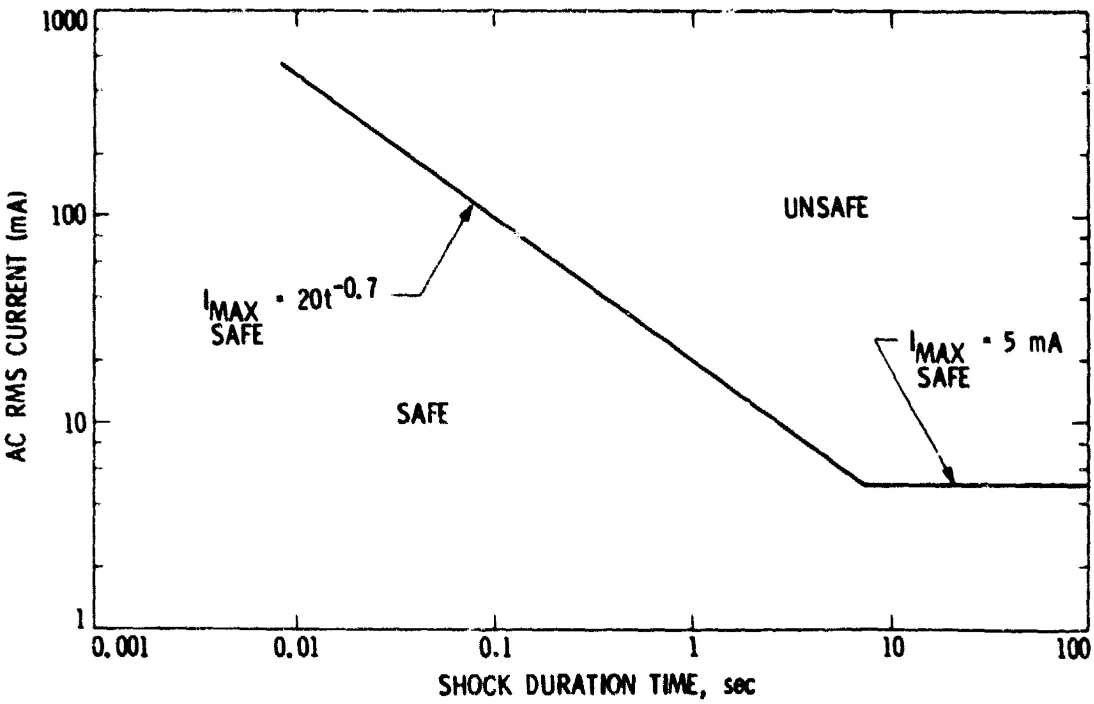
Accepted and Suggested Human Tolerance Levels

- VOLTAGE (1978 NEC)

WAVE FORM	DRY	DAMP
AC	30 V RMS	15 V RMS
INTERRUPTED DC	24.8 V PEAK	12.4 V PEAK
CONTINUOUS DC	60 V	30 V

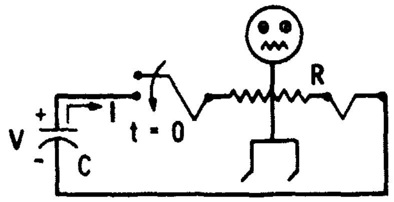
- CURRENT/DURATION (UL)
  - SINUSOIDAL AC
    - ▲ 5 mA RMS IS CONSIDERED NON-HAZARDOUS REGARDLESS OF DURATION
    - ▲ FROM EXPERIMENTS ON SHEEP AND DOGS,
      $I_{\substack{MAX\\SAFE}} = 20t^{-0.7}$ mA RMS, $0.00833\ \sec < t < 7.25\ \sec$

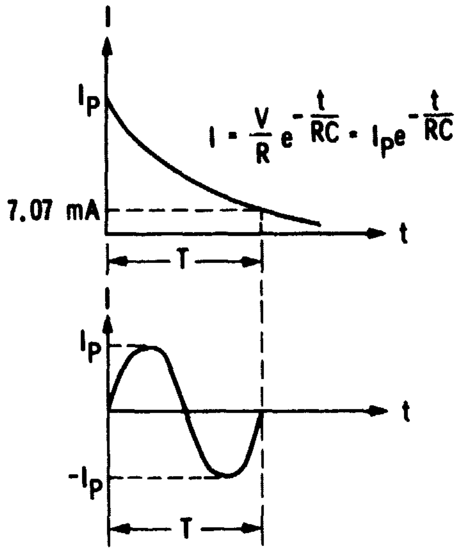
Minimum Fibrillating Current vs Shock Duration for Human Beings (After UL)



Accepted and Suggested Human Tolerance Levels (Cont.)

- CAPACITANCE/VOLTAGE
  - CIRCUIT





  - EQUIVALENCE OF WAVE FORMS

    IT IS ASSUMED THAT THE TWO WAVE FORMS SHOWN PRODUCE THE SAME EFFECT UPON THE HUMAN HEART

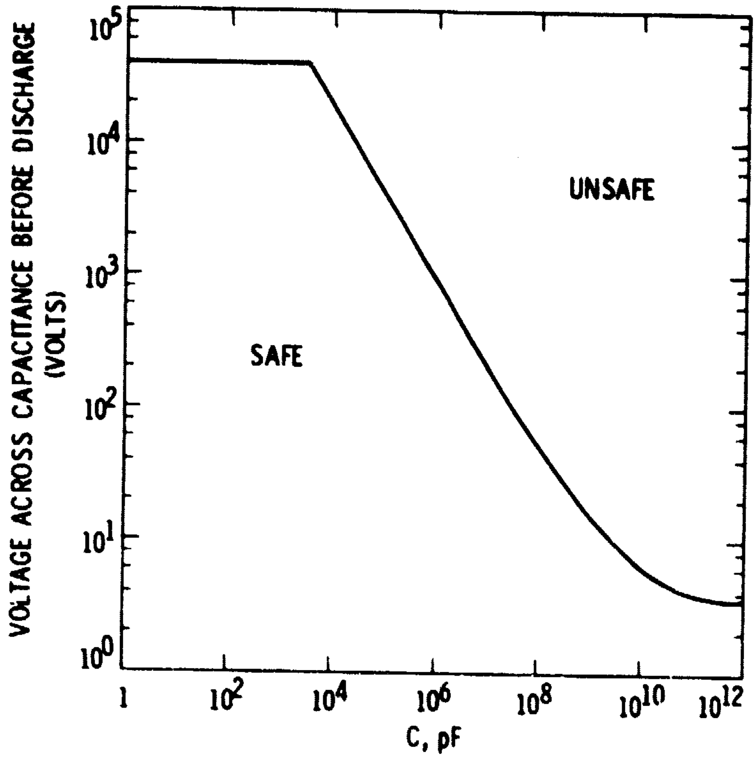
  - MAXIMUM SAFE CAPACITANCE ($R = R_{HUMAN} = 500\Omega$)

    ▲ $C_{\substack{MAX\\SAFE}} = \dfrac{0.0884}{V^{1.43}(\ln V - 1.26)}, \quad 3.5\ V < V < 403.5\ V$

    $= 0.0353\ V^{-1.536}, \quad 403.5\ V < V < 40{,}000\ V$

    ▲ VOLTAGES EXCEEDING 40,000 V ARE CONSIDERED UNSAFE REGARDLESS OF CAPACITANCE SIZE

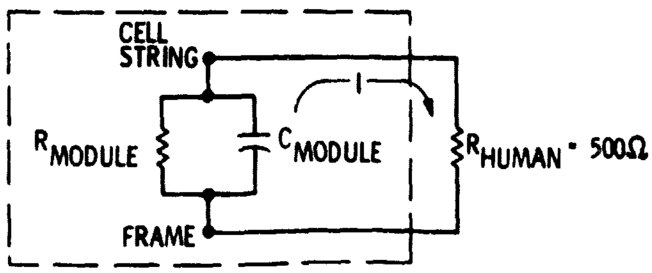
Maximum Safe Capacitance at Voltage (UL)



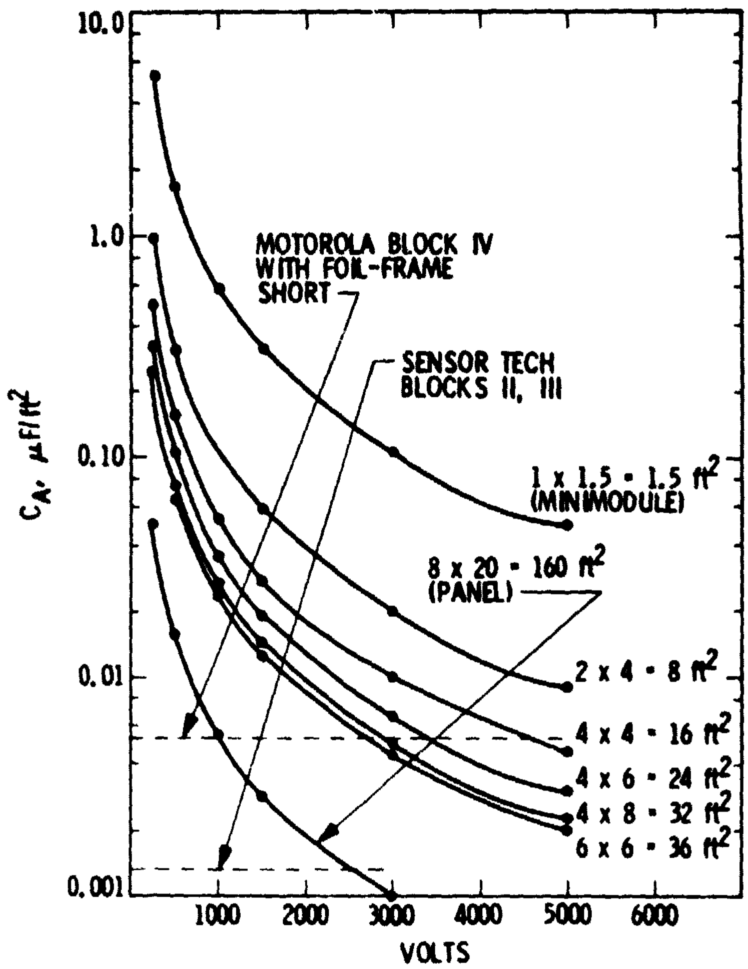
Typical Measured Module Capacitance And Insulation Resistance

VENDOR - BLOCK	TYPE	R_M ($M\Omega$)	C_M (pF)	C_M/A ($\mu F/ft^2$)	$\tau = 3\ R_M C_M$ (sec)
ST - II, III	MM	2500	1500	0.001350	11.25
SP - III	MM	13×10^6	20	0.000017	780
SP - IV	M	200	1750	0.000361	1.05
SL - II	MM	1800	100	0.000087	0.54
SX - II, III	MM	80,000	475	0.000455	114
AS - III	MM	1500	100	0.000111	0.45
MOT - IV	M	50,000	1260	0.000345	189

- MODULE LEAKAGE RESISTANCE IS SO HIGH THAT DISCHARGE CURRENTS WILL PASS ENTIRELY THROUGH HUMAN
- FOR SOME MODULES, CHARGE BLEED-OFF TIME CAN BE QUITE LARGE - SEVERAL MINUTES



Maximum Safe Unit Capacitance vs Operating Voltage (Module Size as Parameter)



Conclusions

- CHARGES STORED IN MODULES JUST EXTRACTED FROM AN ACTIVE ARRAY DO NOT POSE A SAFETY PROBLEM FOR PRESENT ARRAY DESIGNS (MODULE UNIT CAPACITANCES AND ARRAY VOLTAGE LEVELS)

HOT-SPOT ENDURANCE TEST DEVELOPMENT AND RESULTS

JET PROPULSION LABORATORY

J.C. Arnett
C.C. Gonzalez

Hot-Spot Study Objective

DEVELOP TEST PROCEDURES FOR EVALUATING HOT-SPOT ENDURANCE CAPABILITY OF A MODULE UNDER A SEVERE HOT-SPOT FIELD CONDITION:

- 100 mW/cm^2
- 40 ^{o}C AIR
- MODULE AT SHORT CIRCUIT
- WORST-CASE CELL REVERSE I-V CHARACTERISTICS
- WORST-CASE CELL CURRENT MISMATCH
    - CRACKS
    - SHADOWING
    - INTERCONNECT FAILURE
    - SHORTED CELL

Secondary Study Objectives

- TO DETERMINE THE RELATIONSHIP OF $T_{CELL} - T_{AIR}$ vs HOT-SPOT POWER DISSIPATION (mW/cm^2) FOR SEVERAL MODULE CONFIGURATIONS AND CELL SIZES

- TO CORRELATE ABILITY TO WITHSTAND HOT-SPOT HEATING WITH MODULE CONSTRUCTION AND CELL SIZE

- DEVELOP DESIGN GUIDELINES FOR MODULE AND CELL CONFIGURATIONS TO IMPROVE HOT-SPOT ENDURANCE

Approach

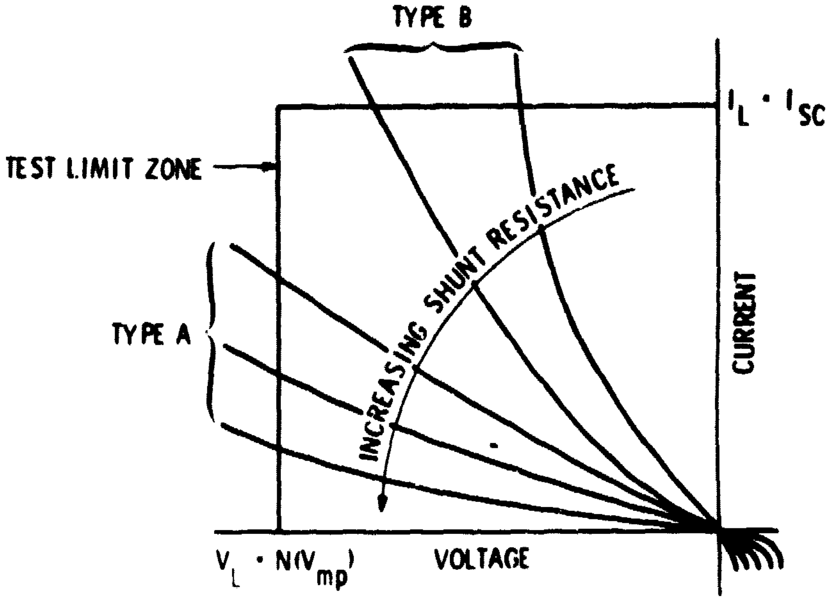
- DETERMINE FACTORS AFFECTING HOT-SPOT HEATING LEVELS
- DEVELOP HOT-SPOT TEST PROCEDURES
- IDENTIFY AND/OR DEVELOP AND TEST REQUIRED EQUIPMENT AND INSTRUMENTATION
- INVESTIGATE CELL REVERSE VOLTAGE (2nd QUADRANT) I-V CHARACTERISTICS
- INVESTIGATE RESPONSE OF MODULES AND CELLS TO POWER DISSIPATION AND PERFORM SUPPORTIVE DIAGNOSTIC TESTS
- CORRELATE RESULTS AND DEVELOP RECOMMENDATIONS

Hot-Spot Test Considerations

FACTORS INFLUENCING HOT-SPOT HEATING LEVEL	CRITICAL TEST CONSTRAINTS
• REVERSE VOLTAGE (2nd QUADRANT) CELL I-V CHARACTERISTICS	• SELECTION OF CELLS WITH APPROPRIATE 2nd-QUADRANT I-V CHARACTERISTICS
• MODULE SERIES-PARALLEL CONFIGURATION	• APPROPRIATE TEST VOLTAGE AND CURRENT SELECTION
• NUMBER OF CELLS PER DIODE STRING	• CONTROL DEGREE OF REVERSE BIASING BY MEANS OF ILLUMINATION LEVEL
• OVERALL MODULE CURRENT LEVEL	
• AMOUNT OF CURRENT LIMITING IN AFFECTED CELL	
• IRRADIANCE LEVEL	

- TEST CELL SELECTION AND INSTRUMENTATION
- DETERMINE CURRENT AND VOLTAGE TEST LEVELS
- ESTABLISH TEST THERMAL ENVIRONMENT
- EVALUATE PERFORMANCE

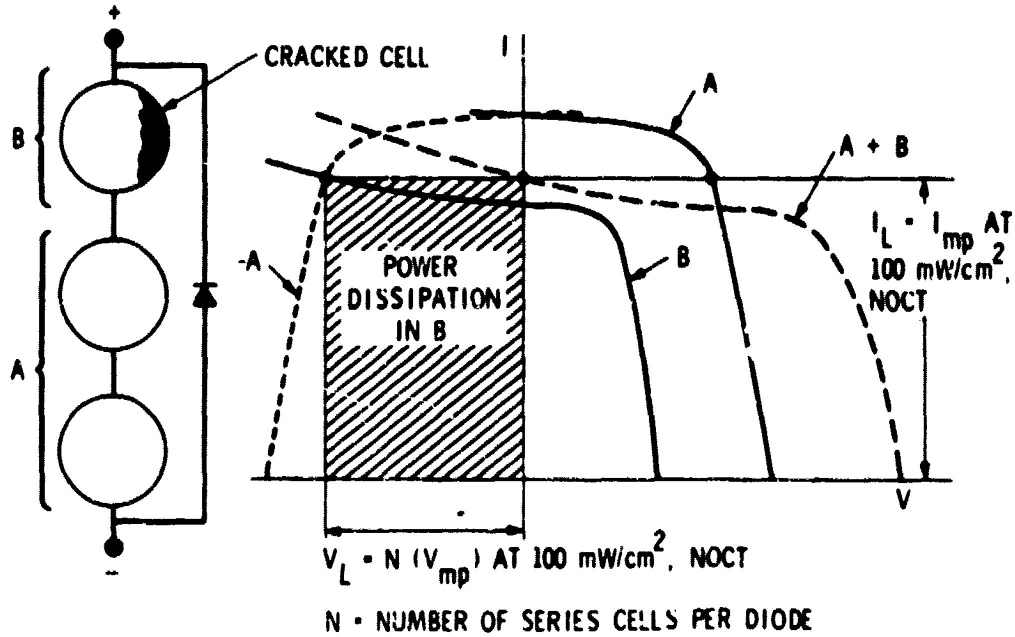
Test Cell Selection Based on 2nd-Quadrant Dark I-V Characteristics



