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Low-Cost
Solar Array Project

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Progress Report 15

for the Period December 1979 to April 1980

and Proceedings of the 15th Project Integration Meeting

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

(JPL PUBLICATION 80-27)

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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period December 1979 to April 1980. 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 April 2 and 3, 1980.

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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)
BSF	Back-surface field
B-T	Bias/temperature
B-T-H	Bias/temperature/humidity
CFP	Continuous-flow pyrolyzer
CLF	Continuous liquid feed
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
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
IPEG 2	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
LSA	Low-Cost Solar Array
MBS	Multiblade sawing
MWS	Multiwire sawing
NDE	Nondestructive evaluation
NOCT	Nominal operating cell temperature
PMMA	Polymethyl methacrylate
P_{max}	Maximum power
PnBA	Poly-n-butyl acrylate
OTC	Optional 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
$POCl_3$	Phosphorus oxychloride
PP&E	Production Process and Equipment Area
ppba	Parts per billion atomic
ppma	Parts per million atomic
PRDA	Program Research and Development Announcement
PV	Photovoltaic
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RNHT	Relative normal hemispherical transmittance
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)
Ti	Titanium
UV	Ultraviolet radiation
V	Vanadium
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage
$ZnCl_2$	Zinc chloride

PROGRESS REPORT

Project Summary

The progress achieved by the Low-Cost Solar Array Project between December 1979 and April 1980 is summarized. A summary of the 15th Project Integration Meeting highlights held April 2-3, 1980 is included.

Project Analysis and Integration Area

- A detailed analysis of Project probability of attaining Technical Readiness in 1982, given three different budget scenarios, was completed.

- An analysis of ingot technology was conducted in cooperation with the Large-Area Sheet Task and the Production Process and Equipment Area.

- A baseline case has been generated to test the residential version of the Lifetime, Cost and Performance model.

Technology Development Area: Silicon Material Task

- Lamar University completed a preliminary economic analysis of the Battelle process for producing silicon by the zinc reduction of $SiCl_4$. The calculated silicon price would be $17.19/kg (1980$) at a 20% ROI.

- The first operational test of Battelle's silicon material process development unit was performed.

- In tests made by Hemlock for their modified Siemens process, it was determined that silicon conversion efficiency and deposition rate for SiH_2Cl_2 are twice those for $SiHCl_3$.

- Union Carbide initiated testing of a free-space reactor process development unit (PDU) for the silane-to-silicon process. A 24-hour continuous operation produced 45 kg of silicon powder at a yield of more than 99%.

- In support of the Union Carbide process development, MIT is studying $SiHCl_3$. A copper catalyst was found to increase the reaction rate significantly.

- Experimental results in JPL's fluidized-bed reactor (in support of Union Carbide process) demonstrated that the production of fines is negligible when the operation is in a practical silane concentration range.

- Large silicon powder particles were formed during operation of the JPL experimental continuous-flow pyrolyzer. The larger particles will permit easier handling and decreased contamination in a Union Carbide type of silicon production plant.

- Phase III summary reports were issued by Westinghouse on the effects of impurities on solar cell performance in which an empirical model for impurities in n- and p-base cells, HCl and POCl gettering of impurities, impurity distributions, aging, and strategies for crystal growth from impure feedstock were discussed.

Technology Development Area: Large-Area Silicon Sheet Task

- Mobil Tyco's EFG 10-cm-wide ribbon growth rate is now commonly 4 cm/min. with no ribbon stress or buckling. A three-ribbon simultaneous growth demonstration was completed successfully. EFG cells of 14 cm^2 with approximately 12% efficiency have been processed.

- Westinghouse has demonstrated a simultaneous melt replenishment and web growth for a one-day cycle, which includes 17 h of web growth and 7 h for cleaning, loading, start-up and cool-down.

- Honeywell's SOC SCIM 1 has been made operational and has coated 5-cm-wide slotted substrates with silicon at a rate of 3 cm/min. Testing of SCIM 2 has begun.

- Crystal Systems has grown a 21 kg HEM ingot (34 x 34 x 10 cm) at a rate of 2 kg/h.

- Hamco has successfully grown six 15-cm-dia Cz ingots (total weight 150 kg) from a single crucible using sequential melt replenishment.

- Crystal Systems' multi-wire saw, using electroplated wire, sliced a 10-cm ingot with 90% yield at a slicing rate of .427 cm/h.

Technology Development Area: Encapsulation Task

- Spire has demonstrated the feasibility of achieving cell metallization using pre-formed metal mesh positioned and bonded to the cell surfaces in one step with the electrostatic bonding process; however, the optimum materials, configurations and surface preparations have yet to be determined.

- Springborn Laboratories has continued to optimize and upgrade EVA as a candidate low-cost solar cell pottant by developing non-blocking (non-sticking) sheet material and by the incorporation of adhesion promoters and processing aids.

- An exploratory study by Professor Paul Bruins of Polytechnical Institute of New York demonstrated that EVA can be directly extruded onto substrate and over interconnected solar cells. The process may be developed further if this approach appears to be attractive for automated module production.

- The most promising new material resulting from Dow Corning's development and evaluation of low-cost silicones was a silicone/acrylic blend film material containing a UV screening agent. This film material is under evaluation at Springborn.

- University of Massachusetts (Professor Otto Vogl) has synthesized a polymerizabale UV stabilizer (vinyl tinuvin) capable of being permanently incorporated into module cover films. Sample quantities have been delivered to Springborn for film fabrication and evaluation.

- Motorola has demonstrated two low-cost approaches to applying AR coatings to module glass covers. The durability and soiling characteristics are to be determined.

- Mini-modules and full-size test panels of glass reinforced concrete (GRC) module substrates fabricated by MBAssociates are now being tested for long life performance. The MBA final report on GRC panels has been published.

- Spectrolab has assembled the design, analysis methods, and computer codes to conduct analyses and optimization studies of low-cost candidate encapsulant systems for predicting optical, thermal, electrical and structural performance.

Production Process and Equipment Area

- Copper metallization by plating has been developed successfully by both Applied Solar Energy Corporation and Motorola. Nickel is necessary to act as a barrier to prevent Cu diffusion into the Si and palladium (Pd) is necessary to form an adequate contact with the Si.

- Metallization by use of metal inks with glass frits is feasible and have shown excellent performance characteristics. The Bernd Ross Associates final report has been completed.

- Spire has a new contract for the development and construction of a pulsed electron-beam annealing (PEBA) machine to be coupled with ion implantation.

- RCA has completed work on developing a complete ion-implanted cell-processing sequence using low-cost wafers (with concomitant crystal imperfections).

- The RCA spray-on AR coating process has produced a uniform coating on both surface-etched and partially texturized cells.

- The programmable robot contract with MBAssociates covering cell interconnection and emplacement for module fabrication has been completed.

Engineering Area

- Series/parallel analysis of multi-cell failures in modules for intermediate load applications and the development of module design guidelines for fault- and hot-spot-tolerant circuit designs was summarized in a Workshop.

- An integrated, low-cost soil-buried foundation/array structure was designed and fabricated.

- Specific recommendations for module series/paralleling, materials selections and structural design and for field repair and maintenance strategies have been developed.

- Cell-reliability testing and analysis activities were summarized in two recent papers.

- Criteria and test methods for the January 1980 draft of the SERI Interim Performance Criteria Document was completed.

- Preparation and release of a new module-design requirement specification for use in the PP&E Phase III effort was accomplished.

Operations Area

- All Block III modules have now been delivered, totalling 217 kW.

- Of the eight Block IV contractors, four have delivered modules to JPL for qualification, two have opted to redesign the modules originally presented in order to lower production costs, and two are simply proceeding at a more deliberate pace than was originally scheduled.

- Quotations for Block IV production modules were received in February. Awards to individual contractors will not be made until module qualification testing has been completed.

- The second LAPSS (large-area pulsed solar simulator) facility is complete and operationally connected to the computer.

- A bimonthly module degradation audit at the JPL module test site has been initiated.

- The anomalous drop in module outputs at the JPL module test site from June 1979 through March 1980 is due to a sky-shadowing problem rather than actual module degradation. As the sun moves south during the fall, the field modules are tilted to higher angles. A loss of indirect sky illumination results in decreased module output.

Proceedings Summary

1. Recent test results of the Hemlock polysilicon process indicate a high probability of achieving a silicon price of less than \$21/kg. This process could have a very high probability of providing early availability of quality polysilicon (if funded).

2. 150 kg of Cz ingots have been grown from a single crucible (6- to 15-cm-dia ingots). Current practice is to grow a single 18 to 20 kg, 10-cm-dia ingot per crucible. The crucible is destroyed during cycle cooldown.

3. Larger wafers, of 15-cm diameter, would be slightly cheaper per square meter (approximately 5%) than 10-cm-dia wafers (assuming \$14/kg silicon). Using \$30/kg silicon, the wafer costs would be about equal.

4. If Cz growth and wafering technologies were frozen at today's level of achievement and large-scale production initiated; it is estimated that wafer-only prices would range from \$1.05/W_p to \$1.75/W_p (assuming a polysilicon price range of \$14/kg to \$100/kg). The price of wafers today ranges from \$5/W_p to \$12/W_p with deliveries in 10 to 35 weeks. An estimated module price by freezing of today's module technology is not available.

5. The estimated 1986 price of modules in which advanced Cz and improved wafering technologies are used would range from \$0.70/W_p to \$0.83/W_p using various ingot growth and wafering techniques and assuming other module price allocation goals were met.

6. Three cell- and module-manufacturing process sequences (for 1986 mass production) have been developed by three contractors that result in module price estimates (by the contractors) ranging from \$0.62/W_p to \$0.76/W_p. They assumed that polysilicon and sheet costs were within allocations.

7. A successful day-and-a-half PV module circuit design (electrical interactions of cells, modules, and arrays) workshop was held just before the PIM by the LSA Engineering Area.

8. Significant cost-reduction methods in array structures and footings have been developed.

9. Block IV module design and test schedules have slipped several months with only four of 10 prototype modules delivered to JPL. Two of these four modules show physical degradation in early environmental testing. Completion of module qualification testing is projected within six months.

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 role 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 the analytical capabilities and performing or participating in the trade-off studies required.

A detailed analysis of Project probability of attaining Technical Readiness in 1982, given three different budget scenarios, was completed. For purposes of this study several simplifying assumptions were made. The method has been under development for several months and proved quite useful in illuminating the relative contributions to Project success of various technological options. No attempt was made in this study to arrive at an optimum mix of options. Furthermore, other degrees of freedom, such as schedule slip or diluting the funding over more options, were not examined. A top-priority effort is in progress to develop a more rigorous and generalized method requiring fewer simplifying assumptions.

The Near-Term Cost Reduction contract results review is continuing in cooperation with the Technology Development and PP&E Areas of the Project. Interim reviews have been completed for five contracts, with two more in progress.

A more versatile version of IPEG is under development. This version will allow the user to run SAMIS to calculate IPEG coefficients precisely for a particular process or sequence. The user can then use IPEG to perform parametric studies of that process. This will circumvent some of the difficulties inherent in using SAMIS to optimize individual process steps. This version will be designated IPEG 4.

A major required-price analysis of ingot technology was conducted in cooperation with the Large-Area Sheet Task and the Production Process and Equipment Area. The results were presented at the 15th Project Integration Meeting and are discussed in the Proceedings of the meeting (pp. 313-320 of this document).

A baseline case has been generated to test the residential version of the Lifetime, Cost and Performance model. The residential version was presented at the 15th PIM and is discussed in the Proceedings (pp. 323-328).

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

INTRODUCTION

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

TECHNICAL GOALS, ORGANIZATION, AND COORDINATION

Solar cells are 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 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 trade-offs 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 Table 1.

Table 1. Silicon Material Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SEMICONDUCTOR-GRADE SILICON PROCESSES	
Battelle Columbus Laboratories Columbus OH JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized bed reactor
Energy Materials Corp. Harvard MA JPL Contract No. 955269 (Near-Term Cost-Reduction contract)	Gaseous melt replenishment system
Hemlock Semiconductor Corp. Hemlock MI JPL Contract No. 955533	Dichlorosilane CVD process for silicon production
Union Carbide Corp. Tonawanda NY JPL Contract No. 954334	Silane/Si process
SOLAR-CELL-GRADE SILICON PROCESSES	
AeroChem Research Laboratories Princeton NJ JPL Contract No. 955491	Silicon halide/alkali metal flames
SRI International Menlo Park CA JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corp. Trafford PA JPL Contract No. 954589	Reduction of $SiCl_4$ by Na in arc heater reactor
IMPURITY STUDIES	
Lawrence Livermore Labs Livermore CA NASA Defense Purchase Request No. WO-8626	Impurity concentration measurements by neutron activation analysis
Sah, C.T., Associates Urbana IL JPL Contract No. 954685	Effects of impurities on solar cell performance

Table 1. Silicon Material Task Contractors
(Continued)

CONTRACTOR	TECHNOLOGY AREA
IMPURITY STUDIES	
Solarex Corp. Rockville MD JPL Contract No. 955307	Effects of impurities on solar cell performance
Westinghouse R&D Center Pittsburgh PA JPL Contract No. 954331	Definition of purity requirements
SUPPORTING STUDIES	
Lamar University Beaumont TX JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge MA JPL Contract No. 955382	Hydrochlorination of metal-lurgical-grade silicon.

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

Four processes for producing Si equal to or approaching semiconductor-grade Si in composition or performance are under development by Battelle Columbus Laboratories, Energy Materials Corp., Hemlock Semiconductor Corp., and Union Carbide Corp.

Battelle Columbus Laboratories completed construction and installation of the Si process development unit (PDU) by substituting a flash-type vaporizer for the one originally intended after a variety of problems were encountered with the latter. After further delays due to operational problems, the first test of the PDU was made on April 14. Although the test was terminated early because some plugging occurred in the system, the PDU was operated for half an hour.

In support studies on the removal of zinc (Zn) from product Si, Battelle found that in the Si granule the Zn is highly segregated and that its physical state is probably the result of occlusion of Zn mist droplets from the Zn feeder. Concentration of Zn ranged from 100 to 3000 ppm. A quantitative relationship, based on experimental data, was obtained that permits the calculation of the ratio of Zn concentration after treatment of particles at elevated temperatures to initial Zn concentration for different particle seed-to-coating ratios. Using this relationship, calculations indicate that Zn removal from fluidized bed reactor (FBR) particles by high-temperature vaporization does not appear practicable because of the excessive time required. It may be possible to limit the Zn concentration to acceptable values by preventing Zn droplet formation in the PDU operation. Previous bench-scale tests indicated that the Zn content could be kept below 100 ppm in this way.

Under a Near-Term Cost Reduction contract, Energy Materials Corp. is developing an Si melt replenishment system for continuous Czochralski crystal growth. The installation of the system was completed more than four months later than projected in the program plan; the delay was caused primarily by late delivery of the reactor chamber. An attempt to make a test was thwarted by a hydrogen leak.

In the effort by Hemlock Semiconductor Corp. in developing a process for making Si from dichlorosilane (SiH_2Cl_2) by a modification of the Siemens process, characterization of an experimental reactor continued with tests using SiH_2Cl_2 feed and trichlorosilane ($SiHCl_3$) feed. For the same reactor operation conditions, silicon conversion efficiency and deposition rate for SiH_2Cl_2 are twice those for $SiHCl_3$. Energy consumption data were calculated for all experiments, and the lowest value obtained for SiH_2Cl_2 was 89 kWh/kg Si. The design of the reactor has not been optimized; in an optimized production-sized reactor, even lower energy consumption should be obtained. As a comparison, the electrical usage in the deposition of semiconductor-grade Si by the commercial Siemens process, which uses $SiHCl_3$, is about 375 kWh/kg Si.

Construction and checkout of a laboratory-scale chlorosilane rearranger unit for investigating the preparation of SiH_2Cl_2 were completed.

Union Carbide Corp. completed installation and checkout of the free-space reactor PDU and proceeded into testing. In one test, the PDU was operated continuously for 24 hours, producing more than 45 kg of Si powder at a yield of more than 99%.

Effort continued on UCC's EPSDU. General facility requirements, including site design and service utility needs, were defined and environmental permit applications were submitted to appropriate municipal agencies. Detailed specifications were written and vendor quotations received for the major portion of all process and waste-treatment equipment associated with producing high-purity silane (SiH_4). Several design modifications were made to improve on operability and economics, including a simplified hydrochlorination reactor feed system and a much simpler waste-treatment system. Equipment procurement and fabrication were initiated.

A subcontract was signed with Hamco for the design and development of an Si powder consolidation process for the EPSDU, and work started on March 1. This process is based on melting the powder, dropping molten Si shot through the bottom of a crucible, and solidifying them in a cooling tower.

In the area of FBR development, all fixed-bed experiments were completed on schedule, and a draft report covering the work was written. This work was performed to obtain data for designing the FBR. Particle separation tests were also completed as scheduled, and test results showed that large particles can be selectively removed from a fluidized bed.

Development of Processes for Producing Solar-Cell-Grade Silicon

Three contracts to produce solar-cell-grade Si are active: with AeroChem Research Laboratories (an effort previously categorized as a supporting study), SRI International, and Westinghouse Electric Corp.

AeroChem's process is based on high-temperature reactions of silicon halide and alkali metals. Difficulties were encountered in collecting Si product in crucibles made of quartz, low-density graphite, alumina, and tantalum (Ta), but a satisfactory graphite material, POCO DFPI, was found. Silicon separation/collection efficiencies over 80% were achieved, and 30- to 80-g samples of consolidated Si were collected in 15-min tests. Initial analyses show less than 10 ppm Na to be present in the product. A new, enlarged sodium (Na) delivery system, which will allow production of 0.5-kg batches of Si in one-hour runs, was installed. Attempts to operate this system were unsuccessful because of Na leaks.

It was decided not to extend the contract with SRI International for the development of a process for producing Si by the Na reduction of silicon tetrafluoride (SiF_4). This decision was based primarily on the fact that insufficient funding is available for the considerable effort needed in the areas of melt separation, establishing product purity, and engineering before the practicality of the process could be considered demonstrated. The draft final report is being prepared.

Effort by Westinghouse on development of an arc-heater process for producing solar-cell-grade silicon was confined to preparation of the draft final report.

Impurity Studies

C. T. Sah Associates investigated the effects on silicon solar cell performance of Zn, which is a major residue impurity in Si prepared by the Zn vapor reduction of silicon tetrachloride ($SiCl_4$) process under development at Battelle. The recombination rates of electrons and holes at the two Zn acceptor levels in Si were obtained by extrapolation of published high-electric-field data and new zero-field measurements using the voltage-stimulated capacitance (VSCAP) method. These data were used to compute the AM1 efficiency of Si solar cells containing Zn recombination centers. For a 17% AM1 efficiency (no surface reflection loss), the Zn concentration in the base must be less than about $4x10^{11}$Zn/cm^3 in an $n^+/p/p^+$ cell and $7x10^{11}$ Zn/cm^3 in a $p^+/n/n^+$ cell for $5x10^{14}$ atoms/cm^3 base doping and 250 μm cell thickness. For bare-surface test cells, a 9.5% AM1 efficiency corresponds to about $2x10^{13}$Zn cm^3 in the base. These results are described in Technical Report No. 3, which has been submitted for approval and is scheduled for distribution in May. Comparison with Si cells on web ribbons grown from Zn-reduced Si will be made to verify the computed results.

In Solarex Corporation's study of the effects of impurities on solar cell performance, work was curtailed on the processing of experimental, control, and monitor lots because of an impending cost overrun. Only 32 of the 45 impurity-containing lots, and their associated control and monitor cells, were fabricated and analyzed. In this reporting period, results on these lots agreed with those obtained during the previous period, i.e., cells grouped into two background resistivity ranges; greater effect of incorporated impurity was generally observed in the current parameter rather than voltage, and there was no evidence of cross-contamination between lots. The results agree with those obtained by Westinghouse, i.e., certain impurities such as titanium (Ti), tantalum (Ta), and vanadium (V) are particularly detrimental even in small concentrations, while cell performance is much less affected by larger concentrations of impurities such as copper (Cu), carbon (C), calcium (Ca), chromium (Cr), iron (Fe), and nickel (Ni).

A final report on this contract was written and reviewed by JPL, and its distribution is expected during the next reporting period.

Westinghouse R&D Center completed the Phase III effort on their program to define the effects of impurities, various thermochemical processes, and impurity-process interactions on the performance of Si solar cells. Summaries of the results and conclusions reached to date in this program, the topics of Phase III being thermochemical processing (including gettering, synergic behavior, and impurity complexing behavior), performance reduction in n- and p-base cells by impurities, non-uniform impurity distributions in conventional Cz ingots and large-area ribbons, and preliminary investigations of aging effects of impurities, follow:

Overall the data show that bulk lifetime reduction by impurities in both n- and p-silicon are the dominant cause of efficiency reduction in silicon solar cells. By use of a mathematical model and impurity concentration data, the performance of solar cells fabricated from impure single-crystal wafers can be projected. Assuming that some form of melt replenishment will be employed to transform polycrystalline silicon to sheet or wafers by means of crystal growth, it is estimated that no more than $\simeq$100 ppma of the more benign impurities will be tolerable in solar-grade feedstocks. For impurities such as Ti or V, which severely degrade cell efficiency, an upper limit on feedstock concentration is about 1 ppma if cell efficiency is to remain within 90% of that of uncontaminated devices. If higher efficiencies are required the impurity tolerance must be reduced further.

Fast-diffusing species like Fe or Cr can be neutralized by phosphorus oxychloride ($POCl_3$) or hydrogen chloride (HCl) gettering at temperatures between 900° and 1000°C. The efficiency of Ti-doped cells can be improved by up to 1.5% (absolute) after a 5-h treatment at 1100°C. Cells contaminated by molybdenum (Mo) show no improvement in performance even after intensive gettering. Collateral results of these experiments are that the data suggest little change in extrapolated cell performance after 20 years for Mo- or Ti-doped devices but that Cr-doped cells may well undergo adverse aging effects. There is no evidence for added device performance degradation due to non-uniform distributions of impurities like Fe, Ti, Cu, or Mn in 7.5-cm-dia Cz crystals or 4-cm-wide silicon webs. Correlations were found between cell performance reduction, impurity segregation, and liquid diffusivities according to the position of a given impurity in the periodic table; this information can be used to estimate impurity effects where hard data are unavailable.

Supporting Studies

Lamar University completed a preliminary economic analysis of the Battelle Columbus Laboratories process for producing Si by the Zn reduction of $SiCl_4$ for Case B (one Si deposition reactor and two Zn electrolysis cells). On the basis of a preliminary process design of a plant for producing 1000 MT/yr of Si, the fixed capital investment is $14.35 million (1980 $), and Si product cost without profit is $11.08/kg. Cost-sensitivity analysis indicates that the product cost is influenced most by plant investment and least by labor. A sales price of $14/kg corresponds to a 14% DCF rate of return on investment after taxes; at 20% ROI, the price is $17.19/kg.

Chemical engineering analysis of the Hemlock Semiconductor Corp. process for Si production was started.

Analyses of process system properties were continued for important chemical materials involved in the processes under development for production of silicon. Major activities centered on physical, thermodynamic, and transport data for Si. Specific property data were reported for vapor pressure, heat of vaporization, heat of sublimation, liquid heat capacity, and solid heat capacity as functions of temperature.

Massachusetts Institute of Technology is conducting a program, supportive of the UCC SiH_4-to-Si process development, to study the hydrochlorination of metallurgical-grade Si to $SiHCl_3$, the feedstock for the chlorosilane disproportionation to SiH_4. Experiments were done to study the effect of Cu catalyst on the hydrochlorination rate as functions of reaction temperature, pressure, and reactant ratio, for the type of Cu catalyst selected for the UCC EPSDU. After an initial stage of reaction during which no catalyst activity was observed, the rate of the hydrochlorination reaction was found to increase significantly compared to the rate with no Cu present. It was also found that formation of dichlorosilane in the presence of

Cu increases by 200% to 300% over the amount produced in the absence of Cu.

JPL in-house studies proceeded in the areas of the FBR, continuous-flow pyrolyzer (CFP), modeling of Si particle growth, and conversion of SiH_4 to molten Si.

Several tests were made in a 2-in.-dia FBR, the longest being for 132 minutes at 700°C, 10 times minimum fluidization velocity, and a feed of 7 mole % SiH_4 in hydrogen. Results were excellent: no clogging of the bed occurred, 96% of the SiH_4 was converted to Si, and less than 1% of the Si produced was in the form of dust. To investigate the extent of Si dust formation in SiH_4 pyrolysis, a series of experiments using a 1-in.-dia FBR was conducted. In these tests, over the range of 1 to 15 mole % SiH_4 in hydrogen at 600° to 700°C, less than 2% of the Si produced was in the form of dust. A considerable amount of bed agglomeration occurred in these tests when the velocicy was less than six times the minimum fluidization velocity (MFV). Above eight times MFV, agglomeration did not occur. The Si deposit was dense when deposited at temperatures above 650°C.

In the area of the CFP, a series of eight SiH_4 pyrolysis tests was made to explore the effects of SiH_4 mass flow rate, concentration, and temperature on Si particle growth rate and on conversion efficiency in a compact reaction zone (18-cm dia, 25 cm long). Temperature ranged from 580 to 840°C, pressure from 1 to 8 atm, and SiH_4 flow rate from 0.02 to 2.5 kg/h. Notably, 100% conversion of SiH_4 to Si was obtained at 800°C and 2.5 kg/h flow rate. At 600°C and 8 atm, relatively large primary particles (average diameter of 0.6 μm) were produced, these particles being the largest obtained to date in FSR Si production, and preliminary SEM examination shows that coagulation and CVD condensation processes occurred simultaneously.

The CFP was modified by installing an automatic scraper for enabling long-duration operation without particle accumulation.

A new in-house effort was begun in December 1979 to study the conversion of SiH_4 to molten Si in a single-step process. The first experiments will be aimed at producing molten Si in graphite vessels coated with alkaline fluorides or alkaline earth fluorides. Design and procurement were completed, and installation of equipment is under way.

Large-Area Silicon Sheet Task

INTRODUCTION

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

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

Growth of silicon crystalline material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth (WEB), low-angle ribbon growth (LAR), vacuum die-casting growth, etc., are possible candidates for the growing of solar cell material. The growing of large ingots requiring very little manpower and machinery would also appear plausible.

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

ORGANIZATION AND COORDINATION

When the LSA Project was initiated (January 1975) a number of methods potentially suitable for growing silicon crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now funded. After a period of accelerated development, these methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured. The Large-Area Silicon Sheet Task effort is organized into four phases: research and development of sheet- growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

Large-Area Silicon Sheet Contracts

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

Table 2. Large-Area Silicon Sheet Task Contractors

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

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

CONTRACTOR	TECHNOLOGY AREA
INGOT TECHNOLOGY	
Hamco Corporation Rochester NY JPL Contract No. 954888	Advanced Cz growth
P. R. Hoffman Co. Carlisle PA JPL Contract No. 955563	MBS wafering
Siltec Corporation Menlo Park CA JPL Contract No. 955282	ID wafering
Siltec Corporation Menlo Park CA JPL Contract No. 954886	Advanced Cz growth
DIE AND CONTAINER MATERIALS STUDIES	
University of Missouri Rolla Columbia MO JPL Contract No. 955415	Partial pressures of reactant gases
MATERIAL EVALUATION	
Applied Solar Energy Corp. (Formerly Optical Coating Laboratory) City of Industry CA JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca NY JPL Contract No. 954852	Characterization--Si properties
Charles Evans and Associates San Mateo, CA JPL Contract No. LK-694028	Technique for impurity and surface analysis
Spectrolab Sylmar CA JPL Contract No. 955055	Cell fabrication and evaluation

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

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

TECHNICAL BACKGROUND

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

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

Shaped-Ribbon Technology: EFG Method--Mobil-Tyco Solar Energy Corp. The EFG technique is based on feeding molten silicon through a slotted die. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material that is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 30 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 analysis, characterication of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

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

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

Ingot Technology: Heat Exchanger Method (HEM)--Crystal Systems. The Schmid-Vicchnicki technique (heat exchanger method) has been developed to grow large single-crystal sapphire. Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This obviates motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchange ingot casting method can be applied to the growth of large shaped silicon crystals (12-in.-cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

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

Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Hamco will demonstrate the growth of 150 kg of single-crystal material using only one crucible by periodic melt replenishment.

Ingot Technology: Fixed Abrasive Sawing Technique (FAST) --Crystal Systems; Inner Diameter (ID) Sawing--Silicon Technology and Siltec. Today most silicon is sliced into wafers with an inside-diameter saw, one wafer at a time being cut from the crystal. Advanced efforts in this area are continuing. The multiwire slicing operation employs reciprocating blade head motion with a fixed workpiece. Multiwire slicing uses 0.005-in. steel wires surrounded by a 0.0015-in. copper sheet, which is impregnated with diamond as an abrasive.

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

Material Evaluation--Applied Solar Energy Corp. (ASEC), Spectrolab, UCLA, Materials Research, Inc., Cornell University and Charles Evans and Associates. Proper assessment of potential low-cost silicon-sheet materials requires the fabrication and testing of solar cells using reproducible and reliable processes and standardized measurement techniques. Wide variations exist, however, in the capability of sheet-growth organizations to fabricate and evaluate photovoltaic devices. It therefore is logical and essential that the various forms of low-cost silicon sheet be impartially evaluated in solar-cell manufacturing environments with well-established techniques and standards. Two solar-cell manufacturers, ASEC and Spectrolab, have been retained to satisfy this need.

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

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

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

SUMMARY OF PROGRESS

Shaped-Ribbon Technology: Arco Solar (Vacuum Casting). SRI is a subcontractor to Arco Solar for silicon casting. A fused-salt liquid-barrier coating consisting of a sodium silicate-sodium fluoride mixture is used to prevent any silicon-graphite reaction. Using coated dies, several silicon discs 30 x 30 x 1 mm have been cast. Water cracking remains a problem. Mobil Tyco (EFG): 10-cm ribbon growth rate is now commonly 4 cm/min. with no stress and no buckling. A three-ribbon simultaneous-growth demonstration was completed successfully. Studies of material quality and purity have continued. EFG cells of 14 cm^2 with efficiencies ~12% have been processed. Westinghouse (WEB): Simultaneous melt replenishment and web growth have been demonstrated for a one-day growth cycle, which includes 17 h of web growth and 7 h for cleaning, loading, start-up and cool-down. Improvements in the thermal gradients within the susceptor, crucible and melt system permit growth under a wide range of conditions.

Supported Film: Honeywell (SOC): SCIM 1 has been made operational and has coated slotted substrates, 2 in. wide, with a very non-uniform thickness of silicon at 0.05 cm/sec. Testing of SCIM 2 has begun. Cell efficiencies have stagnated at 10%.

Ingot Technology: Crystal Systems (HEM): A 10-kg ingot (17 x 17 x 14.6 cm) was cast in a welded flat-plate crucible. The largest and fastest-grown ingot to date is a 21 kg ingot (34 x 34 x 10 cm) grown at a rate of 2 kg/h. The run also demonstrated that the solidification rate increases with increased crucible size. Crystal Systems (FAST): Several runs using both electroplated wire and in-house-impregnated wire were completed in the continuing effort toward wire development. One of the runs using electroplated wire sliced a 4-in. ingot with 90% yield at a slicing rate of 2.8 mils/min. Hamco (Cz growth): Hamco has successfully grown 150 kg of silicon from a single crucible using sequential melt replenishment. Each of the six ingots was approximately 6 in. in diameter, weighing 25 kg, at a throughput rate of 1.5 kg/h. Siltec (Cz): Ingots ~30 kg in weight and 150 mm in diameter were produced using solid-rod fuel/continuous liquid-feed (CLF) Czochralski growth. Siltec (ID Wafering): Ingot slicing of 10-cm-dia wafers continued with etched blade cores. The slipper mounting arrangement for the blade deflection control system on the 100-mm-dia ingot slices has been redesigned and is being fabricated. P. R. Hoffman Co. (Div. Norlin Industries): P. R. Hoffman Co. is now under contract to perform a series of multiple-blade-sawing (MBS) runs. These runs will permit evaluation of this new contractor and comparison of performance capabilities of Varian 686, Meyer-Burger and Hoffman MBS free-abrasive saws. Two runs have been successfully completed and results were presented at the April 1 Task II Ingot and Wafering Technology Critical Review.

Material Evaluation: Applied Solar Energy: Figure 1 summarizes the average efficiencies of silicon sheet materials processed by ASEC.

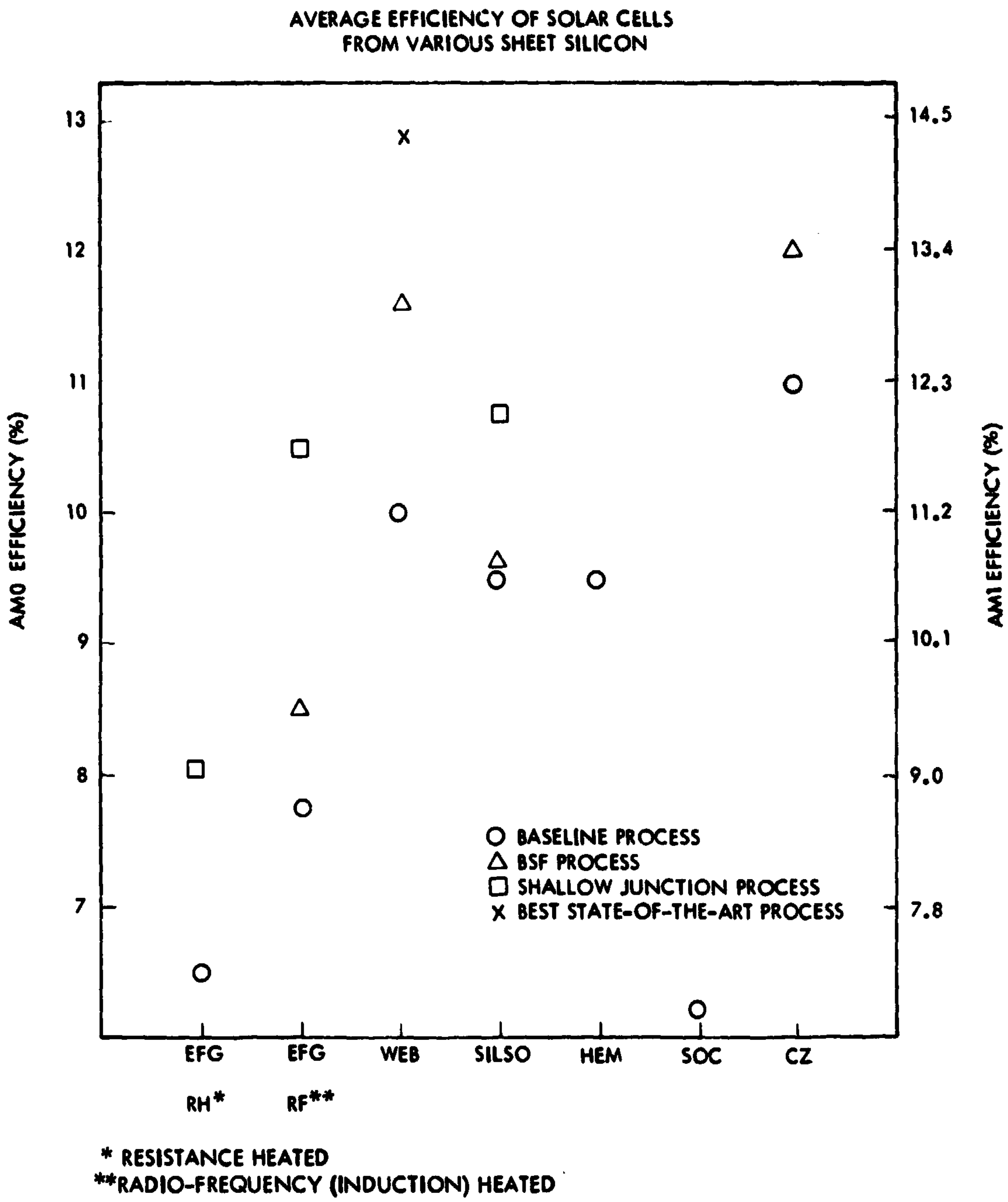


Figure 1. Applied Solar Energy Corp.'s Material Evaluation

Cornell University: Large-grain EFG ribbon was found to have a defect structure similar to that of a small-grain EFG, i.e., the predominant defects are coherent twins and microtwins, incoherent twins in the (112) planes and dislocations. Initial investigation of web material indicate that the predominant defects are coherent twin boundaries in the mid-plane of the ribbon and dislocations. Spectrolab: Table 3 summarizes the results obtained for various sheet materials. UCLA: The multiwavelength analyzer (MWA) technique was unable to detect any change in the diffusion lengths of samples under stress due to high initial diffusion lengths. University of Missouri Rolla: Measurements of partial pressures of oxygen were performed in the growth facilities at Mobil Tyco.

Table 3. Spectrolab's Material Evaluation

I-V DATA FOR HIGHEST EFFICIENCY CELLS IN EACH MATERIAL

MATERIAL	S/N	I_{sc}MA	V_{oc}MV	P_{max}MW	FF	%	Remarks
RTR	5	95	559	39.1	.74	7.2	Baseline, RTR-2
EFG(RH)	D	116	537	45.5	.73	8.4	Baseline, 184-36
EFG(RF)	46	125	567	53.0	.75	9.8	Baseline
WACKER	4	134	554	57.3	.77	10.6	Baseline
HEM	14	135	597	62.1	.77	11.4	BSF, X-tal #857
Web	2	149	584	65.3	.75	12.0	BSF, strip Re 25-23
Hamco	9-T-2	147	602	68.1	.77	12.6	BSF, Top, X-tal #9
Control	3	158	607	73.5	.77	13.6	T & BSF, run WO-1

JPL In-House Activities: Laboratory facilities for small-area (4 cm^2) solar cells are complete and a baseline process has been established for Cz material. Work is continuing on HEM material. A silicon disc fabricated between boron nitride die plates by SRI was submitted to the Materials Fabrication Section and materiallography revealed second-phase precipitates decorating grain boundaries and dislocation clusters. Failure of high-carbon steel blades in water-based slurry systems has been ascribed to stress corrosion.

Encapsulation Task

INTRODUCTION

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

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

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

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

(1) Materials and Processes Development. This effort includes all of the work necessary to develop, demonstrate, and qualify one 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 analyses and testing to develop optimized module designs.

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

SUMMARY OF PROGRESS

Materials and Process Development

Materials for the deliverable electrostatically bonded (ESB) modules of cells with preformed contacts have been selected by Spire Corp. The contact mesh selected is an electroformed silver mesh with the following characteristics:

Line width: 73 μm (2.87 mils)
Thickness: 7 μm (0.3 mil)
Line spacing: 0.13cm (20 lines/width)
Open area: 88.8%

Tests were run to observe the effects of bonding a wire mesh grid to a cell with a very thin premetallization pattern already applied. The premetallization pattern consisted of 10- m lines of 2000 A-thick Ti, spaced at 0.1 cm (98% transparent). These were intended to enhance ohmic interface of the mesh to the cell, rather than to serve as a bulk current conductor. High curve-fill factors were repeatedly obtained in five experiments, although the best results of wire mesh on bare cells are better than those achieved with these cells. This course will be pursued further if repeatability is not found with mesh bonds to bare cells.

Tests have been started to determine if an oxide removal step for the silver mesh before bonding will decrease contact resistance. Initial tests were done with a short dip in dilute sulfuric acid. This has been replaced by a commercial silver tarnish-removing solution. Initial tests have been encouraging but not conclusive. Tests will continue as soon as new bare cells have been manufactured.

A paper detailing the work done with mesh contacts as of the beginning of Phase III of this contract has been published.*

Four small modules, approximately 5 x 12 in., each containing three 3-in. dia cells, were prepared by Professor Paul Bruins of Polytechnic Institute of New York to demonstrate semiautomatic module assembly. Two glass superstrates and two Masonite substrates were carried by a conveyor belt, with cross-linked ethylene/vinyl acetate (EVA) pottant being extruded directly onto the assembly. The results were mixed: one superstrate module and one substrate module were produced in good condition with only a few air bubbles. Cell cracks and bubble entrapment were noted on the other two modules.

On the Motorola sodium silicate AR coating contract (near-term cost-reduction contract), it has been found experimentally that better AR films can be made with very dilute solutions. This discovery was

*Geoffrey A. Landis and Peter Younger, "A Low-Cost Solar-Cell Front Contact Using Trapped Silver Mesh and Electrostatic Bonding," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. CHMT-2, No. 3, September 1979.

completely unexpected. The program started with 50% solutions and now good films are being made with 8% and even 1 to 2% solutions. This means a lower cost during mass production. Steps toward producing 12 x 16-in. samples are being made.

In the Motorola acid-etch contract work it has been found that the temperature of the acid bath had the largest effect on the final film quality. Solutions at 45°, 55° and 65°F took 120 min, 60 min and 22 min to form. Preparation and optical characterization of small samples has begun for eventual delivery to JPL.

The MBAssociates contract on glass-fiber-reinforced concrete (GRC) has ended and the final report has been distributed.

Fifteen minimodules with GRC substrates have been ordered from MBAssociates for evaluation in the JPL minimodule development program. Also, 20 GRC substrates have been ordered for possible future use.

Three module designs including a wood substrate, a metal substrate and a glass superstrate have been selected by Spectrolab for Phase I analytical modeling. The designs have been approved.

Development has been completed by Spectrolab/Hughes of all the analytical models (optical, thermal, structural, and electrical) needed to predict module performance analytically and, ultimately, the most cost-effective module design. The computer models are now being run to determine the sensitivity relationships between predicted performances and the accuracy required of input material properties. Properties of many of the advanced encapsulation materials are not known. The sensitivity analysis will dictate the required accuracy (and significance) of input material properties, and therefore whether estimates will suffice, or precise properties measurement will be necessary.

Thermal analysis runs have already indicated that the back surface of modules should be white, to minimize absorption of reflected solar radiation and to maximize the emittance of infrared radiation.

Vinyl tinuvin (10 g) was synthesized by the University of Massachusetts (Professor Otto Vogl) as scheduled and delivered to Springborn Laboratories for incorporation into Dow Corning silicone/acrylic polymer film as a UV screening agent.

Springborn has demonstrated that the Craneglas non-woven glass mat can be positioned above the top surface of solar cells in a module. This positioning facilitates air removal during lamination, and (judging by I-V measurements) does not affect cell power output. This approach was studied because it is seriously being considered that EVA will be co-extruded with the Craneglas to yield a non-blocking composite that can be rolled and unrolled. The EVA/Craneglas composite will simply be cut to size and used as is in vacuum lamination. As stated, the desirable features of this composite are that it makes a non-blocking EVA roll and that its use facilitates air removal from large-area modules during lamination.

Springborn is setting up the necessary laboratory equipment to produce the Dow Corning outer cover silicone/acrylic film, and should also be able soon to incorporate into this material the UV screening agents made by Vogl's group at the University of Massachusetts.

Wood substrate modules with a Korad outer cover were coated by GE with their recently developed UV-stable abrasion-resistant coating. First observations by Springborn are extremely encouraging, relative to the quality of the surface coating and to the associated surfacing process. GE is testing the coating material in their own weatherometer, and they report that they are up to an equivalent of five years' outdoor exposure with no evidence of deterioration.

The Dow Corning contract on silicone-encapsulant systems ended on December 31, 1979. The final report draft has been received and reviewed.

A candidate primer system that can be physically compounded with EVA to yield a self-priming EVA was developed by Dr. Edwin P. Plueddemann. This will now be evaluated by Springborn.

The Illinois Tool Works is currently depositing candidate antireflective and low-soiling surfacing materials on soda-lime glass by ion plating. These coatings will be evaluated experimentally. Experimental deposition of Ni, Cu, and Al metallization on solar cells is also under way.

Life Prediction and Material Degradation

One year of outdoor weathering was completed in-house on several types of aluminized polymer films and Al foil/polymer film composites. A trilaminate composite of 0.5 mil polyester/1 mil Al/0.5 mil polyester showed degradation in the polyester facing the sun while the side away from the sun remained unchanged. This material is being used extensively as a back cover on experimental minimodules now being readied for outdoor exposure. Trilaminates consisting of polyester/vapor deposited Al/polyvinyl chloride appear to be unaffected except for some curling at the edges of the samples. Trilaminates based on polyester/vapor deposited Al/paper show severe degradation with loss of the paper and erosion of the vapor-deposited Al.

The decision has been made in-house to load 12 x 16-in. minimodules electrically during outdoor weathering. The loads will be 10-ohm resistors with small incandescent lights in parallel to give a positive indication of electrical functioning of each minimodule during field exposure. Small two-cell submodules will not be loaded.

Approximately 90% of the required minimodules and 70% of the required submodules have been received and initial I-V curves taken.

Approximately 480 minimodules and submodules will be tested in the program.

Field studies by Rockwell Science Center using atmospheric corrosion monitors (ACM) installed at the Mead NB site show that moisture condensation probability, and ionic conduction at the corroding surface, control corrosion rates. Protection of the corroding suface by encapsulants, i.e., prevention of moisture condensation, was clearly shown by the ACM recordings maintained on encapsulated units during the August-January exposure period; for unprotected units, changes in corrosion rates chould be correlated with changes in climatic conditions.

Laboratory studies aimed at clarifying corrosion mechanisms using a newly designed simulator are in progress. Results to date show that the macroscopic corrosion mechanisms that occur at Mead can be reproduced in the simulator. UV radiation causes a significant increase in corrosion rates suggesting formation of photodegradation encapsulant products that increase ionic conduction.

Preliminary results of a series of in-house analytical studies of the effects of weathering on RTV silicone rubber pottants used in Mead modules have been obtained. After one year of exposure at Mead, Sylgard 184 and RTV-615 pottant materials showed no significant changes in several material properties including crosslink density, tensile modulus of elasticity, gel fraction, and equilibrium swelling. Modules that have been exposed for two years at Mead are to be obtained and some analyses performed on the two pottants. In addition, a new phase of investigation is being planned to detect any precursory chemical changes in the weathered pottants.

Scheduled in-house testing of 10 Sensor Technology Block II modules to verify the Battelle test design for predicting the service life of the Mead solar array has been postponed because of malfunction of the test equipment refrigeration system. Anticipated start time is mid-May. Test parameters are temperature cycling between -15°C and +95°C, relative humidity of 85% (at 30°C), and SO_2 concentration of 1.0 ppm. Predicted life (to 50% of initial power output) is 4.9 months.

A contract to develop photodegradation rate models was begun by the University of Toronto (Professor James Guillet).

Work has contimued in-house in performing failure analyses of Block III and Block IV modules exhibiting material degradation. Minor degradation phenomena investigated include discoloration of RTV silicone rubber pottant, softening and flowing of edge sealant during temperature cycling (probably due to improper catalysis) and corrosion of interconnects.

The scope of in-house work for thermomechanical modeling planned for the remainder of FY80 can be subdivided into two areas: compatibility of materials and failure modes.

The compatibility area is concerned with the stress distribution in a module with a layered configuration of encapsulants in which the cells are embedded. The stress distribution is a function of the material properties of the merged elements in the module and the geometric configuration including the arrangement of the cells. Therefore, it is logical to consider the properties of the materials as parameters for a specific configuration forming a general guideline regarding the stresses in the bonding as a function of the materials used.

The failure modes to be investigated include fracture failure (delamination) of encapsulation materials, cell cracking and damage to cells and encapsulants from localized hot spots caused by back-biased cells.

Research by Case Western University for the period was on characterizing physical changes in poly-n-butyl acrylate (PnBA) induced by UV degradation. These include determination of changes in molecular weight. Data show that both scission and crosslinking occurs.

The UV source at the University will be calibrated by JPL to make possible quantitative analyses of the physical-property studies at Case and to correlate them with complementary photochemical analyses carried out at JPL.

Photodegradation studies are continuing in-house on PnBA and polymethyl methacrylate (PMMA). All photolysis products have been identified and the rate for formation of several products have been measured.

A controlled-environment accelerated-UV test chamber, designed and contracted in-house, has completed 1000 hours of operation without problems or stoppages. Lamp output degraded by 7%. Temperature was controlled to $\pm$ 2°C.

The problem of predicting unbonding of a (thin) polymer layer from a substrate under long-term use from short-term laboratory tests is being examined at the California Institute of Technology. A critical role is played by the viscoelastic properties of the polymer under cyclic stresses induced by the environment, such as those of temperature and moisture. Changes in polymer mechanical properties resulting from UV radiation can readily be incorporated. Accordingly, for stress and failure analysis purposes the mechanical and thermal properties as well as response to water content of a model polymer (polyvinyl acetate) have now been measured.

The viscoelastic analysis for a two-layer system has been formulated. At present an evaluation for the realistic material behavior is being made. Simultaneously, the experimental apparatus for verifying the stress and deformation analysis is being designed. It is expected that during the coming month the stress analysis portion will be essentially completed and the construction of the apparatus begun.

PRODUCTION PROCESS AND EQUIPMENT AREA

AREA OBJECTIVES

As is shown in Figures 2 and 3, the first two phases of the PP&E Area objectives have been accomplished, but Phases I and II are not entirely inactive. Additional development is continuing with processes that will further reduce the cost of producing solar modules. If sufficient cost reduction occurs, other areas of the LSA Project will benefit.

SUMMARY OF PROGRESS

Sufficient development of processes has occurred in Phase II to allow cost-effective manufacturing of solar modules by more than one sequence. With Phase II accomplished, Phase III is beginning. Proposals have been received and are being evaluated for equipment development contracts.

Process Sequence Development

RCA has completed work on developing a complete ion-implanted photovoltaic cell-processing sequence using low-cost wafers (with concomitant crystal imperfections). They concluded that ion-implanted junctions in this low-cost material do not have sufficient surface concentrations for use with state-of-the-art thick-film silver (Ag) contacts. RCA has shifted emphasis from ion implantations back to gaseous diffusion.

The thin-cell (100 μm) work at Motorola has advanced to the stage where a pilot lot will be fabricated soon. They predict high yields (similar to those of 380 μm cells) using their developed process sequence.

Surface Preparation

The megasonic cleaning system has been transferred from Sommerville NJ to Mountaintop PA and final setup has been completed. After training of necessary personnel to operate the system is completed, the system will be operated in a production-plant environment to collect data on chemical usage and to assess the effectiveness of the cleaning process.

The RCA spray-on AR coating process produced a uniform coating on both surface-etched and partially texturized cells. Fully texturized cells had non-uniform coatings. With the addition of a wetting step, theses cells produced uniform coatings.

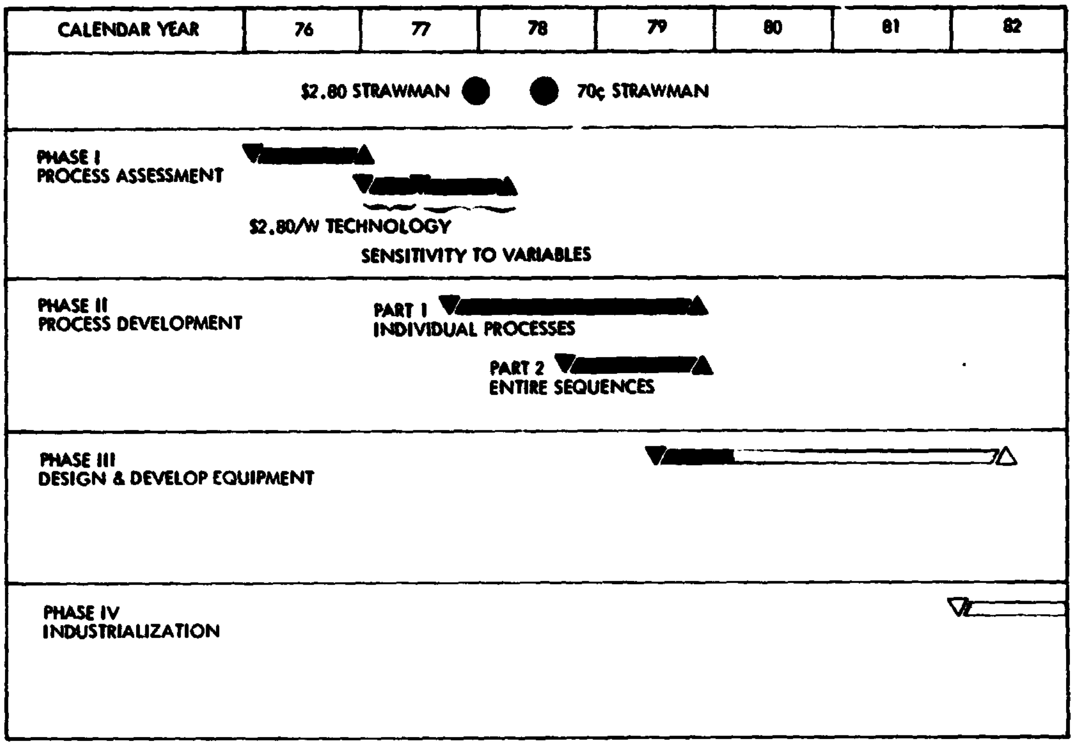


Figure 2. Production Process and Equipment Area Phase Schedule

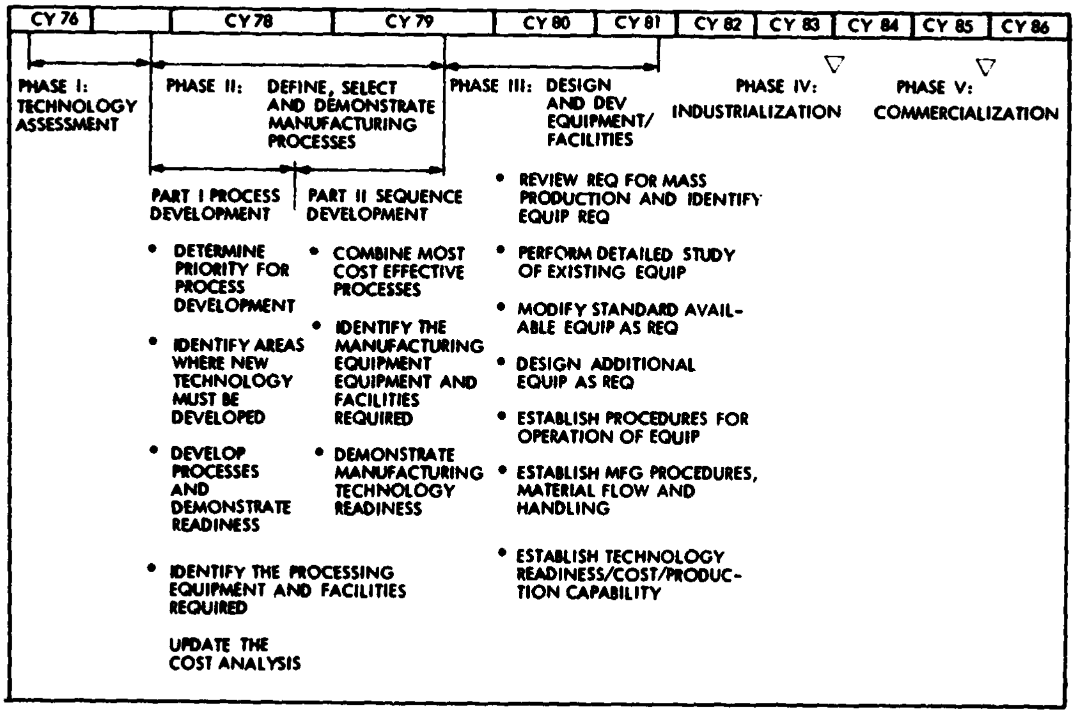


Figure 3. Production Process and Equipment Area Phase Breakdown

Junction Formation

The first ion-implanted cells from the JPL non-mass-analyzed (NMA) source are delayed due to difficulties in getting approval from the safety office regarding this involvement with phosphine gas.

A new contract has been signed (dated 1/10/80) with Spire for the development and construction of a pulsed electron-beam annealing (PEBA) machine to be coupled with ion implantation. The combined implanter/annealing machine will be capable of processing 10 MW per year of 4-in.-dia wafers.

Metallization

Copper metallization by plating has been developed successfully by both Applied Solar Energy Corporation and Motorola. They agree that Ni is necessary to act as a barrier to prevent Cu diffusion into the Si. They also agree that palladium (Pd) is necessary to form an adequate contact with the Si.

The Bernd Ross Associates contract to investigate the feasibility of metal inks without glass frit has been completed and the final report is in. These inks are feasible and have shown excellent performance characteristics.

The near-term cost-impact contract with Motorola to develop a wax-patterning system for plated metal contacts has been extended for an additional three months at no cost. The emphasis is shifting from a molten-wax application to a solvent-based system.

Assembly

The near-term contracts for automatic assembly machines are nearing completion. Both Arco Solar and Kulicke & Soffa are experiencing some difficulties with the developmental work. Arco found it necessary to change the method of supplying heat to the soldering operation from hot gas to RF induction heating. This constituted a major redesign. K&S is eliminating the automatic cell-test step and a few other details in order to reduce cost overrun. Delays are being experienced on subcontracted parts of the machine. At present, the machines are scheduled for completion and demonstration late this year.

The programmable robot contract with MBAssociates has been completed. This development covers the cell interconnection and emplacement for module fabrication. A new contract is being negotiated to extend this development to include module encapsulation and final assembly.

Delivery of six production modules from Applied Solar Energy Corporation was made on 11 April 1980. Delivery of all surplus module materials and contract tooling will be accomplished by mid-May. One item of tooling (x-y soldering machine) will be maintained at ASEC in support of JPL IV work until 30 June 1980, when a replacement unit being purchased by the contractor will be delivered.

Table 4. Production Process and Equipment Area Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
OCLI	954830	Slicing
Sclarex	955077	Thin-wafer study
Theo. Barry Assoc.	955519	Dev. of tech. manual & math models
Univ. of Pennsylvania	954796	Analysis & evaluation of process & equipment
Bernd Ross Assoc.	955164	Economical improved thick-film solar cell contact
Bernd Ross Assoc.	TBD	Fritless Metal Inks
OCLI	955244	Contacts--copper
Spectrolab	955298	Midfilm evaluation
Kinetic Coating	955079	Phase II add-on hermetically sealed cells
Lockheed	955696	Laser anneal
MBAssociates	954882	Phase II add-on automation studies
MBAssociates	TBD	Auto. module assembly
Motorola	954847	Plasma pattern etching Si_3N_4; metallization; cost analysis
Photowatt	TBD	Microwave studies
RCA	954868	Phase II add-on process sequence development
RCA	TBD	Process sequence development

Table 4. Production Process and Equipment Contractors (Continued)

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Sensor Technology	954605	High-energy per unit area solar cell modules
Sensor Technology	954865	Phase II add-on spray-on & microwave evaluacion
Solarex	954854	Phase II add-on metallization; Ni plating
Spectrolab	954853	Phase II add-on process sequence development
Spire	955640	Ion implantation equipment
Westinghouse	955624	Silicon dendritic web material process development
OCLI	955217	Development of high-energy (14%) solar cell array module
OCLI	955423	Laboratory services
OCLI	955118	Evaluation of ion-implanted solar cell array modules
Arco Solar	955278	Automated solar panel assembly line
Kulicke & Soffa	955287	Automated solar module assembly line
Motorola	955324	Wax patterning
Motorola	955328	Thin silicon substrate for solar cells
RCA	955341	Megasonic cleaning
Sensor Technology	955265	Development of low-cost poly-silicon solar cells
Sensor Technology	955266	In-depth study of silicon wafer surface texturizing
Sol/Los	955318	A new method of metallization for silicon solar cells

ENGINEERING AREA

INTRODUCTION

During this reporting period work has been focused on array design and engineering, reliability and durability requirements development and standards. Detailed status of the Engineering Area contracts (listed on p. 40) was reported in the 15th PIM handout.

SUMMARY OF PROGRESS

Array Design and Engineering

Principal in-house work in the module/array circuit design and analysis task within this activity concentrated on application of series/parallel analysis to the problem of multi-cell failures for intermediate load applications and on development of design guidelines for fault- and hot-spot-tolerant circuit designs. Life-cycle costing methods were employed as part of the performance assessment of various series/parallel design approaches and provided important inputs to a paper presented by C. Gonzalez and R. Weaver at the 14th IEEE PV Specialists Conference, "Circuit Design Considerations for PV Modules and Systems." Preparations for the Module/Array Circuit Design Workshop scheduled March 31-April 1, immediately preceding the 15th PIM, continued through this reporting period.

Work continued on design, fabrication, and proof testing of low-cost array-support structures and foundations for intermediate load and utility applications. Full-sized 8 ft x 16 ft panels were fabricated and successfully tested to 50 psf. An integrated, low-cost soil-buried foundation/array structure was designed and fabricated and was on display with a full complement of simulated 4 x 4 and 4 x 8 modules at the 15th PIM. A detailed presentation of the status of this activity was made by A. Wilson at the Engineering and Operations joint technology session of the 15th PIM.

A major continuing in-house activity has been the development of analytical methods to integrate the results of the many ongoing module and array design optimization studies conducted by the Engineering Area. A key analytical tool based on minimizing the total PV system life-cycle energy costs, including repair and replacement of failed cells and modules, is now available. Application of the optimization algorithm has resulted in data demonstrating that significant reduction can be accomplished in the life-cycle costs for large ground-mounted arrays through selection of optimum mechanical and electrical circuit configurations. Specific recommendations for module series/ paralleling, materials selections and structural design and for field repair and maintenance strategies have been developed.

This activity was the subject of a paper, Flat Plate Photovoltaic Array Design Optimization, presented by R.G. Ross Jr., Engineering Area Manager, at the 14th IEEE Photovoltaic Specialists Conference.

The final report by Bechtel on curved-glass module design and electrical insulation and isolation design was received by JPL for final review and approval. Cost savings associated with large-volume production of a curved-superstrate configuration were identified for 1.2 x 2.4 m panels. Technology voids in designing electrical isolation systems for modules were identified, and a real-time voltage endurance stress testing program was recommended. Distribution of the final report is planned for June 1980.

Wind-tunnel testing of simulated flat-plate array structures under the Boeing wind-loading study contract originally planned for March 1980 was rescheduled for mid-May 1980 due to a scheduling conflict in the use of the Colorado State University wind tunnel. The final report, which will compare previously completed analytical work with the wind-tunnel results, is planned for September 1980.

The Burt Hill Kosar Rittelman Associates contract to investigate operation and maintenance costs and requirements for residential applications, which was initiated in October 1979, continued through the quarter. Study activities were essentially completed and progress made on preparation of the final report, scheduled for distribution to the photovoltaic community in May 1980. Six specific topics that were studied are general (normal) maintenance, cleaning, panel replacement, gasket repair or replacement, wiring repair or replacement, and termination repair or replacement. Results of the study confirm that the typical homeowner will be unwilling to perform more than the simplest of maintenance procedures on a rooftop PV array. This implies that all components of the photovoltaic module and array must be designed to be maintenance-free and long-lived. In order to accomplish this, care must be taken in the choice of materials, and a design optimization must include a detailed evaluation of the need for, and the associated costs of, maintenance. Also, photovoltaic module manufacturers must develop maintenance procedures, safety procedures, and maintenance schedules to be incorporated in a detailed operation and maintenance manual.

Motorola/ITT Cannon submitted a final report draft of the results of the PV module termination requirements study contract for review by LSA Engineering. Release of the report for distribution to the PV community is planned before the 16th PIM.

T and E Enterprises has conducted a study to explore the application of photovoltaic modules and arrays in residences. The study related architectural form, materials of construction and installation requirements to current architectural practices. Several conceptual approaches to reducing system installation complexity were proposed. The final report draft was received for review by LSA Engineering and is scheduled for publication in June 1980.

The activities in the Underwriters Laboratories contract for development of PV module and array safety requirements included site visits to the Mead NB 20-kW application and the Mt. Laguna CA 60-kW application to review safety design and grounding provisions for these initial intermediate-load-center installations. Review of existing codes with respect to development of recommended safety practices for specific wiring hardware continued. Preparations were initiated for conduct of UL790 flammability tests of simulated rooftop PV module installations. The tests are now planned for May 1980. UL personnel are supporting, as part of this contract, SERI Interim Performance Criteria development as members of Standards Task Groups 1 and 2.

Reliability and Durability

High-voltage continuous-stress testing of minimodules has continued at JPL Field Site No. 1 with periodic performance measurements and inspections. An analytical investigation of long-term voltage-stress-related degradation factors for various encapsulation systems has been initiated. The effects of high-voltage phenomena, including arc-generated corona excitation and voltage-gradient concentrations, are being evaluated analytically and empirically. Generation of improved high-voltage design guidelines for the higher operating voltages expected in PV utility applications is the goal of this effort.

Work continued on the Phase II module-soiling investigations. Efforts centered on comparing the differences between the relative normal hemispherical transmittance (RNHT) and the integrated hemispherical transmittance (measured at Battelle Pacific Northwest Laboratories). The values measured at Battelle show, in most cases, a greater loss in hemispherical transmittance than previously thought. Additional measurements are under way to resolve these discrepancies. Development of a high-temperature-soak accelerated environmental exposure of modules using the greenhouse effect was initiated. The purpose is to provide a low-cost method for manufacturers to use in checking potential long-term chemical or physical degradation mechanisms in new module designs. The relative importance of UV and high temperatures in module degradation will be investigated. A test box accepting up to eight minimodules has been fabricated and initial exposures are under way.

A solar-cell fracture-mechanics test is under way on groups of wafer-to-cell end items from cell fabrication (each group processed slightly differently) made by various module manufacturers. The test being used is the four-point twist test developed by the Engineering Area. This effort is part of a cooperative effort between LSA Engineering Area and the PV industry to develop a technical basis for new cell designs that will have a lower probability of sustaining a cracked-cell failure. Conceptual design of an improved version of the twist test fixture continued. The new fixture will accept cells up to 150 mm dia and will be used to evaluate the feasibility of quality control proof testing of wafers to improve finished cell yields.

The draft version of Clemson University's Second Annual Report has been reviewed and recommendations have been sent to the contractor. The final release version of this report (DOE/JPL-954929-80/7) will be dated April 1980 and will be distributed to the LSA photovoltaic community.

Contract negotiations have been completed and an Engineering Area contract approved with IIT Research Institute, Chicago, Illinois, for technical support in reliability engineering of photovoltaic modules.

In the area of cell-reliability testing, two poster papers were presented at the 14th Photovoltaic Specialists Conference in San Diego in January 1980. One paper, co-written by C. P. Chou and E. L. Royal (JPL) and H. Klink, Motorola, was titled "Effects of Production Processes on the Fracture Strength of Silicon Solar Cells." The other, presented by the Clemson University team, which is under contract to test cells for the LSA Engineering Area, was titled "Contact Integrity Testing of Stress-Tested Silicon Terrestrial Solar Cells."

Array Standards

The Array Subsystem Task Group delivered to SERI an updated package of criteria and test methods for the January 1980 draft of the Interim Performance Criteria Document, which was a major milestone for SERI's Performance Criteria and Test Standards Project. Engineering Area personnel participated in the review of the draft document of January 21-25, 1980. Future standards work will include: letting contract for the development of criteria test methods for optical systems and PV concentrators, standards for combined photovoltaic-thermal collectors, and further reliability-durability studies.

Preparation and release of a new module-design requirement specification for use in the PP&E Phase III effort was accomplished. The LSA Document 5101-138, "1982 Technical Readiness Module Design and Test Specification-Intermediate Load Applications" dated January 15, 1980, has been released for distribution to the photovoltaic community. A description of the development of this document was presented in a poster paper by J. Arnett and R. Ross at the 14th Photovoltaic Specialists Conference, titled "Influence of Module Requirements on Flat-Plate Module Design Evolution."

Table 5. Engineering Area Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Bechtel National Columbus OH	954698	Curved-glass module and electrical isolation
Boeing Co. Seattle WA	954833	Wind loading study on module/array structures
Burt Hill Kosar Rittelman Associates Butler PA	955614	Residential module O&M requirements study
Clemson University Clemson SC	954929	Solar cell reliability test
DSET Laboratories, Inc. Phoenix AZ	713131	Accelerated sunlight testing of modules
DSET Laboratories, Inc. Phoenix AZ	713137	Spectral radiometric measurements and standards
Motorola, Inc. Phoenix AZ	955367	Study of termination design requirements
T and E Enterprises Los Angeles CA	713135	Integrated low-cost array concepts study
Underwriters Laboratories Melville NY	955392	Solar array and module safety requirements

OPERATIONS AREA

OBJECTIVES

The overall objectives of the Operations Area are (1) to stimulate the use by module manufacturers of the latest improvements in production technology, (2) to provide proven, state-of-the-art module designs for DOE photovoltaic procurements, (3) to assess and report Project progress in meeting interim module price and performance goals, (4) to obtain for DOE limited quantities of modules for engineering evaluation, field test, and applications experiments, and (5) to provide module manufacturers with product performance data and evaluations for the purpose of improving the functional performance and durability of their modules. These objectives are met by carrying out tasks in module production, environmental and field testing, electrical performance measurement, problem/failure analysis, and applications liaison.

Specific objectives for FY80 are to (1) complete the design, test, price analysis, and limited production of the latest generation (Block IV) of modules for residential and intermediate-load applications, (2) to report the results of the environmental testing of Block III, developmental, and selected commercial design modules, (3) to perform and provide interim results reporting of qualification and exploratory environmental tests on Block IV, developmental, and selected commercial module designs, (4) to obtain and report the results of the on-going field and endurance tests at the 16 outdoor test sites, (5) to determine the cause and recommend corrective action for test and field failures of LSA-procured modules and (6) to provide electrical performance measurements standards and consultation for LSA contractors and DOE applications projects using LSA-procured modules.

LARGE-SCALE PRODUCTION TASK

Block III Production

With the delivery of more than 8 kW of modules by Sensor Technology (Photowatt International), the production of 217 kW of modules, purchased under Block III, was completed during this reporting period. Table 6 summarizes the effort.

Table 6. Block III Module Summary

Contractor	Avg. Watts Per Module*	Modules	Total Watts
ARCO Solar	18.55	2009	37,282
Motorola	23.16	2246	52,023
Sensor Tech	8.83	4840	42,748
Solar Power	29.74	1799	53,512
Solarex	18.38	1725	31,714
TOTALS:	---	12,619	217,279

*Power measured at 100 mW/cm^2, AM1, 60°C cell temperature and rated voltage.

Solarex has also completed delivery of high-density modules procured within this task.

Block IV Design and Qualification

Of the eight contractors participating in the Block IV design and qualification effort, four have delivered modules to JPL for qualification, two have opted to redesign the modules originally presented in order to lower production costs, and two are simply proceeding at a more deliberate pace than was originally scheduled. Testing of the GE residential module has been completed and the final design review was held on March 31. The Motorola testing is essentially complete as is the testing of modules made by Spire. The modules of ASEC have started through test.

Sensor Technology (Photowatt International) and Solar Power have presented reviews of revised designs and are expected to produce prototype modules soon. Solarex and Arco have experienced numerous difficulties in reaching the final design state for both their intermediate load module and the residential module. Arco presented a formal review of their modifications of the residential module redesign in March and is expected to be producing these modules soon.

Block IV Production

The request for quotations for the manufacture of the Block IV modules was issued in early January. Responses were received in February. Awards to individual contractors will not be made until module qualification testing has been completed.

Block V

Planning for the Block V procurement is in process.

MODULE TEST AND EVALUATION

Environmental Testing

Four types of Block IV prototype modules were received during this period; two types have completed temperature cycling only and two have completed all of the qualification tests. Of the former, one type was generally satisfactory but the other showed extensive cell cracking during temperature cycling. There was no appreciable electrical degradation. This module has glass/PVB/Tedlar construction. The metal mesh interconnects extend across a full radius at the front of the cell. The cracks were generally found in this area.

One of the modules, a residential type, completed qualification tests satisfactorily. However, there was an intermittent open at one point in this three-module array, assembled as a roof section. A possible explanation is simply a loose electrical connection between modules.

The second module type on which testing was completed had a series of problems:

TEST	RESULTS
Temperature cycling	Sealant between glass and frame extruded
Humidity cycling	Two cells cracked
Mechanical integrity	One cell crack; one frame corner broken off at mounting hole.
Post-tests evaluation	3 of 5 modules failed hi-pot test; one failed ground continuity test.

Of these four module types, three are radically new designs and the fourth has had substantial changes. Problems are to be expected in new designs and solutions are likely to be found without difficulty before Phase II production.

Recent glass-covered versions of a Block III module completed qualification tests. Of eight modules tested, three showed minor delamination and one had more severe frame-seal delamination.

A Production Process and Equipment Area thin-cell developmental module has completed temperature and humidity testing satisfactorily.

Two commercial modules developed problems during testing. One type had significant cell cracking and breaking of the silicon alongside the interconnect. The other type suffered electrical degradation on all four modules (4 to 8%), bubbles both front and back, and discoloration of encapsulant, backing tape, and metallization.

Performance Measurements

New 2 x 2-cm solar cells were received and new reference cells have been fabricated and calibrated for one Block IV manufacturer. Refabrication of these reference cells was found necessary due to metallization failures in the original lot of cells. The second LAPSS facility is complete and operational through the computer. Hardware to convert and connect the first LAPSS to the computer is under construction. The high-current electronic load has been received and installed.

Analysis of the field test data is continuing. It has been determined that the anomalous drop in module outputs from June 1979 through March 1980 is due to a sky-shadowing problem rather than actual module degradation. As the sun moves south during the latter part of the year, the field modules are tilted to higher angles to maintain near-normal solar illumination; each module sees an increasing area of the test stand in front of it as the tilt angle increases. This loss of indirect sky illumination results in decreased module output. The percentage decrease in module output depends on sky conditions and module position on the test stand. Decreases of as much as 9% have been measured.

Field Tests

The principal activities this period were: initiation of a bi-monthly module degradation audit at the JPL site; delivery and successful link-up with the PDP 11/34 of the portable I-V data logger, and preparation for the second tour of the continental remote sites.

Starting with the January-February period, a module degradation audit will be performed every two months. The procedure being employed is as follows:

A daily record is kept of modules whose fill factors differ from those of their reference I-V curves by more than 3%. The I-V curces of these modules are later recalled from stored data and scanned for abnormalities. Modules whose curves appear abnormal are then placed on a degraded-modules list. A summary of the two-month audit period is made, resulting in two key numbers for each module; the number of days a module appears on the list, and the mean peak-power loss for those days. Additional electrical characterization of the degraded modules is performed with the aid of special module interrogations where I-V data is obtained continuously throughout a day. These data show when a module's degradation is intermittent, temperature sensitive, etc. When QA summaries are available, correlations between physical signs of degradation and bad I-V curves are also made. Table 7 and Figure 4 summarize the January-February audit. Table 7 lists the peak-power loss by module type and Figure 4 contains a histogram showing the number of degraded modules for different peak-power loss bands. An examination of Table 7 shows that the Sensor Tech Block II family, with its history of impact cracks, is still the major contributor to the degradation statistics. Since the audit, nine modules have been classified as having failed and will be removed from the field. The failure criterion is that a module must be on the degraded list at least 60% of the time and have a peak-power loss of at least 25%.

A portable I-V data logger, designed and fabricated in-house, has been received. An effort to read and transfer data generated by the data logger to the PDP 11/34 has been successful. Figure 5 shows the acquisition method of the data logger itself, and Figure 6 shows a set of data taken with the data logger and then transferred, decoded, merged, processed and finally plotted by the PDP 11/34. Final shakedown is still in process. The instrument will be used in the field locally before use at the remote sites. Some additional software work is still required to provide archiving capability.

On May 1 the second tour of the remote sites will begin. The first group of sites to be visited are New Orleans, Key West and the Canal Zone, in that order. Preparations have been completed with the exception of a special customs clearance needed to bring test equipment into Panama. Contact has been made with the Panamanian Embassy in Washington to resolve this problem. The itinerary will then include the sites at Crane, New London, and Houghton during the weeks of June 9 and 16; the Mines Peak, Albuquerque, and Dugway sites during the weeks of July 14 and 21, and the two northwest sites, Seattle and Alaska, August 11 to 20.

Failure Analysis

The most significant progress during this reporting period involved the continuing analysis of module performance in the Mount Laguna Air Force Station 60 kW array. In late March, a trip was made by Mount Laguna Failure Analysis personnel to obtain I-V curves of all module strings and of individual modules, where degradation was noted in a string.

Table 8 shows the status of the array at noon. From these data, there are three inoperative strings: 49, 112, and 113. String 49 had a bad string connector. String 112's I-V curve at the string connector was normal, so the problem must have been in the wiring to the blockhouse. String 113 was inoperative because of a grounding problem; the series wiring of the modules had chafed insulation touching the array frame. This problem was corrected and the string was put back on line.

Table 7. Peak-Power Loss (%) by Module Type

MODULE TYPE	0-5	5-10	10-15	15-20	20-25	25-30	30-40	40-50	50-60	>60
SENSOR TECH I		(1)	(3)							(1)
SPECTROLAB I	[1]								(1)	[1]
SOLAREX I			(1)						(2)	[2]
SOLAR POWER I			[1]		[1]				[1]	
SENSOR TECH II		[6]	[2] (2)	[4] (2)		(1)				
SPECTROLAB II										
SOLAREX II								(1)		
SOLAR POWER II		[1]		[2]			[1]			
ARCO SOLAR III	[1]									
MOTOROLA III										

[ ] NUMBER DEGRADED AS OF 8/31/79
( ) NUMBER DEGRADED AFTER 8/31/79

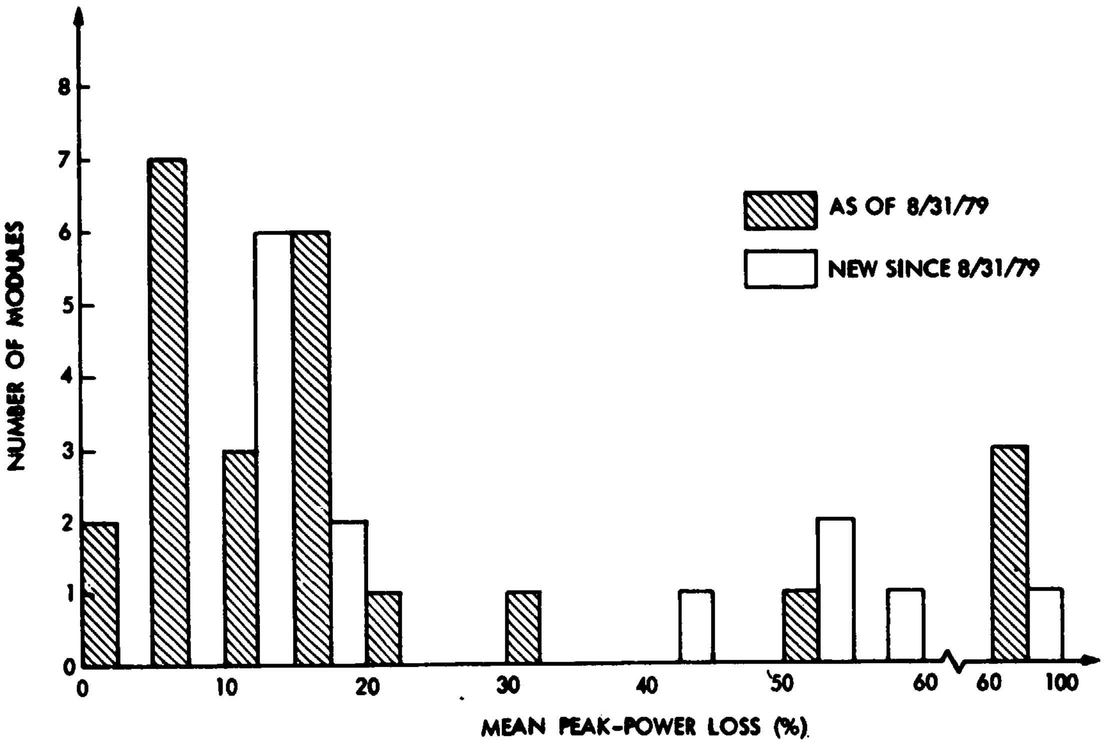


Figure 4. Degraded-Module Histogram for the JPL Site as of 2/29/80 (Total Modules Under Test = 269; Total Number Degraded = 39; Number of Modules Subsequently Removed = 9).

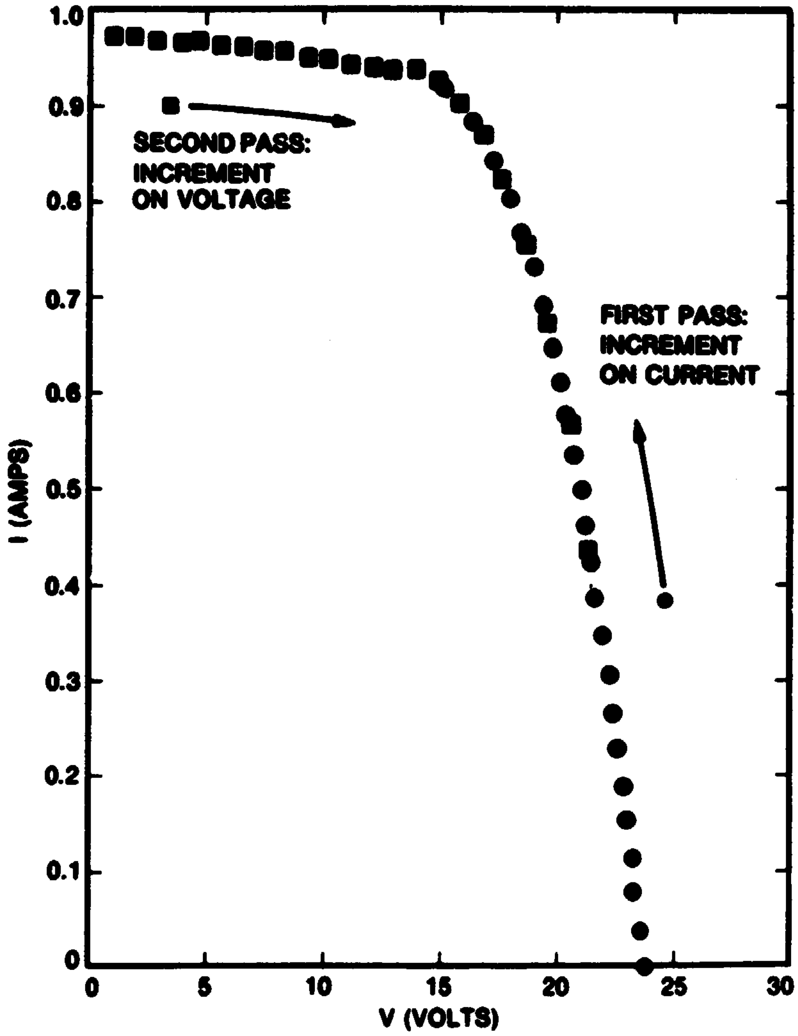


Figure 5. I-V Data From Portable I-V Data Logger

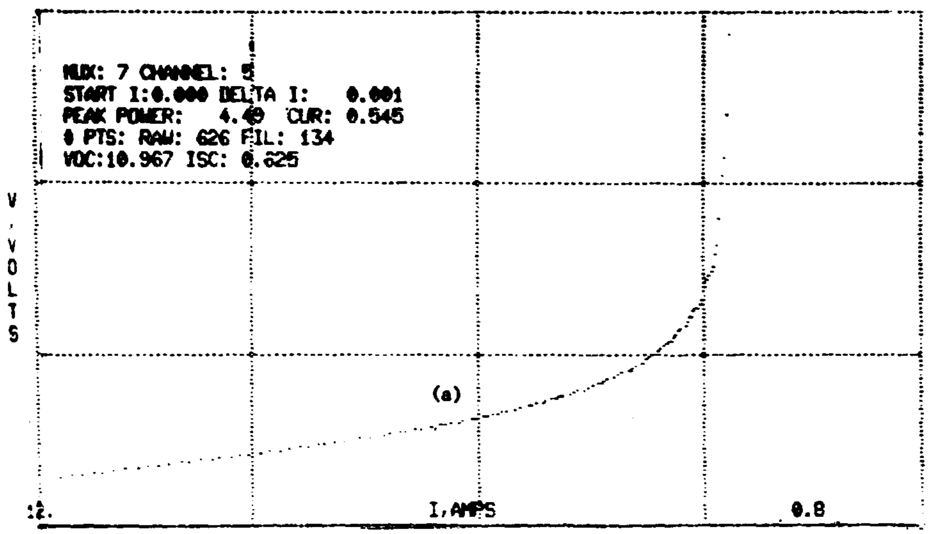


Figure 6. Typical Plotted Data: Field Data Transferred, Decoded, Merged, Processed, and Plotted at the JPL Test Site by the Field Test PDP 11/34 Computer. The Data Will Also Be Archived on Tape for Future Analysis and Comparison.