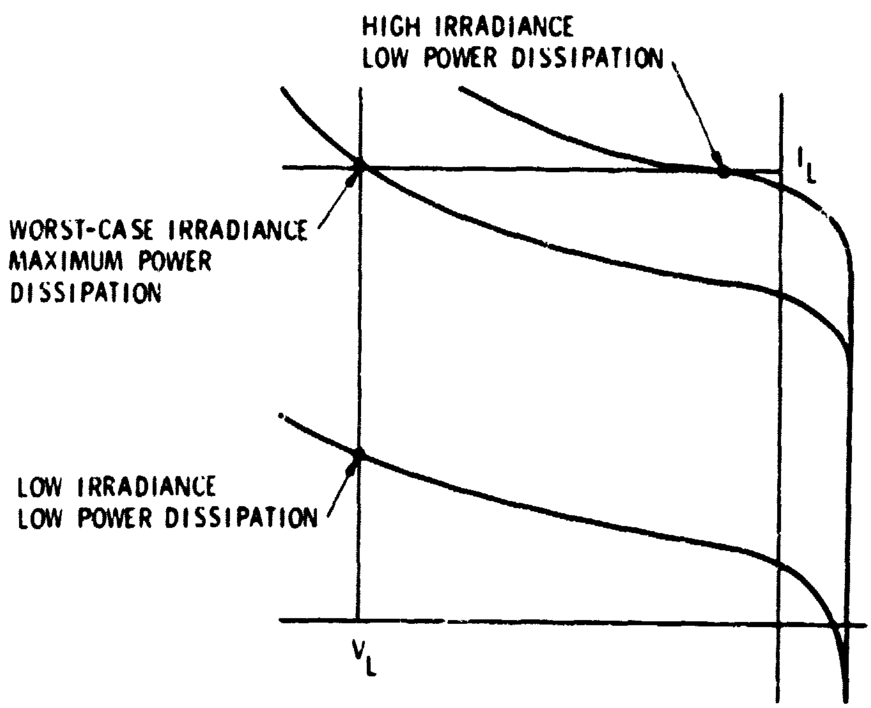
Selection of Module Evaluation Criteria

- SAFETY CRITERIA
  - VISUAL INSPECTION: NO DETERIORATION THAT WOULD IMPAIR PERFORMANCE
  - HI-POT: SATISFY INITIAL ELECTRICAL ISOLATION REQUIREMENT
- PERFORMANCE
  - ELECTRICAL POWER $\geqq$ 95% OF PRETEST

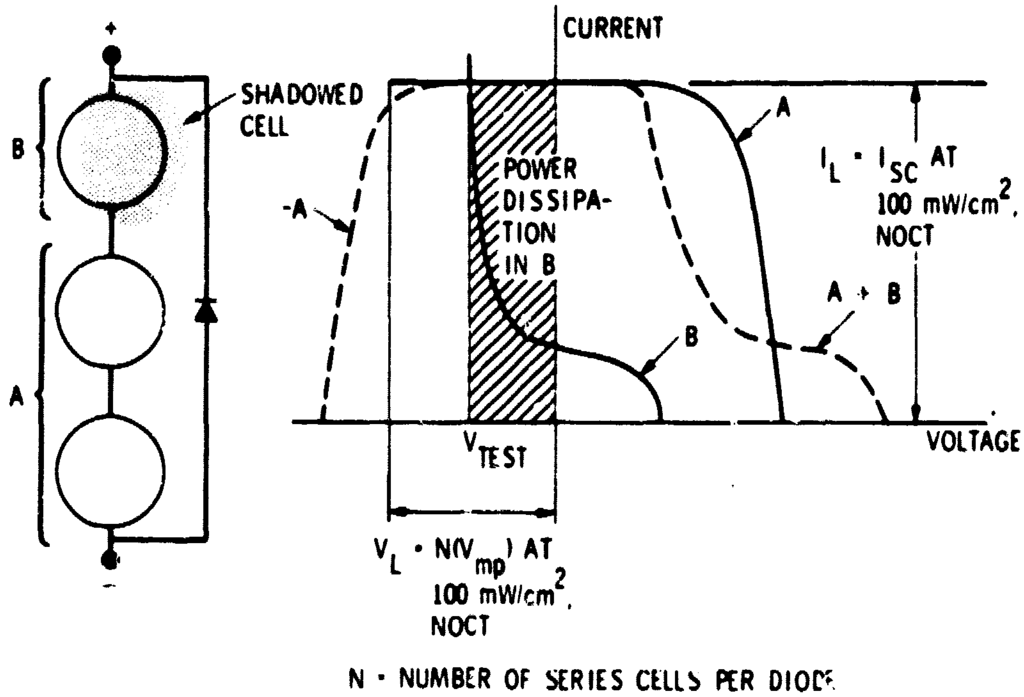
Selection of Test Voltage and Current for Type A Cell



Illumination Level Selected to Control Degree Of Reverse Biasing (Type A Cells)



Selection of Test Voltage and Current for Type B Cell



Selection of Test Thermal Environment To Simulate 100 mW/cm^2, 40°C Field Condition

- AIR TEMPERATURE = 20 °C, STILL AIR
- IRRADIANCE =
  - VISIBLE AT SELECTED LEVEL
  - IR TO ACHIEVE PRE-HOT-SPOT CELL AND BACKGROUND TEMPERATURE = NOCT

Selection of Test Sequence

SCHEDULE:

- POWER CYCLED ON-OFF
- 1 HOUR, POWER ON: HOT-SPOT HEATING
- POWER OFF: COOLING TO INITIAL THERMAL CONDITIONS (NOCT $\pm$ 5 ^{0}C)

DURATION:

- 100 HOURS ACCUMULATED HOT-SPOT POWER ON-TIME

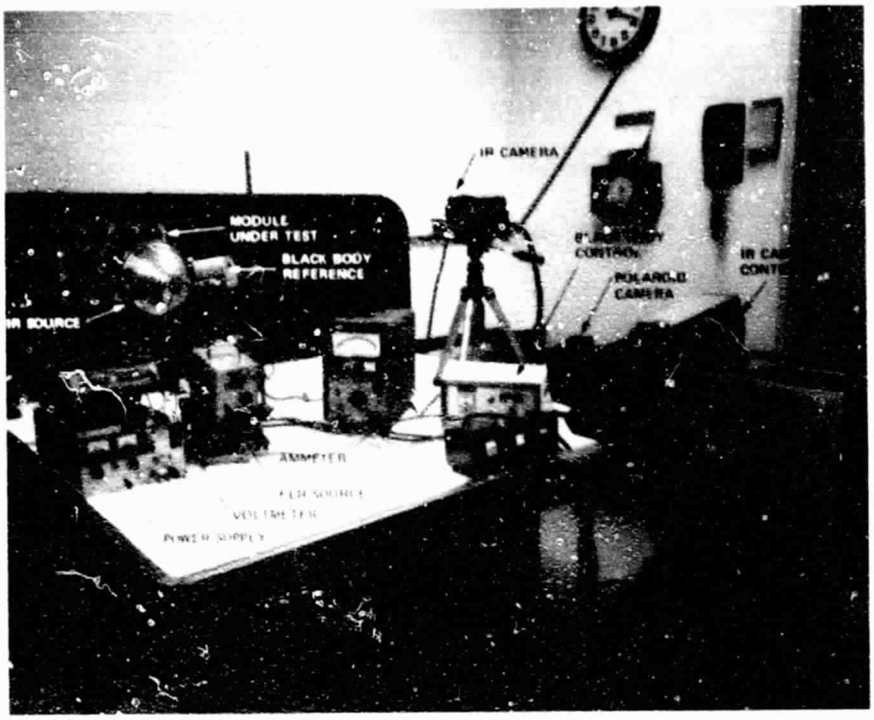
Selection of Module Evaluation Criteria

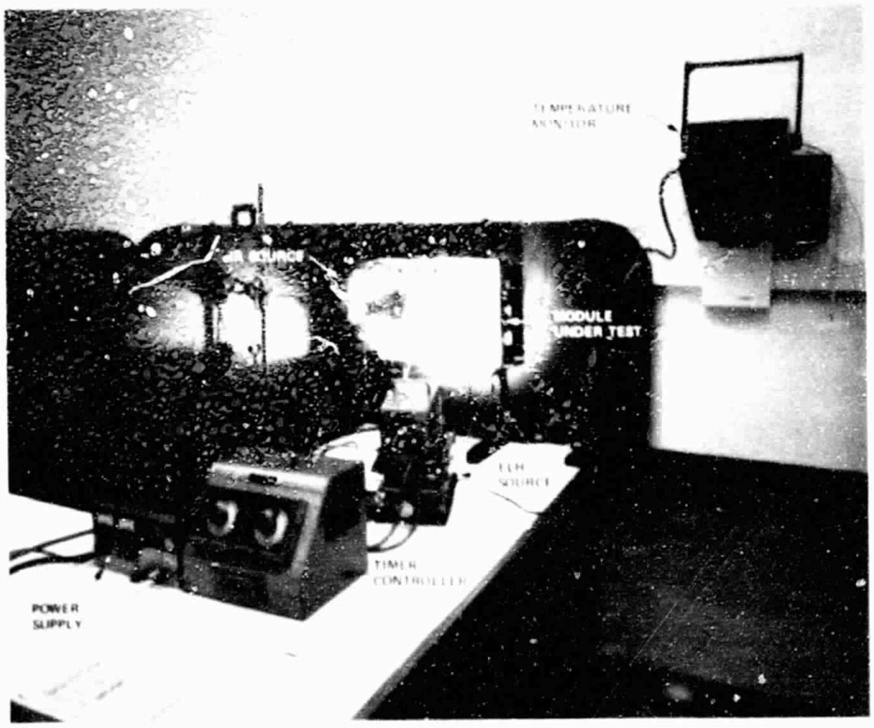
- VISUAL INSPECTION:
  - MUST MEET PRODUCTION MODULE ACCEPTANCE REQUIREMENTS
- ELECTRICAL PERFORMANCE
  - $\geqq$ 95% OF PRETEST POWER WITH ANY DISRUPTED INTERCONNECTS RECONNECTED
- ELECTRICAL ISOLATION
  - MUST MEET INITIAL HI-POT REQUIREMENT

Hot-Spot Endurance Test Summary

- TEST CURRENT –
  - TYPE A: $I_L = I_{MP}$ OF AVERAGE CELL AT 100 mW/cm^2, NOCT
  - TYPE B: $I_L = I_{SC}$ OF AVERAGE CELL AT 100 mW/cm^2, NOCT
- TEST VOLTAGE –
  - $V_T \leq V_L = N \times V_{MP}$ (100 mW/cm^2, NOCT) FOR N SERIES CELLS/DIODE
- TEST CELLS –
  - 3 SELECTED REPRESENTATIVE OF RANGE OF 2nd-QUADRANT I - V CURVES
- THERMAL CONDITION –
  - CELLS AT INITIAL TEMPERATURE = NOCT (IR SOURCE WITH LOW VISIBLE CONTENT)
- ILLUMINATION – (TYPE A ONLY)
  - UNIFORM SOURCE WITH LOW IR CONTENT (e.g., TYPE ELH)
- LABORATORY AMBIENT – 20 °C, NO AIR CURRENTS

Hot-Spot Endurance Test Equipment Arrangement





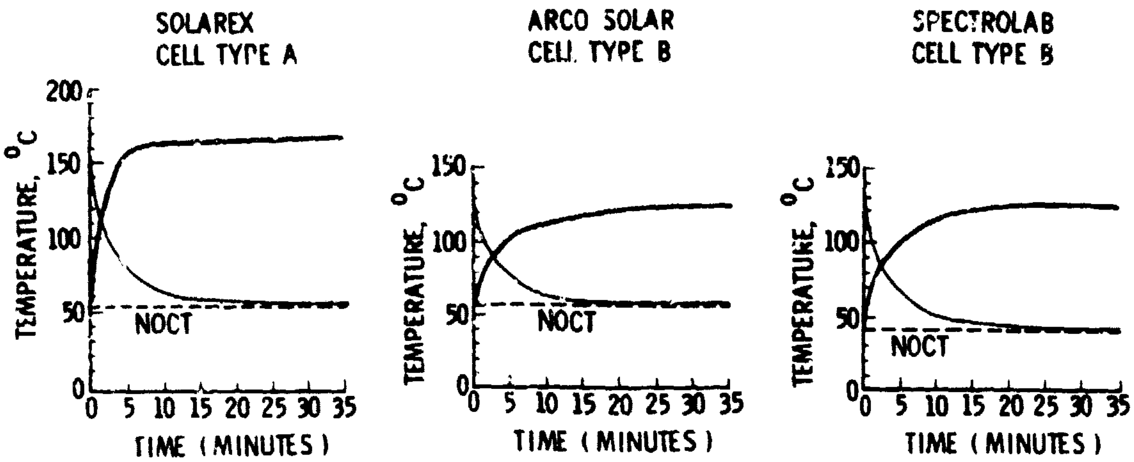
Typical Hot-Spot Test Results

- TIME TO ACHIEVE EQUILIBRIUM TEMPERATURE
- CELL THERMAL GRADIENTS UNDER TEST
- MEASURED CELL TEMPERATURE vs NUMBER OF SERIES CELLS PER DIODE
- HOT-SPOT TEMPERATURES FOR FIELD ENVIRONMENT (PREDICTED)
- VISUAL OBSERVATIONS AT INCREASING CELL TEMPERATURES

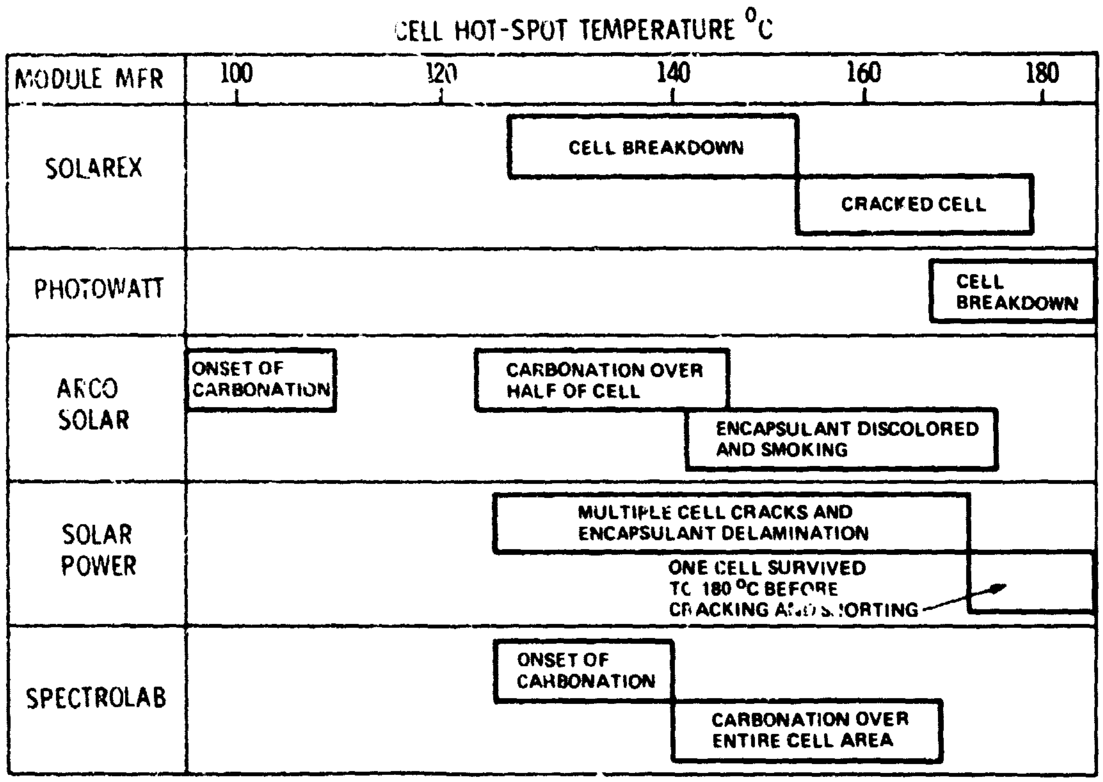
Characteristics of Modules Tested

MODULE MFG	MODULE CHARACTERISTICS
SOLAREX	GLASS-FIBER-REINFORCED POLYESTER SUBSTRATE SYLGARD 184 ENCAPSULANT ALUMINUM FRAME CELL SIZE: 3 in.
PHOTOWATT	ALUMINUM SUBSTRATE GLASS SUPERSTRATE RTV 615 ENCAPSULANT ALUMINUM FINS CELL SIZE: 2.2 in.
ARCO SOLAR	GLASS SUPERSTRATE PVB ENCAPSULANT ALUMINUM FRAME CELL SIZE: 3 in.
SOLAR POWER	GLASS REINFORCED POLYESTER SUBSTRATE SYLGARD 184 ENCAPSULANT CELL SIZE: 4 in.
SPECTROLAB	GLASS SUPERSTRATE PVB ENCAPSULANT ALUMINUM FRAME CELL SIZE: 2 in.