Table 8. Array Status at Noon

at 12:07:59 on Mar 20, 1980

Tabulation of string currents from the array

1.99	1.85	1.90	1.68	2.05	2.09	1.90	1.76	1.94	1.87
1.79	1.73	1.56	2.02	1.70	2.10	2.08	2.03	2.03	2.13
1.72	2.23	1.90	2.00	1.99	1.73	1.64	2.05	1.88	1.58
1.61	1.65	1.29	2.06	1.63	1.84	1.80	1.21	1.68	1.92
1.92	1.76	2.05	1.89	1.98	1.84	1.94	1.63	.01	1.91
1.98	2.09	1.83	1.59	1.82	1.77	1.69	1.84	1.81	1.81
1.97	1.17	1.66	1.65	1.81	1.21	1.93	2.00	1.51	1.75
1.72	1.76	2.01	2.06	1.58	1.80	1.75	1.99	1.73	1.65
1.08	1.97	1.96	1.86	1.39	1.43	1.46	1.86	1.87	1.93
2.02	2.03	1.63	2.01	1.98	1.91	2.03	1.99	2.06	2.07
2.47	2.73	1.65	2.09	1.71	2.14	1.59	1.88	.33	1.61
1.58	.01	.02	1.76	1.58	1.26	1.06	1.23	.97	1.03
1.13	1.24	1.11	1.02	1.16	1.25	1.22	1.29	1.24	1.24
1.16	1.24	1.20	1.15	1.17	1.15	1.13	.96	1.13	1.17
1.06	1.23	1.19	1.23	1.00	1.18	1.17	1.22	1.13	1.14
1.20	1.17	1.11	1.15	1.15	1.19	1.03	1.19	1.16	1.23
1.18	1.21	1.23	1.04	1.23	1.21	1.18	1.26	1.22	

Plane of array radiation is 1088.26 W/m^2
Total horizontal radiation is 935.22 W/m^2

Ambient air temperature is 11.92°C
Average wind velocity is 3.10 m/sec
Peak wind velocity is 4.66 m/sec
Wind direction is 210.35°
Barometric pressure is 1027.24 mbar

Array output power is 57.66 kW
Array output current is 254.17 A
Array output voltage is 227.62 V
Converter output power is 52.57 kW

String #112 inoperative (wiring to blockhouse?)
String #113 inoperative (string grounded to frame)
String #49 inoperative (bad string connector)

Figure 7 is a typical I-V curve of a 14-module series string in normal operation with no modules showing electrical degradation.

Figure 8 shows an I-V curve of a degraded series string. The individual I-V curves taken for the string show the contribution of each module. These individual curves were taken using a module shadowing technique by successively uncovering modules.

Figure 9 shows distribution of module short-circuit current degraded in 5% increments for the module type with extensive cracked cells caused by reverse-bias heating. Once a significant mismatch occurs, a degraded module will be bypassed by the diode.

Figure 10 gives the overall status of the Mount Laguna array.

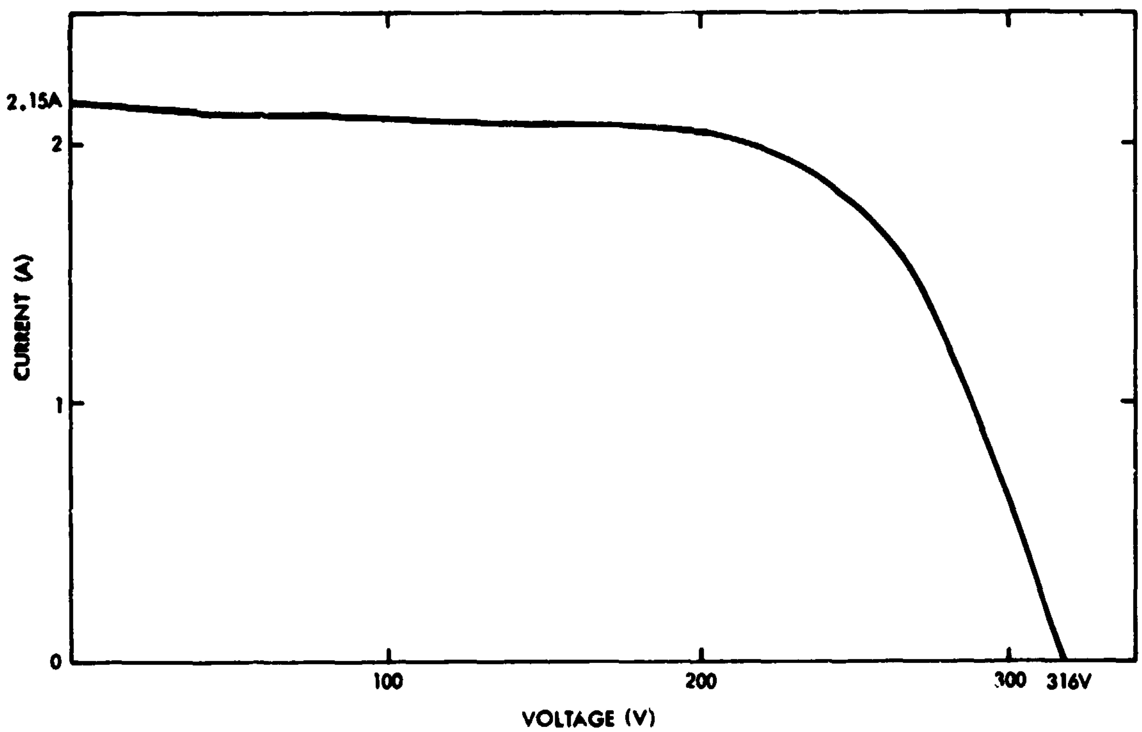


Figure 7. Normal 14-Module Series String I-V Curve

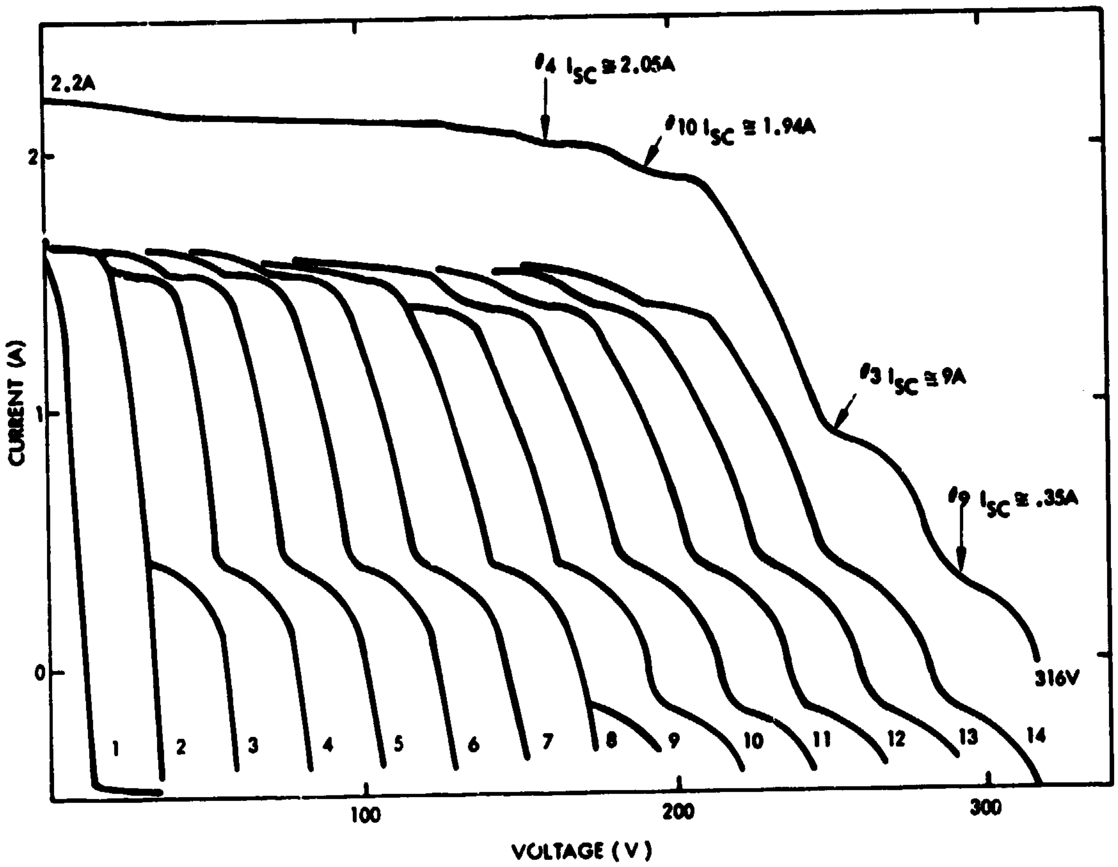


Figure 8. Degraded String With Three Modules Degraded >5%

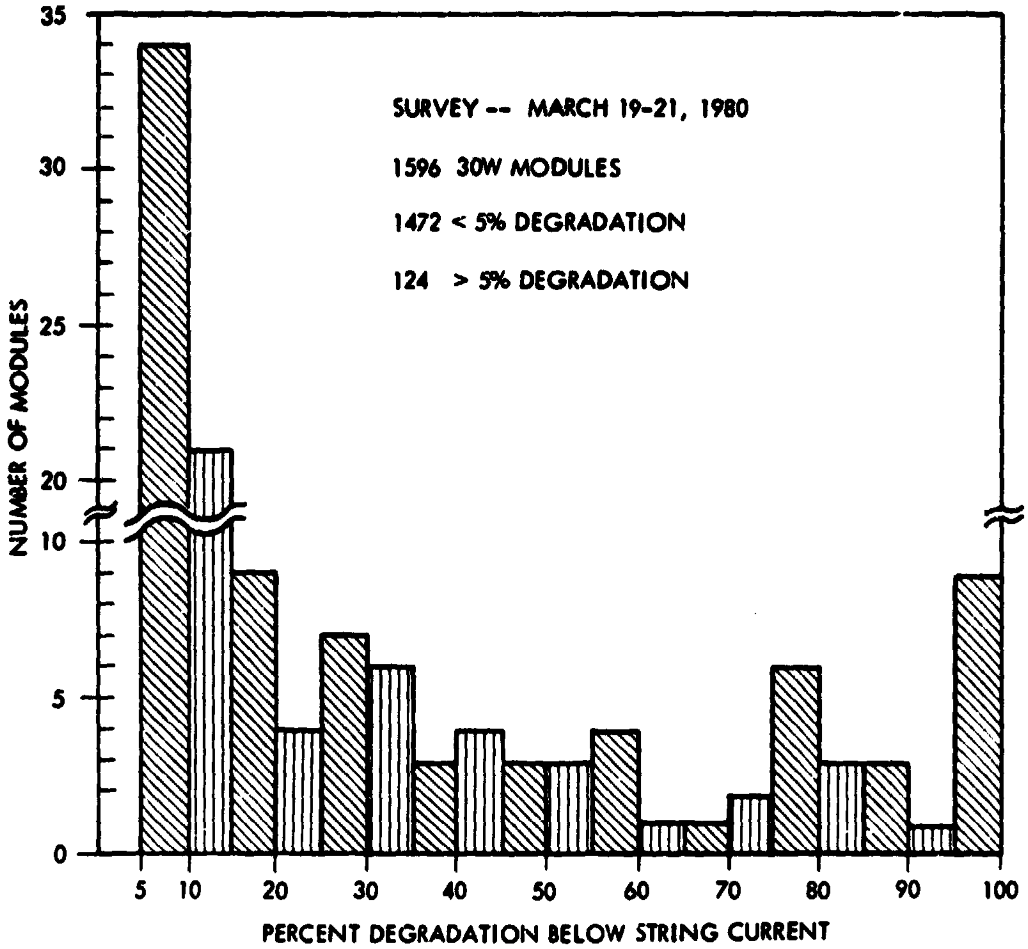
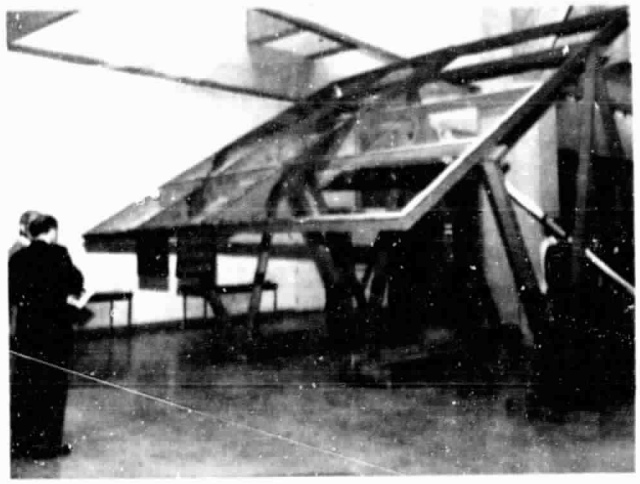


Figure 9. Mt. Laguna Short-Circuit Current Degradation

MODULE TYPE	NUMBER OF STRINGS		NUMBER OF STRINGS	NO. OF MODULES DEGRADED >5%	% OF MODULES WITH DEGRADATION		
	DEGRADED	NOT DEGRADED			>5%	>10%	>15%
30 W	67	47	114*	124	7.8	5.6	4.3
20 W	6	48	54	6	.79	.79	.79
TOTAL	73	95	168	--	--	--	--

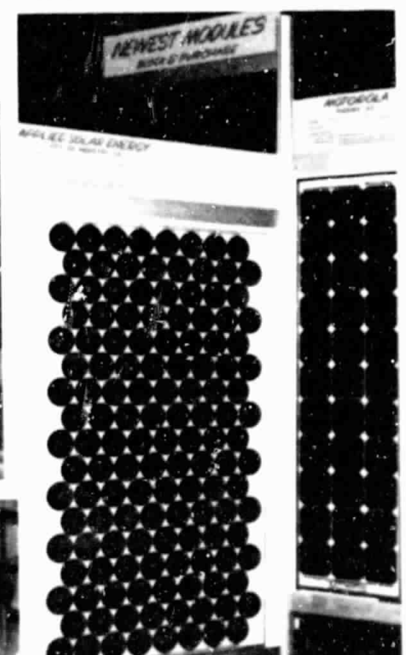
*STRING NUMBER 49 INOPERATIVE (BAD STRING CONNECTOR)

Figure 10. Status of Mt. Laguna Array







NEWEST MODULES
MOTOROLA



PROCEEDINGS

of the 15th Low-Cost Solar Array Project Integration
Meeting Held in Pasadena CA on April 2 and 3, 1980

AGENDA

Wednesday, April 2, 1980

7:30	Registration		
8:30	Welcome; LSA Announcements	W. Callaghan	
8:40	DOE, NASA, LC Announcements	P. Maycock L. Magid R. Forney	
9:00	Cz Ingot & Wafering Summary	J. Liu	(pp. 54-77)
10:00	SAMICS Results Overview	P. Henry	
10:50	PP&E Phase II Overview	D. Bickler	
11:50	Module & Array Circuit Design Overview	R. Ross	(pp. 78-80)
12:00	SERI PV R&D Overview	S. Wagner	
1:30	Technology Sessions (simultaneous)		
	Silicon Material	R. Lutwack	(pp. 81-112)
	PP&E Review of Phase II: Process and Sequence Development	D. Bickler	(pp. 113-204)
3:45	Encapsulation	C. Coulbert	(pp. 205-229)

Thursday, April 3, 1980

8:00	Technology Sessions (simultaneous)		
	Silicon Material	R. Lutwack	(pp. 81-112)
	Large-Area Sheet	J. Liu	(pp. 230-311)
	Encapsulation	C. Coulbert	(pp. 205-229)
	PP&E	D. Bickler	(pp. 113-204)
	PA&I	P. Henry	(pp. 312-328)
	Engineering and Operations (joint session)	R. Ross L. Dumas	(pp. 329-353)
1:30	Parallel Sessions		
	Effects of Wafer Dimensions	M. Leipold	
	Module Applications	L. Dumas	(pp. 354-372)
3:15	Summaries		
4:45	End of meeting		

TECHNOLOGY DEVELOPMENT AREA

Large-Area Sheet Task

PLENARY SESSION

J. Liu, Chairman

Hamco Division of Kayex Corp. (Advanced Cz)

Successful demonstration of growth of 150 kg of silicon ingot from a single crucible was reported by Hamco/Kayex. This run closely followed two successful 100 kg growth runs, which completed the first phase of the program. Cell efficiencies from one of the 100 kg runs showed little decrease in efficiency from the first ingot to the ninth, but did show lower efficiencies for cells from the bottom of the ingot compared to those from the top. The near-term cost-reduction program for microprocessor control of the growth process is proceeding on schedule with control of initial meltdown, melt temperature stabilization and all motor functions now controllable by microprocessor.

Siltec Corp. (Advanced Cz)

Ingots 730 kg in weight and 150 mm in diameter were grown using continuous liquid-feed (CLF) melt replenishment on two occasions. The size of the transfer tube was significantly reduced and many temperature profiles were taken along the transfer tube to ascertain the requirements for a heating element to avoid melt solidification inside the tube during continuous melt replenishment.

P.R. Hoffman Co. (MBS)

Wafering of a 100-mm-dia wafer has been done on two of the three saws being evaluated. Yield from the Varian 686 saw was encouraging, with only three of 273 wafers damaged in slicing. Major difficulties encountered have been in mounting the ingot securely to the work holder and in supporting partically completed wafers to eliminate the tendency to tilt to one side, resulting in greater kerf loss and in tapered wafers.

Crystal Systems, Inc. (FAST)

Recent experiments with slicing at high surface speeds have produced low yields. Slicing experiments at lower speeds have produced higher yields but reduced the life of the wires. The large bladehead currently being fabricated has been designed to provide rigid support at high speeds, which should provide effective slicing and long blade life.

Siltec Corp. (Enhanced I.D. Ingot Slicing)

Ingot cutting with ingot rotation has produced slices 100 mm in dia, 250 μm in thickness with kerfs of 152 μm. Typically achieved cutting feed rates are in the range of 13 to 15 mm/min. Cutting test runs showed that typical blade deflections of 50-75 μm with low-kerf blades of 152 μm can be reduced by an order of magnitude through the use of dynamic cutting edge control.

ADVANCED CZOCHRALSKI GROWTH AND WAFERING REVIEW

- SUMMARY OF TECHNICAL AND PROGRAMMATIC REVIEW OF ADVANCED CZ AND WAFERING CONTRACTS HELD ON 4/1/80 AT JPL
  - CRITICAL ASSESSMENT OF THE CURRENT STATE OF TECHNOLOGY DEVELOPMENT
  - EVALUATION OF TODAY'S AND POTENTIAL SILICON SHEET PRICE

<u>ADVANCED CZOCHRALSKI TECHNOLOGY</u>

- BATCH RECHARGING TECHNIQUE (HAMCO/KAYEX)
- CONTINUOUS RECHARGING TECHNIQUE (SILTEC)

<u>ADVANCED WAFERING TECHNOLOGIES</u>

- MULTIBLADE SLURRY SAWING TECHNIQUE (HOFFMAN)
- MULTIWIRE FIXED ABRASIVE SLICING TECHNIQUE (CRYSTAL SYSTEMS)
- INTERNAL DIAMETER SAWING TECHNIQUE (SILTEC)

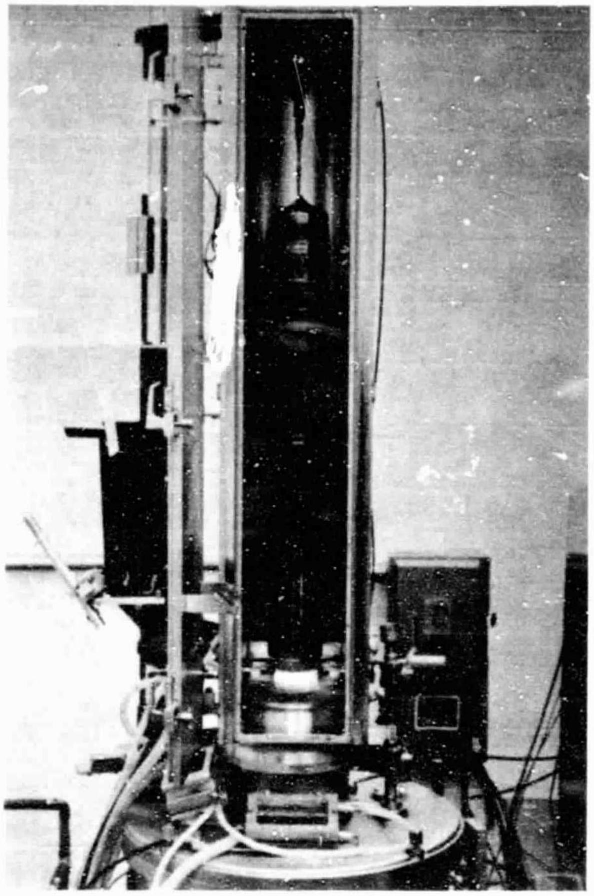
TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

CONTINUOUS Cz GROWTH BY PERIODIC MELT REPLENISHMENT

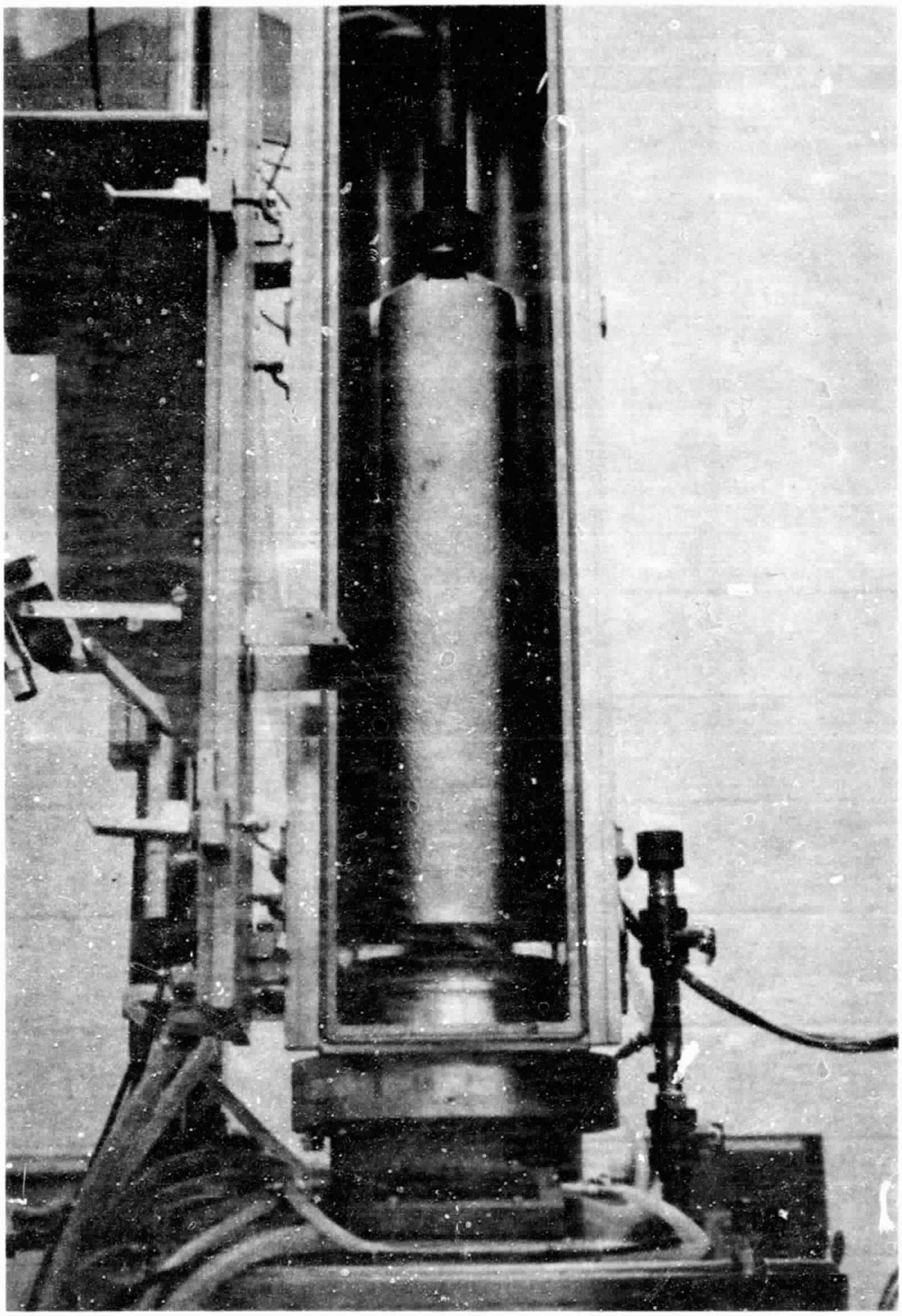
KAYEX CORP.

TECHNOLOGY INGOT GROWTH	REPORT DATE: APRIL 1, 1980 START DATE: OCTOBER, 1977
APPROACH CONTINUOUS CZOCHRALSKI GROWTH BY PERIODIC MELT REPLENISHMENT CONTRACTOR CONTRACT NO. 954888 KAYEX CORPORATION	STATUS - 150 KG FROM 1 CRUCIBLE ACHIEVED - SIX INGOTS, 25 KG EACH, ACHIEVED - 15 CM DIAMETER ROUTINE - GROWTH RATE (AVG SUSTAINED) - 9.2 CM/HR AT 10.2 CM DIA (1.75 KG/HR) 7.3 CM/HR AT 12.7 CM (2.16 KG/HR) 7.0 CM/HR AT 15.2 CM DIA (2.96 KG/HR)
GOALS - 150 KG FROM ONE CRUCIBLE - SIX INGOTS, 25 KG EACH - DIAMETER 15 CM (6 IN) - GROWTH RATE - 10 CM/HR - RESISTIVITY 1-3 OHM-CM P-TYPE - SOLAR EFFICIENCY 14% AM-1 - AFTER GROWTH YIELD 90% - MONOCRYSTALLINE INGOTS	- RESISTIVITY SPECIFICATIONS ACHIEVED ROUTINELY - AVERAGE SOLAR EFF. OF 12.9% AVERAGE FOR 100 KG - OVER 90% PULLED YIELD ROUTINE - 86% OF 100 KG MONOCRYSTALLINE DEMONSTRATED

25 kg Ingot With Hamco Cz Grower



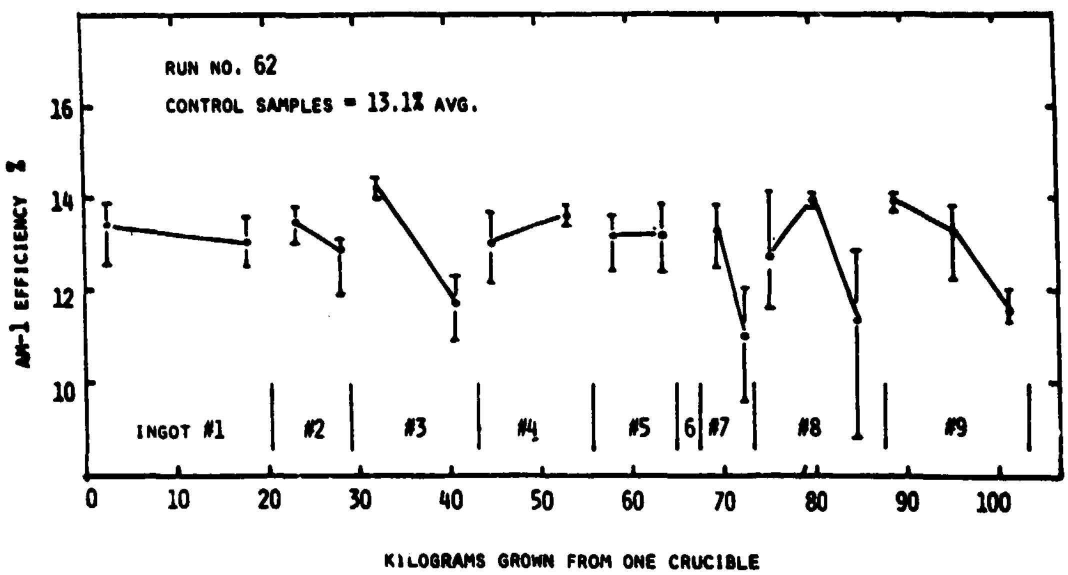
Closeup of Hamco's Recharging Chamber With Poly Ingot Ready for Recharging



Continuous Cz Growth Summary

DATE	RUN NO.	TOTAL PULLED (KG)	NO. OF INGOTS	DIAMETER (CM)	AVG PULL RATE (CM/HR)	RUN TIME (HR)	THROUGH-PUT (KG/HR)	MONO-CRYSTAL (%)	AM-1 EFFICIENCY, % RUN AVG	AM-1 EFFICIENCY, % MONO-CRYSTAL	AM-1 EFFICIENCY, % POLY CRYSTAL
2/78	5	22	1	11	9.1	18	0.82	100	-	-	-
4/78	9	27	3	11	8.7	39	0.70	85	11.5	11.6	11.4
6/78	11	43	4	11	9.1	44	0.97	88	11.8	11.9	11.2
10/78	19	57	6	13	8.9	64	0.89	56	11.8	-	-
11/78	21	53	5	13	8.4	44	1.21	62	-	-	-
12/78	22	46	5	13	9.0	50	0.93	91	-	-	-
1/79	30	99	6	13	8.7	79	1.25	27	11.2	13.3	9.8
6/79	47	60	5	13	6.8	52	1.17	88	13.0	13.0	-
7/79	49	108	9	13	7.0	66	1.26	85	13.8	13.8	-
10/79	55	101	10	13	7.2	91	1.11	75	12.0	13.0	9.7
10/79	2	100	9	13	7.7	109	0.92	64	12.3	12.7	10.6
12/79	60	100	8	13	7.6	85	1.18	61	12.0	13.0	11.0
1/80	62	103	9	13	7.9	97	1.06	89	12.9	13.2	11.2
2/80	70	152	6	15	6.9	99	1.53	44	-	-	-
3/80	72	151	6	15	7.0	94	1.61	17	-	-	-

Solar Efficiency vs kg Grown



Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS: CZ #3*

CRUCIBLE DIAMETER	14 IN	GROWTH RATE CM/HR	10
TOTAL GROWN PER CRUC.	150 KG	YIELD	80%
INGOT DIAMETER	15.2 CM	SLICING YIELD	1 M^2/KG
INGOT MASS, EACH	25 KG		

PROJECTION

CZ ADD-ON COST	\$15.6 /M^2*	\$.11 /WATT
WITH \$14/KG SILICON	\$35.8 /M^2*	\$.25 /WATT

*ASSUMING 1 M^2/KG

APRIL 1, 1980

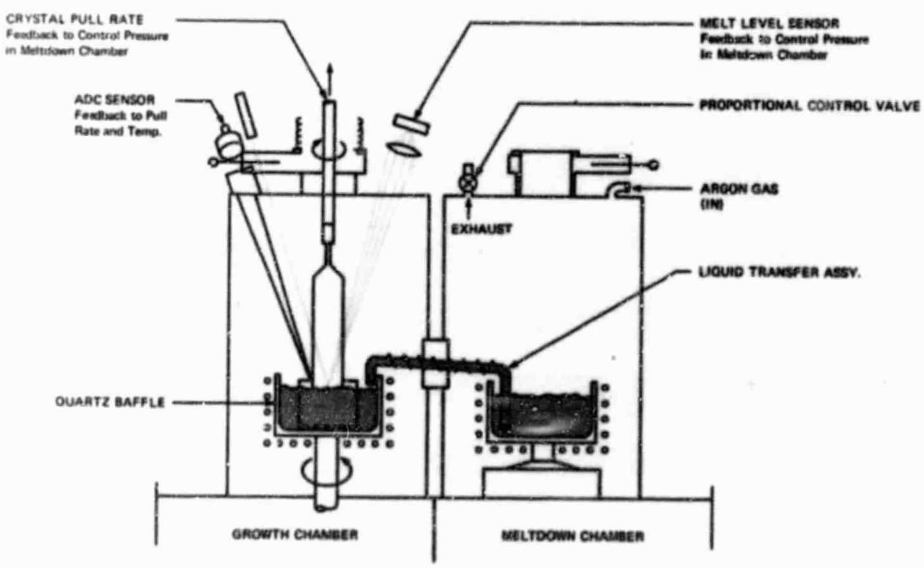
STARTED OCTOBER, 1977

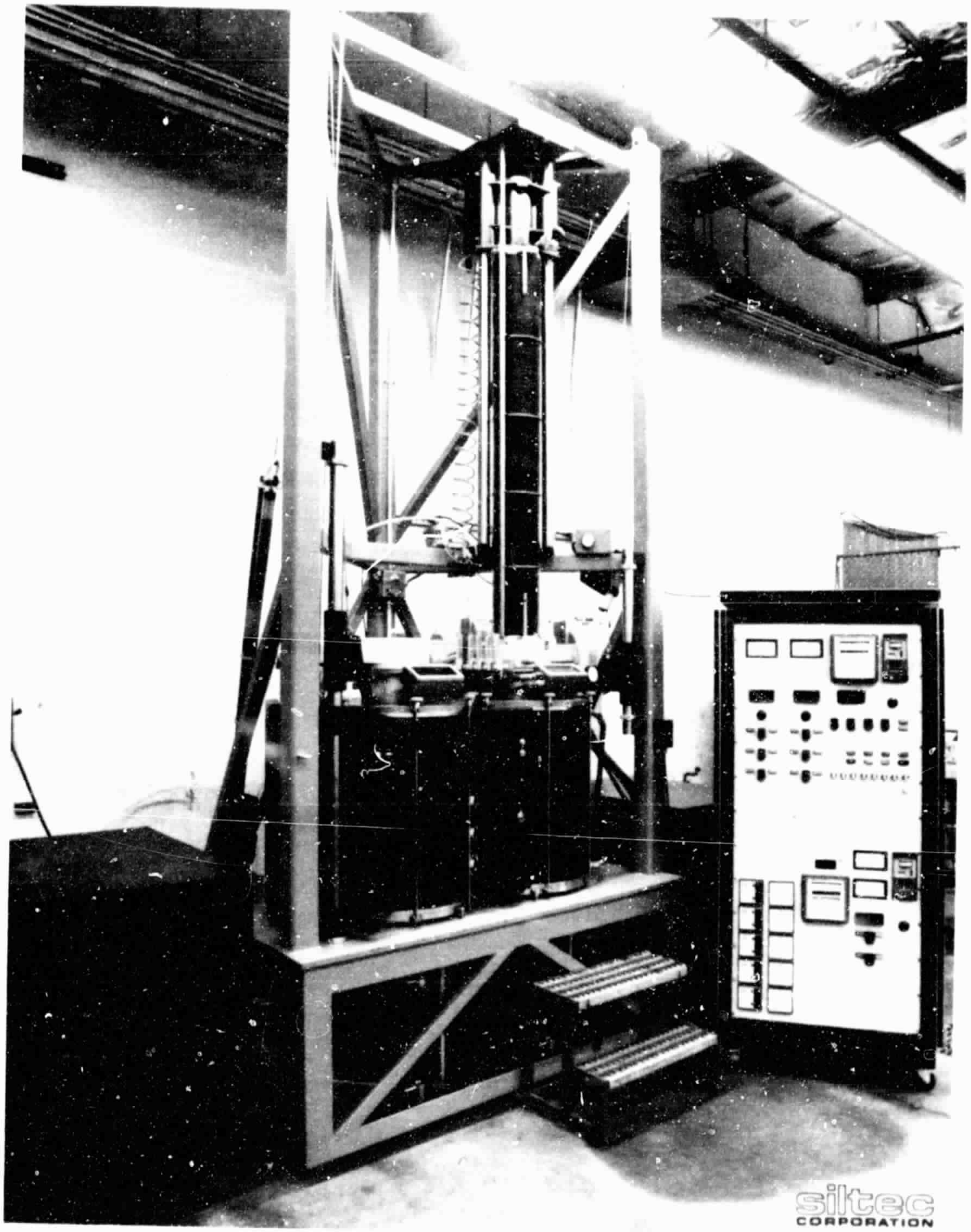
CONTINUOUS LIQUID-FEED Cz GROWTH

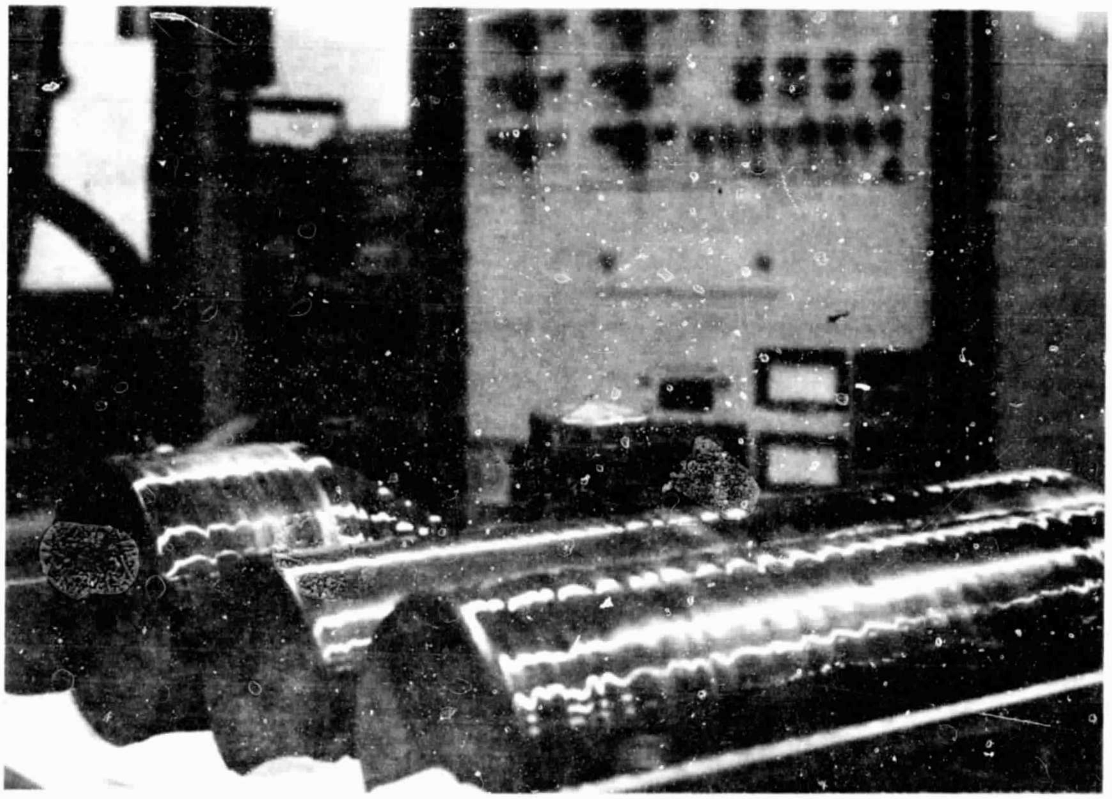
SILTEC CORP

TECHNOLOGY ADVANCED CZOCHRALSKI	REPORT DATE 04/02/80
APPROACH CONTINUOUS LIQUID FEED CZ - GROWTH CONTRACTOR SILTEC CORPORATION	STATUS INDIVIDUAL ACCOMPLISHMENTS
GOALS . 150 KG OF INGOTS/CRUCIBLE . 15 CM DIAMETER INGOTS . 2 KG/HR GROWTH RATE . AUTOMATION . 90% YIELD . 16.9% SOLAR CELL EFFICIENCY . TECHNICAL FEATURES DEMO 03/31/80 . TECHNOLOGY READINESS 11/30/81	. 70 KG OF INGOTS/CRUCIBLE . 12.5 CM/15 CM DIAMETER INGOTS . 2.5 KG/HR GROWTH RATE . UNDER DEVELOPMENT . 85% YIELD . 14% SOLAR CELL EFFICIENCY SIMULTANEOUS ACCOMPLISHMENTS 70 HOURS (1 KG/HR)

Liquid-Transfer Crystal-Growth System




siltec
CORPORATION



Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS: EQUIPMENT COST $160,000 (MACHINES IN QUANTITY, WITH μPROCESSOR CONTROL)

1 OPERATOR/4 PULLERS

90% EQUIPMENT UTILIZATION

10 CM/HR GROWTH VELOCITY (6"∅ , 4 KG/HR)

56.85 HRS RUN CYCLE TIME

150 KG RUN SIZE, 3 INGOTS/RUN, 86% GROWING YIELD

PROJECTION

$12.75/KG CRYSTAL ADD ON COST

$11.88/$M^2$ (25 SLICES/CM)

ADVANCED Cz GROWTH AND WAFERING REVIEW

HAMCO/KAYEX CORP. AND SILTEC CORP.

TECHNICAL FEATURES	1977	1980[1]	1982[2]	COMMENTS
OUTPUT/CRUCIBLE (KG)	20	150	150	MULTIPLE INGOT GROWTH
INGOTS/CRUCIBLE	1	6	3[3],5[4]	[3]SILTEC, [4]HAMCO
INGOT DIAMETER (CM)	10	15	15	ROUTINE
GROWTH RATE (KG/HR)	1.6	3.3	4	INGOT GROWTH RATE
THROUGHPUT RATE (KG/HR)	.8	1.5	2.5	MACHINE PRODUCTION RATE
INGOT YIELD (%)	90	98	90	INGOT GROWN/POLY MELTED
SINGLE CRYSTAL YIELD (%)	100	89	100	OF USABLE INGOT
CELL EFFICIENCY (% AM1)	16	14[5]	16	[5]BASELINE PROCESS, NO BSF
AUTOMATION	NONE	PARTIAL	FULL	

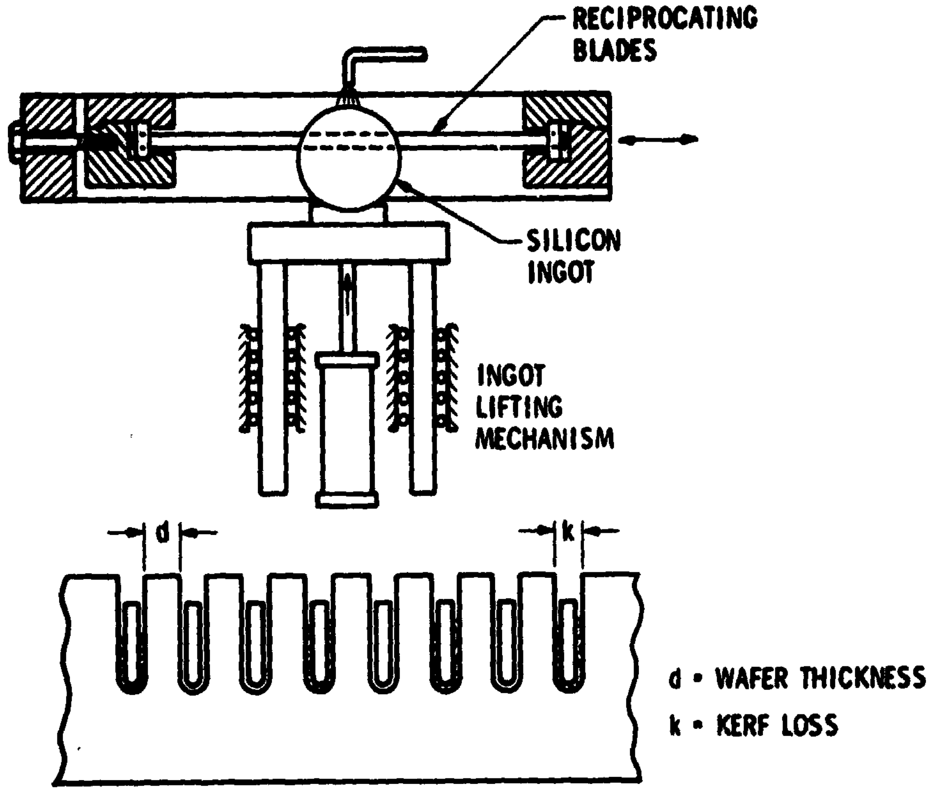
[1]INDIVIDUAL ACCOMPLISHMENTS [2]SIMULTANEOUS ACHIEVEMENT

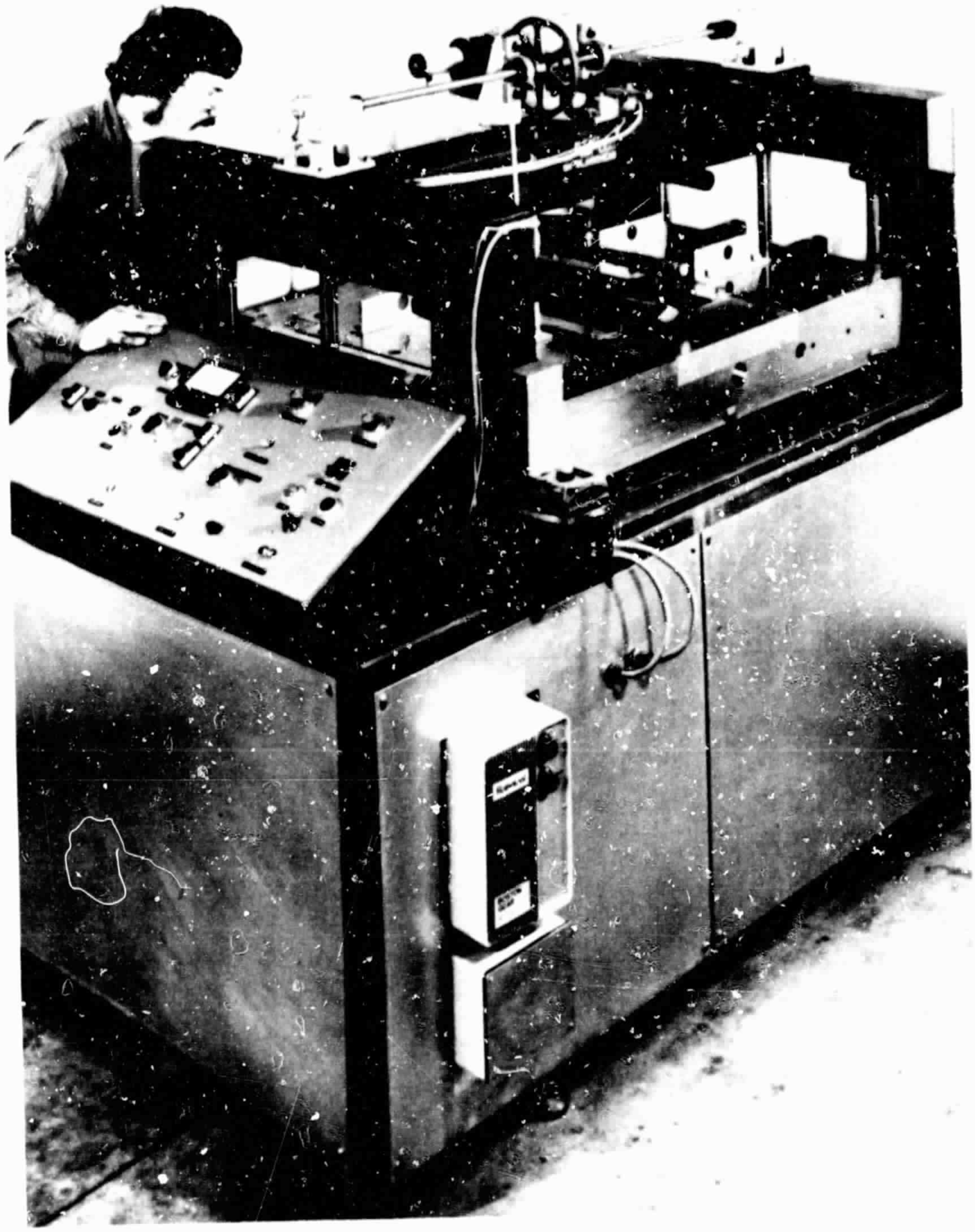
FREE ABRASIVE MULTIPLE-BLADE SAWING

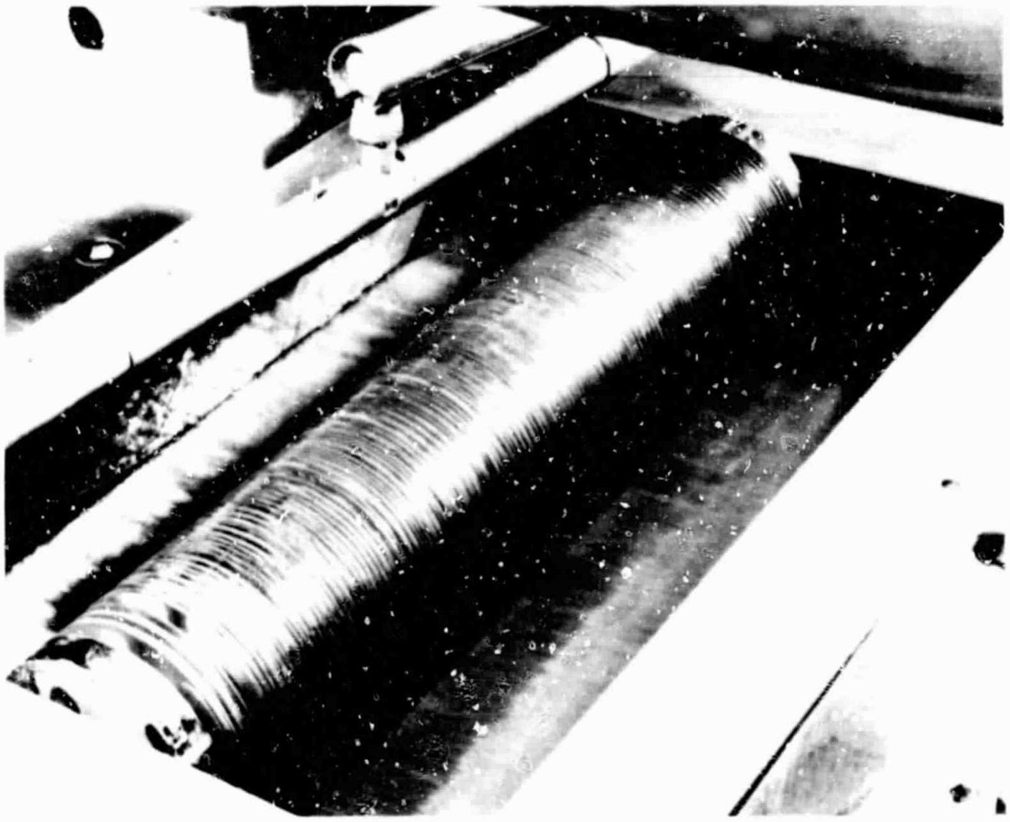
P. R. HOFFMAN CO.

TECHNOLOGY ADVANCED INGOT WAFERING	**REPORT DATE** 04/01/80
APPROACH FREE ABRASIVE MULTIPLE BLADE SAWING (MBS) **CONTRACTOR** VARIAN	**STATUS** • 21.9 WAFERS/CM (100mmØ) • ~.5 WAFER/MIN • 128 $/M² VALUE ADDED (88 SAWS) • CONTRACT AT VARIAN CLOSED OUT • FEASIBILITY STUDY AT P.R. HOFFMAN (DIVISION OF NORLIN INDUSTRIES)
GOALS • 1 M²/KG AREA CONVERSION • 25 WAFERS/CM • 95% YIELD • 1 WAFER/MIN THROUGHPUT • ~$14/M² ADD-ON COST	

Multiblade Slurry Sawing







Cost Projection (1980 $) SAMICS/IPEG

ASSUMPTIONS:

(1986 SCENARIO)

EQUIPMENT COST $77K/EA

NO. OF SAWS - 122

FLOOR SPACE TOTAL - 7300 FT^2

NO. OF OPERATORS - 30

NO. OF ASSEMBLERS - 14

MATERIALS (TOTAL/ANNUM) $1.7M

YIELD - 95%

$1M^2/KG$

LOW COST VEHICLE

66% RECLAIMED ABRASIVE

150MM Ø INGOT

4.6MM/HR CUT RATE

1000 SLICES/RUN

PROJECTION:

517,820M^2/ANNUM THROUGHPUT

19.2 $/$M^2$ VALUE ADDED

0.13 $/$W_p$ VALUE ADDED

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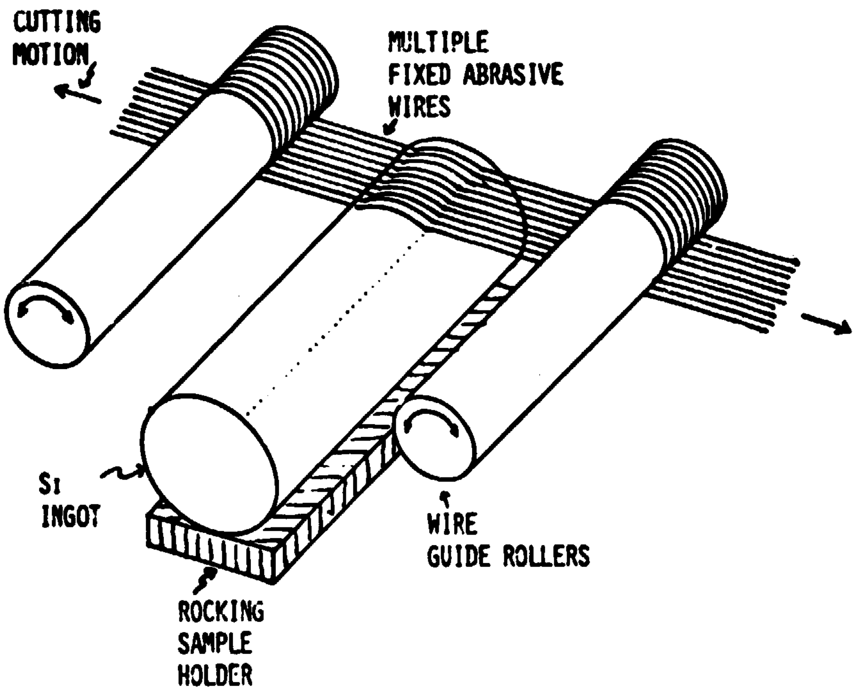
TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

INGOT SLICING

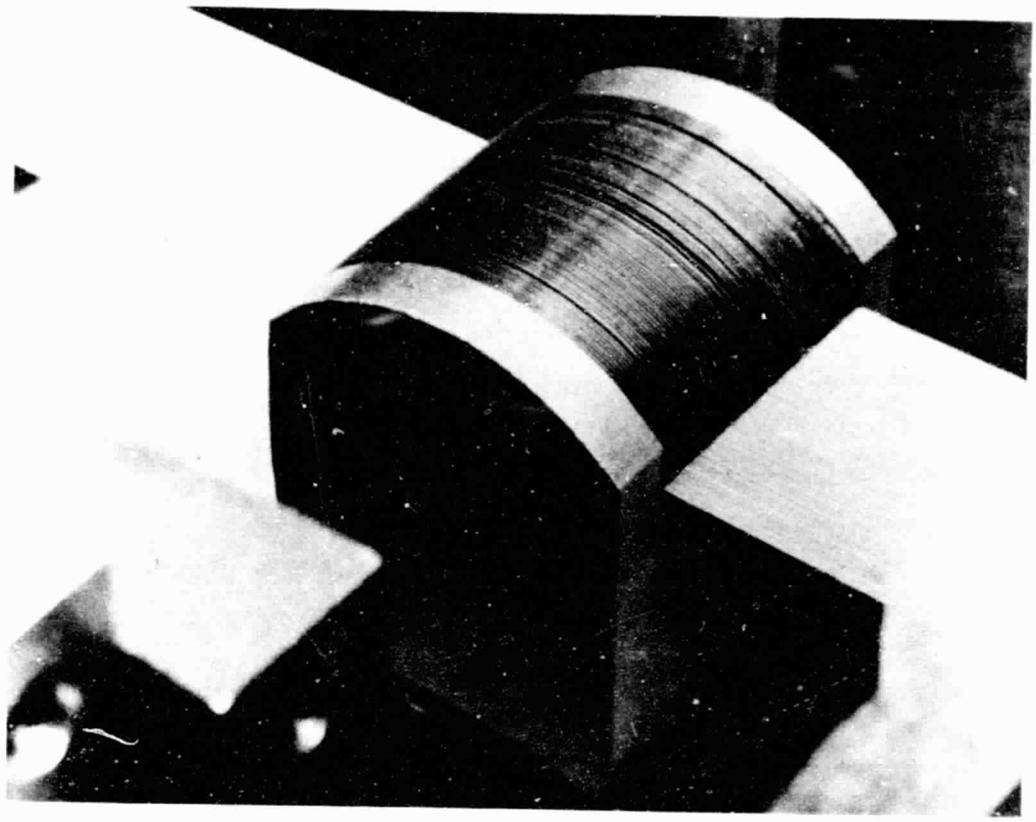
CRYSTAL SYSTEMS, INC.

TECHNOLOGY INGOT SLICING	**REPORT DATE** 03/10/80
APPROACH FIXED ABRASIVE SLICING TECHNIQUE (FAST) **CONTRACTOR** CRYSTAL SYSTEMS, INC.	**STATUS** . 10 CM DIAMETER WORKPIECE . 175 PARALLEL SLICES . 19 WAFERS/CM DEMONSTRATION OF . 0.14 MM/MIN SLICING RATE . 98% YIELD . 3 SLICES/WIRE
GOALS . 10 CM x 10 CM WORKPIECE . 750 PARALLEL SLICES . 25 WAFERS/CM . 0.1 MM/MIN. SLICING RATE . 95% YIELD . 5 SLICES/WIRE . TECHNICAL FEATURES DEMONSTRATION 12/15/80 . TECHNOLOGY READINESS 10/01/82	

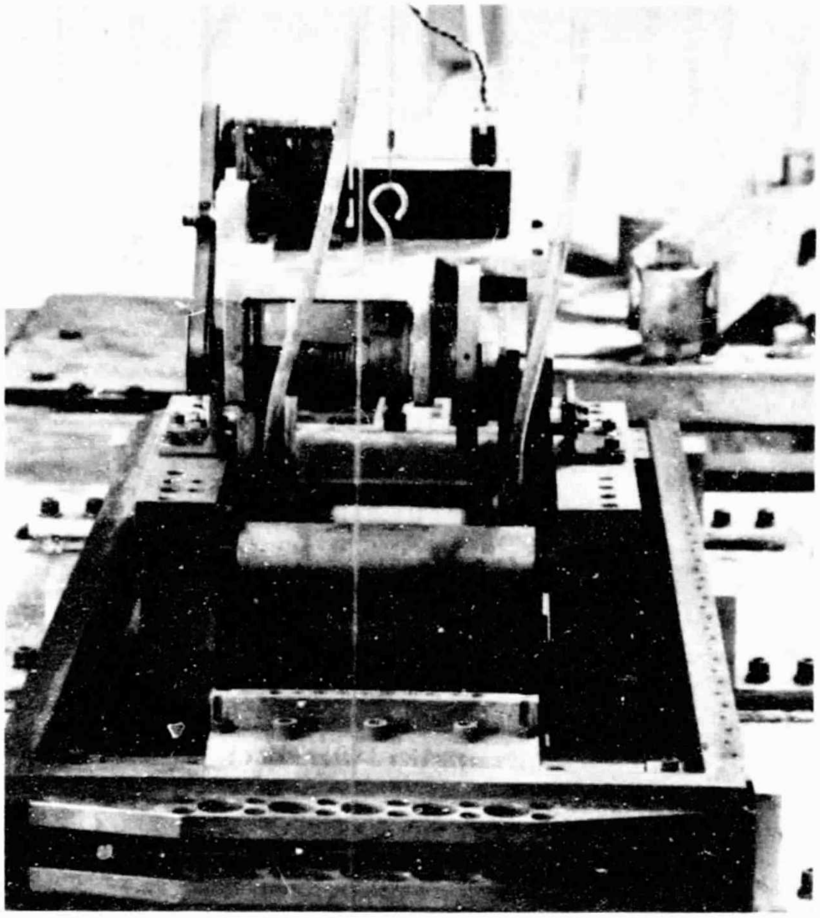
Fixed Abrasive Slicing Technique (FAST)



Multiwire



Slicer for Multiwire FAST



Testing

ACHIEVEMENTS

- 64 WAFERS/INCH (25/CM) ON 4 CM x 4 CM WORKPIECE
- 48 WAFERS/INCH (19/CM) ON 10 CM DIAMETER WORKPIECE
- LOW KERF: 6.2 MILS, 0.16 MM
- THIN WAFERS: 4 CM x 4 CM x 0.10 MM
- LOW SURFACE DAMAGE: 3 - 5 μM
- SLICING RATES: 0.14 MM/MIN ON 10 CM DIAMETER
- WIRE BLADE LIFE: 3 WAFERS/WIRE (10 CM DIAMETER)
- YIELDS: 98% ON 10 CM DIAMETER WORKPIECE

Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS:

EQUIPMENT COST - $35,000
FLOOR SPACE - 80 SQ. FT.
1 OPERATOR/10 UNITS
$70/WIRE PACK
10 SLICES PER WIRE
25 WAFERS/CM
0.1 MM/MIN SLICING RATE
1500 PARALLEL SLICES (2 WIRE PACKS/MACHINE)
10 CM x 10 CM WORKPIECE
95% YIELD
DUTY CYCLE - 95%

PROJECTION

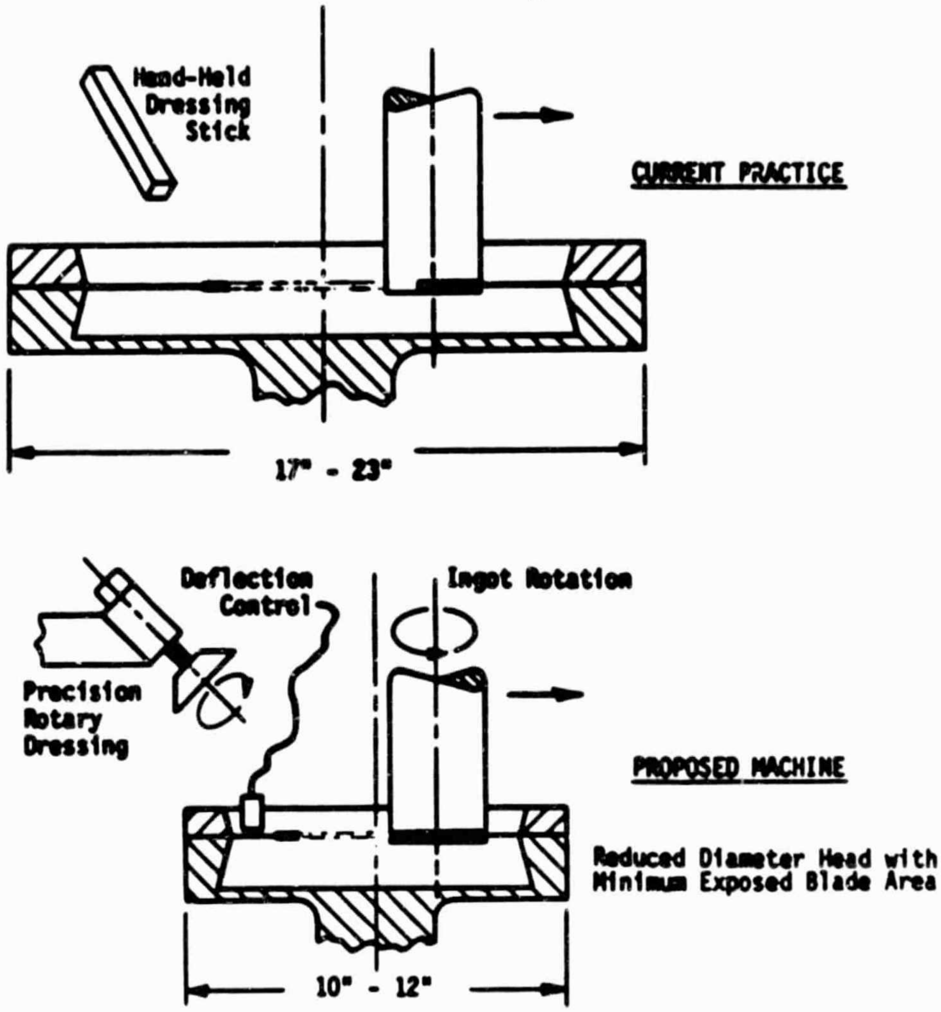
$6.48/M^2 VALUE ADDED
$0.043/W$_p$ VALUE ADDED
(ASSUMING η = 15%)

ADVANCED INGOT WAFERING

SILTEC CORP

TECHNOLOGY ADVANCED INGOT WAFERING	**REPORT DATE** 04/02/80
APPROACH ENHANCED I.D. SLICING **CONTRACTOR** SILTEC CORPORATION	**STATUS**
GOALS . 25 WAFERS/CM OF INGOT (250 μM THICK, 152 μM KERF) . 10 CM DIA WAFERS . 1.0 WAFERS/MIN . 95% YIELD . TECHNICAL FEATURES DEMO 07/30/80 . TECHNOLOGY READINESS 11/30/81	. 22 WAFERS/CM OF INGOT 0.5 WAFERS/MIN, 100 MM DIA . 25 WAFERS/CM OF INGOT 0.25 WAFERS/MIN, 100 MM DIA . 150 CM WAFERS . 0.5 WAFERS/MIN . 90% YIELD

Blade-Head Configuration



Advanced Wafering Techniques

GENERAL OBSERVATIONS	MBS	FAST	ID
INDUSTRIAL PRODUCTION EXPERIENCE	QUARTZ	NEW	SILICON
WAFERING FORMAT	MULTIPLE	MULTIPLE	SINGLE
SAW INDUCED DAMAGE	LOW	LOW	HIGH
EXPENDABLE COSTS	HIGH	LOW	LOW
MINIMUM KERF (MILS)	6	6	6
WAFER SHAPE LIMITATIONS	YES	NO?	NO

CONTRACTORS: CSI, HOFFMAN, SILTEC

TECHNICAL FEATURES	1976	1980[1]	1982[2]	COMMENTS
WAFER SIZE (CM DIA)	10	15	15,10X10[3]	[3]FOR CSI'S HEM INGOT
WAFERS/CM INGOT	16	25[4]	25	[4]FOR 10 CM DIA WAFER
WAFERS/MIN	0.4[5]	0.5[5]	0.5[6]	[5]10 CM, [6]15 CM DIA
MACHINE THRUPUT (M^2/HR)	0.2[5]	0.25[5]	0.5[6]	" "
WAFER THICKNESS (MILS)	12[5]	10[5],12[6]	10[6]	" "
KERF (MILS)	13[5]	6[5],10[6]	6[6]	" "
YIELD (%)	95	98	95	

[1]INDIVIDUAL ACCOMPLISHMENTS [2]SIMULTANEOUS ACHIEVEMENT

ID Wafering Add-on Price (1980 $) Assuming Frozen Technique

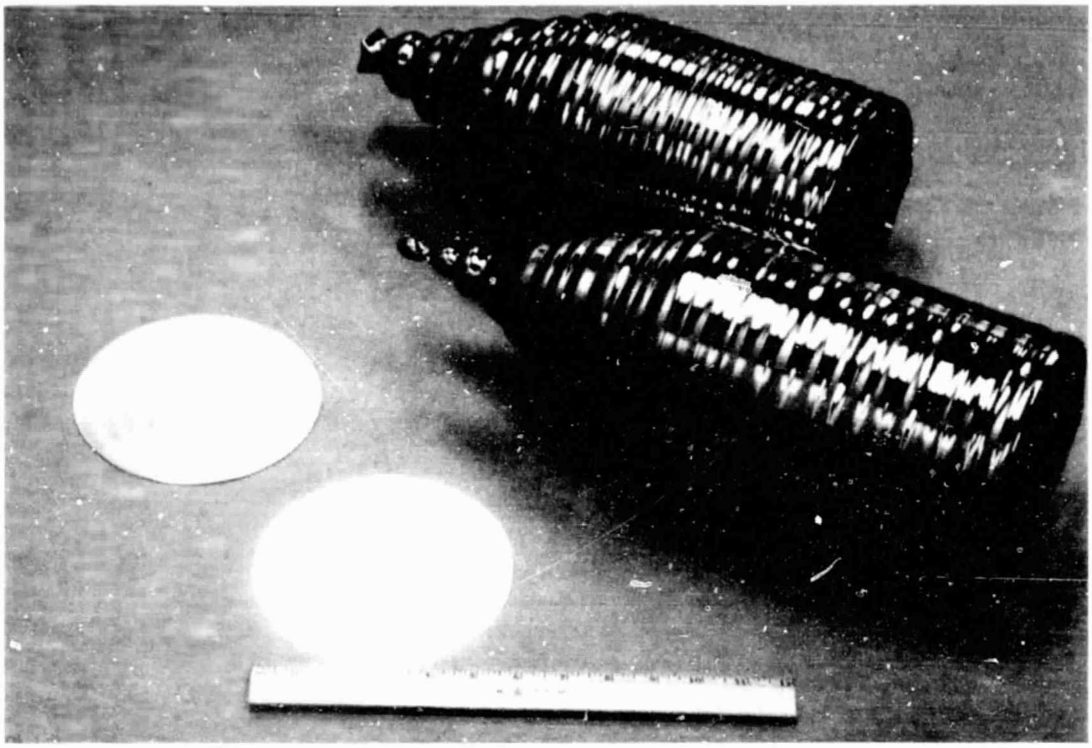
ASSUMPTIONS:

MACHINE COST	$30,000
SAWS/OPERATOR	3
INGOT DIAMETER	15 CM
WAFERS/SAW/24 HOURS	500
CUTS/BLADE	2000
WAFERING YIELD	90%

PROJECTION:

$26.0/$M^2$ WAFERING ADD-ON

$0.17/WPK ASSUMING 15% AM1



Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS: Machine cost $30,000
1 operator/6 saws
150 mm ingot diameter
Productivity/machine/24 hours 900 wafers
Cuts/blade 2000
Slicing yield 95%

PROJECTION

$10.48/m^2 wafering add on cost - 150 mm
$11.58/m^2 wafering add on cost - 100 mm

Cost Calculation Assuming Frozen Technique

ASSUMPTIONS:

INGOT SIZE ------------------------- 25 KG
INGOT DIAMETER -------------------- 15 CM
NO. INGOTS PER CRUCIBLE ----------- 6 (150 KG)
GROWTH RATE ----------------------- 7 CM/HR
CRUCIBLE DIAMETER ----------------- 14 IN
YIELD MONOCRYSTAL ----------------- 70%
NO. OPERATORS PER GROWER ---------- 1

SAMICS CALCULATION:

C_1 • EQPT ----------------------- $ 85369
C_2 • SQFT ----------------------- 27132
C_3 • DLAB ----------------------- 119624
C_4 • MATS ----------------------- 106732
C_5 • UTIL ----------------------- 19176
QUAN ----------------------------- 13454 KG/YR

GROWTH ADD-ON COST ---------------- $26.6/KG

Silicon Sheet Price Projections (1980 $)

	1976[1]	1980[2]	1982	COMMENTS
INGOT SIZE (CM DIA)	10	15	15	
GROWTH ADD-ON ($/KG)	66.2	26.6	12.8-15.6	
WAFERING ADD-ON ($/M²)	36.3[3]	26.0[3]	6.5-19.2	[3]ID WAFERING
MAT'L UTILIZATION (M²/KG)	0.75	0.82	1.08	
WAFERS/CM	17.5	19	25	
YIELD (%)	90	90	95	
SHEET ADD-ON ($/M²)	134.4	62.0	19.0-34.4	
" " ($/WPK)	0.90	0.41	0.13-0.23	ASSUMES 15% ENC. EFFIC.

[1]CURRENT SEMICONDUCTOR TECHNOLOGY OPTIMIZED FOR SOLAR APPLICATIONS

[2]TECHNICAL READINESS FEATURES EXCEPT: NO AUTOMATION, 1.6 KG/HR THRUPUT, D+K OF 14+7 MILS

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Conclusions

- TECHNICAL FEATURES REQUIRED FOR \$0.70/WPK TR HAVE BEEN INDIVIDUALLY DEMONSTRATED FOR THE CZOCHRALSKI GROWTH TECHNOLOGY.
- TECHNICAL FEATURES FOR 10 CM DIAMETER INGOT WAFERING TECHNOLOGY TR HAVE BEEN DEMONSTRATED.
- MATERIAL UTILIZATION REQUIRED FOR 15 CM DIAMETER INGOT TR NEEDS MORE TIME FOR DEMONSTRATION.
- 'FREEZING' THE CURRENT DEMONSTRATED GROWTH AND WAFERING TECHNOLOGY RESULTS IN A POTENTIAL ARRAY PRICE OF \$1.00 - \$1.50/WPK AT TECHNICAL READINESS.

ENGINEERING AREA

PLENARY SESSION **R. G. Ross Jr., Chairman**

PHOTOVOLTAIC CIRCUIT DESIGN WORKSHOP
March 31-April 1, 1980

JET PROPULSION LABORATORY

Objective

PROVIDE DESIGN STRATEGIES AND GUIDELINES TO MAXIMIZE MODULE AND ARRAY RELIABILITY THROUGH FAULT-TOLERANT CIRCUITRY DESIGN

Agenda

MARCH 31

2:30	INTRODUCTION	ROSS/GONZALEZ
3:00	BACKGROUND REVIEW	
	● NOMENCLATURE	ROSS
	● STATISTICS	WEAVER
	● DESIGN CONSTRAINTS	SUGIMURA

APRIL 1

8:00	MISMATCH LOSSES	GONZALEZ/COX
8:40	MANUFACTURING YIELD	GONZALEZ
9:20	HOT-SPOT HEATING	ROSS
10:00	COFFEE	
10:15	ARRAY FAULT TOLERANCE	GONZALEZ
11:30	LUNCH	
12:30	OVERALL DESIGN OPTIMIZATION	WEAVER
1:15	SIMPLIFIED DESIGN METHOD	ROSS
1:45	EXAMPLE PROBLEMS	ROSS/GONZALEZ
3:00	COFFEE	
3:30	DISCUSSION OF PROBLEMS	ALL

Attendance Summary

DISCIPLINE		PERSONS
MODULE MANUFACTURERS		25
CONCENTRATOR MANUFACTURERS		3
PHOTOVOLTAIC DEVICE DEVELOPMENT		5
RELIABILITY RESEARCH AND STANDARDS		5
SYSTEMS MANUFACTURES AND A&E		13
NATIONAL LABS (NON -JPL)		7
MODULE WIRING MANUFACTURERS		3
	TOTAL	61

Array Performance Worksheet

MECHANICAL CONFIGURATION

Module Size, m x m = ______ x ______
Module Area, (A), m^2 = ______
Panel Size, m x m = ______ x ______
Cell Contact Pattern = ______

ELECTRICAL CONFIGURATION

Total Cells per Module = ______
Series Cells per Module = ______
Parallel Cells per Module = ______
Series Blocks per Module = ______
Diodes per Module = ______
Series Cells per Branch Circuit (NS) = ______
Parallel Cells per BC = ______
Series Blocks per BC (SB) = ______
Diodes per BC = ______
Series Cells per Diode = ______
Cells per Substring (NC) = NS/SB = ______

SYSTEM ELECTRICAL EFFICIENCY

Encapsulated Cell Efficiency = ______
NOCT Efficiency = ______
Cell Mismatch Efficiency = ______
Cell Packing Efficiency = ______
Array Soiling Efficiency = ______
Array Wiring Efficiency = ______
Power Conditioning Efficiency = ______
Total Plant Efficiency = ☐

FAILURE STATISTICS

Cracked Cell Density - Mfg/Shipping = ______
Failed Cell Density - Mfg/Shipping = ______
Cell Cracking Rate - Field Exposure = ______
Cell Failure Rate - Field Exposure (F) = ______
Module Yield (Mfg/Shipping) = ☐

ARRAY INITIAL COSTS ($/$m^2$ of Array)

Module Cost before Cell Breakage (C_M) = ______
Module Yield Cost (C_Y) = (1/yield - 1) x C_M = ______
Panel Frame Structure & Assembly = ______
Panel Wiring = ______
Panel Installation = ______
Installed Field Structure & Foundations = ______
Land and Preparation = ______
Total = ☐

ARRAY REPLACEMENT COST ($/Module Failure)

Fault Identification = ______
Field Substitution Labor = ______
Module Repair/Replacement Labor = ______
Replacement Module Parts (C_M + C_Y) x A = ______
Total = ☐

BALANCE-OF-PLANT LIFE-CYCLE COST ($/kW) = ☐

LIFE-CYCLE COST DISCOUNT RATE (k) = ______

ANNUAL INCIDENT INSOLATION (kW-h/m^2/yr) = ☐

LIFE-CYCLE ENERGY FRACTION (ϵ_{LC})

- For Module Replacement Each Cell Failure:

$\epsilon_{LC1} = a_{\overline{n}|} = (1-(1+k)^{-20})/k$ = ☐

- For No Module Replacement:

$$\begin{pmatrix}\text{Array Substring}\\ \text{5-year Failure}\\ \text{Density}\end{pmatrix} = 1-(1-5 \times F)^{NC} = \_\_\_\_\_\_$$

5-year Power Loss Fraction (from plot) = ______

ϵ_{LCO} = ☐ (from plot)

LIFE-CYCLE O&M COSTS ($/$m^2$ of Array)

- For Module Replacement Each Cell Failure:

$$\text{LCOM1} = \frac{\begin{pmatrix}\text{Cost per}\\ \text{Replacement}\\ \text{Action, \$}\end{pmatrix} \times \begin{pmatrix}\text{Cell}\\ \text{Failure}\\ \text{Rate}\end{pmatrix} \times \begin{pmatrix}\text{Cells}\\ \text{per}\\ \text{Module}\end{pmatrix} \times a_{\overline{n}|}}{(\text{Module Area, m}^2)}$$

= ____ x ____ x ____ x ____ / ____

= ☐

- For No Module Replacement:

LCOMO = Minor Upkeep Cost ≈ 0

LIFE-CYCLE COST PERFORMANCE CALCULATION

$$\frac{\$}{\text{kWh}} = \frac{\left(\begin{matrix}\text{Balance}\\ \text{of Plant}\\ \text{Cost, \$/kW}\end{matrix}\right) + \frac{\left(\begin{matrix}\text{Initial}\\ \text{Array}\\ \text{Cost/m}^2\end{matrix} + \begin{matrix}\text{Array}\\ \text{L-C O\&M}\\ \text{Cost/m}^2\end{matrix}\right)}{\left(\begin{matrix}\text{Plant}\\ \text{Efficiency}\\ \text{100mW/cm}^2\text{, NOCT}\end{matrix}\right)}}{\left(\begin{matrix}\text{Annual}\\ \text{Insolation}\\ \text{kW-h/m}^2\text{/yr}\end{matrix} \times \begin{matrix}\text{L-C Energy}\\ \text{Fraction}\end{matrix}\right)}$$

- For Module Replacement Each Cell Failure:

$$= \frac{(\quad) + \frac{(\quad) + (\quad)}{(\quad)}}{(\quad) \times (\quad)} = \boxed{\quad}\ \$/\text{kW-h}$$

- For No Module Replacement:

$$= \frac{(\quad) + \frac{(\quad) + (\ 0\ )}{(\quad)}}{(\quad) \times (\quad)} = \boxed{\quad}\ \$/\text{kW-h}$$

HOT SPOT HEATING

Cell Shunt Resistance = ______
Power Dissipation (cracked cell) P/P_{max} = ______
(open circuit) P/P_{max} = ______
Temperature above Ambient (cracked), °C = ______
(open), °C = ______
Cracked Cell Heating: OK __ , Marginal __ , Bad __
Open Circuit Heating: OK __ , Marginal __ , Bad __

COMMENTS: ______________________

TECHNOLOGY DEVELOPMENT AREA
Silicon Material Task

TECHNOLOGY SESSION — Tony Briglio, Chairman

Eight contractors and JPL personnel reported on progress in developing silicon production processes and in supporting activities.

Energy Materials Corp. reported that construction of the prototype system for their process was completed, and portions of it were tested. A hydrogen leak precluded a full test. The Union Carbide Corporation is proceeding with design and engineering of the 100-MT/yr EPSDU (Experimental Process System Development Unit) for making silicon (Si) by the silane-to-silicon process. Equipment procurement and fabrication are under way. Massachusetts Institute of Technology presented results of their study of the hydrochlorination of metallurgical-grade Si to produce trichlorosilane ($SiHCl_3$), in support of the Union Carbide Corp. effort (in the UCC process, $SiHCl_3$ is converted to silane).

Battelle Columbus Laboratories reported on problems encountered in efforts to start up the PDU (Process Development Unit), in which the process based on zinc reduction of silicon tetrachloride will be studied. Battelle also reported on results of experiments aimed at reducing the amount of zinc in the product Si.

Hemlock Semiconductor Corp., which is developing a process to produce Si by chemical vapor deposition from dichlorosilane (SiH_2Cl_2), described progress in characterizing the performance of an experimental reactor, in which the Si deposition rate from SiH_2Cl_2 is double that from $SiHCl_3$ and the energy use is substantially reduced. AeroChem Research Laboratories reported on their process, the reduction of silicon halides by alkali metals. A laboratory-scale apparatus is making small batches of Si at a nominal rate of 0.5 kg/h.

In the area of impurity studies, the Westinghouse R&D Center reported on its work on the effects of impurities on solar cell performance.

As part of the supporting studies now under way, Lamar University described initial efforts in analysis of the Hemlock process. Jet Propulsion Laboratory personnel presented results of work on the continuous-flow pyrolyzer, on fluidized bed reactors, and on a scheme for producing molten Si directly from silane.

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

TECHNOLOGY DEVELOPMENT AREA: Silicon Material Task

GASEOUS MELT REPLENISHMENT SYSTEM

ENERGY MATERIALS CORP.

TECHNOLOGY PRODUCTION OF SOLAR GRADE SILICON	**REPORT DATE** APRIL 3, 1980
APPROACH H_2 REDUCTION OF $HSiCl_3$/MELTING OF DEPOSITED SILICON TO REPLENISH CZOCHRALSKI CRYSTAL GROWTH CRUCIBLE **CONTRACTOR** ENERGY MATERIALS CORPORATION **GOALS** DESIGN, CONSTRUCT AND DEMONSTRATE SYSTEM OPERATION SYSTEM FOR 24 HRS. OPTIMIZE REACTION VESSEL DESIGN OPERATE SYSTEM FOR 96 HOURS DESIGN, CONSTRUCT AND DEMONSTRATE DELIVERY TUBE INTEGRATE DEPOSITION VESSEL, DELIVERY TUBE AND CZOCHRALSKI GROWER FOR A 1 WEEK CONTINUOUS RUN PRODUCE ½KG/HR. @ 18% CONVERSION	**STATUS** - DESIGN, CONSTRUCTION OF A PROTOTYPE SYSTEM HAS BEEN COMPLETED

Cost Projections (1980$) SAMICS/IPEG

ASSUMPTIONS:
- CURRENT PRICE (80¢/LB) TRICHLOROSILANE
- 1 VESSEL/10 DAYS @ $1,000 EACH
- 100% OVERHEAD
- 10 DAY RUN, 24 HRS/ DAY

CASE 1.
- NO RECYCLE OF HALOSILANE BY-PRODUCTS
- 30% CONVERSION OF TRICHLOROSILANE TO SILICON
- 1 OPERATOR, FULL TIME

CASE 2.
- RECYCLE OF HALOSILANES; THEREFORE, 100% CONVERSION TO SILICON
½ OPERATOR, FULL TIME

PROJECTION

CASE 1. $80/ KG SILICON

CASE 2. $35/KG SILICON

C-2

Cost Projections (1980$) SAMICS/IPEG

ASSUMPTIONS:

PLANT SIZE:	1000 MT/YR SEMI-CONDUCTOR 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

DCF RATE, %	PRODUCT COST, $/KG
10	8.77
15	9.77
20	10.90

Problems and Concerns

EPSDU ENGINEERING & CONSTRUCTION

- DUE TO UNUSUALLY HIGH RATE OF INFLATION, COST OF CONSTRUCTION SUBCONTRACTS MAY BE HIGH.
- FREE-SPACE REACTOR DESIGN NOT FINALIZED YET. TWO MONTH DELAY ANTICIPATED.
- MELTER/CONSOLIDATOR SUBCONTRACT WAS JUST SIGNED. WE ARE CONFIDENT THAT AN ACCEPTABLE EQUIPMENT SUITABLE FOR EPSDU WILL BE DEVELOPED ON TIME, BUT WE WILL NOT KNOW FOR SURE FOR ANOTHER SIX MONTHS.

Silane-Silicon EPSDU Process Improvements

- SMALLER HYDROGENATION REACTOR - BASED ON JEFF MUI'S NEW DATA OBTAINED AT MIT
- SMALLER SILANE DISTILLATION COLUMN - CHANGED FROM 12 IN. DIA TRAYED COLUMN TO 8 IN. DIA PACKED COLUMN
- SIMPLER WASTE TREATMENT SYSTEM - NEUTRALIZATION WITH CAUSTIC SODA INSTEAD OF RECOVERING MARKETABLE MURIATIC ACID
- LESS LABOR INTENSIVE MELTER/CONSOLIDATOR - CHANGED FROM SUCTION CASTING TO SHOTTING
- NUMEROUS SMALL CHANGES THROUGHT THE PROCESS TO IMPROVE OPERABILITY AND TO REDUCE CAPITAL/OPERATING COST

Problems and Concerns

- ACHIEVING GREATER THAN 18% CONVERSION EFFICIENCY
- COLLECTION OF SILICON WITHIN VESSEL IN POWDER FORMATION CASES
- QUARTZ VESSEL LIFETIME
- U-TUBE SEALING

POLYCRYSTALLINE SILICON

UNION CARBIDE CORP.