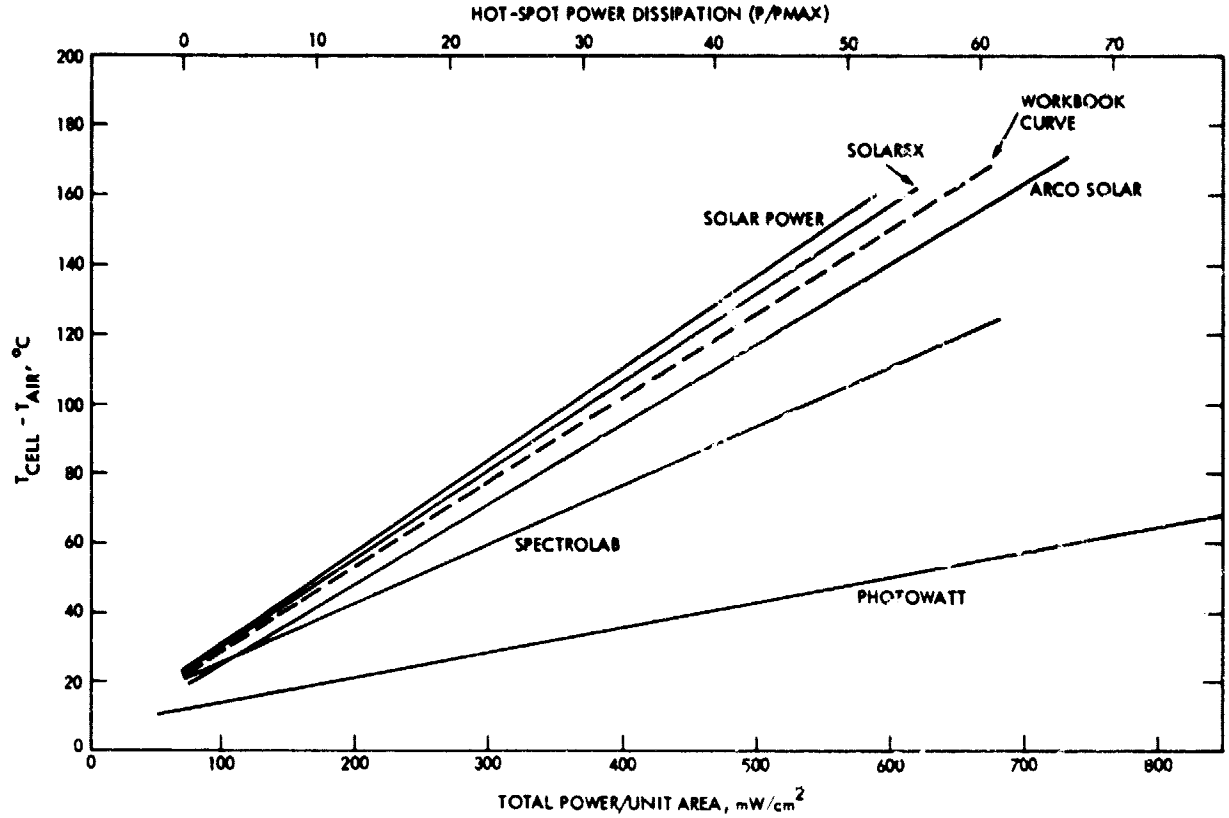
Time to Reach Equilibrium Temperature



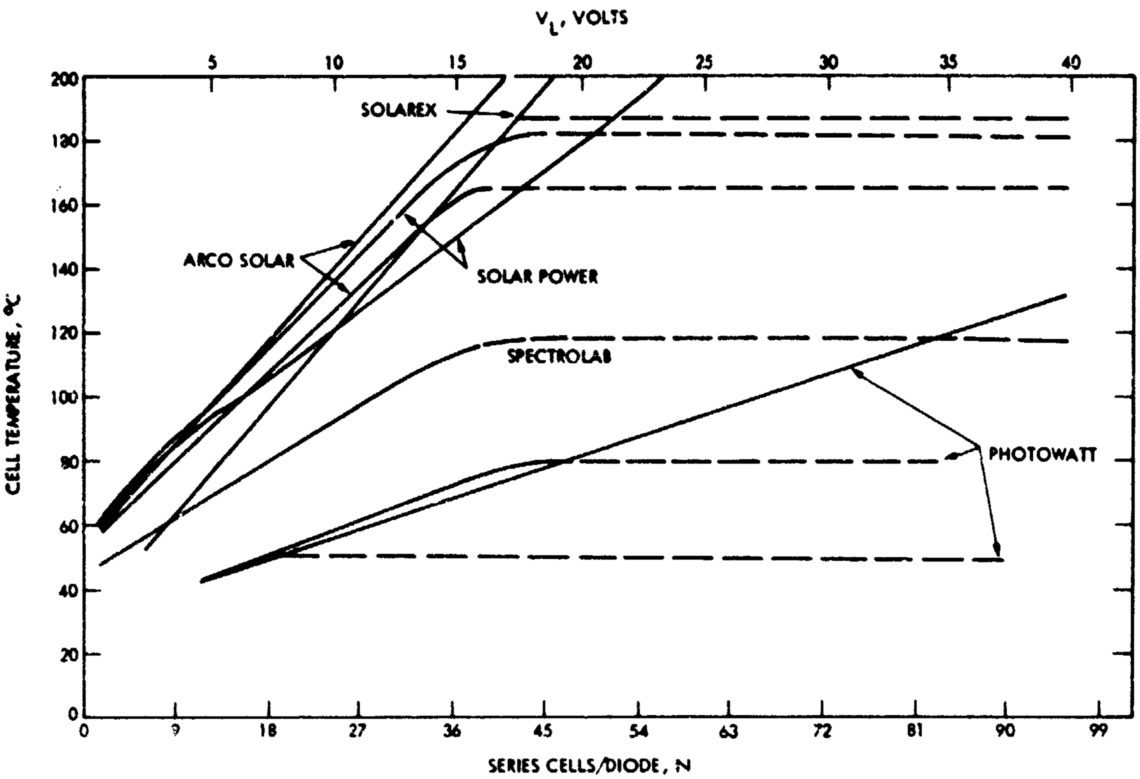
Observed Module Response vs Cell Temperature



Hot-Spot Temperature Above Ambient vs Power Into Cell (Field Environment)



Measured Hot-Spot Temperature vs Number of Series Cells per Diode



Calculation of Expected Hot-Spot Temperature

- KEY MODULE AND CELL PARAMETERS
  - 4 in. CELLS, 103.2 cm^2 OF AREA
  - 36 CELLS, 1 DIODE PER MODULE
  - V_{MAXP} (NOCT) = 0.42 V
  - I_{SC} = 2 A
  - TYPE A CELL
- V_L = 15 V, I_L = 2 A
- AT 0 ILLUMINATION, CURRENT AT 15 V IS 0.25 A

CELL TEMPERATURE - LABORATORY ENVIRONMENT
20 °C AIR TEMPERATURE

$$P_e = \frac{\text{POWER}}{\text{UNIT AREA}} = 30\text{W}/103.2\ \text{cm}^2 = 291\ \text{mW/cm}^2$$

$$P_{ILL} = \frac{(I_{LL} = I_L - 0.25\text{A})}{I_L} \times 100\ \text{mW/cm}^2 = 87.5\ \text{mW/cm}^2$$

NOCT EQUIVALENT = 80 mW/cm^2

$$P_T = P_e + P_{ILL} + 80\ \text{mW/cm}^2 = 458.5\ \text{mW/cm}^2$$

$$T_{CELL} - T_{AIR} = 120\ ^{\circ}\text{C},\ T_{CELL} = 140\ ^{\circ}\text{C}$$

CELL TEMPERATURE - FIELD ENVIRONMENT
40 °C AIR TEMPERATURE

$$P_T = P_e + 100\ \text{mW/cm}^2 = 391\ \text{mW/cm}^2$$

$$T_{CELL} - T_{AIR} = 100\ ^{\circ}\text{C},\ T_{CELL} = 140\ ^{\circ}\text{C}$$

Summary

- TEST PROCEDURES DEVELOPED
- EXPERIMENTAL VERIFICATION
- DETERMINATION OF MODULE AND CELL RESPONSE TO HOT-SPOT HEATING
- CRITICAL ASPECTS AND PROBLEM AREAS IDENTIFIED

Future Work

- CONTINUE INVESTIGATION OF CORRELATION OF MODULE AND CELL CONFIGURATION AND PHYSICAL PARAMETERS WITH HOT-SPOT HEATING ENDURANCE, AS NEW MODULES BECOME AVAILABLE

- REFINE TEST PROCEDURES AND ACCURACY BASED ON INDUSTRY RESPONSE AND FEEDBACK

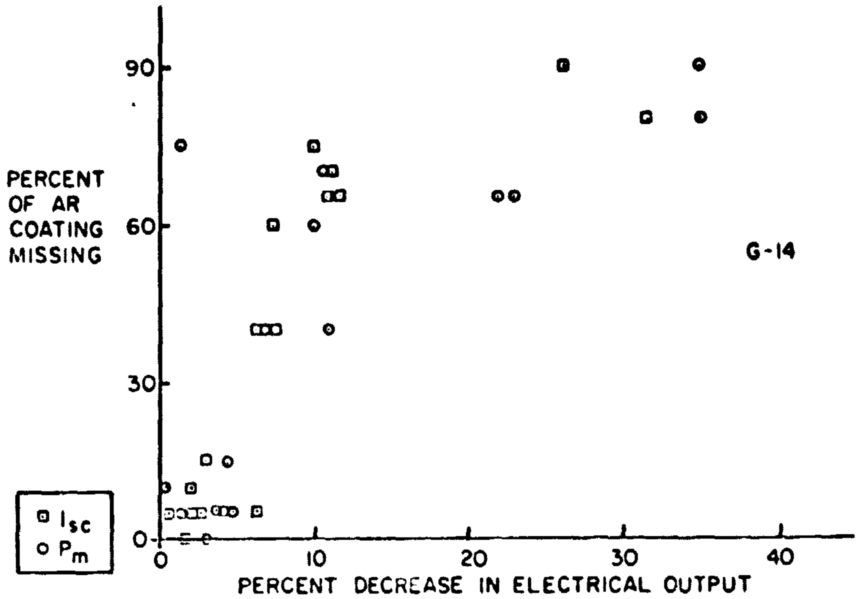
- DEVELOP DESIGN GUIDELINES FOR HOT-SPOT ENDURANCE

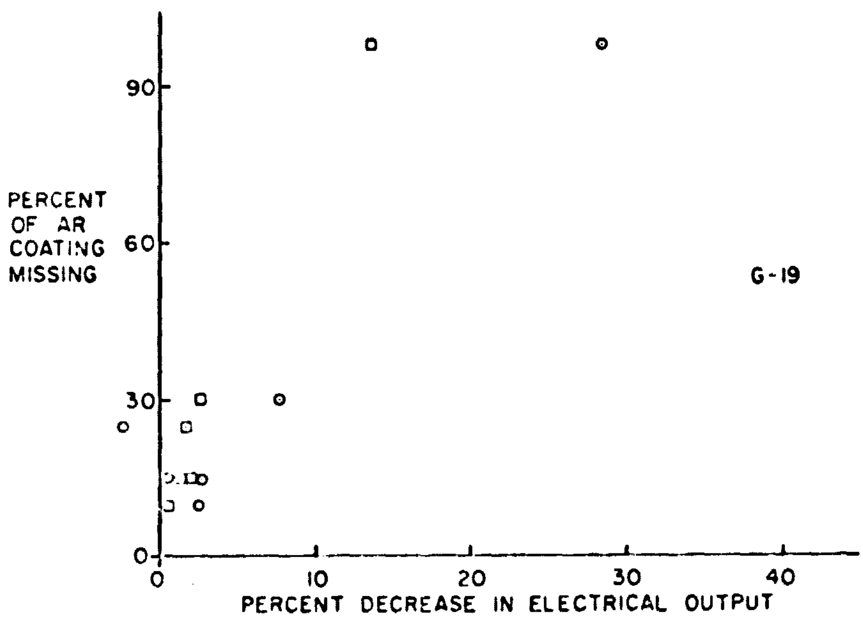
- PREPARE TASK REPORT

AR COATING DEGRADATION STUDIES

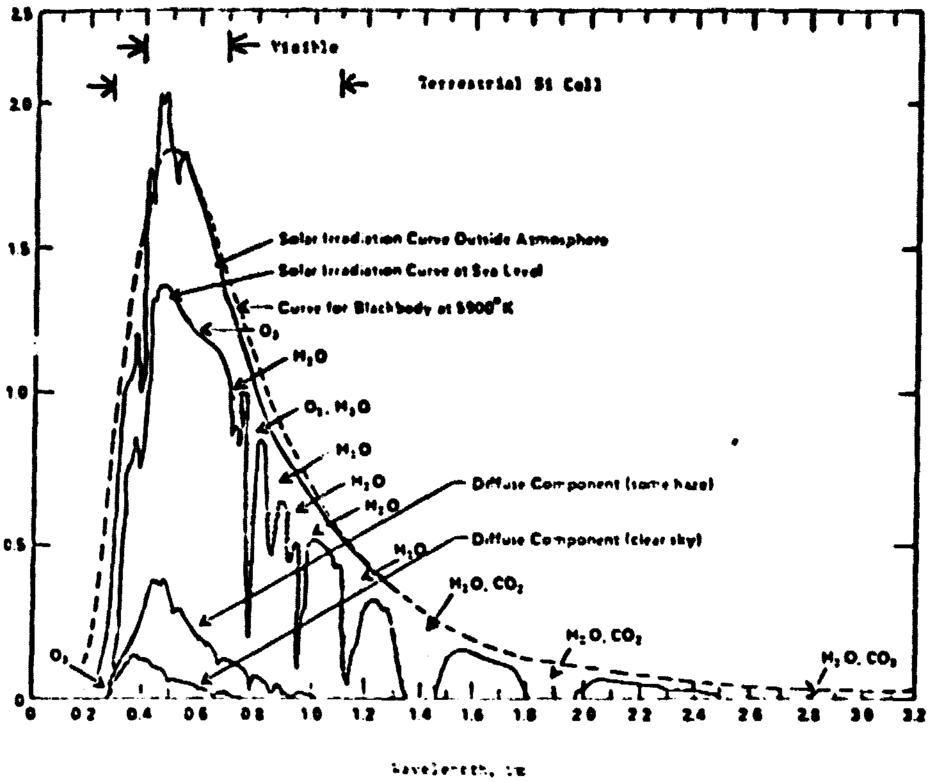
CLEMSON UNIVERSITY

H.A. Walker
J.W. Lathrop

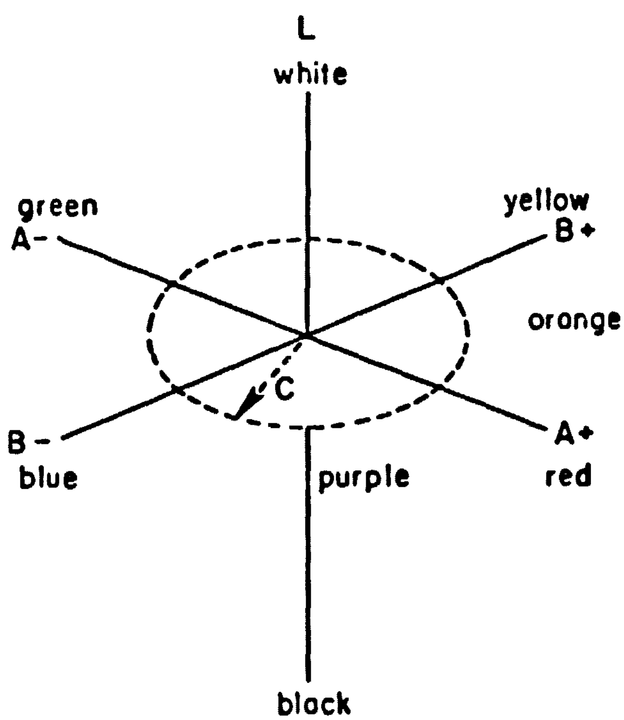




Visually Estimated % of AR Coating Removed vs. Measured % Decrease in Isc and Pm for Lots G-14 and G-19 after 500 Hours Pressure Cooker



Spectral Distribution of Solar Radiation Received Outside the Atmosphere and at Sea Level



1976 CIE L*A*B Color Space

Tristimulus Values

	X (RED)	Y (GREEN)	Z (BLUE)
RANGE FOR ILLUMINANT A	0-110	0-100	0-35
I-CELL RANGE	1.5-10.5	1.2-9.5	0.4-4.0

New Cell Color Data

CELL 1-87 AREA 1 MEAS

SPECTRAL DATA

WAVEL	SAMPLE REFL.	STANDARD REFL.
400	7.64	
410	9.92	
420	9.02	
430	7.95	
440	6.98	
450	6.13	
460	5.39	
470	4.64	
480	4.04	
490	3.50	
500	3.05	
510	2.63	
520	2.30	
530	2.10	
540	1.85	
550	1.70	
560	1.56	
570	1.48	
580	1.41	
590	1.35	
600	1.30	
610	1.27	
620	1.25	
630	1.22	
640	1.19	
650	1.20	
660	1.19	
670	1.22	
680	1.20	
690	1.21	
700	1.28	

SAMP: ILLUM=A OBSVR=10

TRIST: X Y Z
SAMP 1.79 1.73 2.01
CHROMA: X Y
SAMP 0.3230 0.3133
COLOR COORD: L*A*B*
SAMP 14.04 -3.17 -25.29

Stressed Cell Color Data

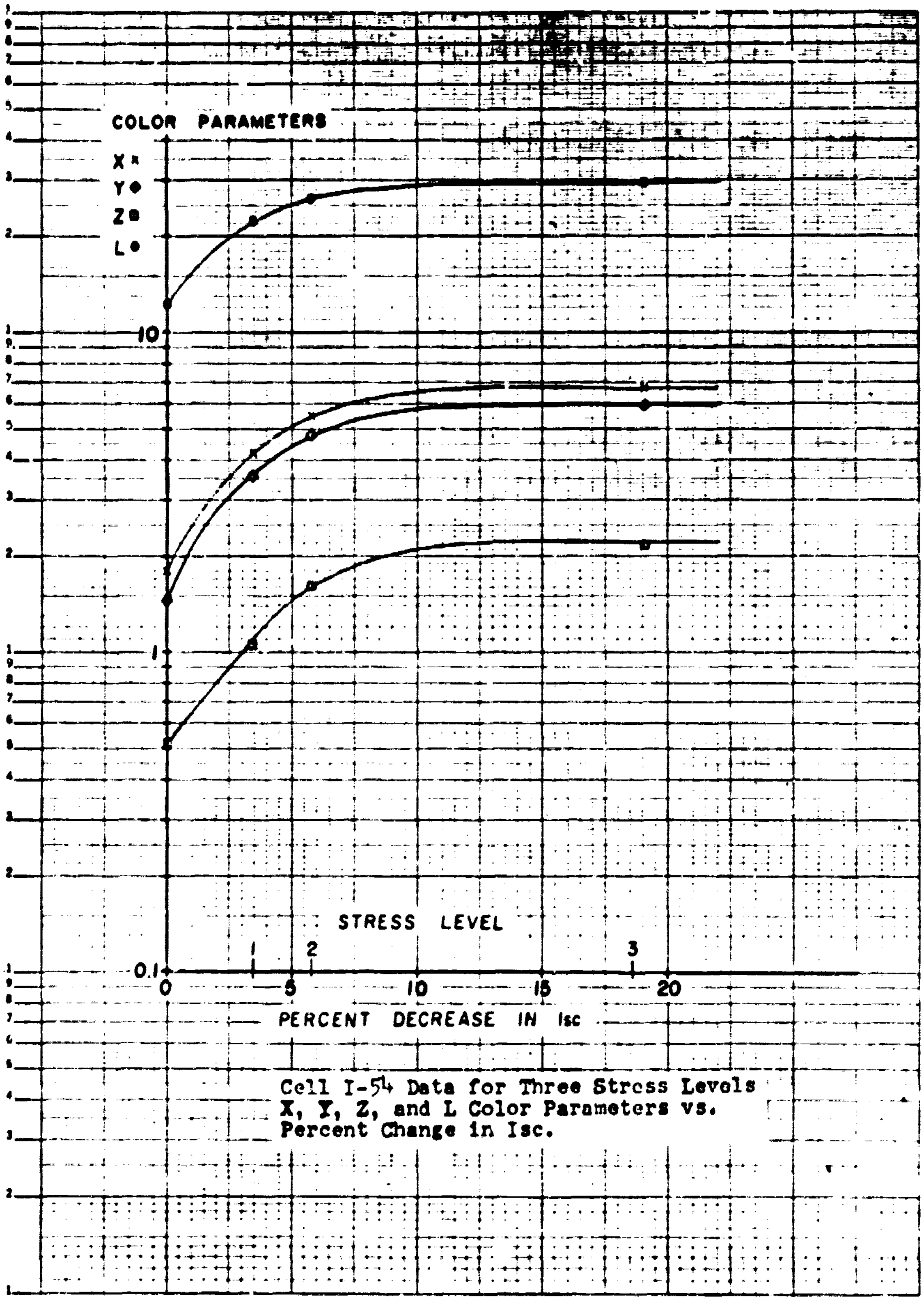
CELL 1-87 AREA 1 MEAS

SPECTRAL DATA

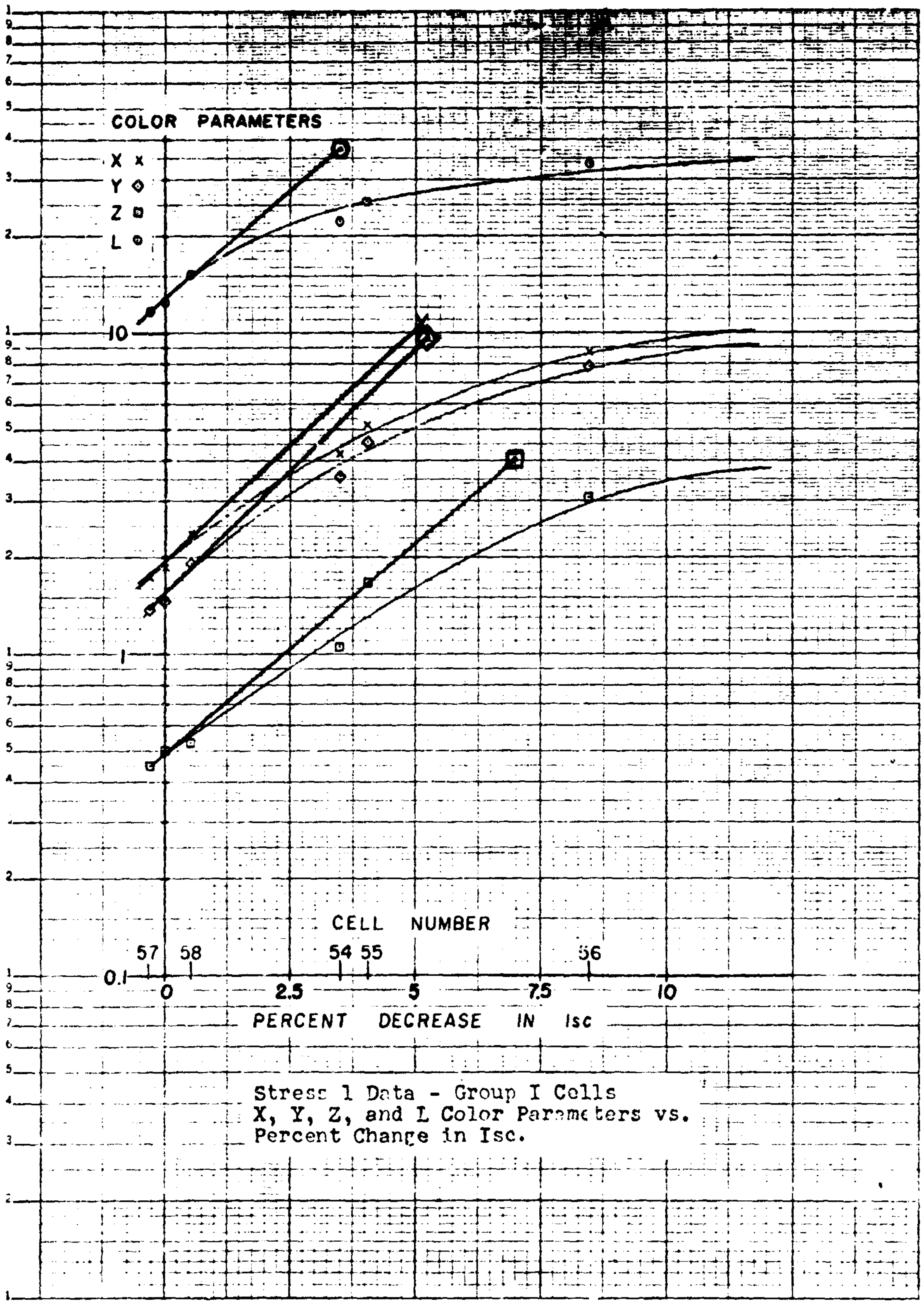
WAVEL	SAMPLE REFL.	STANDARD REFL.
400	7.04	
410	10.00	
420	9.67	
430	9.32	
440	8.97	
450	8.70	
460	8.55	
470	8.27	
480	8.12	
490	7.94	
500	7.78	
510	7.66	
520	7.56	
530	7.46	
540	7.36	
550	7.32	
560	7.29	
570	7.23	
580	7.17	
590	7.17	
600	7.10	
610	7.10	
620	7.07	
630	7.01	
640	7.[illegible]	
650	[illegible]	
660	[illegible]	
670	[illegible]	
680	[illegible]	
690	[illegible]	
700	[illegible]	

SAMP: ILLUM=A OBSVR=10

TRIST: X Y Z
SAMP 8.02 7.30 3.03
CHROMA: X Y
SAMP 0.4370 0.3978
COLOR COORD: L*A*B*
SAMP 32.49 -0.75 -4.74



Cell I-54 Data for Three Stress Levels
X, Y, Z, and L Color Parameters vs.
Percent Change in Isc.



Stress 1 Data - Group I Cells
X, Y, Z, and L Color Parameters vs.
Percent Change in Isc.

Conclusions (I Cells)

- 3-7% DECREASE IN Isc (4-9% Pm)

- TOTAL % DECREASE IN Isc IS DUE TO MORE THAN JUST AR COATING LOSS

- POSSIBILITY OF RELATING FIELD RESULTS TO COLOR MEASUREMENTS

MINIMODULE ACCELERATED WEATHERING

DSET LABORATORIES, INC.

E. Zerlaut

Technical Approach

- REAL-TIME WEATHERING
- EXPOSURE OF MICROMODULES ON EMMA(QUA) TEST MACHINES
- LONG-TERM EXPOSURE OF MINIMODULES ON SUPERMAQ TEST MACHINE (EQUIVALENT TO 10-20 YEARS)
- REGULAR, PERIODIC INSPECTIONS AND I-V MEASUREMENTS

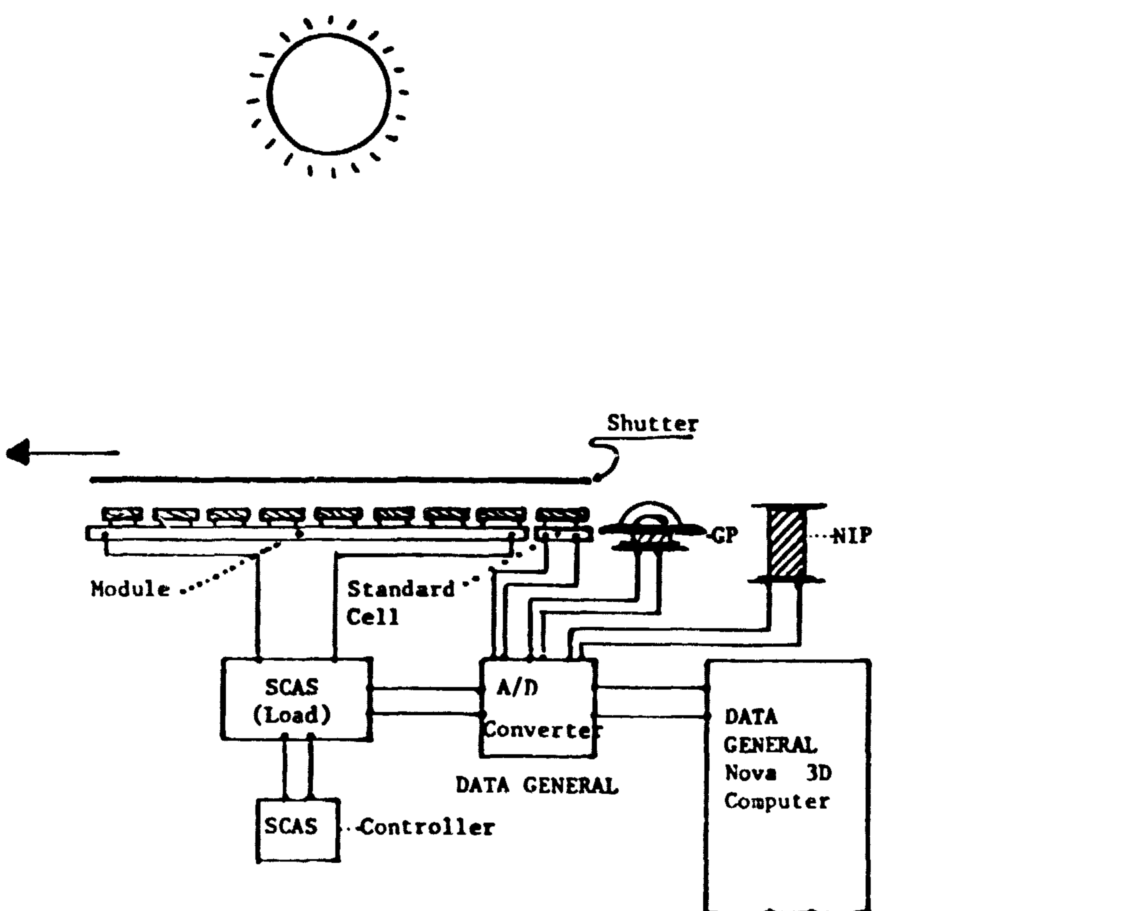
Objectives

- GAIN EXPERIENCE IN THE APPLICATION OF ACCELERATED AGING TECHNIQUES TO PHOTOVOLTAIC MODULES
- ACCURATELY SIMULATE ENCAPSULATION SYSTEM DESIGNS OF FULL-SCALE MODULES DEPLOYED IN THE FIELD
- PROVIDE A TEST BED FOR PERFORMING AGING TESTS WITH SAMPLES WHICH CAN BE SCALED TO FULL SIZE
- OBTAIN BASIS FOR CORRELATION OF ACCELERATED DEGRADATION MODES TO REAL-TIME FIELD EXPERIENCE

I-V Testing of Photovoltaics

- Reference cell perferred for measurement of I_T
- If reference cell not same as test cell, global pyranometric measurement preferred.
- Direct normal "beam" measurement not desirable
- DSET uses outdoor pulse method
- IV data taken in 1 sec.

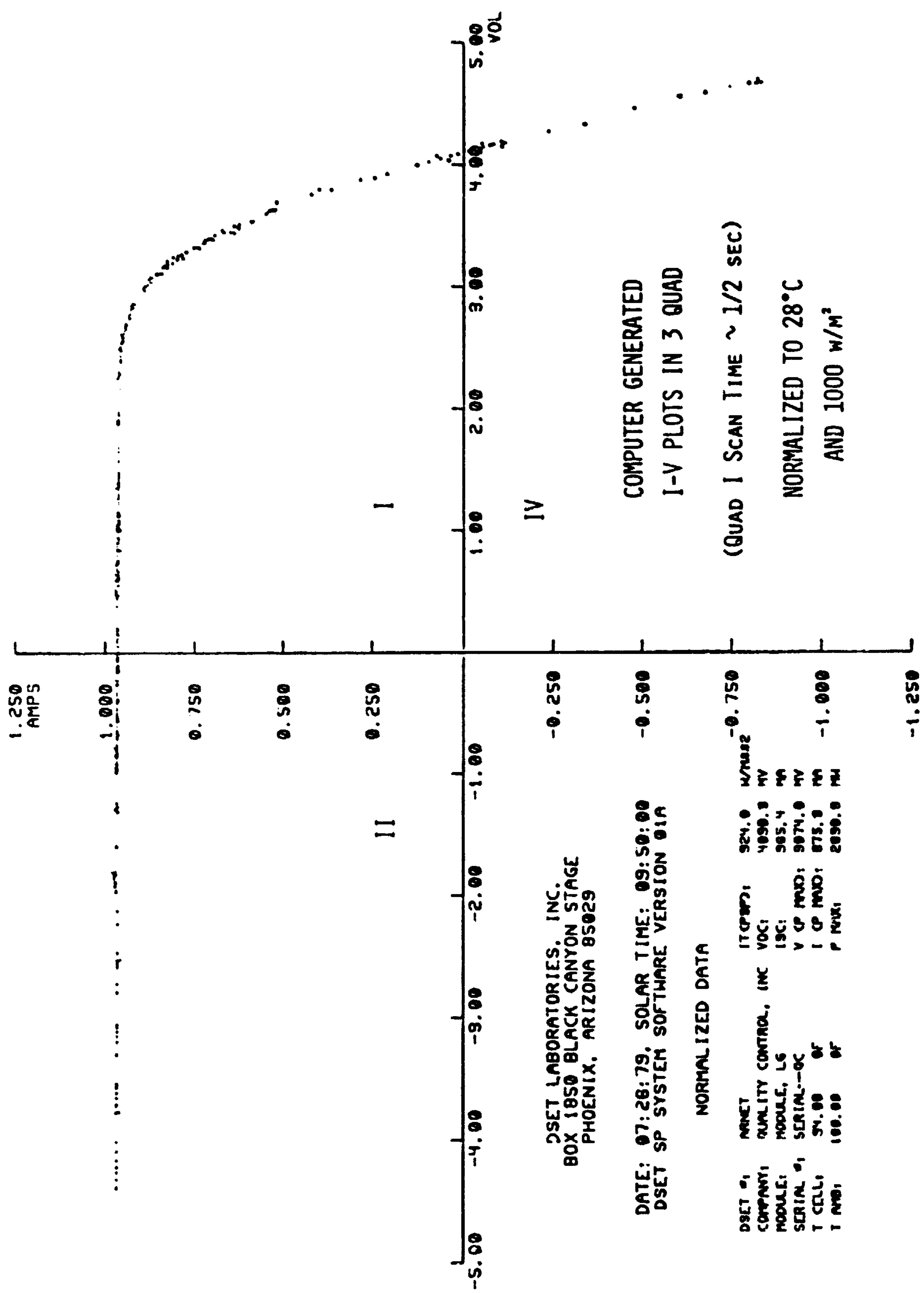
Pulse Testing in Direct Natural Sunlight