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	04/02/80
APPROACH HIGH-PURITY SILANE PRODUCTION FROM METALLURGICAL-GRADE SILICON; AND SILANE PYROLYSIS AND CONSOLIDATION TO FORM SEMI-CONDUCTOR GRADE POLYCRYSTALLINE SILICON **CONTRACTOR** UNION CARBIDE CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY AND ENGINEERING PRACTICALITY. • ESTABLISH TECHNOLOGY READINESS USING "EPSDU" SIZED TO 100 MT/YR IN 1982. • SILICON PRICE OF LESS THAN $14/KG FOR HIGH VOLUME PROCESS. • DEFINE PROCESS ECONOMICS.	**STATUS** DESIGN & ENGINEERING WORK ON THE EPSDU • GENERAL FACILITY REQUIREMENTS SPECIFIED • DETAILED EQUIPMENT SPECIFICATIONS WRITTEN • EQUIPMENT PROCUREMENT INITIATED IN FEBRUARY • SITE & FACILITY LAYOUT COMPLETED • EPSDU GROUND BREAKING TARGETED IN JULY SILANE PYROLYSIS R & D • A LONG DURATION RUN WITH THE FREE-SPACE REACTOR PDU SUCCESSFUL. • A SUBCONTRACT WORK ON POWDER MELTING AND SOLIDIFYING WAS SIGNED, AND WORK IS UNDERWAY. • DESIGN OF FLUID-BED PYROLYSIS PDU HAS STARTED. • THE EPSDU Q.C. SYSTEM WAS FINALIZED, AND KEY PIECES OF EQUIPMENT ARE BEING BUILT FOR TESTING PRIOR TO INSTALLATION.

Free-Space Reactor PDU

PURPOSE:

- TO MAKE A LONG DURATION RUN AT A HIGH THROUGHPUT (5 LB/HR)
- TO ATTAIN A HIGH SILANE CONVERSION RATE OF 99% OR BETTER
- TO DESIGN A FSR FOR THE EPSDU

STATUS:

- A LONG DURATION RUN OF 24 HOURS WAS SUCCESSFUL (SILANE FLOW: 4.3 LB/HR, REACTOR TEMPERATURE: 1600°F, PRESSURE: 20.7 PSIA)
- CONVERSION EFFICIENCY WAS 99.6%

PROBLEMS:

- SILANE REGULATOR FAILED DUE TO JT FREEZING. PREHEATING SILANE TO 100°F AND REPLACING THE REGULATOR FROM MATHESON TO LINDE SOLVED THE PROBLEM
- POWDER SCRAPER STUCK DURING UP-STROKE. IMPROVED SHAFT/ SEAL DESIGN SOLVED THE PROBLEM
- QUARTZ LINER BROKE DURING THE RUN. LINER WILL BE SPRING LOADED TO MINIMIZE THERMAL SHOCK

Melting and Consolidation System

- A SUBCONTRACT WAS AWARDED TO HAMCO DIVISION, KEYEX CORPORATION, AND WORK STARTED ON 3/1/80
- HAMCO WILL DESIGN AND TEST A PDU IN AN 18-MONTH PROGRAM, CULMINATING IN A DETAILED DESIGN PACKAGE SUITABLE FOR THE EPSDU SYSTEM
- A GOAL OF THE PROGRAM IS THAT THE PDU BUILT BY HAMCO IS SUITABLE FOR INSTALLATION IN THE EPSDU
- THE PRODUCT WILL BE 0.5 TO 2 MM DIA SHOTS, IDEAL FOR SUBSEQUENT PROCESSING

Fluidized-Bed Pyrolysis

PURPOSE

- TO DEVELOP AN INEXPENSIVE METHOD OF PYROLIZING SILANE INTO HIGH-PURITY POLYCRYSTALLINE SILICON

STATUS

- OPTIMUM SILANE FEED CONCENTRATION, TEMPERATURE, AND DEPOSITION RATE DETERMINED IN A FIXED BED
- DIRECT HEATING OF THE BED WAS SUCCESSFUL THROUGH HIGH-FREQUENCY CAPACITIVE HEATING
- LARGE PARTICLES (PRODUCT) WERE SEPARATED IN A BOOT FOR REMOVAL FROM THE BED
- FLUIDIZED BED PDU IS UNDER DESIGN

Conclusion

- EPSDU ENGINEERING - OCTOBER 81 START-UP STILL VALID
- EPSDU EQUIPMENT & ENGINEERING COSTS - STILL ACCORDING TO BUDGET
- EPSDU CONSTRUCTION SUBCONTRACT COST - COULD BE HIGHER THAN BUDGETED, WON'T KNOW UNTIL BIDS ARE RECEIVED THIS SUMMER
- FREE-SPACE REACTOR – NO SERIOUS PROBLEMS ANTICIPATED
- MELTING & CONSOLIDATION - PROGRAM JUST STARTED. CONFIDENT.
- FLUIDIZED BED PYROLYSIS - THE PDU DESIGN JUST STARTED. RESULTS SO FAR ARE ENCOURAGING.

POLYCRYSTALLINE SILICON

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TECHNOLOGY	REPORT DATE
POLYCRYSTALLINE SILICON	APRIL 2, 1980 15TH PIM
APPROACH HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE 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 MEASURED AS A FUNCTION OF • TEMPERATURE 400°-550°C • PRESSURE 300 AND 500 PSIG • $H_2/SiCl_4$ RATIO 1.0 AND 2.8 II EFFECT OF CATALYST ON REACTION RATE MEASURED IN THE PRESENCE OF • 5% CEMENT COPPER • 5% CUPROUS CHLORIDE III COPPER CATALYST SIGNIFICANTLY INCREASES THE RATE OF THE HYDROCHLORINATION REACTION IV 500 PSIG RATE DATA CONFIRM THE MASS TRANSFER REQUIREMENT FOR THE UNION CARBIDE EPSDU

Reaction Mechanism: Role of Copper

FACTS

(1) AN INDUCTION PERIOD IS OBSERVED WITH COPPER OXIDE BASE CEMENT COPPER

$$CuO,\ Cu_2O,\ Cu^\circ + H_2 \longrightarrow Cu^\circ + H_2O$$

(2) NO INDUCTION PERIOD FOR CUPROUS CHLORIDE FOR THE KNOWN REACTION,

$$CuCl + Si \longrightarrow \underset{\text{ALLOY}}{Cu\text{-}Si} + SiCl_4$$

(3) ONCE ACTIVATED BOTH CEMENT COPPER AND CuCl GAVE THE SAME CATALYTIC ACTIVITY

Conclusion

- INDUCTION PERIOD FOR CEMENT COPPER IS THE TIME REQUIRED FOR THE Cu-Si ALLOY FORMATION

$$Cu^{\circ} + Cl^{-} \longrightarrow CuCl$$
$$CuCl + Si \longrightarrow Cu\text{-}Si + SiCl_4$$

- FACT (3) SUGGESTS A COMMON CATALYTIC SPECIES FOR THE HYDROCHLORINATION REACTION REGARDLESS OF WHAT FORM OF COPPER IS USED INITIALLY

- THE ACTIVE CATALYTIC SPECIES IS THE COPPER-SILICON ALLOYS

Summary

(1) COPPER CATALYZES THE HYDROCHLORINATION OF $SiCl_4$ TO $SiHCl_3$

(2) REACTION RATE INCREASED BY ~100%

(3) CUPROUS CHLORIDE IS THE PREFERRED CATALYST OVER CEMENT COPPER, FOR

- CuCl REACTIVE 100% OF THE Si MASS LIFE VERSUS 75% FOR CEMENT COPPER

- WITH CuCl, COPPER IS IMMEDIATELY PLATED ONTO Si METAL SURFACE ELIMINATING THE LOSS OF FINELY DIVIDED COPPER BY ELUTRIATION

Future Work

- COPPER CATALYST CONCENTRATION STUDIES, 2.5 WT% AND 1.0 WT%

- PARTICLE SIZE DISTRIBUTION (SURFACE AREA)

- IMPURITIES IN M.G. SILICON

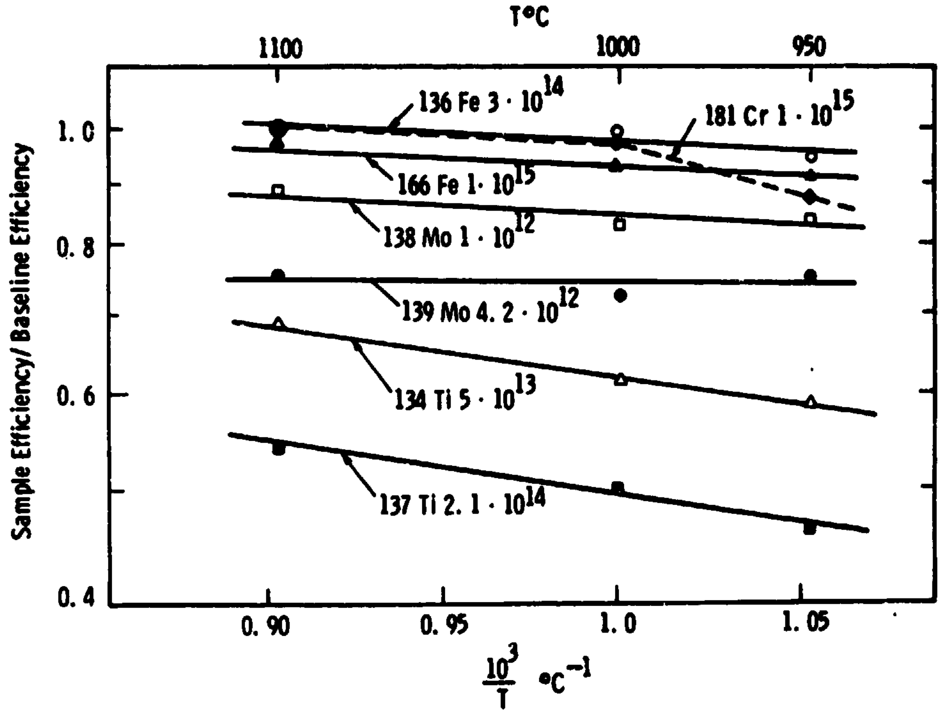
TECHNOLOGY DEVELOPMENT AREA: Silicon Material Task

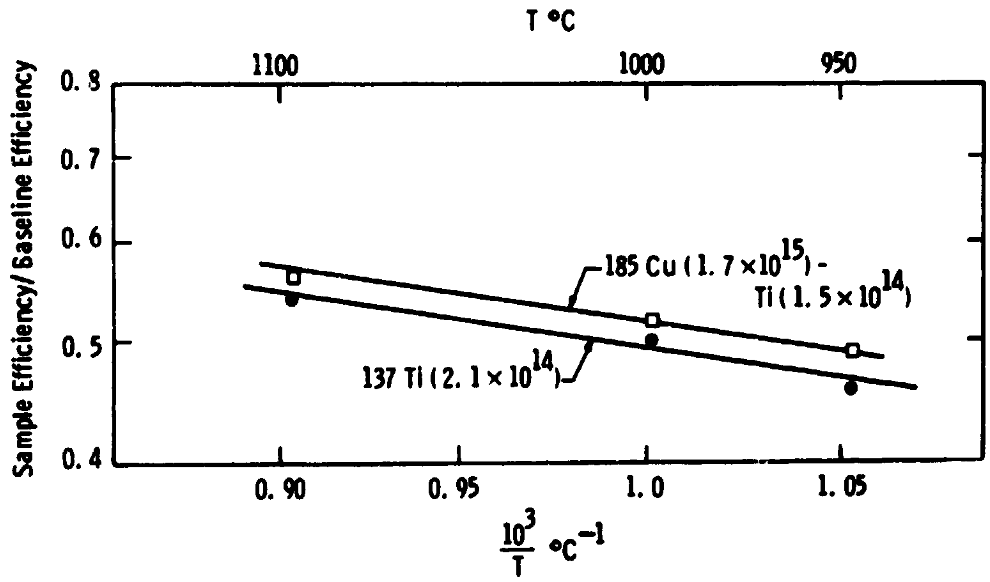
IMPURITY EFFECTS IN SILICON

WESTINGHOUSE ELECTRIC CORP.
R&D CENTER

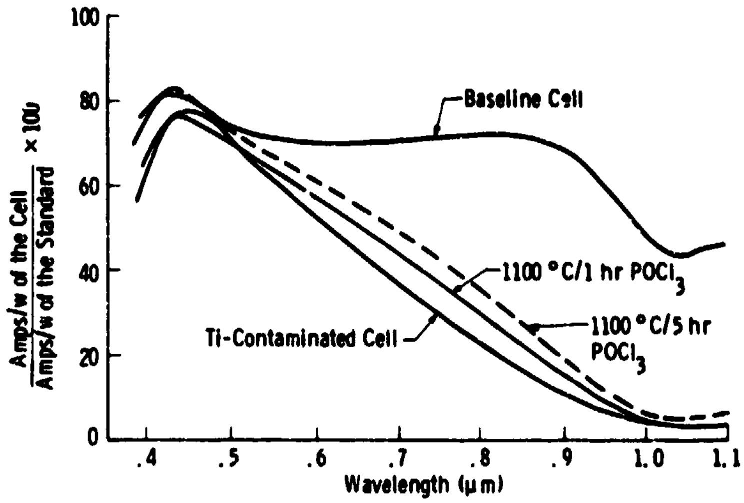
Technology Impurity effects in silicon	**Report Date** 04/03/80
Approach Analysis of silicon material and solar cells with controlled impurity additions **Contractor** Westinghouse Electric Corp., R&D Center	**Status** (1) Phase III completed; Two volume summary report issued (2) Major Conclusions: • Efficiency loss mainly impurity-induced lifetime reduction • W, Ta, Mo, Ti, V, most harmful; Cu, Ni, Al, P, least • Impurity anisotropy minimal in large CZ ingots • Impurity synergy minimal • $HCl/POCl_3$ gettering can raise cell efficiency up to 2% in some cases. • Long term impurity degradation is species dependent (3) Phase IV Initiated
Phase IV **Goals** Evaluate impurity effects in: • Polycrystalline silicon • High efficiency cells • Experimental silicon materials • Cells subjected to processing, e.g. gettering • Cells treated to simulate long term behavior	

$POCl_3$ Gettering

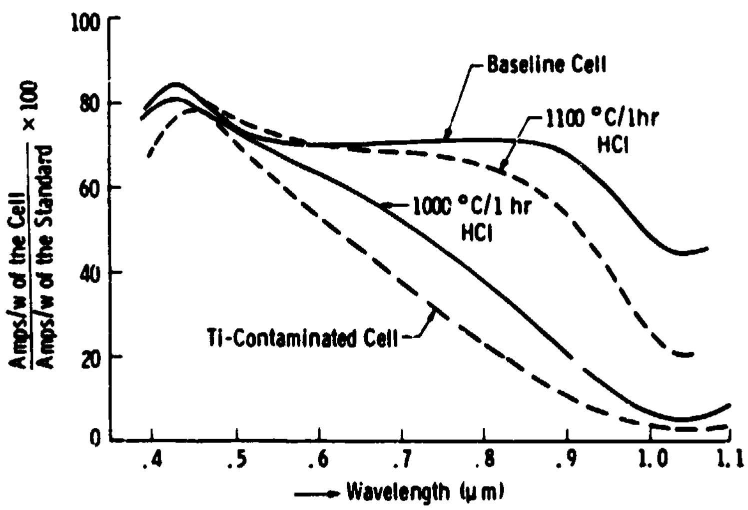




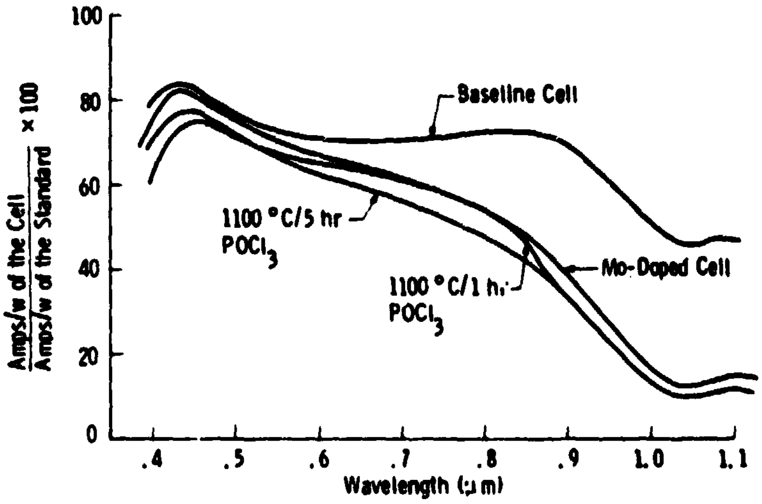
$POCl_3$ Gettering of Ti

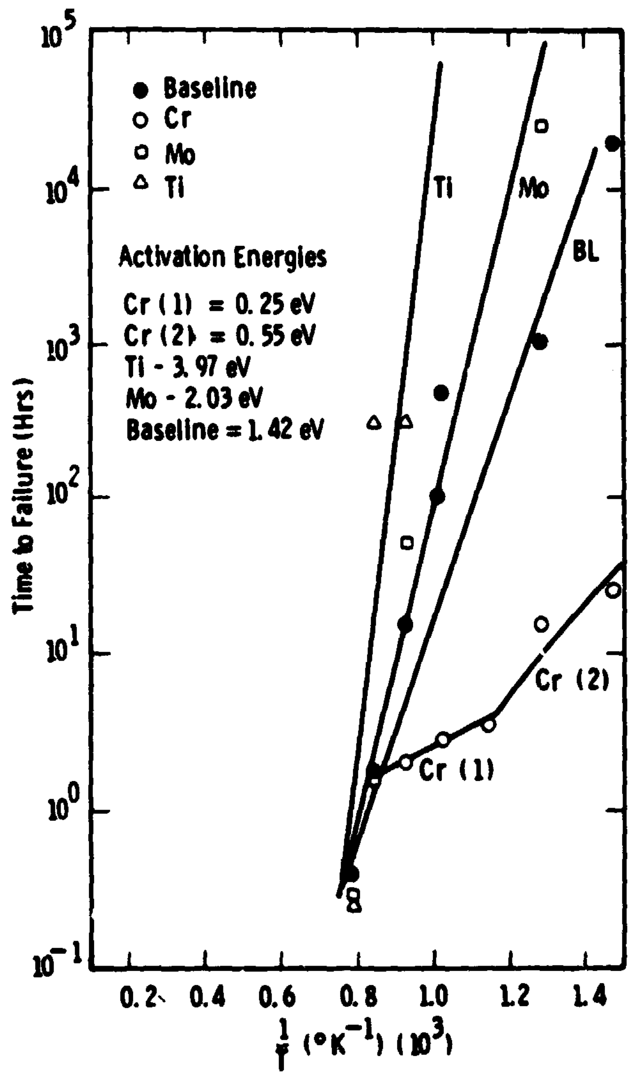


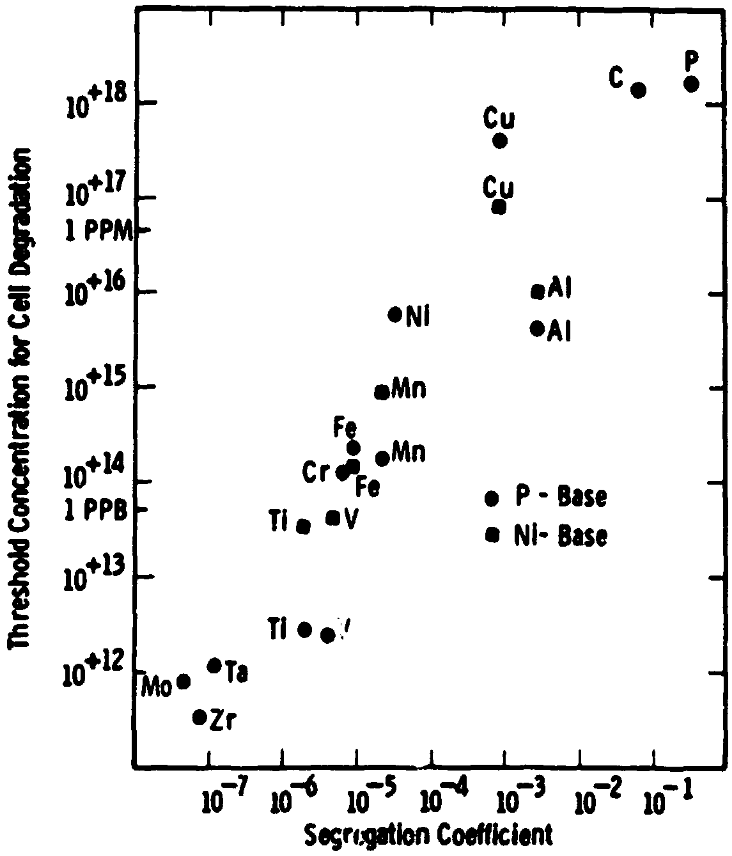
HCl Gettering of Ti



$POCl_3$ Gettering of Mo






Threshold Concentration for Cell Degradation
10^{+18}
10^{+17}
1 PPM
10^{+16}
10^{+15}
10^{+14}
1 PPB
10^{+13}
10^{+12}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
Segregation Coefficient
P
C
Cu
Cu
Al
Al
Ni
Mn
Fe
Mn
Cr
Fe
Ti
V
Ti
Mo
Ta
Zr
P - Base
Ni- Base

POLYCRYSTALLINE SILICON
ZINC VAPOR REDUCTION OF SILICON TETRACHLORIDE IN A FLUIDIZED BED OF SEED PARTICLES

BATTELLE COLUMBUS LABORATORIES

TECHNOLOGY	REPORT DATE
TASK I: POLYCRYSTALLINE SILICON	MARCH 18, 1980
APPROACH PREPARATION OF SILICON BY ZINC REDUCTION OF SILICON TETRACHLORIDE **CONTRACTOR** BATTELLE COLUMBUS LABORATORIES **GOALS** • DEMONSTRATE PROCESS FEASIBILITY • ESTABLISH TECHNICAL READINESS IN 1982 BY OPERATION OF EPSDU SIZED TO 50 MT/yr • SILICON PRICE OF LESS THAN $14/kg FOR HIGH-VOLUME PROCESS • DEFINE PROCESS ECONOMICS	**STATUS** • PROCESS FEASIBILITY DEMONSTRATED ON LABORATORY SCALE. • WEB DENDRITE GROWN FROM FREE-FLOWING GRANULAR PRODUCT YIELDED 12.8% AM1 CELLS. • PROCESS DEVELOPMENT UNIT (25MT/yr, BATCH-WISE OPERATION) READY FOR OPERATION. • ECONOMIC ANALYSES INDICATE COST WITHIN $14/kg GOAL. • ALTERNATIVE ROUTES TO MINIMIZATION OF RESIDUAL ZINC CONTENT BEING STUDIED.

COST PROJECTIONS ($ 1980)

ASSUMPTIONS

1000 MT Si/YEAR PRODUCTION LEVEL

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

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

PROJECTION

	2 REACTORS 6 CELLS	2 REACTORS 2 CELLS	1 REACTOR 2 CELLS	1 REACTOR 1 CELL
BCL (0% ROI)	$ -	$ 11.66/KG	$ -	$ 10.29/KG
LAMAR (0% ROI)	12.08/KG	-	11.08/KG	-
LAMAR (10% ROI)	15.80/KG	-	14.13/KG	-
LAMAR (15% DCF)	16.01/KG	-	14.31/KG	-

Problems and Concerns

- OPERABILITY OF COMPLEX EQUIPMENT AT HIGH TEMPERATURES, UNUSUAL REACTANTS
- IN-PROCESS ELIMINATION OR POST-PROCESS REMOVAL OF 100 TO 3000 PPMW RESIDUAL ZINC IN GRANULES
- ULTIMATE PRODUCT PURITY RELATIVE TO MATERIALS OF CONSTRUCTION

Residual Zinc in Silicon Granules

CONDITION: HIGHLY SEGREGATED, UP TO 2.5 W/O IN 1 μm^3 VOLUME. (2-PHASE, SOLUBILITY = 0.5 PPMW AT 1100 C)

RANGE: 100 TO 3000 PPMW IN DEPOSITED SILICON DEPENDING UPON REACTOR GEOMETRY AND RUN CONDITIONS.

ORIGIN: APPARENTLY RESULT OF OCCLUSION OF MIST DROPLETS FROM ZINC VAPORIZER.

CORRECTION: IN-PROCESS: ELIMINATE ZN MIST (OR RAISE FLUIDIZED BED TEMPERATURE?)

POST-PROCESS: VACUUM OR ATMOSPHERE HEAT TREATMENT

Zinc Diffusion Studies

OBJECTIVE:

OBTAIN GENERAL OUTGASSING EQUATION RELATING TIME, TEMPERATURE, GRANULE SIZE, DEPOSIT THICKNESS, CONCENTRATION

APPROACH:

MEASURE ZINC EVOLUTION FROM GRANULES IN HEATED END OF EVACUATED QUARTZ TUBES AS FUNCTION OF TIME AND TEMPERATURE

SILICON SAMPLES USED:

RUN 96, 250 μM DIA, 12% SEED, 2300 PPMW ZN
RUN 50, 318 μM DIA, 50% SEED, 150 PPMW ZN

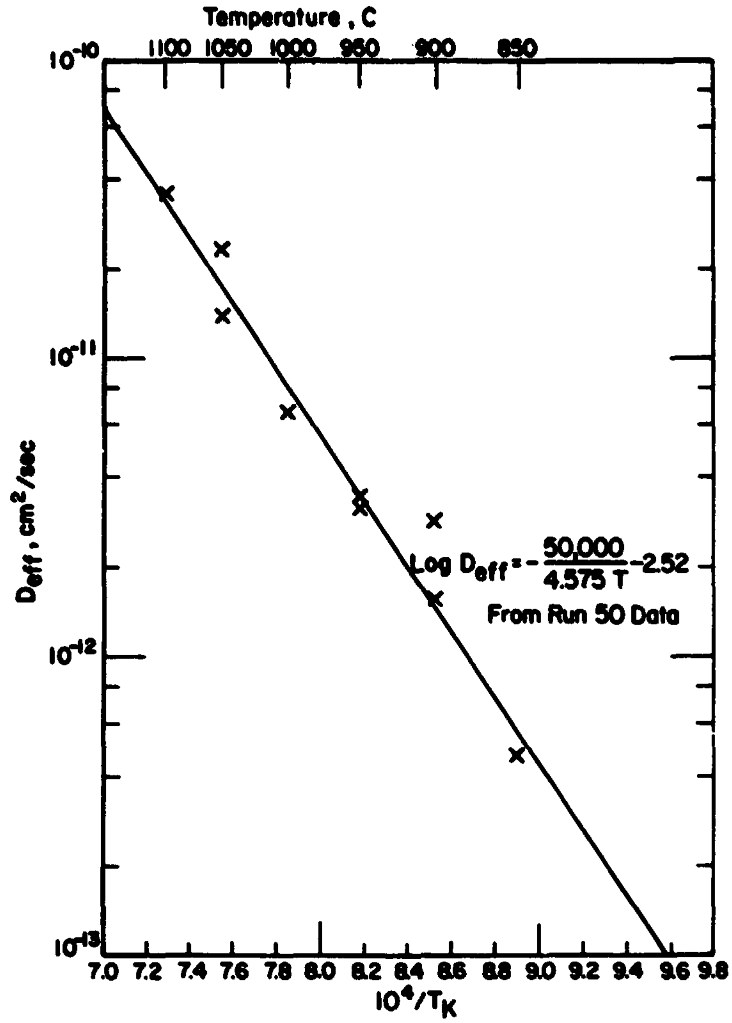
RESULT:

$$D_{EFF},\ \text{CM}^2/\text{SEC} = 3.02 \times 10^{-3}\, e^{-\frac{50{,}000}{RT}}$$

$$E_{ACT} = 50{,}000 \text{ CAL/GRAM ATOM}$$
$$= 2.17 \text{ EV./ATOM}$$

RESERVATIONS:

- PARTICLES NOT DESIGNED FOR EXPERIMENT
- GEOMETRY NOT WELL DEFINED (IRREGULAR SHAPE, RANGE OF PARTICLE SIZE, RANGE OF COATING THICKNESS)
- THICKNESS OF SILICON LAYER (SQUARED TERM IN D) NOT ACCURATELY KNOWN
- DATA NEED CONFIRMATION (WITH ACCURATELY DESIGNED PARTICLES) BEFORE PUBLICATION
- RELATION OF D_{EFF} TO TRUE DIFFUSIVITY NOT YET DETERMINED



Time (h) to Outgas Spherical Silicon Particles

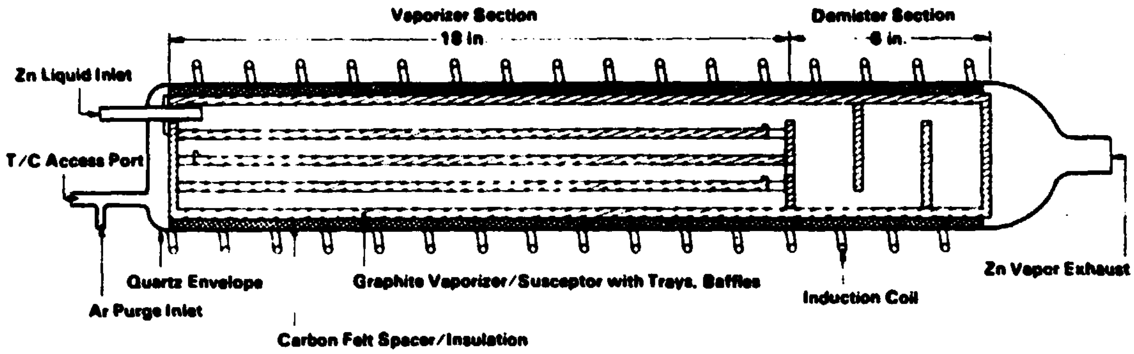
Temp., C	1100			1200			1300			1400		
D_{EFF}, cm^2/sec.	3.31E-11			1.15E-10			3.40E-10			8.86E-10		
C/C_o (A)	0.1	0.05	0.01	0.1	0.05	0.01	0.1	0.05	0.01	0.1	0.05	0.01
D, µm (B)												
200	45	59	94	13	17	27	4.3	5.8	9.1	1.7	2.2	3.5
400	402	536	842	116	154	242	39	52	82	15	10	31
600	1116	1488	2338	321	428	673	109	145	118	42	56	87
800	2187	2916	4583	630	839	1319	213	284	446	82	109	171

(A) C = final zinc concentration; C_o = initial zinc concentration

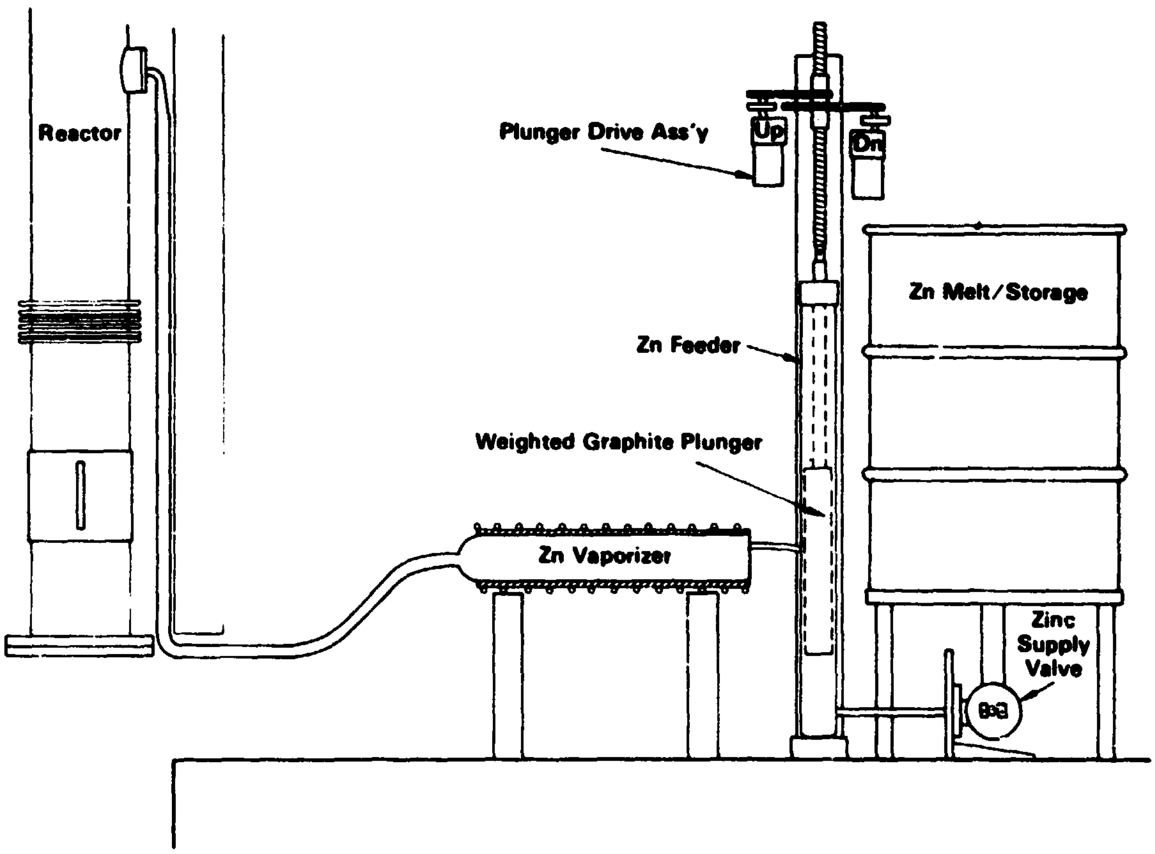
(B) Diameter, µm, of particles with 150µm dia seed

(SEE RESERVATIONS)

Zinc Flash Vaporizer



Zinc Feed System



TECHNOLOGY DEVELOPMENT AREA: Silicon Material Task

POLYCRYSTALLINE SILICON

HEMLOCK SEMICONDUCTOR CORP.

<table>
<tr><td><u>TECHNOLOGY</u>
POLYCRYSTALLINE SILICON</td><td><u>REPORT DATE</u>
04/03/80</td></tr>
<tr><td><u>APPROACH</u>
CHEMICAL VAPOR DEPOSITION OF SILICON FROM DICHLOROSILANE (DCS)

<u>CONTRACTOR</u>
HEMLOCK SEMICONDUCTOR CORPORATION</td><td rowspan="2"><u>STATUS</u>
SILICON GROWN FROM DCS IN EXPERIMENTAL REACTOR WITH
• 2X TCS DEPOSITION RATE
• SUBSTANTIALLY LOWER POWER CONSUMPTION
• DIAMETER UP TO 42 MM
• GOOD SURFACE QUALITY
• FEW OPERATIONAL PROBLEMS

• LABORATORY REARRANGER OPERATIONAL
• PDU DESIGN COMPLETE
• PDU EQUIPMENT PROCUREMENT UNDERWAY</td></tr>
<tr><td><u>GOALS</u>
• DEMONSTRATE PROCESS FEASIBILITY
• ESTABLISH TECHNICAL READINESS BY OPERATION OF EPSDU SIZED TO 150 MT/YR
• SILICON PRICE OF LESS THAN $21/KG (LOW-RISK PROGRAM)
• DEFINE PROCESS ECONOMICS</td></tr>
</table>

Cost Projections (1980$) SAMICS/IPEG

ASSUMPTIONS:

- 1000 METRIC TONNE/YR. SILICON PRODUCTION
- HIGH PURITY POLYCRYSTALLINE SILICON PRODUCT
- DICHLOROSILANE PRODUCTION VIA TRICHLOROSILANE REDISTRIBUTION
- HYDROGENATION OF $SiCl_4$ AS DEMONSTRATED BY UNION CARBIDE CORPORATION

PROJECTION

< $21/KG. SILICON

Silicon CVD From Dichlorosilane: Qualitative Features

- NO VAPOR NUCLEATION
- SLIGHT BELL JAR DEPOSITION
- CONVERSION ABOUT 2X TRICHLOROSILANE CVD
- RESPECTABLE SURFACE QUALITY
- LOW POWER CONSUMPTION
- NO OPERATIONAL PROBLEMS EXCEPT CONDENSATION IN FLOW METER

PDU Objectives

- PRODUCTION OF DICHLOROSILANE @ 10-30 LBS/HR.
- PURIFICATION AND INTERIM STORAGE OF DICHLOROSILANE
- PROVIDE DICHLOROSILANE FEED FOR PRODUCTION REACTOR
- EVALUATION DICHLOROSILANE PURITY IN A REACTOR

(LABORATORY REARRANGER)

- PROVIDE KINETIC DATA FOR PDU DESIGN AND OPERATION
- ALLOW INVESTIGATION OF CATALYST BEHAVIOR
- ALLOW DEVELOPMENT OF SAFE, RELIABLE ANALYTICAL TECHNIQUES

Vapor Phase Rearranger Data

- TRICHLOROSILANE FULLY EQUILIBRATED AT 70°C IN < 30 SEC.
- YIELD CONSTANT FOR 40 HOURS
- SILICON GROWN DIRECTLY FROM UNSEPARATED CHLOROSILANE PRODUCTS
- QUALITY ANALYSIS ON SILICON:

  BORON: 1.0 PPBA

  DONOR: 3.6 PPBA

  RESISTIVITY: 40 OHM-CM

Summary of PDU Status

- DESIGN FINALIZED EXCEPT FOR FIRE/SPILL PROTECTION FEATURES
- SITE SELECTION MADE
- PROCUREMENT OF MAJOR EQUIPMENT ITEMS UNDERWAY
- ADDITIONAL SAFETY-RELATED INFORMATION NECESSARY

Problems and Concerns

- DICHLOROSILANE CONDENSATION IN FLOWMETER ON EXPERIMENTAL REACTOR
- SAFETY-RELATED DESIGN CONSIDERATIONS
- DICHLOROSILANE PURITY

TECHNOLOGY DEVELOPMENT AREA: Silicon Material Task

PRODUCTION OF SOLAR GRADE SILICON

AEROCHEM RESEARCH LABORATORIES, INC.

<table>
<tr><td>TECHNOLOGY
PRODUCTION OF SOLAR GRADE SILICON</td><td>REPORT DATE
APRIL 3, 1980</td></tr>
<tr><td>APPROACH
HIGH TEMPERATURE, SILICON HALIDE-ALKALI METAL REACTOR/JET IMPINGEMENT COLLECTOR

CONTRACTOR
AEROCHEM RESEARCH LABORATORIES, INC.

GOALS
DESIGN AND CONSTRUCTION OF REACTOR SYSTEM
SUCCESSFUL 20 MIN RUNS
DEMONSTRATE 30% Si/NaCl SEPARATION
SUCCESSFUL 60 MIN RUNS
DEMONSTRATE 50% SEPARATION
Na-FREE SILICON PRODUCT
FIRST 0.25 kg Na-FREE Si SAMPLE BY 4/1/80
SUCCESSFUL 4-8 HR RUNS
0.5 kg Si SAMPLES (< 10 PPM IMPURITY), BY 11/3/80
SCALABILITY & ECONOMIC ASSESSMENT</td><td>STATUS
REACTOR SYSTEM CONSTRUCTED
• 20 MIN RUNS ARE ROUTINELY PERFORMED
• RUNS MADE WITH UP TO 80% SEPARATION/ COLLECTION OF SILICON
• Na IMPURITY IS LESS THAN 10 PPM
• 3 ATTEMPTS MADE AT 60 MIN, 0.25-0.5 kg RUNS. UNSUCCESSFUL DUE TO Na LEAKS IN NEW DELIVERY SYSTEM
• INITIAL ECONOMIC ANALYSES PERFORMED</td></tr>
</table>

Reaction Studies

CONCLUSIONS: Reaction is complete under all conditions tested to date

REACTOR VOLUME	**0.58 ℓ**
NOZZLE DIAMETER RANGE	**0.68 -1.91 cm**
PRESSURE RANGE	**0.25 - 0.032 atm**
RESIDENCE TIME RANGE	**50 - 6.3 ms**

No $SiCl_4$ or Na observed in process vessal downstream of reactor

Reactor Studies

All Runs to Date have been with Reactor Walls above 1700 K

- MATERIALS EXAMINED INCLUDE GRAPHITE (LOW QUALITY), TANTALUM, QUARTZ, SIC, ALUMINA, MOLYBDENUM

- ONLY SIC IS UNAFFECTED BY EITHER OF THE REACTANTS OR THE PRODUCTS

- Ta AND Mo ARE ATTACKED BY $SiCl_4$ AND/OR NaCl(g)

- QUARTZ (RAPIDLY) AND ALUMINA (SLOWLY) ARE ATTACKED BY Na(g)

GRAPHITE IS RESISTANT TO Na IF T > 1100K BUT IS ERODED BY $SiCl_4$

Separation and Collection Studies

- Si SEPARATION FROM NaCl ACHIEVED

WITH GRAPHITE IMPACTOR - 80 %

OF Si HAS BEEN COLLECTED

Status

30 TO 80 g SAMPLES OF CONSOLIDATED METALLIC SILICON HAVE BEEN COLLECTED IN 15 MIN RUNS

INITIAL ANALYSES SHOW < 10 ppm Na IN THE SILICON

- THREE TRIAL RUNS WITH NEW, LARGER SODIUM DELIVERY SYSTEM HAVE FAILED DUE TO LEAKS AND PROBLEMS WITH LIQUID DELIVERY

- 80 % SEPARATION/COLLECTION OF SILICON HAS BEEN ACHIEVED

Plans

- CONTINUE TO IMPROVE LARGER SODIUM DELIVERY SYSTEM

- INVESTIGATE LOWER REACTOR WALL TEMPERATURES

- INVESTIGATE PARAMETERS GOVERNING SEPARATION/COLLECTION EFFICIENCIES

- COLLECT 0.25 - 0.5 kg SILICON SAMPLES IN ONE HOUR RUNS

TECHNOLOGY DEVELOPMENT AREA: Silicon Material Task

CHEMICAL ENGINEERING AND ECONOMIC ANALYSIS OF POLYSILICON PROCESSES

LAMAR UNIVERSITY

TECHNOLOGY	REPORT DATE
CHEMICAL ENGINEERING AND ECONOMIC ANALYSIS OF POLYSILICON PROCESSES	
APPROACH PERFORM ANALYSES IN AREAS OF PROCESS SYSTEM PROPERTIES, CHEMICAL ENGINEERING, AND ECONOMICS FOR PROCESSES BEING DEVELOPED FOR THE HIGH VOLUME, LOW COST PRODUCTION OF POLYSILICON. **CONTRACTOR** LAMAR UNIVERSITY **GOALS** 1. PERFORM ANALYSIS OF HEMLOCK SEMICONDUCTOR PROCESS (1980) -DCS PRODUCTION (AUG., 1980) -POLYSILICON PRODUCTION (DEC., 1980) 2. PERFORM OTHER ANALYSES (1981-82) -AEROCHEM PROCESS -OTHER 3. UPDATE ANALYSIS OF UNION CARBIDE PROCESS (1981-82) 4. UPDATE ANALYSIS OF BATTELLE PROCESS (1981-82) 5. UPDATE ANALYSES AS REQUIRED (1980-85)	**STATUS** 1. COMPLETED INITIAL ANALYSIS OF SIEMENS PROCESS -1977 2. COMPLETED INITIAL ANALYSIS OF UNION CARBIDE PROCESS -1978 3. COMPLETED ANALYSIS OF BATTELLE PROCESS -1979 4. ANALYSIS OF HEMLOCK SEMICONDUCTOR PROCESS BEING PERFORMED -1980 -BASE CASE CONDITIONS -REACTION CHEMISTRY -PROCESS FLOW DIAGRAM

HSC Process (Hemlock Semiconductor Corp.)

- Chemical Engineering Analysis Initiated Recently
  - -Base Case Conditions
  - -Reaction Chemistry
  - -Process Flow Diagram

- Approach For HSC Process
  - -Synthesis of DCS (SiH_2Cl_2)
  - -Utilizing DCS To Produce Polysilicon (Si)
    - -Conventional Siemen's Tech.
    - -Hot Rod Reactor

Polysilicon Deposition (DCS Decomposition)

$$SiH_2Cl_2 + H_2 \xrightarrow{1000\text{-}1100C} Si + \text{By-Products}$$

By-Products: H_2, HCl, SiH_2Cl_2, $SiHCl_3$, $SiCl_4$

Equilibrium Conversions: TCS to Si = 30 - 40%
DCS to Si = 60 - 70%

Chemical Engineering Analysis: Progress and Status

	Prior	Present
1. Base Case Conditions -Hydrogenations -DCS Synthesis -Polysilicon Deposition -Distillation -Other	0%	35%
2. Reaction Chemistry	0%	30%
3. Process Flow Diagram	0%	25%

Plans

1. Complete Present Chemical Engineering Analysis Activities (5/80)
2. Start Preliminary Process Design (6/80)
3. Forward Design Package for Economic Analysis (7/80)
4. Complete Economic Analysis (8/80)

IN-HOUSE LSA PROGRAMS

JET PROPULSION LABORATORY

THE CONTINUOUS-FLOW PYROLYZER

TECHNOLOGY: POLYCRYSTALLINE SILICON

APPROACH: PYROLYSIS OF SILANE IN A FREE SPACE REACTOR

$$SiH_4 \rightarrow 2\,H_2 + Si$$

Goals

TO CONDUCT SILANE PYROLYSIS STUDIES IN THE AREAS OF

- DESIGN OF REACTOR
- SELECTION OF REACTOR MATERIALS
- DETERMINATION OF OPTIMUM RUN CONDITIONS
- ESTABLISHMENT OF PRODUCT PURITY

IN SUPPORT OF LSA SILICON MATERIAL TASK CONTRACTUAL ACTIVITIES AND GOALS

Status

1979

BUILT AND RAN CFP-II

STUDIED BROADLY THE EFFECTS OF $\dot{m}$, C AND T ON SILICON PARTICLE GROWTH AND PRODUCT YIELD

EXPERIMENTED WITH CVD ON SILICON SEED MATERIAL

1980, FEBRUARY

BEGAN MODIFICATION OF CFP-II IN APPLICATION OF INTERNAL SCRAPER, INTERNAL WALL COATINGS, AND HYDROGEN AS THE AUXILIARY GAS

Milestones

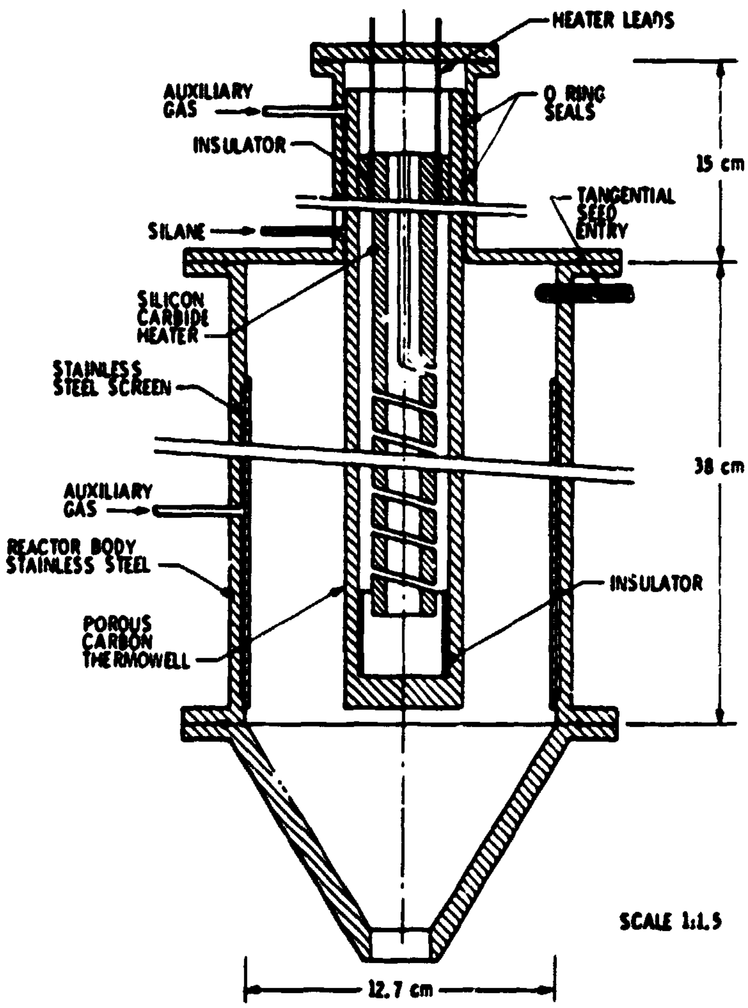
1980, APRIL

BEGIN PARAMETRIC STUDIES TO DETERMINE OPTIMUM CFP RUN CONDITIONS AND TO DEVELOP AND TEST A CHEMICAL KINETIC MODEL OF THE SILANE PYROLYSIS PROCESS

1980, AUGUST

BEGIN DESIGN AND CONSTRUCTION OF A MODULAR SCALE (e.g. 25 metric ton/yr) CFP

CFP-II



Equations for Pyrolysis of Silane

- HOMOGENEOUS SILANE PYROLYSIS

$$-dC/dt = k_0 C$$

- HETEROGENEOUS SILANE PYROLYSIS

$$-dC/dt = k_1 SC$$

WHERE

$$k_1 = \frac{1}{4} \gamma \left(\frac{8RT}{\pi M_{SiH_4}} \right)^{1/2}$$

- HETEROGENEOUS SILANE PYROLYSIS IN FREE SPACE

$$-dC/dt = k_2 (1/a)(C_0 - C)C$$

WHERE

$$k_2 = \frac{3}{2} \gamma \left(\frac{M_{Si}}{\rho_{Si}} \right) \left(\frac{8RT}{\pi M_{SiH_4}} \right)^{1/2}$$

- HYPOTHESIS: IN FREE SPACE AT LOW TEMPERATURE, e.g., 600° C,

$$k_2 (1/a)(C_0\ C) >> k_0$$

Problems and Concerns

PROBLEMS:

- ELIMINATION OF PEACTOR CLOGGING

CONCERNS:

- GROWTH OF LARGE SILICON PARTICLES IN CFP
- POSSIBLE TRADE-OFF:

PARTICLE SIZE
VS
PRODUCTION RATE

SILANE TO MOLTEN SILICON CONVERSION

TECHNOLOGY: POLYCRYSTALLINE SILICON

APPROACH: PYROLYSIS CONVERSION OF SILANE TO MOLTEN SILICON WITHIN A SINGLE REACTOR IN A SINGLE-STEP PROCESS

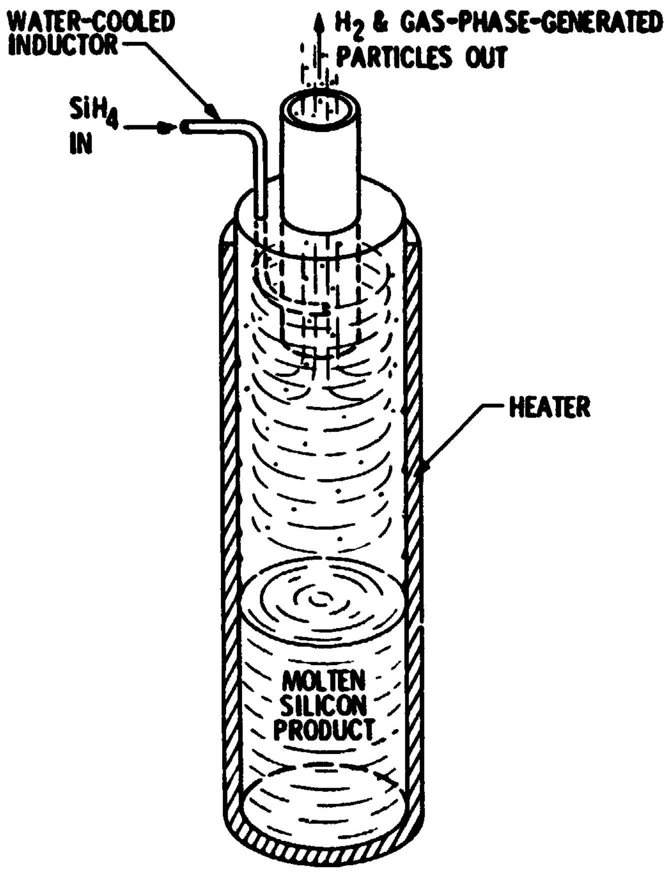
Status

- SYSTEM DESIGN COMPLETED; PROCUREMENT COMPLETED; FABRICATION AND INSTALLATION UNDERWAY
- 1980, JUNE

  REACTOR MATERIAL STUDY - EXPERIMENTAL PHASE
  REACTOR DESIGN STUDY - EXPERIMENTAL PHASE

  ARE SCHEDULED TO BEGIN

Silane to Molten Silicon, or SMS Conversion



Problems and Concerns

- CONVERSION OF SILANE TO MOLTEN SILICON WITH MINIMAL RELEASE OF SILICON POWDER
- SELECTION OF REACTOR COATING OR LINING THAT WILL NEITHER CONTAMINATE THE SILICON OR DAMAGE THE REACTOR

AND SUBSEQUENTLY

- TRANSFER OF MOLTEN SILICON FROM THE REACTOR

SILICON MATERIAL IN-HOUSE SUPPORT OF R&D

TECHNOLOGY

Polycrystalline Silicon

APPROACH

Fluidized Bed Silicon Deposition from Silane

TECHNICAL GOALS

- Experimentally Determine Range of Operating Conditions to Support Contractors
  - Range of Velocities to Avoid Bed Agglomeration
  - Range of Concentration to Avoid Powder Formation
- Obtain Engineering Data from Long Term Runs in 2" F.B.R.

PROGRESS

- 2" Stainless Steel FBR Run for 132 min at 700°C, 15% SiH_4 and $U/U_{mf} > 8$
  - No Agglomeration
  - < 1% Dust
  - 1.72 g/min Production Rate
  - Dense Deposit
- Tests Started in 1" FBR to find Minimum Velocities to Avoid Bed Agglomeration
- High Purity Seed Samples Cleaned By BMI, UCC, and JPL Techniques Sent to LLL for Analysis

Problems and Concerns

- Need to use High Purity Seed for Future Experiments
  - Grinding Equipment has Been Ordered
  - Various Acid Cleaning Techniques Being Compared
- Dust Experiments Need To Be Done Above 15% SiH_4 In Feed
- Operating Range For Avoiding Bed Agglomeration Must Be Confirmed In Larger Engineering System

PRODUCTION PROCESS AND EQUIPMENT AREA

TECHNOLOGY SESSION Don Bickler, Chairman

The central thrust of Phase II process development has been under three contracts: RCA (954868), Spectrolab (954853), and Westinghouse (954873). Each made a presentation of 50 minutes, followed by a 10-minute question-and-answer period, based upon key elements of the statement of work, beginning with the contractor's detailed process sequence. Each process within the sequence was discussed in terms of its input/output criteria and the significance of the process to the overall performance of the finished solar modules. A summary of the SAMICS-type cost breakdown was given in 1980 dollars (1975 dollars times 1.4) starting with either $.31/W sliced Cz material or $.24/W sheet material of other forms. Development of the contractor's final sequence from the original sequence at the start of the contract was discussed, including the logic behind any changes. The remainder of the PP&E contractors made presentations of 10 to 20 minutes (including questions) on progress made in the last four months. The majority of these contracts have finished or are just finishing and their data are of major significance in Phase II.

AUTOMATED SOLAR PANEL ASSEMBLY LINE

ARCO SOLAR, INC.

MODULE STATUS:	SUCCESSFULLY COMPLETED 750 THERMAL CYCLES (-40°C TO +90°C), 60 DAYS HUMIDITY CYCLING (23°C to 75°C AT 95% RH) AND FOUR MONTHS FIELD TESTING IN HIGH ALTITUDE TROPICAL ENVIRONMENT.
SOLDERING MACHINE STATUS:	PROTOTYPE TRANSPORT AND RF SOLDERING STATION OPERATED SIX MONTHS AT 15 CELLS/MINUTE - - - - - - - - - AUTOMATED MACHINE SUCCESSFULLY COMPLETED FIRST TRIAL RUNS.

PRODUCTION PROCESS AND EQUIPMENT AREA

LAMINATING MACHINE STATUS:	≈10,000 MODULES HAVE BEEN LAMINATED WITH 97% PROCESS YIELD - - - - - AUTOMATED LAMINATION SYSTEM INSTALLED IN PILOT LINE - - - - - - - - - TWO AUTOMATED LAMINATORS HAVE BEEN DELIVERED TO JPL.

Approach

MODULE DESIGN:	100 MM SOLAR CELL WITH FULLY REDUNDANT INTERCONNECTS, GLASS SUPERSTRATE, METAL FOIL BACKING AND HOT MELT EDGE SEALANT.
SOLDERING MACHINE:	AUTOMATIC CASSETTE UNLOADING, SIMULTANEOUS BONDING OF TOP AND BOTTOM CELL INTERCONNECTS AND IN-LINE SOLDER FLUX REMOVAL.
LAMINATING MACHINE:	INTEGRATED VACUUM/IR HEATING SYSTEM, DIAPHRAGM SEALING AND AUTOMATED PROCESS CYCLING.

Objectives

1. DEVELOP MODULE DESIGN COMPATIBLE WITH AUTOMATED ASSEMBLY.
2. DESIGN AND FABRICATE AUTOMATED SOLAR CELL SOLDERING MACHINE CAPABLE OF INTERCONNECTING 12 CELLS/MINUTE.
3. DESIGN AND FABRICATE AUTOMATED MODULE LAMINATING MACHINE WITH A CAPABILITY OF 12 MODULES/HOUR.
4. OPERATED AUTOMATED PILOT PRODUCTION LINE.

AUTOMATED ARRAY ASSEMBLY, PHASE II

RCA LABORATORIES

Objectives of Phase II

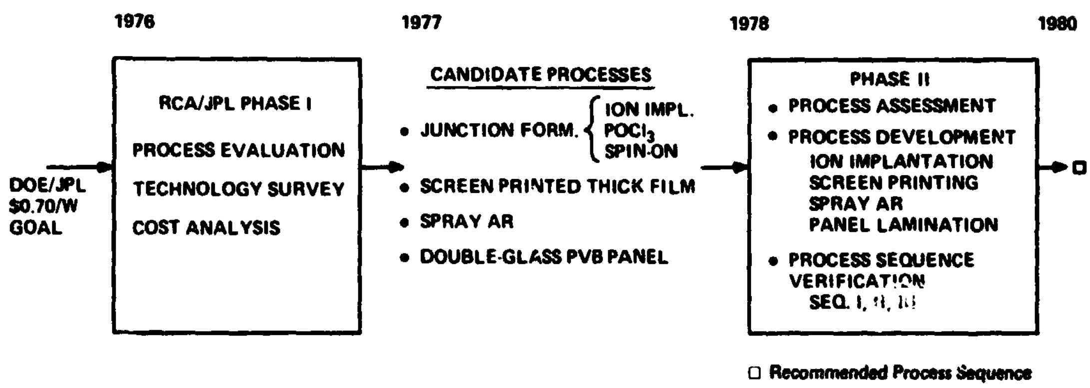
OVERALL –

SPECIFICATION OF A PROCESS SEQUENCE WHICH, WHEN AUTOMATED, WOULD HAVE THE POTENTIAL OF MASS-PRODUCING SILICON SOLAR MODULES ENCAPSULATED FOR PROTECTION AGAINST THE EARTH ENVIRONMENT.

ELEMENTS –

- CRITICAL ANALYSIS OF SEQUENCE FOR
  - COST-EFFECTIVENESS
  - THROUGHPUT CAPABILITY
  - REPRODUCIBILITY
- PROVIDE DEVELOPMENT TO BRING KEY PROCESS STEPS TO STATE OF TECHNOLOGICAL READINESS.
- PROVIDE VERIFICATION TESTING AND COST ANALYSES OF PROCESS SEQUENCES TO ESTABLISH COST/PERFORMANCE READINESS.

Historical Perspective of RCA Participation



Junction Formation

REQUIREMENTS	PROCESS		
INPUT	ION-IMPL.	$POCl_3$	SPIN/SPRAY-ON
SHAPE	ANY (Platten)	ANY	ROUND/ANY
SIZE	BEAM dia./SCAN	< 5" + THICK	< 5"/ANY
SURFACE FINISH	FLAT PREFER	ANY	FLAT/ANY
DEFECTS	ANNEAL	GETTERING	GETTERING ?
CRYSTALLINITY	SINGLE CRYSTAL PREF.	ANY	? (Grain bndy)
MACHINE			
HIGH THROUGHPUT	NFD	YES	NFD/YES
RELIABLE	YES	YES	YES/ ?
AUTOMATED	YES (NFD)	YES (NFD)	YES/YES
LOW MATERIALS REQ	NO	YES	YES/YES (?)
REASONABLE COST	NO (NFD)	YES	YES/YES
OUTPUT			
DIFFUSION LENGTH	YES (NFD)	YES (Gettering)	YES (?)
SHALLOW JUNCTION	YES	YES	YES
SHEET RESISTANCE	DEPENDS ON INPUT Si	YES	YES
NEXT PROCESS	YES	NO	NO (NFD)
COST EFFECTIVE	YES IF THROUGHPUT, MATS. REQ. AND ANNEAL ARE DEVELOPED.	YES	YES LIQUID SOURCE-STABLE, AND COMPAT. WITH SPRAY MACHINE
ESTIMATED COST	\$0.01 – 0.04/W	0.01 – 0.015/W	? / ?

Screen-Printed Thick-Film Metallization

REQUIREMENTS	
INPUT	
SHAPE	NOT CRITICAL, RECTANGULAR SLIGHT PREFERENCE
SIZE	UP TO 6 INCHES LINEAR DIM. OK, THICKNESS CRITICAL
SURFACE FINISH	FLAT PREFERRED
MACHINE	
HIGH THROUGHPUT	YES, 3000 – 4000/hr
RELIABLE	YES
AUTOMATED	YES
MATERIAL REQUIREMENTS	LOWER COST INK TO REPLACE Ag
COST	ACCEPTABLE \$40,000
OUTPUT	
METAL SHEET RESISTANCE	GOOD (~ 1.5 X BULK METAL)
CONTACT RESISTANCE	N F D
LINE DEFINITION	> 5 mils, ACCEPTABLE
THICKNESS CONTROL	GOOD IN REQUIRED RANGE
NEXT PROCESS	YES
COST	
FRONT GRID (Ag)	\$0.02 – \$0.04/W
BACK CONTACT (Al)	\$0.005 – \$0.015/W

Spray-on AR Coating

REQUIREMENTS

INPUT

SHAPE	NOT CRITICAL
SIZE	NOT CRITICAL
SURFACE FINISH	ETCHED SURFACE PREFERRED
SURFACE CONDITION	CLEAN
LOT SIZE	CASSETTE

MACHINE

HIGH THROUGHPUT	YES, 4000 – 6000/hr
RELIABLE	YES
AUTOMATED	YES
MATERIAL REQUIREMENTS	NOT CRITICAL (STORAGE OF SOLUTION ~ 6 mos)
AMBIENT	RH < 45%
COST	ACCEPTABLE

OUTPUT

THICKNESS	YES, DEMONSTRATED NOT CRITICAL
INDEX	YES
STABILITY	YES, DEMONSTRATED
COMPATIBILITY	YES, DEMONSTRATED WITH PVB
NEXT PROCESS	MAY NEED REMOVAL FROM BUS AREA

COST

SINGLE LAYER	COST EFFECTIVE \$0.005 – \$0.01/W

Reflow Solder Interconnect

REQUIREMENTS

INPUT

SHAPE	NOT CRITICAL, RECTANGULAR PREFERRED
SIZE	NOT CRITICAL
METALIZATION	SOLDERABLE
SURFACE	CLEAN
LOT SIZE	CASSETTE

MACHINE

HIGH THROUGHPUT	NEEDS FURTHER DEVELOPMENT (tabbing esp.)
RELIABLE	NEEDS FURTHER DEMONSTRATION
AUTOMATED	NO, (NFD)
MATERIAL REQUIREMENTS	NOT CRITICAL
COST	ACCEPTABLE ~ \$150K

OUTPUT

STRING	YES
ARRAY	YES
COMPATIBILITY	YES, WITH SOLDERABLE METALS
NEXT PROCESS	YES, (flux removal facilitated)

COST ~ \$0.05/W (NFD)

PRODUCTION PROCESS AND EQUIPMENT AREA

Array Assembly (Glass/PVB/Glass)

REQUIREMENTS

INPUT

ARRAY SIZE	4 ft x 4 ft (1.2 m x 1.2 m) OR 1.2 ft x 4 ft (0.36 m x 1.2 m)
BOND SURFACE	SMOOTH AND FLAT
CELL ARRAY DESIGN	CLOSE-PACKED, RECTANGULAR CELLS
CELL LINEAR DIMENSION	NOT CRITICAL
CELL THICKNESS/STRENGTH	THICKNESS CRITICAL ONLY IF NON-FLAT AND STRESSED

MACHINE

HIGH THROUGHPUT	NEEDS FURTHER DEVELOPMENT (Double-glass req. 2 step process)
RELIABLE	YES
AUTOMATED	NO, NFD
MATERIAL REQUIREMENTS	PVB NOT OPTIMUM FOR COST, HANDLING AND PHYS. PROP.
CAPITAL COST	MODERATE TO HIGH (Autoclave)

OUTPUT

YIELD	POOR (Glass and cell cracking problems)
ENVIRONMENTAL PROTECT.	GOOD
OPTICAL TRANSMISSION	HIGH IRON GLASS CAUSES EXTRA 8% LOSS

COST

\$0.20 – \$0.23/W (Reduction possible – material cost in PVB → EVA, and process throughput improvement)

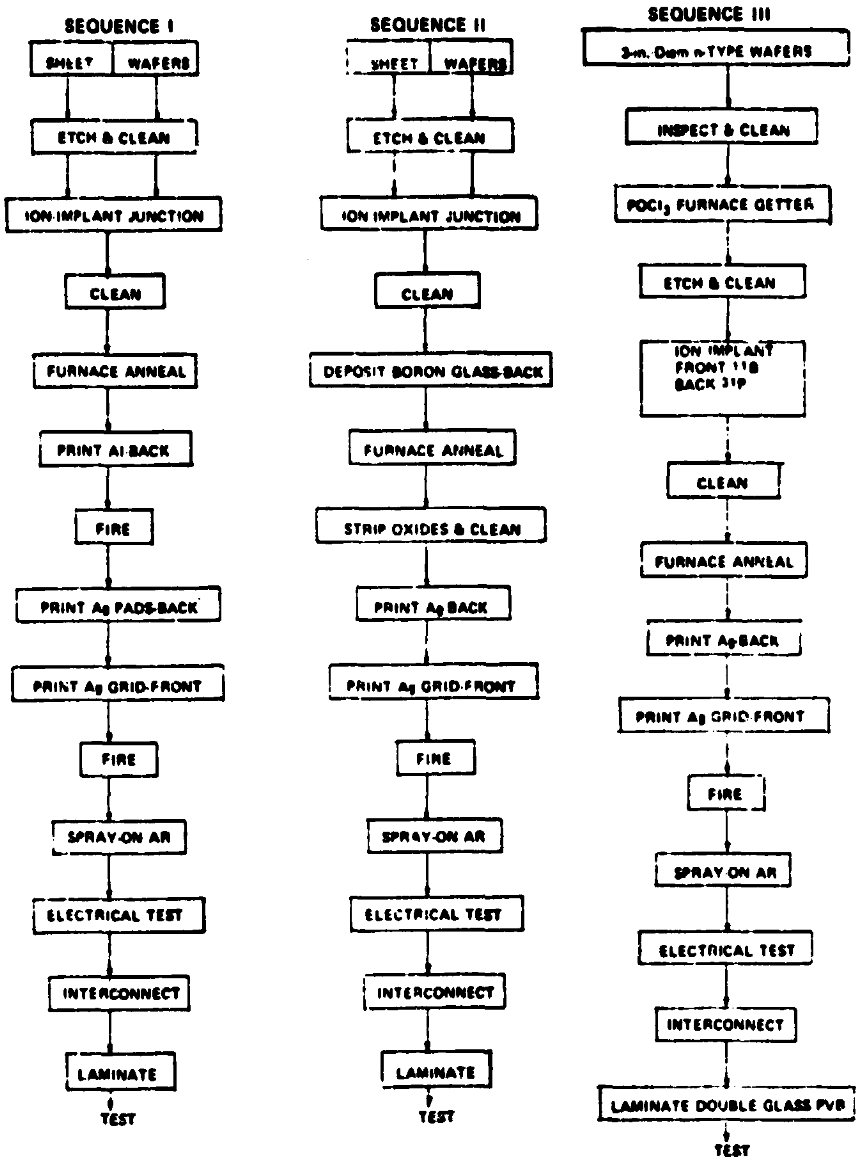
Process Sequence Development

OBJECTIVES:

DEVELOPMENT OF CRITICAL PROCESSES AND OF ALTERNATIVE MANUFACTURING PROCESS SEQUENCES BY:

- VERIFICATION OF ALTERNATIVE SEQUENCES BY THE FABRICATION AND TESTING OF SOLAR CELLS AND MODULES.
- ASSESSMENT AND IMPROVEMENT OF COST-EFFECTIVENESS OF EACH SEQUENCE WITH SAMICS/SAMIS USED AS A GUIDE.

Process Sequences Studied



SAMICS Cost Analysis Seq I, II & III

ASSUMPTIONS

GENERAL

500 MW ANNUAL PRODUCTION

7.8 cm DIA CZ WAFERS @ $0.31/W (1980)

HIGH THROUGHOUT, AUTOMATED PROCESSES (1986)

225 CELL CLOSE PACKED (ROUND–WAFER) MODULE

SEQUENCE SPECIFIC – CELL EFFICIENCIES FROM EXPERIMENTAL RESULTS

SEQ I	10.7%	(115 W/MODULE)
SEQ II	11.9%	(128 W/MODULE)
SEQ III	13.0%	(140 W/MODULE)

SAMICS Cost Analysis Summaries Seq I, II, III

SEQ. I	$/W	SEQ. II	$/W	SEQ. III	$/W
RWAFER	0.31	RWAFER	0.31	RWAFER	0.31
ETCHWAFER	0.021	ETCHWAFER	0.018	MSCLN-1	0.022
IONIMPPJ	0.039	IONIMPLPJ	0.036	POCIGET	0.011
MSCLN-1	0.028	MSCLN-1	0.024	ETCHWAFER	0.017
4HRANNEAL	0.019	BORONDEP	0.020	IONIMPLPB	0.033
SPALBACK	0.028	900DEGDIF	0.011	IONIMPLBJ	0.033
MSCLN-2	0.028	GLASSREM	0.014	MSCLN-2	0.022
SPAGPAD	0.028	CONGRD	0.054	900DEGDIF	0.010
SPAGFRONT	0.061	SPAGFRONT	0.056	CONGRD	0.051
HFDIP	0.013	HFDIP	0.012	SPAGFRONT	0.051
SPRAYAR	0.027	SPRAYAR	0.024	HFDIP	0.011
TESTCELL	0.018	TESTCELL	0.016	SPRAYAR	0.021
RSINTERCN	0.076	RSINTERCN	0.069	TESTCELL	0.015
ARRAYASSM	0.289	ARRAYASSM	0.265	RSINTERCN	0.065
FRAME	0.009	FRAME	0.008	ARRAYASSM	0.245
PACK	0.018	PACK	0.017	FRAME	0.008
				PACK	0.015
TOTAL	0.987		0.919		0.909
NET YIELD	85.1%		85.6%		85.5%

All seq. costs affected most by:

1. Use of 3" dia. wafers, use of 6" dia. would reduce costs by 17%.
2. High double-glass array assembly cost due to low yield and high material cost (PVB + back glass).
3. High silver paste cost in grid and back pad.

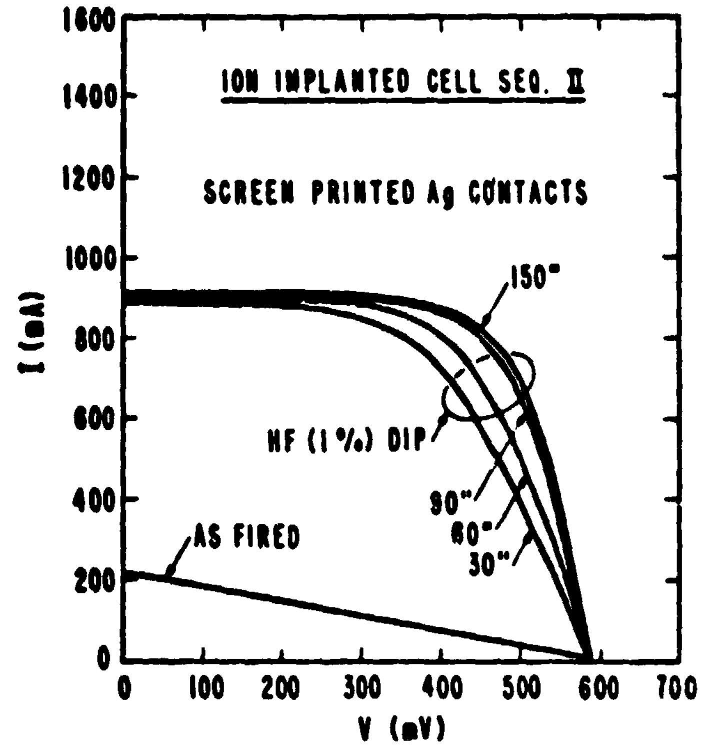
Seq. I and II affected by lower achieved cell efficiencies.

Comparison of Average Solar Cell Parameters for Sequence I, II, III

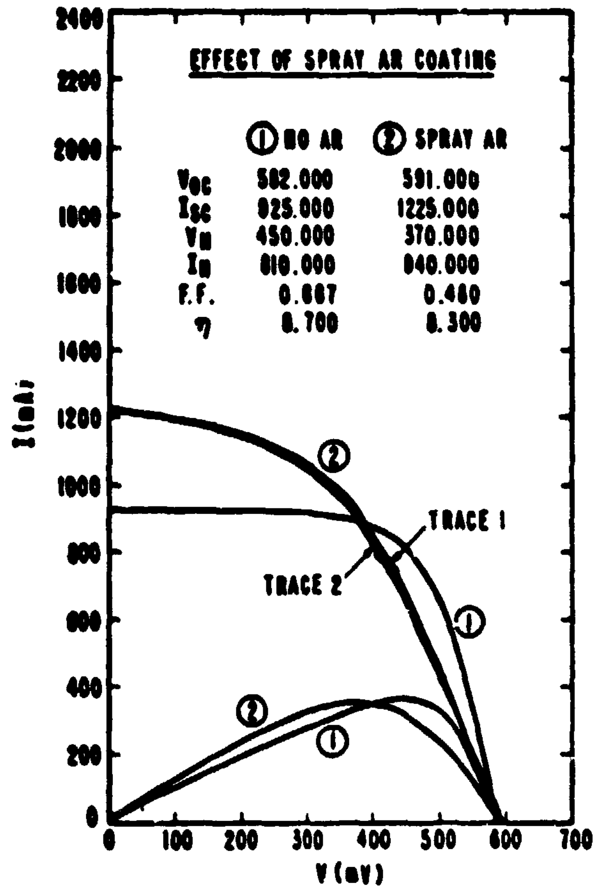
		MEASURED – NO AR				ESTIMATED – WITH AR				BEST MEASURED WITH AR			
MANUFACTURING SEQUENCE	Structure	$\bar{I}_{sc}$ mA	$\bar{V}_{oc}$ mV	$\overline{F.F.}$ –	$\bar{\eta}$[a] %	$\bar{I}_{sc}$ mA	$\bar{V}_{oc}$ mV	$\overline{F.F.}$ –	$\bar{\eta}$ %	$\bar{I}_{sc}$ mA	$\bar{V}_{oc}$ mV	$\overline{F.F.}$ –	$\bar{\eta}$ %
I	$n^+/p/p^+$	870	557	0.701	8.1	1140	567	0.673	10.4	1146	571	0.686	10.7
I II	$n^+/p/p^+$	970	574	0.675	8.9	1280	584	0.650	11.6	1268	578	0.680	11.9
III	$p^+/n/n^+$	1020	585	0.686	9.7	1336	595	0.660	12.5	1368	597	0.670	13.0
$POCl_3$	$n^+/p/p^+$	867	584	0.755	9.3	{1177	594	0.748	12.7}[b]	1205	610	0.761	13.2

(a) Cell area = 42 cm^2.
(b) Measured values.

Performance of Sequence II Ion-Implanted Cells



Effect of Spray AR Coating on Performance Of Ion-Implanted Cells



Major Results and Recommendations
For Sequence I, II, III Study

- ION IMPLANTATION/SCREEN PRINTING/SPRAY AR COMPATIBILITY PROBLEMS MANIFEST – PREVENT HIGH YIELD AT HIGH EFFICIENCY

- GETTERING (SEQ II, III) IS REQUIRED AND SHOWN SUCCESSFUL AND COST EFFECTIVE WITH HIGH EFFICIENCY.

- SOME HIGH EFFICIENCY MEASURED ($\eta \geqslant 13\%$) DESPITE PROBLEMS

- SEQUENCE III P/N/N$^+$ HAD HIGHEST CELL EFFICIENCY AS PREDICTED

- PRELIMINARY EVALUATION OF DENDRITIC WEB WITH SCREEN-PRINTING (Al BACK, Ag GRID) INDICATED WEB IS COMPATIBLE WITH SCREEN-PRINTING PROCESS

- TWO STEP DOUBLE-GLASS LAMINATION PROCESS FOR PANEL FABRICATION-SOLDERING IS CRITICAL AND YIELD IS UNCERTAIN

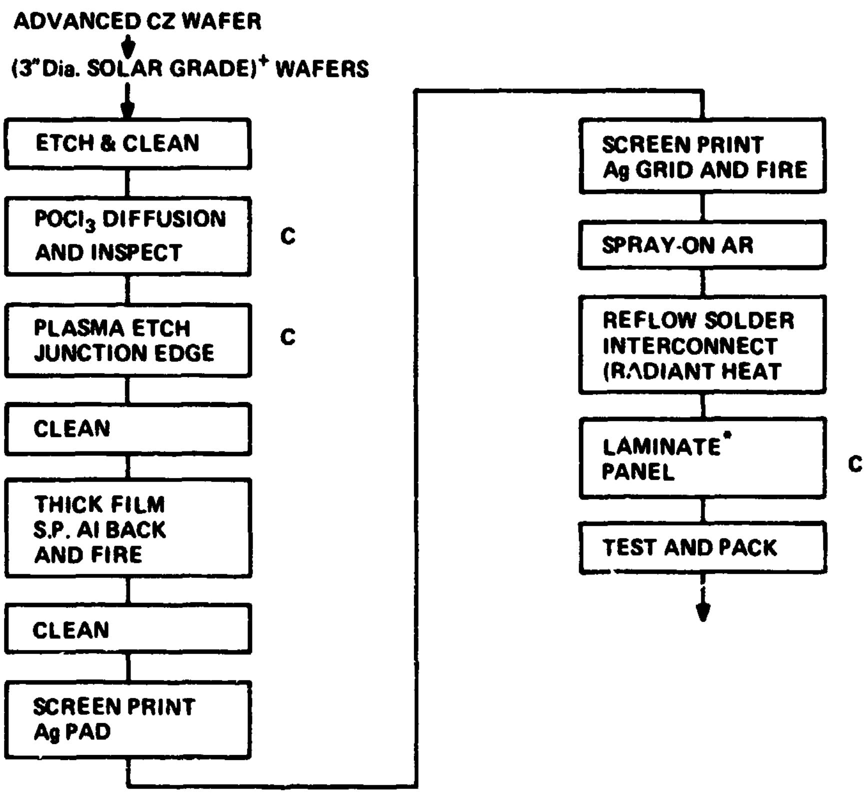
Recommendation

PROCESS COMPATIBILITY PROBLEMS PREVENT AFFIRMATIVE RECOMMENDATION OF THESE SEQUENCES FROM A TECHNICAL STANDPOINT. HOWEVER, IN THE ABSENCE OF PROBLEMS, AND WITH THE USE OF LOWER COST OR LARGER (> 3" DIA) AREA SILICON SHEET, THESE SEQUENCES CAN BE COST EFFECTIVE AND COME CLOSE TO MEETING THE 1986 GOALS

Recommended Process Sequence

RATIONALE:

PROCESS SEQUENCES STUDIED ARE BASICALLY SOUND AND COST-EFFECTIVE. SELECTION OF AN ALTERNATIVE JUNCTION FORMATION PROCESS HAS BEEN SHOWN TO REMOVE COMPATIBILITY PROBLEMS AND TO RESULT IN A HIGH-PERFORMANCE, COST-EFFECTIVE SEQUENCE. THE CHANGED AND RECOMMENDED PROCESS SEQUENCE IS AS FOLLOWS:



* Conformal flexible back now preferred for high yield.
C Indicates changes from previous sequences.
\+ Used in the experimental verification.

Recommended Sequence Performance

(PLASMA ETCH JUNCTION EDGE)

		J_{SC}	VOC.	F.F.	η	
PLASMA ETCH	<AVE>	29.2	598	0.753	13.1	<F.F.> ± 1%
NO PLASMA EDGE	TYP.	30.9	579	0.555	10.0	<F.F.> ± 2%

SAMICS Cost Comparisons for Recommended Sequence

ASSUMPTIONS:

GENERAL

500 Mw ANNUAL PRODUCTION

ADV. CZ WAFERS @ $0.31/W (1980) INDEPENDENT OF WAFER SIZE

HIGH-THROUGHPUT, AUTOMATED PROCESSES (1986)

ALL COSTS AND RESULTS IN 1980$

SPECIFIC

FOR 3" DIA. vs 6" DIA. WAFERS, AMOUNT OF MATERIALS INCREASED BY 4X IN MOST CASES.

ALL OTHER VARIABLES (YIELD, THROUGHPUT etc) HELD FIXED.

3" WAFER MODULE – 225 WAFERS/MODULE (150.5 W/MOD)

6" WAFER MODULE – 64 WAFER/MODULE (161.2 W/MOD)

CELL EFFICIENCY 14.0% BOTH CASES.