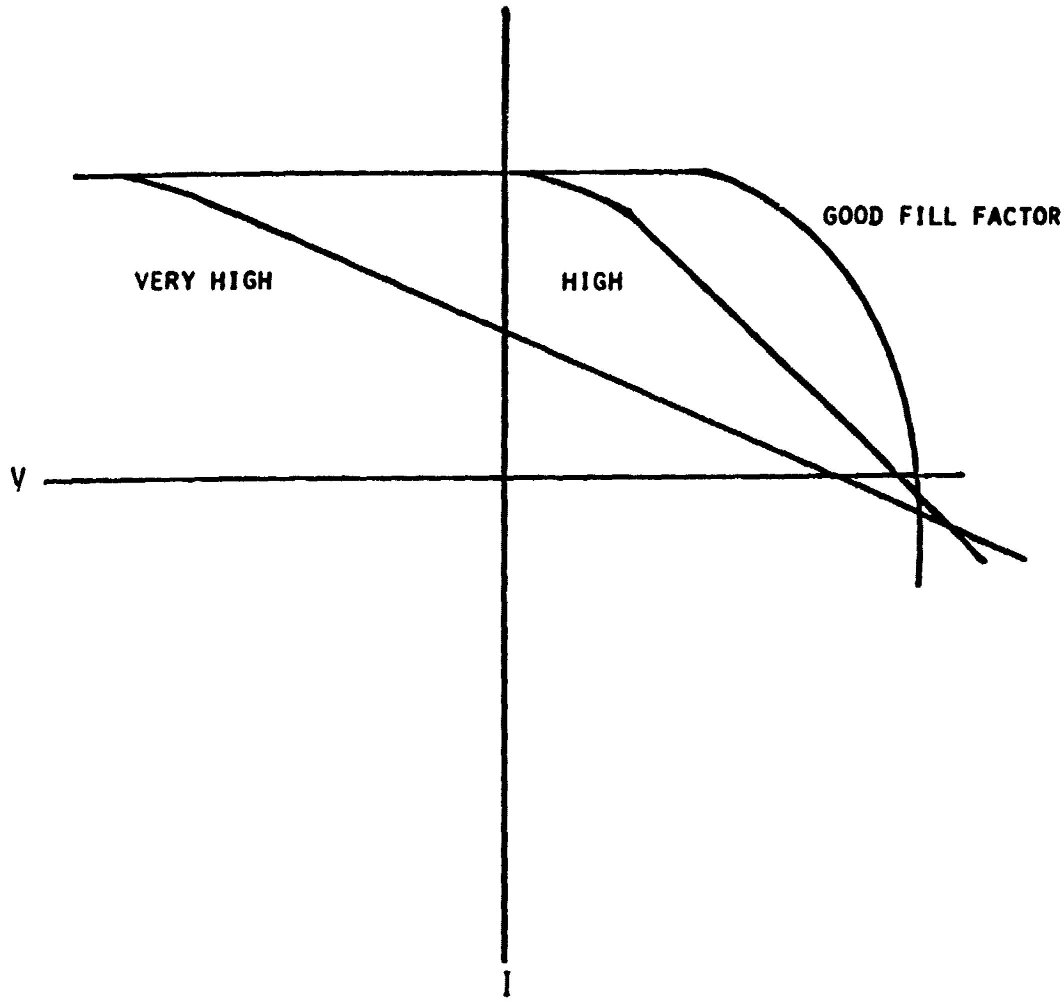
SCAS = Solar Cell Array Scanner (Dynamic Load)
± 25 V/ 4Amps (100 watts)
SCAS Controller = Dynamic Load Ramp Generator

GP= Global Pyranometer

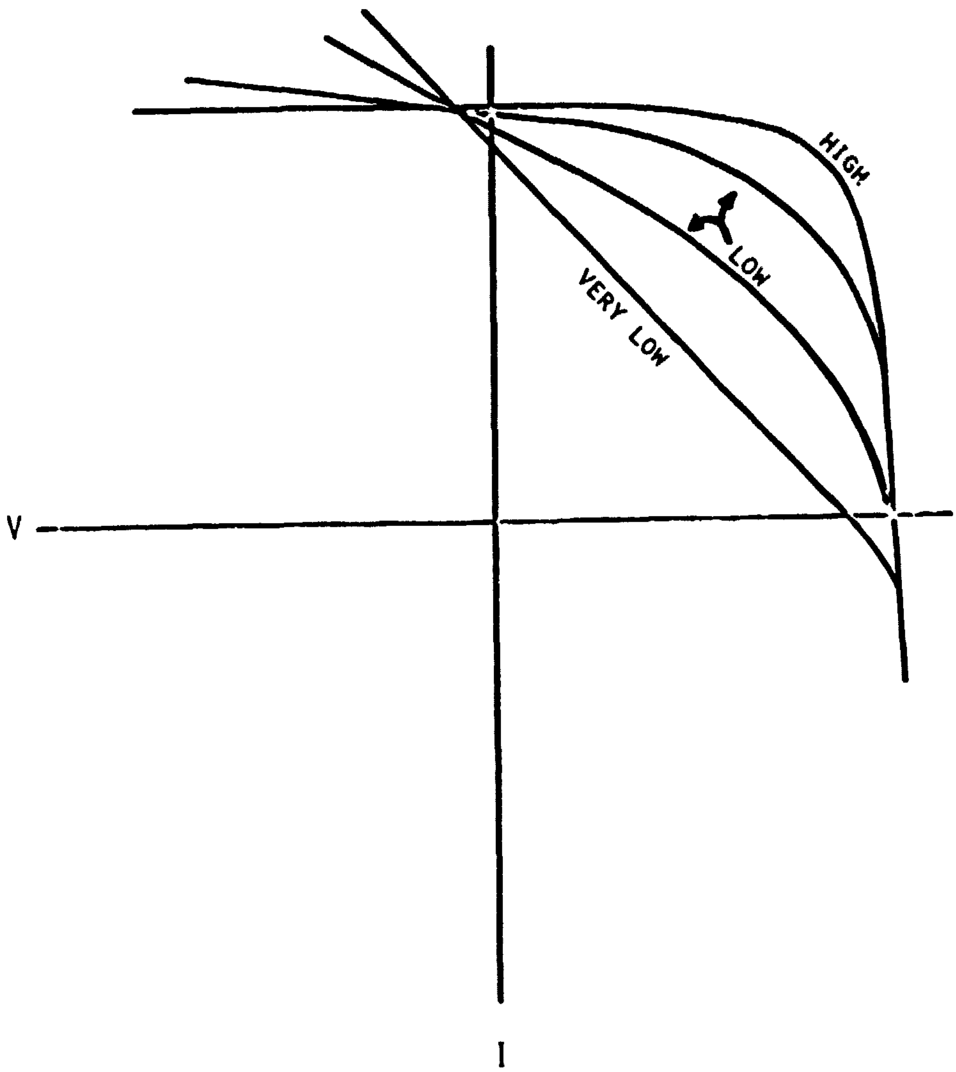
NIP= Normal Incidence Pyrheliometer

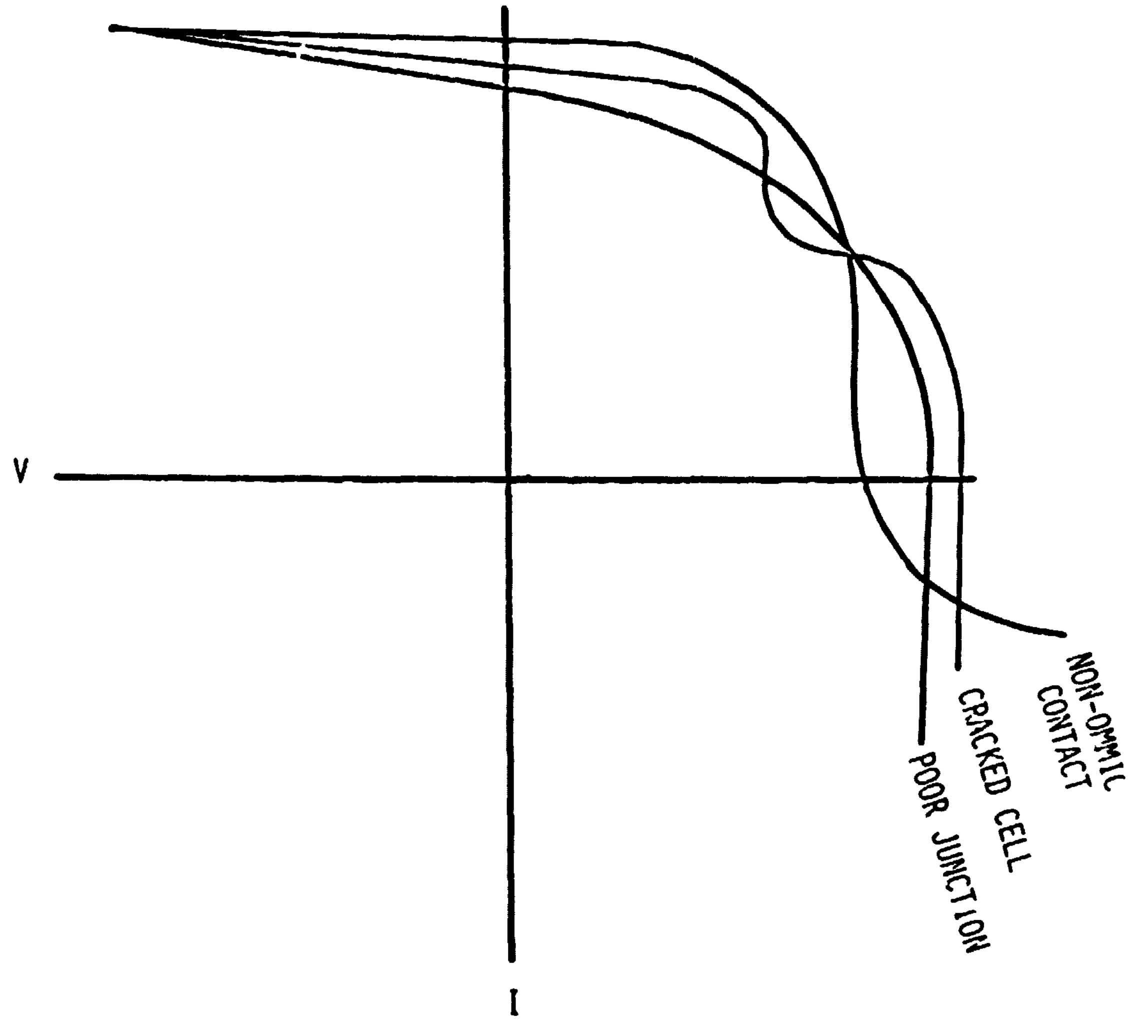

COMPUTER GENERATED
I-V PLOTS IN 3 QUAD
(QUAD I SCAN TIME ~ 1/2 SEC)
NORMALIZED TO 28°C
AND 1000 W/M²
I
II
IV
AMPS
VOL
DSET LABORATORIES, INC.
BOX 1850 BLACK CANYON STAGE
PHOENIX, ARIZONA 85029
DATE: 07:28:79, SOLAR TIME: 09:50:00
DSET SP SYSTEM SOFTWARE VERSION 01A
NORMALIZED DATA

Series Resistance



Shunt Resistance



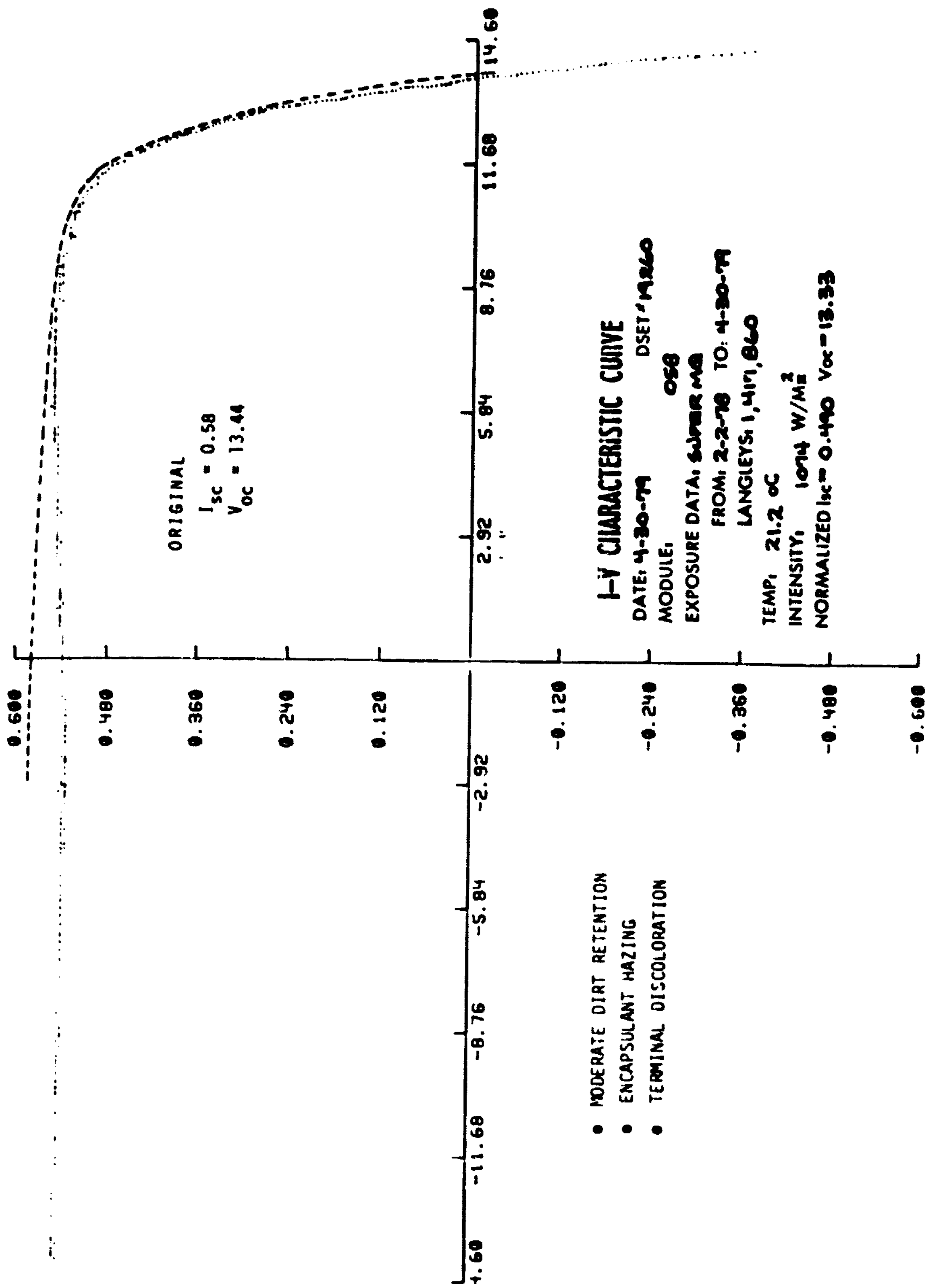


Degradation Modes That Have Correlated Well With Field Experience

- Cracked cells
- Delamination
- Encapsulant carbonation
- Glazing failure
- Contact corrosion

Exposure Response History of Block II Modules to Super-Maq Testing

MODULE	SN		INITIAL	EXPOSURE, KLYS 955	1,245	1,418	REMARKS
SILICONE RUBBER ENCAP., POLYESTER SUBSTRATE	021	I_{sc}	1.43	1.34	1.28	1.27	YELLOWING OF INTERCONNECTS &
		V_{oc}	6.71	6.93	6.59	6.53	SUBSTRATE. MODERATE WATER SPOTTING
	024	I_{sc}	1.48	1.37	1.31	1.31	SLIGHT DIRT RETENTION.
		V_{oc}	6.77	6.96	6.66	6.60	
SILICONE RUBBER ENCAP., ALUMINUM SUBSTRATE	002	I_{sc}	0.52	0.50	0.47	0.34	MODERATE DIRT RETENTION & WATER
		V_{oc}	13.43	13.77	13.16	13.19	SPOTTING. SLIGHT HAZE OF ENCAPSULANT.
	058	I_{sc}	0.58	0.54	0.51	0.49	TERMINAL DISCOLORATION.
		V_{oc}	13.44	13.42	13.25	13.33	
SILICONE RUBBER ENCAP., MOLDED POLYESTER SUBSTRATE	826	I_{sc}	2.19	(TERMINATED 8/7/78)			EXTENSIVE DELAMINATION (SWELLING);
		V_{oc}	4.71	("	")		CRACKED CELLS
	828	I_{sc}	2.21	0.39	0.41	0.23	DELAMINATION OF ENCAPSULANTS; YELLOWING
		V_{oc}	4.76	5.15	4.65	5.54	CRACKED CELL. WATER SPOTTING.
GLASS SUPERSTRATE, PVB/ MYLAR LAMINATE	028	I_{sc}	2.02	0.62	(TERMINATED 8/7/78)		SEVERE CARBONATION; CRACKED GLAZING,
		V_{oc}	5.04	4.80	("	")	WHITE & YELLOW HAZE EXTENSIVE
	042	I_{sc}	2.03	1.81	1.71	1.65	CARBONATION; SLIGHT WATER SPOTTING;
		V_{oc}	4.96	5.12	4.55	4.54	YELLOWING OF INTERCONNECTS.
			EXP.	807	1,098	1,271	KLYS
	EQIVALENT YEARS =			5	6-1/2	7-1/2	YEARS
	EXCEPT V =			4-1/4	5-3/4	6-3/4	YEARS



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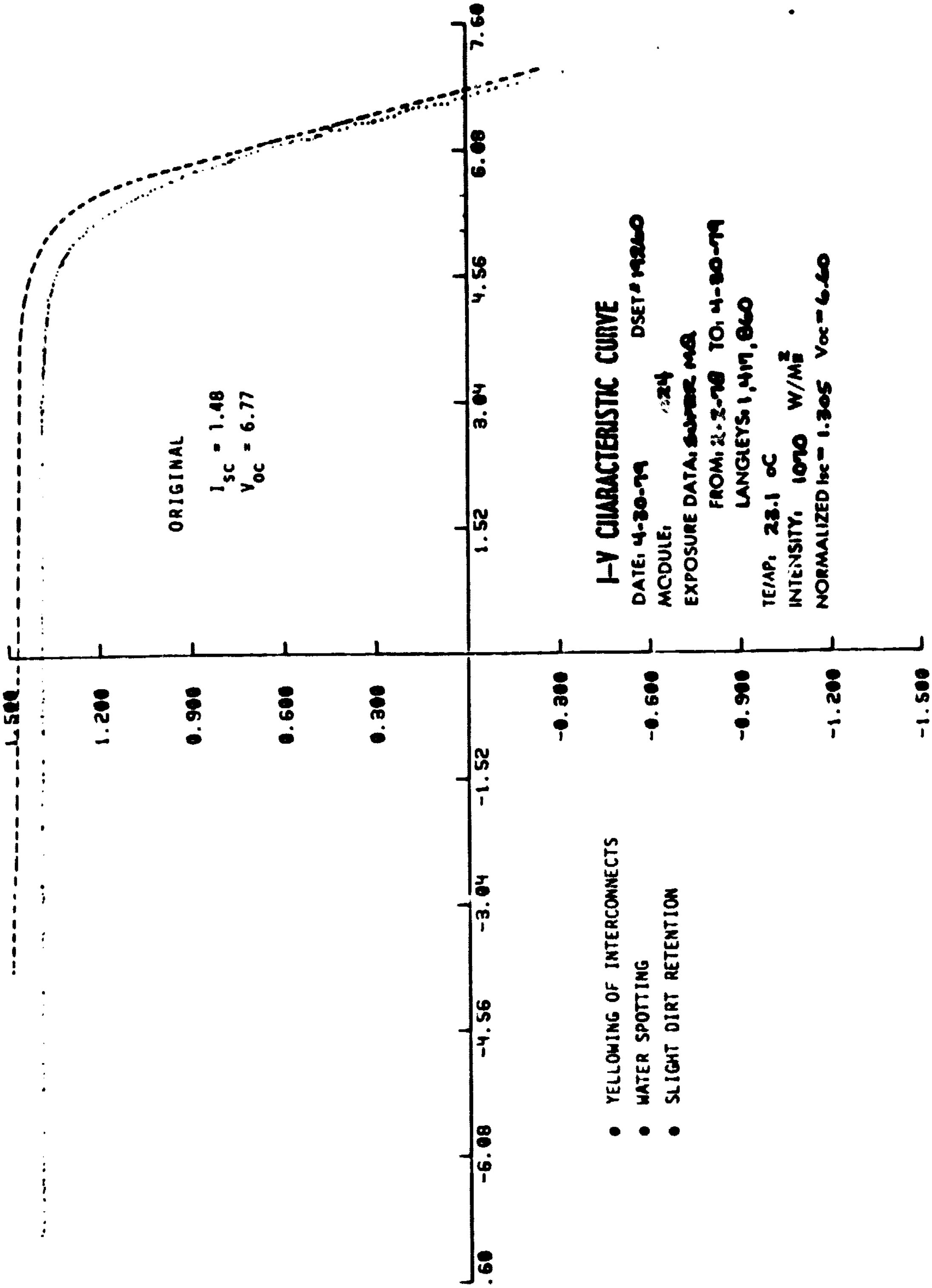
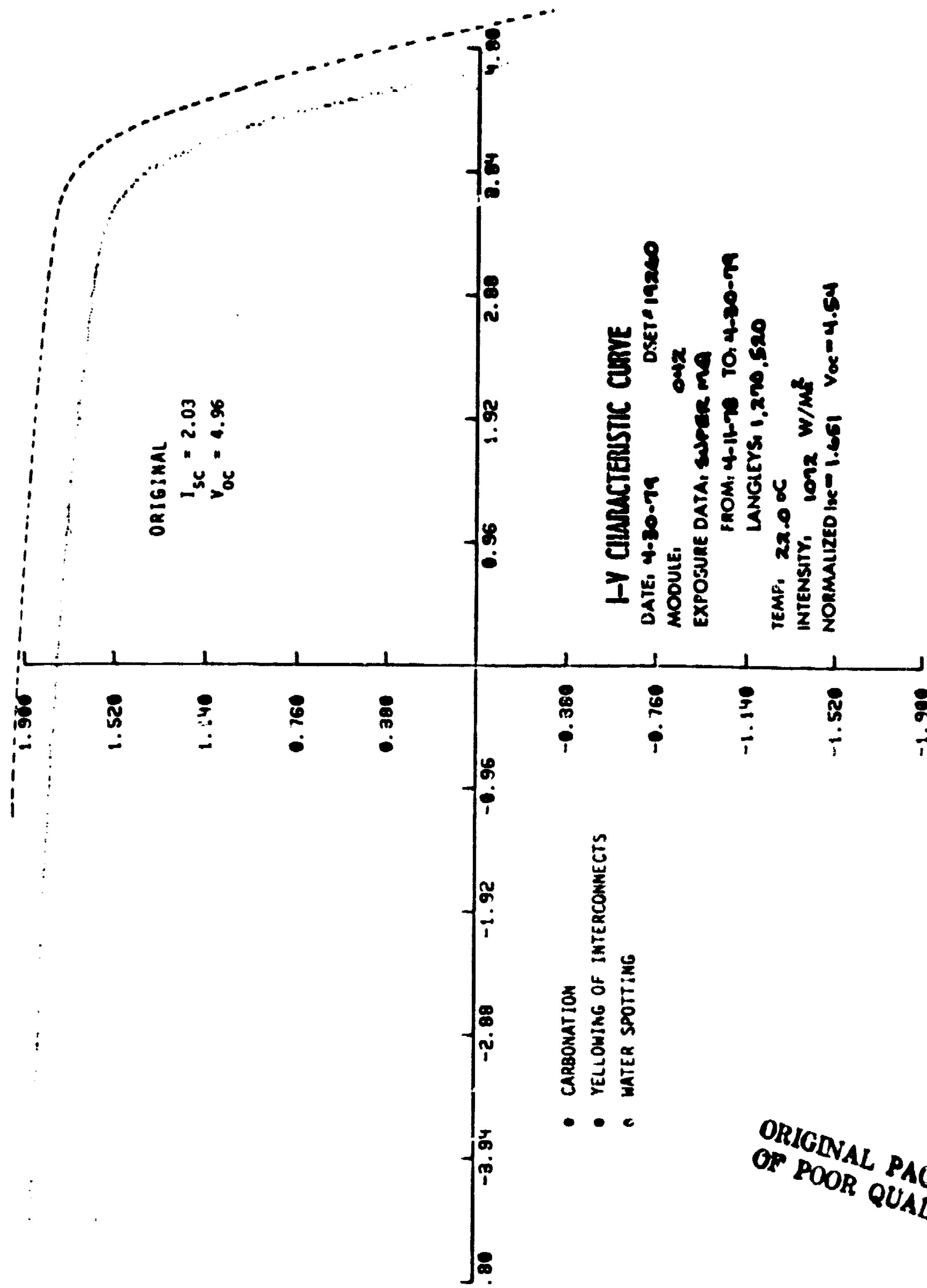
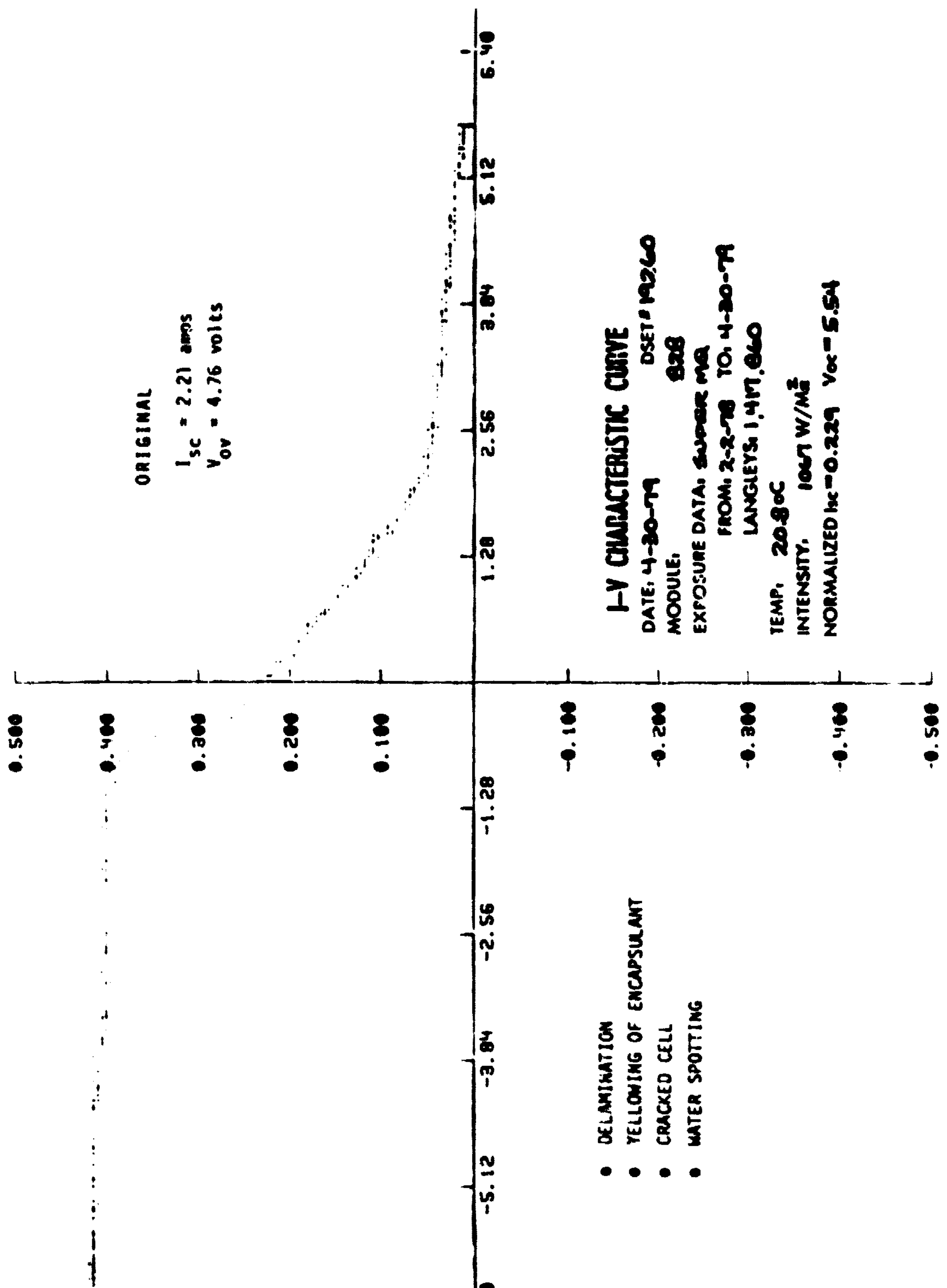
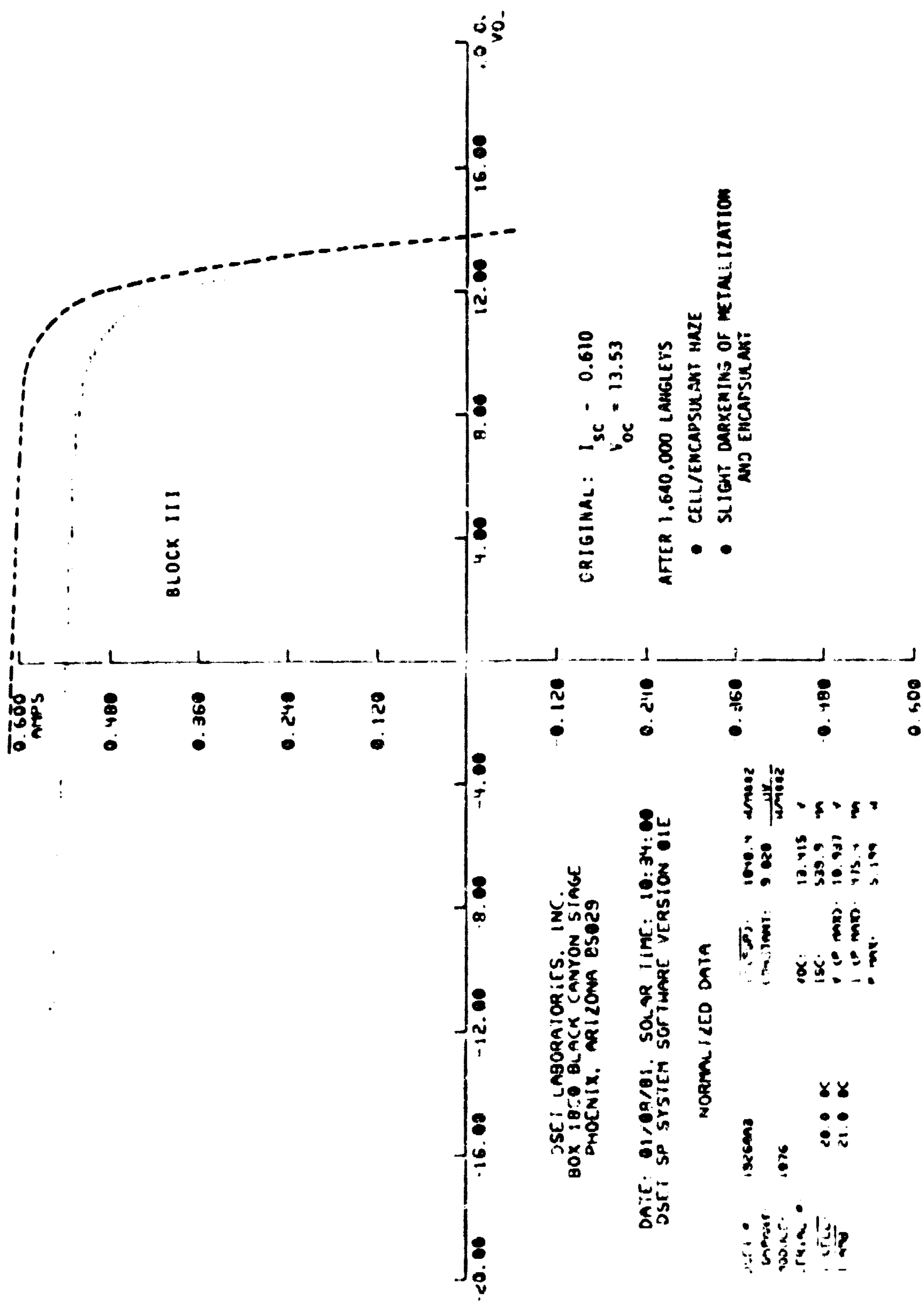
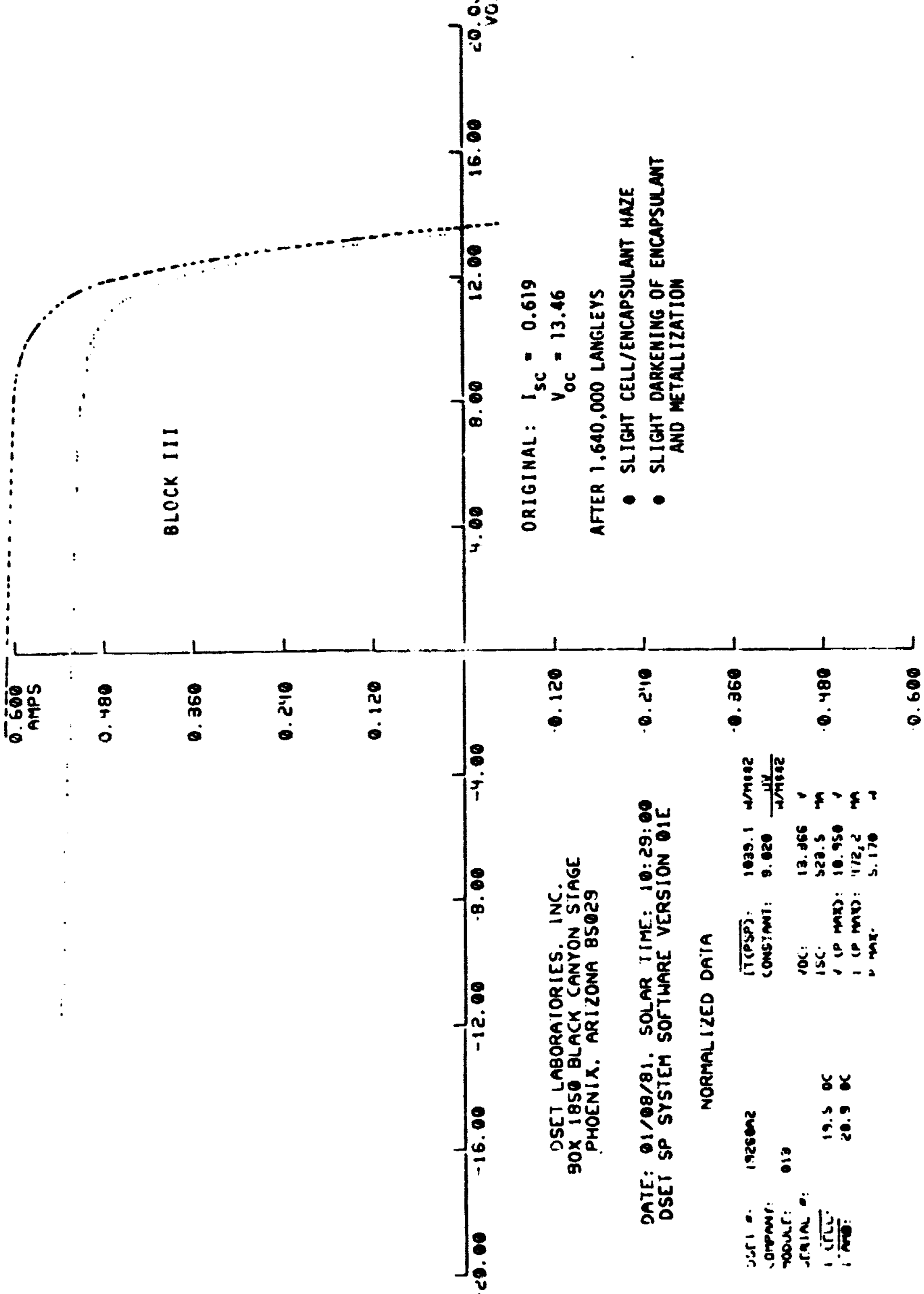