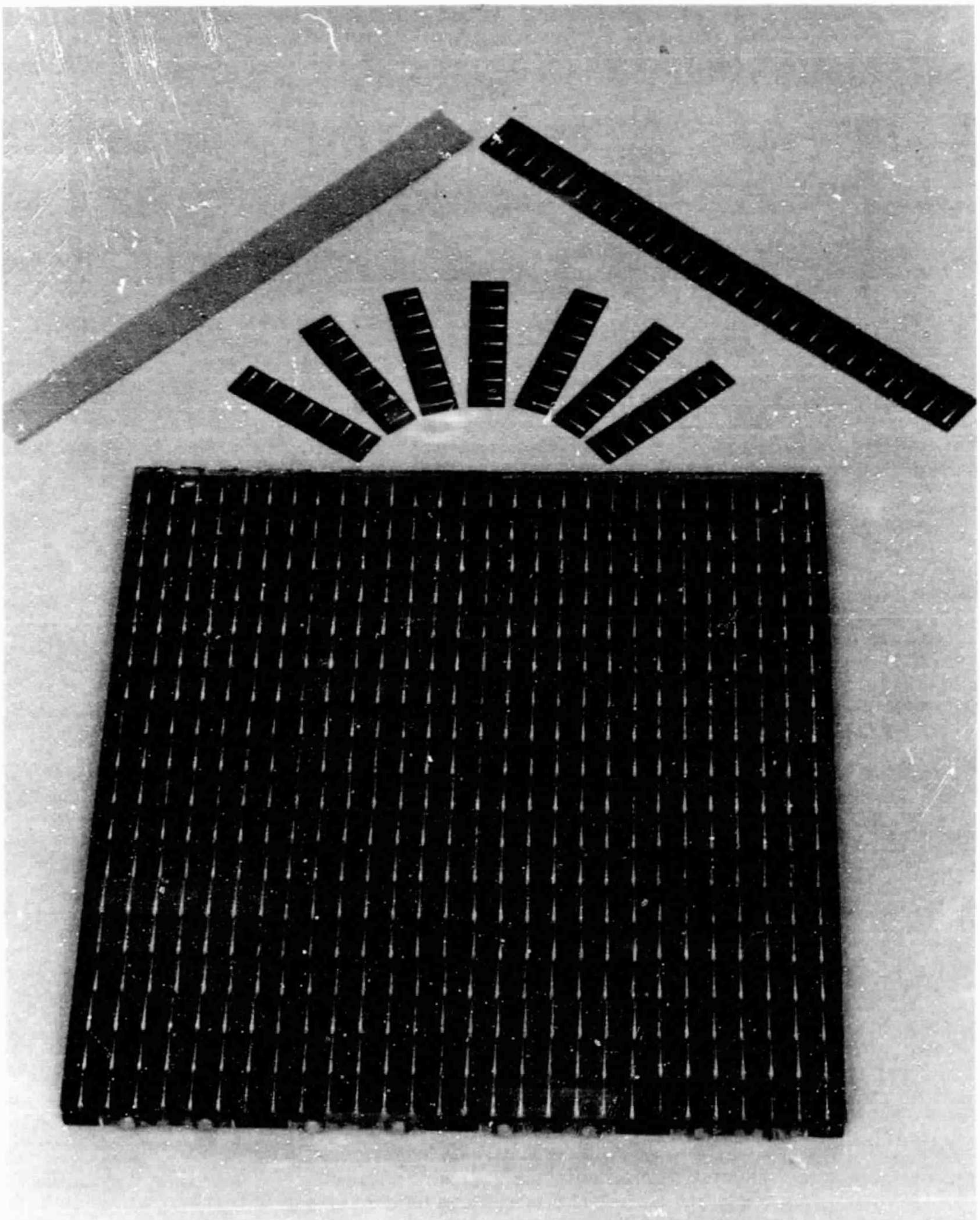
SAMICS Cost Analysis Results

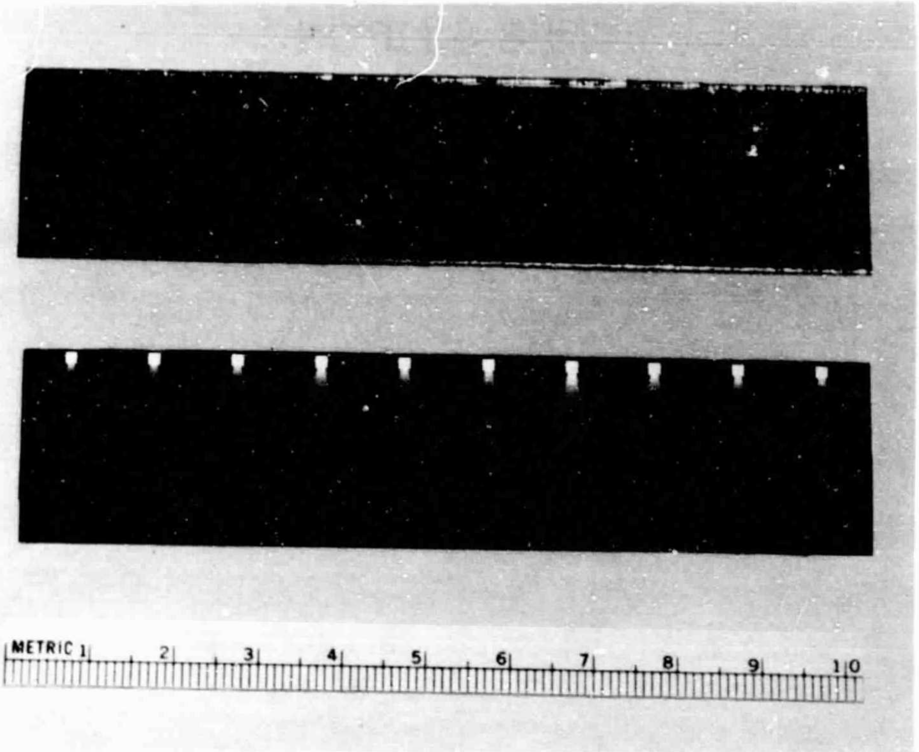
3" dia. RCA	$/W	6" dia. RCA $/W	JPL ADV. CZ 6" dia. STRAWMAN	$/W
RWAFER	0.31	0.31	INGOTGROW	0.324
ETCHWAFER	0.018	0.008	GROPGRIND	0.005
MSCLN	0.024	0.011	MBSAW	0.135
$POCl_3DIF$	0.011	0.008	ETCHCLN	0.005
INSPECT (10%)	0.007	0.003	$POCl_3DIF$	0.007
PLASJUNCEDG	0.017	0.007	AIBACK	0.003
MSCLN	0.024	0.011	CLN	0.005
SPALBACK	0.022	0.017	AGFRONT	0.011
MSCLN	0.023	0.010	SPRAYAR	0.006
SPAGPAD	0.021	0.016	INTERCN	0.025
SPAGFRONT	0.047	0.045	MODULE	0.087
HFDIP	0.014	0.010	MODCLN	0.013
SPRAYAR	0.022	0.009	HEATVAC	0.005
TESTCELL	0.014	0.010	FRAME	0.006
RSINTERCN	0.061	0.054	TEST	0.007
ARRAYASSM	0.229	0.205	PACK	0.006
FRAME	0.008	0.007		
PACK	0.020	0.018		
TOTAL	$\boxed{0.833}$	$\boxed{0.689}$		$\boxed{0.68}$
NET YIELD	84.2%	84.2%		94.7%

GENERAL CONCLUSION IS 1986 PRICE GOAL CAN BE MET WITH THE EQUIVALENT OF LARGER THAN 3" WAFER (i.e., 6" MAY NOT BE ABSOLUTE REQUIREMENT)

SOLAR MODULES FROM DENDRITIC WEB SILICON

WESTINGHOUSE ELECTRIC CORP.





Defined Process Sequence

- PRE–DIFFUSION CLEANING
- $POCL_3$ DIFFUSION
- BACK SURFACE FIELD – AL DEPOSITION + DRIVE IN
- ANTIREFLECTION COATING APPLICATION BY DIPPING
- PHOTORESIST LAYER APPLICATION BY DIPPING
- GRID DELINEATION
- METALLIZATION BY EVAPORATION
- REJECTION AND PLATING
- CELL SEPARATION AND TESTING
- CELL INTERCONNECTION BY ULTRASONIC BONDING
- ENCAPSULATION

Material Characteristics of Dendritic Web Silicon for Solar Modules

1. SINGLE CRYSTAL – (111) ORIENTATION
2. THE ETCH PIT DENSITY (AFTER 5 MIN. SIRTL ETCH) TO BE $\leq 3 \times 10^4/cm^2$
3. RESIDUAL STRESS IN WEB $\leq 1.5 \times 10^8$ DYNES/cm^2 (160 PSI)
4. WEB TO BE FLAT; NO TWIST OR BOW
5. SURFACE OF WEB TO BE FLAT WITH NO VARIATIONS IN HEIGHT GREATER THAN 0.5 μm
6. THE WIDTH, INCLUDING DENDRITES, SHOULD BE 28 mm OR GREATER FOR A 25 mm WIDE CELL
7. THE THICKNESS OF WEB AT CENTER TO BE 120 $\mu m \pm 20$ μm
8. THE WEB SHOULD BE P–TYPE
9. THE RESISTIVITY SHOULD BE 4–12 $\Omega \cdot cm$ (TENTATIVE)

Plasma Cleaning Test

TREATMENT	J_{SC} ($\frac{mA}{cm^2}$)	V_{OC} (V)	FF	EFF (%)	τ_{ocd} (μsec)
HF CLEAN + 3 MIN. PLASMA CLEAN	33.3	.545	.743	13.3	23.0
CHEMICAL – CHELATING CLEAN	33.2	.545	.737	13.1	24.7

WEB – RE26–5; 10 Ω-cm; BORON BSF

AR COATED; MEASURED AT AM1; 100 mw/cm^2

Pre-Diffusion Plasma Cleaning

PURPOSE:	REMOVE SURFACE OXIDES AND PREPARE WEB FOR DIFFUSION
PROCESS:	HF + DI H_2O + DRY PLASMA CLEAN – 3 MIN/O_2
PROCESS INPUT:	AS GROWN LENGTH OF WEB HAVING CHARACTERISTICS AS SHOWN
PROCESS CONTROLS:	200 WATTS ± 10 WATTS RF POWER 300 cc/MIN ± 10 cc/MIN OF O_2 – HOLD 3 MIN. AT T < 120°C
PROCESS OUTPUT:	CLEANED WEB
VALUE ADDED: (25 MW/YR)	\$0.027/PEAK WATT (+\$0.24/W_p FOR INPUT DENDRITIC WEB SILICON
CONCLUSIONS:	SURFACE CONDITION OF WEB EQUAL TO THAT USING ORIGINALLY DEFINED EXTENSIVE CHEMICAL CLEANING: PROCESS IS MORE COST EFFECTIVE

NOTE: ALL COSTS GIVEN IN 1980$.

$POCl_3$ Diffusion

PURPOSE:	FORMATION OF N^+PN^+ STRUCTURE BY DIFFUSION OF $POCL_3$ INTO P–BASE WEB
PROCESS:	$POCL_3$ DIFFUSION, STANDARD DIFFUSION FURNACE; ETCH TO REMOVE OXIDE
PROCESS INPUT:	CLEANED WEB
PROCESS CONTROLS:	$\left.\begin{array}{l}\text{200 cc/MIN } N_2 \text{ THROUGH } POCL_3\\ \text{1560 cc/MIN } N_2 \text{ CARRIER}\\ \text{62.5 cc/MIN } O_2 \text{ CARRIER}\end{array}\right\} \pm 10\%$
$T = 850^\circ C \left\{\begin{array}{l}+5^\circ C\\ -10^\circ C\end{array}\right.$;	T = 35 MIN ± 10 MIN
COOLING RATE:	5°C/MIN FROM 850°C → 700°C ± 1°C/MIN
PROCESS OUTPUT:	DIFFUSED/WEB WITH SHEET RESISTIVITY OF 50 $\frac{\Omega}{\square}$ ± 5 $\frac{\Omega}{\square}$
VALUE ADDED: (25 MW/YR)	\$0.028/PEAK WATT (1980$)
CONCLUSIONS:	CAN HOLD X_J TO 0.3 ± 0.05 μm WITH ABOVE CONTROLS

Back-Surface Field (1)

PURPOSE:	FORM N^+PP^+ STRUCTURE
PROCESS:	DEPOSIT AL BY PLASMA SPRAYING; ALLOY AT 850°C
PROCESS INPUT:	LENGTH OF WEB WITH N^+PN^+ STRUCTURE
PROCESS CONTROLS:	PLASMA SPRAY 20 $\mu m \pm 5\ \mu m$ ON ONE N^+ SIDE ALLOY AT 850°C ±3°C FOR 1 MIN ±0.25 MIN IN N_2 COOLING RATE 50°C/MIN ±25°C/MIN
PROCESS OUTPUT:	N^+PP^+ STRUCTURE WITH P^+P JUNCTION OF 6–10 μm
VALUE ADDED:	$0.038/WATT PEAK (PLASMA SPRAYED AL) $0.053/WATT PEAK (SPUTTERED AL)
CONCLUSIONS:	V_{OC} ENHANCEMENT OF 40-50 mV, STRUCTURAL PROBLEMS WITH WEB – BOWING, BRITTLENESS; YIELD COULD BE A PROBLEM

Back-Surface Field (2)

ORIGINAL BSF DEFINED WAS BORON DIFFUSED. PROCESS CHANGED TO AL BSF DUE TO INCREASED V_{OC} AND LOWER COST

BACK SURFACE TREATMENT	V_{OC} (V)	YIELD (%)	VALUE ADDED (1980$/PEAK WATT)
NONE	.520 – .540	100	0
B-DIFFUSED	.560–.580	99	0.072
AL-ALLOYED	.580–.600	85	0.038

- COST BASED ON 100% YIELD
- INCREASE IN V_{OC} MAY BE OUTWEIGHED BY YIELD FACTOR

Antireflection Coating

PURPOSE:	APPLY AR COATING (WHICH ALSO ACTS AS A PLATING MASK)
PROCESS:	WITHDRAW (BY DIPPING) WEB FROM MIXED TiO_2/SiO_2 METAL–ORGANIC SOLUTION
PROCESS INPUT:	WEB LENGTH WITH N^+PP^+ STRUCTURE
PROCESS CONTROLS:	SOLUTION: 3.5% MIXED OXIDES IN ALCOHOL (88% TiO_2 – 12% SiO_2) WITHDRAW AT 30 cm/MIN ±3 cm/MIN (RATE = F (VISCOSITY & CONC.) HEAT IN AIR FOR 15 MIN AT 400°C ±10°C
PROCESS OUTPUT:	LENGTH OF WEB WITH N^+ SURFACE COATED WITH BLUE/BLACK ADHERENT GLASS LAYER
VALUE ADDED:	$0.007/WATT
CONCLUSIONS:	A COST EFFECTIVE TECHNIQUE TO APPLY AN AR LAYER ENHANCEMENT VALUES TO 48% OBTAINED; 42–45% NOMINAL

Photoresist Layer

PURPOSE:	APPLY PR LAYER FOR GRID DEFINITION
PROCESS:	PR APPLIED TO WEB LENGTH BY WITHDRAWING FROM POSITIVE PR SOLUTION
PROCESS CONTROLS:	50/50 SOLUTION OF PR & PR THINNER WITHDRAW AT 25 cm/MIN $\pm$5 cm/MIN FOR 1 μm COATING BAKE (AIR) AT 90°C $\pm$3°C FOR 25 MIN $\pm$3 MIN
PROCESS OUTPUT:	LENGTH OF WEB WITH N^+ SIDE COATED WITH AR & PR LAYERS
VALUE ADDED:	$0.025/WATT PEAK
CONCLUSIONS:	• COST OF PR MINIMIZED WITH THIN COAT • GRID LINES OF 25 μm EASILY OBTAINED • LESS AREA COVERAGE ($\approx$4–5%) VS 10% FOR SCREENED CONTACTS; LEADS TO HIGHER EFFICIENCY SAVING COST

Expose PR/Develop PR/Etch AR

PURPOSE:	DEFINE GRID
PROCESS:	EXPOSE PR; DEVELOP AND ETCH TO DEFINE GRID
PROCESS CONTROLS:	NEGATIVE MASK – FIT BETWEEN DENDRITES – EXPOSE 55 mj/cm^2 DEVELOP PR – 60 SEC AT 20°C RINSE DI H_2O ETCH AR – 3:1::H_2O:HF RINSE AND DRY WIDTH OF GRID LINES TO BE 25 μm $\begin{cases} +5\ \mu m \\ -0\ \mu m \end{cases}$
PROCESS OUTPUT:	LENGTH OF WEB WITH DELINEATED GRID
VALUE ADDED:	$0.009/WATT PEAK
CONCLUSIONS:	IS COST EFFECTIVE PROCESS CAN OBTAIN GRID STRUCTURE WITH $\approx$5% AREA COVERAGE

Metallization

PURPOSE:	APPLY FIRST METALS
PROCESS:	EVAPORATION OF THIN LAYERS OF Ti-Pd-Ag (Cu) ON LENGTH OF WEB
PROCESS INPUT:	LENGTH OF WEB WITH DELINEATED GRID
PROCESS CONTROLS:	AT 10^{-6} TORR; E–BEAM EVAPORATE: 300 Å $\pm$ 50 Å OF Ti AT 2–5 Å/SEC 300 Å $\pm$ 50 Å OF Pd AT 2–5 Å/SEC 300 Å $\pm$ 50 Å OF Ag (Cu) AT 2–5 Å/SEC
PROCESS OUTPUT:	ENTIRE LENGTH OF WEB COATED WITH ABOVE METALS
VALUE ADDED:	$0.041/WATT PEAK
CONCLUSIONS:	Ti (OR OTHER MATERIAL) REQUIRED AS BARRIER SPACE QUALIFIED CONTACT SYSTEM Cu SUITABLE SUBSTITUTE FOR Ag

Rejection of Excess Metal

PURPOSE:	TO REMOVE EXCESS METAL
PROCESS:	DISSOLVE PR AND THUS REMOVE ALL METAL EXCEPT IN GRID
PROCESS INPUT:	LENGTH OF WEB WITH METAL COATING
PROCESS CONTROLS:	IMMERSE WEB IN ACETONE ULTRASONIC AGITATION RINSE WITH MEOH–H_2O–DRY
PROCESS OUTPUT:	LENGTH OF WEB WITH THIN LAYERS OF METALS IN GRID
VALUE ADDED:	\$0.01/WATT PEAK
CONCLUSIONS:	THIN LAYERS OF METAL LOST HAVE MINIMAL COST IMPACT

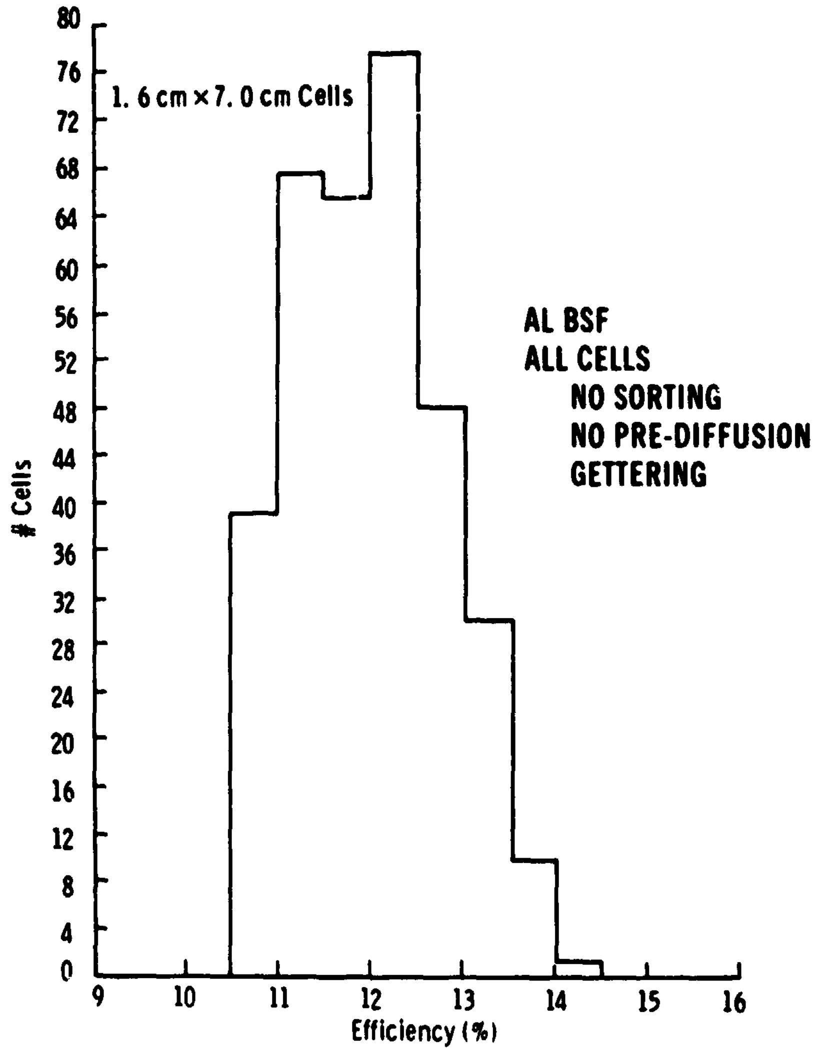
Copper Electroplating

PURPOSE:	OBTAIN THICK CONDUCTIVE LAYER ON GRID
PROCESS:	APPLY Cu TO GRID BY ELECTROPLATING
PROCESS INPUT:	LENGTH OF WEB WITH TiPdCu IN GRID
PROCESS CONTROLS:	• USE BASIC COPPER BATH • PLATE AT 10–20 ma/cm^2 FOR 10 MIN. • WASH DI H_2O/DRY • PLATED Cu SHOULD BE 6–8 μm THICK
PROCESS OUTPUT:	LENGTH OF WEB WITH COMPLETE METALLIZED GRID
VALUE ADDED:	\$0.039/WATT PEAK
CONCLUSIONS:	COPPER SUITABLE SUBSTITUTE FOR Ag AND IS MORE COST EFFECTIVE

Cell Separation and Test

PURPOSE:	TO SEPARATE CELL FROM DENDRITE–WEB MATRIX
PROCESS:	BY LASER SCRIBING, AND FRACTURING–SEPARATE CELL FROM MATRIX – TEST
PROCESS INPUT:	LENGTH OF WEB WITH PLATED GRID
PROCESS CONTROLS:	LASER SCRIBE FROM BACK; $\approx$50μm DEEP FRACTURE OUT CELL CELL AREA = Ao $\pm$0.5% TEST
PROCESS OUTPUT:	FINISHED/TESTED CELL
VALUE ADDED:	\$0.027/WATT PEAK
CONCLUSIONS:	VERY COST EFFECTIVE PROCESS HIGH YIELD

Output of Lab Scale Production Run



Efficiency distribution of cells used in demonstration modules

PRODUCTION PROCESS AND EQUIPMENT AREA

Interconnection (1)

PURPOSE:	TO INTERCONNECT CELLS IN REQUIRED SERIES/PARALLEL SYSTEM
PROCESS:	USE ULTRASONIC BONDING TECHNIQUE FOR FRONT AND BACK INTERCONNECTIONS TO CELLS
PROCESS INPUT:	CELLS
PROCESS CONTROLS:	BOND PULL STRENGTH >50 GMF BOND RESISTANCE $<10^{-5}\,\Omega$
PROCESS OUTPUT:	INTERCONNECTED STRINGS
VALUE ADDED:	$0.026/WATT PEAK
CONCLUSIONS:	COST EFFECTIVE PROCESS BUT YIELD NEEDS TO BE IMPROVED

Interconnection (2)

STATUS:

1. BONDING TO FRONT Cu GRID WITH PROPER FIXTURING SHOULD GIVE ACCEPTABLE YIELD
2. BONDING TO AL BACK IS UNDER DEVELOPMENT
3. SEAM BONDING VS SPOT BONDING STATUS
4. PRESENTLY WORKING ON PROGRAM TO IMPROVE YIELD

Encapsulation

PURPOSE:	PROTECT CELLS FROM ENVIRONMENT
PROCESS:	POT CELLS IN RTV ENCAPSULANT
PROCESS INPUT:	CONNECTED STRINGS OF CELLS
PROCESS CONTROLS:	MINIMUM AMOUNT OF BUBBLES SIMPLE OUTSIDE CONNECTIONS ENCAPSULANT PARTS SUITABLE FOR 20 YR LIFETIME
PROCESS OUTPUT:	SOLAR MODULE
VALUE ADDED:	$0.162/WATT PEAK (+$0.010/WATT PEAK – CRATING)
CONCLUSIONS:	• LAMINATION PROCESS BEING STUDIED • TO MEET JPL TEST GOALS MUST RELY ON INHERENT STRENGTH OF MATERIALS – FRAME AND GLASS SUPERSTRATE

SAMICS Analysis
Conceptual Factory Used in Calculation

1. 25 MW/YR PRODUCTION
2. AUTOMATED PROCESSES
3. AUTOMATED MATERIAL HANDLING
4. CELLS TO BE 5 cm x 20 cm
5. PANELS TO BE 1 m x 2 m
6. BALANCED LINE
7. 345 DAYS/YR OPERATION – 3 SHIFTS
8. WEB INPUT COST – \$0.24/PEAK WATT (1980\$)
9. 13% MODULE
10. 85% YIELD OF CELLS
11. 95% YIELD OF PANELS
12. OVERALL YIELD = 81%

SAMICS Analysis

RESULTS: (1980\$)

CAPITAL	\$10,350,000
DIRECT LABOR	1,920,000
FLOOR SPACE	4,800 SQ. FT.
COMMODITIES	3,410,000

SELLING PRICE PER PEAK WATT: \$0.68

SAMICS Analysis Process Step Costs

PROCESS STEP	VALUE ADDED (1980\$/WATT PEAK)	COMMENTS
1. PREDIFFUSION CLEAN	0.027	+\$0.24 FOR INPUT SI
2. $POCL_3$ DIFFUSION	0.025	INCLUDES OXIDE ETCH
3. BACK SURFACE FIELD	0.038	PLASMA SPRAY AL
4. AR/PR – DIP & BAKE	0.032	AR–0.007; PR–0.025
5. EXPOSE–ETCH	0.009	
6. METALLIZE	0.041	
7. REJECT/Cu PLATE	0.043	
8. CELL SEP'N – TEST	0.027	
9. INTERCONNECTION	0.026	
10. ENCAPSULATION	0.162	SILICONE POTTING
11. CRATING	0.010	

TOTAL \$0.68/WATT PEAK (1980\$)

SAMICS Analysis Sensitivity of Inputs, 1980$

YIELD: IN 70% – 90% YIELD RANGE, EACH 10% INCREASE IN YIELD, DECREASES THE SELLING PRICE BY $0.07/WATT PEAK.

MODULE EFFICIENCY: IN THE RANGE OF 10% – 15% MODULE EFFICIENCY, EACH 1% INCREASE IN EFFICIENCY DECREASES THE SELLING PRICE BY $0.08/WATT PEAK

CAPITAL: FOR EACH $10^6$$ IN CAPITAL ADDED, THE SELLING PRICE INCREASES BY $0.03/WATT PEAK
(ASSUME INITIAL CAPITAL – 10 x $10^6$$)

WEB WIDTH: IF WIDTH OF DENDRITIC WEB SILICON CELL IS DECREASED FROM 5cm TO 2.5cm, THE SELLING PRICE INCREASES BY $0.07/WATT PEAK.
(ASSUMING EQUAL YIELDS)

Conclusions

1. HAVE DEFINED A CONSERVATIVE COST EFFECTIVE PROCESS SEQUENCE FOR DENDRITIC WEB SILICON ($0.68/PEAK WATT) 1980$
2. DENDRITIC WEB SILICON MOST ECONOMICALLY PROCESSED IN LONG LENGTHS (20-60 cm)
3. A NUMBER OF PROCESS STEPS ARE DESIGNED SPECIFICALLY FOR DENDRITIC WEB SILICON
4. CAPITAL INTENSIVE PROCESS HAS BEST CHANCE OF ACHIEVING COST GOALS
5. EFFICIENCY OF CELLS AND MODULES OF PRIME IMPORTANCE IN OVERALL COSTS

AUTOMATED ARRAY ASSEMBLY, PHASE II

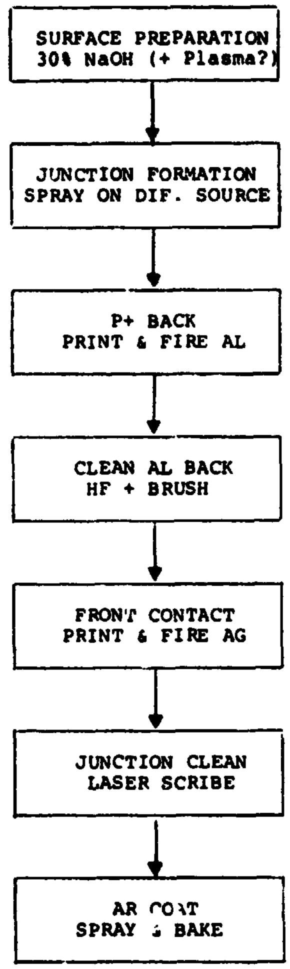
SPECTROLAB, INC.

William E. Taylor

Assumptions

- 100 MM SQUARE HEM SLICE
- 1.2 M SQUARE GLASS SUPERSTRATE MODULE
- 12% MODULE EFFICIENCY
- 95% YIELD
- 3 SHIFTS, 7 DAYS/WK., 50 WEEKS/YR.
- 90% UP TIME

Process Sequence: Cells



Surface Preparation

ASSUMPTIONS:

4" SQUARE WAFERS (HEM)

EQUIP.	128,000	$1980
OUTPUT	25	PARTS/MIN
SPACE	75	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	.25	PRSN/SHIFT
MATERIALS	0.14	$1980/MIN
POWER	0.10	kW HR/MIN
QUAN.	14.0	MWP/YR
P(IPEG)/WP	0.0164	$1980

Diffusion

ASSUMPTIONS:

SPIN ON PX 10
15 MIN AT 375°C

EQUIP.	230,000	$1980
OUTPUT	12.5	PARTS/MIN.
SPACE	1,120	SQ. FT.
ASSEMBLERS	2	PRSN/SHIFT
MAINT. PERS.	0.1	PRSN/SHIFT
MATERIALS	0.008	$1980/MIN.
POWER	1.9	kW HR/MIN.
QUAN.	7.0	MWP/YR
P (IPEG)/WP	0.0584	$1980

Back Contact

ASSUMPTIONS:

PRINTED ALUMINUM

EQUIP.	134,800	$1980
OUTPUT	25	PARTS/MIN
SPACE	750	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.25	PRSN/SHIFT
MATERIALS	0.077	$1980/MIN.
POWER	1.5	kW HR/MIN.
QUAN.	14.0	MWP/YR.
P (IPEG)/WP	0.0262	$1980

Clean Aluminum Back

ASSUMPTIONS:

ACID DIP + MECHANICAL BRUSHING

EQUIP.	300,000	$1980
OUTPUT	12.5	PARTS/MIN
SPACE	150	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	0.1	PRSN/SHIFT
MATERIALS	0.20	$1980/MIN
POWER	0.2	kW HR/MIN
QUAN.	7.0	MWP/YR
P (IPEG)/WP	.0336	$1930

Front Contact

ASSUMPTIONS:

SCREEN PRINTED SILVER 8% COVERAGE, $20/OZ

EQUIP.	134,800	$1930
OUTPUT	25	PARTS/MIN
SPACE	750	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.25	PRSN/SHIFT
MATERIALS	1.65	$1980/MIN
POWER	1.5	kW HR/MIN
QUAN.	14.0	MWP/YR
P (IPEG)/WP	0.0927	$1930

Junction Clean

ASSUMPTIONS:

FRONT SURFACE LASER SCRIBE

EQUIP.	98,000	$1980
OUTPUT	12.5	PARTS/MIN
SPACE	100	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.10	PRSN/SHIFT
MATERIALS	0	$1980/MIN
POWER	0.4	kW HR/MIN
QUAN.	7.0	MWP/YR.
P (IPEG)	0.0242	$1975

Antireflection Coating

ASSUMPTIONS:

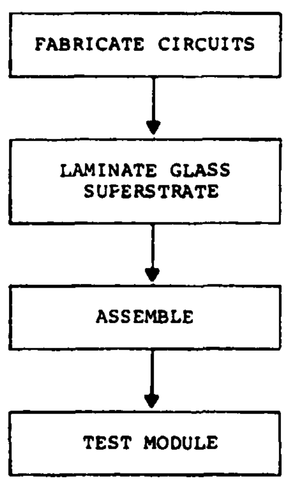
SPRAY ON TI ISOPROPOXIDE

EQUIP.	35,000	$1980
OUTPUT	12.5	PARTS/MIN
SPACE	120	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	0.1	PRSN/SHIFT
MATERIALS	0.029	$1980/MIN.
POWER	0.4	kW HR/MIN.
QUAN.	7.0	MWP/YR.
P (IPEG)	0.0161	$1980

Cell Test and Sort

EQUIP.	100,000	$1980
OUTPUT	25	PARTS/MIN.
SPACE	120	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	0.1	PRSN/SHIFT
MATERIALS	0	$1980/MIN.
POWER	0.2	KW HR/MIN.
QUAN.	14.0	MWP/YR.
P (IPEG)	0.0087	$1980

Process Sequence: Modules



Circuit Fabrication

ASSUMPTIONS:

SOLDERED INTERCONNECTS, REDUNDANT

EQUIP.	145,000	$1980
OUTPUT	6	CKTS/HR. (792 CELLS/HR)
SPACE	580	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.4	PRSN/SHIFT
MATERIALS	0.40	$1980/MIN.
POWER	0.10	kW HR/MIN.
QUAN	7.4	MWP/YR.
P (IPEG)/WP	0.0716	$1980

Laminate

ASSUMPTIONS:

TEMPERED GLASS, EVA, AL FOIL

EQUIP.	30,000	$1980
OUTPUT	3	LAMINATES/HR (396 CELLS/AR)
SPACE	400	SQ. FT.
ASSEMBLERS	0.25	PRSN/SHIFT
MAINT. PERS.	0.05	PRSN/SHIFT
MATERIALS	0.45	$1980/MIN
POWER	0.3	kW HR/MIN
QUAN.	3.68	MWP/YR.
P (IPEG)/WP	0.1038	$1980

PRODUCTION PROCESS AND EQUIPMENT AREA

Module Assembly

ASSUMPTIONS:

EXTRUDED AL FRAME, J BOXES

EQUIP.	45,000	$1980
OUTPUT	12	MODULES/HR (1584 CELLS/HR)
SPACE	300	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.25	PRSN/SHIFT
MATERIALS	0.58	$1980/MIN.
POWER	0	KW HR/MIN.
QUAN.	14.0	MWP/HR.
P (IPEG)/WP	0.0369	$1980

Module Test

EQUIP.	85,000	$1980
OUTPUT	40	MODULES/HR (5280 CELLS/YR.)
SPACE	300	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	0.2	PRSN/SHIFT
MATERIALS	0	$1980/MIN.
POWER	0.1	KW HR/MIN.
QUAN	49.3	MWP/YR.
P (IPEG)/WP	0.0028	$1980

IPEG Cost Summary (I)

$1980

	SURFACE PREPARATION	DIFFUSION	BACK CONTACT	CLEAN BACK
EQUIP	0.0045	0.0182	0.0065	0.0210
SPACE	0.0005	0.0060	0.0052	0.0021
LABOR	0.0053	0.0272	0.0086	0.0081
MATERIALS	0.0059	0.0014	0.0032	0.0017
POWER	0.0002	0.0055	0.0023	0.0008
TOTAL ($1980)	0.0164	0.0591	0.0262	0.0336

IPEG Cost Summary (II)

$1980

	FRONT CONTACT	JUNCTION CLEAN	AR COAT	TEST & SORT	CELL TOTAL
EQUIP	0.0066	0.0068	0.0025	0.0035	0.0694
SPACE	0.0052	0.0014	0.0017	0.0008	0.0230
LABOR	0.0085	0.0144	0.0031	0.0041	0.0844
MATERIALS	0.0697	-0-	0.0025	-0-	0.0843
POWER	0.0028	0.0015	0.0015	0.0004	0.0156
TOTAL ($1980)	0.0927	0.0242	0.0162	0.0087	0.2772

IPEG Cost Summary (III)

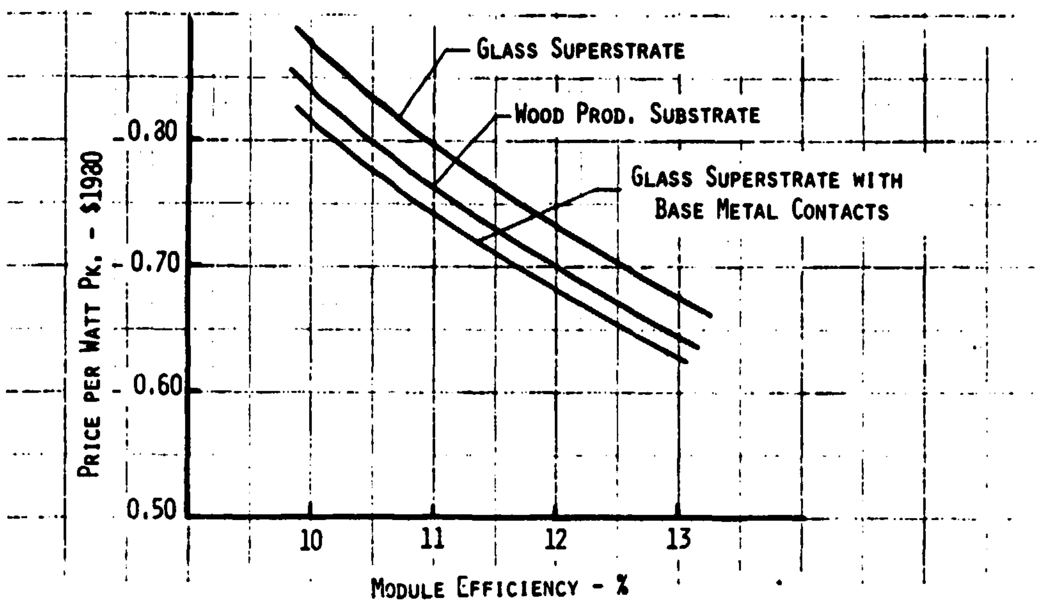
$1980

	CIRCUIT ASSEMBLY	LAMINATE	FRAME	TEST	MODULE TOTAL
EQUIP	0.0095	0.0106	0.0016	0.0009	0.0266
SPACE	0.0076	0.0104	0.0024	0.0006	0.0210
LABOR	0.0185	0.0077	0.0086	0.0014	0.0362
MATERIALS	0.0354	0.0728	0.0244	-0-	0.1327
POWER	0.0004	0.0022	-0-	0.0001	0.0027
TOTAL ($1980)	0.0716	0.1038	0.0355	0.0029	0.2152

IPEG Cost Summary (IV)

WAFER COST	0.2400
CELL FAB. COST	0.2772
MODULE FAB COST	0.2152
TOTAL	0.7324

Sensitivity to Module Efficiency



DEVELOPMENT OF LOW-COST CONTACTS TO SILICON SOLAR CELLS

APPLIED SOLAR ENERGY CORP.

Process

1) PRINT ON MASK
2) DRY
3) HF DIP
4) IMMERSION PD BATH
5) REMOVE PLATING MASK
6) SINTER 300 DEG C IN N2
7) AQUA REGIA DIP
8) RINSE
9) HF DIP
10) ELECTROLESS NI
11) RINSE
12) ELECTROLYTIC CU
13) SINTER 300 DEG C IN N2
14) EDGE GRIND

Electroless Nickel Bath, Boron Activated

1) NICKEL SULFATE 20g/L
2) POTASSIUM SODIUM TARTRATE 40g/L
3) SODIUM BOROHYRIDE 20g/L
4) Ph (ADJUST WITH NAOH) 12.5
5) TEMPERATURE 40-45 DEG C

Electroless Nickel Bath, Acid Based

1) NICKEL SULFATE 30g/L

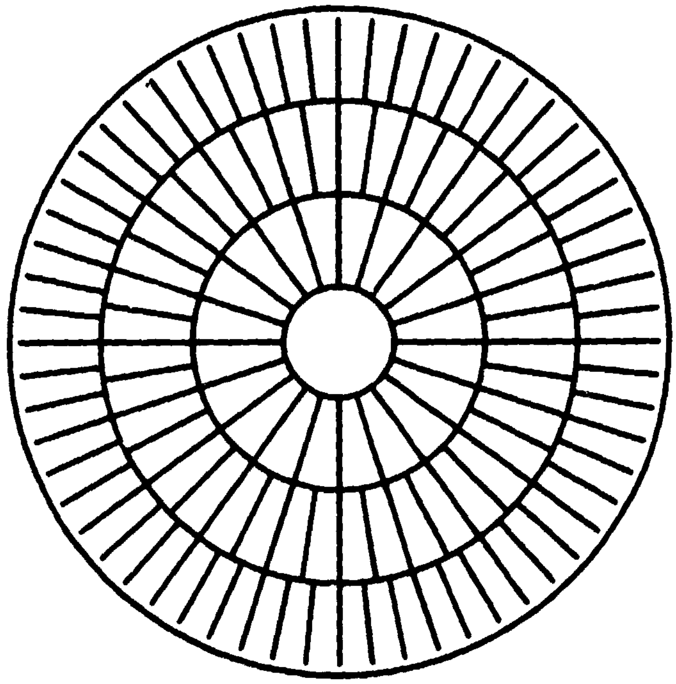
2) SODIUM ACETATE 12g/L

3) BORIC ACID 8g/L

4) AMMONIUM CHLORIDE 8g/L

5) SODIUM HYPOPHOSPHITE 24g/L

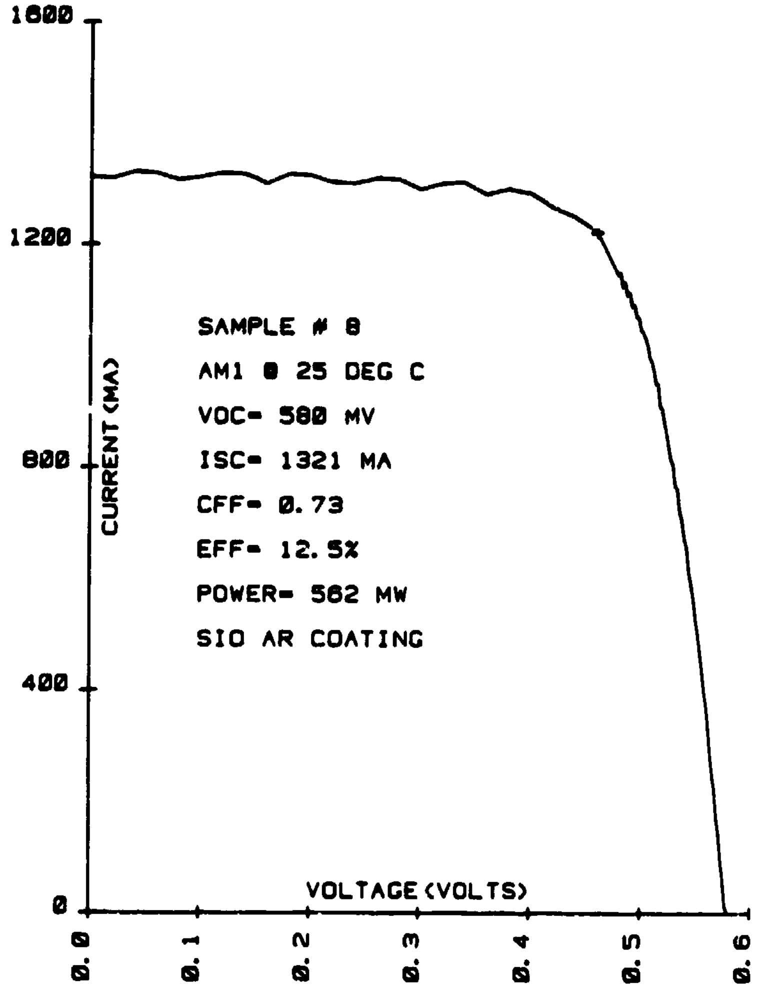
6) TEMPERATURE 90 DEG C



CONTACT COVERAGE 10%

GRID LINE WIDTH 5mils

Plated Pd-Ni-Cu Contacts



DEVELOPMENT OF HIGH-EFFICIENCY (14%) SOLAR ARRAY MODULE

APPLIED SOLAR ENERGY CORP

Goal

THE PURPOSE OF THE PROGRAM IS TO DESIGN AND FABRICATE 3" DIAMETER P/N SOLAR CELL WITH THE CONVERSION EFFICIENCY OF 16.5% OR BETTER AT AM1. 28°C. UPON COMPLETION OF THE SOLAR CELL DEVELOPMENT. ASEC IS TO DESIGN, FABRICATE AND DELIVER SIX (6) HIGH EFFICIENCY MODULES, APPROXIMATELY 2'X 4', WITH A MINIMUM OUTPUT OF 90 WATTS AND WITH THE DESIGN GOAL OF 14 % OVERALL MODULE EFFICIENCY.

Solar Cell Status

THE OBJECTIVE OF DEVELOPING 3" DIAMETER P/N CELLS OF 16.5% EFFICIENCY OR BETTER WAS MORE DIFFICULT THAN EXPECTED. THE MAJOR PROBLEMS WERE:

(I) LOW AND INCONSISTENCY OF Voc
(II) CELL SHUNTING
(III) AR COATING ANOMALY

(I) LOW AND INCONSISTENT VOC:

VOC VARIES FROM 550 TO 580 MV. WE ARE NOT SURE WHY VOC IS AS LOW AS IT IS, BUT WE HAVE THE FELLING THAT THE LOW VOC IS RELATED TO MATERIALS AND BORON NITRIDE DIFFUSION.

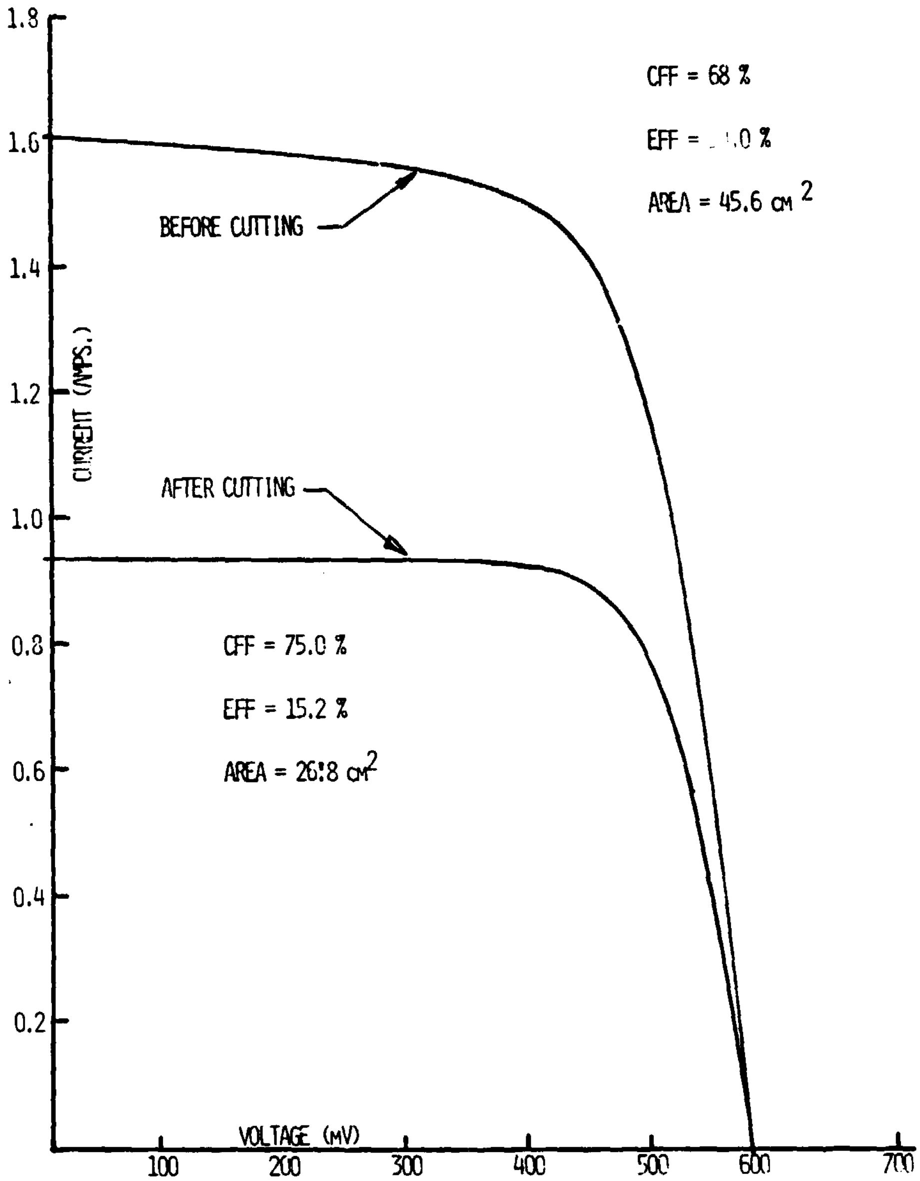
(II) CELL SHUNTING:

FIGURE 1. SHOWS THE SHUNTING I-V CHARACTERISTICS OF THE P/N SOLAR CELL. AN EXPERIMENT WAS PERFORMED BY CUTTING OFF THE EDGES OF THE CELLS MAKING RECTANGULAR CELLS FROM CIRCULAR CELLS, SHUNTING SEEMED TO BE MINIMIZED AFTER CUTTING. THE EXPERIMENT INDICATES THAT SOLAR CELL SHUNTING OCCURES AROUND THE PERIPHERIES OF THE CELLS,POSSILY DUE TO NON-UNIFORM DIFFUSION OF BORON NITRIDE DIFFUSION. THE CFF IMPROVED FROM 68% BEFORE CUTTING TO 75% AFTER CUTTING. THE EFFICIENCY ALSO IMPROVED FROM 14% TO 15.2%.

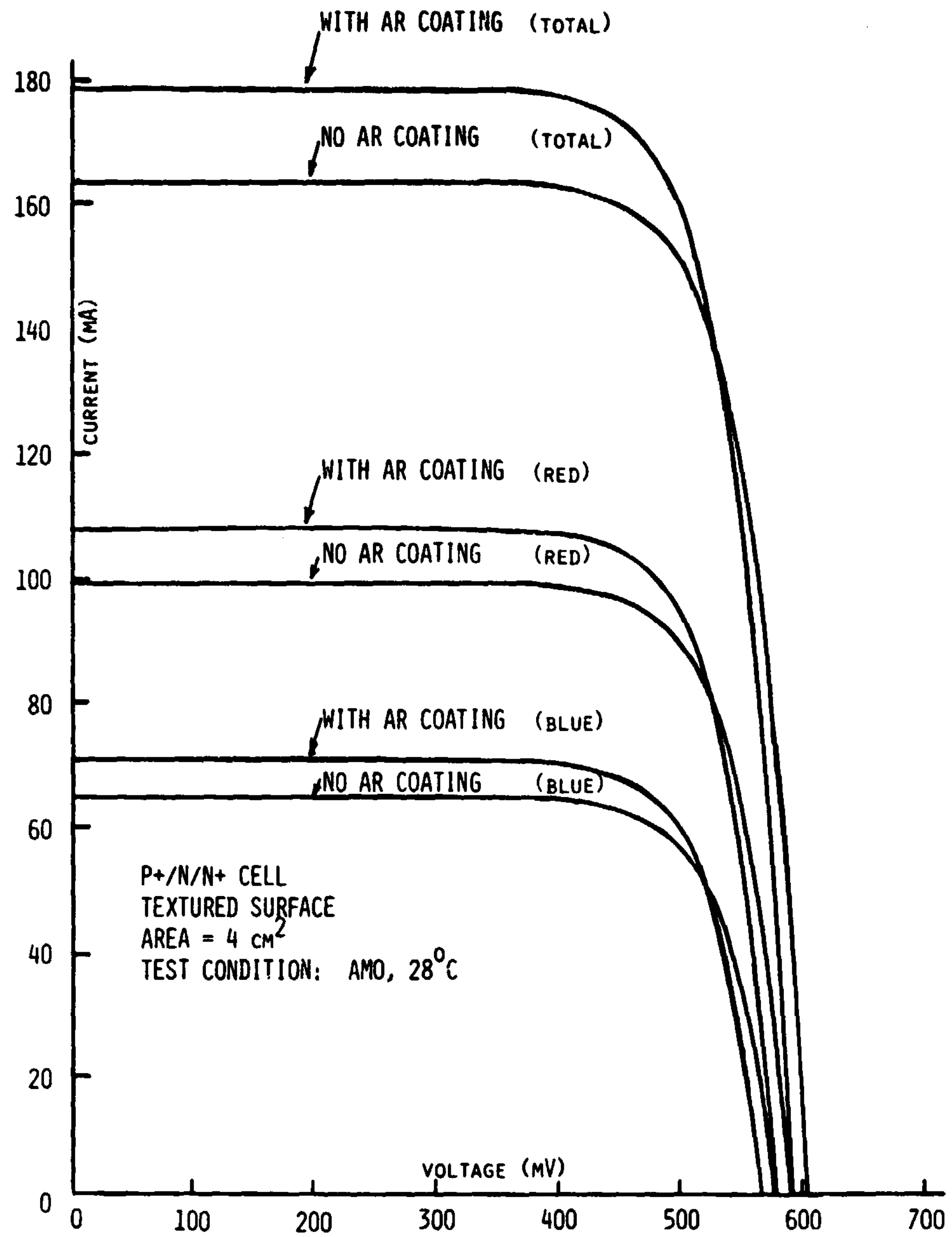
(III) AR COATING ANOMALY:

FIGURE 2. SHOWS THE AR COATING ANOMALY OF TEXTURED P/N SOLAR CELL. THE FIGURE SHOWS THE I-V CHARACTERISTICS OF A 2 x 2 CM^2 P/N CELL BEFORE AND AFTER MLAR COATING. THE ISC INCREASED AS EXPECTED AFTER COATING, BUT VOC DECREADED BY ~ 10MV (-1.7%) AFTER MLAR AND SIO COATINGS. THIS DECREASE IN VOC WAS ALSO DETECTED WHEN WESTINGHOUSE SPIN-ON AR WAS USED, BUT THE DECREASE WAS ONLY 4 MV. THE DECREASE IN VOC RESULTS IN A LOWER POWER THAN EXPECTED. THE VOC DECREASE IS SIMILAR FOR ALL THREE ILLUMINATION CONDITIONS, INDICATING THAT THE CHANGE IS NOT SPECTRALLY SENSITIVE OR INTENSITY SENSITIVE OVER A 2:1 RANGE. THE PROBLEM IS UNDER INVESTIGATION.

Cell Cutting Experiment



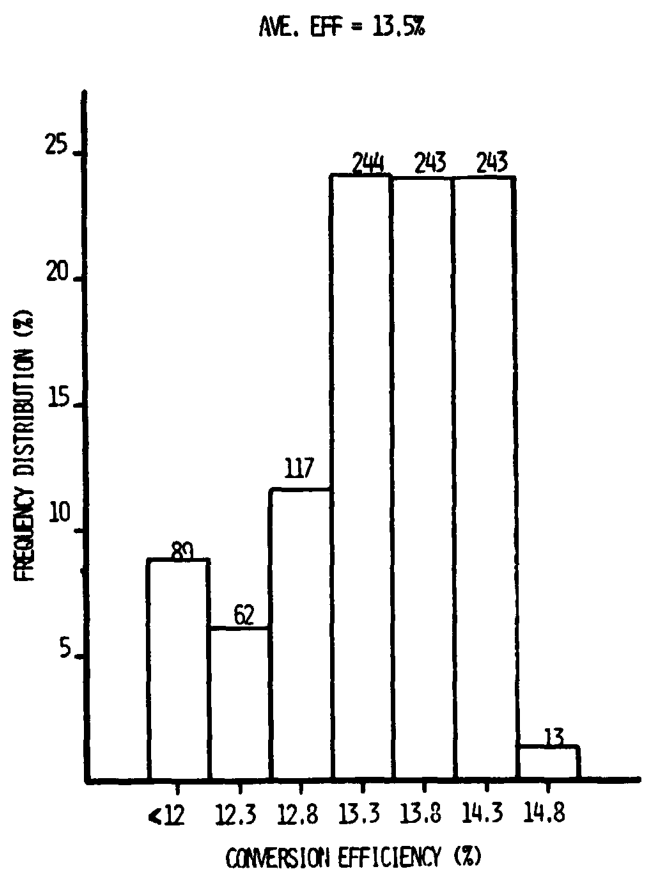
AR Coating Anomaly



Production Run

THE BEST PROCESS WAS CHOSEN AND 1112CELLS WERE PROCESSED. THE ELECTRICAL DISTRIBUTION AT AM1, 28°C OF 1011 CELLS IS GIVEN IN FIGURE 3. THE AVERAGE EFFICIENCY WAS 13.5%.

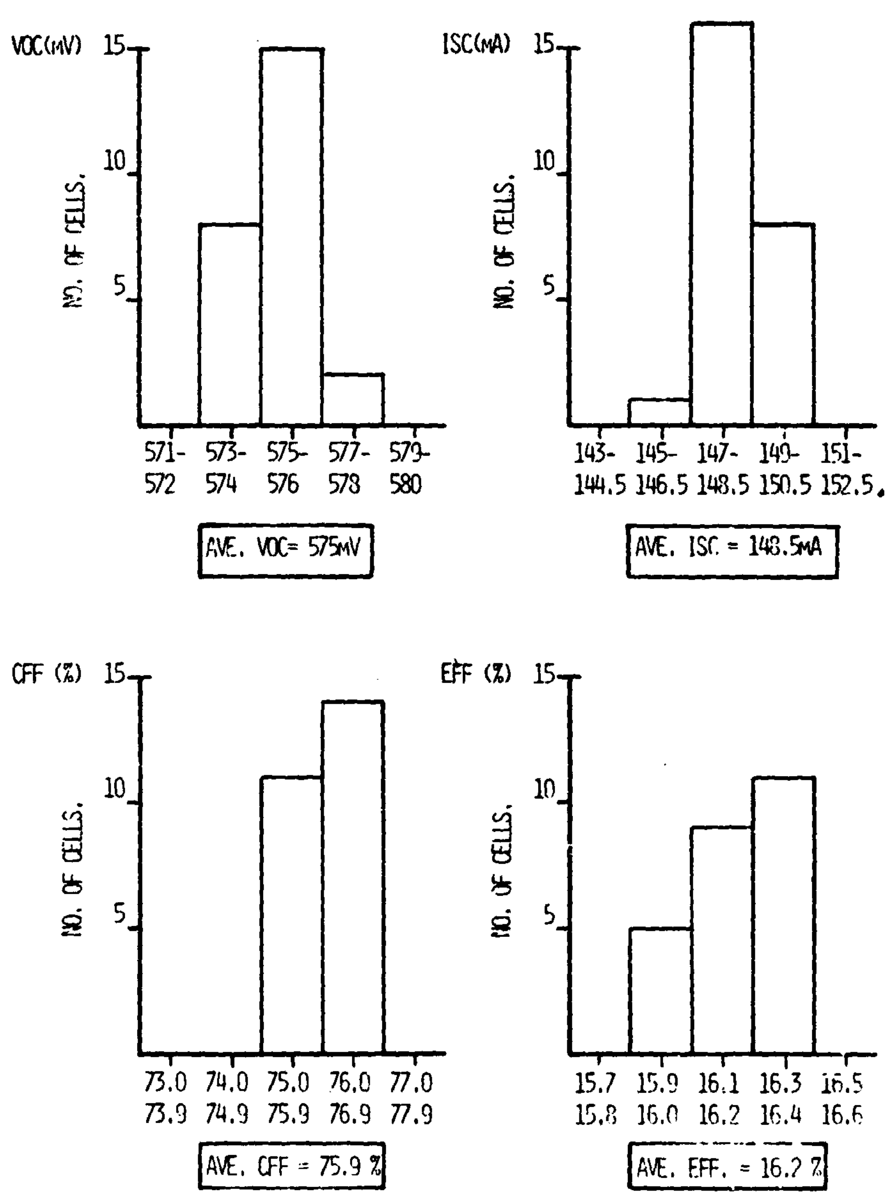
Efficiency Distribution of 1101 3-in.-Dia p/n Cells (AM1, 28°C)



Reference Cells

2 X 2 CM^2 P/N REFERENCE CELLS WERE FABRICATED AS PART OF THE PRODUCTION RUN. THE FIRST 25 CELLS WERE TESTED AND DELIEVERED TO JPL. THE ELECTRICAL OUTPUT IS SHOWN IN FIGURE 4. THE AVERAGE V_{OC} IS 575mV. THE AVERAGE I_{SC} IS 148.5 mA. THE AVERAGE CFF IS 75.9%. THE AVERAGE EFFICIENCY IS 16.2%. THESE REFERENCE CELLS SHOW A VERY TIGHT ELECTRICAL DISTRIBUTION.

AM1 Data for 25 Reference Cells



Modules

SIX (6) MODULES WERE FABRICATED. EACH MODULE HAS 120 - 3" DIAMETER P/N CELLS, CONNECTED 15 CELLS IN SERIES AND 8 CELLS IN PARALLEL.

THE PROJECTED POWER IS 78 WATTS.

THE PROJECTED MODULE EFFICIENCY IS 11.3 %.

Module Data

CELL AREA: 3" DIAMETER
TOTAL NO. OF CELLS: 120
CELL TYPE: P/N SOLAR CELL
ELECTRICAL INTERCONNECT: 8P,15S
PACKING FACTOR: 79.4%
TOTAL MODULE DIMENTION: 22.25"X 48"

TESTED DATA AT 100MW/CM , 28°C, NATURAL SUNLIGHT

MODULE NO.	POWER (WATTS)	CELL EFF. (%)	MODULE EFF. (%)
1	74.4	13.6	10.8
2	76.0	13.9	11.0
3	75.7	13.8	11.0
4	75.1	13.7	10.9
5	75.1	13.7	10.9
6	75.5	13.8	11.0

Conclusion

1.0 REASONABLE HIGH EFFICIENCY LARGE AREA P/N CELLS WERE MADE IN REASONABLE LARGE QUANTITIES

2.0 HIGH EFFICIENCY P/N CELLS IN EXCESS OF 16 % WERE SUCCESSFULLY MADE IN 2 X 2 cm^2 CONFIGURATION.

3.0 NO APPARENT DIFFICULITY IN MODULE ASSEMBLY USING TEXTURED P/N SOLAR CELLS.

4.0 MODULES ARE FUNCTIONING WELL.

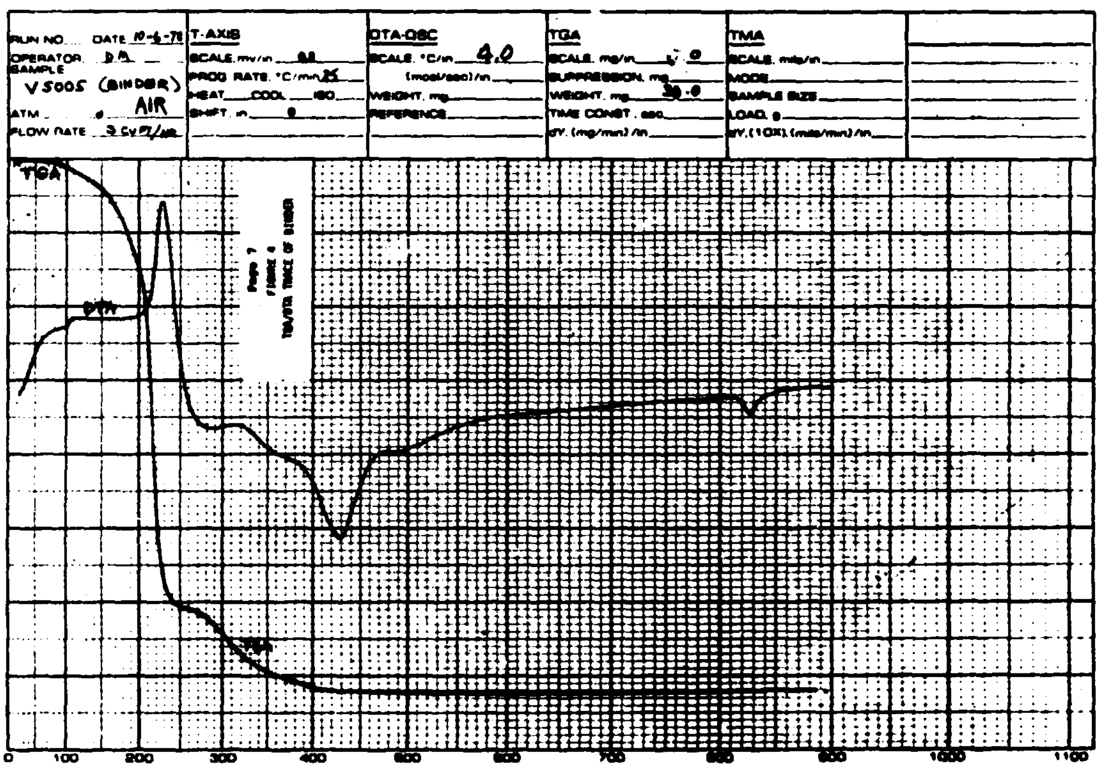
5.0 HIGHER EFFICIENCY, LARGE AREA P/N CELLS CAN BE REACHED WITH SOME FINE TUNE PROCESS DEVELOPMENT.

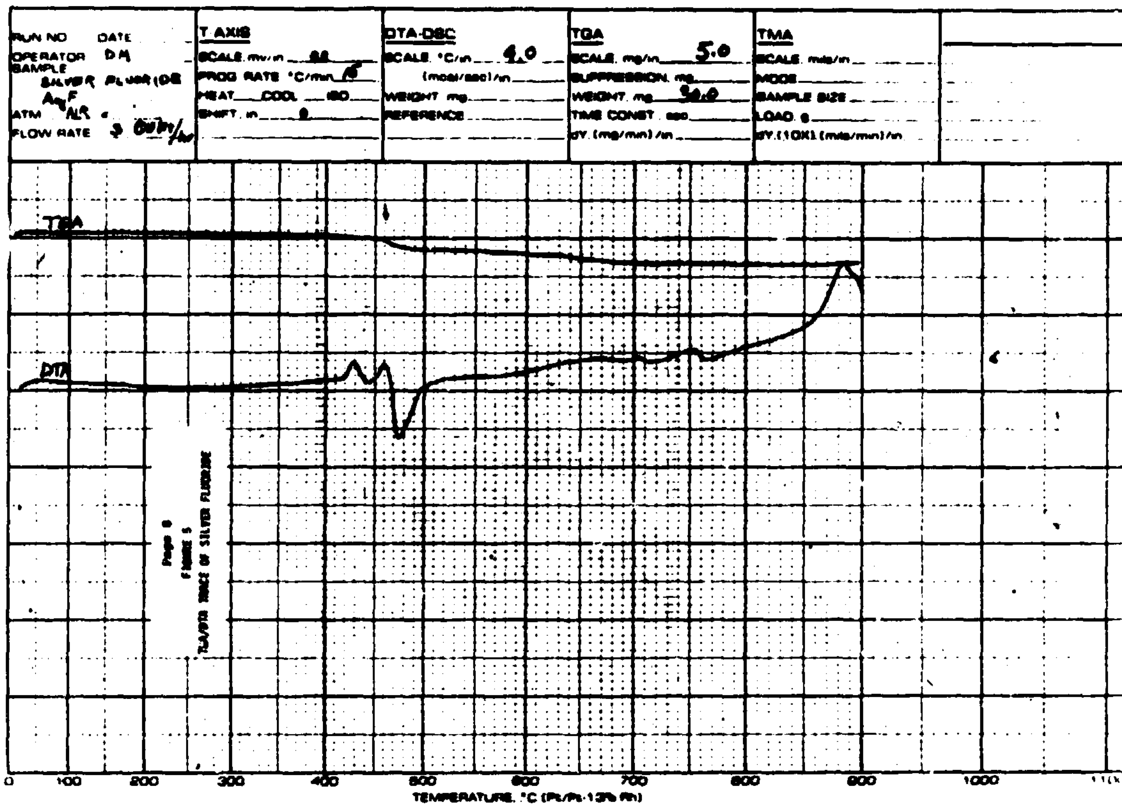
DEVELOPMENT OF ECONOMICAL IMPROVED THICK-FILM SOLAR CELL CONTACTS

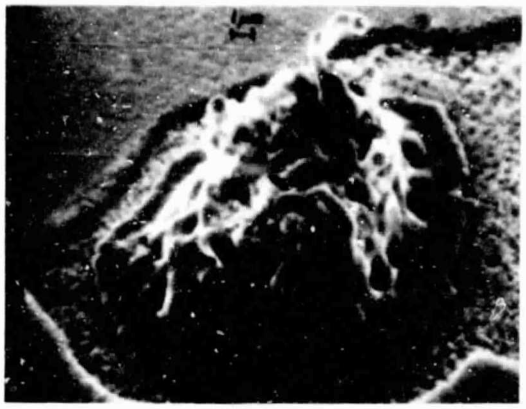
BERND ROSS ASSOCIATES

Objectives

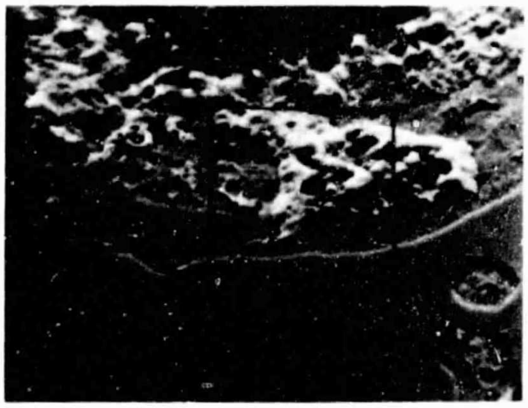
1. PROVIDE AN ALL-METAL SCREENABLE INK FOR SOLAR CELL CONTACTS.
2. ELIMINATE GLASS FRIT.
3. SUBSTITUTE LOW MELTING METAL POWDER "FRIT" PROMOTING SINTERING IN LIQUID PHASE
4. DETERMINE A SCREENABLE OXIDE SCAVENGER, REMOVING NATIVE SILICON OXIDE DURING FIRING STEP, AND WHICH DOES NOT AFFECT MATURED ELECTRODE PROPERTIES.
5. MAINTAIN COGNIZANCE OF LSA COST OBJECTIVES IN MATERIAL AND PROCESS SELECTION.



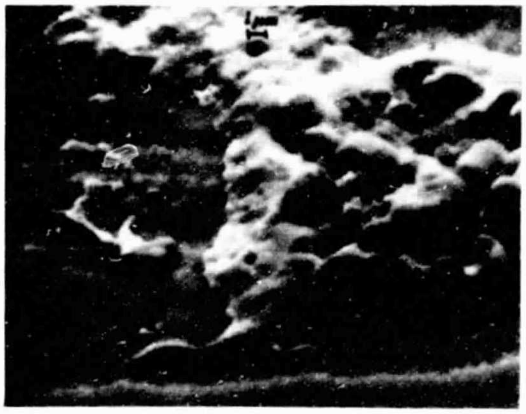

RUN NO DATE
OPERATOR DM
SAMPLE SILVER FLUORIDE AgF
ATM AIR
FLOW RATE
T AXIS
SCALE mv/in
PROG RATE °C/min
HEAT COOL ISO
SHIFT in
DTA-DSC
SCALE °C/in 4.0
(mcal/sec)/in
WEIGHT mg
REFERENCE
TGA
SCALE mg/in 5.0
SUPPRESSION mg
WEIGHT mg 30.0
TIME CONST sec
dY (mg/min)/in
TMA
SCALE mils/in
MODE
SAMPLE SIZE
LOAD g
dY (10X) (mils/min)/in
TGA
DTA
0
100
200
300
400
500
600
700
800
900
1000
TEMPERATURE, °C (Pt/Pt-13% Rh)



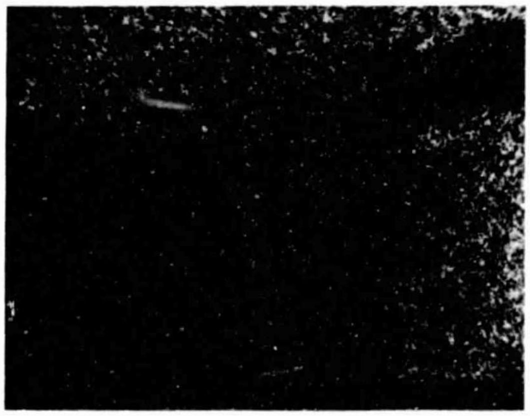
(A) MAGNIFICATION OF CAMBRIDGE SEM (4000X)



(B) DIFFERENT PORTION OF SAME SAMPLE TAKEN IN BACKSCATTER MODE AT 1500X

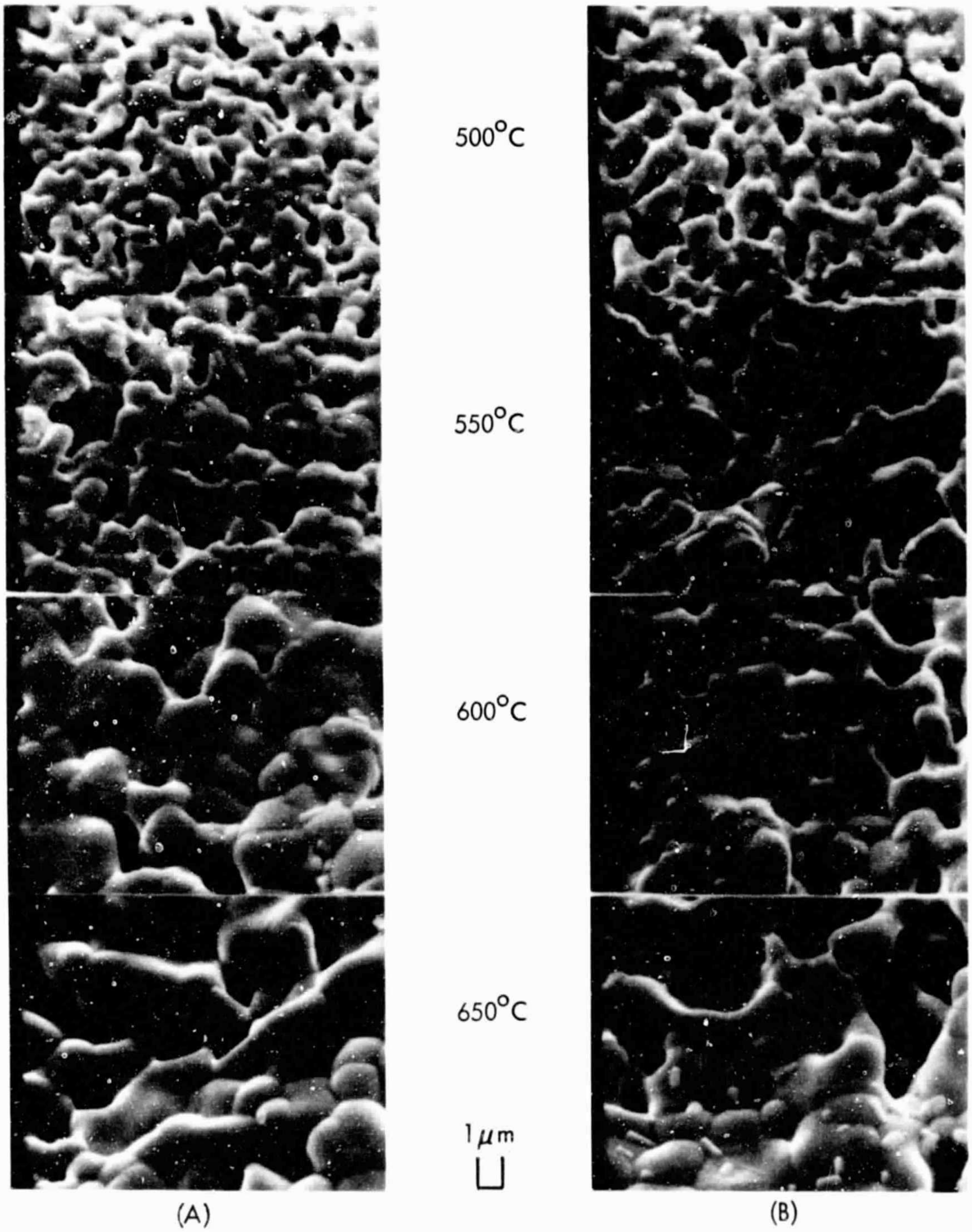


(C) AT 3700X



(D) SILVER MAP OF (C) USING 2.98 keV L_{α} FOR 1000 SEC.

DECOMPOSED SILVER FLUORIDE ON OXIDIZED SILICON (SILICON OXIDE THICKNESS 300 NM); FIRING TEMPERATURE 500°C



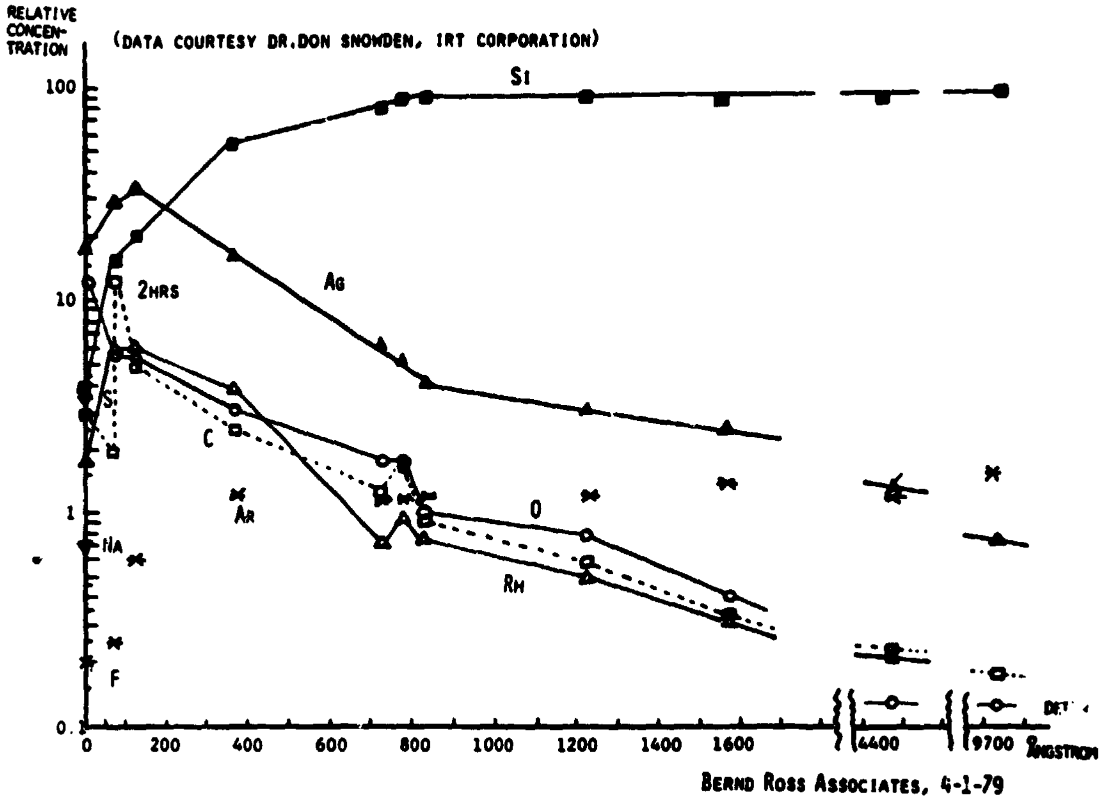
SEQUENCE OF PHOTOMICROGRAPHS TAKEN ON CAMBRIDGE SEM AT 5000X MAGNIFICATION OF

(A) S019 PRINTS WITH 2% AgF + 5%Pb

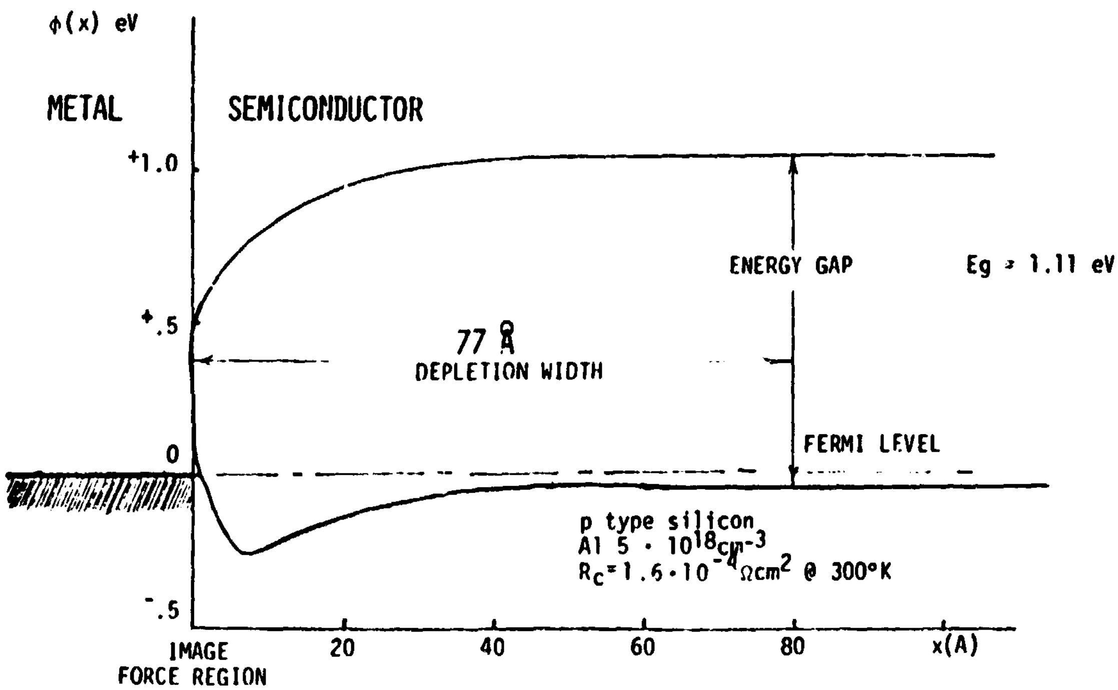
(B) S020 PRINTS WITH 2% AgF + 10% Pb

FIRED AT THE INDICATED TEMPERATURES IN NITROGEN

Auger Surface Spectra vs Etch Depth Of Decomposed AgF-Si Interface



Energy Level Diagram: Al Alloy Regrowth Contact



EVALUATION OF LASER ANNEALING FOR JUNCTION FORMATION

LOCKHEED MISSILES & SPACE CO., INC.

OBJECTIVES: (1) EVALUATE MERITS OF LARGE SPOT SIZE PULSED LASER ANNEALING OF ^{31}P IMPLANTED WAFERS.

(2) PROJECT FEASIBILITY AND DETERMINE REQUIREMENTS FOR A LASER SYSTEM TO ANNEAL 3-INCH DIAMETER WAFERS AT A RATE OF 1 WAFER/SEC.

EVALUATION MATERIAL:

- 3-INCH DIAMETER CZ P TYPE SILICON(100), -10 ΩCM
- POLISHED, FE AND TE SURFACES (ASEC)
- ION IMPLANTED PHOSPHORUS @ 5 AND 10 KEV AND 2.5 AND 4 x $10^{15}/cm^2$ DOSAGE. (SPIRE)

EVALUATION PARAMETERS:

- SINGLE VS OVERLAP PULSE AND EFFECTS ON CONVERSION EFFICIENCIES
- 1064 AND 532 NM WAVELENGTH ANNEALING AND COMBINATION
- EFFICIENCY VS. SURFACE FINISH.

EXPERIMENTAL HARDWARE (2 x 2'S, 2 x 4'S AND 3-INCH DIAMETER SIZES):

- ION IMPLANT/THERMAL ANNEAL/WITH AND WITHOUT BSF/VAC DEPOSITED TI-PD-AG/MULTI-LAYER AR (FOR REF.)
- ION IMPLANT/LASER ANNEAL/WITH AND WITHOUT BSF/VAC DEPOSITED TI-PD-AG/MULTI-LAYER AR
- DIFFUSED JUNCTION SOLAR CELLS (FOR REF.)
- ION IMPLANT/UNANNEALED FOR JPL EXPERIMENTATION.

ANALYSIS AND TESTING TECHNIQUES:

- SIMS, TEM, RUTHERFORD BACKSCATTER, SEM, MINORITY CARRIER LIFETIME AND ELECTRICAL OUTPUT.

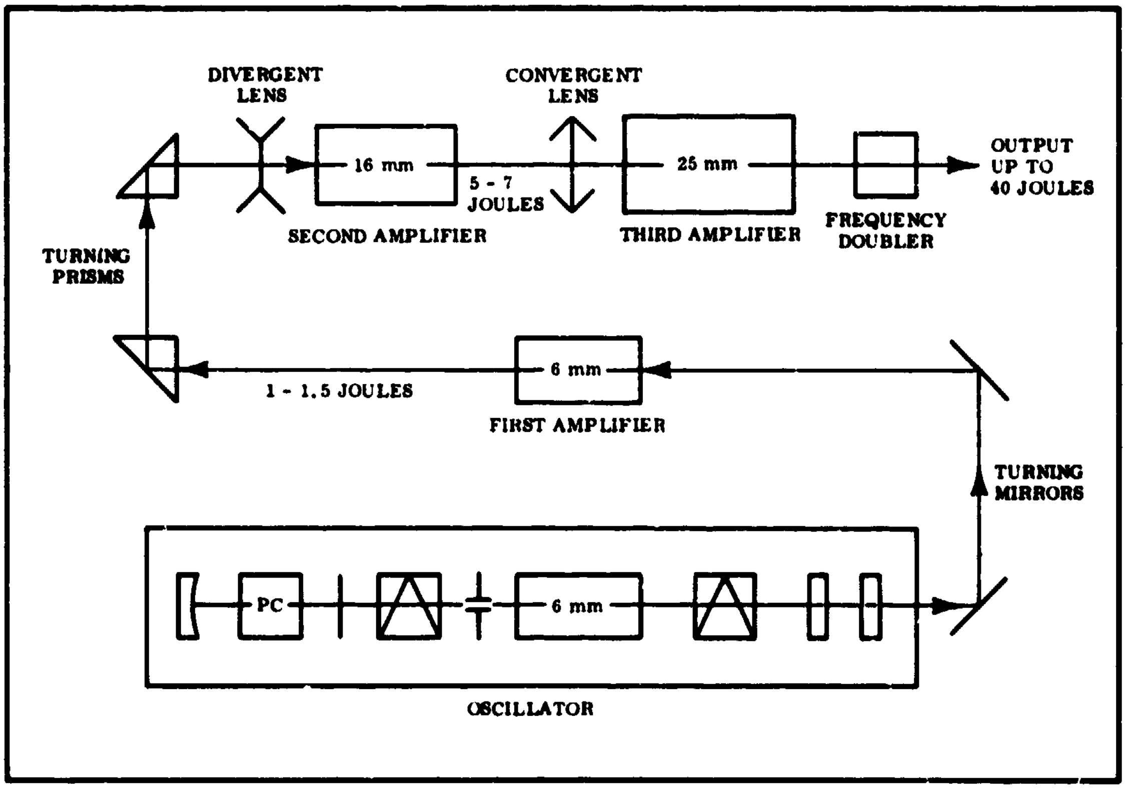
1986 THRUPUT OBJECTIVE PROJECTIONS:

- LASER EQUIPMENT CONFIGURATION SPECIFICATION
- SAMICS FORMAT A INPUTS.