ORIGINAL
Isc = 1.48
Voc = 6.77
I-V CHARACTERISTIC CURVE
DATE: 4-30-79
DSET#
MODULE:
EXPOSURE DATA:
FROM:
TO: 4-30-79
LANGLEYS:
TEMP: 23.1 oC
INTENSITY: 1070 W/M2
NORMALIZED Isc = 1.305 Voc = 6.60
YELLOWING OF INTERCONNECTS
WATER SPOTTING
SLIGHT DIRT RETENTION
7.60
6.08
4.56
3.04
1.52
-1.52
-3.04
-4.56
-6.08
1.500
1.200
0.900
0.600
0.300
-0.300
-0.600
-0.900
-1.200
-1.500


ORIGINAL
I_{sc} = 2.03
V_{oc} = 4.96
I-V CHARACTERISTIC CURVE
CARBONATION
YELLOWING OF INTERCONNECTS
WATER SPOTTING

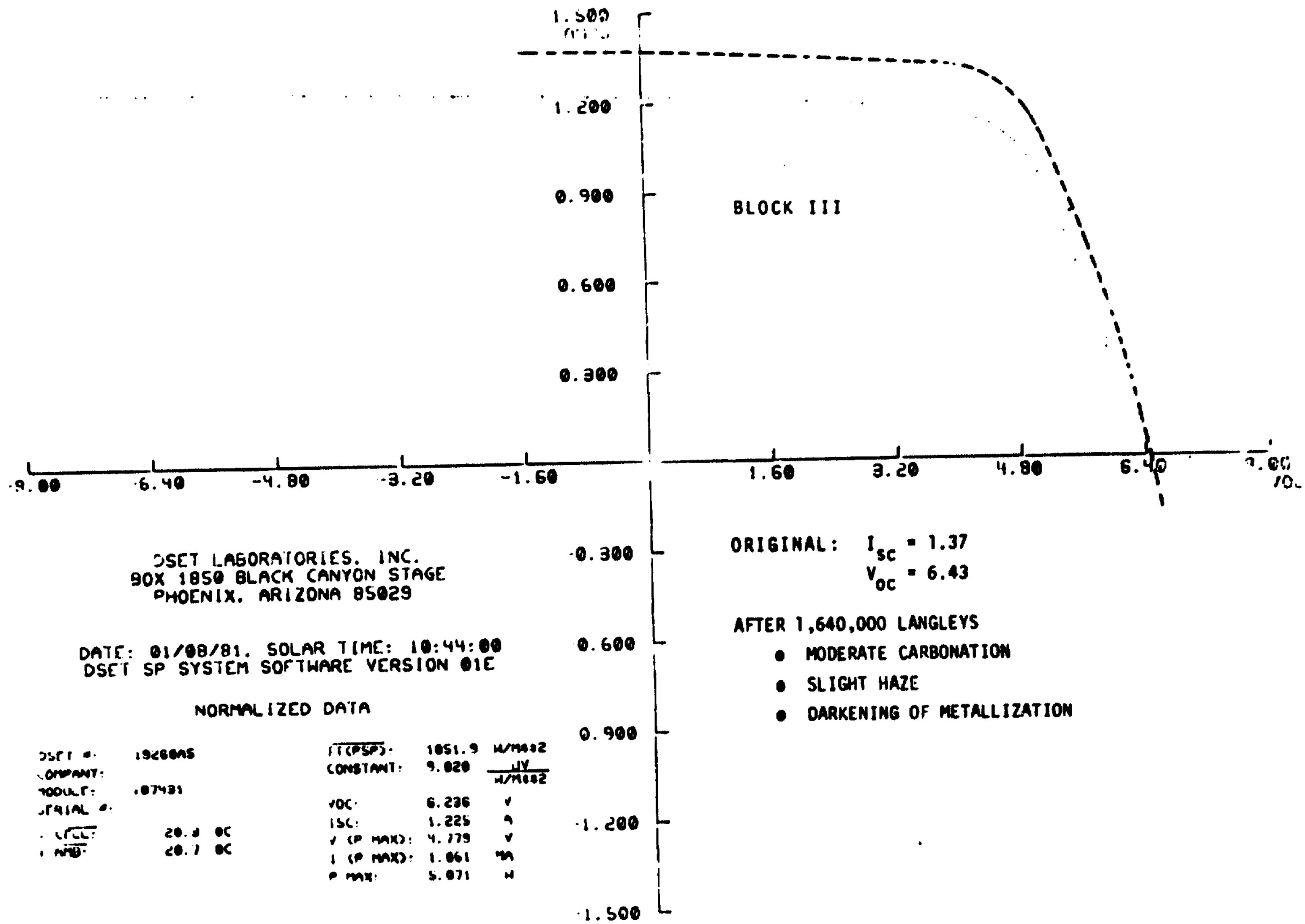


ORIGINAL
I sc = 2.21 amps
V ov = 4.76 volts
I-V CHARACTERISTIC CURVE
DATE:
MODULE:
EXPOSURE DATA:
FROM:
TO:
LANGLEYS:
TEMP:
INTENSITY:
NORMALIZED Isc
Voc
DSET#
0.500
0.400
0.300
0.200
0.100
-0.100
-0.200
-0.300
-0.400
-0.500
1.28
2.56
3.84
5.12
6.40
-1.28
-2.56
-3.84
-5.12
DELAMINATION
YELLOWING OF ENCAPSULANT
CRACKED CELL
WATER SPOTTING


0.600 AMPS
0.480
0.360
0.240
0.120
-0.120
-0.240
-0.360
-0.480
-0.600
-20.00
-16.00
-12.00
-8.00
-4.00
4.00
8.00
12.00
16.00
VO
BLOCK III
ORIGINAL: I_{sc} - 0.610
V_{oc} = 13.53
AFTER 1,640,000 LANGLEYS
• CELL/ENCAPSULANT HAZE
• SLIGHT DARKENING OF METALLIZATION AND ENCAPSULANT
DSET LABORATORIES, INC.
PHOENIX, ARIZONA 85029
DSET SP SYSTEM SOFTWARE VERSION 01E
NORMALIZED DATA
VOC: 13.415 V
ISC: 539.9
P MAX: 5.199


0.600 AMPS
0.480
0.360
0.240
0.120
-0.120
-0.240
-0.360
-0.480
-0.600
-20.00
-16.00
-12.00
-8.00
-4.00
4.00
8.00
12.00
16.00
20.0 VO
BLOCK III
ORIGINAL: Isc = 0.619
Voc = 13.46
AFTER 1,640,000 LANGLEYS
• SLIGHT CELL/ENCAPSULANT HAZE
• SLIGHT DARKENING OF ENCAPSULANT AND METALLIZATION
DSET LABORATORIES, INC.
BOX 1850 BLACK CANYON STAGE
PHOENIX, ARIZONA 85029
DATE: 01/08/81, SOLAR TIME: 10:29:00
DSET SP SYSTEM SOFTWARE VERSION 01E
NORMALIZED DATA
DSET #: 192602
COMPANY:
MODULE: 019
SERIAL #:
T CELL: 19.5 OC
T AMB: 20.9 OC
IT(PSP): 1039.1 W/M**2
CONSTANT: 9.020 UV / W/M**2
VOC: 13.366 V
ISC: 520.5 MA
V (P MAX): 10.950 V
I (P MAX): 472.2 MA
P MAX: 5.170 W

C-6


BLOCK III
1.500
1.200
0.900
0.600
0.300
-0.300
-0.600
-0.900
-1.200
-1.500
-8.00
-6.40
-4.80
-3.20
-1.60
1.60
3.20
4.80
6.40
ORIGINAL: I_{sc} = 1.37
V_{oc} = 6.43
AFTER 1,640,000 LANGLEYS
● MODERATE CARBONATION
● SLIGHT HAZE
● DARKENING OF METALLIZATION
DSET LABORATORIES, INC.
BOX 1850 BLACK CANYON STAGE
PHOENIX, ARIZONA 85029
DATE: 01/08/81, SOLAR TIME: 10:44:00
DSET SP SYSTEM SOFTWARE VERSION 01E
NORMALIZED DATA
VOC: 6.236 V
ISC: 1.225 A
V (P MAX): 4.779 V
I (P MAX): 1.061 A
P MAX: 5.071 W

E-6

Conclusions

- Field failure modes have been duplicated
- Acceleration factors of 6x to 8x are attainable
- Test method is feasible as a predictive tool for PV lifetime durability assessment

SOLAR SPECTRAL MEASUREMENTS

DSET LABORATORIES, INC.

R. Whitaker

Scanning Spectroradiometer

- Materials Durability
- Energy Availability
- Site Specific Spectral Characteristics
- Efficient Data Acquisition, and Measurement Analysis
- Contract Essentials

Capabilities

- SOLAR SPECTRUM 280 - 2500 NM

- GLOBAL NORMAL, GLOBAL FIXED, AND DIRECT NORMAL

  AZIMUTH: ± 90°
  ELEVATION: HORIZON TO 90°

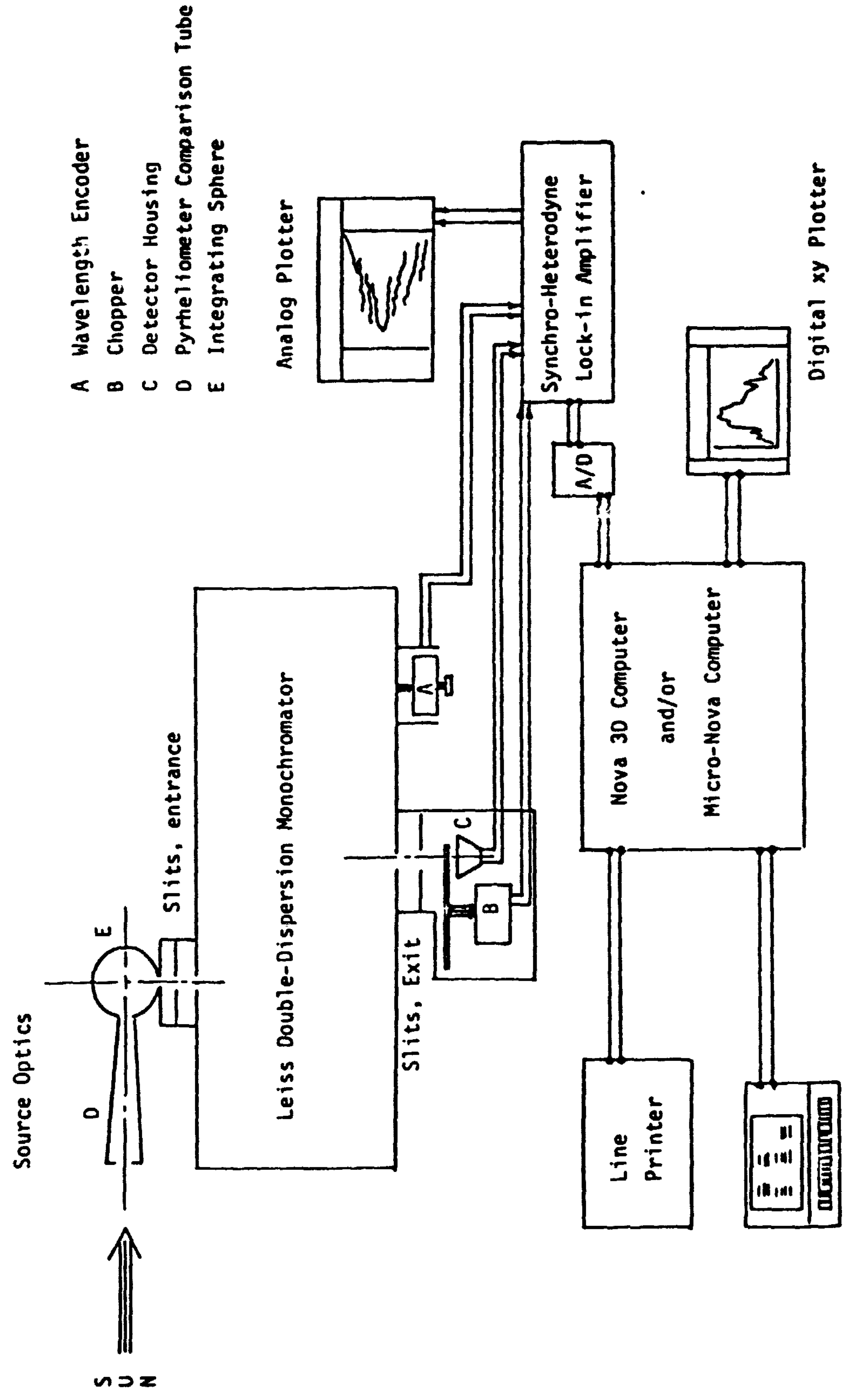
- ACCURACY

  INTENSITY: BETTER THAN ± 5%
  WAVELENGTH: BETTER THAN ± 1 NM

- OPERATION

  MEASUREMENT: 10 MINUTES
  DATA REDUCTION: 30 MINUTES
  OUTDOOR/INDOOR
  TRANSPORTABLE

DSET Spectroradiometer



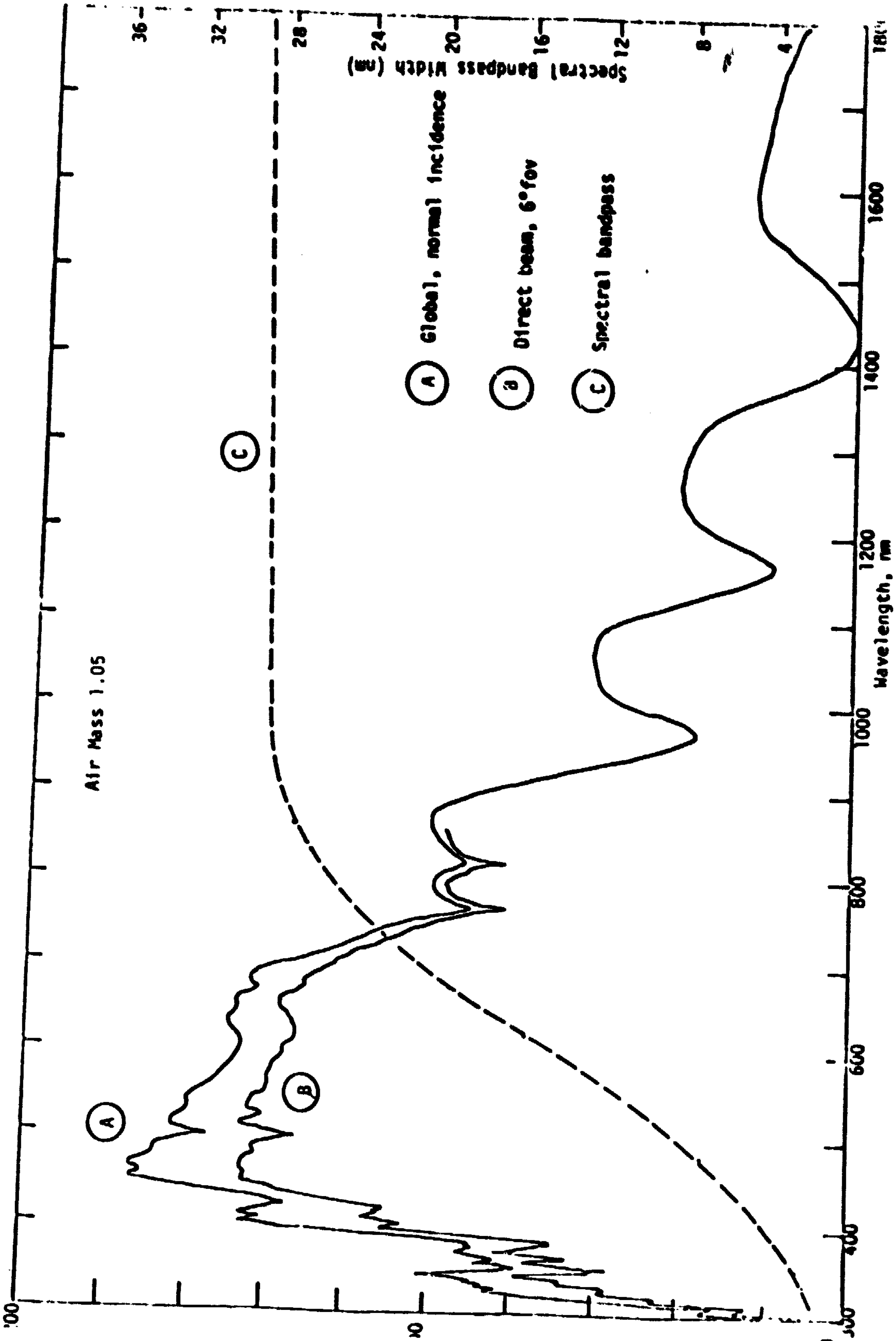
Software

READ	INTERFACE TO AND CONTROL OF INSTRUMENT AMPLIFIER
⇩	
COMPUTATIONAL	APPLICATION OF CALIBRATION VALUES TO RAW SIGNAL DATA
⇩	
FORMATTING/ ANALYSIS	DATA SCALING AND DETECTOR DATA COMBINATION, BAND IRRADIANCE CALCULATION
⇩	
PRESENTATION	GENERATION OF SPECTRAL PLOTS AND TABULAR HARDCOPY MAGNETIC STORAGE ARCHIVAL