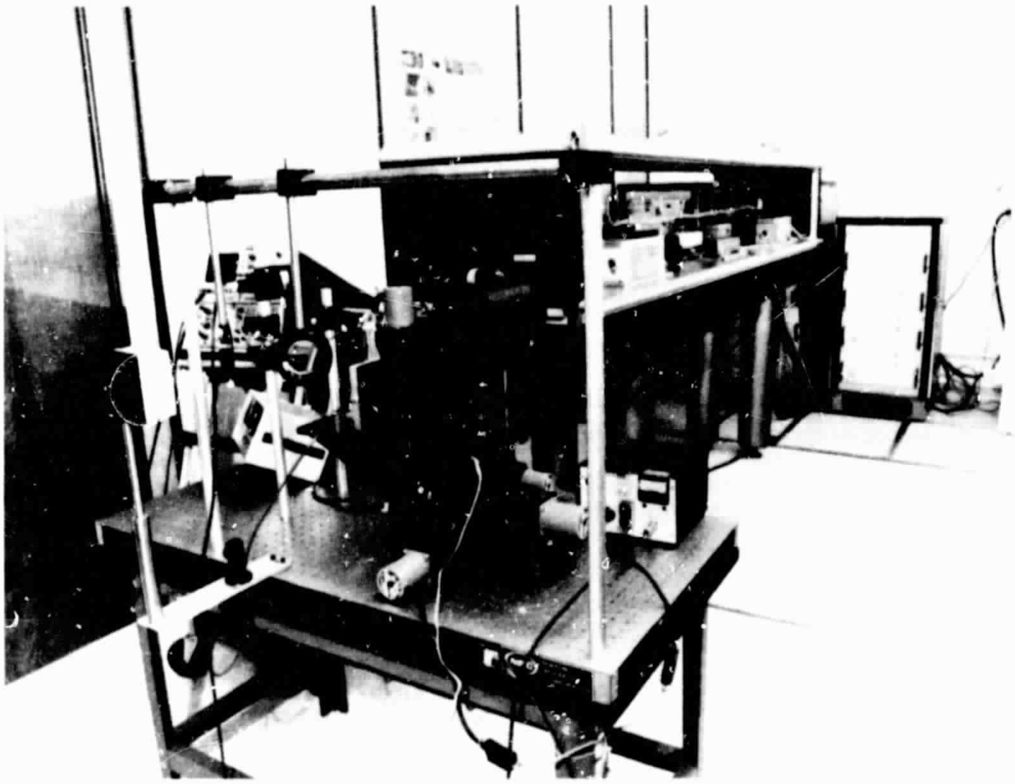
Laser Annealing Capability

LASER TYPE:	Q-SWITCHED Nd:GLASS WITH SHG (SECOND HARMONIC GENERATOR)	
OUTPUT ENERGY: TEM_{00} MODE	20 JOULES AT	= 1064 nm
	6 JOULES AT	= 532 nm
PULSE DURATION:	20 - 50 nSEC.	
PULSE REPETITION: RATE	4 PPM	
BEAM DIAMETER:	25 mm	

The Optical Path of the Laser



Q-Switched Nd: Glass Laser and Wafer Positioning Stage



ETCH-RESISTANT WAX PATTERNS ON SOLAR CELLS

MOTOROLA, INC.

Patterned Wax Masking

A. ATTEMPT TO REPLACE PHOTORESIST PROCESSING WITH A PATTERN PRINTING TECHNIQUE.

B. PHOTORESIST DISADVANTAGES.
1. REQUIRES CONTROLLED HUMIDITY AND TEMPERATURE.
2. REQUIRES SPECIAL ROOM ILLUMINATION.
3. REQUIRES EXPENSIVE ALIGNERS, DEVELOPERS.
4. REQUIRES COSTLY PREPARATION OF DELICATE PHOTOMASKS.
5. TIME CONSUMING PROCESS CYCLE.
6. HIGH MATERIAL COST.
7. LIMITED SHELF LIFE.
8. NO RECYCLE POTENTIAL.

C. REPLACEMENT TECHNIQUE.
1. REPLACE PHOTORESIST WITH INERT WAX.
2. APPLY WAX WITH A PRINTING PLATE.

D. ADVANTAGES
1. LOW COST
2. NO SPECIAL SAFETY ILLUMINATION, HUMIDITY CONTROL, ETC.
3. INDEFINITE SHELF LIFE
4. SIMPLE AND QUICK PROCESSING
5. USES DURABLE, EASILY PRODUCED PRINTING PLATES.
6. POSSIBILITY OF WAX RECYCLE.

E. PROJECT TASKS
1. PRODUCE MASTER PLATE MOLDS.
2. PRODUCE PRINTING PLATES.
3. RESEARCH MASKING WAX PROPERTIES.
4. DESIGN AND CONSTRUCT PRINTING DEVICE.
5. EVALUATE PRINTING PERFORMANCE.
6. DETERMINE WAX ETCH RESIST BEHAVIOR.
7. COST ANALYSIS.

PRODUCTION PROCESS AND EQUIPMENT AREA

F. PROGRESS

1. APIEZON W APPEARS MOST ADAPTABLE TO PROCESS

2. WAX VISCOSITY CAN BE CONTROLLED BY DILUTION WITH PERCHLOROETHYLENE

3. CURVED PRINTING PLATES ARE PREFERRED OVER FLAT PLATES

G. RESEARCH

1. PATTERN DEFINITION

2. WAX RECYCLE

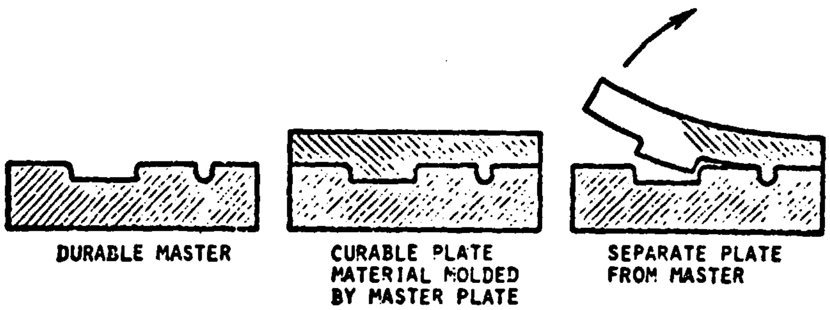
3. WATER REMOVAL OF WAX FROM WAFERS

4. PRINTING DEVICE CONFIGURATION

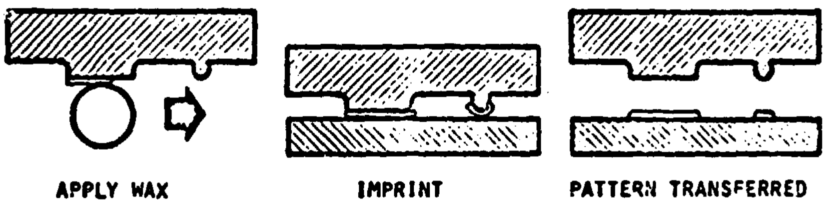
5. COST

Printing Techniques

PRODUCE PRINTING PLATES IN QUANTITY FROM DURABLE MASTERS



PRINT BY LETTERPRESS TECHNIQUE



SOLAR CELL SIZE vs PROCESS COSTS

MOTOROLA, INC.

R.A. Pryor

TOTAL COSTS =

MATERIAL COSTS + PROCESSING COSTS

COST VARIATIONS ARE DEPENDENT UPON

EITHER

CELL AREA

OR

CELL QUANTITY

MATERIALS COSTS ARE INFLUENCED BY

- SILICON USAGE
  - SUBSTRATE THINNESS
  - KERF LOSSES
- ADDITIVE AND CONSUMED MATERIALS
  - RINSE WATER
  - METAL COVERAGE
  - ENCAPSULATION
  - ETC.
- AREA DEPENDENCE

Today's Wafer Thickness vs Size

WAFER DIAMETER	STANDARD WAFER THICKNESS	THINESS
2 INCHES		8 MILS
3 INCHES	15 MILS (380 MICRONS)	4-7 MILS
4 INCHES (100 MM)	25 MILS (625 MICRONS)	
5 INCHES (125 MM)	25 MILS (625 MICRONS)	10 MILS

Processing Costs

INFLUENCED BY

SUBSTRATE THINNESS (OPTIMIZED EFFICIENCY)

- YIELD LOSS - FRAGILITY
- EQUIPMENT COMPLEXITY
- PROCESS SEQUENCE CHOICE - STRESS

SUBSTRATE AREA (DEGRADED EFFICIENCY)

- YIELD LOSS - "CATASTROPHIC"
- EQUIPMENT CAPABILITY/CAPACITY
- PROCESS SEQUENCE CHOICE - UNIFORMITY
  CONTROL PROBLEMS
  DISTRIBUTION LOSSES

C_T = TOTAL COST PER UNIT AREA

C_M = MATERIALS COST PER UNIT AREA, CONSTANT

C_P = PROCESSING COST PER SLICE, CONSTANT

A = AREA PER SLICE

$$C_T = C_M + \frac{C_P}{A}$$

K_O = RATIO OF MATERIALS COST PER UNIT AREA TO PROCESS COST PER UNIT AREA FOR PRESENT FACTORY

A_O = AREA OF PRESENT SLICE

$$K_O = \frac{C_M}{C_P/A_O} = \frac{C_M A_O}{C_P}$$

$$C_P = \frac{C_M A_O}{K_O}$$

$$C_T = C_M + \frac{C_P}{A}$$

$$= C_M + \frac{C_M A_O}{K_O} \frac{1}{A}$$

$$= C_M \left[1 + \frac{1}{K_O} \frac{A_O}{A} \right]$$

Cost per Watt

$\eta(A)$ = CELL EFFICIENCY

$$\frac{C_T(A)}{\eta(A)} = C_M \left[1 + \frac{1}{K_O} \frac{A_O}{A} \right] \frac{1}{\eta(A)}$$

PRODUCTION PROCESS AND EQUIPMENT AREA

Efficiency Concerns

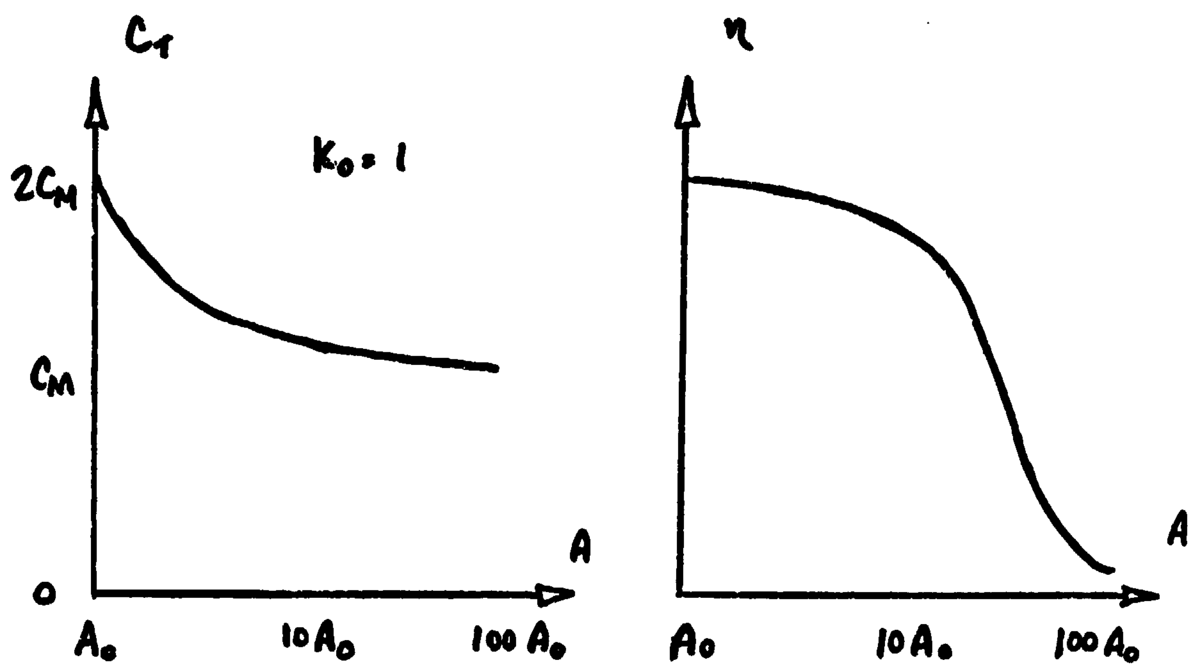
DEGRADATION WITH SIZE, IN GENERAL

DEGRATATION WITH NON-UNIFORMITIES

AS INGOT SIZE IN INCREASED, SUBSTRATE UNIFORMITY IS JEOPARDIZED

POINT TO POINT

WAFER TO WAFER



AUTOMATED ARRAY ASSEMBLY

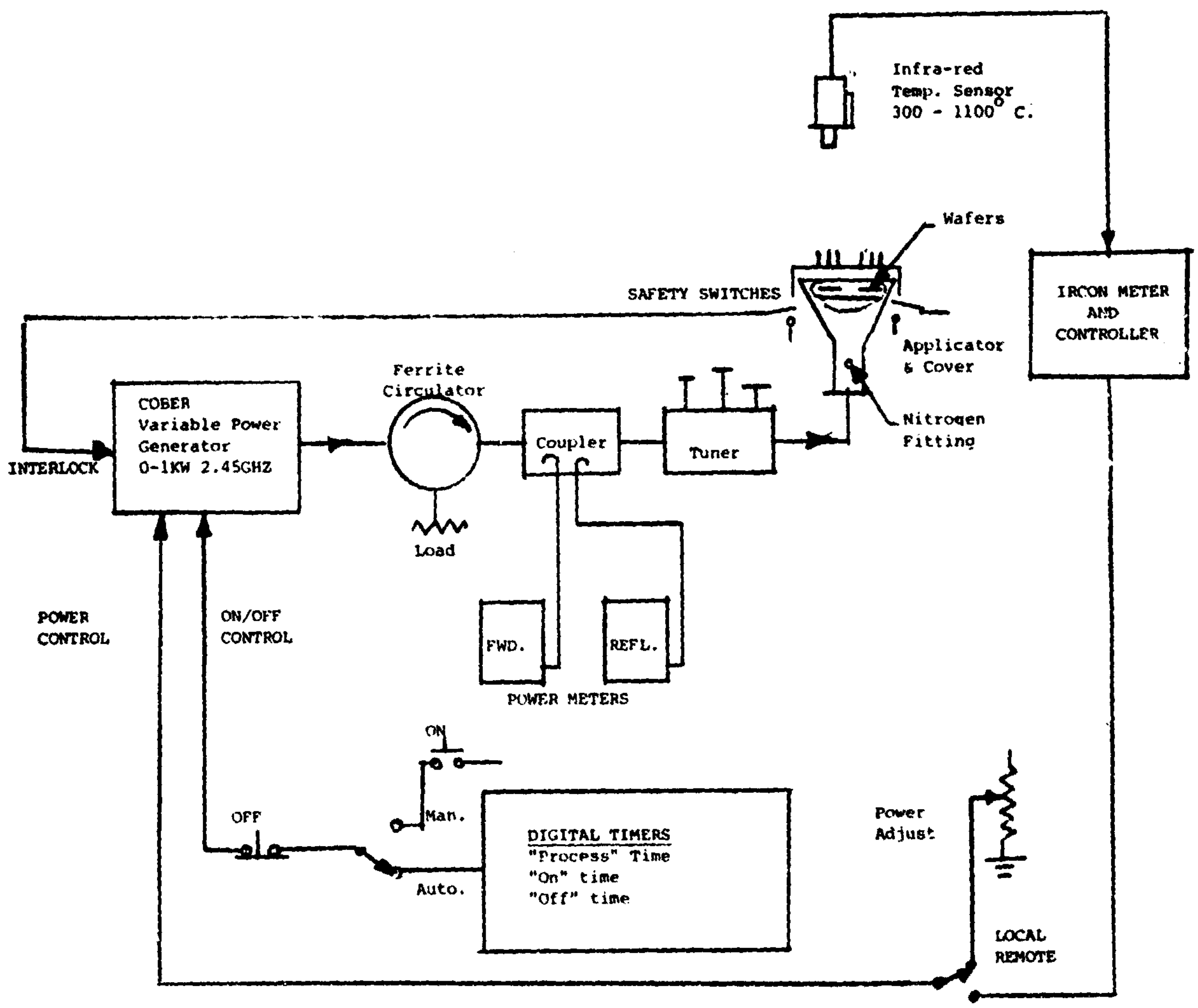
PHOTOWATT INTERNATIONAL, INC.

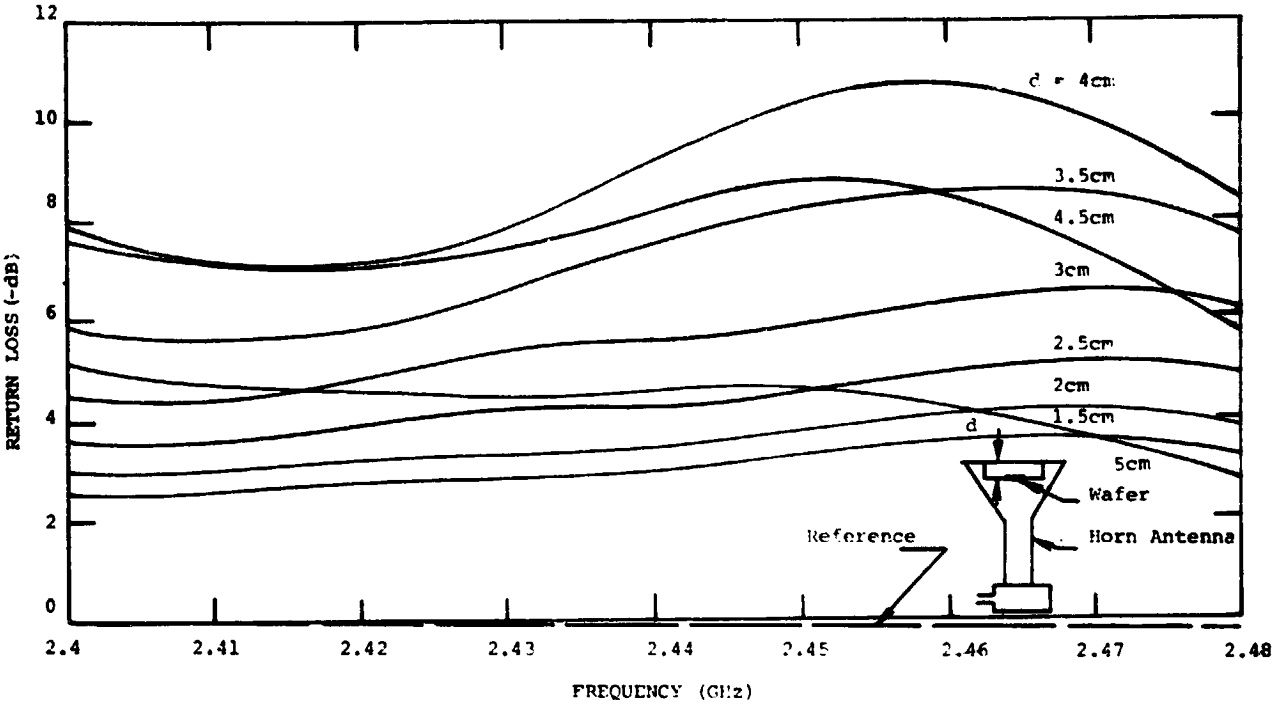
Gregory T. Jones and Clay Olson

Project Status and Results

A. RECTANGULAR WAVEGUIDE HORN APPLICATOR AND EXPERIMENTAL RESULTS

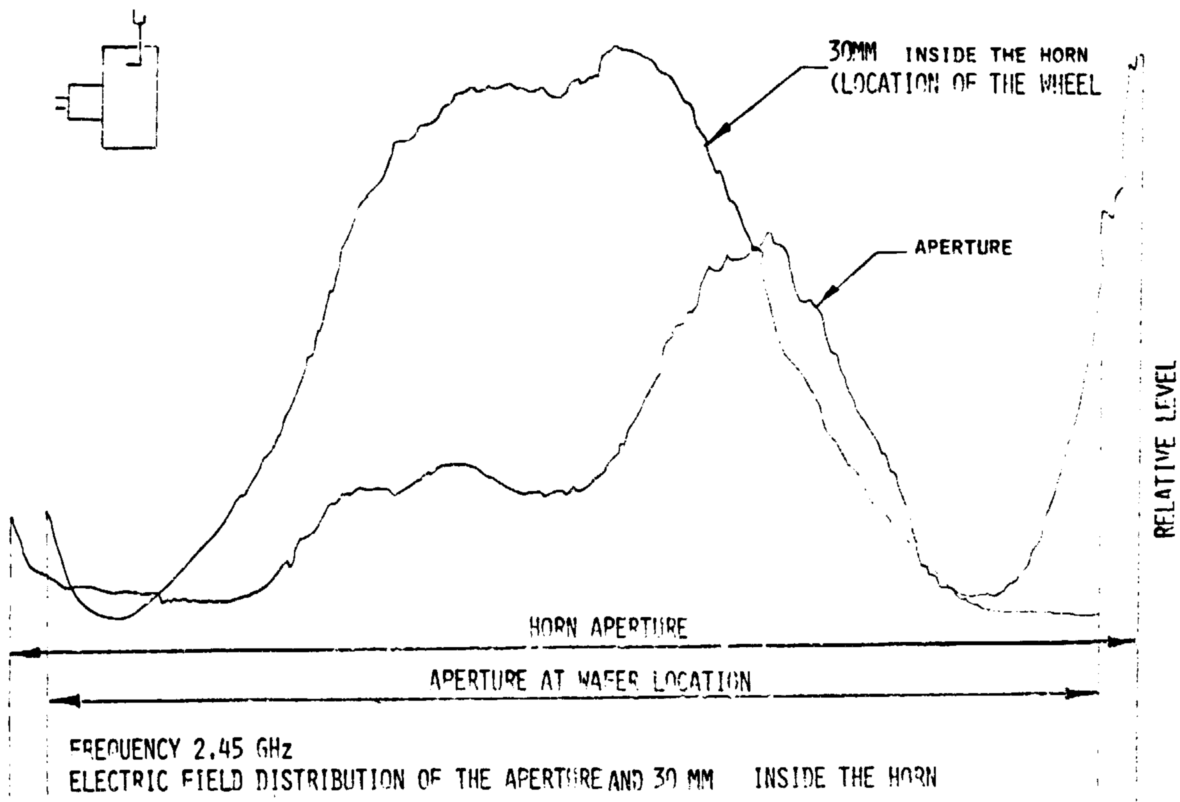
Wafer Heating Apparatus



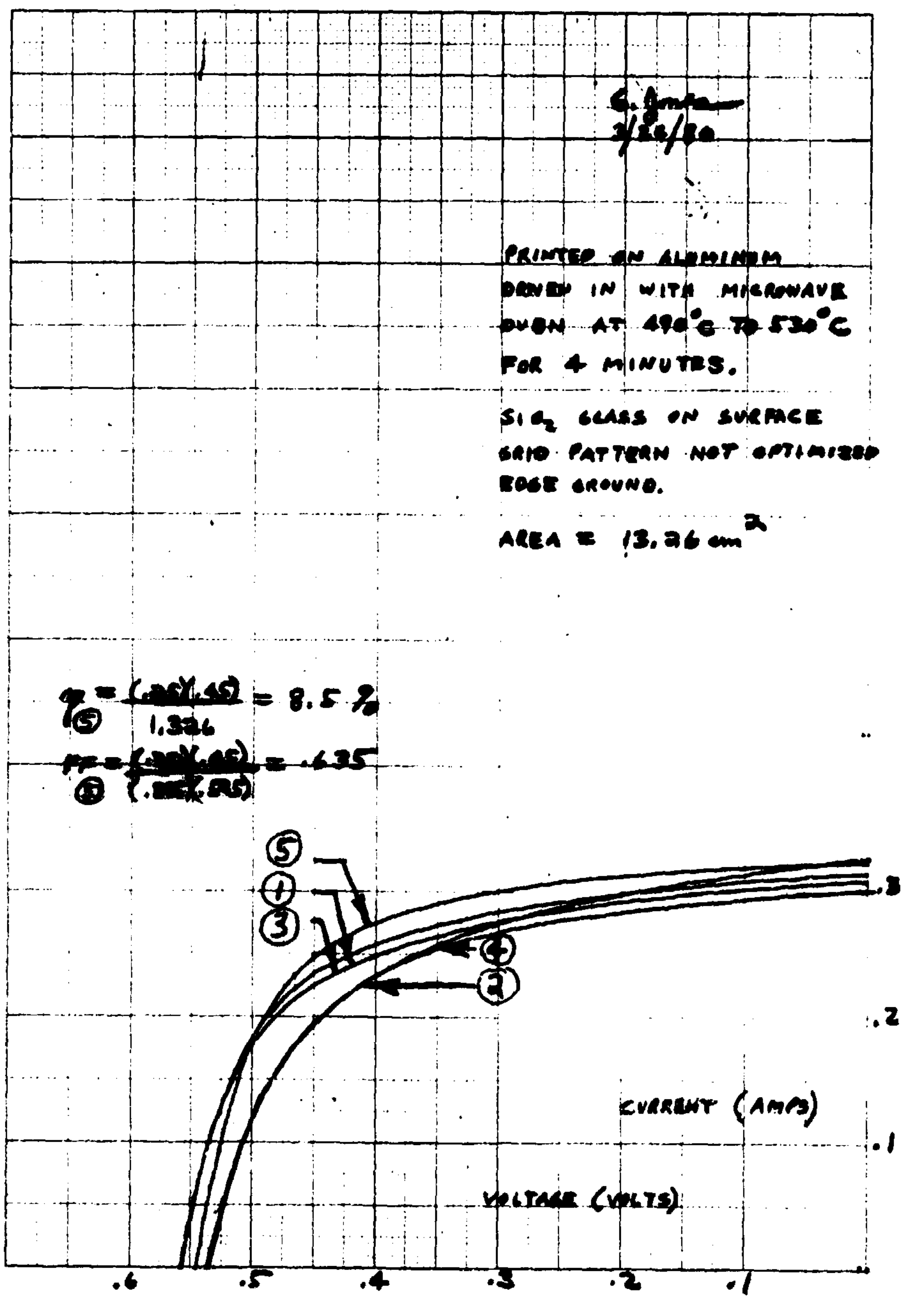


Impendance matching (return loss) for a single wafer for distances, d, from the short circuit metal plate to the wafer between 1.5cm and 5cm.

644 Narda Horn



FREQUENCY 2.45 GHz
ELECTRIC FIELD DISTRIBUTION OF THE APERTURE AND 30 MM INSIDE THE HORN


PRINTED ON ALUMINUM
DRIED IN WITH MICROWAVE
OVEN AT 490°C TO 530°C
FOR 4 MINUTES.
SiO2 GLASS ON SURFACE
GRID PATTERN NOT OPTIMIZED
EDGE GROUND.
AREA = 13.26 cm²
= 8.5 %
= .635
CURRENT (AMPS)
VOLTAGE (VOLTS)
.3
.2
.1
.6
.5
.4
.3
.2
.1

B. MICROWAVE HEATING APPLICATIONS
(WAFER SAMPLES ON DISPLAY)

1. PRINTED ALUMINUM WAFERS
2. EVAPORATED ALUMINUM WAFERS
3. PLATED NICKEL/GOLD WAFERS
4. PLATED NICKEL WAFERS

C. PRESENT STATUS AND FUTURE POTENTIAL OF MICROWAVE HEATING SYSTEMS FOR SOLAR CELL APPLICATIONS

1. PRESENT STATUS - EARLY STAGE OF DEVELOPMENT
2. TEMPERATURES HIGHER THAN 900°C HAVE BEEN REACHED, BUT HEATING UNIFORMITY AND ENERGY COUPLING EFFICIENCY REQUIRES A SIGNIFICANT BASIC DEVELOPMENT EFFORT.
3. FUTURE POTENTIAL LOOKS PROMISING BUT WILL REQUIRE ADDITIONAL BASIC WORK TO DEVELOP.

D. PRESENT STATUS OF SPRAY-ON ALUMINUM METALLIZATION TASK

1. METALLIZATION EQUIPMENT WAS INSTALLED AND SPRAY-ON DOPANT EQUIPMENT WAS OVERHAULED THIS QUARTER.
2. INITIAL EXPERIMENTS AT THE MANUFACTURER GAVE HIGH V_{OC}. (REPORTED LAST QUARTER)
3. PRELIMINARY EXPERIMENTS PERFORMED AT PHOTOWATT AND ARE YET TO BE EVALUATED.

LOW-COST POLYSILICON SOLAR CELLS

PHOTOWATT INTERNATIONAL, INC.

Gregory T. Jones

Aim and Objectives

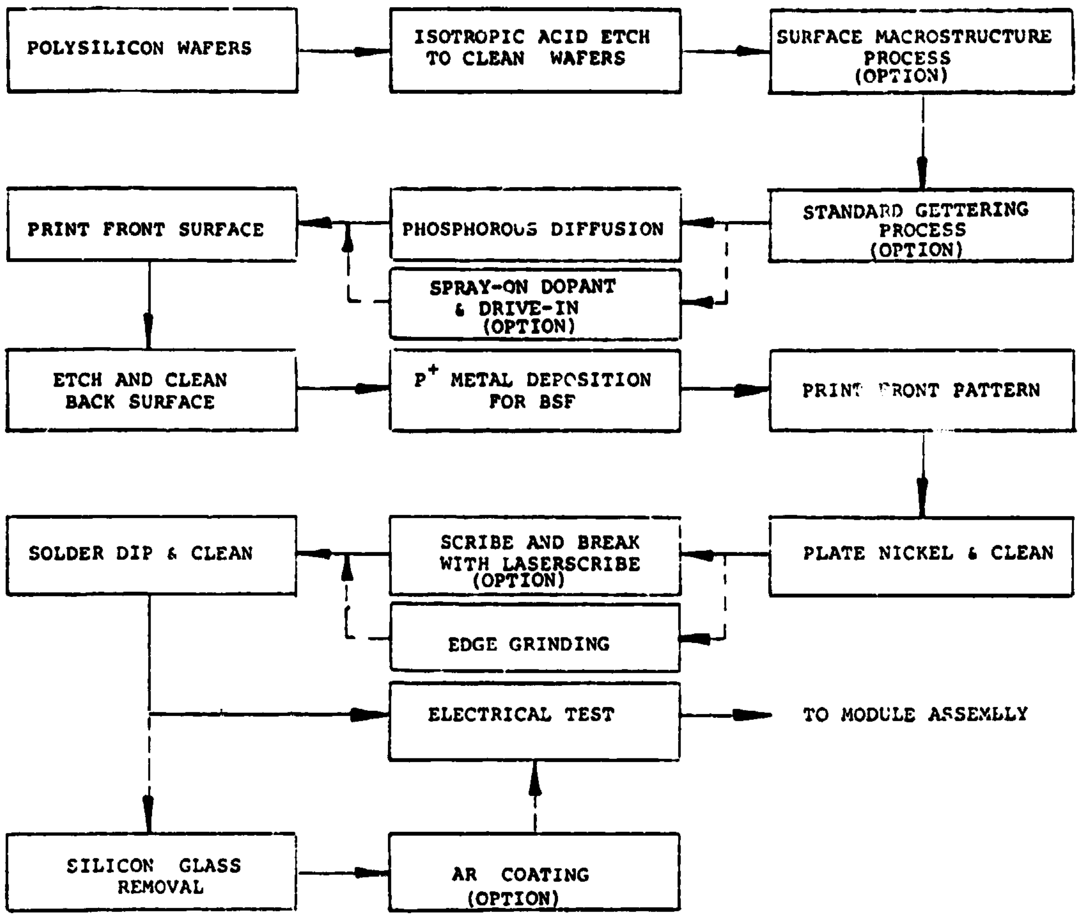
1. LOW-COST POLYSILICON SOLAR CELL PROCESS SEQUENCE WHICH ACHIEVES 10% EFFICIENT LARGE AREA POLYSILICON SOLAR CELLS IN BATCH QUANTITIES.
2. FRONT SURFACE GRID PATTERN OPTIMIZATION WITH RESPECT TO CRYSTAL GRAIN SIZE.
3. WAFER SURFACE MACROSTRUCTURE (OR TEXTURIZING) PROCESS.
4. JUNCTION FORMATION TECHNIQUES.
5. A.R. COATINGS.
6. OTHER PROCESS INCLUDING SPRAY-ON DOPANTS, AND $POCL_3$ GETTERING.

Project Status and Results

1. POLYSILICON MATERIAL: WACKER, CRYSTAL SYSTEM (HEM) EXOTIC MATERIALS (FAST CZ)

2. RECENT PROCESSING RESULTS (NO A.R. COATING)
   - WACKER MATERIAL (25 cm^2) WITH STANDARD PRODUCTION PROCESS
   - SINGLE CRYSTAL PRODUCTION CELLS (41.4 cm^2) PROCESSED WITH THE WACKER MATERIAL
   - LARGE AREA WACKER MATERIAL (50.8 cm^2)
     - DIFFUSED SOLAR CELLS
     - SPRAY-ON N^+ DOPED SOLAR CELLS
     - PRINTED ALUMINUM SOLAR CELLS
   - EXOTIC MATERIALS (FAST CZ)

Baseline Processing Sequence for Polysilicon Solar Cells



ELECTRICAL PERFORMANCE RESULTS FOR SINGLE CRYSTAL AND WACKER POLYSILICON SOLAR CELLS. FIFTEEN WAFERS OF EACH TYPE WERE PROCESSED TOGETHER.

BATCH	I_{SC} (A)	V_{OC} (V)	I_{PP} (A)	V_{PP} (V)	η (%)	FF
P-511	STANDARD PROCESS, TEXTURIZED, NO A.R. COATING, POLYSILICON ACTIVE AREA IS 22.6 CM^2					
HIGH	.530	.525	.450	.425	8.6	.687
LOW	.510	.505	.350	.425	6.6	.578
WT. AVE.	.520	.515	.400	.425	7.5	.635
S-511	STANDARD PROCESS, TEXTURIZED, NO A.R. COATING, SINGLE CRYSTAL ACTIVE AREA IS 41.4 CM^2					
HIGH	1.16	.580	1.10	.465	12.4	.760
LOW	1.13	.570	1.00	.465	11.2	.722
WT. AVE.	1.15	.575	1.06	.465	11.9	.745

ELECTRICAL PERFORMANCE RESULTS FOR WACKER POLYSILICON SOLAR CELLS WITH THREE PROCESS SEQUENCES. TWENTY WAFERS OF EACH TYPE WERE PROCESSED.

BATCH	I_{SC} (A)	V_{OC} (V)	I_{PP} (A)	V_{PP} (V)	η (%)	FF
P-512 SURFACE ETCHED, DOUBLE DIFFUSION, PRINTED ALUMINUM BACK, NICKEL PLATING, NO A.R. COATING						
HIGH	1.08	.535	.950	.425	9.1	.700
LOW	.94	.520	.780	.425	7.5	.678
WT. AVE.	1.00	.530	.870	.425	8.3	.698
P-513 SURFACE ETCHED, SINGLE DIFFUSION, PRINTED ALUMINUM BACK, NICKEL PLATING, NO A.R. COATING						
HIGH	1.03	.545	.870	.425	8.3	.659
LOW	.88	.520	.700	.425	6.7	.650
WT. AVE.	.94	.535	.810	.425	7.7	.685
P-514 SURFACE ETCHED, SPRAY-ON N^+ POLYMER, PRINTED ALUMINUM BACK, NICKEL PLATING, NO A.R. COATING, PLASMA ETCH EDGES.						
HIGH	1.06	.526	.900	.425	7.5	.686
LOW	.97	.515	.700	.425	5.9	.596
WT. AVE.	.99	.520	.820	.425	6.9	.677

Electrical Performance Results

Summary Of Electrical Performance Results For Spray-On Doped 3.85 X 3.85 Inch Square Wacker Polysilicon Solar Cells.

BATCH	I_{sc} (a)	V_{oc} (v)	I_{pp} (a)	V_{pp} (v)	η (%)	FF	$\frac{\Delta\eta}{\eta}$ (%)	$\frac{\Delta FF}{FF}$ (%)
P-103	$POCl_3$ getter, NaOH etch, spray-on N^+ dopant, with SiO AR coating.							
High	2.875	.525	2.55	.395	10.53	.667	+4.36%	+1.52%
Low	2.80	.510	2.45	.375	9.61	.643	-4.75%	-2.13%
Ave.	2.825	.520	2.475	.390	10.09	.657		

MEGASONIC CLEANING

RCA RESEARCH CENTER

Highlights

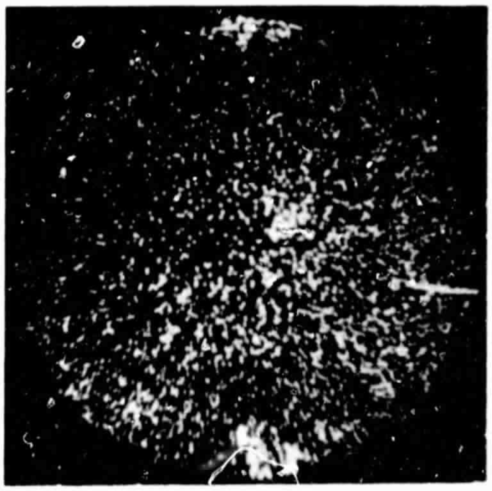
CLEANING RATE OF 4500 WAFERS/HOUR DEMONSTRATED IN 3/32" SPACED QUARTZ BOATS

160 WATTS/TRANSDUCER YIELDS ADEQUATE CLEANING

COOL AIR DRYING RATE OF 3300 WAFERS/HOUR DEMONSTRATED IN 3/32" SPACED QUARTZ BOATS

MEGASONIC CLEANED SOLAR CELLS SHOW HIGHER EFFICIENCY

Megasonic Cleaning



BEFORE

(0.5 g/L 0.03 mμ Al_2O_3)

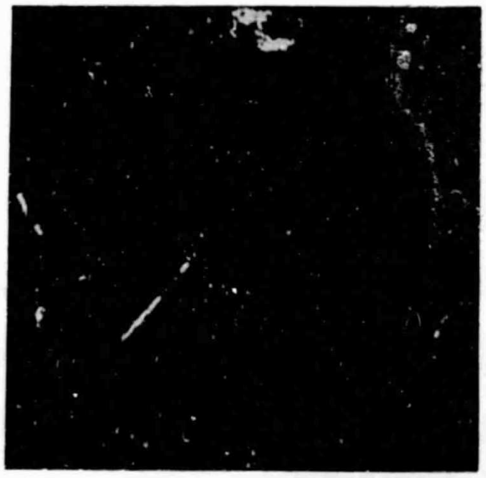
COUNT = 3619

AFTER

(160 WATT, 15 cm/min)

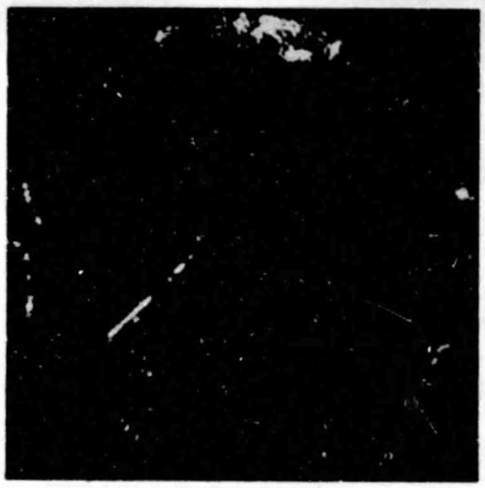
COUNT = 248

Transfer Power vs Cleaning Ability



2×160 WATT
COUNT=360

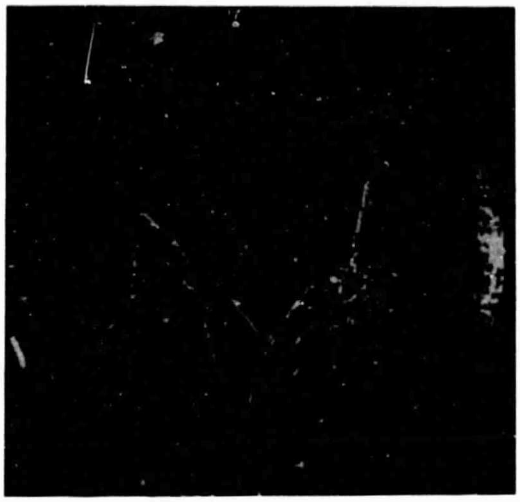
2×220 WATT
COUNT=371



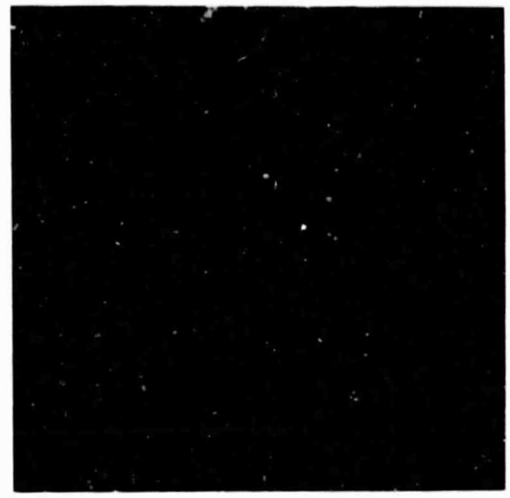
2×300 WATT
COUNT=378

C-3

Cool Air Dryer Material Choice

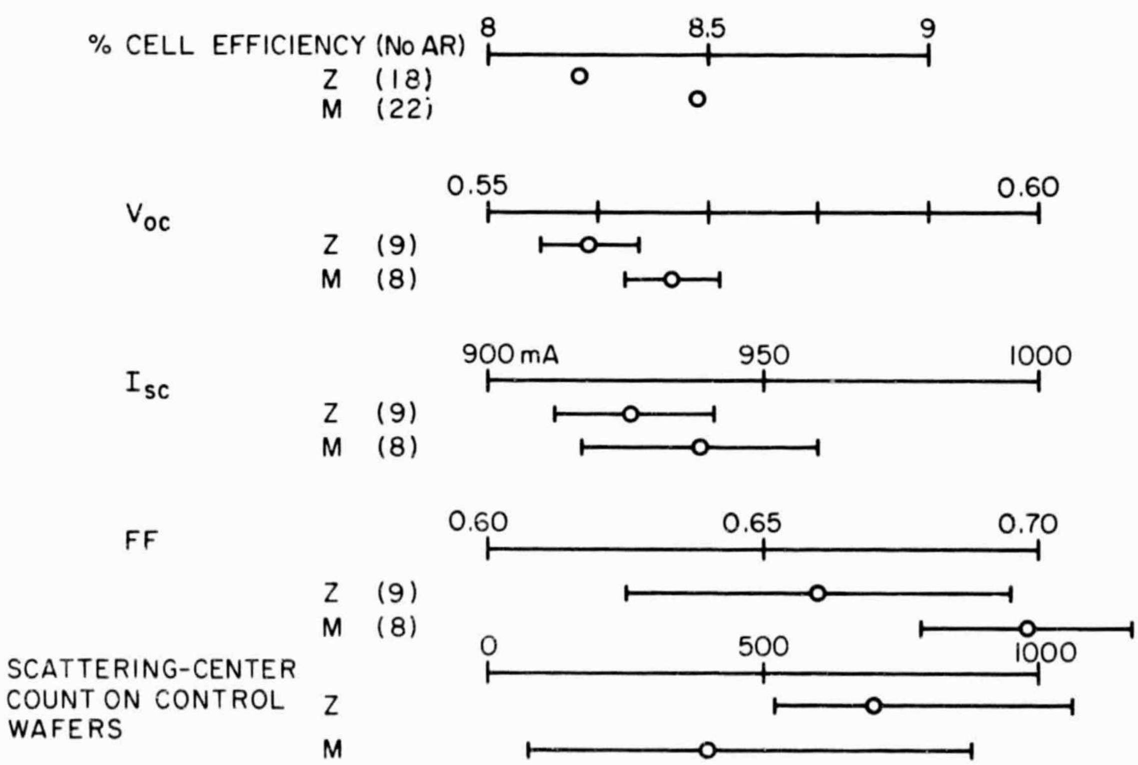


ALUMINUM SLED
COUNT = 1024

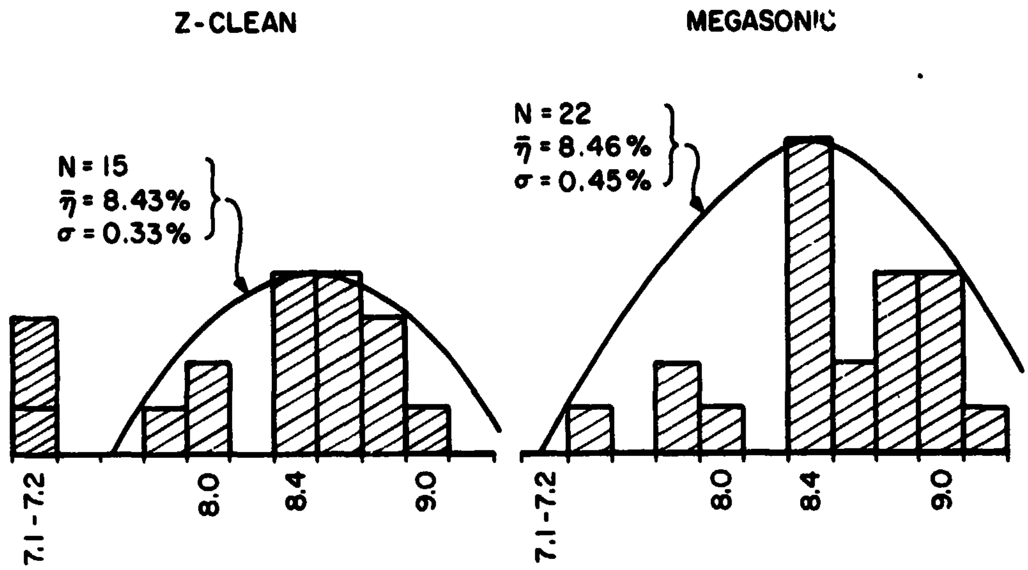


POLYPROPYLENE SLED
COUNT = 117

Preliminary Solar Cell Data



Solar Cell Efficiency



Program Tasks

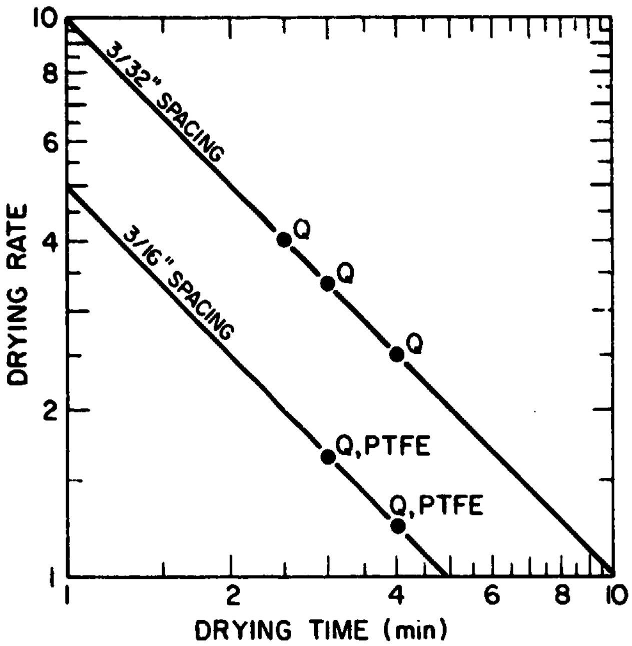
TASK 1 DESIGN, DEVELOP AND ASSEMBLE CONTINUOUS MEGASONIC SYSTEM WITH SOLUTION FILTRATION AND AIR DRYING SYSTEM

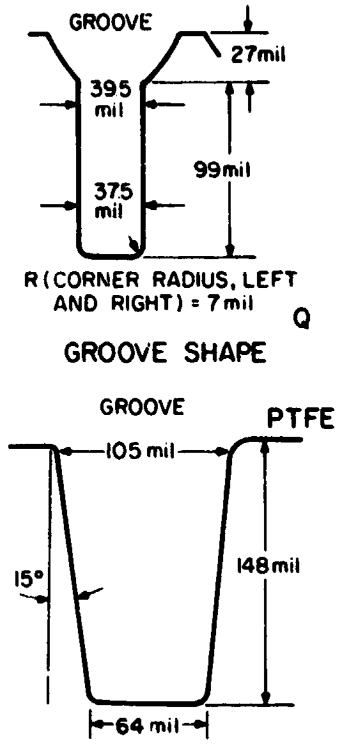
TASK 2 DEBUG, TEST, AND OPERATE TOTAL SYSTEM TO PREPARE FOR MANUFACTURING TRIAL

TASK 3 OPERATE SYSTEM WITH PRODUCTION PERSONNEL IN RCA PRODUCTION FACILITY

TASK 4 OPERATE THE MEGASONIC CLEANING SYSTEM FOR A PERIOD NOT LESS THAN 4 MONTHS AND COLLECT DATA

Cool Air Dryer





Status

TASK 1 DEVELOPMENT OF EQUIPMENT
ALL EQUIPMENT DESIGNED AND ASSEMBLED AT SOMERVILLE EXCEPT DRYING SYSTEM BELT DRIVE

TASK 2 SYSTEM DEBUGGING ESSENTIALLY COMPLETE

TASK 3 SYSTEM SHIPPED TO RCA PRODUCTION FACILITY

TASK 4 SYSTEM PARTIALLY EXCERSIZED IN LABORATORY

ELECTROLESS NICKEL PLATING ON OXIDE FILMS

SOLAREX CORP.

George Storti

Nickel/Solder Contacts on Silicon

- ENVIRONMENTAL STRESSES
- PLATING ON SILICON OXIDE AND SINTERING
- EFFECT OF PLATING SOLUTION ON CELLS
- NICKEL PENETRATION OF SILICON
- EVALUATION OF MOTOROLA PROCESS

Environmental Stress Task Observations

1. B-T-H (85°C - 85% RH - 0.45 VOLT) 1074 HOURS
   - VISUAL INSPECTION - LIGHT I-V CURVES - TAB PULL TESTS
     NO EVIDENCE OF DEGRADATION
2. 150°C - 1008 HOURS
   - DEGRADATION AND CONTACT LIFTING IN MOST CELLS
   - CELLS WHICH LOOK PERFECT SHOW LITTLE CHANGE IN ELECTRICAL PROPERTIES
   - CONTACTS FAIL AT Si-Ni INTERFACE
     NO EVIDENCE OF Si DAMAGE
3. THERMAL CYCLE (-65°C TO +150°C) 100 CYCLES - IN AIR
   - LIFTING OF CONTACTS IN ALL CELLS
   - SOME SILICON DAMAGE EVIDENT
4. THERMAL SHOCK (-65°C TO +150°C) 25 CYCLES - IN FC
   - LIFTING OF CONTACTS IN MOST CELLS
   - SILICON DAMAGE EXTENSIVE
   - SOME CELLS LOOKED PERFECT AND SHOWED LITTLE CHANGE IN LIGHT I-V CURVES, BUT TAB PULL TESTS INDICATED WEAKENED CONTACTS.

Environmental Stress Task Conclusions

1. CELLS SURVIVED B-T-H TEST PERFECTLY.
2. TEMPERATURE EXTREMES OF -65°C AND +150°C WERE TOO SEVERE.
3. TAB PULL MEASUREMENTS APPEARED TO BE A MORE SENSITIVE MEASURE OF CONTACT QUALITY THAN DID ELECTRICAL MEASUREMENTS.
4. DIFFERENT MODES OF FAILURE OBSERVED WITH DIFFERENT STRESSES INDICATE AT LEAST TWO DIFFERENT FAILURE MODES OPERATING.

Electroless Nickel Plating on Oxide Films

- DIFFUSE
- ALLOY
- OXIDE (O_2, HEAT) VARIED THICKNESSES
- MEASURE OXIDE THICKNESS - ELLIPSOMETER
- PLATE NICKEL
- SINTER - 1 MIN. - VARIOUS TEMPERATURES
- SOLDER DIP
- SOLDER TABS
- PULL TABS
- MAKE CELLS AND TEST

DISCOVERED PLATING SOLUTION DISSOLVES OXIDE BEFORE PLATING NICKEL.

Oxide Dissolution by Nickel Plating Solution

OPERATION	RESULTS		
	CELL D	CELL E	CELL H
MEASURE OXIDE THICKNESS	110 Å	157 Å	177 Å
IMMERSE 12 MINUTES	NO PLATE	NO PLATE	NO PLATE
MEASURE OXIDE THICKNESS	55 Å	92 Å	114 Å
IMMERSE 6 MINUTES	PLATED	PLATED	NO PLATE
MEASURE OXIDE THICKNESS	----	----	51 Å

TABLE 2

OXIDE DISSOLUTION WITHOUT $NiCl_2$

TIME	OXIDE FILM THICKNESS	
	CELL E3	CELL H4
BEFORE IMMERSION	157 Å	177 Å
AFTER 3 MINUTES IMMERSION	108 Å	135 Å
AFTER 6 MINUTES IMMERSION	69 Å	82 Å
AFTER 9 MINUTES IMMERSION	DARK BLOTCHES (BLUE TO GOLDEN BROWN) STAINED BOTH CELLS.	

Oxide Dissolution Without $NiCl_2$

INITIALLY NO SODIUM CITRATE

OPERATION	RESULTS (OXIDE THICKNESSES)		
	CELL H3	CELL E2	CONTROL
MEASURE OXIDE THICKNESS	177 Å	155 Å	— —
IMMERSE 3 MIN, MEASURE OXIDE	157 Å	131 Å	BLUE-BROWN STAIN
IMMERSE 9 MIN, MEASURE OXIDE	157 Å	133 Å	
ADD 250 ML CONC NH4OH IMMERSE 3 MIN, MEASURE OXIDE	157 Å	133 Å	
ADD 168 G SODIUM CITRATE IMMERSE 3 MIN, MEASURE OXIDE	152 Å	114 Å	
IMMERSE 6 MIN, MEASURE OXIDE	71 Å	37 Å	
IMMERSE 3 MIN	BLUE-BROWN STAIN ON BOTH CELLS		

Tab Pull on Oxidized Silicon

SINTER TEMP	AVERAGE PULL STRENGTH (G) 70 Å OXIDE 10 MIN PLATE	NO OXIDE 10 MIN PLATE	NO OXIDE 6 MIN PLATE
NONE	549	301	353
200°C	536	683	727
250°C	731	490	853
300°C	593	519	756

Effect of Plating Solution on Solar Cells

DOES EXPOSURE TO PLATING SOLUTION HARM
CELL JUNCTION?

FABRICATE CELLS USING A RANGE OF Ni PLATING
TIMES

MEASURE LIGHT I-V CHARACTERISTICS
DARK FORWARD AND REVERSE I-V

Dark I-V Characteristics

DIODE N-FACTORS DETERMINED FROM DARK
I-V DATA SHOW NO TREND WITH PLATING TIME

Conclusions

CELL PROPERTIES NOT AFFECTED BY EXPOSURE
TO PLATING SOLUTION FROM 4 TO 14 MINUTES
EXCEPT FOR EFFECT OF NICKEL THICKNESS ON
CONTACT QUALITY

Influence of Ni Plating Time on Electrical Characteristics of Cells

	Plating Time (Min)					
	4	6	8	10	12	14
V_{oc} white mV	559 (8)	561 (12)	566 (13)	569 (17)	565 (14)	574 (10)
V_{oc} red mV	542 (9)	545 (12)	550 (13)	552 (15)	548 (14)	557 (10)
V_{oc} blue mV	508 (11)	507 (16)	520 (13)	518 (20)	512 (22)	515 (20)
P_m white mW	45.6 (3.1)	49.8 (3.0)	51.7 (2.7)	51.5 (3.0)	45.1 (6.8)	46.3 (3.3)
P_m red mW	25.4 (1.9)	27.7 (1.1)	28.7 (2.4)	27.9 (1.7)	24.7 (5.1)	26.0 (2.8)
I_{sc} white mA	114.7 (8.7)	121.6 (4.6)	121.9 (3.5)	121.8 (3.3	110.1 (13.5)	113.7 (2.7)
I_{sc} red mA	65.4 (3.1)	70.4 (3.3)	69.4 (3.4)	68.9 (1.7)	62.5 (8.9)	66.4 (1.7)
I_{sc} blue mA	26.7 (2.7)	25.4 (2.3)	28.1 (1.7)	26.6 (3.2)	24.9 (2.4)	24.0 (0.8)
R_{series} ohm	.279 (.145)	.209 (.077)	.179 (.047)	.168 (.053)	.249 (.137)	.266 (.084)
No. of Cells	8	9	13	11	18	11

Mean values and (standard deviations)

AM0 2 cm square cells

Ni Penetration of Silicon

PLATE - SINTER - ANGLE LAP
MICROPROBE ANALYSIS

NO EVIDENCE OF NICKEL PENETRATION UP TO

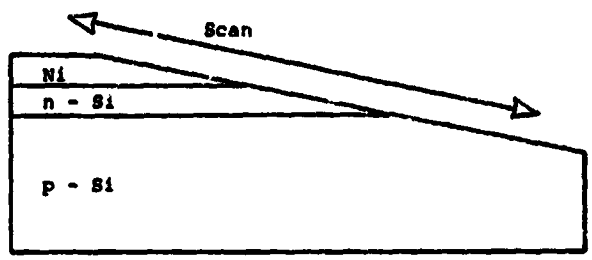
425°C, 12 MIN
450°C, 2 MIN

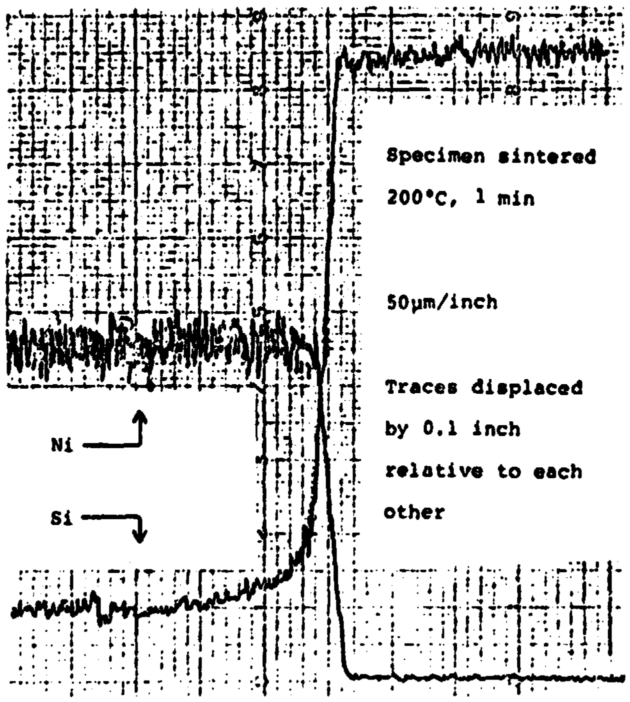
EXTENSIVE NICKEL PENETRATION AT

450°C, 20, 30, 40 MIN

CONSISTENT WITH EARLIER LEAKAGE CURRENT DATA

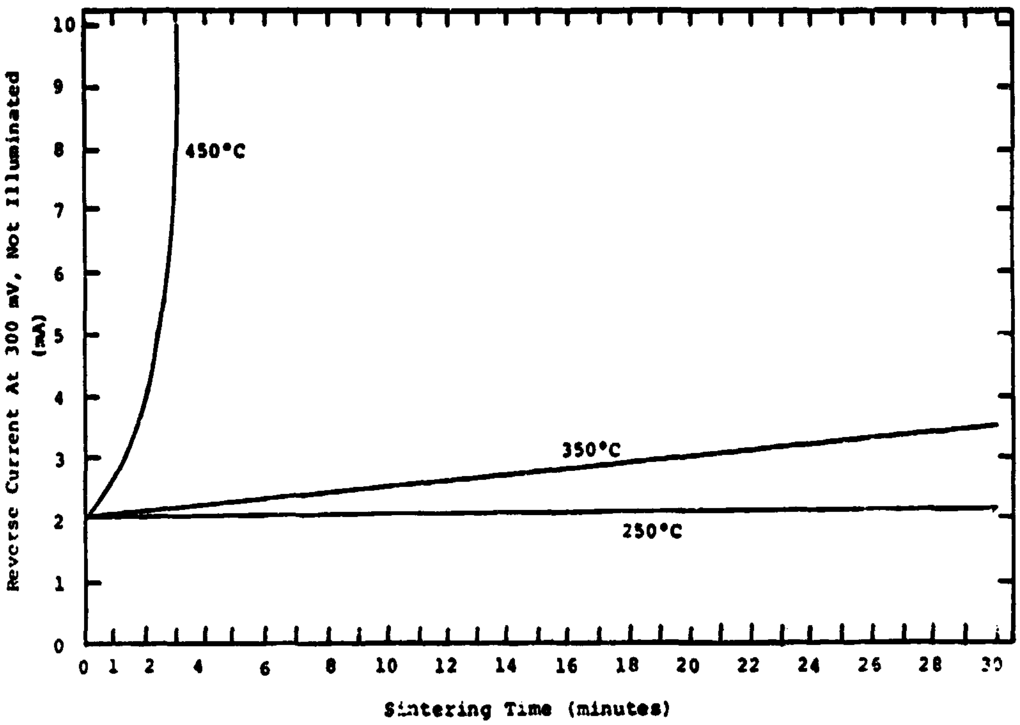
Electron Microprobe Analysis





Schematic of scan (above); data from a typical scan (below).

Ni Sintering and Leakage Current



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

SPECTROLAB, INC.

Nick Mardesich

Standard Cell Processing

SURFACE PREPARATION - 30% NaOH

JUNCTION FORMATION - SPIN-ON DIFFUSION SOURCE

ALUMINUM BACK SURFACE FIELD - SCREEN PRINTED ALUMINUM PASTE

CLEAN RESIDUAL ALUMINUM AND DIFFUSION OXIDE - HF AND BRUSH

JUNCTION CLEAN - LASER SCRIBE

*FRONT CONTACT - MIDFILM

AR COAT - EVAPORATED SiO_x

*FRONT CONTACT APPLIED AT FERRO IN OHIO AND SHIPPED TO SPECTROLAB FOR FIRING

Series Resistance of Midfilm Cells

LOT		1	2	3	4	5
Total resistance (mΩ)	1)	450	290	620	-	450
	2)	375	100	325	-	925
	3)	1050	1275	1050	-	1860
	4)	575	216	525	-	
Computed resistance:						
Gridline Thickness		4μ	8.5μ	5μ	7μ	8.5μ
Base Resistance (mΩ)		3.92	3.92	3.92	3.92	3.92
Diffuse Layer Resistance (mΩ)		3.90	3.90	3.90	3.90	3.90
Gridline Resistance (mΩ)		51.0	24.0	40.8	29.2	24.0
Ohmic Collector Resistance (mΩ)		14.3	6.72	11.5	8.2	6.72
Total (cal.) Resistance (mΩ)		73.1	38.5	60.1	45.2	38.5

Screen Printed Control Cells

	Cell No.	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{sh} (ohm)	R_{series} (m ohm)
	4	596	188	174	156	-
	37	607	200	185	29.4	200
	69	608	209	193	56.8	100
	80	610	207	191	116.3	150
	97	607	207	185	38.5	-
	102	602	188	172	82.0	-
	127	607	203	187	55.6	150
	153	592	174	151	53.2	-
	168	598	186	170	114	-
	190	605	194	152	80.7	-
AVERAGE		603.2	195.6	176	78.3	150*
σ		5.98	11.5	15.11	39.94	

* Average of four samples.

Midfilm Metallization Process

Cell No.	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{shunt} (ohm)	R_{series} (m ohm)	ΔV_{oc} (mV)	ΔI_{sc} (mA)	ΔI_{500} (mA)	ΔR_{shunt} (ohm)	ΔR_{series} (m ohm)	After Tape Pull ΔV_{oc} (mV)	After Tape Pull ΔI_{sc} (mA)	After Tape Pull ΔI_{500} (mA)
				Environmental Evaluation - Humidity Test									
59	608	203	184	89	150	2	(1)	3	(17)	(100)	5	(1)	4
52	609	205	175	88	150	2	(3)	(2)	(44)	(200:	6	(3)	9
66	605	202	165	116	375	2	(3)	11	(76)	(125)	4	(5)	18
40	603	195	144	91	560	5	(1)	47	(41)	(600)	9	17	65
42	600	205	124	91	825	3	3	25	(34)	(275)	broken		
				Environmental Evaluation - Thermal Cycle									
61	607	202	180	91	160	2	2	2	0	10	4	4	5
67	608	204	176	200	300	1	3	0	(50)	50	2	3	(1)
54	604	199	165	119	350	(1)	2	3	(20)	0	1	3	8
72	597	202	150	128	400	(2)	4	2	(7)	0	1	1	10
38	597	194	132	147	615	0	6	6	(5)	(5)	3	1	6
				Environmental Evaluation - 5 min. boiling									
53	608	202	182	102	150	4	0	10	(2)	(6)	4	3	4
70	605	200	158	109	415	3	3	8	0	(35)	5	4	15
48	605	199	165	116	360	5	2	7	(9)	(5)	4	1	10
89	603	202	135	104	700	3	2	5	(10)	90	4	1	15
36	602	200	121	98	890	4	2	4	(2)	(25)	5	2	18

90° Soldered Lead Pull Test

Powder Composition #2, IR Fired Cells

Cell No.	Grams
98	75
122	75
116	100
123	75
63	-
45	100
8	-
119	200
77	200

Screen Printed Cells, Tube Fired

Cell No.	Grams
360	425
341	410
349	500
318	410
376	275
205	500
204	210
301	205
356	500

Compositions of Alternative Metals

	RH-3622-A	RH-3622-B	RH3622-C	RH-3631-A	RH-3631-B	RH-3631-C
Copper Powder (Alpha 00094)	90.25	-	-	90.25	-	-
Nickel Powder (Inco Type 123)	-	90.25	-	-	90.25	-
Molybdenum Powder (Atlantic Equipment Engineers Mo 209)	-	-	90.25	-	-	90.25
Tin Powder (Atlantic Equipment Engineers)	4.75	4.75	4.75	4.75	4.75	4.75
TFS Frit	5.00	5.00	5.00	-	-	-
Drankenfeld Fritz Metz "c" Frit	-	-	-	5.00	5.00	5.00
	100.00	100.00	100.00	100.00	100.00	100.00

Alternative Metals

PROBLEMS

1) Oxidization of Metals during Ashing of Photoresist (N_i-Sn-Frit & Mo-Sn Frit)
2) High series resistance (N_i-Sn-Frit & Mo-Sn Frit)
3) Poor contact adherence (N_i-Sn-Frit & Mo-Sn-Frit)
4) Junction Degradation (Cu-Sn-Frit)

PROPOSED SOLUTIONS

1) Obtain a Air-Fireable Nickel powder. (Available from Thick-Film Systems)
2) Solder coat Nickel contact.

PRODUCTION PROCESS AND EQUIPMENT AREA

Midfilm Problems

PROBLEMS	PROPOSED SOLUTIONS
1) HIGH SERIES RESISTANCE	OPTIMIZE POWDER COMPOSITION OPTIMIZE APPLICATION PROCEDURE MINIMUM HANDLING OF WAFERS
2) LOW SHUNT RESISTANCE	OPTIMIZE FIRING CONDITIONS WITH 3347 TFS FRIT OR EQUIVALENT
3) SILVER - SOLDER INTERACTION	SILVER APPEASED SOLDER LOWER SOLDER TEMPERATURE BY PREHEATING CELL

SOLAR CELL JUNCTION PROCESSING SYSTEM

SPIRE CORP.

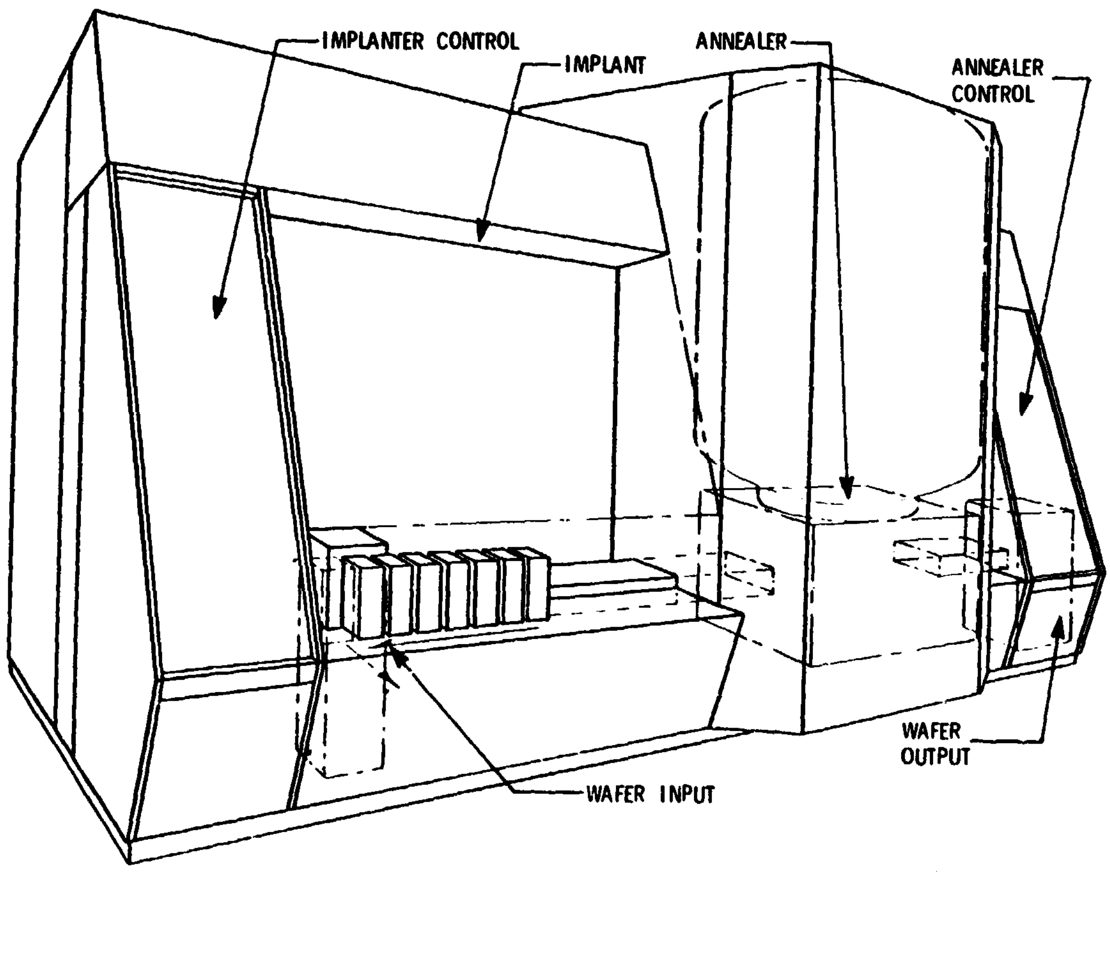
Junction Processor Specifications

ION IMPLANTER

Beam Energy	-	10 keV
Beam Current	-	16 mA
Beam Size	-	1 cm x 10 cm (nominal)
Wobble Rate	-	60 cps
Junction Dose	-	2.5×10^{15} P^{+}_{31}/cm^2
Implant Time	-	1.8 sec
Wafer Rate	-	1800/hour (max)

PULSER

Beam Energy	-	15 keV (average)
Beam Current	-	50 kA
Fluence	-	2 J/cm^2 (max)
Beam Area	-	Up to 100 cm^2
Repetition Rate	-	1 pps (max)
Wafer Rate	-	1800/hour (max)



Project Tasks

1. PULSED ELECTRON BEAM SUBSYSTEM DEVELOPMENT

   1.1 Developmental Testing
   1.2 Design and Fabrication
   1.3 Test and Evaluation

2. WAFER TRANSPORT SYSTEM DEVELOPMENT

   2.1 Design
   2.2 Wafer Holding Fixtures
   2.3 Fabrication
   2.4 Control Electronics

3. ION IMPLANTER DEVELOPMENT

   3.1 Ion Source
   3.2 Beam Optics
   3.3 Integration with Wafer Transport

4. JUNCTION PROCESSING SYSTEM INTEGRATION

   4.1 Mechanical and Electrical Integration
   4.2 Test and Demonstration

Solid vs Liquid Phase Anneal

- LIQUID PHASE EPITAXIAL REGROWTH REQUIRES

  <2 J/CM^2 } LOW ENERGY
  <1 MICROSECOND } FAST THROUGHPUT

  EASIEST FOR ONE LARGE PULSE, MOST DIFFICULT BEAM GENERATION

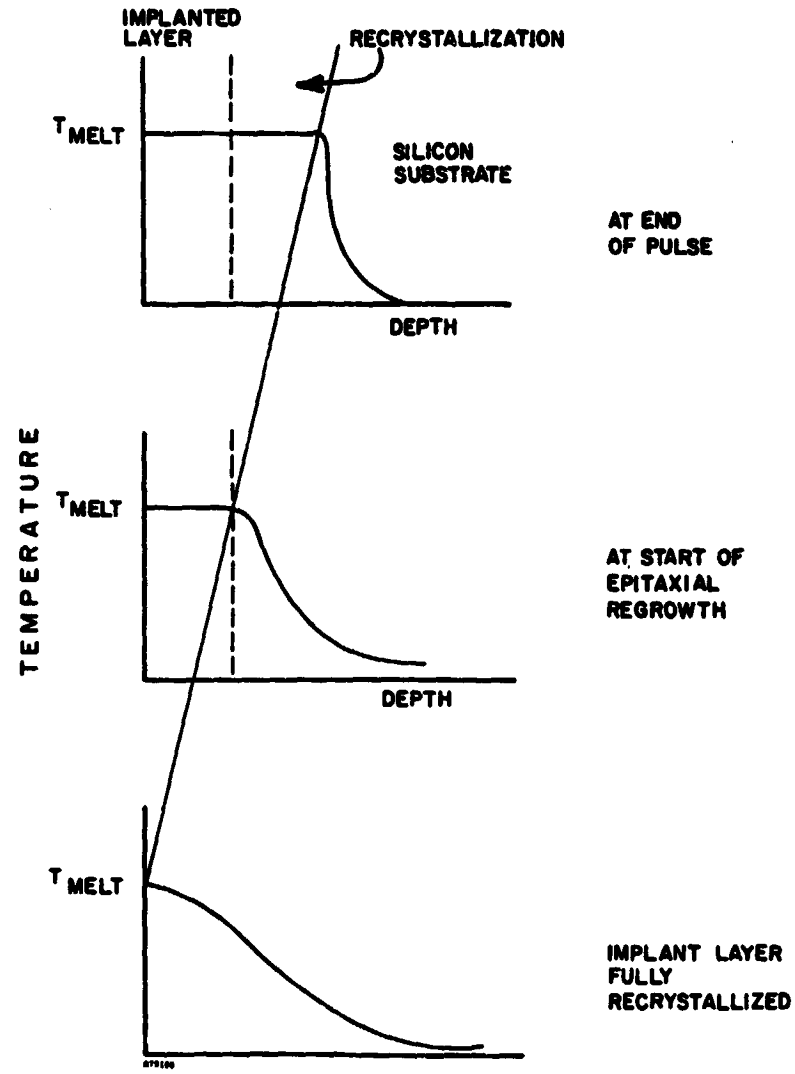
- SOLID PHASE EPITAXIAL REGROWTH REQUIRES

  >20 J/CM^2 (FURNACE > 200 J/CM^2)
  >100 MICROSECONDS (1300°C)

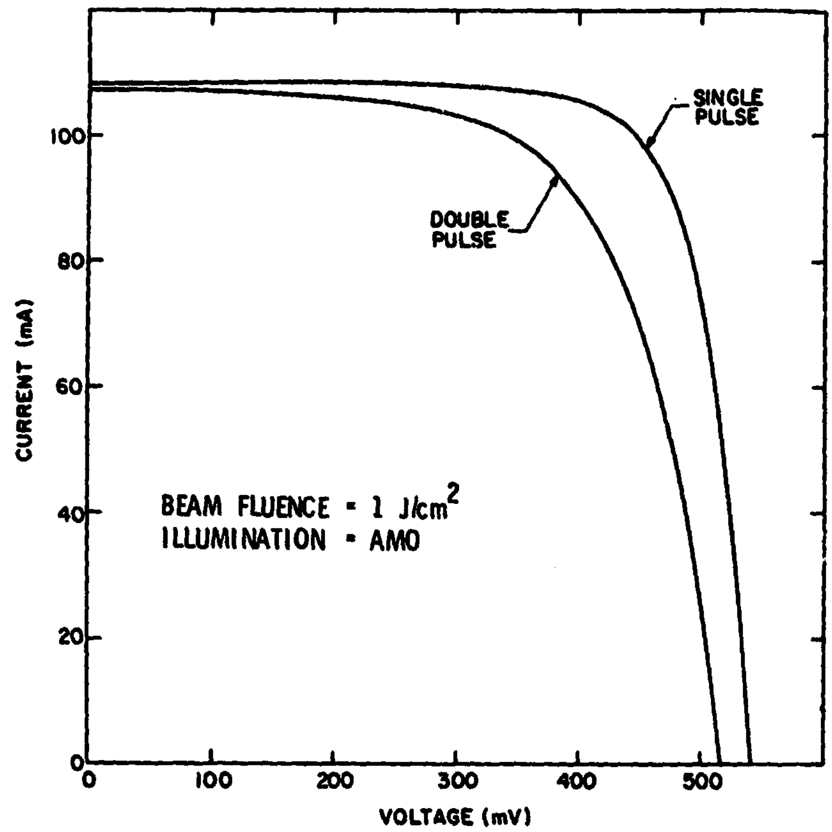
  CANNOT BE DONE WITH MULTIPLE PULSES IF COOLED BETWEEN EACH PULSE

  IF NOT COOLED BETWEEN PULSES, OR WITH GREATER PULSE WIDTH, WAFER CRACKS IF NOT HEATED OVER 300°C.
  POOR DOPANT PROFILE

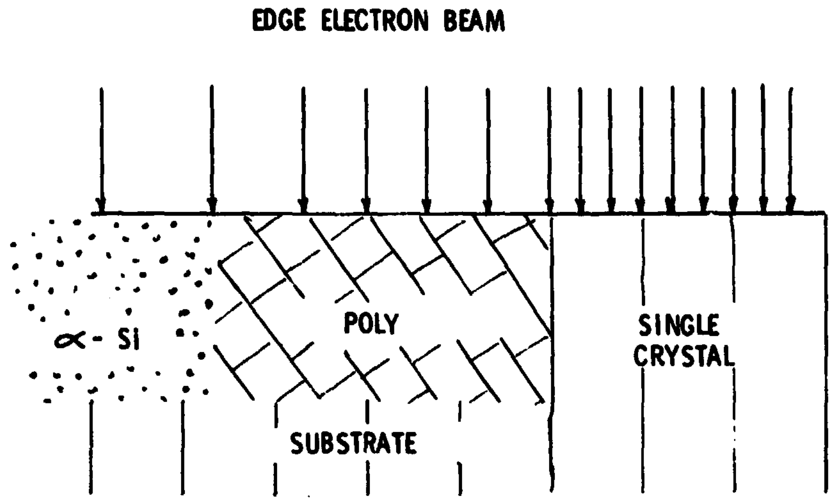
LIQUID PHASE PREFERRED METHOD


IMPLANTED LAYER
RECRYSTALLIZATION
T_{MELT}
SILICON SUBSTRATE
AT END OF PULSE
DEPTH
TEMPERATURE
T_{MELT}
AT START OF EPITAXIAL REGROWTH
DEPTH
T_{MELT}
IMPLANT LAYER FULLY RECRYSTALLIZED

PEBA Overlapping Pulse Experiment



Abutting Electron Beams



- HIGH FLUENCE MELTS ENTIRE DAMAGED REGION -- SINGLE CRYSTAL REGROWTH
- LOW FLUENCE NEAR BEAM EDGE DOES NOT MELT ENTIRE DAMAGED LAYER CAUSING POLYCRYSTALLINE REGROWTH
- NEXT PULSE MUST MELT POLY SILICON AT HIGHER FLUENCE THAN REQUIRED FOR α-SI

Single-Step 100 cm² Wafer Annealer

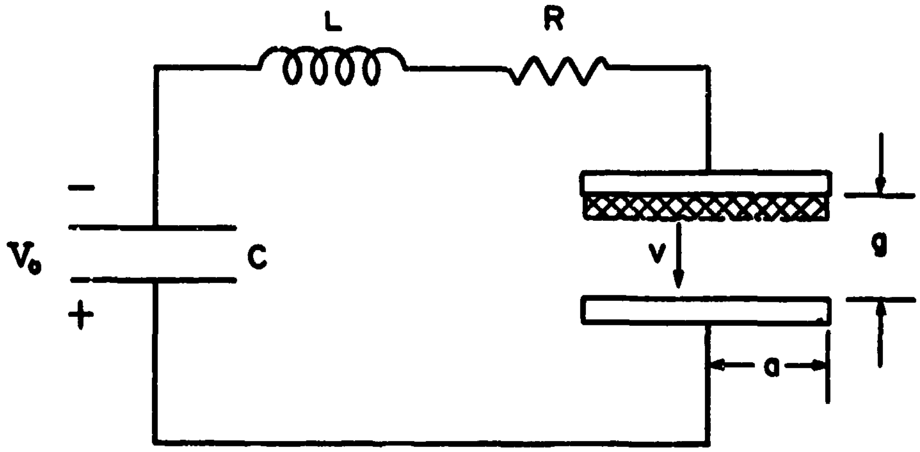
BEAM PARAMETERS:

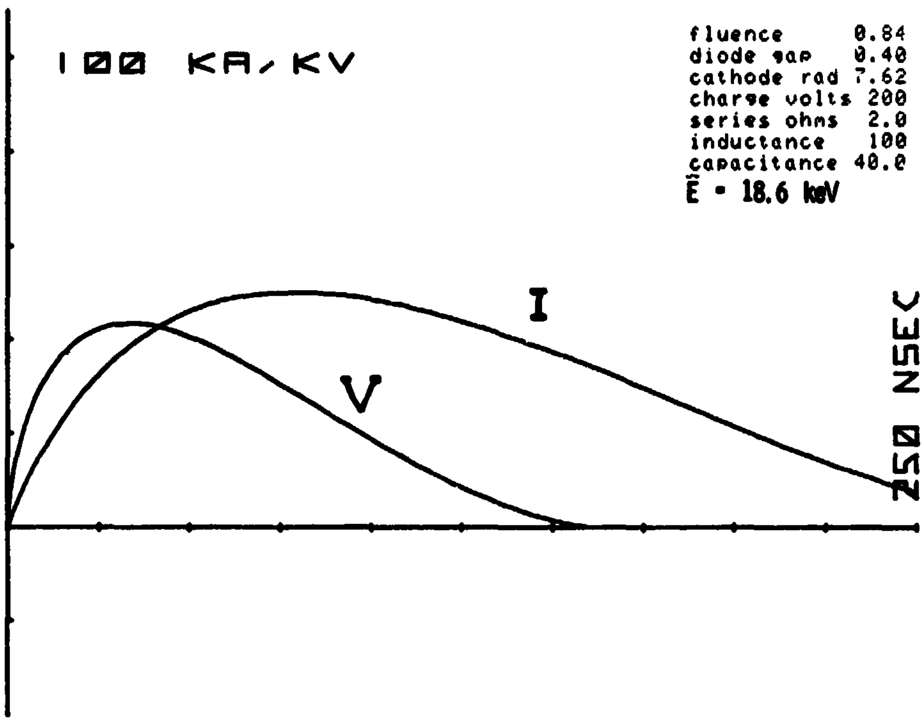
Fluence	≤ 2 J/cm^2
Electron Energy	$<$ 20 keV
Diameter	$\geq$100 mm

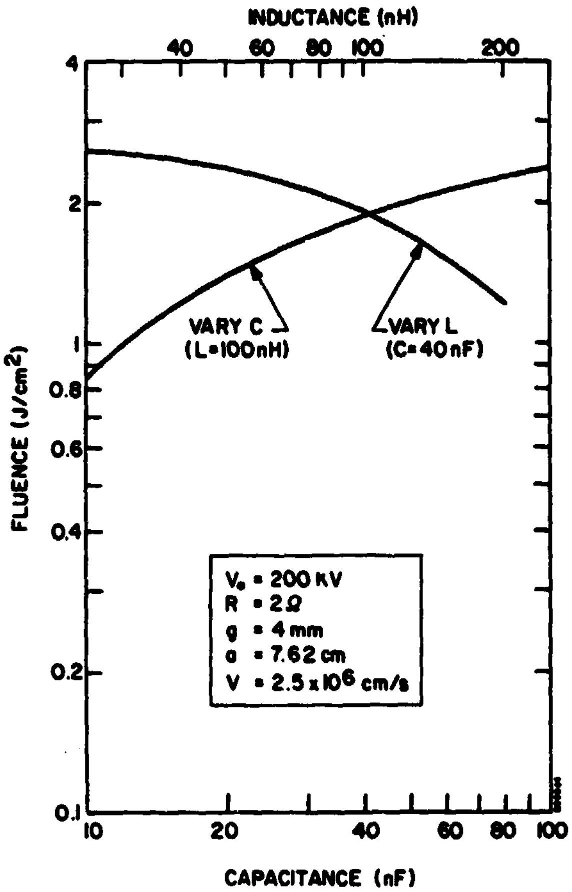
PULSER PARAMETERS:

Total Capacitance	$\geq$40 nF
Front-End Inductance	$\leq$100 nH
Charging Voltage	$\leq$300 kV
Charging Current	$\leq$15 mA

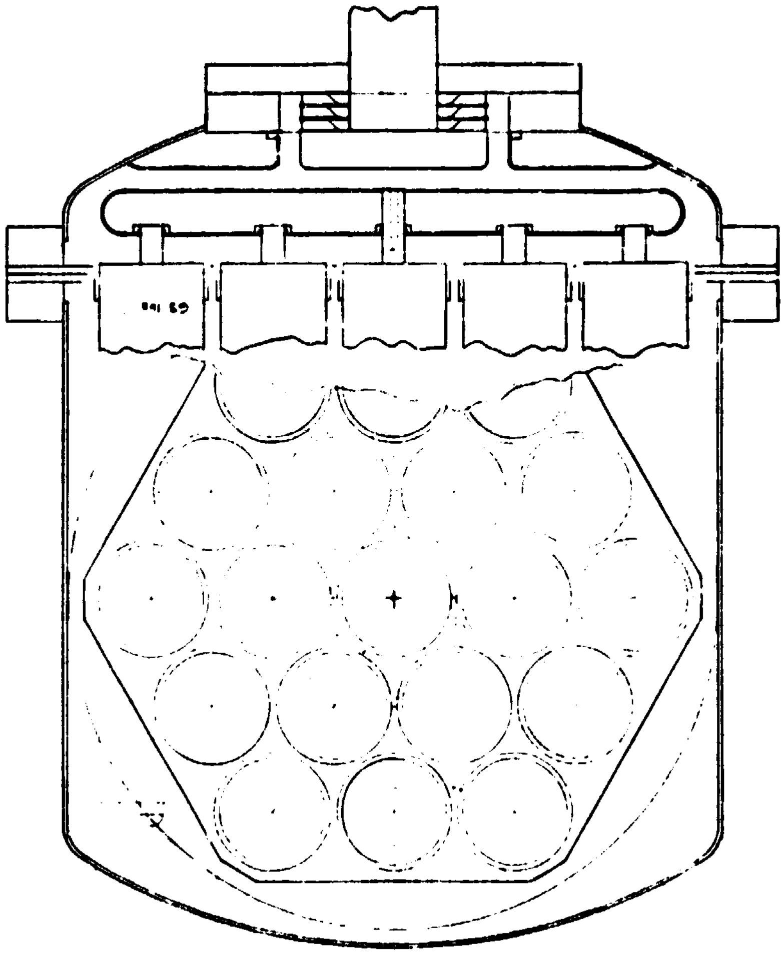
Pulsed Annealer Model






INDUCTANCE (nH)
40
60
80
100
200
4
2
1
0.8
0.6
0.4
0.2
0.1
FLUENCE (J/cm²)
VARY C
(L=100nH)
VARY L
(C=40nF)
V₀ = 200 KV
R = 2Ω
g = 4 mm
a = 7.62 cm
V = 2.5 x 10⁶ cm/s
10
20
40
60
80
100
CAPACITANCE (nF)

L/O Charge Store, SPI Pulse 7000

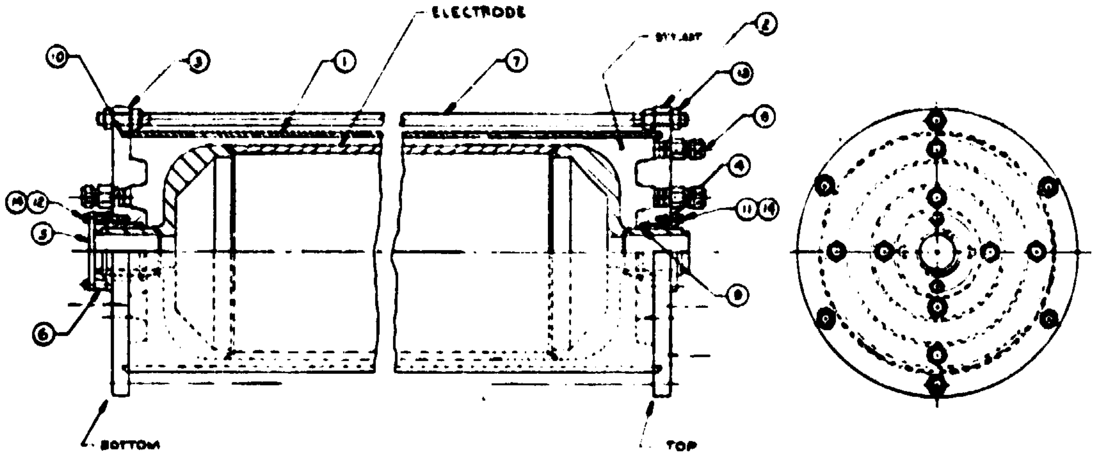


Line Design

CAPACITANCE	• 2.9 nF
INDUCTANCE	• 14.2 nH
ELECTRICAL LENGTH	• 41 in.
OVERALL LENGTH	• 53 in.
DIAMETER	• 9.5 in.
DIELECTRIC THICKNESS	• 0.31 in. Cast Epoxy

FABRICATION: Utilize Technology of SPI-PULSE 300

TESTING: High Voltage Tests of Prototype with SPI-PULSE 600



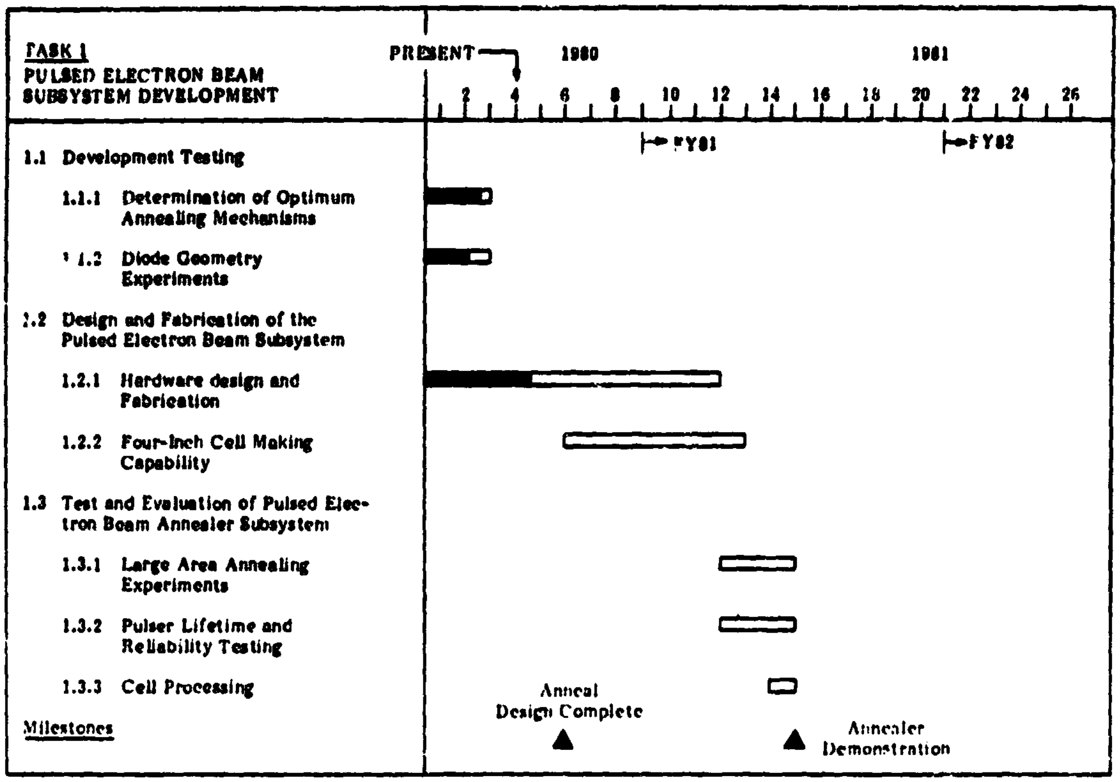
1. DEVELOPMENTAL TESTING

- Liquid-Phase Epitaxy Preferable over Solid-Phase
- Beam Overlap Experiments Indicate Poor Junction Parameters in Overlapped Regions
- Abutting Beam Experiments in Progress
- Wafer Heating Experiments in Progress
- Diode Geometry Experiments in Progress

PEBA Subsystem Development

- Preliminary Design Completed:
  - Energy storage lines
  - Process chamber
  - Diode assembly
  - Pressure vessel
  - Interim wafer transport
  - Magnet system
  - Power system
  - Main frame assembly
- Detailed Design Initiated
- Fabrication of Prototype Line Initiated

PRODUCTION PROCESS AND EQUIPMENT AREA



TECHNOLOGY DEVELOPMENT AREA
Encapsulation Task

TECHNOLOGY SESSION — C.D. Coulbert, Chairman

The continuing evaluation of low-cost encapsulation material systems containing ethylene vinylacetate (EVA) provides increasing confidence that the LSA cost, performance, and life goals can be achieved. Processing and production fabrication techniques are being developed and integrated into candidate module production sequences by PV module manufacturers.

To facilitate the use of laminating sheets of EVA, three approaches to eliminating the sheet sticking (blocking) problem have been demonstrated. These techniques, developed by Springborn, are (1) embossing the EVA sheet with a finely textured platen or forming surface, (2) dusting the surface of the EVA with finely divided polyethylene (which is incorporated into the pottant melt when it is laminated) and (3) prelaminating the EVA with a sheet of non-woven glass scrim. Each of these approaches is being investigated further for storage stability and temperature effects.

The prospects for early and adequate supplies of solar grade EVA are deemed excellent, based on recent JPL contacts with potential industrial suppliers.

A major factor in assessing the commercial potential of EVA as a module encapsulant is an understanding, and quantitative evaluation, of its life-limiting degradation mechanisms. This area is being aggressively investigated by Springborn, University of Toronto and JPL. Accelerated laboratory exposures and ongoing field-test exposures are in progress for the solar grade (UV stabilized) EVA as a material and as incorporated into complete encapsulated solar modules.

Accelerated radiation exposures of EVA in field and laboratory tests equivalent to one to seven years of normal use indicate excellent potential for 20-year module life for designs with UV screening covers of glass or weatherable cover films. Chemical modeling studies of EVA and experimental verification tests conducted at the University of Toronto will provide an improved basis for predicting material degradation over 20 years and also criteria for the degree of environmental protection needed.

Ultraviolet screening agents formulated as copolymers for use in low-cost, long-life cover films have been developed by the University of Massachussetts and are currently being analyzed and the formulation processes are being scaled up for more extensive evaluation.

Development and evaluation efforts on several other candidate encapsulation materials and processes are continuing. In anticipation of the requirement for encapsulation systems optimized for a variety of geographic sites, power applications and solar cell types, the LSA encapsulation task continues to support the development and evaluation of alternative encapsulation materials and processes. In general these developments are in the stage of minimodule design and test evaluation. Low-cost candidate encapsulant materials undergoing fabrication and testing include low-cost silicones, silicone/acrylic blends, poly-n butyl acrylate, PVC plastisol, borosilicate glass, steel, wood hardboard, metal-foil laminates, glass-reinforced concrete and the currently used materials such as PVB, Tedlar, Korad, and various types of glass.

A process for low-pressure electrostatic bonding (ESB) of silicon solar cells directly to a glass superstrate has been demonstrated by Spire Corp. A potential application for this concept is to bond very thin silicon wafers to the glass and then apply an interdigitated back-contact metallization.

Initial evaluation by Illinois Tool Works of the process of gasless ion plating of metal contacts and AR coatings on silicon cells shows no deleterious effects on the cell junction. Active solar cells made with ion-plated silver metallization show excellent adhesion and good electrical characteristics. The potential for lower-cost corrosion-resistant metal candidates will be evaluated during the coming months.

To narrow the field of material and process candidates and provide a basis for optimum selection of materials and material configurations, a contract with Spectrolab is providing an analysis and test verification of the optical, electrical, thermal, and structural performance of encapsulated modules as a function of material, material thickness and environmental stresses. Completion of quantitative analyses for selected designs is expected during the coming six months.

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

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

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.

TECHNOLOGY DEVELOPMENT AREA: Encapsulation Task

Material degradation data for low-cost advanced encapsulation systems is being gathered using various test hardware such as minimodules (12 x 16 in.), two-cell modules and individual material samples. Exposure facilities include JPL laboratory test chambers and selected California field test sites at Point Vicente, JPL, Goldstone, and Table Mountain.

A structural computer model has been formulated to study failure modes associated with temperature and moisture expansion stresses within the module encapsulation system. The purpose of this study is to identify areas of potential cracking and delamination and evaluate the possible propagation of these failures.

A long-term accelerated module life test is being implemented to evaluate a life-testing plan developed by Battelle. A closely controlled and monitored module degradation-rate experiment with accelerated temperature cycling, high humidity, SO_2 gas and applied current flow will be conducted with 10 prototype modules simultaneously over a four- to six-month period. The test chamber has been modified and preliminary experiments are being conducted in preparation for prototype module testing to be initiated in the coming months.

A basic requirement for assessing, tracking, and predicting the state of health of photovoltaic modules in the field is the availability of measurement techniques for detecting and recording both environmental stress parameters and progressive changes in encapsulated module properties leading to eventual array performance deterioration. The following measurement techniques are currently under development and evaluation for the Encapsulation Task:

a. Actinometer for field measurement and integration of selected ultraviolet radiation dosage.

b. Acid rain meter for field evaluation of the acidity and electrical conductivity of rainfall.

c. Atmospheric corrosion monitor (ACM) for the field evaluation of the probable time of wetness of module components subject to corrosion.

d. AC impedance meter for the field detection of small changes in the shunt and series resistance of solar cells and modules due to deterioration of the solar cell metallization or circuit continuity.

e. Automatic network analyzer for detecting small changes in cell or module circuit characteristics due to degrading stresses.

MATERIALS AND PROCESSES

ETHYLENE VINYL ACETATE (EVA) DEVELOPMENT AND EVALUATION

- NON-STICKING SHEET PROCESSES DEVELOPED (SPRINGBORN) EMBOSSED/POLYETHYLENE DUSTING/GLASS MAT CO-LAMINATE
- INDUSTRIAL SUPPLY POTENTIAL EXCELLENT
- UV STABILITY INCREASED AND VERIFIED
- UV DEGRADATION MECHANISMS MODELED AND TESTED

ELECTROSTATIC BONDING (ESB) (SPIRE)

- LOW-COST BONDER FOR BACK SURFACE METALLIZATION CELLS DEMONSTRATED

MODULE COVER FILMS

- UV SCREENING CRITERIA DEFINED FOR LONG LIFE
- UV SCREENING AGENTS FORMULATED AS COPOLYMER

1986 ENCAPSULATION DESIGNS BEING ANALYZED FOR INTEGRATED STRUCTURAL/OPTICAL/THERMAL/ELECTRICAL PERFORMANCE (SPECTROLAB)

ION PLATING OF AR COATING AND METALLIZATION (ITW)

- DOES NOT DEGRADE CELL JUNCTIONS
- ACTIVE CELLS MADE
- AR COATED GLASS MADE

LIFE PREDICTION AND MATERIAL DEGRADATION

- NOW HAVE DETAILED UNDERSTANDING OF MATERIAL AGING MECHANISMS AND THIS IS THE BASIS FOR RATE PREDICTION, PROTECTION CRITERIA AND TEST METHODS
- PHOTOTHERMAL GRADIENT TEST CHAMBER HAS BEEN DESIGNED FOR FULL-SCALE MODULE ACCELERATED LIFE TESTING (UV, TEMPERATURE, ATMOSPHERE MATRIX ON EACH MODULE)
- SENSITIVE DIAGNOSTIC TECHNIQUES ARE AVAILABLE FOR ENCAPSULANT AND MODULE WEAR-OUT CHARACTERIZATION

TECHNOLOGY DEVELOPMENT AREA: Encapsulation Task

MATERIALS AND PROCESS DEVELOPMENT CONTRACTORS

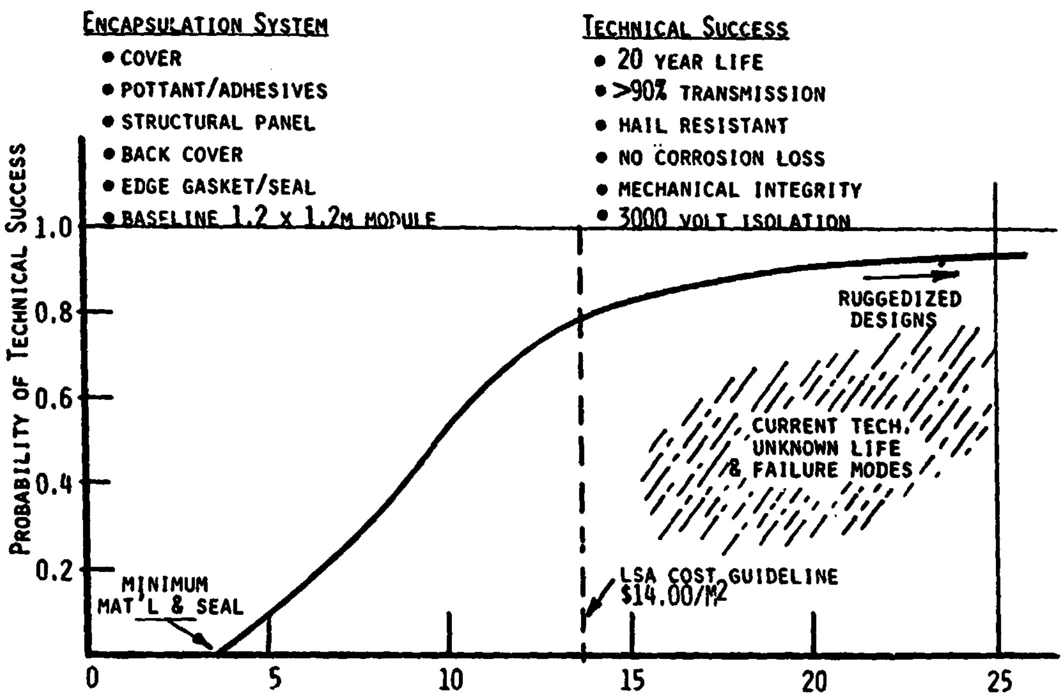
SPRINGBORN LABS	LOW-COST MATERIALS
SPIRE CORP.	ELECTROSTATIC BONDING
ILLINOIS TOOL WORKS	ION PLATING
*MOTOROLA	ANTIREFLECTION COATINGS
UNIV. OF MASSACHUSETTS	ULTRAVIOLET SCREEN MATERIALS
*MB ASSOCIATES	GLASS REINFORCED CONCRETE
*DOW CORNING	SILICONE ENCAPSULANTS

PERFORMANCE AND LIFE PREDICTION CONTRACTORS

SPECTROLAB INC.	DESIGN ANALYSIS & VERIFICATION
ROCKWELL SCIENCE CTR.	INTERFACE & SURFACE MECHANISMS (CORROSION)
CASE WESTERN	BASIC AGING AND DIFFUSION (PNBA)
UNIV. OF TORONTO	PHOTODEGRADATION MODELING (EVA)
*BATTELLE	ACCELERATED TEST DESIGN
CALTECH	MECHANICS OF FRACTURE (DELAMINATION)

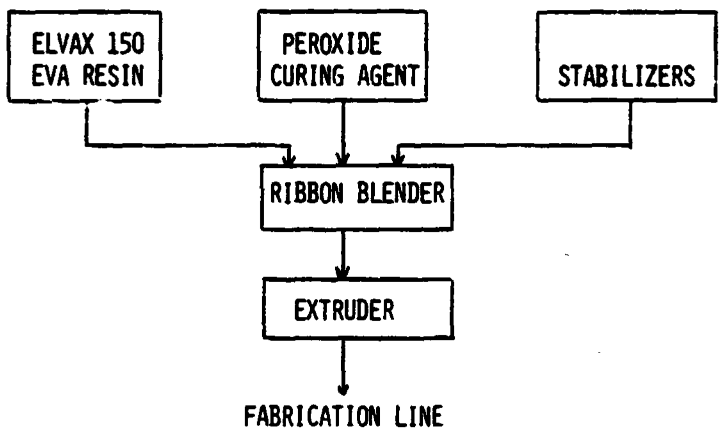
*COMPLETED EFFORT

Cost of Encapsulation Materials, \$/m² (1980\$)



ETHYLENE VINYL ACETATE (EVA) SHEET

SPRINGBORN LABORATORIES, INC.



MANUFACTURING COST: $0.95/LB (CLEAR)
$0.98/LB (PIGMENTED)

- INCLUDES LABOR, MATERIAL, INSURANCE, TAXES, RETURN ON INVESTMENT, ETC.
- BASED ON PRODUCTION OF 50 MILLION FT^2 OF MODULE PER YEAR

Manufacturing Cost Comparison

POTTANT	$/LB	$/FT^2 (A)
EVA, SHEET, CLEAR	0.95	0.09
EVA, SHEET, PIGMENTED	0.98	0.10
EPDM, SHEET	1.10	0.10
PU, SYRUP	1.66	0.18
PVC, SYRUP	0.83	0.10
BA, SYRUP	0.55	0.06
BA, SHEET	0.72	0.08

- AUTOMATED PRODUCTION
- SUFFICIENT FOR 50 MILLION FT^2 MODULE/YEAR
- COST INCLUDES RETURN ON INVESTMENT

(A) AS SHEET OF 20-MIL THICKNESS

Anti-Blocking Treatments

PROBLEM: EVA SHEET BLOCKS TO ITSELF AND OTHER MODULE COMPONENTS

APPROACHES:

A. SURFACE DUSTING

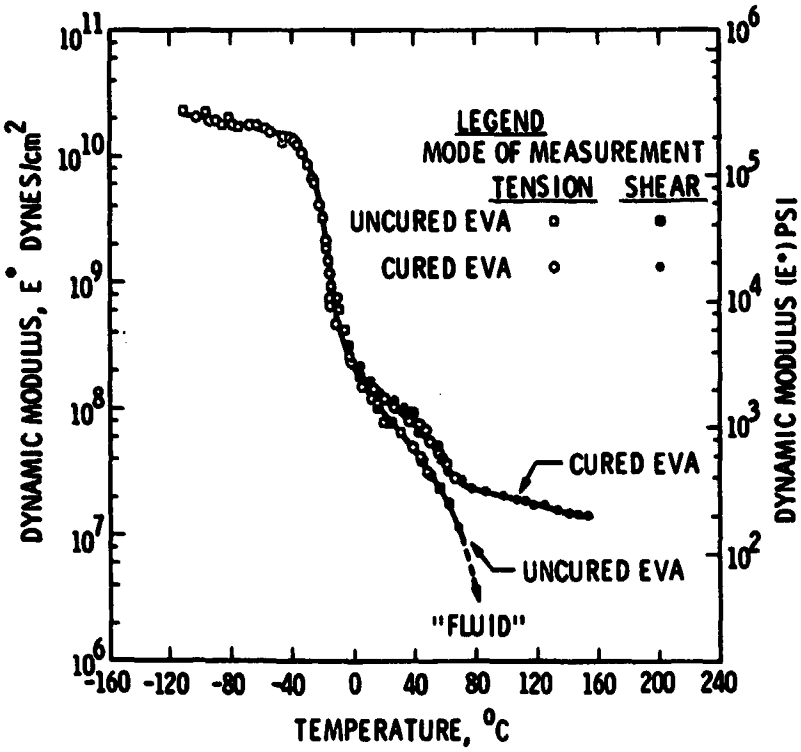
B. EMBOSSING THE SURFACE

C. EXTRUSION ONTO NON-WOVEN GLASS MAT

ALSO ELIMINATES USE OF DISPOSABLE RELEASE PAPER USED AS INTERLEAVING IN CURRENT PRODUCTION

Dynamic Mechanical Properties

Dynamic Modulus (E*) of Encapsulation-Grade EVA (A9918) at 110 Hz



RS/4 Fluorescent Sunlamp Exposure Studies

EVA COMPOUNDS

- CLEAR STABILIZED EVA EXPOSED 9,000 HOURS WITH NO DETERIORATION
  (NO COVER FILM)

	TOTAL INTEGRATED TRANSMISSION	ULTIMATE ELONGATION	TENSILE STRENGTH
CONTROL	91.0%	510%	1890 PSI
EXPOSED 9,000 HRS	90.6%	560%	1870 PSI

- UNSTABILIZED ELVAX 150 (EVA) BECOMES SOFT, TACKY AND LOSES PHYSICAL PROPERTIES IN LESS THAN 1,000 HOURS
- WHITE PIGMENTED EVA ALSO SHOWS NO CHANGE IN PROPERTIES

CROSSLINKED EVA: PHOTODEGRADATION STUDIES

JET PROPULSION LABORATORY

Actinometry and Radiometry

λ	SOLAR IRRADIATION	LAMP IRRADIANCE
300 - 380 nm	1.3×10^{19} photons / day	2×10^{16} photons / sec

UV ACCELERATION: $\frac{\text{10.5 min OF LAMP}}{\text{1 day OF SOLAR IRRADIANCE}}$.

CAROUSEL FACTOR: 1/15

NET ACCELERATION: 2.6 hrs OF LAMP IS EQUIVALENT TO 1 day OF OUTDOOR EXPOSURE

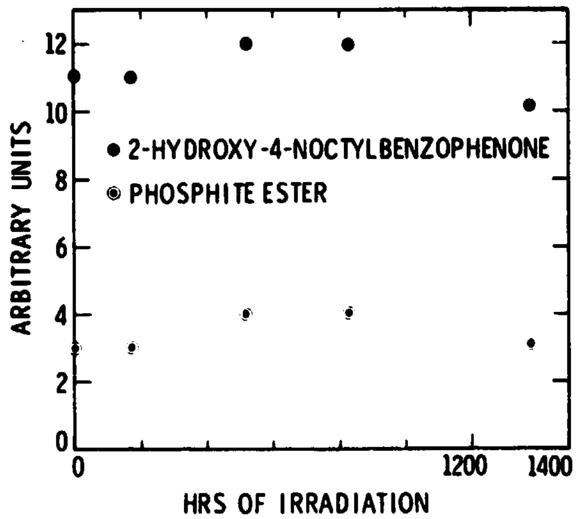
Molecular Weight Distribution of Extracted EVA

TIME OF IRRADIATION (hrs)	$\bar{M}_n$	$\bar{M}_w$	$\bar{M}_w/\bar{M}_n$
0	35,000	101,000	2.91
168	38,000	114,000	3.01
524	34,000	112,000	3.26
836	41,000	116,000	2.84
1078	35,000	106,000	3.00
1388	38,000	108,000	2.88

MEASURED BY HPLC / POLYSTYRENE CALIBRATION

- NO SIGNIFICANT CHANGE IN MOLECULAR WEIGHT OF EXTRACTIBLES
- NO CHAIN SCISSION OR CROSSLINKING

Concentration of Additives in Extracted EVA



- NO SIGNIFICANT PHOTODEGRADATION OF THE UV STABILIZER OR THE ANTIOXIDANT
- THE MAJOR DEGRADATION PROCESS IS EXPECTED TO BE LOSS OF ADDITIVES DUE TO LEACHING

Conclusions

- INITIAL PHOTODEGRADATION CAUSES DECOMPOSITION OF INITIATOR (RESIDUAL)
- NO SUBSEQUENT SPECTRAL CHANGE RULING OUT DOUBLE BOND FORMATION
- NO CHANGE IN MOLECULAR WEIGHT OR EXTRACTIBLES
- NO CHANGE IN STRUCTURE OR EXTRACTIBILITY OF ADDITIVES
- SLOW PHOTOXIDATION ⟶ LEADS TO ALCOHOLS/ACID FORMATION
- FAILURE MODES TO BE INVESTIGATED
  - DELAMINATION
  - CORROSION

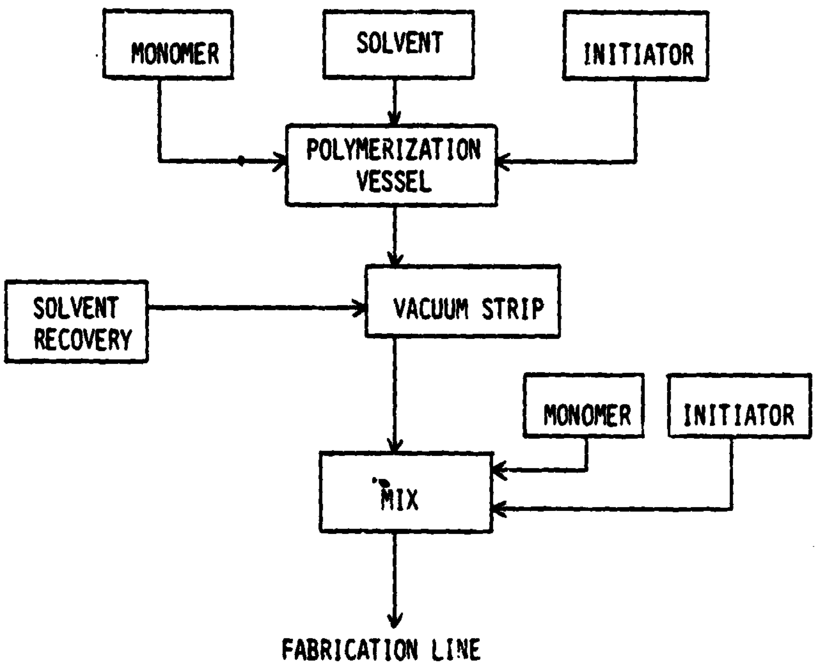
PNBA PROCESSING

Curing of PnBA Casting Syrup

- TIME / TEMPERATURE MATRIX DEVELOPED
- OPTIMUM CURING CONDITION
    - 2 psi ARGON
    - 80°C
    - 4 h
- CROSSLINKING OF PNBA ALSO TIES UP THE UV SCREENING AGENT
- PRODUCT CREEPS LESS THAN 0.1 mm AFTER 200 h AT 90°C
- CURING PROCESS STUDIED AS FUNCTION OF MOLECULAR WEIGHT OF PREPOLYMER

Commercial Manufacturing Process

Butyl Acrylate Casting Syrup

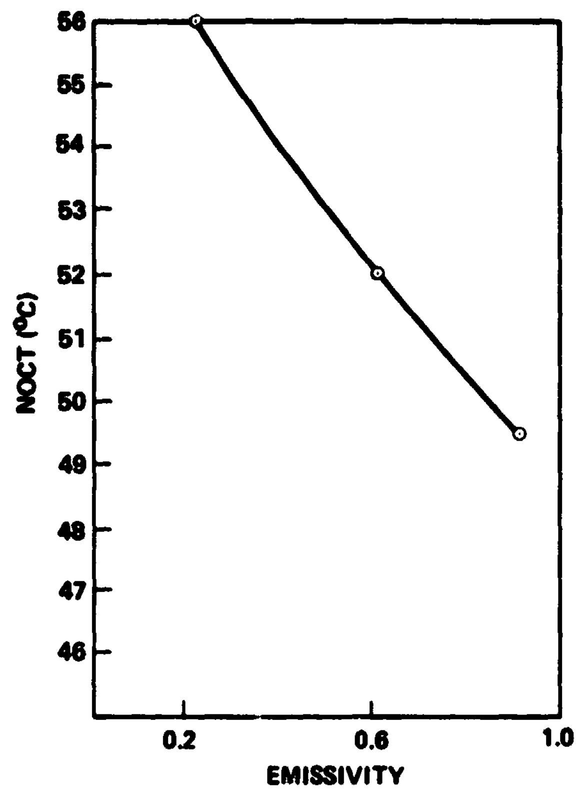


MANUFACTURING COST: $0.55/LB

INCLUDES LABOR, MATERIALS, INSURANCE, TAXES
RETURN ON INVESTMENT, ETC.

BASED ON 50 MILLION FT^2 OF MODULE PRODUCTION PER YEAR

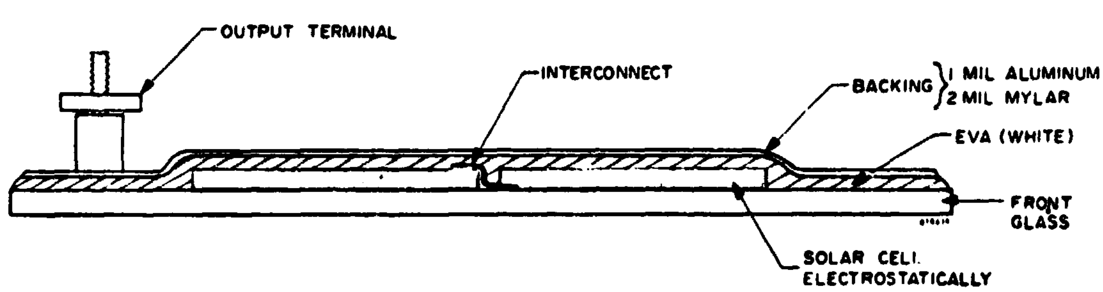
NOCT vs Module Backside Emissivity (Superstrate Design)



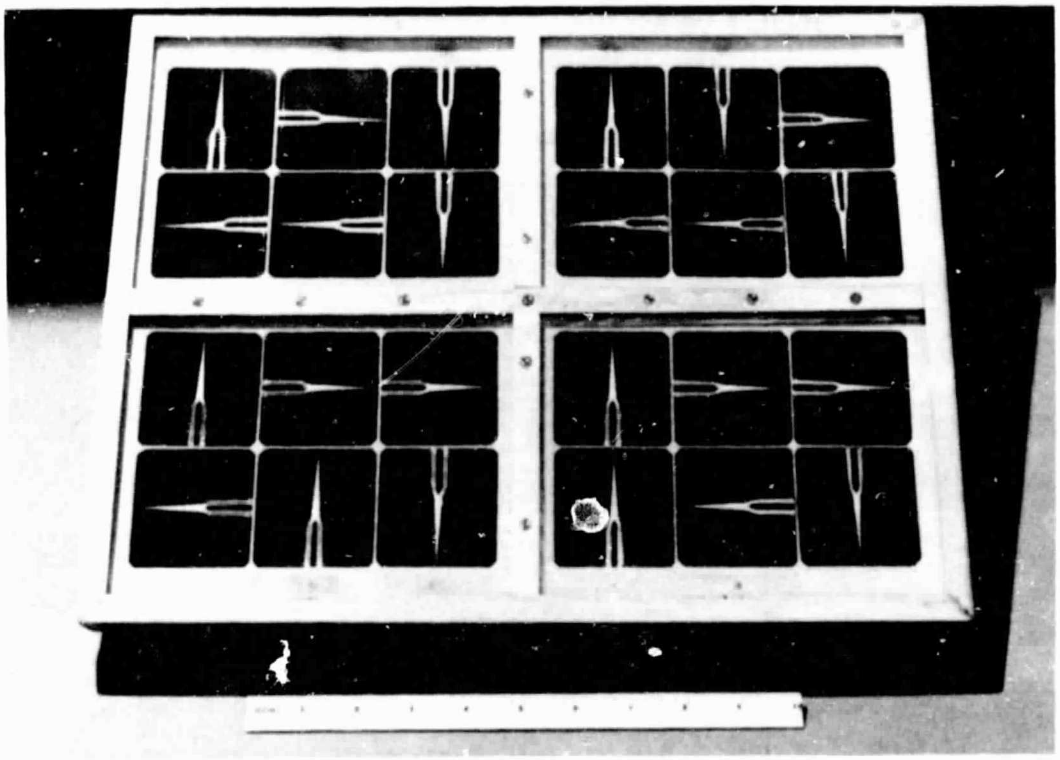
ELECTROSTATIC BONDING

SPIRE CORP.

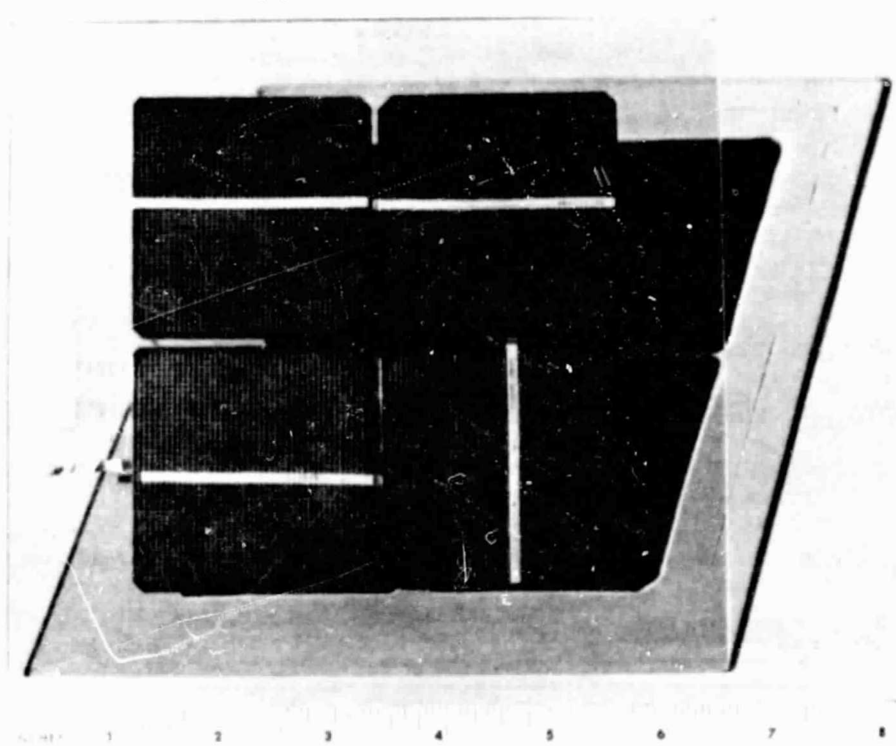
Cross-Sectional View of Integral Front Electrostatically Bonded Module Assembly



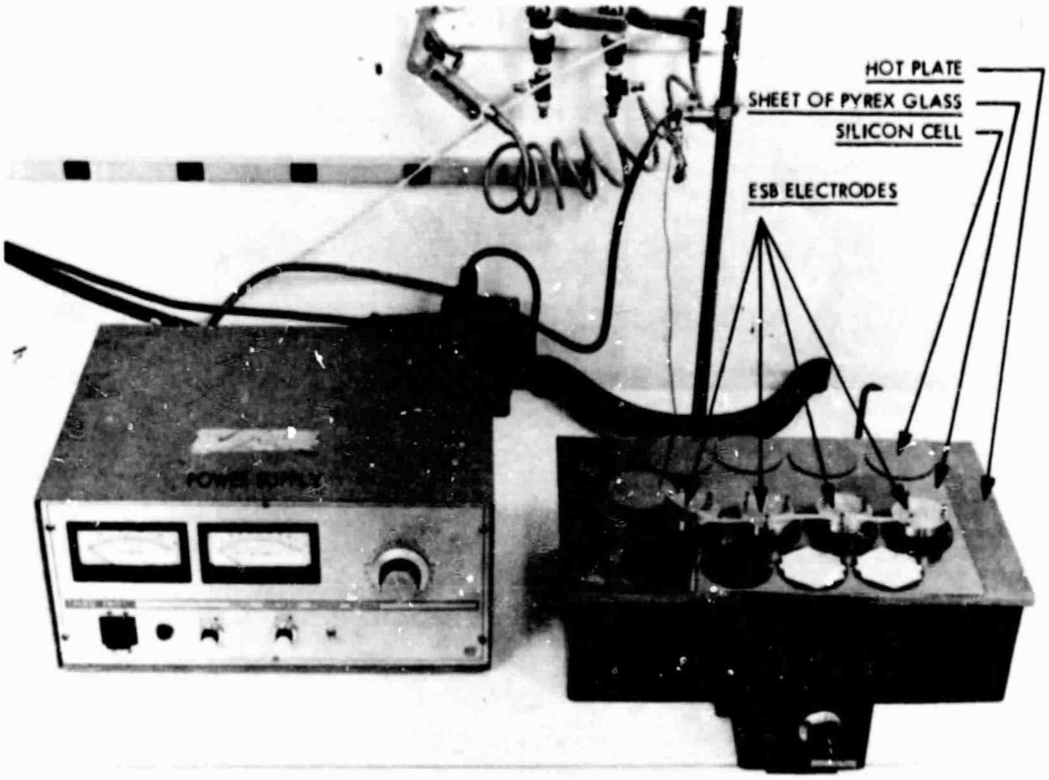
Electrostatically Bonded Minimodule by Spire



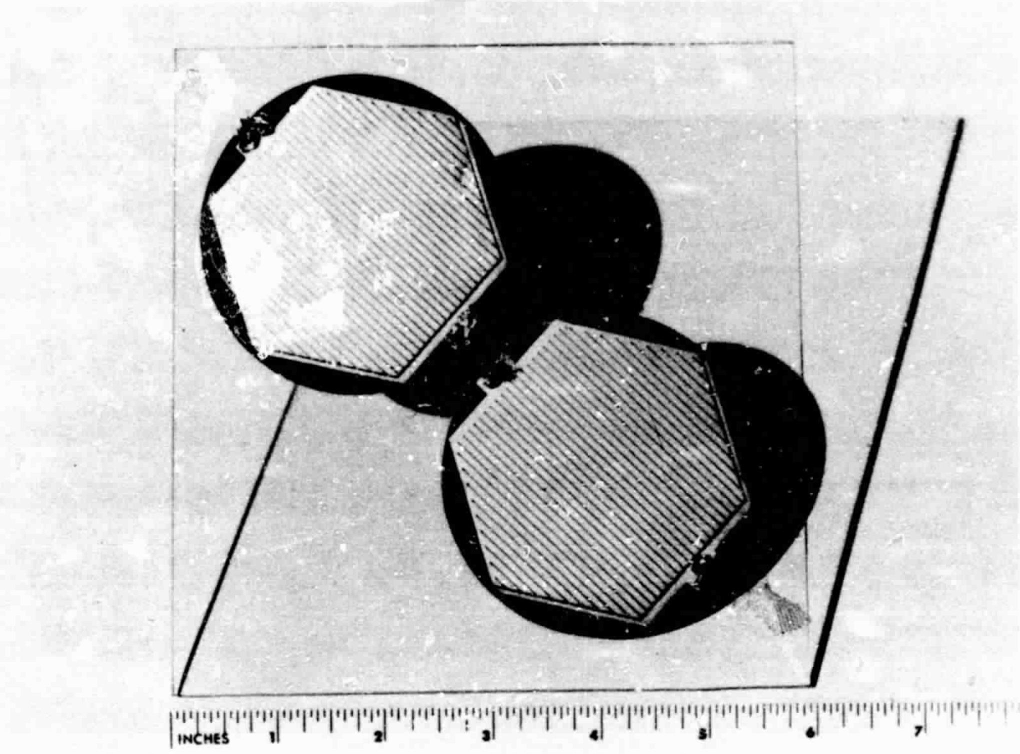
Spire Electrostatically Bonded Module
With Trapped Mesh Metallization



Low-Pressure ESB Experiment



Interdigitated Back-Contact Solar Cells Bonded to Pyrex Glass Sheet



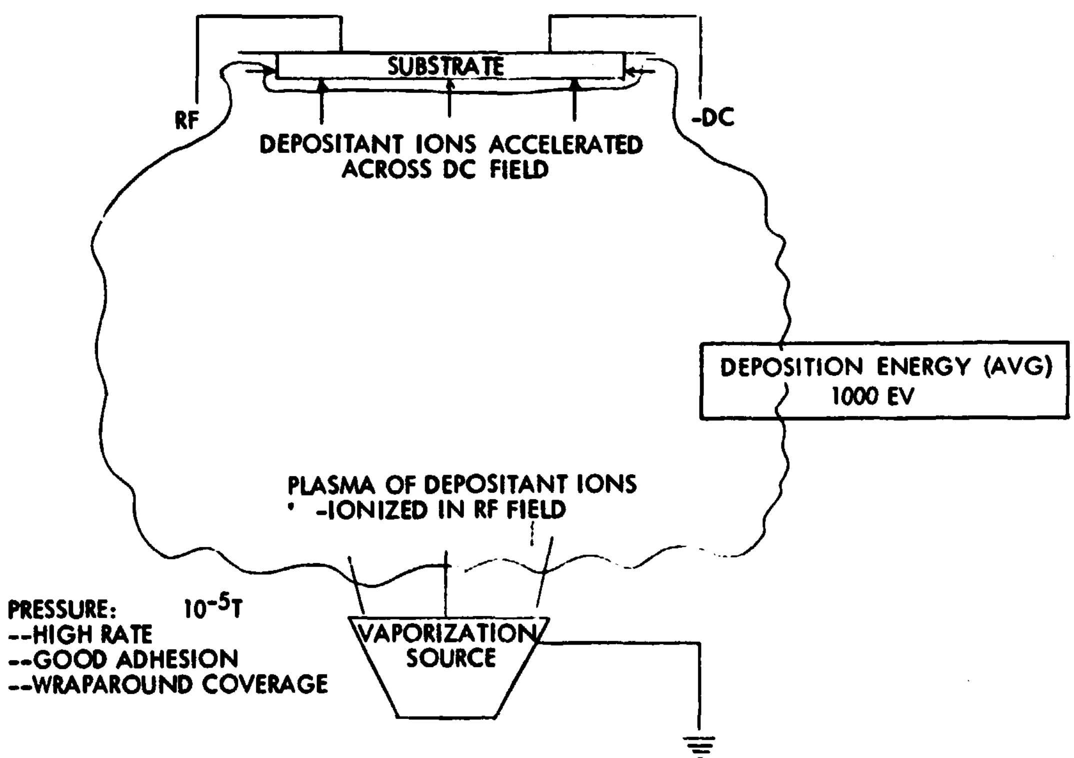
ION PLATING

ILLINOIS TOOL WORKS

Applicability of Ion Plating to Solar Cells

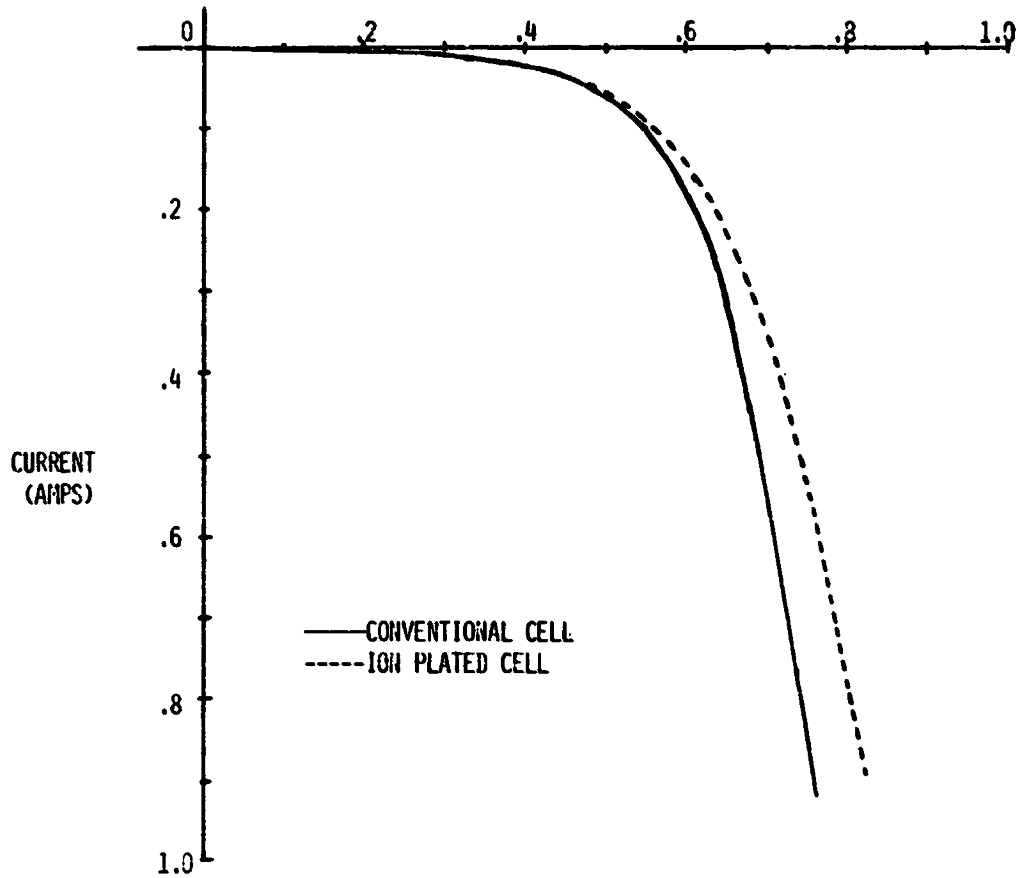
1. IP YIELDS EXCELLENT ADHESION TO VARIOUS SUBSTRATES.
2. IP CAN BE USED TO APPLY A VARIETY OF METALLIZATION SYSTEMS AS WELL AS AR MATERIALS.
3. CONDUCTIVITY OF IP METALS IS NEAR BOOK VALUES.
4. IP MAY PERMIT USE OF INHERENTLY NONCORRODING METALLIZATION SYSTEMS.
5. IP MAY PERMIT USE OF INEXPENSIVE METALLIZATION SYSTEMS.
6. IP MAY ALLOW PROTECTION BY INEXPENSIVE ENCAPSULATION SYSTEMS.
7. IP MAY BE USED TO APPLY ANTISOILING COATINGS TO SOLAR CELLS OR COVERINGS.
8. IT IS PROJECTED THAT IP CAN MEET THE COST GOALS OF THE LSA PROJECT.

Gasless Ion Plating



DEPOSITION ENERGY (AVG)
1000 EV

Comparison of Dark Parameters
Conventional vs Ion-Plated Metallization



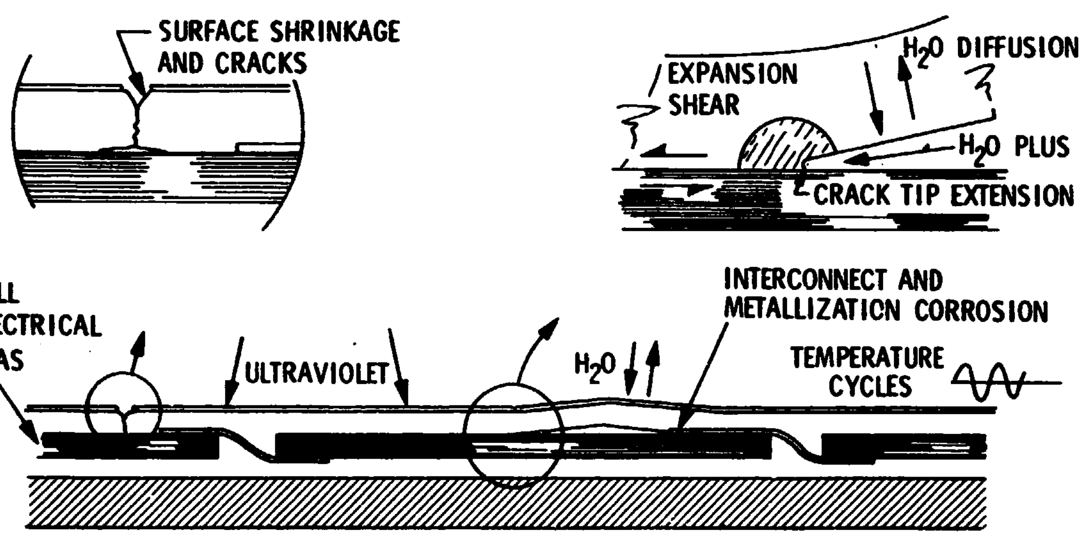
MINIMODULE TESTING PROGRAM

JET PROPULSION LABORATORY

Distribution of Modules

MODULE MANUFACTURER	TOTAL No. OF EACH TYPE	OUTDOOR EXPOSURE			DSET	JPL ACC TESTING	NOCT HIPOT CORONA	JPL QUAL TEST	CONTROL
		JPL	GOLD-STONE	PT VICENTE					
MINI-MODULES									
SPRINGBORN (3 TYPES)	15 (45 TOTAL)	3	3	3	1	0	1	3	1
APPLIED SOLAR ENERGY (3 TYPES)	15 (45 TOTAL)	3	3	3	1	0	1	3	1
MB ASSOCIATES (1 TYPE)	15 (15 TOTAL)	3	3	3	1	0	1	3	1
SPIRE (1 TYPE)	10 (10 TOTAL)	2	2	2	1	0	1	1	1
GE (3 TYPES)	5 (15 TOTAL)	TBD							
SUB-MODULES									
SPRINGBORN (4 TYPES)	90 (360 TOTAL)	25	25	25	15		0	0	0

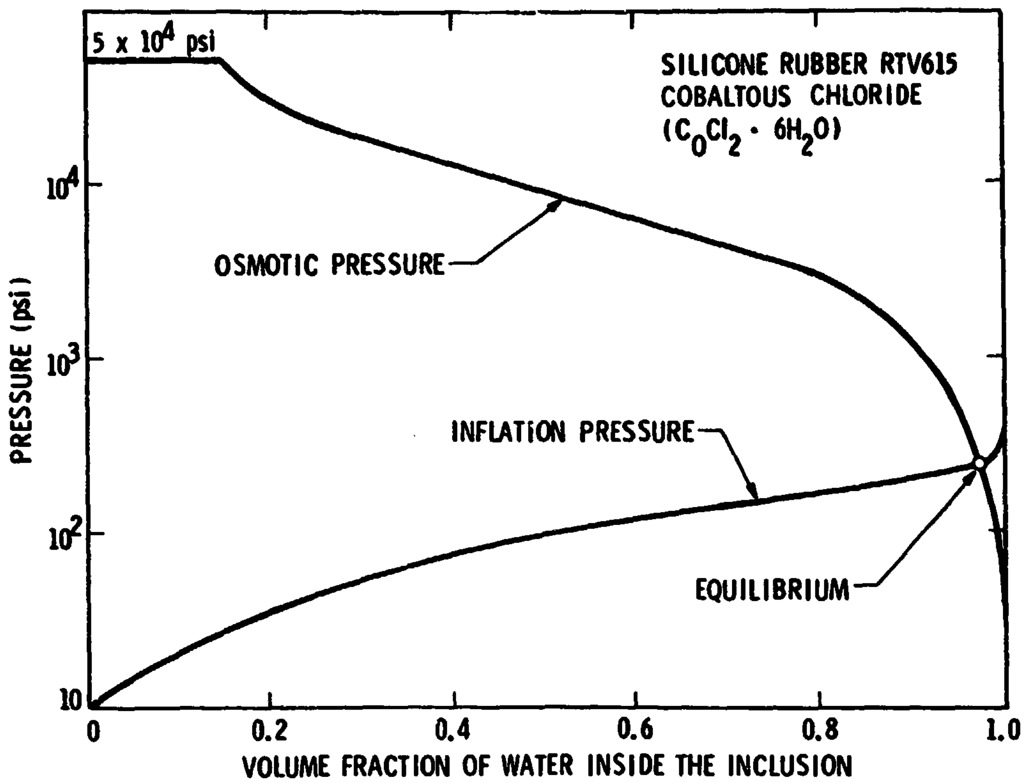
Delamination and Corrosion Mechanisms



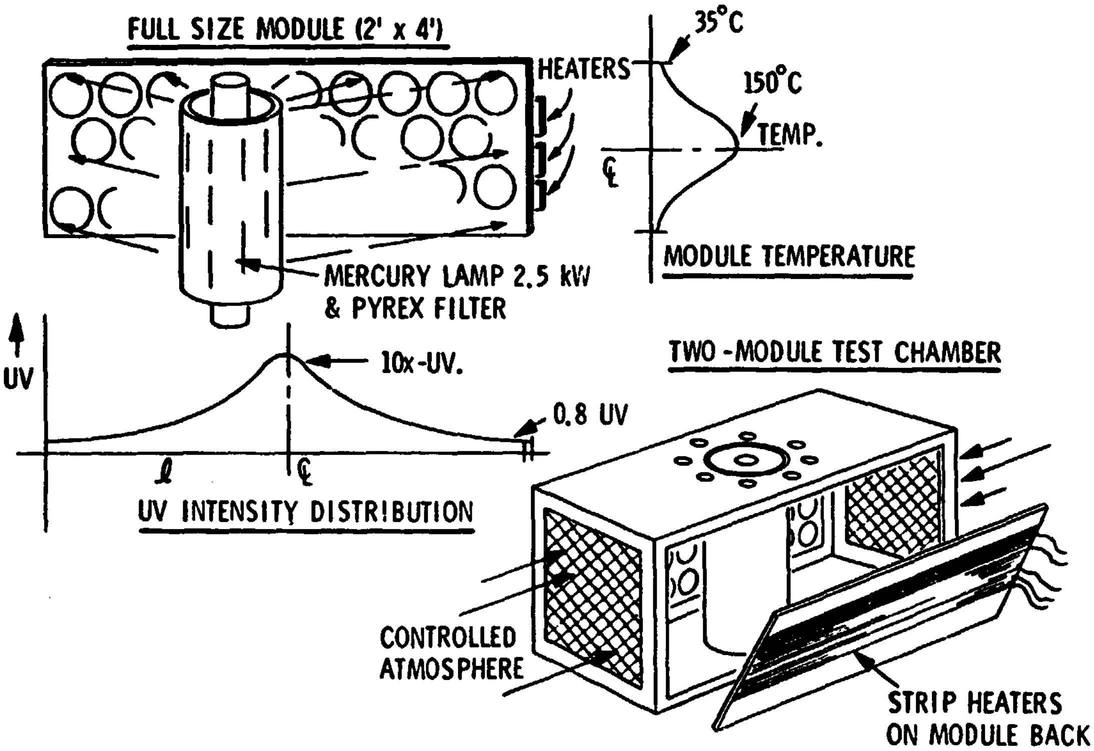
ANALYSIS APPROACHES

- STRESS MODEL
- FRACTURE AT INTERFACES
- INTERFACE BONDING CRITERIA
- ACCELERATED LAB & FIELD TESTS
- UV DEGRADATION OF BONDS & BULK
- HYDROMECHANICAL MODEL
- CORROSION MODEL
- FIELD TESTING

Hydromechanical Failure Model: Calculated Osmotic Pressure and Inflation Pressure

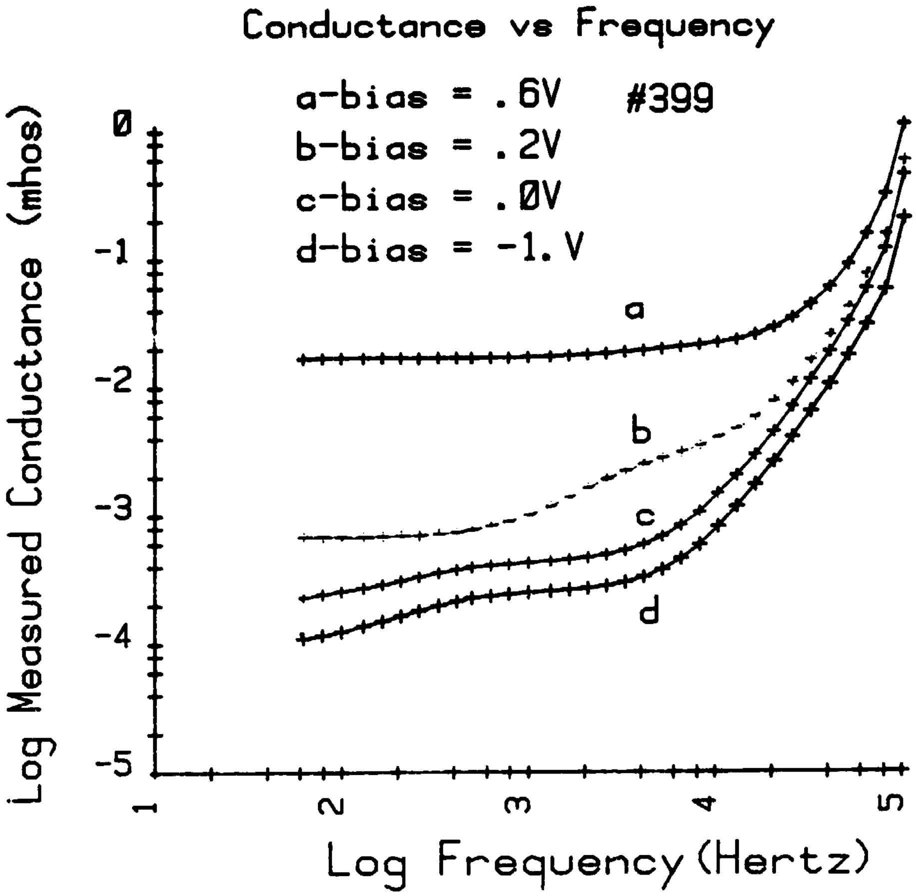


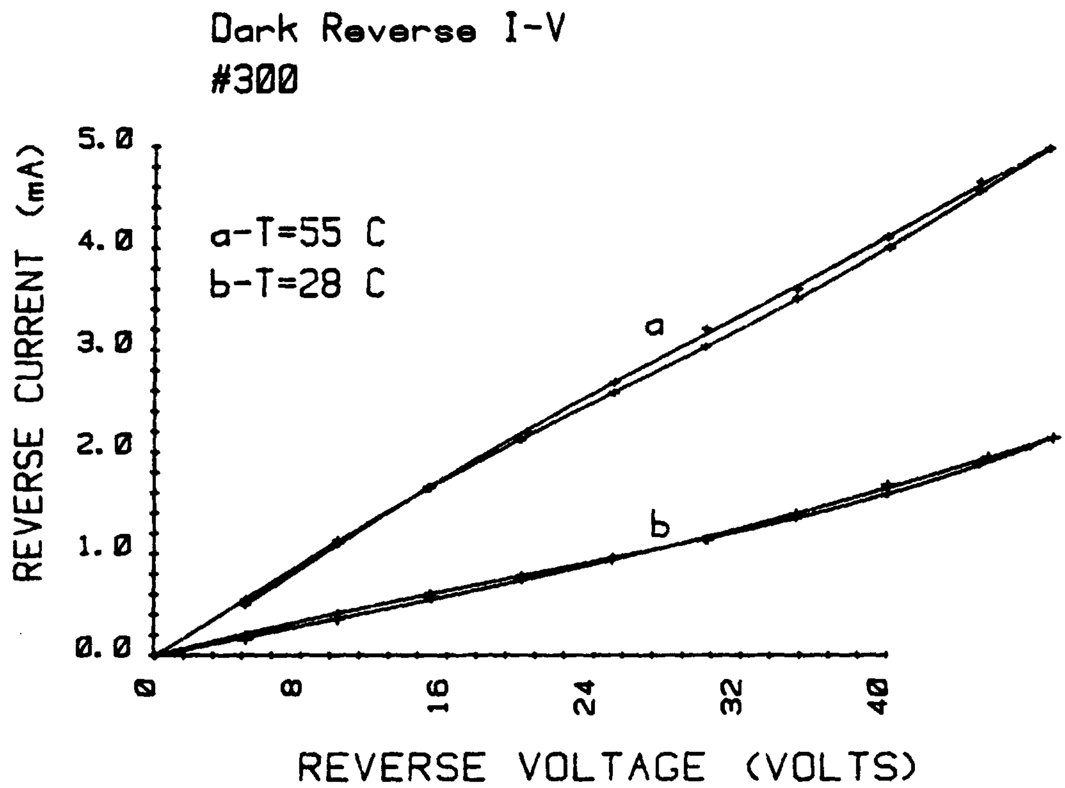
Temperature/UV Matrix Test



CANDIDATE SOLAR CELL DIAGNOSTIC DATA

COLORADO STATE UNIVERSITY

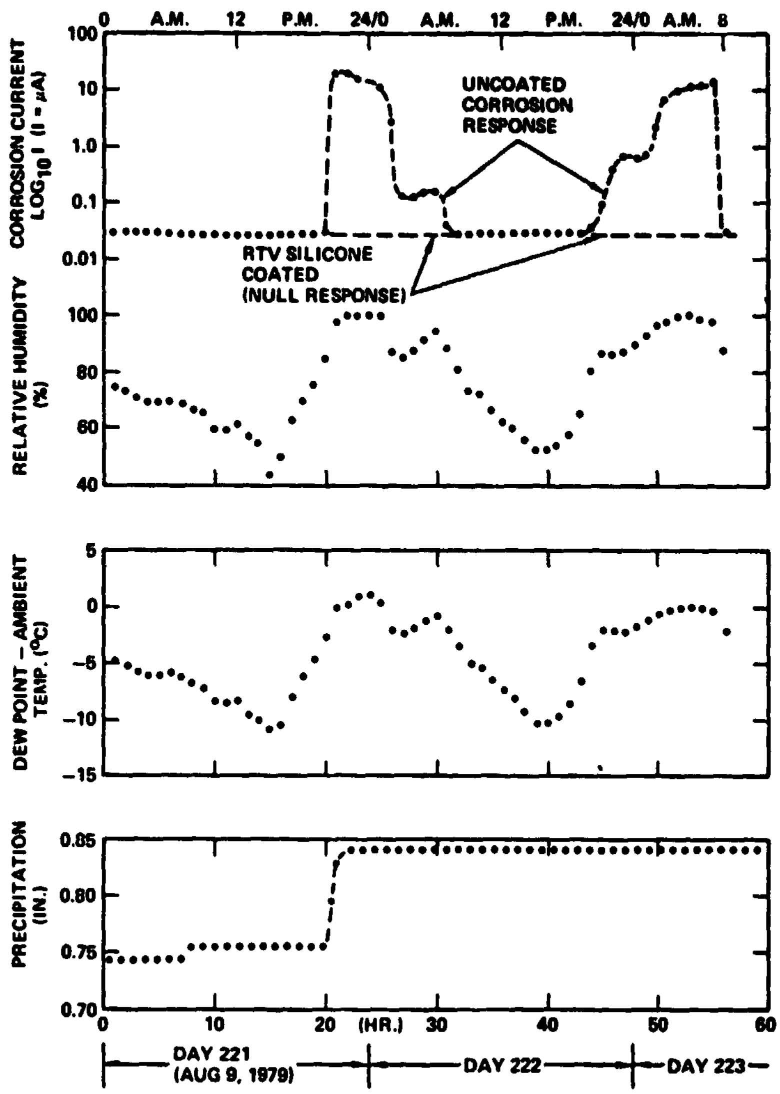



Dark Reverse I-V
#300
a-T=55 C
b-T=28 C
a
b
REVERSE CURRENT (mA)
5.0
4.0
3.0
2.0
1.0
0.0
0
8
16
24
32
40
REVERSE VOLTAGE (VOLTS)

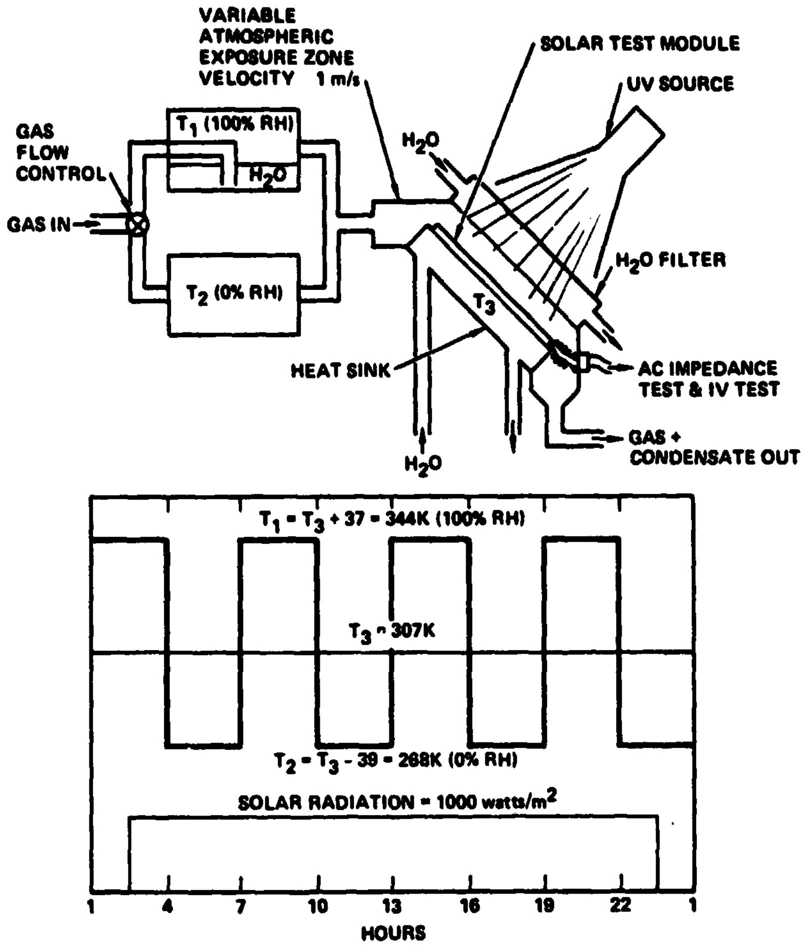
INTERFACE & SURFACE MECHANISMS

ROCKWELL SCIENCE CENTER

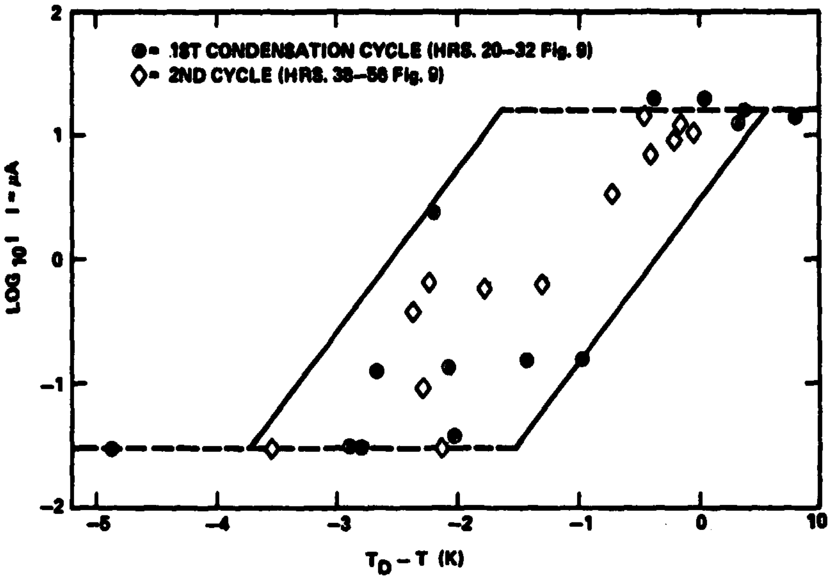
Atmospheric Corrosion Monitor Data From Mead NB Array



Laboratory Simulation Of Accelerated Corrosion Environment



Corrosion Monitor Current vs Dewpoint Minus Ambient Temperature



TECHNOLOGY DEVELOPMENT AREA

Large-Area Silicon Sheet Task

TECHNOLOGY SESSION **J. Liu, Chairman**

AGENDA

Characterization of Silicon Sheet	Cornell University
Low-Angle Silicon Sheet	Energy Materials Corp.
HEM	Crystal Systems, Inc.
SOC	Honeywell Corp.
EFG	Mobil Tyco Corp.
WEB	Westinghouse Electric Corp.
Vacuum Die Casting	ARCO Solar
Oxygen Partial Pressure	University of Missouri Rolla
Cell Fabrication	Applied Solar Energy Corp.
Cell Fabrication	Spectrolab

Cornell University

Large-grain EFG and web material was investigated by optical microscopy, X-ray, EBIC, TEM and HVTEM (high-voltage transmission electron microscopy). Results obtained to date:

Large-grain EFG: The defect structure of this material is similar to that of small-grain EFG, i.e., the predominant defects are coherent twins and microtwins, incoherent twins on 112 planes, and dislocations. The dislocation distribution is uneven and varies greatly from grain to grain. No precipitates were found during TEM studies although a search was made in view of the eutectic theory of large-grain EFG. It should be noted that small carbon-related defects may be invisible in the TEM due to lack of strain contrast.

Energy Materials Corp.

Initial experiments demonstrated the utility of a scraper mechanism to stabilize the meniscus under the growing ribbon. Ribbons were grown up to 68 cm long and 2.5 cm wide with thickness ranging from 0.06 to 0.25 cm. Growth rates up to 70 cm/min have been achieved easily. The present ribbon length limitations are the length of the puller mechanism and/or decrease in melt level.

Crystal Systems, Inc. (HEM)

Two significant developments toward reducing costs have been achieved. A 10-kg ingot was cast using flat plates welded to form a crucible that gave the ingot a perfectly square cross-section. The ingot measures 17 x 17 x 14.6 cm, and has no bulges or crucible attachment. Slagging experiments during directional solidification with low-cost UMG melt stock have improved the structure of cast ingots of UMG Silicon.

Honeywell Corp.

Variation in substrate doping, diffusion time, diffusion temperature and layer thickness have not led to significant changes in cell efficiency. The best efficiencies have been obtained with material grown at 0.06 cm/sec (230 μm thick) with a base doping concentration of $5 \times 10^{16}/cm^3$ and a PH_3 diffusion at 850°C for 60 min. The average efficiency is just over 9% with the best cells measuring 10%, which is short of the efficiency goal of 11%. The basic limitiation is I_{sc}, which decreases as doping increases. Early studies of hydrogen passivation with a hydrogen plasma (at Sandia Labs) shows that recombination of grain boundaries is reduced by a factor of three.

Mobil Tyco Solar Energy Corp.

In a single-ribbon growth unit, 10-cm-wide ribbon of a thickness between 150 and 200 m has been grown repeatedly at speeds of 3.8-4.2 cm/min. Multiple growth of three 10-cm-wide ribbons under continuous melt replenishment has been demonstrated over six hours. The speed at which stable growth occured was restricted to 2.8 cm/min due to edge instabilities, which require further investigation. Efficiencies of 5 x 10-cm^2 cells from 10-cm-wide ribbons have been around 9.5%, but 12.5% (AM1) has been reached for a 2.5 x 5-cm^2 cell from a 5-cm-wide ribbon.

Westinghouse Electric Corp.

Simultaneous melt replenishment and web growth has been demonstrated for periods up to one day of growth cycle, which includes 17 h of web growth and 7 h of non-growth time. Melt-level sensing provides a visual (meter) output and permits manual control of the polysilicon feed rate. An economic analysis of dendrite utilization indicated that there is less than $0.01/$W_p$ difference in cost between salvaging dendrites and discarding them.

Web: the defects in this material (dendrites excluded) are a coherent twin boundary in the midplane of the ribbon and dislocations. EBIC shows that the twin boundary is not electrically active but it appears to act as a dislocation source. The dislocation density drops from $5 \times 10^5/cm^2$ in the center to $10^4/cm^2$ near the dendrites.

ARCO Solar, Inc.

The vacuum aspect of this program has been replaced by a casting technique at atmospheric pressure in which sheets are formed by pressing a liquid drop of silicon in a two-piece die. Die materials of high-density graphite coated with a fused barrier layer of $NaF-Na_2SiO_3$ have been selected. Difficulties encountered with the process are (1) incomplete filling of the die, (2) surface crazing of the sheets and (3) bulk cracking. Incomplete filling of the die seems to involve both the reaction of silicon with NaF and die symmetry. Surface crazing is due to differential contraction between the fused salts and the silicon during cooling. Bulk cracking appears to be associated with the expansion of silicon as it solidifies.

University of Missouri Rolla

During this period the interaction of molten silicon with various substrates, including hot pressed silicon nitride, sialon, silicon carbide-coated graphite and CVD silicon nitride on hot pressed silicon nitride, was investigated. The behavior was similar to that of CNTD silicon nitride, but anomalous results were found with the sialon substrates and the silicon carbide on graphite. The thoria-yttria oxygen cell has been modified to provide a better seal against possible leaks when operating at slight negative pressures.

Applied Solar Energy Corp.

Four sheets, EFG (RH) multi-ribbon, dendritic web, SOC and HEM, were processed and evaluated. A 9% AMO efficient cell was fabricated on the EFG material. Slight improvement in I_{sc} was seen in EFG ribbon after a surface treatment but there was no significent change when a phosphorus-glass gettering step was added. A 14.2% AMO cell as fabricated on dendritic web by using a shallow junction (SJ), back-surface field (BSF), back-surface reflector (BSR) and a multi-layer AR (MLAR) coating of Al_2O_3 and TiO_2. The best cell reported on SOC material was 9% AMO on a $17cm^2$ area. HEM material of 0.5-1.5 Ω-cm, showed no significant difference between cells fabricated on single-crystal silicon and cells fabricated on polycrystalline silicon with 5-to-10-mm grains.

Ion microprobe/SIMS analysis suggested that junction shunting was caused by aluminum contamination in the form of alloy penetration pits.

Spectrolab, Inc.

Data was presented on solar cells made from EFG, HEM, web and Hamco silicon. A standard baseline process was used for EFG and web while the HEM and Hamco materials were subjected to a phosphorus gettering step before cell fabrication. A conversion factor for AMO to AM1 efficiencies was found to be approximately 1.18. The major problem encountered during this period was shunting of the junction during screen printing of the Ag contacts.

CHARACTERIZATION OF LARGE-GRAIN EFG AND OF DENDRITIC WEB SILICON

CORNELL UNIVERSITY

D.E. Ast

EFG ◆ TEM (100 KeV)
HVTEM (1.2 MeV) } CORRELATE
EBIC (10..25KeV) }
(PREVIOUS PIM: ETCHING, X-RAY)

WEB ◆ ETCHING } CORRELATE
TEM (100 KeV) }
EBIC }
X-RAY

Large-Grain EFG

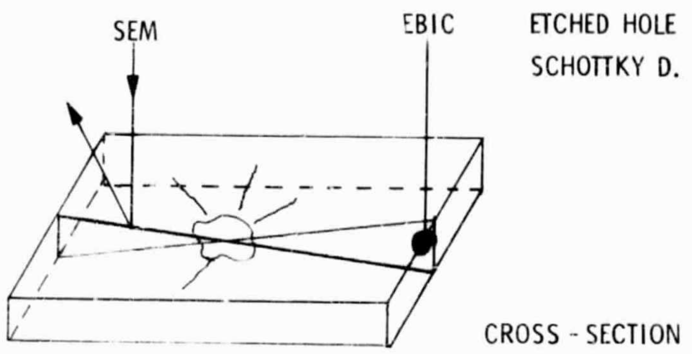
- TEM

  BASICALLY IDENTICAL TO SMALL-GRAIN EFG; i.e., PREDOMINANT DEFECTS ARE COHERENT TWIN BOUNDARIES, MICROTWINS, INCOHERENT TWINS ON (112) PLANES (DISLOCATION DENSITY VARIES GREATLY FROM GRAIN TO GRAIN).
  NO EVIDENCE FOR SMALL PRECIPITATES

- HVTEM + EBIC
  ◆ AIM IS TO STUDY ELECTRICAL ACTIVITY OF COHERENT TWIN BOUNDARIES. ELECTRICAL ACTIVITY OF THESE DEFECTS VARIES WIDELY

  ◆ APPROACH IS EBIC, FOLLOWED BY TEM. SINCE EBIC REQUIRES A MINIMUM SPECIMEN THICKNESS OF ~ 2 TO 4 μm, TEM MUST BE CARRIED OUT AT ABOUT 1 MeV

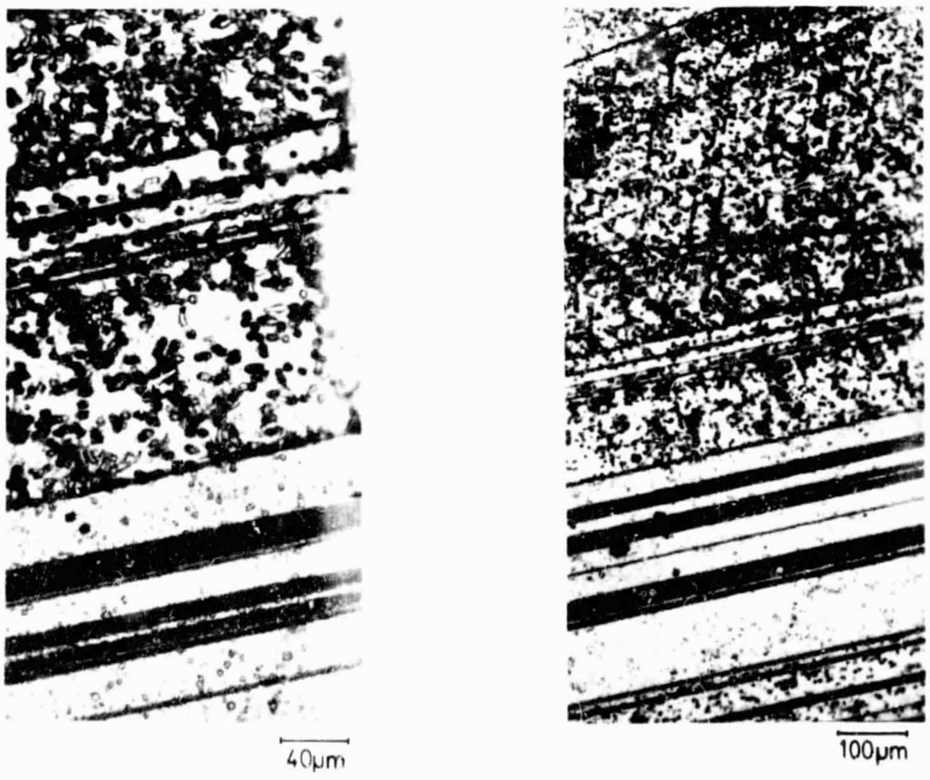
Experimental Arrangement

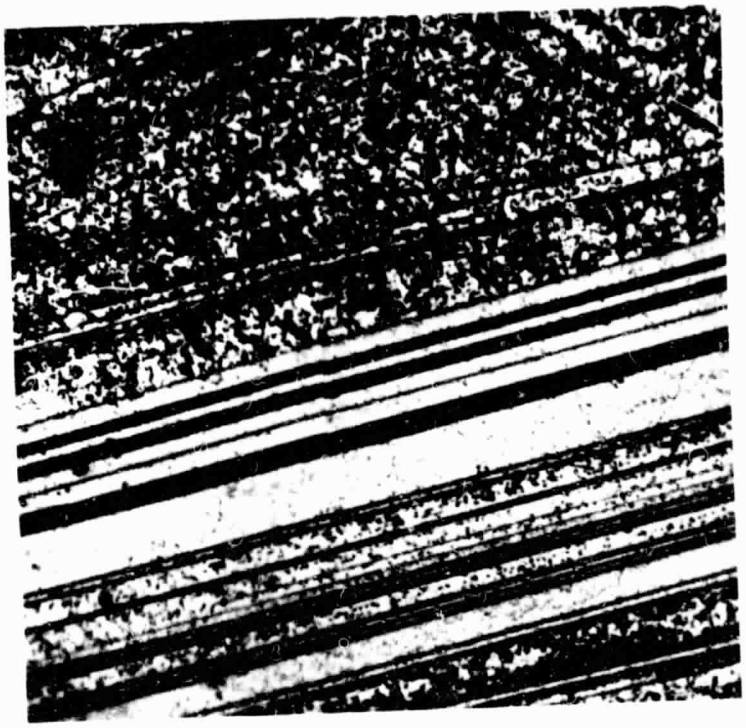


EBIC SIGNAL WILL FADE AS SPECIMEN THICKNESS FALLS BELOW $\sim 2\,\mu m$. HENCE AREA IN VICINITY OF HOLE WILL NOT BE IMAGED

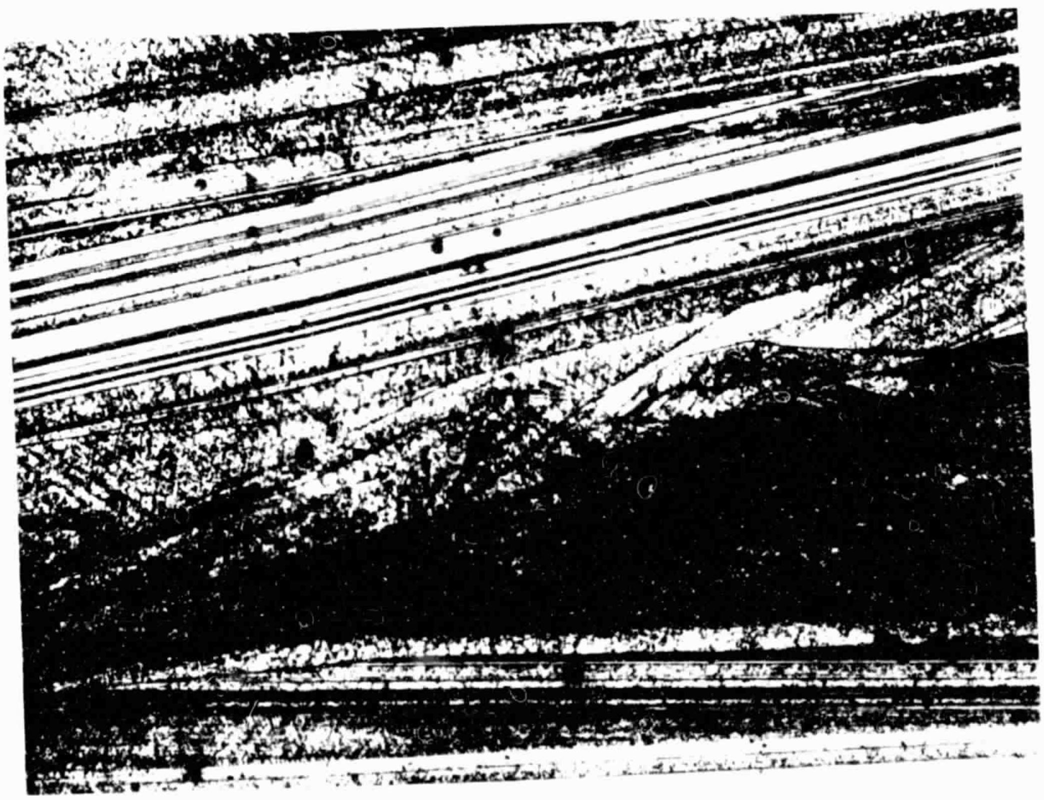
SEM SECONDARY ELECTRONS WILL OUTLINE HOLE CONTOUR

Etched EFG Silicon Ribbon



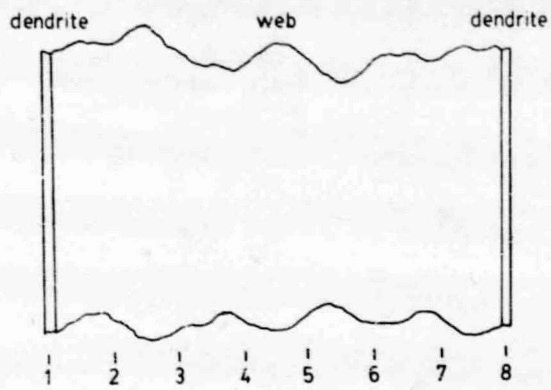


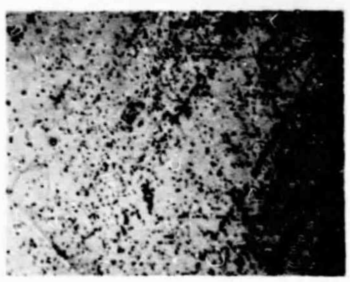
200μm



400μm

Dislocation Etch Pits in Dendritic Web Silicon

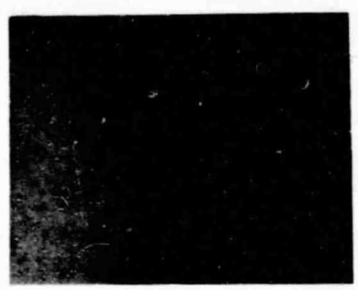




3

4

7



8

Dislocation etch pits in web-dendritic silicon

B Cunningham / D G Ast

Web

TEM - DISLOCATIONS, OTHERWISE FEATURELESS

X-RAY - COHERENT TWIN BETWEEN FRONT/BACK SURFACE

ETCHING -

- DISLOCATION DISTRIBUTION ACROSS RIBBON
- INFLUENCE OF DISLOCATION ON MINORITY CARRIER LIFETIME (FROM C. M. MELLIAR - SMITH, TREAT. ON MAT. SCI. & TED., VOL. 11, ACAD. PRESS, 1977, p. 57)

➧ ORIGIN OF BELL-SHAPED DISTRIBUTION PROB. RELATED TO 'BUCKLING'

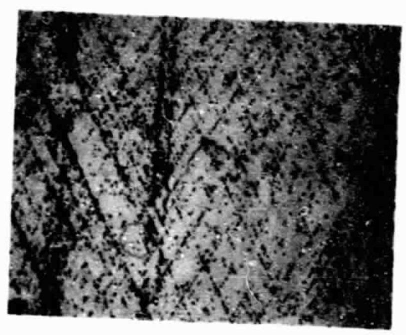
➧ REDUCTION BY 1 ORDER OF MAGN. LIKELY TO INCREASE M. C. L. T.