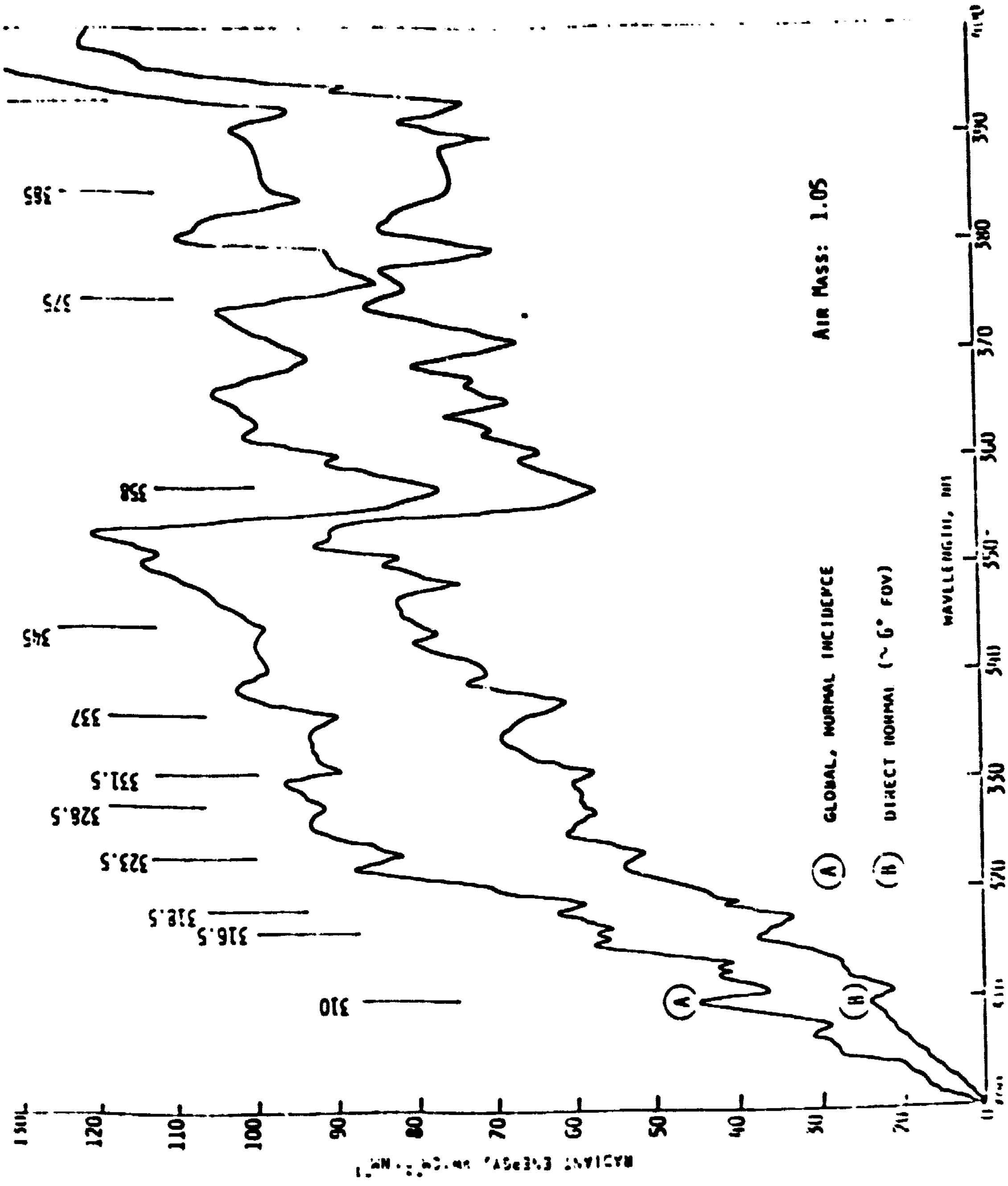
Calibration

- WAVELENGTH
  - 5 LAMPS 185 - 1050 NM
    - ARGON
    - KRYPTON
    - NEON
    - XENON
    - MERCURY - ARGON
  - 3 FILTERS
    - DIDYMIUM - VIS/NEAR IR
    - HOLMIUM OXIDE - VIS/NEAR IR
    - TRICHLOROBENZENE - NEAR IR
- INTENSITY
  - NBS 1000 WATT QUARTZ IODINE LAMP
  - EPPLEY LABORATORIES (CAL./TRANS.)
  - 250 - 2500 NM
  - 214 DISCRETE CALIBRATIONS, 280 - 2500 NM

Solar Spectral Irradiance: New River, Arizona
(July 9, 1979)



Hemispherical and Direct Spectral UV: New River, Arizona (July 9, 1979)



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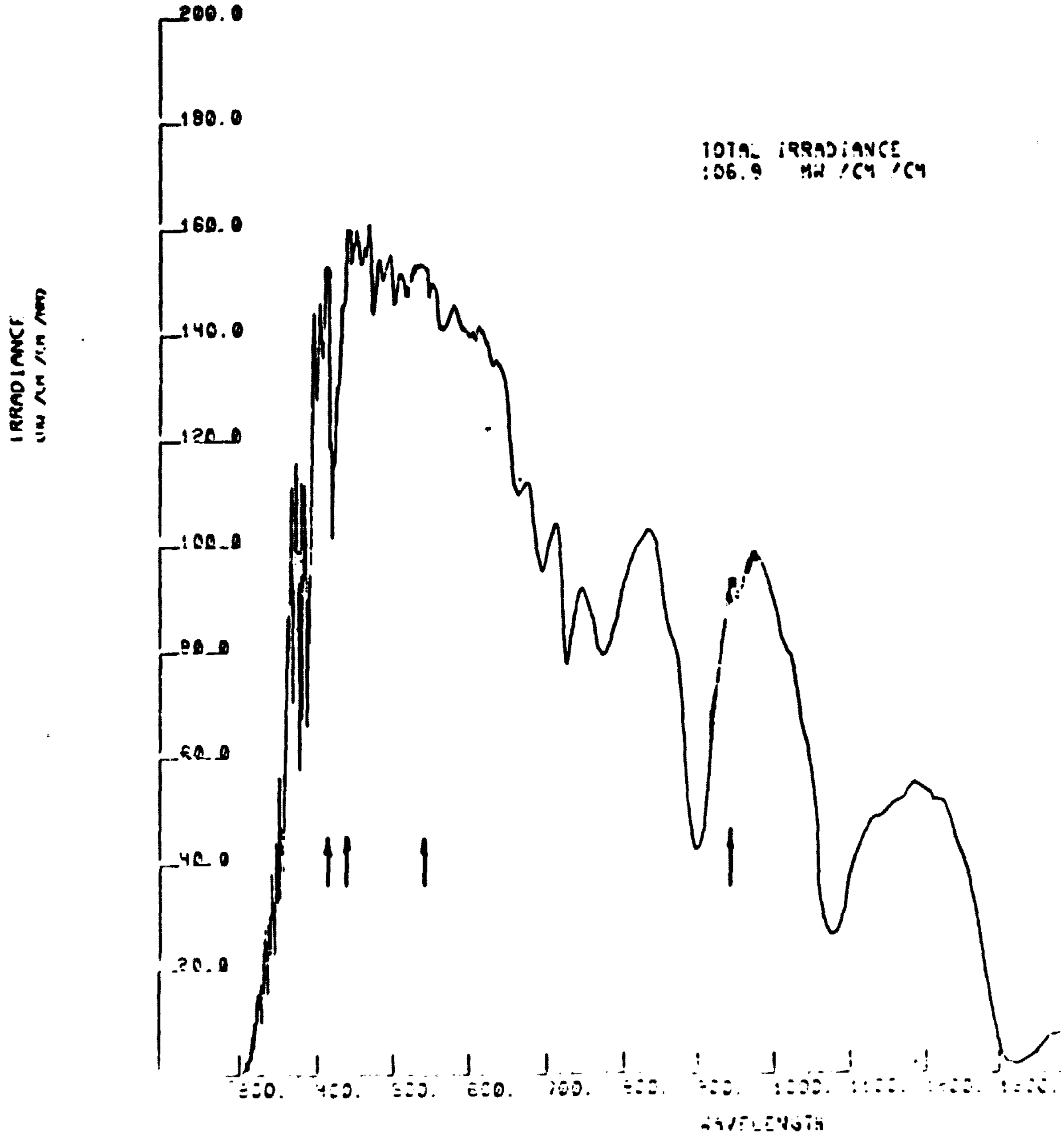

200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
IRRADIANCE
TOTAL IRRADIANCE
106.9 MW /CM /CM
300.
400.
500.
600.
700.

Spectroradiometer Total Spectrum Plot

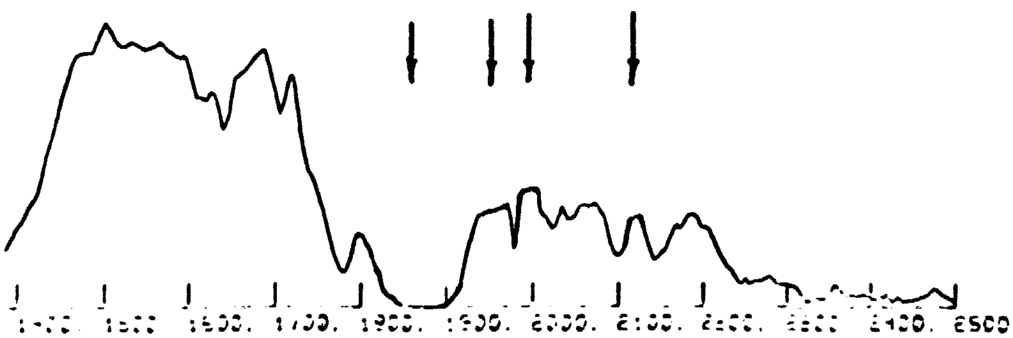
SPECTRA # [illegible]

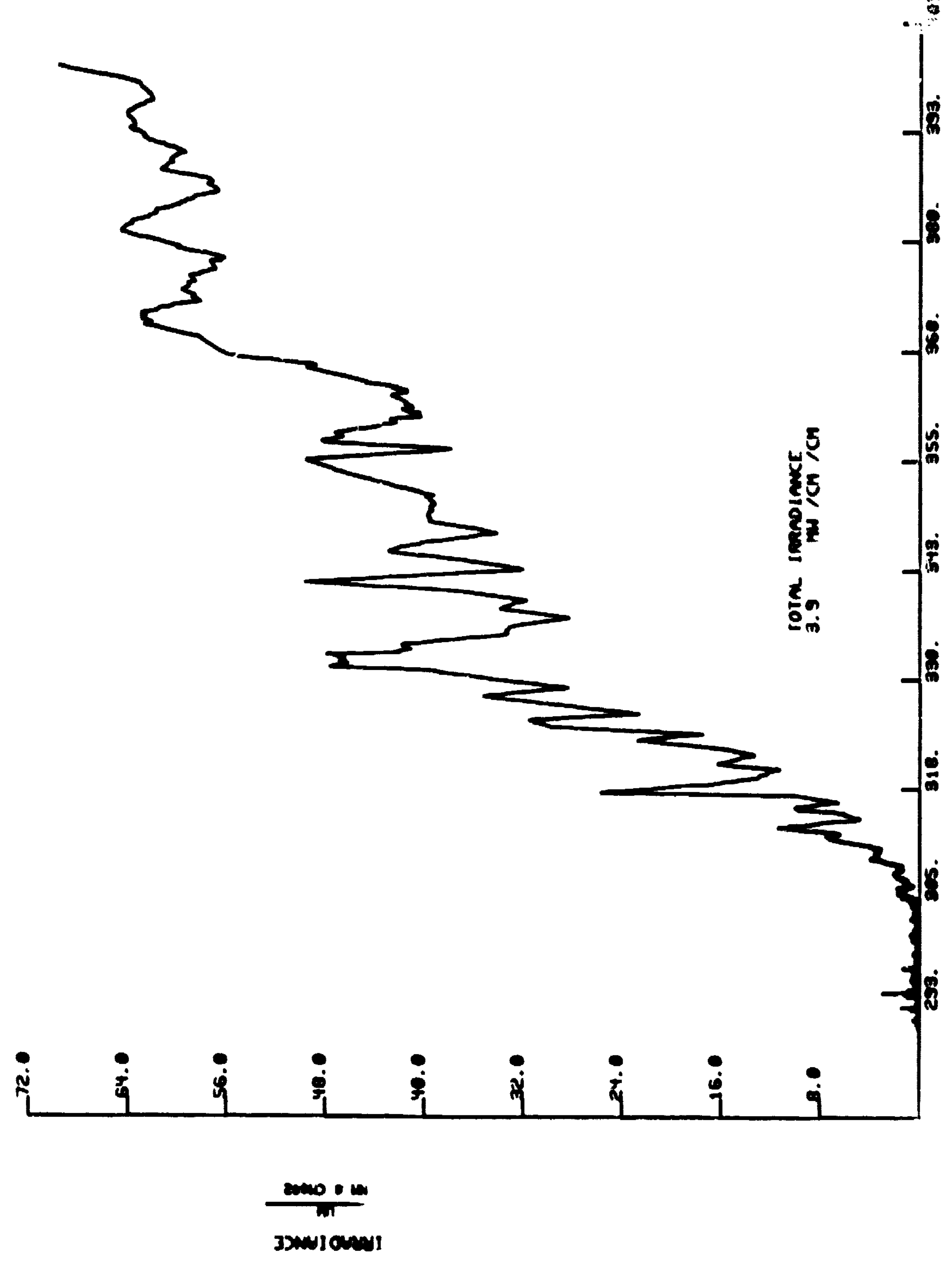
DSET LABORATORIES, INC.
BOX 1850 BLACK CANYON STAGE
PHOENIX, ARIZONA 85029

DSET SPECTRORADIOMETER SOFTWARE SYSTEM [illegible]

DATE	11 IX 1983
MODE	GLOBAL
TILT	NORMAL
SOLAR TIME	13:54 - 14:04
GEOMETRIC AIR MASS	CIRROCUMULUS
SLIT WIDTH	.2 MM
SITE	NEW RIVER
LATITUDE	33 DEG 50 MIN
LONGITUDE	112 DEG 10' W
ALTITUDE	2034'

ORIGINAL PAGE IS OF POOR QUALITY




TOTAL IRRADIANCE
3.9 MW /CM /CM
WAVELENGTH
IRRADIANCE
72.0
64.0
56.0
48.0
40.0
32.0
24.0
16.0
8.0

Selected Band Energy Analysis

DATE	11 IX 1980
MODE	GLOBAL
TILT	NORMAL
SOLAR TIME	13:54 - 14:04
GEOMETRIC AIR MASS	CIRROCUMULUS
SLIT WIDTH	.2 MM
SITE	NEW RIVER
LATITUDE	33 DEG 50 MIN
LONGITUDE	112 DEG 10' W
ALTITUDE	2034'

WAVEBAND nm FROM	TO	IRRADIANCE uW / cm**2
280.000	315.000	14.677
315.000	330.000	126.548
330.000	350.000	485.761
350.000	400.000	4181.672
400.000	750.000	46553.987
750.000	2500.000	55576.973

Near-Term Future Capabilities

- INCREASED OPERATIONAL EFFICIENCY

  MEASUREMENT: 5 MINUTES

  DATA REDUCTION: 15 MINUTES

- IMPROVED ACCURACY

  INCREASED INTENSITY RESOLUTION, ESPECIALLY IN ULTRAVIOLET

  INCREASED BAND