Dislocation Etch Pits in Dendritic Web Silicon

1

400μm

2



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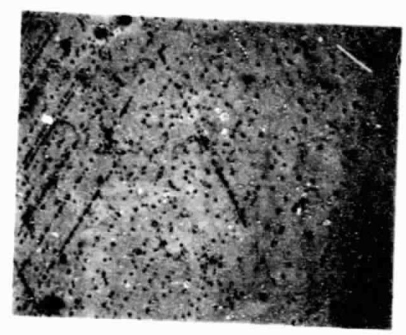

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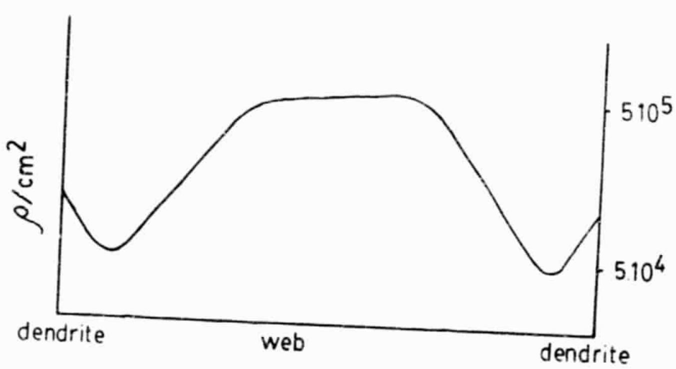
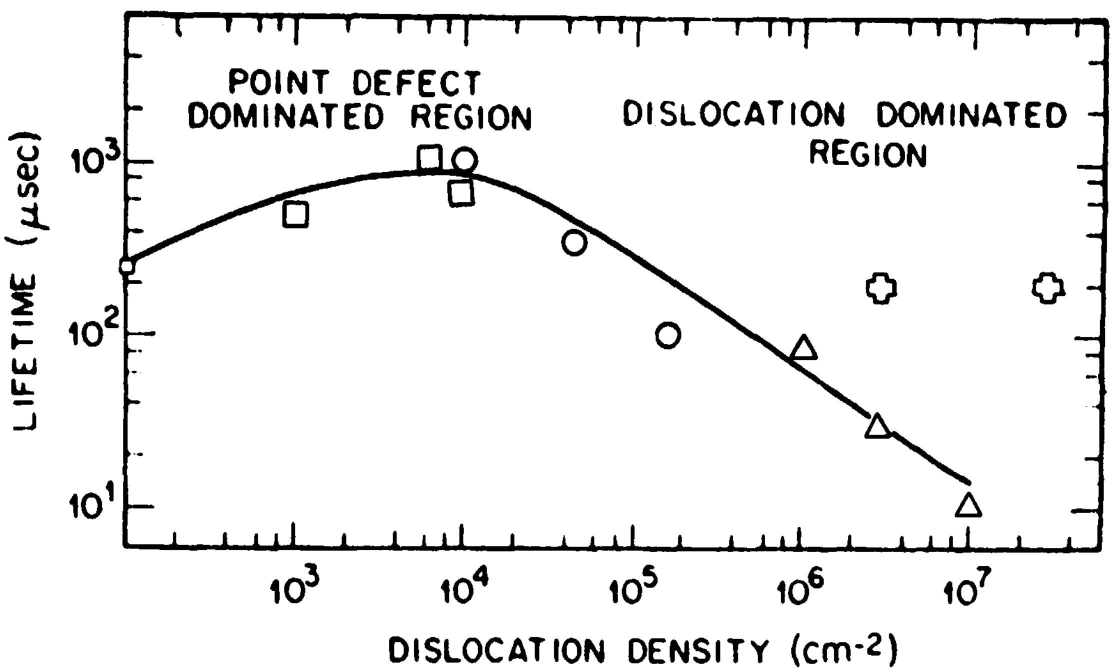


Minority Carrier Lifetime



Minority carrier lifetime as a function of dislocation densitv (○, from Lemke, 1965; □, from Noack, 1969; △, from Kurtz et al., 1956; ⬡, from Glaenzer and Jordan, 1969a)

EBIC on Web Material

HVTEM REQUIRES TRANSFER (TO HVTEM) BUT NO FURTHER MANIPULATION

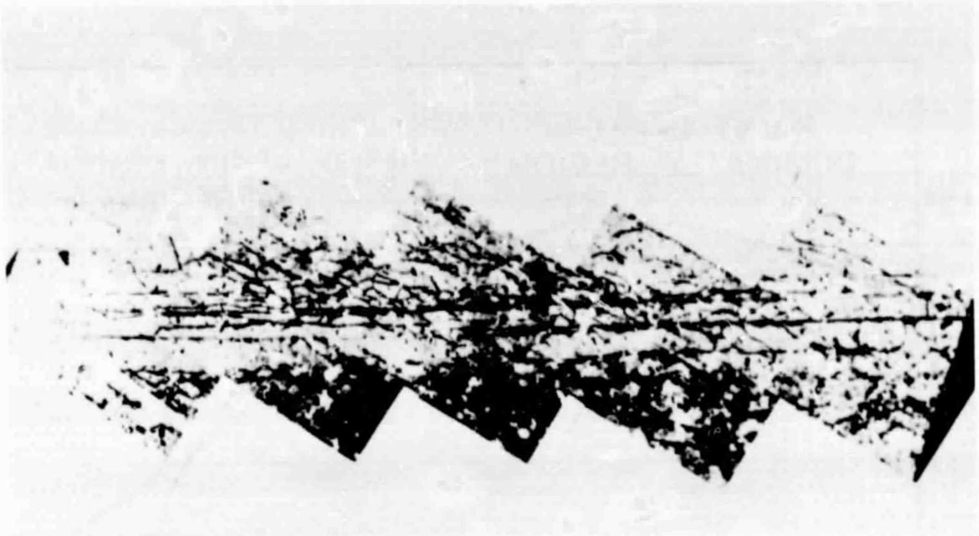
- SLIDE, MICROTWIN
- SLIDE, CORRELATION WITH EBIC

- INITIAL AIM IS TO STUDY ELECTRICAL ACTIVITY OF INTRINSIC g.b. DISLOCATIONS (Σ : 3 - Sh. PARTIALS) AND TO TRY TO RELATE KINK DENSITY TO ELECTR. ACTIVITY (AVOIDS PROBLEM OF DISSOCIATION OF COMPLETE DISLOCATIONS WHICH IS KNOWN TO CONTROL ELEC. ACTIV)

- POINT DEFECTS ....PLANAR DEFECT INTERACTION

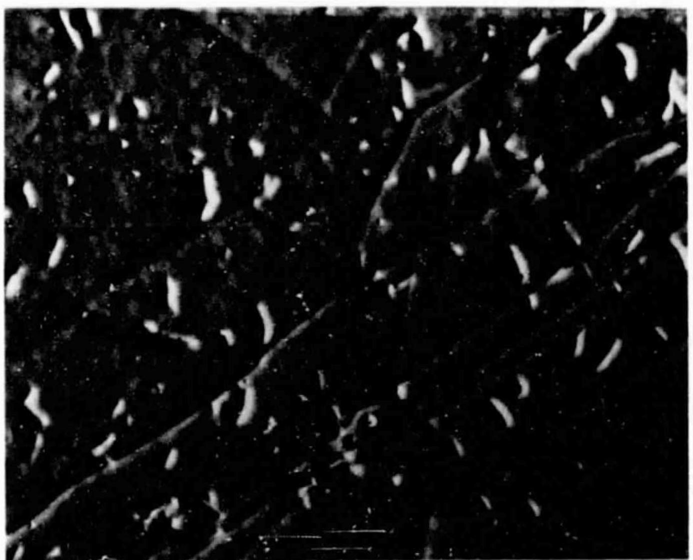
INFLUENCE OF PROCESSING ON DEFECT POPULATION

Web, EBIC



EBIC

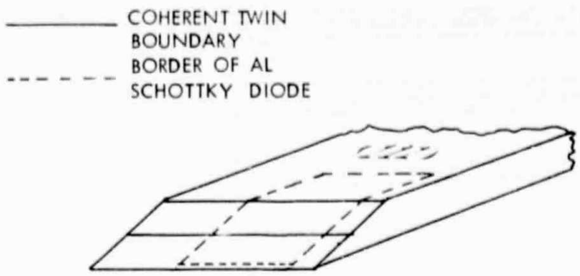
21 kV



20 μm

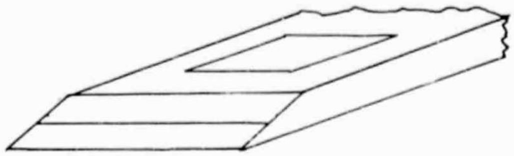
Fracture line

(A)



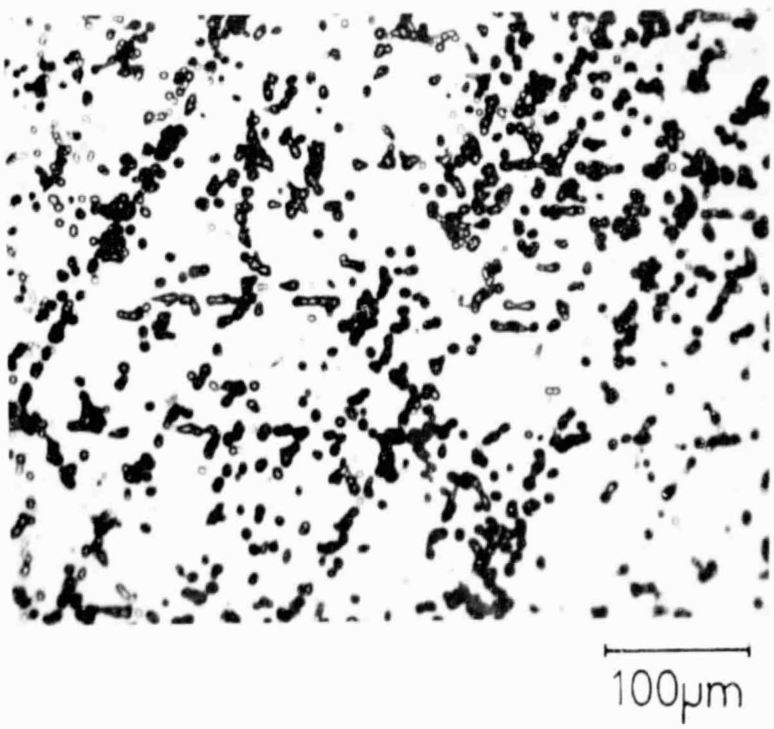
- EBIC SHOWS THAT TWIN BOUNDARY NOT ELECTRICALLY ACTIVE
- TWIN BOUNDARY APPEARS TO ACT AS DISLOCATION SOURCE

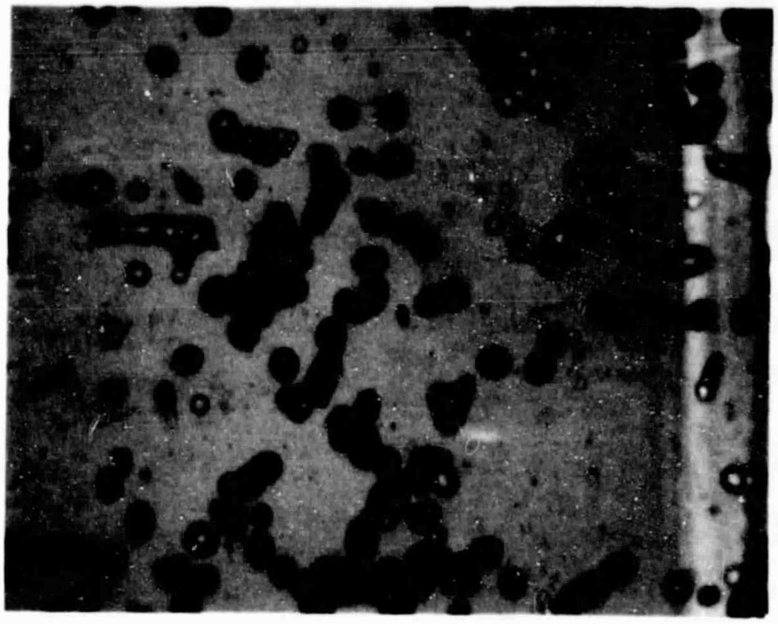
(B)



- OCCASIONAL BUNDLE OF DISLOCATIONS
  PREFERRED SITES FOR FRACTURE

Etch Pits in Dendritic Web Silicon





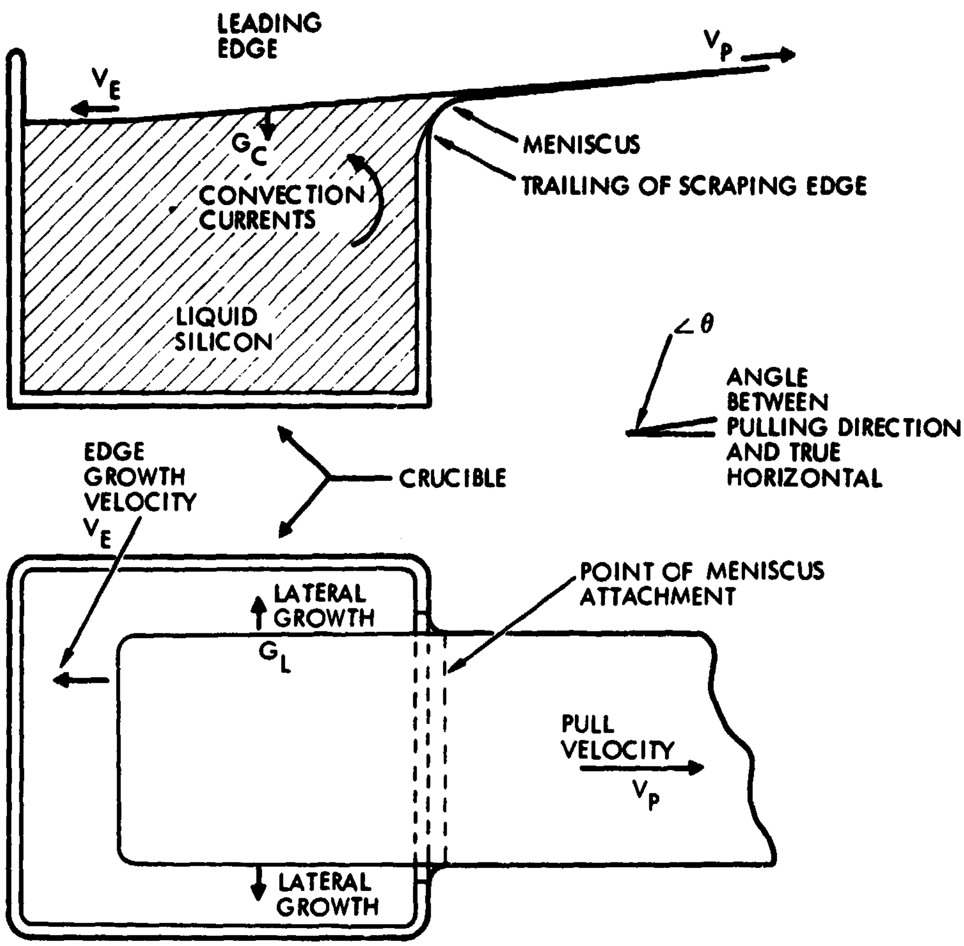
40um

PRODUCTION OF LOW-COST SILICON SHEET

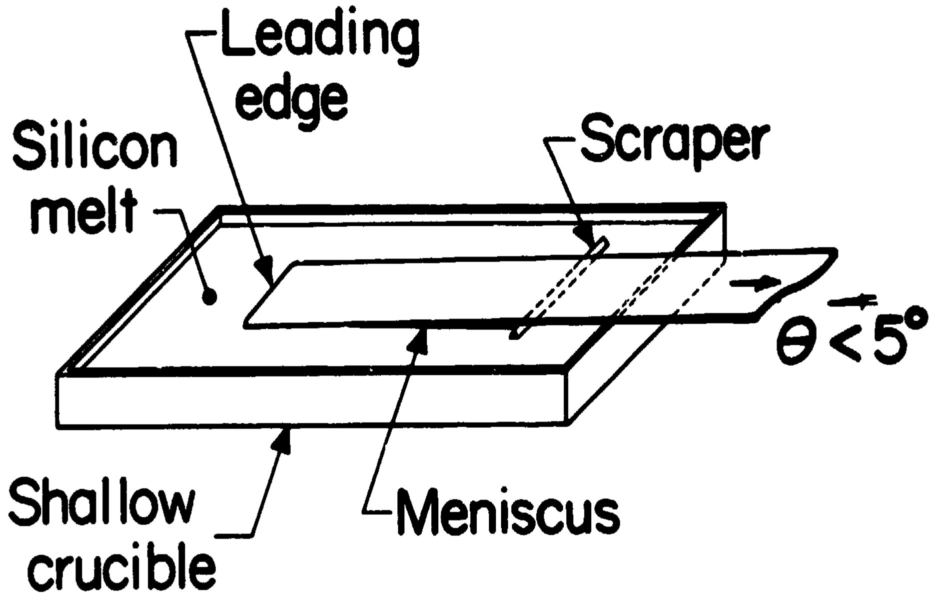
ENERGY MATERIALS CORP.

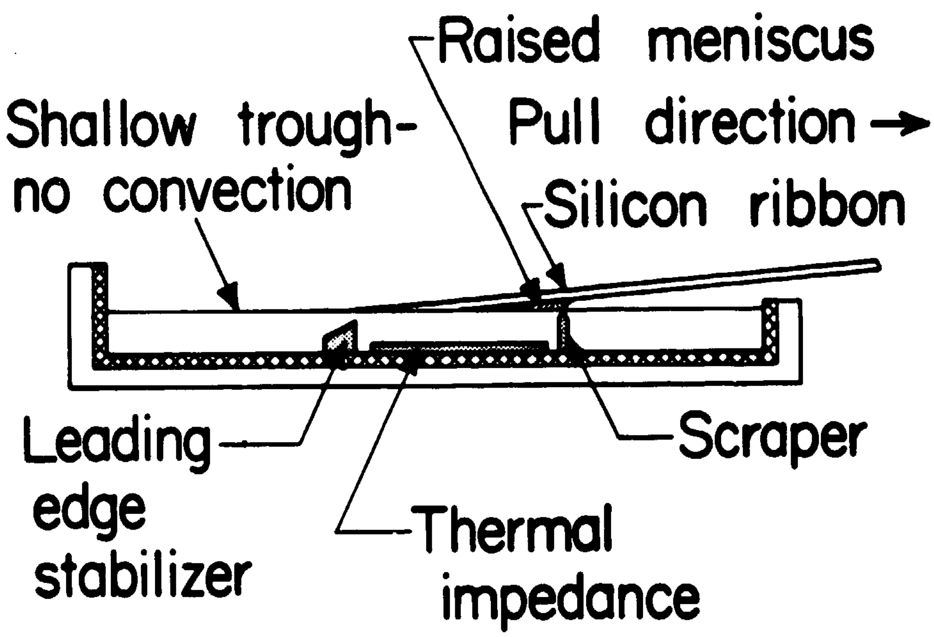
TECHNOLOGY PRODUCTION OF LOW COST SILICON SHEET	**REPORT DATE** APRIL 3 1980
APPROACH LOW ANGLE SHEET GROWTH FROM MELT SURFACE - CONTROL OF GROWTH PROCESSES BY THERMAL IMPEDANCES **CONTRACTOR** ENERGY MATERIALS CORPORATION **GOALS** • DEMONSTRATE PROCESS FEASIBILITY • EVALUATE SCRAPER & THERMAL IMPEDANCE EFFECTS	**STATUS** • FEASIBILITY DEMONSTRATED RATE: 20 ≥60 CM/MIN WIDTH: 2.5 CM THICKNESS: 0.3 - 1 MM LENGTH: TO 75 CM (MELT LEVEL & PULLER LIMITATIONS)

Horizontal Crystal Growth



HORIZONTAL CRYSTAL GROWTH
SCHEMATIC DIAGRAM


Leading edge
Silicon melt
Scraper
$\theta < 5°$
Shallow crucible
Meniscus


Raised meniscus
Shallow trough-no convection
Pull direction →
Silicon ribbon
Leading edge stabilizer
Scraper
Thermal impedance

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Low-Angle Si Sheet Growth: Projected Advantages

- HIGH LINEAR GROWTH RATE
- HIGH PRODUCTIVITY
- SEPARATION OF CONTROL ELEMENTS
- LOW BULK GROWTH RATE
- PURIFICATION BY IMPURITY REJECTION
- HIGH CRYSTAL QUALITY

Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS: 5 CM WIDTH x 25 CM/ MIN - 10 RIBBONS/MACHINE/OPERATOR - 3 SHIFT/6 DAY WEEK - LABOR RATE: $8/HR - OVERHEAD: 100% - SET UP COSTS: $50,000/YR - UTILITIES: $75,000/YR - DEPRECIATION: $40,000/YR (5 YR. S.L.)

PROJECTION

PRODUCTIVITY: $10 \times 5 \times 25 \times 60 \times 7200 \times .75 \times 10^{-4} = 40{,}500$ M^2/YR.

PRODUCTION COST: $280,000 (NO POLY COST)

ADD-ON COST: $6.90/$M^2$

TOTAL SHEET COST: $18.70/$M^2$ ($10/KG;15 MIL)

Problems and Concerns

- MELT LEVEL CONTROL
- MELT REPLENISHMENT
- GUIDANCE

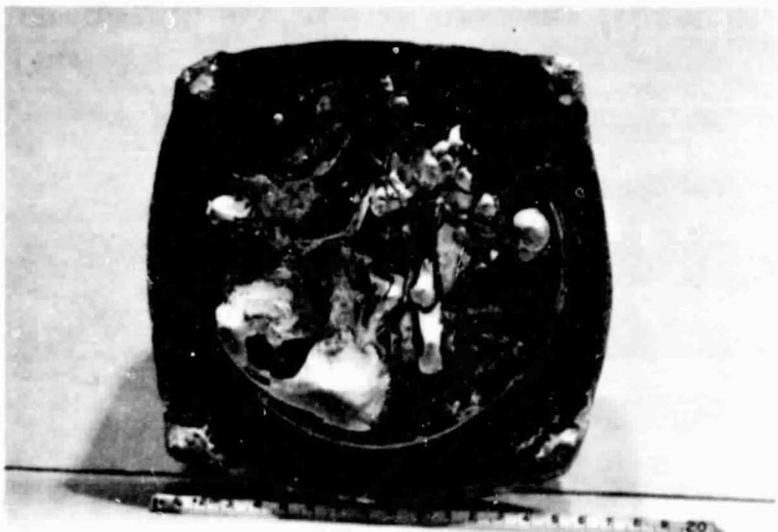
SILICON INGOT CASTING: HEAT EXCHANGER METHOD (HEM)

CRYSTAL SYSTEMS, INC.

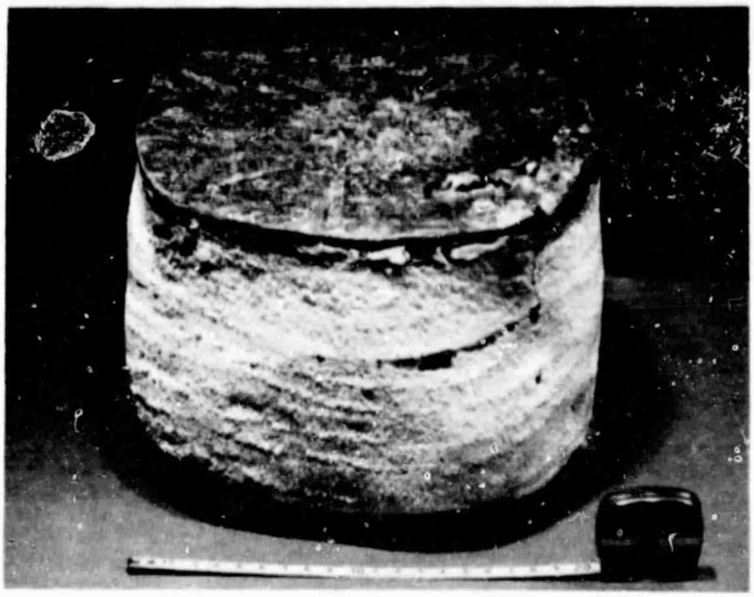
F. Schmid and C.P. Khattak

5-kg Ingot Solidified in Crucible Fabricated From Flat Plates

Same Ingot After Removal of Crucible

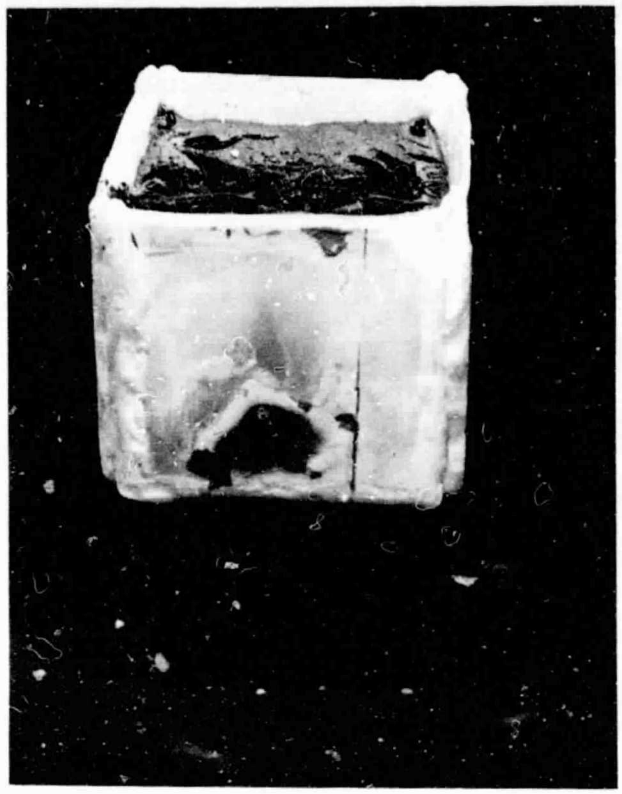


20-cm Cube Ingot Solidified in New Furnace

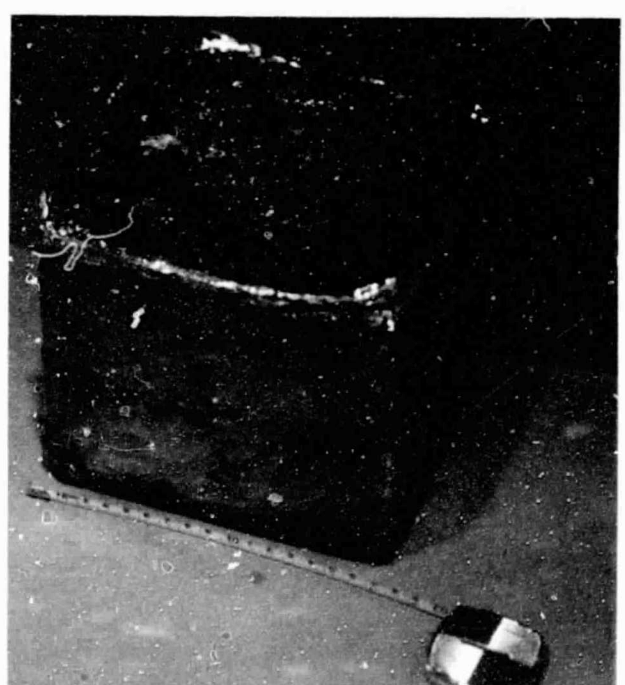


Structure of Upgraded Metallurgical Si Meltstock After Slagging during HEM Solidification

17-cm Cube (10 kg) Solidified in Crucible Fabricated from 20 x 20-cm Flat Plates



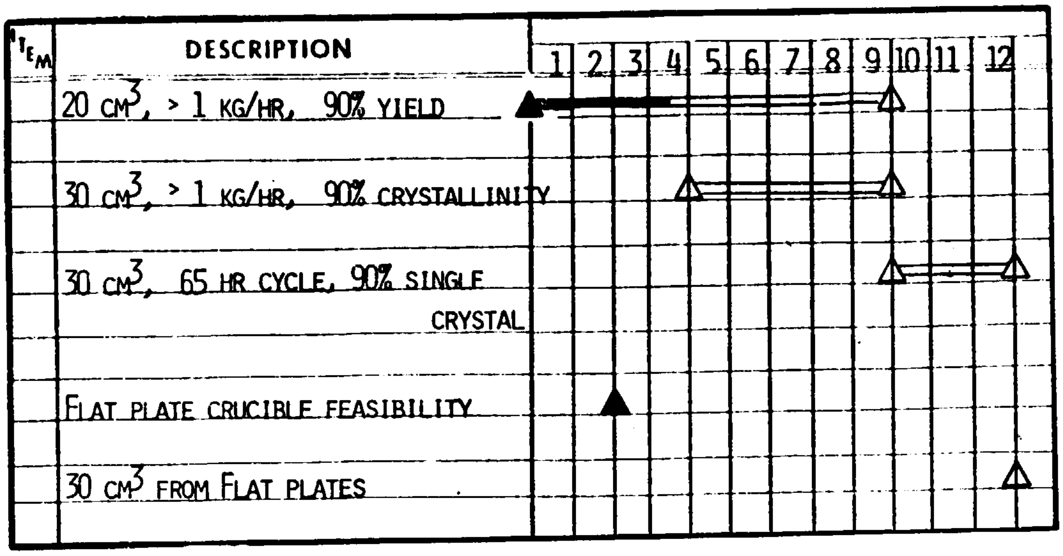
Same Ingot After Removal of Crucible



New HEM Furnace for Solidifying 30-cm Cube Ingots

Significant Developments

- FEASIBILITY OF USING CRUCIBLES FABRICATED FROM FLAT PLATES ESTABLISHED
- SOLIDIFIED INGOTS WITH SQUARE CORNERS
- DEMONSTRATION OF MELTSTOCK LOADING TO USE SHORTER CRUCIBLES
- DEMONSTRATION OF 12.5% EFFICIENCY SOLAR CELLS USING UMG MELTSTOCK



SILICON-ON-CERAMIC PROCESS

HONEYWELL CORP.

Dear Sir,

Once a year Guildford Grammar School of W.A has a solar energy prize.

I heard that you can produce a solar cell at only 50¢ a watt, and I wondered if you could send me 5 watts worth please.

I will send the amount of money spent on postage and the cost of 5 watts as soon as possible.

Please send me details on any other ways of making solar energy.

Yours Faithfully
Martin Oldfield
(aged 13)

Approaches

ORIGINAL APPROACH: DIP-COATING

CONTINUOUS APPROACH: SCIM-COATING
TWO 12.5 x 100 cm
MULLITE-BASED SUBSTRATES

Goals and Achievements

REPORT DATE 4/3/80

APPROACH

SCIM-COATED SOC
TWO 12 x 100 cm CERAMIC PANELS

CONTRACTOR

HONEYWELL INC. } DOE
$1658K FUNDING } DOE
10/1/75 - 1/31/80
$550K LBM } HONEYWELL THROUGH '80
$200K CAP. EQ. } HONEYWELL THROUGH '80

GOALS

12 cm WIDE x 100 cm LONG
0.25 cm/sec PULL SPEED
350 cm^2/sec THROUGHPUT
11% CELL EFFICIENCY
9.8% AVERAGE EFFICIENCY
TECHNICAL FEATURES DEMONSTRATION 12/31/80

STATUS

- SCIM-COATING DEMONSTRATED. (5 cm WIDE)
- 0.25 cm/sec DEMONSTRATED (DIPCOATING)
- 10% CELL EFFICIENCY (DIPCOATED)
- 9% AVERAGE EFFICIENCY - 1979 BASELINE CELLS (AR, AM1)

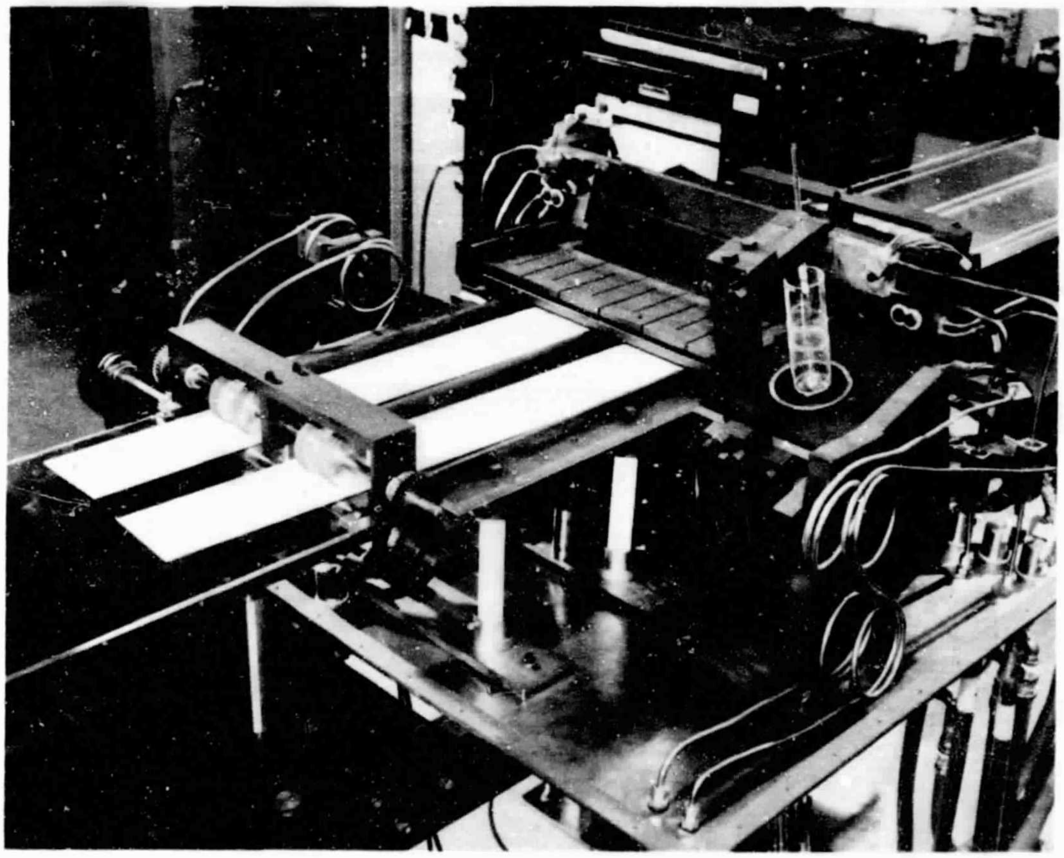
- SCIM-COATED SLOTTED SUBSTRATES*
- SCIM-II READY FOR TEST 3/25/80
- FAST GROWTH MODE WITH OBTUSE ANGLE LSI DEMONSTRATED.

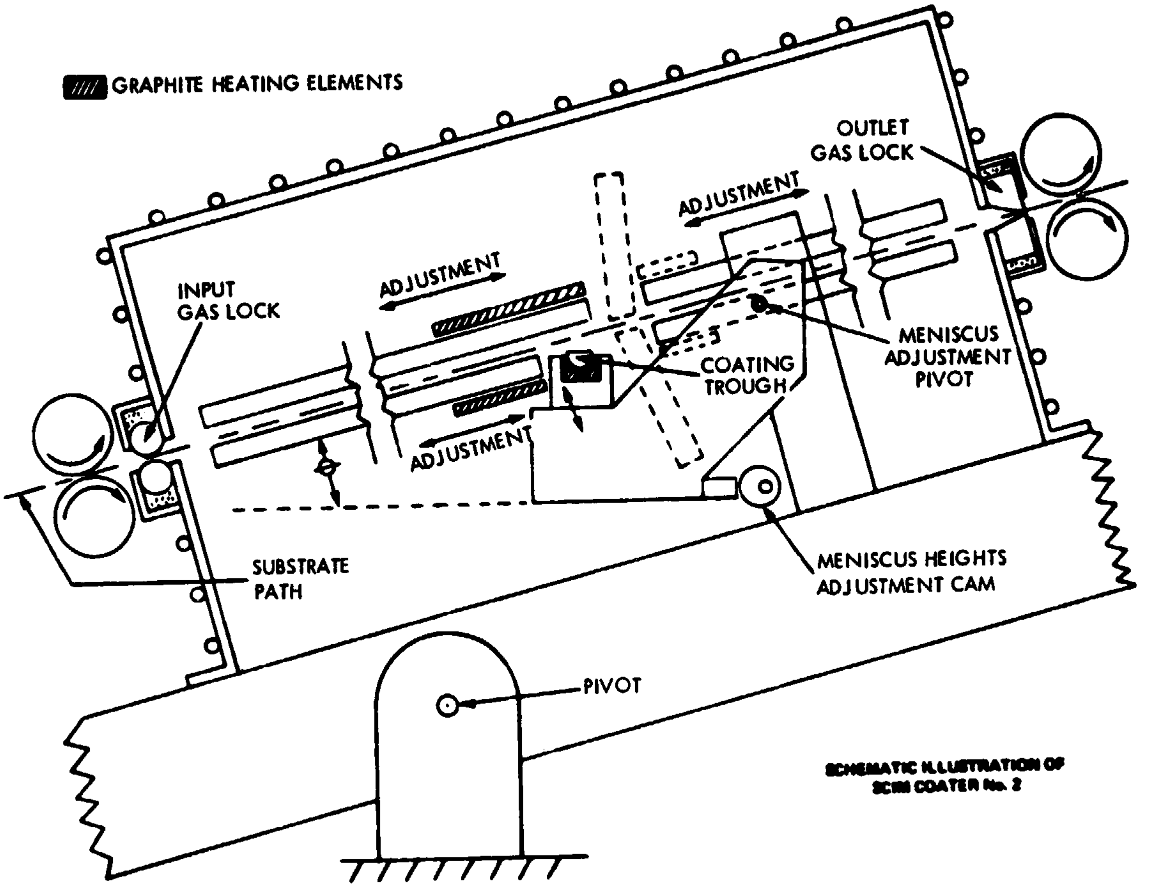
* NEW RESULTS

1979 Goals and Accomplishments

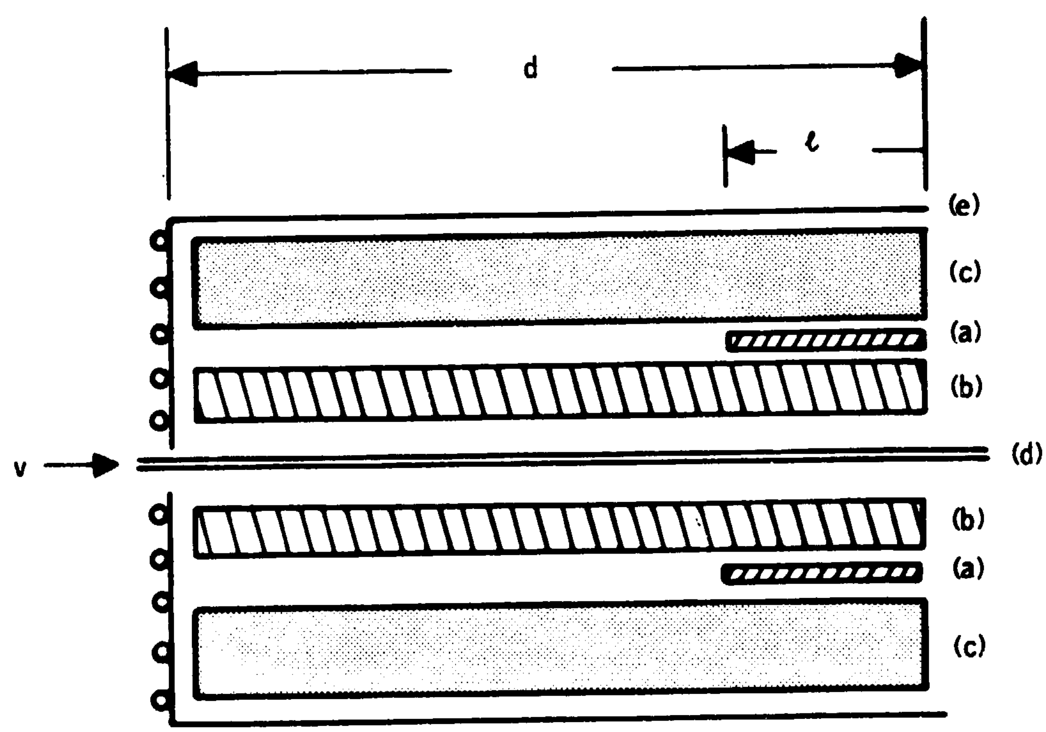
1979 CONTRACT GOALS	1979 ACCOMPLISHMENTS
11% EFFICIENCY, 10 CM^2	10%, 4 CM^2 (AM1, AR) 9.9%, 10 CM^2
OPTIMIZE MATERIAL QUALITY AT HIGH GROWTH SPEEDS 0.2-0.3 CM/SEC.	DEMONSTRATED: 0.25 CM/SEC, $T > 100\ \mu M$
DETERMINE IMPORTANCE OF GRAIN BOUNDARIES VS IMPURITIES	DETERMINED: J_{SC} VS DIP-NUMBER L_N WITHIN GRAINS, AT GRAIN BOUNDARIES

SCIM II Coater

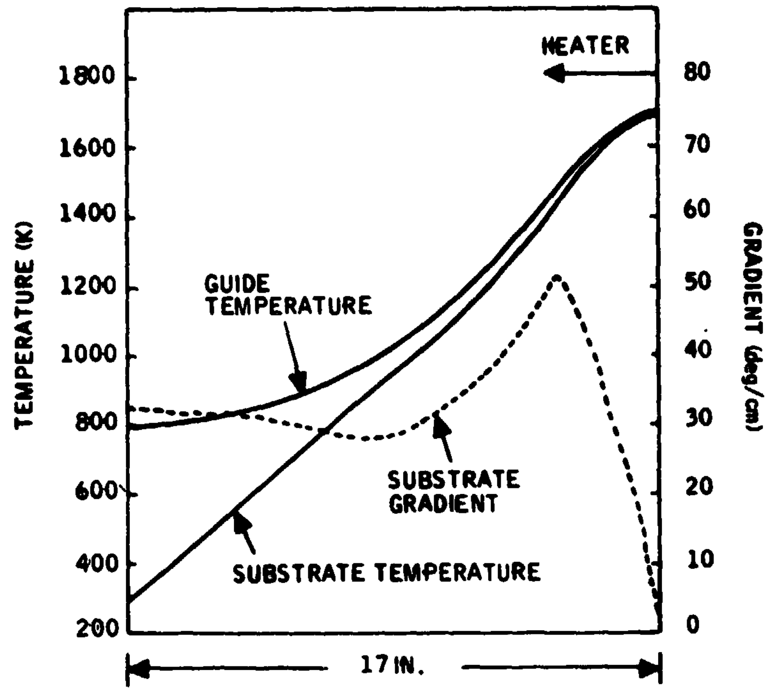




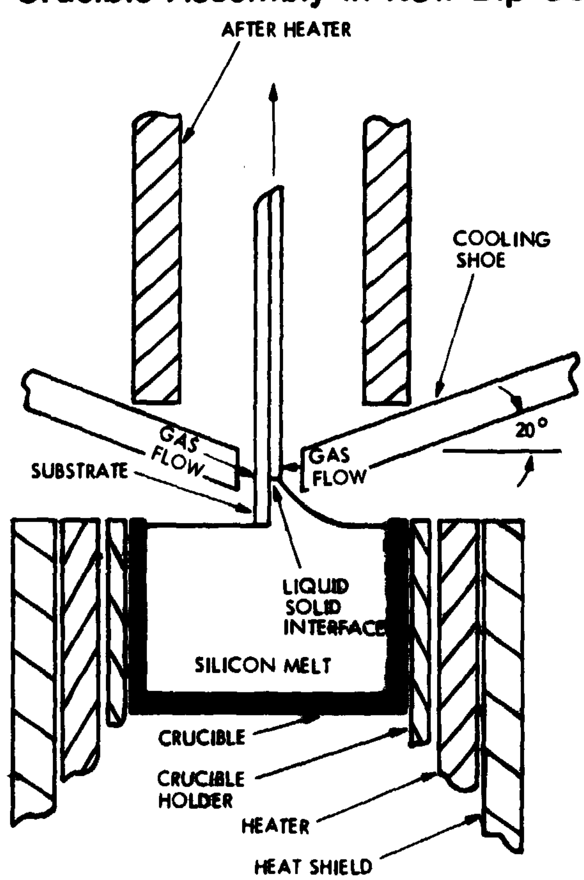
SCIM II Entrance Tunnel



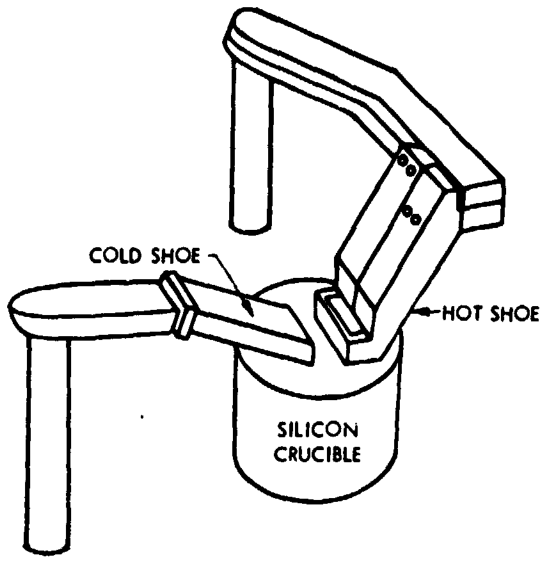
Calculated Temperature Profile



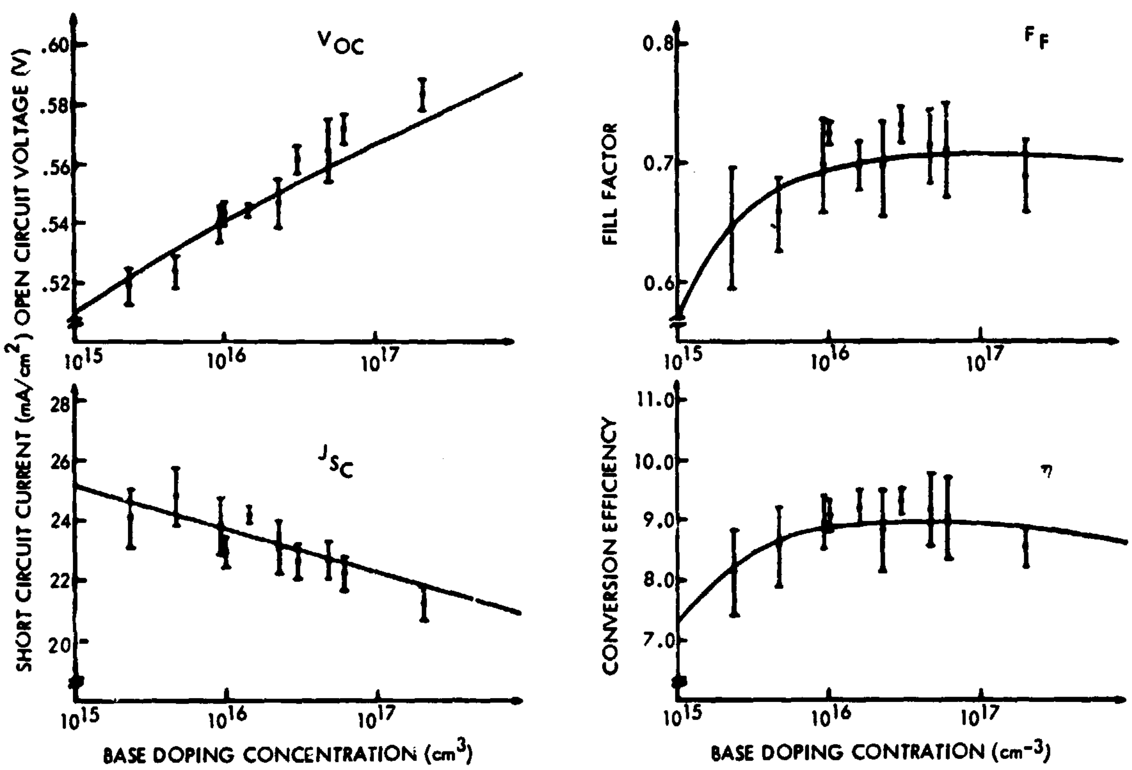
Relationship of Afterheater, Cooling Shoes And Crucible Assembly in New Dip Coater



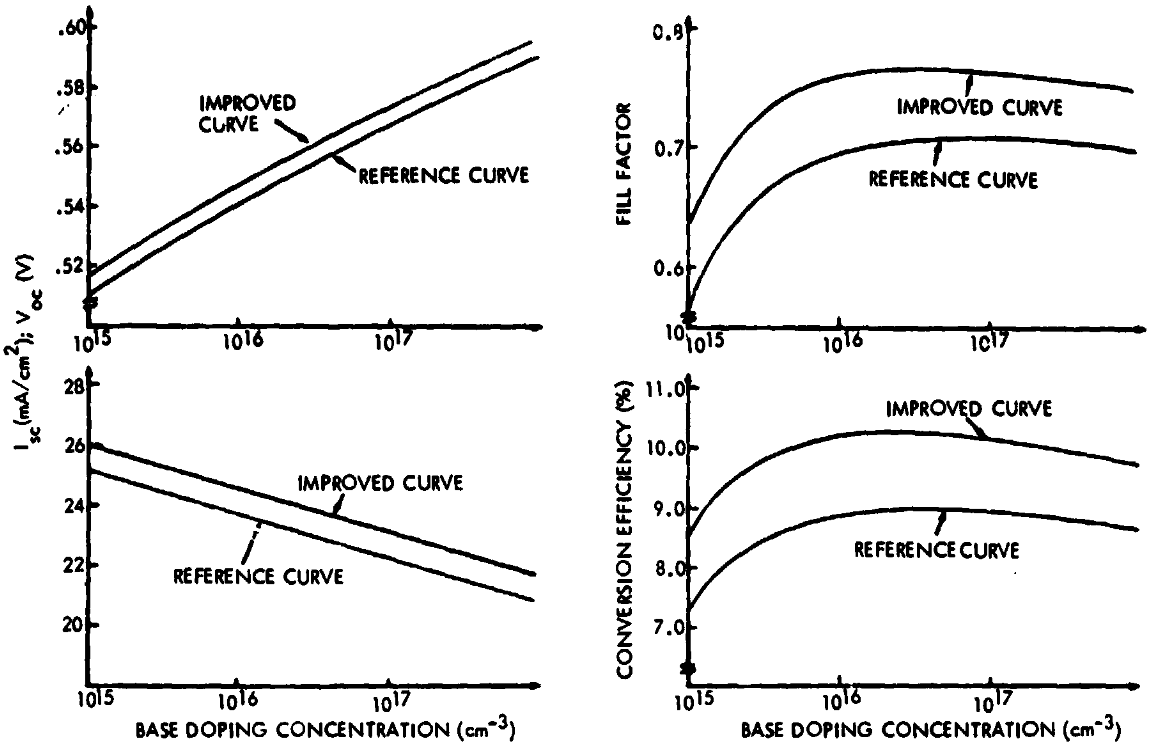
Asymmetric Heat Removal: High-Speed Growth Mode

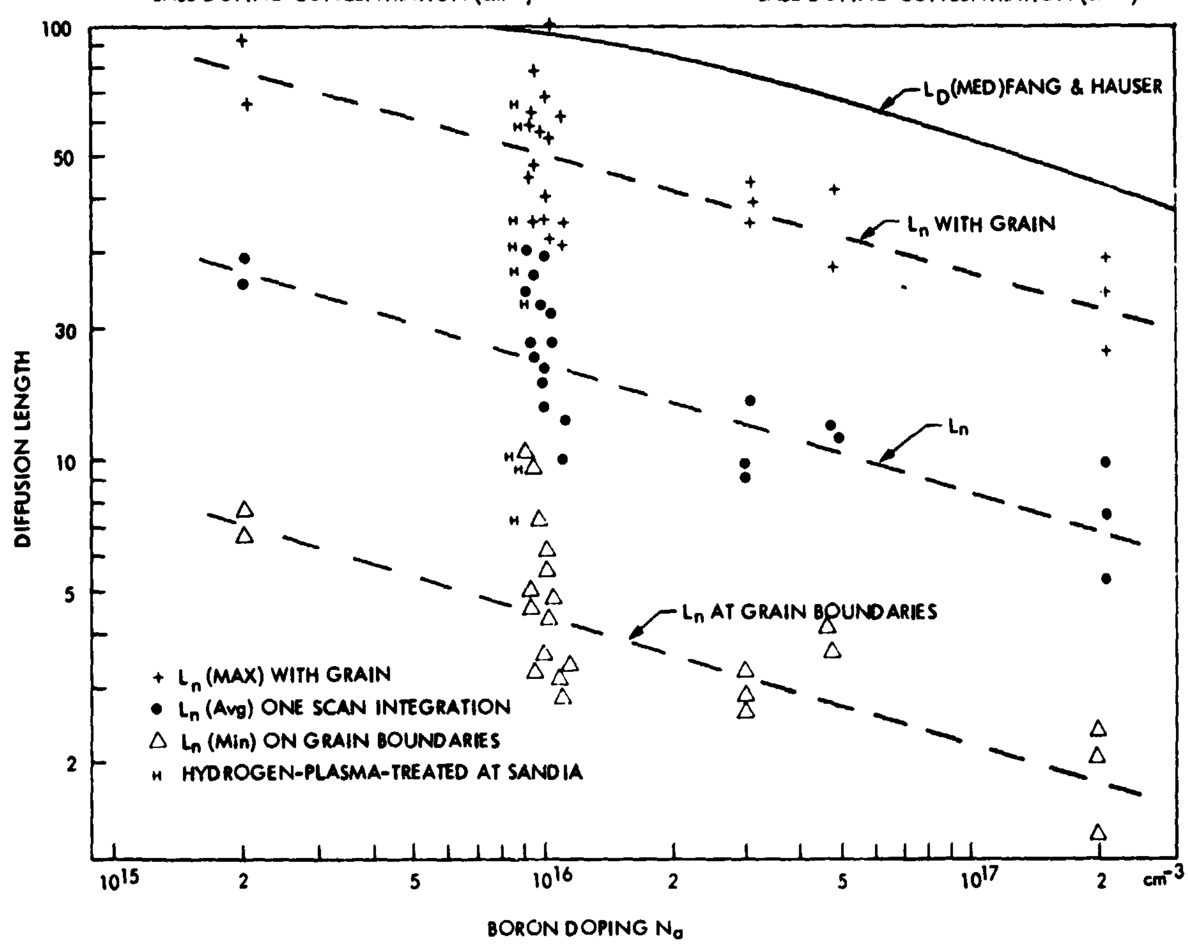


1979 Baseline Cells



Effects of Simultaneous Improvements in J_{01}, R_SA and J_{SC}





TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS:	PROJECTIONS (1980 TECHNOLOGY)
TECHNOLOGY FROZEN 1980	$21.6/M^2$ ADDED VALUE
$3.97/M^2$ CERAMICS COST	$24/M^2$ ADDED VALUE (YIELDED)
$50.800 PER SCIM-COATER	$34/M^2$ TOTAL SHEET (YIELDED)
2 PANELS/SCIM-COATER	
0.06 CM/SEC PULL SPEED	30¢/W_p ADDED VALUE
1 OPERATOR/12 COATERS	42¢/W_p TOTAL SHEET VALUE
85% DUTY CYCLE	
83% YIELD (CERAMIC TO MODULE)	
8 MIL SHEET THICKNESS	
$14/KG SILICON COST	
8% AM1 MODULE EFFICIENCY	

ASSUMPTIONS:	PROJECTIONS:
$3.97/M^2$ CERAMIC COSTS	$10.5/M^2$ ADDED VALUE
$50.800 PER SCIM-COATER	$11.7/M^2$ ADDED VALUE (YIELDED)
2 PANELS/SCIM-COATER	$16.8/M^2$ TOTAL SHEET VALUE (YIELDED)
0.25 CM/SEC PULL SPEED	
1 OPERATOR/12 COATERS	11.7¢/W_p ADDED VALUE (10% MODULE)
85% DUTY CYCLE	16.8¢/W_p TOTAL SHEET VALUE (10% MODULE)
83% YIELD (CERAMIC TO MODULE)	
4 MIL SHEET THICKNESS	13¢/W_p ADDED VALUE (9% MODULE)
$14/KG SILICON COST	19¢/W_p TOTAL SHEET VALUE (9% MODULE)

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Problems and Concerns

- TRANSVERSE TEMPERATURE GRADIENTS
- SUBSTRATE TRANSPORT
- THICKNESS NON-UNIFORMITIES AT FAST SPEEDS
- CELL EFFICIENCY LIMITED BY DIFFUSION LENGTH (L_N)
  - GRAIN BOUNDARIES REDUCE $\overline{L}_N$
  - BORON DOPANT REDUCES L_N
- CONTRACT GOALS WILL BE DIFFICULT TO MEET BY 12/31/80
  - 11% CELL EFFICIENCY
  - 9.8% AVERAGE CELL EFFICIENCY
  - 350 CM^2/MIN THROUGHPUT

LARGE-AREA SILICON SHEET BY EFG

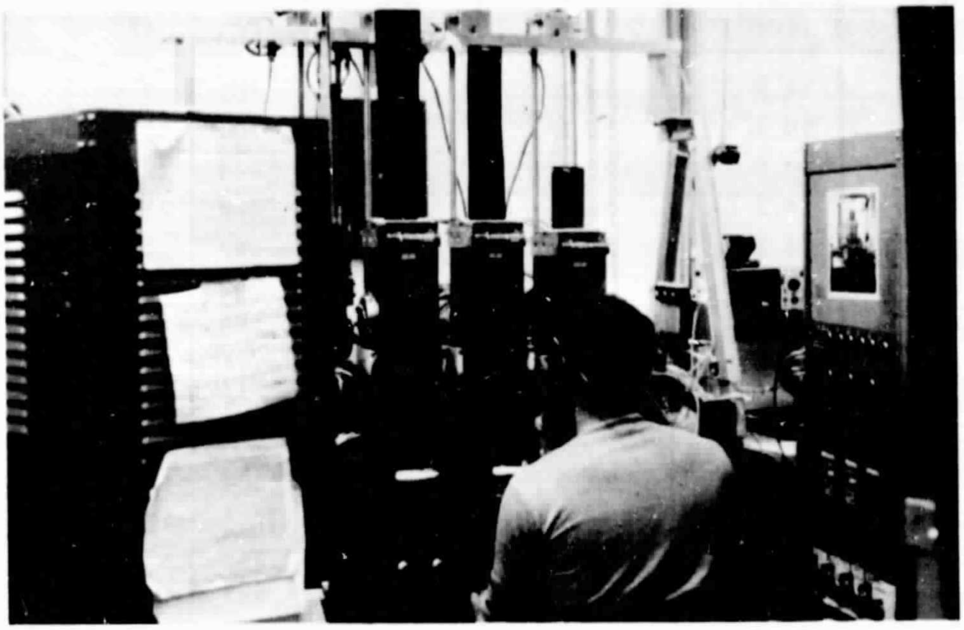
MOBIL TYCO SOLAR ENERGY CORP.

Goals

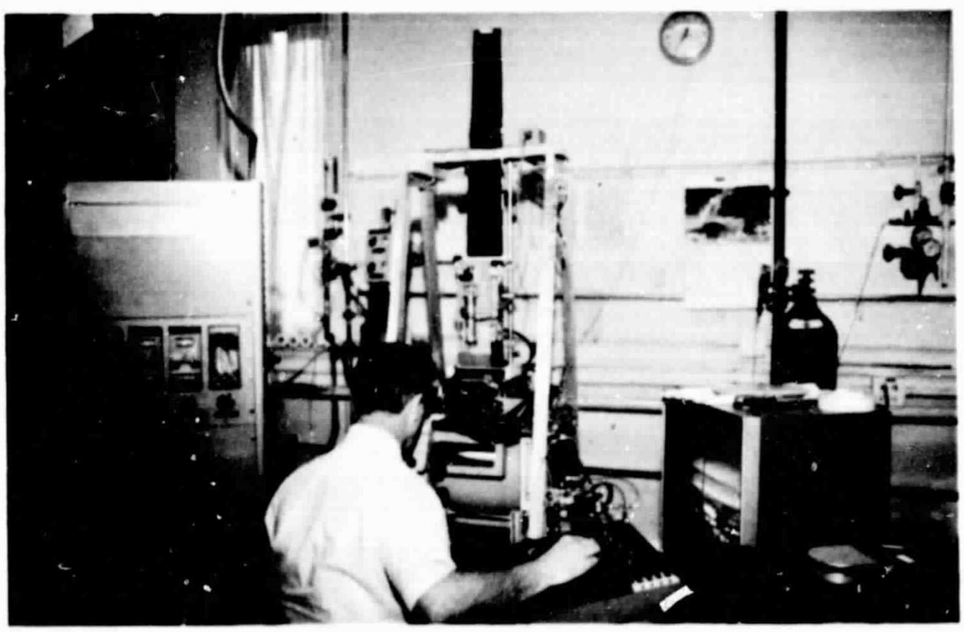
1/1/80

- SMALL CELL DEMONSTRATION; 2 x 2 CM-RH MATERIAL $\geq$ 12% η.
- 10 CM SINGLE CARTRIDGE GROWTH AT 3.5 CM/MINUTE WITH 50 CM^2 CELL $\geq$ 10% η.
- MULTIPLE RIBBON GROWTH, THREE AT 10 CM x 3.5 CM/MIN FOR TWO HOURS.
- AUTO CONTROLS RESPONDING.

Furnace 3A: Three Ribbons 4 in. Wide



Machine 17: 4-in. Wide Ribbon TV Control System



Run JPL-HE-2: Growth Run 18-172; Ribbons PH_3 Processed

CELL NO.	AREA (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (volt)	FF	η (%)	NOTE
HE-2-1	14.3	28.5	.578	.701	11.6	1" x 2" ribbon blanks
HE-2-2	14.4	28.6	.578	.707	11.7	
HE-2-3	14.8	28.1	.579	.744	12.1	
HE-2-4	14.2	28.0	.581	.722	11.8	
HE-2-5	14.1	28.3	.579	.747	12.2	
HE-2-6	14.1	28.5	.581	.742	12.3	
HE-2-7	14.1	27.4	.574	.702	11.1	
HE-2-9	8.1	27.9	.581	.769	12.5	
	(13.5)	(28.2)	(.579)	(.729)	(11.9)	
HE-2-1A	5.8	29.0	.581	.764	12.9	Scribing off edges
HE-2-1B	5.8	29.1	.581	.779	13.2	
HE-2-3A	3.8	28.3	.575	.769	12.5	
HE-2-7A	6.0	27.6	.575	.751	11.9	
HE-2-7B	6.2	27.9	.573	.773	12.4	
HE-2-7	7.1	27.7	.578	.783	12.5	
	(5.8)	(28.3)	(.577)	(.770)	(12.6)	

Machine 17 Runs

JPL MACHINE 17; ALL GRAPHITE SYSTEM; COLD SHOE RUNS AT SPEEDS BETWEEN 3.2 TO 4.0 CM/MIN; 10 CM WIDE RIBBON CELL RESULTS; NOVEMBER 1979 TO FEBRUARY 1980; 5 CM x 10 CM CELL SIZE; CVD DIFFUSION; 1025°C

RIBBON GROWTH NO.	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)
17-062* Nov. 1979	24.3	.549	.673	9.0
	24.6	.545	.640	8.6
	24.5	.546	.681	9.1
17-064*	23.0	.541	.730	9.1
	23.7	.553	.734	9.6
	23.8	.551	.744	9.8
	24.3	.542	.664	8.7
	24.2	.545	.768	10.1
	24.2	.547	.737	9.8
17-065	22.0	.528	.747	8.7
17-072	22.1	.539	.753	9.0
	23.5	.535	.728	9.2
	24.0	.544	.706	9.2
17-074	23.2	.540	.739	9.3
	23.7	.543	.738	9.5
	23.2	.542	.708	8.9
	23.0	.541	.720	9.0
17-078	24.5	.543	.637	8.5
	24.5	.541	.671	8.9
	24.7	.546	.671	9.0
	24.4	.542	.709	9.4
	25.0	.550	.696	9.6
17-080 Feb. 1980	24.5	.545	.680	9.1
	24.9	.535	.610	8.1
17-081 4 cm/min	25.3	.545	.729	10.1
	24.5	.545	.737	9.8
	24.8	.556	.717	9.9
	25.9	.550	.660	9.4
	24.3	.545	.708	9.4
	24.0	.547	.755	9.9
17-082	23.3	.542	.736	9.3
	23.6	.544	.622	8.0
	22.8	.535	.722	8.8
	23.8	.536	.694	8.9
	23.1	.532	.609	7.5
	23.5	.534	.675	8.5
	23.1	.535	.687	8.5
	23.8	.535	.644	8.2
	23.0	.535	.612	7.5
	23.7	.543	.696	9.0

*2.5 cm x 10 cm cell size.

First Multiple (3) 10-cm-Width Growth Experiment

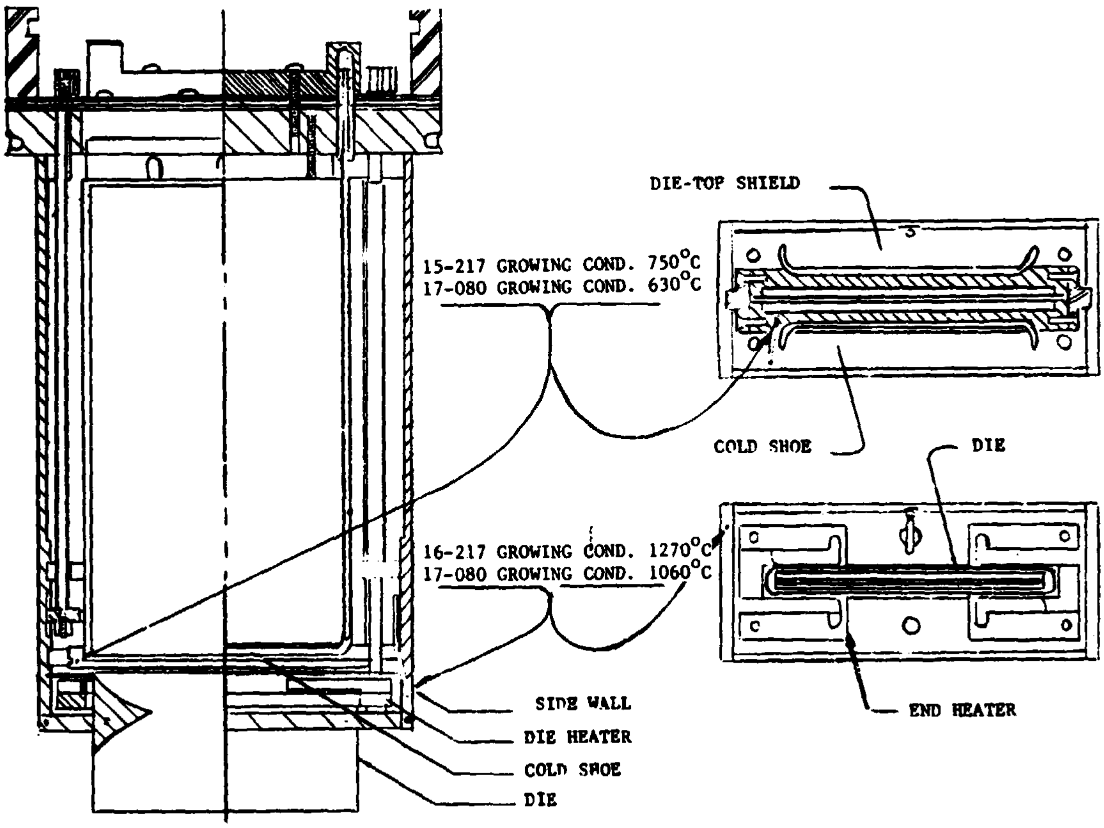
RUN 16-215

TOTAL GROWN:	21.5 m
TOTAL 100 mm WIDE:	11.9 m
% 100 mm WIDE:	55%
AVERAGE THICKNESS:	300 TO 350 μm

	CARTRIDGE #1	CARTRIDGE #2	CARTRIDGE #3
TOTAL GROWN:	6.6 m	4.1 m	10.8 m
TOTAL 100 mm WIDE:	3.7 m	1.2 m	7.0 m
% 100 mm WIDE:	56%	28%	65%

	CARTRIDGE #1	CARTRIDGE #2	CARTRIDGE #3
GROWTH TIME TOTAL:	3 HRS, 41 MINS	3 HRS, 21 MINS	6 HRS, 59 MINS
LONGEST GROWTH TIME:	1 HR, 32 MINS	2 HRS, 8 MINS	4 HRS, 33 MINS
NUMBER OF FREEZES:	11	5	6
AVERAGE GROWTH SPEED:	2.8 CM/MIN	2.8 CM/MIN	2.8 CM/MIN

Mobil Tyco 10-cm Ribbon-Growth Cartridge



Multiple (3) 10-cm-Wide Ribbons

	CELL NO.	AREA (cm^2)	V_{oc} (V)	I_{sc} (mA/cm^2)	FF	P (mW/cm^2)
CARTRIDGE 1	2	55.6	0.525	21.3	0.683	7.6
	1	51.1	0.540	22.4	0.721	8.7
	4	50.3	0.531	22.0	0.686	8.0
	5	51.8	0.537	24.4	0.609	8.0
CARTRIDGE 2	4	50.6	0.524	22.4	0.619	7.3
	5	49.6	0.531	23.9	0.666	8.5
	6	42.7	0.529	23.3	0.671	8.3
CARTRIDGE 3	5	52.9	0.522	22.2	0.678	7.9

NOTE:

THE MATERIAL PRODUCED IN THIS, THE FIRST 10 CM WIDE RIBBON MULTIPLE RUN WAS NOT PARTICULARLY FLAT. THUS, SCRIBING PROBLEMS WHICH LED TO VERY UNEVEN CELL EDGES RESULTED. ALSO, METALLIZATION WAS SOMEWHAT IMPERFECT. FINGERS WERE OFTEN QUITE WIDE BUT ALSO INTERRUPTED ON SOME CELLS. OVERALL, HOWEVER, THESE RESULTS SHOW THAT NO REGRESSION IN CELL QUALITY IS EVIDENT WHEN COMPARING WITH THE 5 CM RIBBON MULTIPLE DEMONSTRATION RUN OF MAY 1979 (NO. 16-187).

Quality Improvement Program: Slow-Speed Growth

BASELINE FOR LARGE AREA CELLS UNDER STANDARD AMBIENT CONDITIONS ESTABLISHED AT 20 TO 30 μm FOR DIFFUSION LENGTHS, 8 TO 10% FOR EFFICIENCY.

OPTIMIZATION OF AMBIENT EFFECTS IN SLOW SPEED (1.8 TO 2.5 CM/MIN) SYSTEM HAS PRODUCED:

SPV DIFFUSION LENGTHS:	40 TO 60 μm AVERAGE OVER LARGE AREAS, OVER 80 μm ON SINGLE 1 CM DIAMETER BARRIERS.
CELL EFFICIENCIES:	10 TO 12.5%.

- REPRODUCIBLE IMPROVEMENTS BOTH WITH REDUCED MAIN ZONE PURGE RATES AND WITH DELIBERATE INTRODUCTION OF CO_2.

- PROCESSING IS AN IMPORTANT FACTOR IN CELL EFFICIENCY (PH_3 VERSUS CVD).

Atmosphere Effects

IDENTIFIABLE AND REPRODUCIBLE EFFECTS ARISING FROM MAIN ZONE PURGE RATE VARIATION (DECREASE).

- SUPPRESSION OF DIE-TOP SiC GROWTH, FILM APPEARANCE.
- REPRODUCIBLE INCREASES IN SPV L_D.
- SOLAR CELL EFFICIENCIES UP TO 11.5% ON LARGE AREA CELLS (5 CM x 10 CM).
- CHANGE IN MATERIAL STRUCTURE.
- EFFECTS VERY SENSITIVE TO MENISCUS HEIGHT (RIBBON THICKNESS).

SPV L_D Variation With Main Zone Flow

SAMPLE	MAIN ZONE FLOW RATE (ℓ/MIN)	CO (PPM)		L_D (μm)
		KITAGAWA	IR	
18-183-1G	5	10	45	17.2
-2I	5	10	56	29.7
-3A	3	15	120	30.7
-3B	2.5	30	94	41.6
-3F	2	40	112	41.6
-3H	1	80	226	39.2
-3J	1	110	222	49.7

Large-Grained EFG Ribbon

- EXPERIMENTS SUGGEST LARGE GRAIN APPEARANCE REQUIRES:

  (i) CARBON HOMOGENEITY.

  (ii) FAVORABLE INTERFACE SHAPE.

- BOTH (i) AND (ii) MAY OCCUR AS A RESULT OF AMBIENT COMPOSITION MANIPULATION.

Sources of Oxygen in Furnace

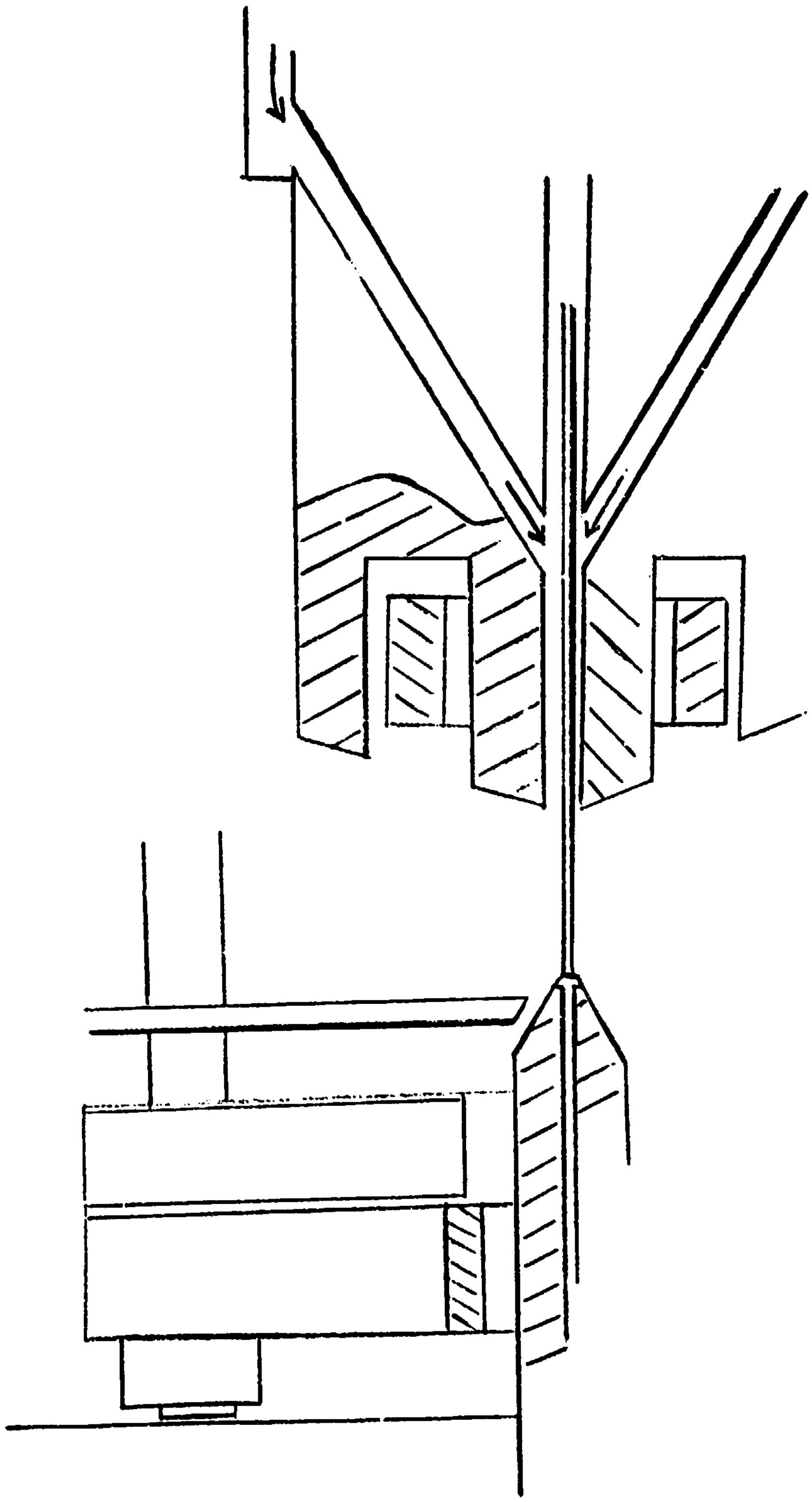
- O_2 AND H_2O IN ARGON SUPPLY, MEASURED ~20 TO 200 ppm

- OUTGASSING OF FURNACE COMPONENTS, CHEMISORBED O_2 AND H_2O, "ACTIVATED CHARCOAL EFFECT"

- BACKSTREAMING OF AIR AROUND THE EXITING RIBBON

- OXYGEN IN THE MELT FROM STARTING MATERIAL, OR QUARTZ CRUCIBLES (WHEN USED)

Gas Jet Configuration



Hypotheses for Ambient Influence

1. THERMO-MECHANICAL

- REDUCED THERMAL PERTURBATION OF GROWTH INTERFACE, INCREASED GROWTH STABILITY DUE TO REDUCED SiC PARTICLE PERTURBATION.

- CHANGE IN HEAT FLUX BALANCE, HENCE INTERFACE SHAPE.

2. CHEMICAL

- CHANGES IN MATERIAL PROPERTIES ARISE FROM SHIFT IN BALANCE OF CARBON, OXYGEN AND IMPURITIES IN MELT AND RIBBON.

- COULD BE DUE TO COMPOSITION SHIFT INTO THE EUTECTIC Si-SiC COMPOSITION (~100 ppm SiC). AT AN EUTECTIC POINT, THE SOLIDIFICATION IS ISOTHERMAL, LEADING TO DRASTIC CHANGES IN GROWTH CONDITIONS, I.E., PLANAR GROWTH FRONT, NO CONSTITUTIONAL SUPERCOOLING. AN EXPECTED EFFECT THEN WOULD BE ENHANCED SiC PRECIPITATION THROUGHOUT THE RIBBON VOLUME, PROBABLY AS VERY SMALL PRECIPITATES.

Experimental Program

1. GROWTH WITH CO_2, CO, CH_4, H_2O GASES INTRODUCED INTO AMBIENT.

2. ALUMINUM-DOPED MELT WITH CO_2.

3. COLD SHOE SYSTEM WITH CO.

4. RIBBON QUENCHING.

Results to Date

- ALL GASES QUALITATIVELY REPRODUCE FILM/SiC EFFECTS SEEN WITH REDUCED MAIN ZONE PURGE RATE.

- MOST OF FILM IS FORMED ABOVE GROWTH INTERFACE ON RIBBON (SOLID) SURFACE.

- CO_2 GIVES MOST REPRODUCIBLE RESULTS IN 500 TO 2,000 ppm RANGE.

SPV Diffusion-Length Variation With Ambient Changes

RUN NO.	AMBIENT GAS	L_D (μm) BASELINE, ARGON ONLY	L_D (μm) WITH ADDED SPECIES
18-170	CO_2	37	49
-171	CO_2	36	45
-172	CO_2	-	41
-173	CO	20	36
-174	CO	22	42
-175	CH_4	32	47
-176	CH_4	28	32
-177	CO_2	19	30
-179	CO_2	26	40
-180	H_2O	33	30
-190	CO_2	29	40
-191	CO_2	34	48
-195	CO_2	25	38
-196	CO_2	-	42
-197	CO_2	36	45
-199	CO_2	35	55

Run 18-171, CO_2 Experiment

	Main Zone Gas (ℓ/min)	1% CO_2 (ℓ/min)	L_D (μm)
18-171-1B	10	0	36.5
-3E	10	0	35.5
-4D	10	0.4	37.5
-5D	5	0.4	49.0
-5I	5	0.4	45.0
-7I	5	0	35.3
-8D	2	0	34.8
-8H	2	3	48.4

Average without CO_2: 35.5 μm

Average with CO_2: 45.0 μm

References to Diffusion Processes Used in Preparation of EFG Solar Cells

PROCESS 1: "PHOSPHINE (PH_3) DIFFUSION"

B.H. MACKINTOSH ET AL., "LARGE AREA SILICON SHEET BY EFG," FIRST QUARTERLY REPORT 1977, JPL SUBCONTRACT NO. 954355, MARCH 15, 1977, pp. 42 - 46.

PROCESS 2: "CVD DIFFUSION"

R. GONSIORAWSKI, "MANUFACTURE OF SOLAR CELLS," U.S. PATENT NO. 4 152 824, MAY 8, 1979. ASSIGNED TO: MOBIL TYCO SOLAR ENERGY CORPORATION.

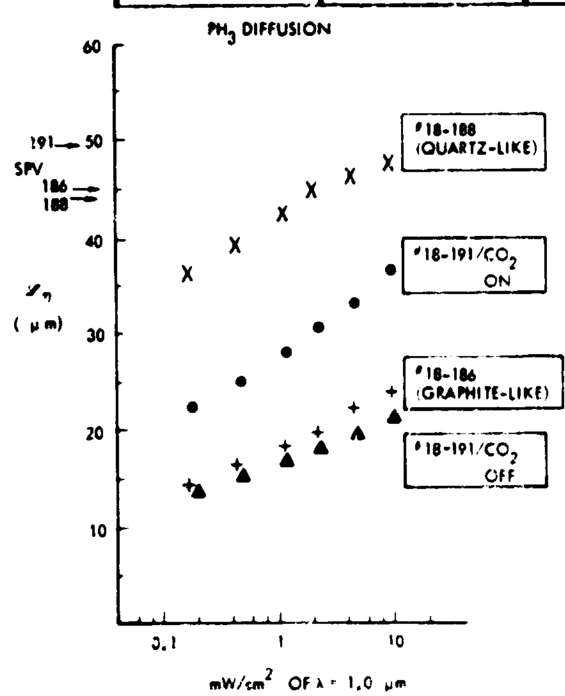
IN THE CELLS REPORTED HERE AS "CVD," HOWEVER, THE METALLIZATION FROM PROCESS 1 WAS GENERALLY USED.

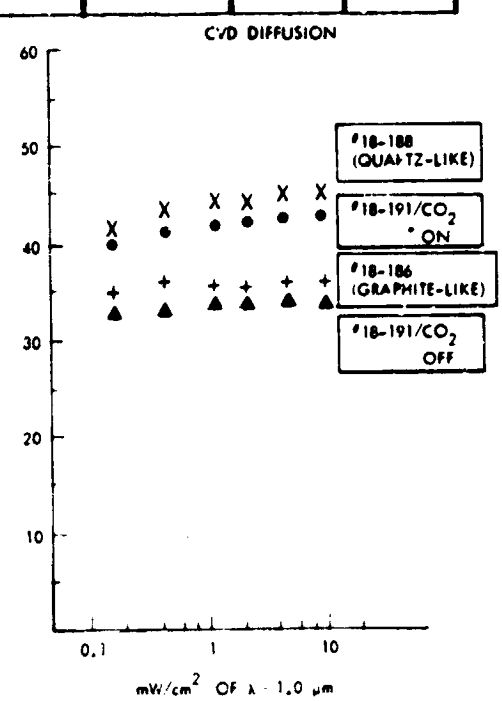
Ribbons From Reduced Ambient Experiment

RIBBON GROWTH NO.	DIFFUSION PROCESS	J_{sc}	V_{oc}	FF	η	NOTES
18-185	CVD	26.4	.560	.717	10.6	1" x 2"
		25.5	.561	.749	10.7	
		25.7	.564	.766	11.1	
		25.5	.564	.704	10.1	
		26.7	.569	.770	11.7	
		25.8	.559	.752	10.8	
		27.0	.569	.753	11.6	
		26.8	.569	.767	11.7	
		26.3	.560	.745	11.0	
		26.3	.575	.741	11.2	
		25.9	.573	.734	10.9	
18-186	PH_3	24.9	.518	.558	7.2	1" x 2"
		25.4	.532	.658	8.9	
		24.4	.519	.698	8.8	
		23.9	.523	.697	8.7	
		24.5	.535	.750	9.8	
	CVD	26.7	.555	.667	9.9	"GRAPHITE-LIKE"
		27.0	.554	.622	9.3	
		26.4	.553	.707	10.3	
		26.5	.553	.770	11.3	
		27.2	.561	.726	11.1	
		26.4	.557	.777	11.4	
		25.5	.565	.672	9.7	
		26.1	.550	.690	9.9	
		25.6	.546	.761	10.7	
18-188	PH_3	28.3	.560	.686	10.9	1" x 2"
		27.8	.559	.673	10.5	
		27.4	.558	.674	10.3	
		27.6	.560	.722	11.1	
		27.9	.557	.705	11.0	
		27.8	.559	.652	10.1	
	CVD	26.4	.561	.697	10.3	"QUARTZ-LIKE"
		25.6	.554	.713	10.1	

Hypotheses on Possible Positive Influence of O_2 On Minority Carrier Lifetime of Si

AMBIENT CONDITION	DIFFUSION PROCESS	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)
CO_2 "ON"	PH_3	27.2	.557	.753	11.4
		27.0	.553	.750	11.2
		26.0	.544	.752	10.6
		26.6	.550	.744	10.9
		24.5	.536	.734	9.7
		26.7	.551	.769	11.3
CO_2 "OFF"		24.2	.520	.746	4.4
		21.0	.505	.739	8.0
		22.0	.505	.741	8.2
		21.6	.501	.701	7.6
		21.7	.507	.726	8.0
CO_2 "ON"	CVD	24.5	.557	.767	10.5
		25.2	.552	.743	10.4
		26.7	.553	.768	11.3
CO_2 "OFF"		24.7	.550	.767	10.4
		25.2	.553	.739	10.3
		25.2	.549	.731	10.1
		24.8	.543	.762	10.3
		24.1	.547	.713	9.4
		25.2	.548	.682	9.4
		25.1	.542	.777	10.6





Ribbons From Gas Ambient Experiment Run 18-191

I. OXYGEN COMPLEXES RANDOM IMPURITIES.

II. OXYGEN COMPLEXES CARBON RELATED POINT DEFECTS.

III. OXYGEN COMPLEXES RANDOM LINE OR PLANAR CRYSTALLOGRAPHIC DEFECTS.

SILICON WEB PROCESS

WESTINGHOUSE ELECTRIC CORP.

Technology Single crystal ribbon growth	**Report Date** 04/03/80
Approach Silicon dendritic web growth **Contractor** Westinghouse Electric Corp. Research & Development Center **Goals** • Area rate of growth 25 cm^2/minute • Continuous melt replenishment • Cell efficiency $\geq$ 15% AM1 • Semi-automatic growth • Thickness 100-200 μm • Dislocation density $< 10^4/cm^2$	**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 development in progress • Thickness routinely 100-200 μm • Dislocation density routinely $< 10^4/cm^2$

Overview of Approach

- **Program rationale combines key developments necessary to equal or exceed DOE/JPL 1986 cost goal. Developments identified on basis of experiment, thermal modeling and economic analysis**
- **Key developments are:**
  - **Area throughput rate - 25 cm^2/min (> 18 cm^2/min)***
  - **Cell efficiency - 15% AM1**
  - **Melt replenished growth - 3 day cycle (~ 2 day cycle)***
  - **Semi-automated growth**
- **Key assumptions:**
  - **Polysilicon price $14/kg in 1980 dollars (< $35/kg)***
  - **Solar grade polysilicon acceptable to process**

*** Any one of these can be a minimum requirement if all other requirements are satisfied**

Cost Projections (1980 $) SAMICS/IPEG

Assumptions:

Area throughput rate 25 cm^2/minute
Cell efficiency 15% AM1
Continuously melt-replenished 3 day growth cycle
Semi-automated growth
Solar grade polysilicon price $14/kg
Thickness 150 μm

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

C-4

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Cost If Development Is Frozen as of March 1980

Assume:
- One day or two day growth cycle
- 3 employees per shift for 6 growth furnaces
- Throughput rate of 10 cm^2/minute
- Polysilicon price of \$100 per kilogram
- Cell efficiency of 15% AM1

Cost Projection

Growth Cycle	Value Added Wafer Cost	Polysilicon Cost	Total Cost
One Day	\$1.84/W_{pk}	\$.28/W_{pk}	\$2.02/W_{pk}
Two Days	\$1.43/W_{pk}	\$.28/W_{pk}	\$1.71/W_{pk}

Contract Goals and Achievements vs Schedule

Task 1- Melt Replenishment	Complete. Delayed three months by late delivery of critical components
Task 2- Thermal Trimming	On schedule
Task 3- Combine 1 and 2	Delayed because of task 1 slippage
Task 4- Semi-Automatic Closed-Loop Control	Delayed because of task 1 slippage
Task 5- Semi-Automatic Growth	Delayed because of task 4 delay
Task 6- New Furnace Design	On schedule
Task 7- Web Characterization	On schedule
Task 8- Deliver Solar Cells	Short delay
Task 9- Deliver Silicon Web	On schedule
Task 10- Economic Analysis	On schedule
Task 11- Documentation	Per schedule
Task 12- Meetings	Per schedule

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Current Developments and Status

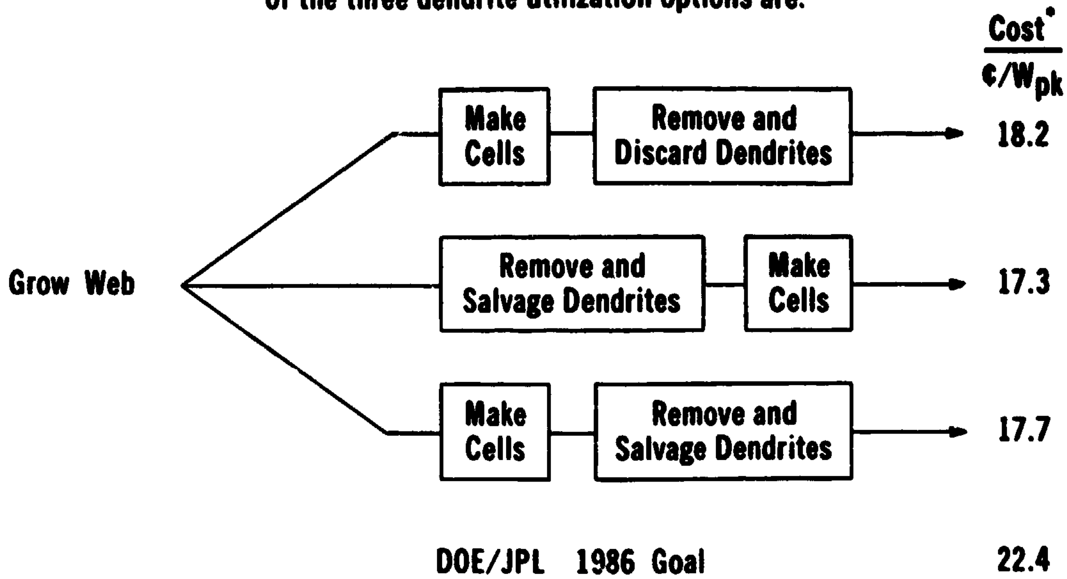
	December 1979	March 1980
• Melt Replenishment	5 Hours	17 Hours
• Melt Level Sensing	Designed	Built & Operating
• Semi-Automatic Growth	Concept Defined	Development in Progress
• Improved Polysilicon Feeder	Need Identified	Redesigned, Built & Operating
• Conversion of 2nd Furnace to Melt Replenishment	Need Identified	Converted & Operating
• Dendrite Recycling		Web Grown from Recycled Dendrites. Economic Anaylsis Completed

Economics of Recycling Dendrites

Three dendrite options have been considered:

- Discard (throw away) dendrites
- Salvage (re-melt) dendrites removed from web before cell fabrication
- Salvage dendrites removed from web after cell fabrication

Assuming the key developments are attained, comparative costs of the three dendrite utilization options are:



* Combined polysilicon and value-added wafer cost in 1980 dollars

New Technology

- Furnace concept for high throughput silicon web growth
- Thermal model for low stress web growth
- Melt level sensor system for silicon web growth
- Melt replenishment concept for silicon web growth
- Method for control of thermal gradient in susceptor system
- Method for maintaining melt distribution in compartmented crucible

Westinghouse-Funded Activities in Silicon Web

At The Research and Development Center (R&D)

- Basic crystal and cell development of silicon web
- Design, development, construction and operation of 2nd generation web growth furnaces

At The Advanced Energy Systems Division (AESD)

Provided plant, equipment and personnel to:

- Transfer technology from R&D
- Install 50 kilowatt prepilot facility to demonstrate polysilicon-to-module technology

Problems and Concerns

Problem Areas

Three month delay of melt replenished growth development caused by late delivery of critical system components

Other Concerns

Availability, form and price of solar grade polysilicon

Summary

Achievements in 12/79-3/80 Period

- Long term melt replenishment demonstrated
- Melt level sensor built, installed and operating
- Polysilicon pellet feed system improved
- Second web growth system modified for melt replenishment
- Web successfully grown from re-cycled dendrites

Status of Overall Goals

- Throughput goal exceeded (27 cm^2/minute)
- Cell efficiency exceeded (15.5% AM1)
- Continuous Melt Replenishment Demonstrated (manually operated one day growth cycle)
- Development of semi-automated growth in progress
- Dislocation density goal routinely satisfied ($< 10^4/cm^2$)
- Thickness goal routinely satisfied (100-200 μm)

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

VACUUM DIE CASTING OF SILICON SHEET

ARCO SOLAR, INC.: SRI INTERNATIONAL

TECHNOLOGY DIE CAST SHEETS	**REPORT DATE** 04/03/80
APPROACH DIE PRESSING OF SILICON DROPS INTO WAFERS **CONTRACTOR** ARCO SOLAR/SRI INTERNATIONAL	**STATUS** • DEVELOPED LIQUID BARRIER COATED GRAPHITE DIE • DEMONSTRATED REUSABLE DIES • PRODUCED 2.5 cm X 2.5 cm X 0.1 cm* DIE PRESSED SHEETS • INVESTIGATED GRAIN BOUNDARY PASSIVATION BY HYDROGEN PLASMA AND GETTERING.
GOALS • SHEET AREA 10 cm X 2.5 cm • THICKNESS 0.03 cm • CRYSTAL STRUCTURE--CHARACTERISED • CELL EFFICIENCY 12% AT AM 1 (2 cm X 2 cm)	*NEW ACHIEVEMENT

Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS:

1 WAFER/MINUTE EACH MACHINE
80% DUTY CYCLE
90% YIELD
1 OPERATOR/3 MACHINES

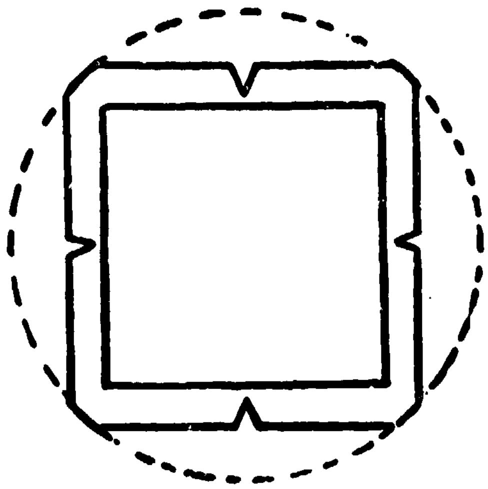
PROJECTION

$45.60/M^2 VALUE ADDED
$.38/W VALUE ADDED (EFF=12%)

Problems and Concerns

- IMPROVE CASTING PROCEDURE TO ELIMINATE CRACKS IN SHEET.
- FORM SHEETS THINNER THAN 1 MM.

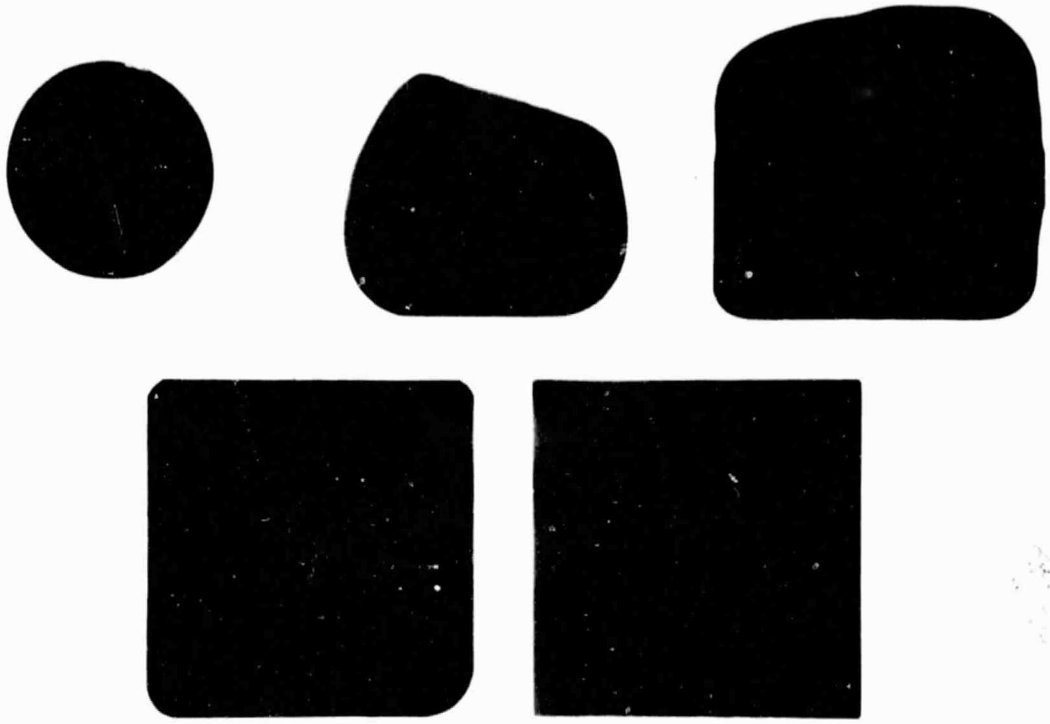
Expendable Ring



Problem Areas

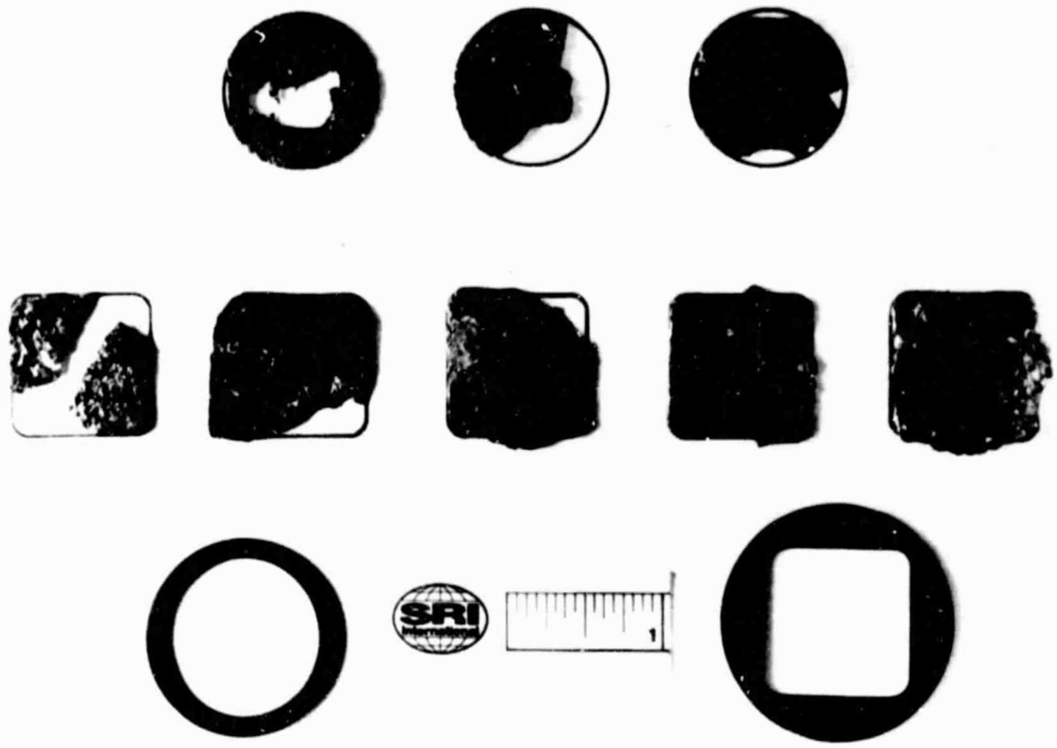
- INCOMPLETE FILLING OF THE DIE CAVITY
- DIFFICULT TO ETCH AWAY THE FUSED SALTS
- CRACKING OF THE SHEETS

Stages in Formation of Liquid Sheet 50 x 50 x 1 mm by Pressing A Sessile Drop of Mercury in Glass



25 x 25 x 0.1 mm

Sheet Silicon Produced by Die Pressing



Polished Surface of Pressed Silicon Sheet

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

SESSILE DROP EXPERIMENTS UNDER CONTROLLED OXYGEN PARTIAL PRESSURE

UNIVERSITY OF MISSOURI ROLLA P.D. Ownby and H.V. Romero

Work accomplished since the 14th PIM:

Sessile drop experiments have been conducted on the following possible candidate die and container materials supplied by JPL:

Candidate Material	Source
Silicon Carbide Coated Graphite	Ultracarbon Corp.
Hot-Pressed Silicon Nitride	Kawecki Berylco Inc.
Hot-Pressed Silicon Nitride	AVCO
Silicon Nitride CNTD Coated on Silicon Nitride	Chemetal Corp.- Eagle-Picher Inc.
Hot-Pressed Sialon	Batelle Columbus Laboratories

Experimental Conditions

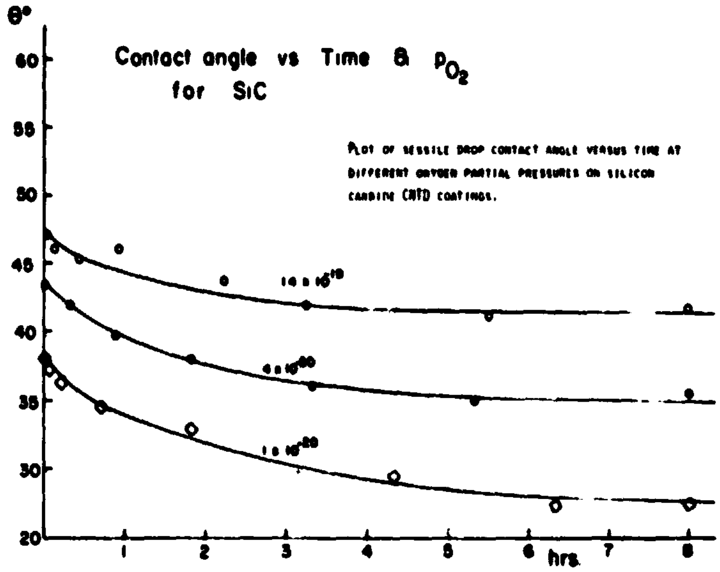
All experiments were conducted below the equilibrium oxygen partial pressure for the formation of SiO_2 from the elements, at a temperature just above the melting piont of silicon (1430°C).

The oxygen activity in the environment was controlled using a flowing-gas buffer system composed of hydrogen and water vapor.

The oxygen activity in the flowing gas stream was measured using a thoria-yttria ceramic solid electrolyte.

The precursor silicon cube was propped up in a tilted altitude, which we have shown previously to be important to allow the bottom surface of the cube and the adjacent substrate surface to equilibrate with the flowing gas environment.

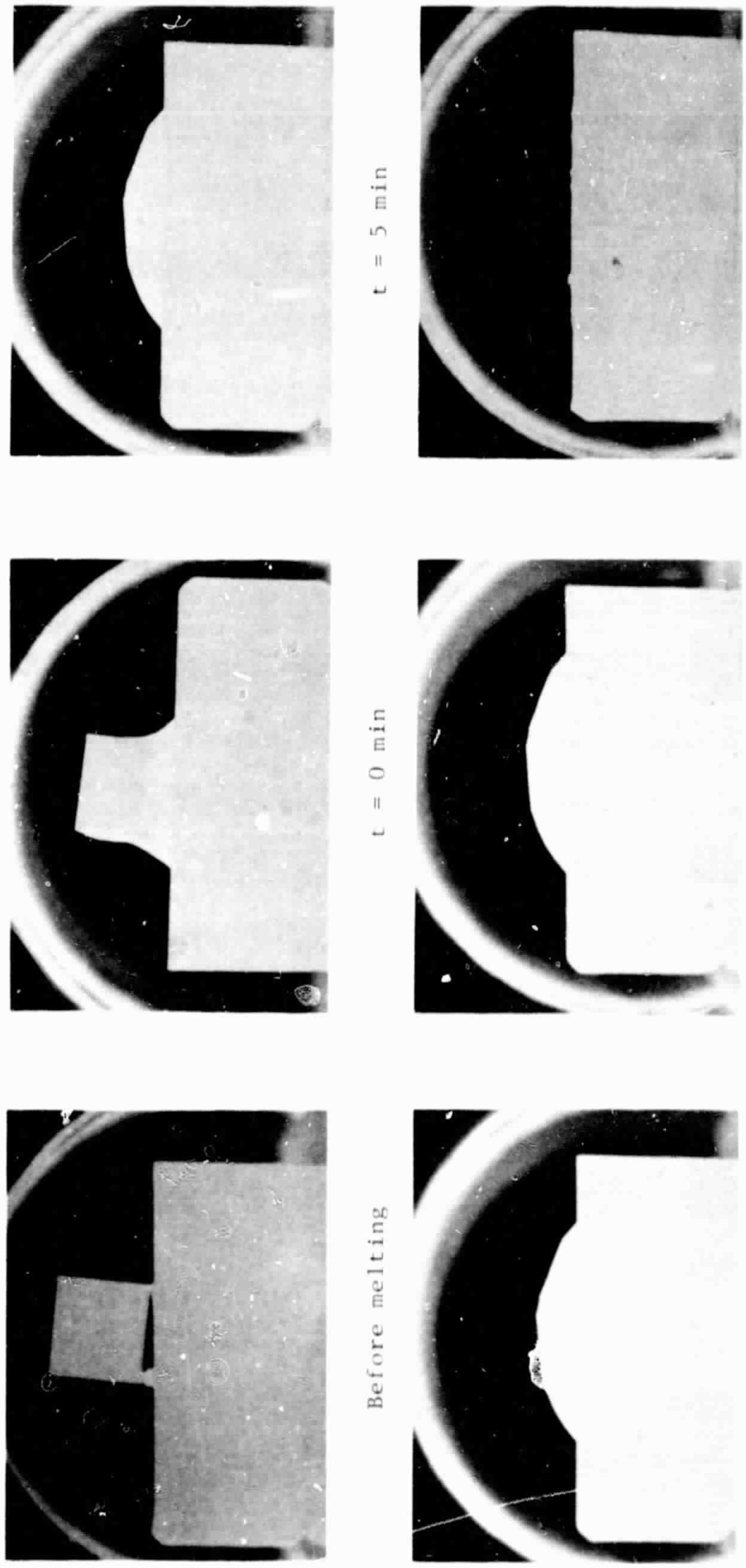
Molten Silicon on ONTD Silicon Carbide



Review of wetting behavior of molten silicon on CNTD silicon carbide showing contact angle change with time at various oxygen partial pressures, from our previous work.

Sessile Drop Profile Sequence

$P_{O_2} = 10^{-19.9}$ atm



In-situ photographs of sessile drop profile sequence on polished silicon carbide-coated graphite from Ultra Carbon Corp. Showing Unexpected Disappearance of Molten Silicon Into Substrate

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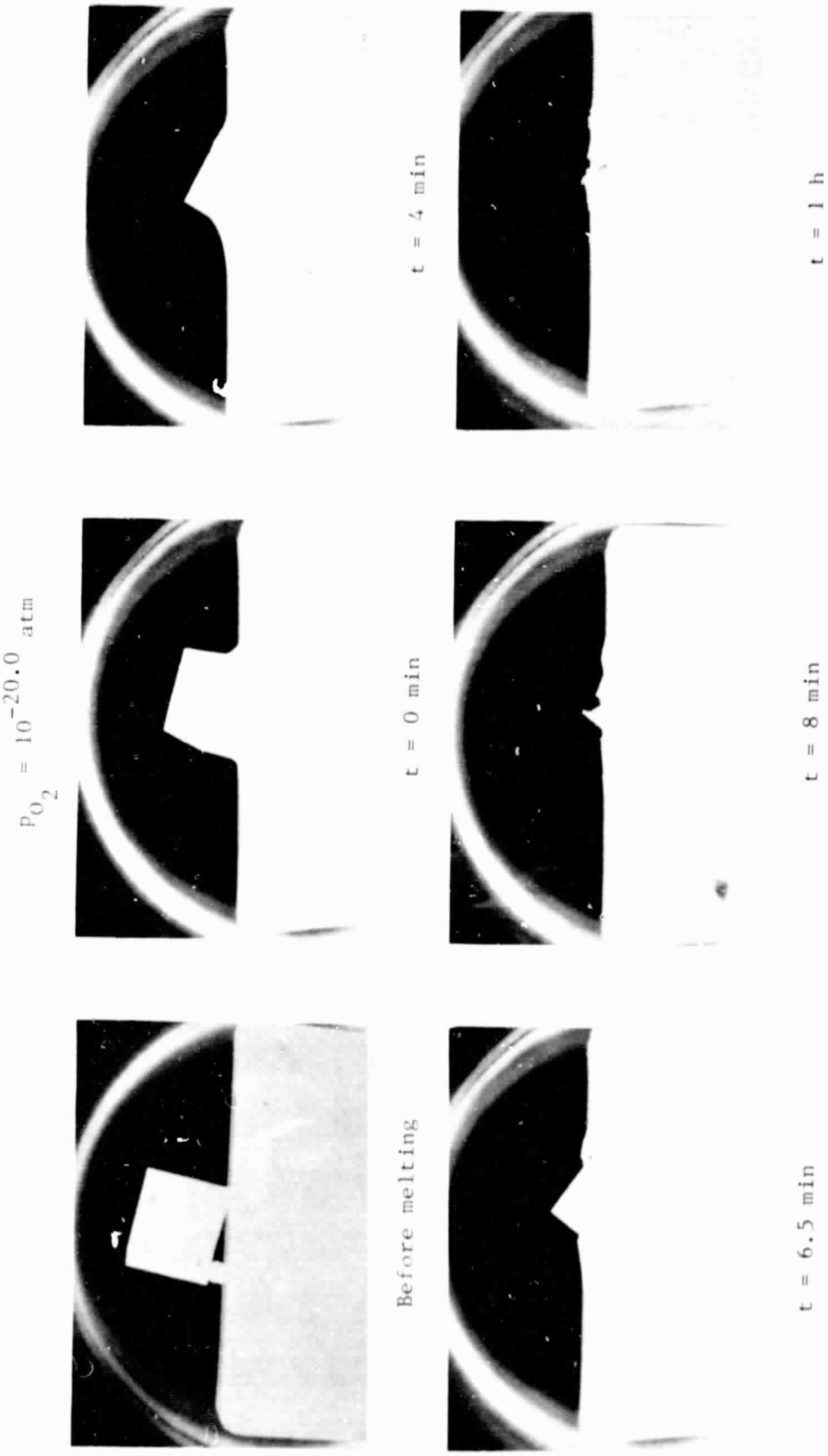
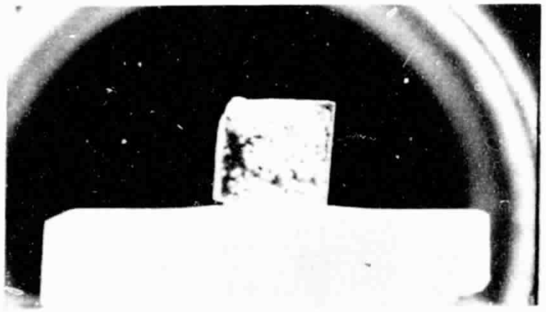


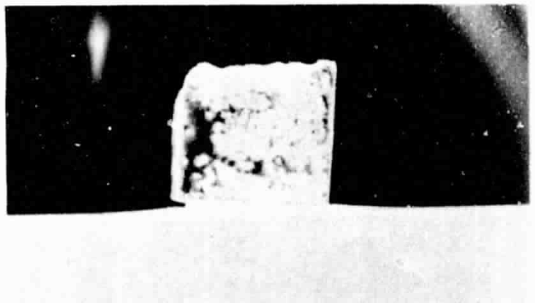
In-situ photographs of sessile drop profile sequence on unpolished silicon carbide coated graphite from Ultra Carbon Corp. showing even more rapid penetration of the coating and underlying graphite.

Sessile Drop Profile Sequences

(a) $p_{O_2} = 10^{-19.6}$ atm

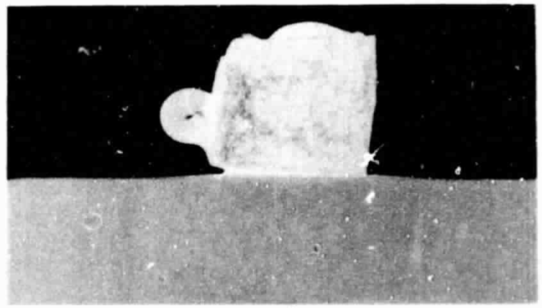


t = 33 min



t = 53 min

No apparent melt above T_{mp}

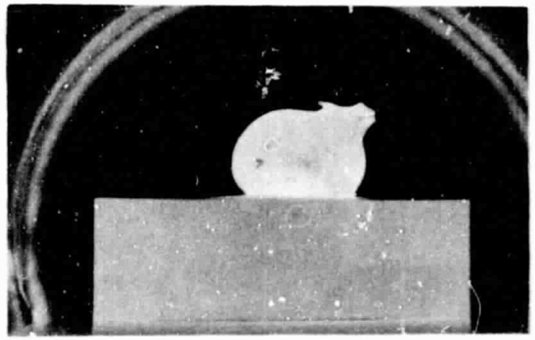


On cooling below T_{mp} solidifying liquid breaks out through skin

(b) $p_{O_2} = 10^{-20.0}$ atm

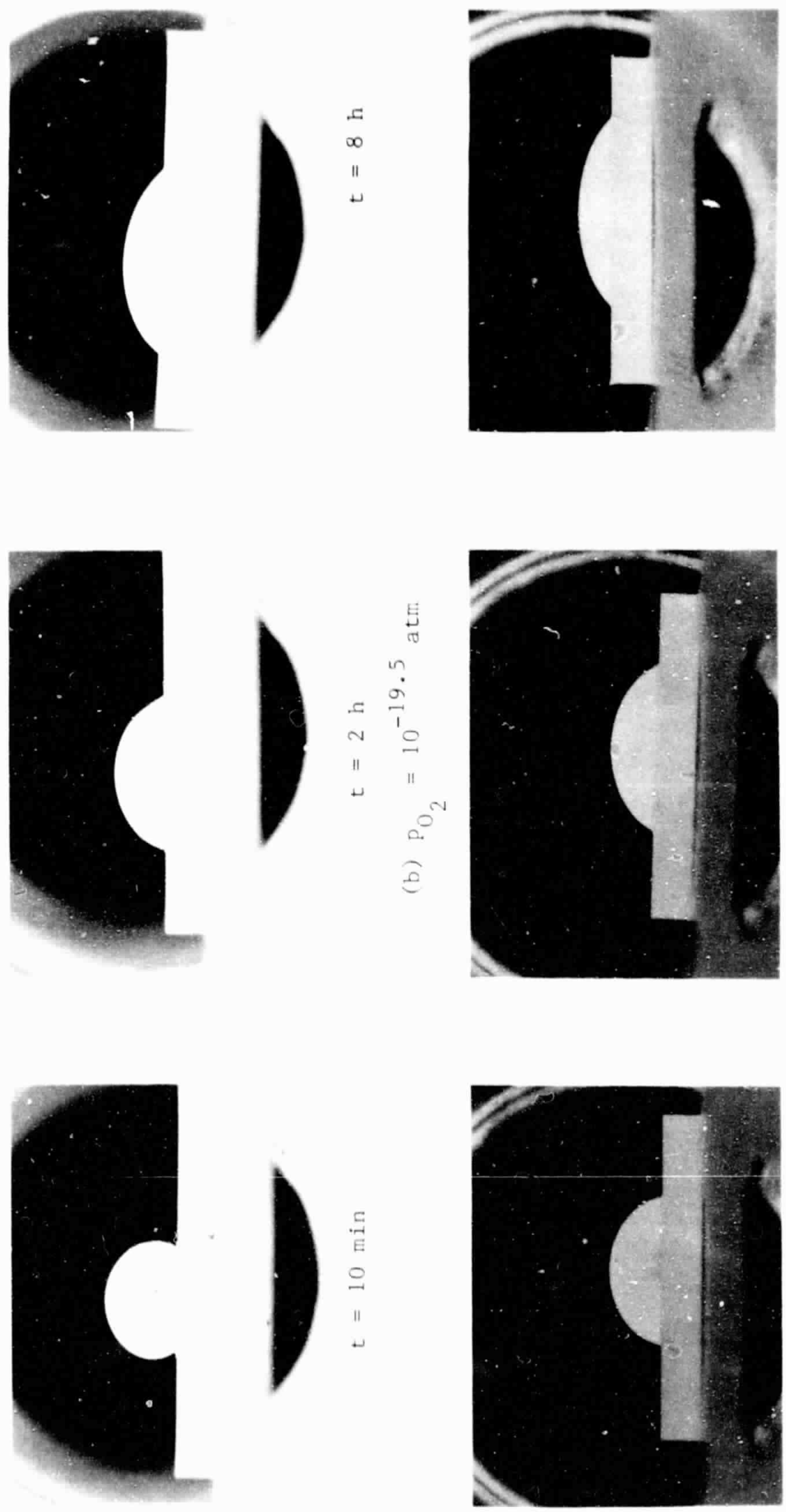
t = 25 min

t = 6 h



In-situ photographs of sessile drop profile sequence on polished Battelle silicon with:
(a) 3 h hold time before melt; (b) no hold before melt.
Skin develops on silicon surface after one hour, obviating obtaining equilibrium shape in both cases.
(CAUTION SHOULD BE EXERCISED IN INTERPRETING CONTACT ANGLE; DATA NOT REPRESENTATIVE OF EQUILIBRIUM)

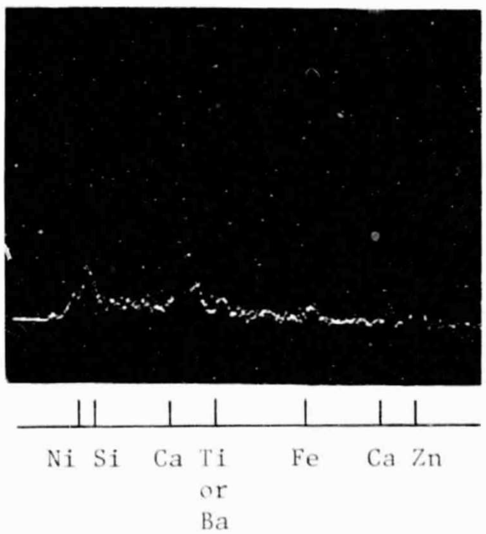
*Ω'-sialon with formula $Si_{8-x}Al_xN_{2-x}O_{1+x}$ where x = 0.75



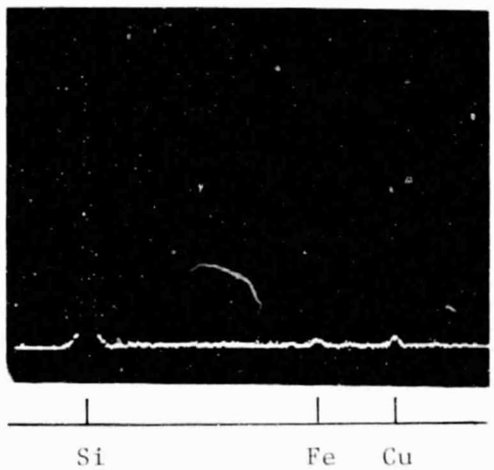
In-situ photographs of sessile drop profile sequence on KBI silicon nitride with:
(a) no hold before melting; (b) 3 h hold before melting. Importance of surface equilibration with gas phase before melting is demonstrated.

Silicon Surface After Sessile Drop Experiment

SEM photograph of silicon surface after sessile drop experiment on Battele sialon; $p_{O_2} = 10^{-19.7}$.



(Light area in SEM)



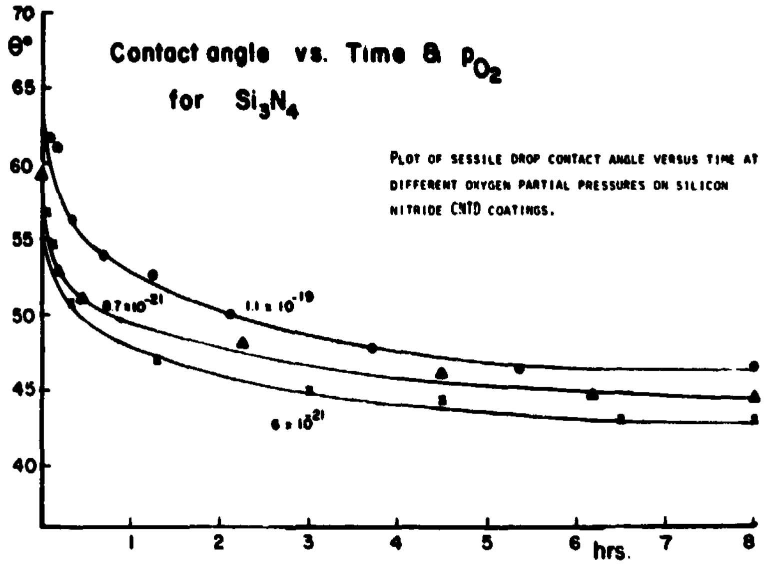
(Dark area in SEM)

Results of analysis of skin that forms on Battelle sialon:

(a) Skin becomes thicker and rough with time, as shown by SEM; skin phase produces clean X-ray diffraction pattern unrepresentative of Si or SiO_2 phases

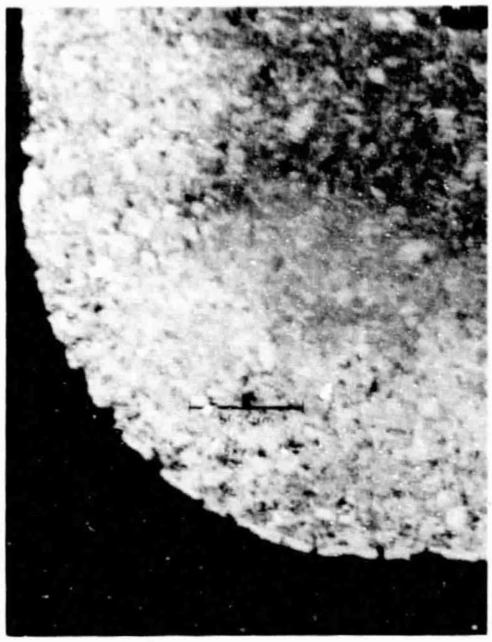
(b, c) Non-dispersive X-ray analysis shows very high calcium content of skin, which is believed to have segregated from bulk sialon.

Wetting Behavior



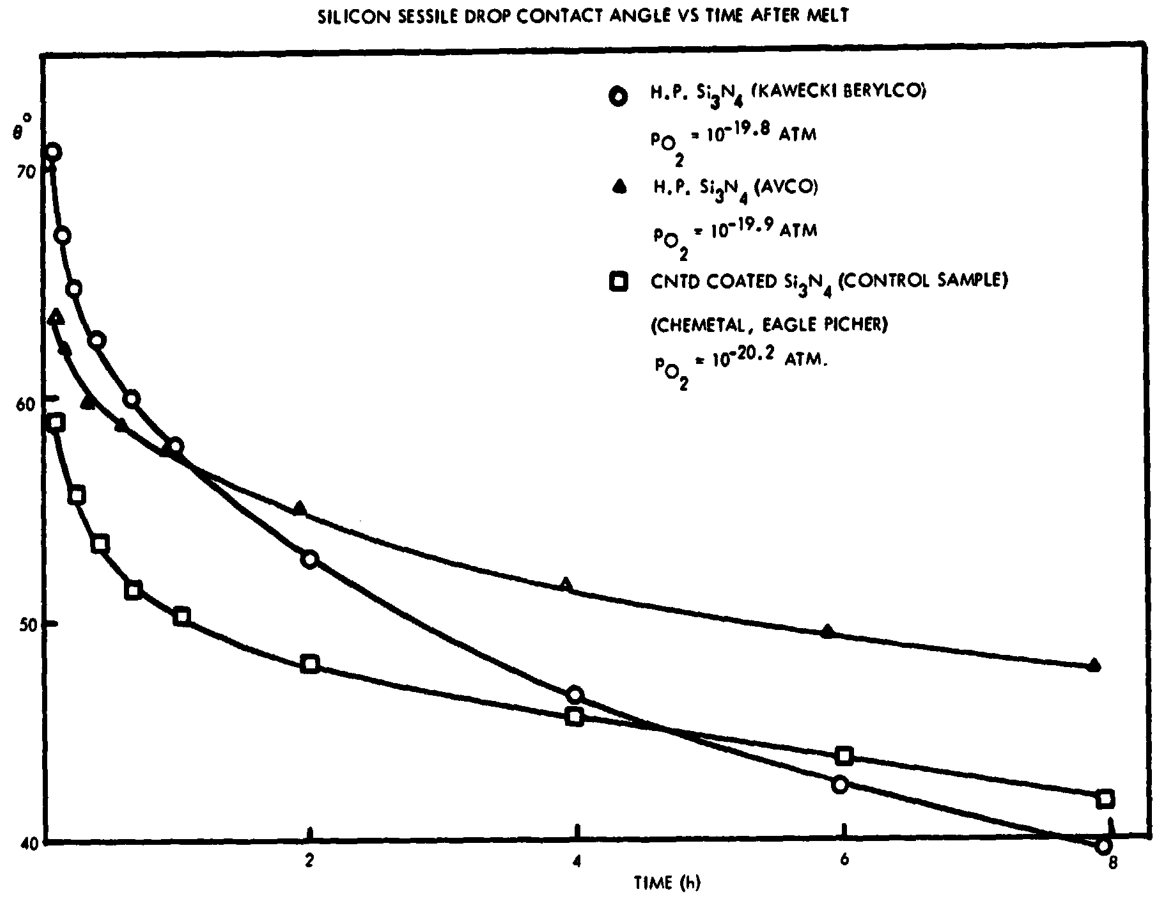
Review of wetting behavior of molten silicon on CNTD silicon nitride, showing contact angle change with time at various partial pressures of oxygen, from our previous work.

Post-Sessile-Drop Section of Ultra-Carbon SiC on Graphite



Silicon has penetrated the SiC coating, impregnated the graphite, and spread out uniformly under the SiC coating: (a) under original position of silicon cube, (b) corner of substrate well away from silicon cube position. $p_{O_2} = 10^{-19.9}$.

Silicon Sessile Drop Contact Angle vs Time After Melt



Agreement is seen between previous and current CNTD silicon nitride. Avco silicon nitride is seen to behave similarly to CNTD silicon nitride; contact angle on KBI substrate does not stabilize like those in Avco and CNTD substrate, indicating greater chemical attack and interaction with substrate.

Summary

1. Molten silicon penetrates the coating of the Ultra Carbon Corp. silicon carbide-coated graphite and impregnates the graphite in a uniformly thick layer under the coating.

2. Molten silicon on Batelle sialon acquires a coating containing high amounts of calcium; the thickness of the coating depends on the length of time at temperature.

3. Contact-angle results on Avco silicon nitride suggests that this material resists molten silscon attack to about the same degree as does CNTD silicon nitride from Chemetal-Eagle Picher, while the KBI silicon nitride experiences a higher degree of attack.

CELL FABRICATION

APPLIED SOLAR ENERGY CORP.

OBJECTIVE

(1) TO DEVELOP AND APPLY APPROPRIATE TECHNOLOGIES TO IMPROVE THE PERFORMANCE OF SOLAR CELLS MADE FROM VARIOUS SILICON SHEET MATERIALS

(2) TO EVALUATE AND CHARACTERIZE THE PROPERTIES OF VARIOUS SILICON SHEET MATERIALS

SCOPE

(1) ELECTRICAL PERFORMANCE OF CELLS (AMØ, 25 C)
   (A) SILICON ON CERAMIC (HONEYWELL)
   (B) CAST SILICON BY HEM (CRYSTAL SYSTEM)
   (C) DENDRITIC WEB (WESTINGHOUSE)
   (D) EFG (RH) MULTI-RIBBON (MOBIL TYCO)

(2) JUNCTION SHUNTING BY ALUMINUM PENETRATION

SUMMARY

Silicon on Ceramic (Honeywell)

	AVERAGE VALUE (AMO, 25 DegC)			
	VOC (mv)	JSC (ma/cm↑2)	CFF (%)	EFF (%)
STANDARD	529	25.5	66	6.5
SHALLOW+SIO	528	26.9	64	6.7
SHALLOW+MLAR	529	26.Ø	68	6.9

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

HEM (Crystal Systems, Inc.)

		AVERAGE VALUE (AMO, 25 DegC)			
		VOC (mv)	JSC (ma/cm↑2)	CFF (%)	EFF (%)
STANDARD	(SINGLE)	596	29.7	76	10.0
	(POLY)	591	30.8	75	9.7
SHALLOW+SIO	(SINGLE)	591	30.4	76	10.1
	(POLY)	589	31.1	75	10.2
PHOSPHORUS GETTERING	(SINGLE)	596	33.0	71	10.3
	(POLY)	588	31.3	72	9.8

Dendritic Web (Westinghouse)

	AVERAGE VALUE (AMO, 25 DegC)			
	VOC (mv)	JSC (ma/cm↑2)	CFF (%)	EFF (%)
STANDARD	551	32.7	76	10.1
SHALLOW+BSF+MLAR	572	36.2	73	11.1
SHALLOW+BSF+BSR+MLAR	585	39.4	75	12.8

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

EFG Multiribbon (Mobil Tyco)

	AVERAGE VALUE (AMO, 25 DegC)			
	VOC (mv)	JSC (ma/cm↑2)	CFF (%)	EFF (%)
STANDARD	507	22.3	73	6.1
SHALLOW+MLAR	525	28.0	69	7.6
STANDARD+BSF	532	26.2	71	7.3
SURFACE ETCHING	514	25.4	63	6.1
CONTROL (EFG)	505	23.5	69	6.2
SURFACE TEXTURING	519	24.0	70	5.9
CONTROL (EFG)	512	21.2	69	5.6
PHOSPHORUS GETTERING	506	22.4	71	6.0
CONTROL (EFG)	501	24.0	70	6.2
G.B. PASSIVATION	537	25.9	73	7.5

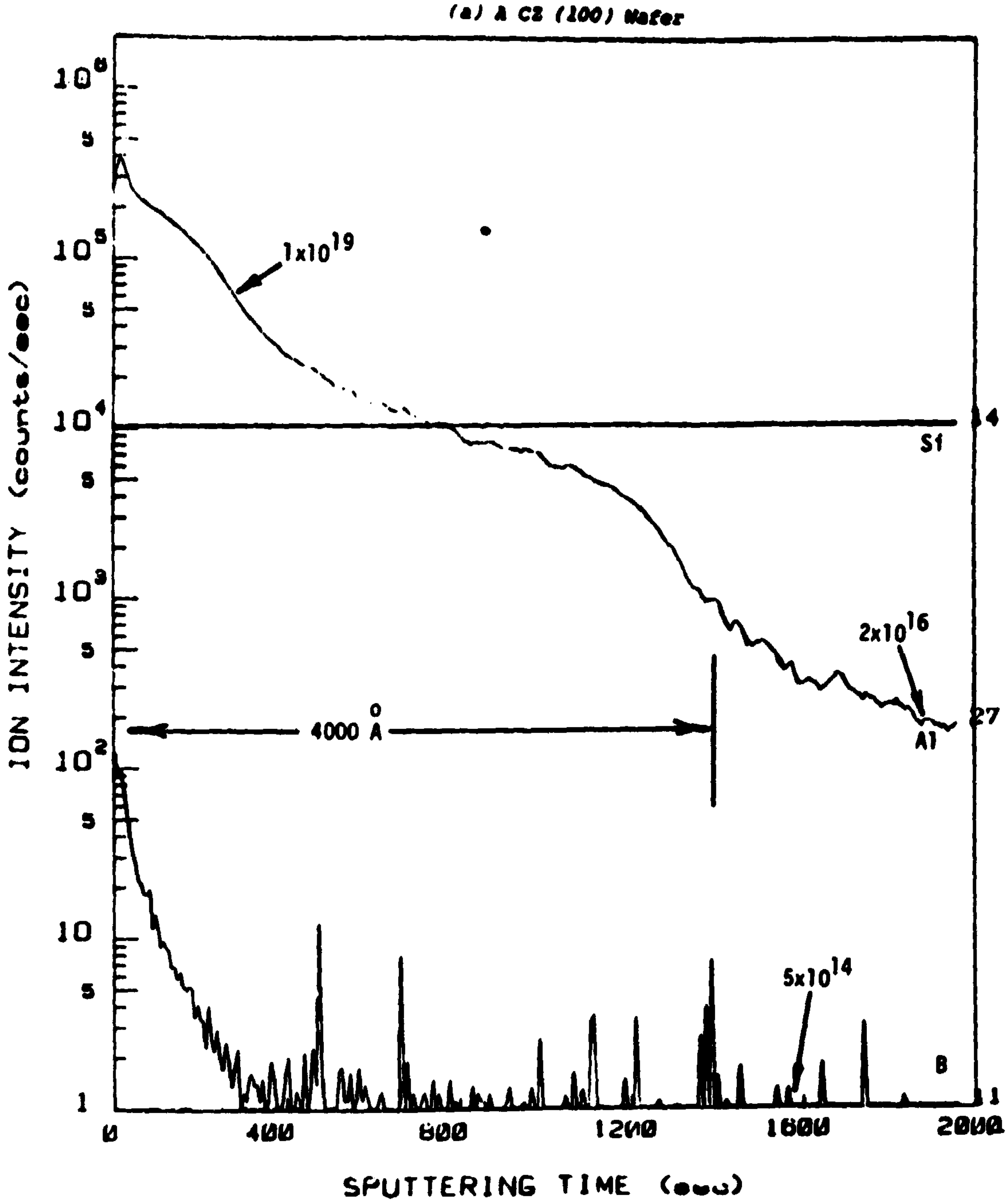
Surface Junction Contaminants From BSF Process

Contaminants on (100) Wafer

Contaminants on (111) Wafer

Aluminum Image (Bright Triangle Pattern) by Ion Microprobe/SIMS

Aluminum Penetration Profile (SIMS) on Cz (100) Wafer



TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Summary

(1) PERFORMANCE IMPROVEMENT HAS BEEN ACHIEVED FROM PROCESS MODIFICATIONS (SHALLOW JUNCTION, FINE LINE CONTACT, MLAR)

(2) SUCESS OF PROCESS MODIFICATIONS SEEMS TO DEPEND ON THE PROPERTIES OF SILICON MATERIAL (GETTERING, G. B. PASSIVATION)

(3) BETTER HANDLING SKILL AND TOOLING, LESS VARIATION IN THICKNESS AND WARPAGE REDUCED BREAKAGE SIGNIFICANTLY

(4) THE ELECTRICAL PERFORMANCE ARE IN GOOD AGREEMENT WITH RESULTS OBTAINED FROM VARIOUS MEASUREMENT TECHNIQUES USED

(5) CONTAMINATION OF ALUMINUM PASTE ALLOYED PROCESS (USED FOR BSF) CAUSES JUNCTION SHUNTING PROBLEM

CELL FABRICATION

SPECTROLAB

Contract Goals

EVALUATE SOLAR CELL POTENTIAL OF UNCONVENTIONAL SILICON OF INTEREST TO THE LARGE AREA SHEET TASK OF LSA

SOLAR CONVERSION EFFICIENCY OF 12% AT AM0, 28°C

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Approach

FABRICATION OF SOLAR CELLS BY BASELINE PROCESS

MEASURE CHARACTERISTICS (AMO) BY STANDARDIZED METHODS

PHASE I

FABRICATION OF SOLAR CELLS USING OPTIMIZED PROCESSES

MEASURE CHARACTERISTICS AMO

EVALUATE OPTIMIZATION

PHASE II

FABRICATION OF SOLAR CELLS USING OPTIMIZED PROCESSES

INTRODUCE LOW COST METHODS

MEASURE CHARACTERISTICS AMO & AM1

EVALUATE OPTIMIZATION

IDENTIFY CELL LOSS VIA BREAKAGE

Silicon Materials in Phase I

WACKER SILSO CAST POLYCRYSTALLINE	
MOTOROLA RIBBON TO RIBBON	RTR
MOBIL TYCO EDGE-DEFINED FILM-FED GROWTH	EFG-RH*
MOBIL TYCO EDGE-DEFINED FILM-FED GROWTH	RGH-RH
WESTINGHOUSE DENDRITIC GROWTH	WEB
CRYSTAL SYSTEMS HEAT EXCHANGE METHOD	HEM
KAYEX-HAMCO CONTINUOUS CZ	HAMCO
HONEYWELL SILICON ON CERAMIC	SOC**

* FOR BASELINE PROCESSING ONLY

** DID NOT COMPLETE FABRICATION

Silicon Materials in Phase II

MOBIL TYCO	EFG-RH
WESTINGHOUSE	WEB
CRYSTAL SYSTEMS	HEM
KAYEX	CZ
HONEYWELL	SOC
OTHERS	-

TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task

Status

PHASE I - COMPLETED.

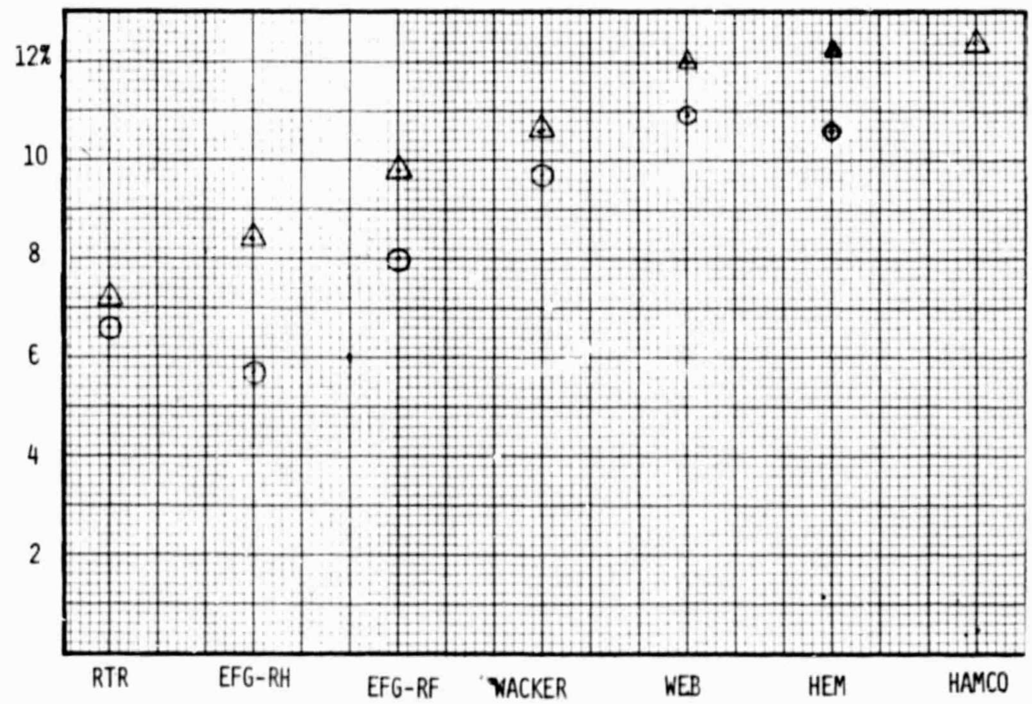
PHASE II - BASELINE CELL FABRICATION COMPLETED ON EFG, WEB, HEM AND HAMCO. PARTIAL COMPLETION OF OPTIMIZATION AND LOW COST PROCESSING ON EFG, WEB, HEM AND HAMCO.

Projection

COMPLETION OF SOC BASELINE CELLS.

COMPLETION OF ALL OPTIMIZED PROCESSING.

SCREEN PRINTED CONTACTS ON LARGE AREA CELLS.



Cells by Low-Cost Processing (Area - 9 cm^2)

METHODS

(A) BASE ETCHES FOR SIZE ETCHING
(B) SPIN-ON DIFFUSANT SOURCE
(C) SCREEN PRINTED AL FOR BSF
(D) SCREEN PRINTED AG CONTACTS

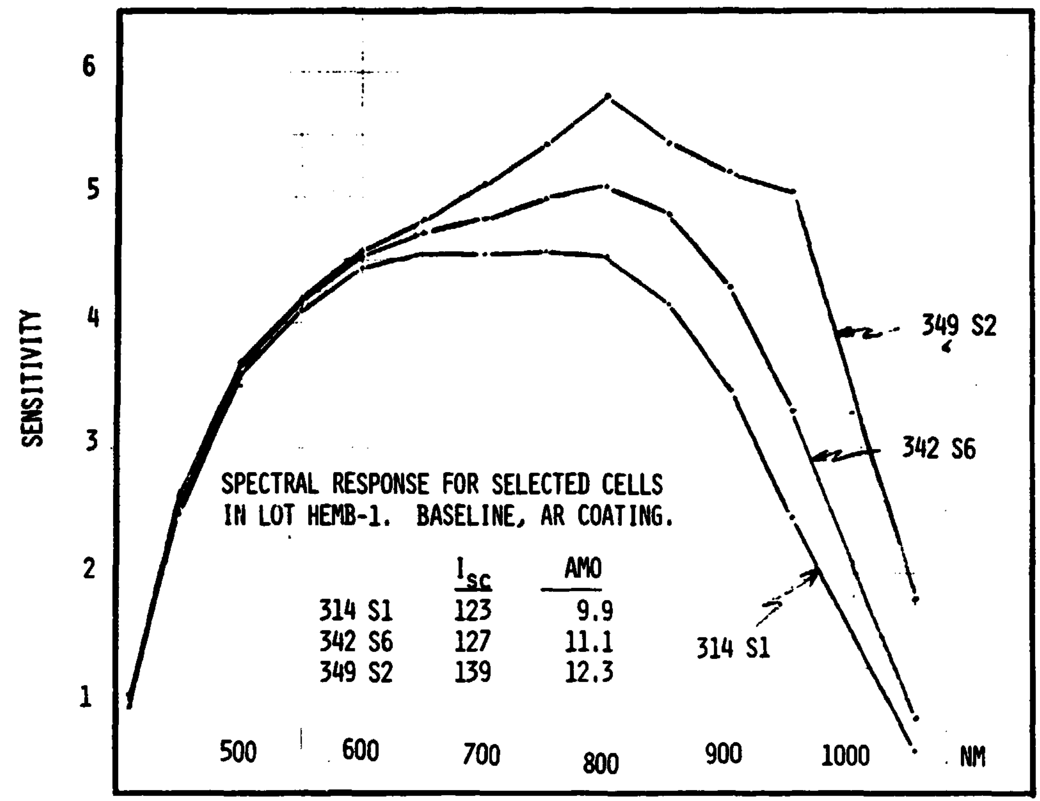
A METHOD	B METHOD (BSF)	C METHOD (BSF)
5.3%(AMO)	4.7%	6.0%
571 MV	579	594
218 MA	195	239
.517 FF	.499	502

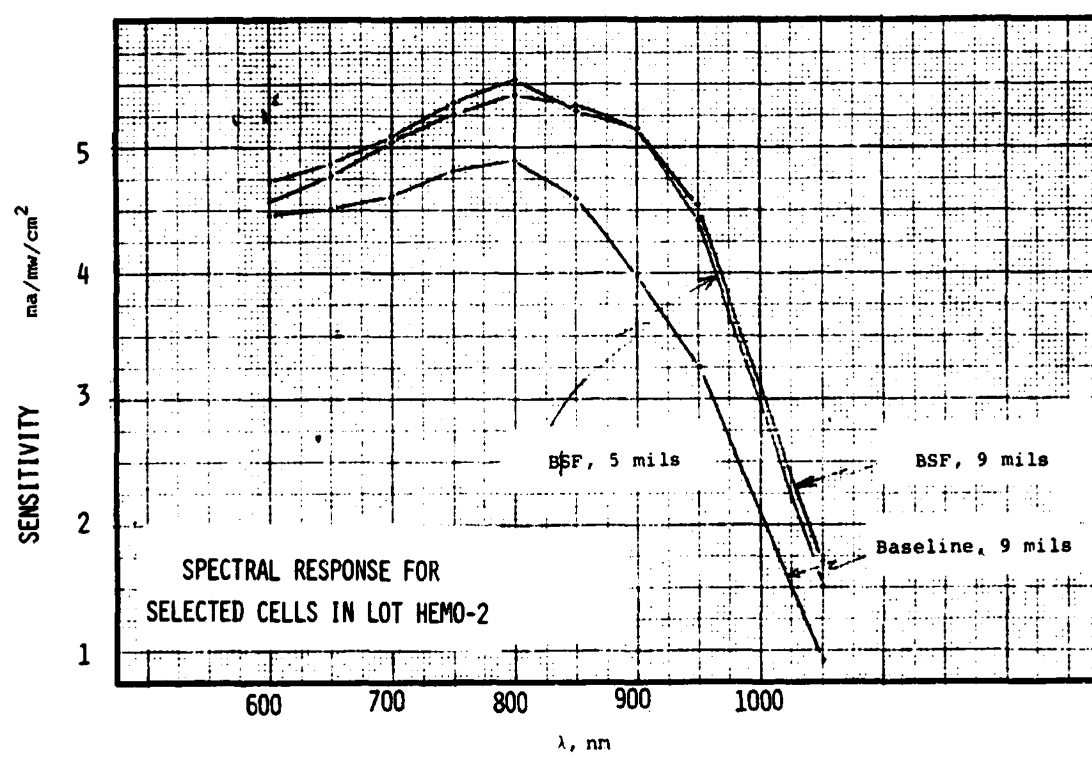
(AVERAGE VALUES)

I-V Data: HEM Si, 28°C, 2 x 2 cm, Cell Lot HEMB-1, AR Coating, Baseline

S/N	V_{oc}	I_{sc}	FF	%AMO	%AM1*
314 S1 E1	567	123	.763	9.9	11.7
314 S1 E2	456	118	.321	3.2	-
314 S3 M	574	124	.701	9.2	10.9**
314 SB E2	SHUNTED**				
342 S2 E1	594	128	.747	10.5	12.4
342 S2 M	597	128	.748	10.6	12.5
342 S2 E2	598	129	.755	10.8	12.7
342 S6 M	595	127	.798	11.1	13.1
349 S2 E1	605	139	.790	12.3	14.5
349 S2 M	603	135	.785	11.8	13.9
349 S6 E1	597	127	.718	10.1	11.9
349 S6 M	607	138	.771	11.9	14.0
349 S6 E2	580	124	.766	10.2	12.0

* CALCULATED FROM AM1/AMO = 1.18:1
** POLYCRYSTALLINE


SENSITIVITY
6
5
4
3
2
1
500
600
700
800
900
1000
NM
349 S2
342 S6
314 S1
SPECTRAL RESPONSE FOR SELECTED CELLS
IN LOT HEMB-1. BASELINE, AR COATING.
I_{SC}
AMO
314 S1 123 9.9
342 S6 127 11.1
349 S2 139 12.3


SENSITIVITY
ma/mw/cm^2
5
4
3
2
1
600
700
800
900
1000
λ, nm
BSF, 5 mils
BSF, 9 mils
Baseline, 9 mils
SPECTRAL RESPONSE FOR
SELECTED CELLS IN LOT HEMO-2

I-V Data: Web Si, Lot WEBO-1, 2 x 2 cm & 2 x 4 cm, AR Coating, BSF

S/N	V_{oc}	I_{sc}	FF	AMO	AM1	REMARKS
1	549	127	.755	9.7	11.8	BSF
2	546	245	.759	9.4	11.1	•
3	544	238	.688	8.3	9.9	• BSF
4	533	245	.626	7.6	8.4	• BSF
6	538	126	.670	8.4	9.7	BSF
8	544	242	.747	9.1	10.5	• BSF
	STRIP J187-3.5A					
B	530	247	.737	8.9	10.4	• BSF
C	528	246	.734	8.8	10.3	• BSF
D	526	251	.724	8.8	10.4	• BSF
E	530	253	.747	9.2	10.8	• BSF
F	526	244	.745	8.8	10.3	• BSF
G	531	253	.699	8.7	10.3	• BSF
	STRIP J191-2.5A					

• 2 cm x 4 cm

I-V Data: WEBO-1, Average Values

STRIP	V_{OC} MV	J_{SC} MA/CM^2	FF	%AMO	%AM1	
1 AVG	542	30.8	.697	8.6	10.0	BSF*
S	6	.8	.054	.9	1.2	ALL
AVG	544	31.6	.713	9.1	10.7	4CM^2
	546	30.6	.759	9.4	11.1	8CM^2,BASE.
2 AVG	529	31.1	.731	8.9	10.4	3CM^2,BSF
S	2	.5	.018	.2	.2	
3 AVG	578	33.6	.658	9.5	-	8CM^{2}BSF
S	43	.8	.132	2.4	-	
AVG	588	35.5	.523	8.0	-	4CM^{2}BSF
S	15	.6	.159	2.9		
AVG	598	34.1	.758	11.5	13.1	BASE. ALL.
MAX	598	34.5	.778	11.9	13.7	BASE.

S - SAMPLE STANDARD DEVIATION

1 - J 187-3.5A

2 - J 191-2.5A

3 - CONTROLS

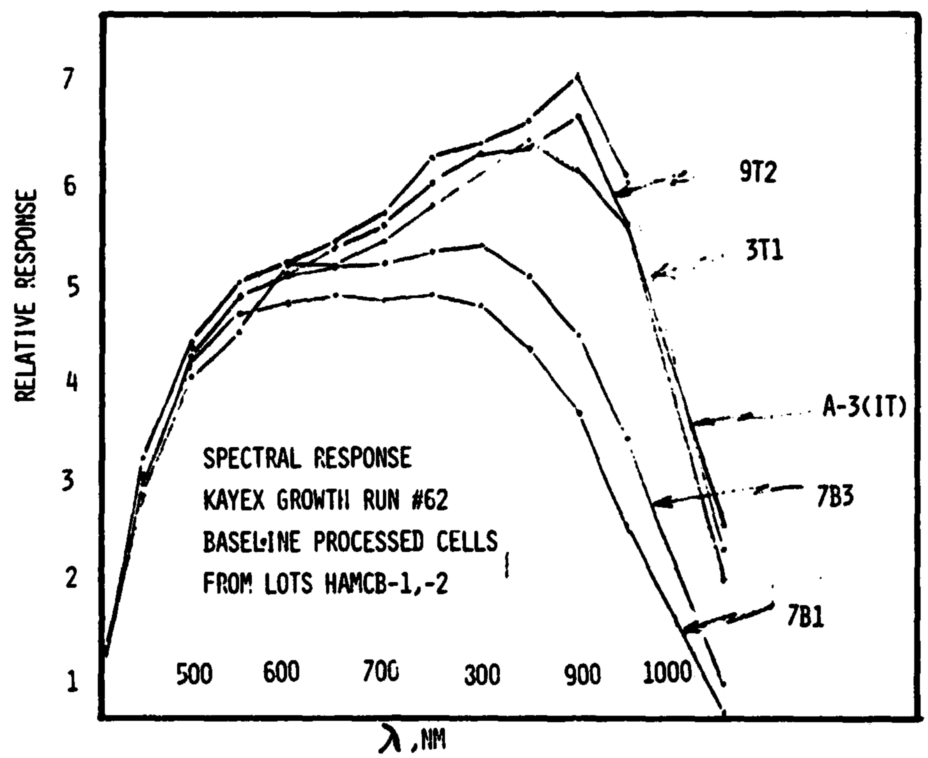
* - SCREEN PRINTED BSF SOURCE

Illuminated Data for Keyex Cell Lot HAMCB-1, 28°C, Baseline; Run No. 62, Crystal No. 1, Top 2 x 2 cm, AR Coating

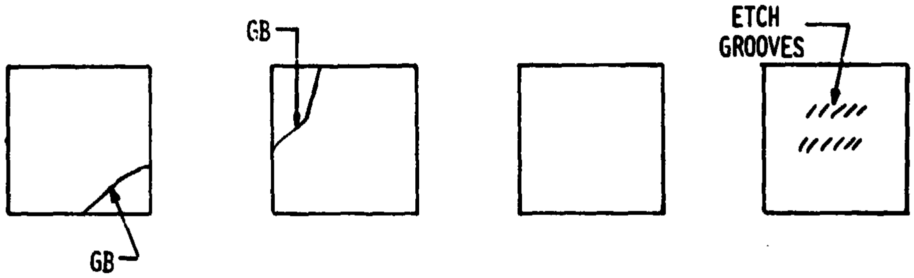
	S/N	V_{oc}	I_{sc}	FF	η%AM0	η%AM1	η%(1.4:1)
	A-1	581	138	.795	11.8	14.2	16.5
	-2	578	138	.794	11.7	14.2	16.4
	-3	582	141	.789	11.9	14.5	16.7
	-5	578	140	.621	9.3	-	
	-6	579	137	.775	11.4	13.8	16.0
	-7	569	135	.649	9.2	-	
	-8	556	138	.567	8.0	-	
	-9	572	139	.684	10.0	-	
	-10	581	139	.743	11.1	-	
	-11	575	136	.704	10.2	-	
	-12	577	140	.743	11.1	-	
	B-1	566	133	.651	9.1	-	
	-2	574	140	.543	8.1	-	
	-3	575	138	.756	11.1	-	
	-4	581	138	.773	11.5	13.8	16.1
	-5	577	135	.778	11.2	13.5	15.7
	-6	571	139	.703	10.3	-	
	-8	579	139	.774	11.5	13.9	16.1
	-9	578	138	.788	11.6	14.1	16.2
	-10	551	137	.506	7.1	-	
	-11	424	134	.408	4.3	-	
	-12	581	137	.790	11.6	14.0	16.2
CONTROL	-1	598	135	.809	12.1	14.3	16.9
	-5	583	145	.782	12.2	14.6	17.1

Illuminated Data for Keyex Cell Lot HAMCB-2, 28°C, Baseline; Run No. 62, 2 x 2 cm. AR Coating

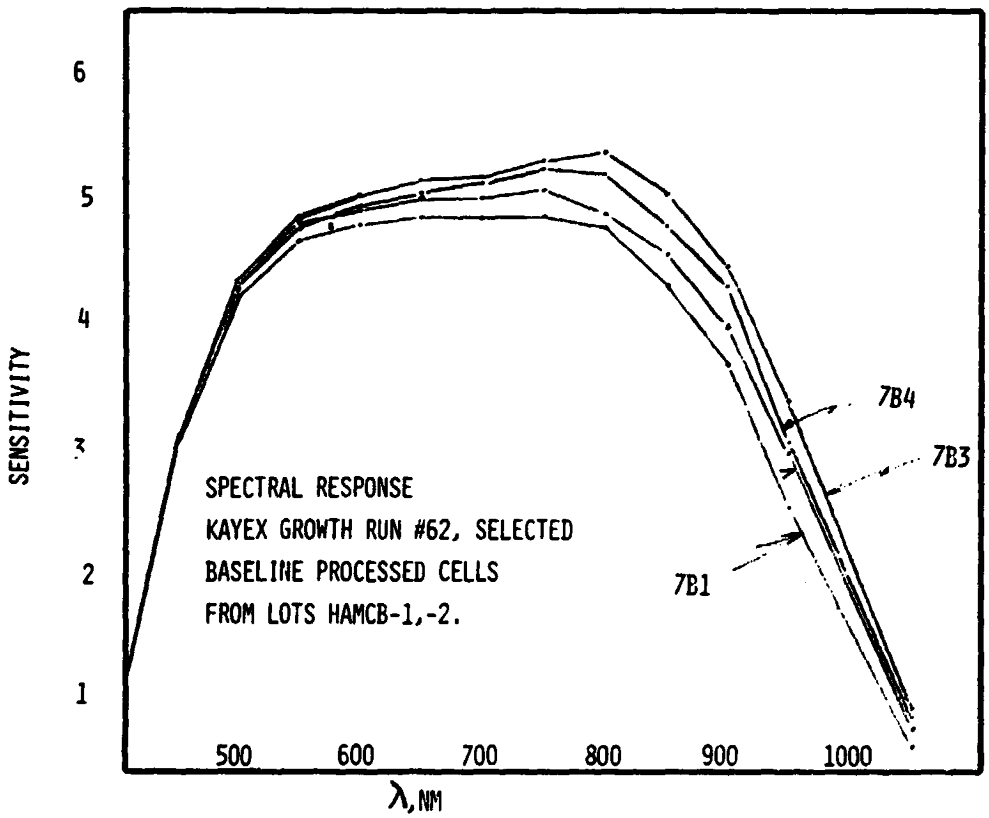
	S/N	V_{oc}	I_{sc}	FF	η %AMO	η %AM1	η %1.4:1
	3T1	579	136	.773	11.2	13.4	15.7
	5T2	575	132	.772	10.8	12.9	15.1
	9T2	581	130	.790	11.0	13.1	15.4
	9M1	581	130	.783	10.9	13.0	15.3
	9M2	582	131	.780	11.0	13.1	15.4
	1B1	580	135	.773	11.2	13.4	15.7
	7B1	570	123	.753	9.8	11.5	13.7
	7B2	574	128	.778	10.6	12.5	14.8
	7B3	582	132	.780	11.1	13.0	15.5
	7B4	551	116	.769	9.1	10.7	12.7
	9B1	559	116	.767	9.2	10.8	12.9
CONTROL	-1	580	143	.765	11.7	14.0	16.4
	-2	581	139	.782	11.7	13.9	16.4



TECHNOLOGY DEVELOPMENT AREA: Large Area Silicon Sheet Task



7B1	7B2	7B3	7B4	S/N
570 MV	574	582	551	V_{oc}
123 MA	123	132	116	I_{sc}
.753 FF	.778	.780	.769	FF
9.3%	10.6	11.1	9.1	AMO



Breakage Loss on Phase II

MATERIAL	1	2	3	4	5	6	7	8	9	10	TOTAL
EFG			7.3%		5.5%		3.6%				16.4%
WEB	27.3		3.0		3.0	9.1				3.0	45.5
HEM	3.3	1.1		5.6		2.2	6.7	4.4	1.1		24.4
HAMCO	8.9	4.4		2.2	-		2.2		2.2		20.0

1 - CUTTING OR SCRIBING
2 - SIZE ETCH
3 - V/I PROBE
4 - BACK ETCH
5 - SCREEN PRINTING
6 - EVAPORATION
7 - EDGE ETCH
8 - MASK & CLEAN
9 - AR COATING
10 - TESTING

AM1 Measurements

SPECTROLAB SOLAR SIMULATOR

AM1 PYREX-WATER FILTER

AM1 CALIBRATED SOLAR CELL (NASA)

STANDARD CELL, TEST FIXTURE & AM1 FILTER AT CONSTANT TEMPERATURE

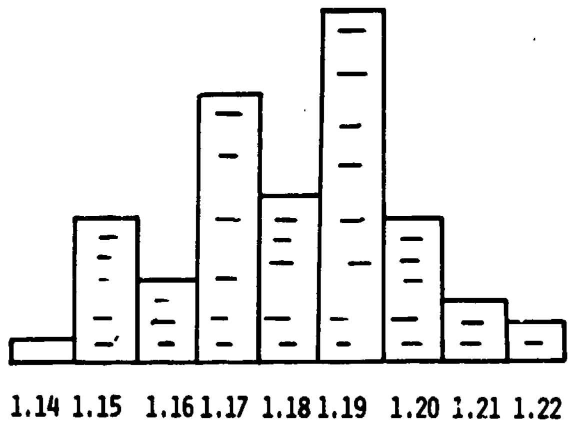
Ratio, AM1 Efficiency to AM0 Efficiency

MATERIAL	$\bar{R}$	S	N
HEM	1.17	.01	12
WEB	1.18	.02	18
HAMCO	1.19	.02	15
CONTROL	1.18	.02	22
COMPOSITE	1.18	.02	67

$R = \eta_{AM1}/\eta_{AM0}$
S = SAMPLE STANDARD DEVIATION
N = SAMPLE SIZE

Ratio of AM1 Conversion Efficiency to AM0 Conversion Efficiency

WEB	HEM	HAMCO	CONTROL
$\bar{R}$ = 1.18	$\bar{R}$ = 1.17	$\bar{R}$ = 1.19	$\bar{R}$ = 1.18
S = .02	S = .01	S = .02	S = .02
N = 18	N = 12	N = 15	N = 22



TOTAL
$\bar{R}$ = 1.18
S = .02
N = 67

I-V Data for Highest-Efficiency Cells by Material to Date

MATERIAL	J_{sc} MA/CM^2	V_{oc} MV	FF	η% (AMO)	REMARKS
RTR	23.8	559	.74	7.2	RTR-2(3.5%AM1)*
EFG-RH	29.0	537	.73	8.4	134-36(9.9% AM1)*
EFG-RF	31.3	567	.75	9.3	(11.6% AM1)*
WACKER SILSO	33.5	554	.77	10.6	(12.5% AM1)*
WEB	37.3	534	.75	12.0	RE 25-23(14.2% AM1)*
HEM	34.8	605	.79	12.3	CRYSTAL 349(14.5% AM1)*
HAMCO	37.5	533	.77	12.4	CRYSTAL TOP (3T)(14.6% AM1)*
CONTROL	39.5	607	.77	13.6	WO-1 (16.0% AM1)*

* CALCULATED FROM 1.18:1 RATIO

PROJECT ANALYSIS AND INTEGRATION AREA

Technology Session

Paul Henry, Chairman

Twenty-five candidate factories, based on ingot technology, were presented in the PA&I session. An analysis was performed to investigate the sensitivity of module price to different ingot growth methods, ingot diameter and sawing methods.

The input data for this analysis were supplied by Large-Area Sheet Task personnel. A single cell-processing sequence, applied to all the different sheet materials, was supplied by the Production Process and Equipment Area. The sawing methods, ID, multiblade and wire, were input as either conservative or optimistic. The conservative cases assume that all further development is discontinued and the present technology is scaled up to large-scale production. The optimistic cases assume that the 1982 Technical Readiness goals for sawing are attained.

The required prices obtained in this study ranged from $0.83/Wp for 5-in. dia Czochralski ingots with conservative wire sawing cost to $0.58/Wp for HEM ingots with optimistic wire-sawing cost. Optimistic assumptions were required for any Czochralski case to meet the program goals.

Discussion of these results centered mostly on the HEM results, where the contractor believed the assumptions were too conservative, especially the assumed crystal growth rate. This will be reviewed and a revised estimate will be published.

The impending release of SAMIS III, Release III, was discussed. This version has variable-operating-schedules capability and minor improvements in the financial model and user interface. The release, scheduled for April 1, 1980, was delayed since a number of users were using the Release II version for proposal preparation and a new release would have caused an unwarranted perturbation of their efforts.

The Technology Development and Applications Lead Center was invited to present a review of the status of the residential version of the lifetime cost and performance model. Viewgraphs describing the model and its status are included in the following section.

SAMICS ANALYSIS: 15th PIM CANDIDATE FACTORIES

JET PROPULSION LABORATORY
R. W. Aster

- GENERAL DESCRIPTIONS AND RESULTS
- IMPACT OF CELL SIZE
- SPECIFIC CASES

15th PIM Candidate Factory Description

ONE TYPE OF FACTORY FOR CELL PROCESSING AND MODULE FABRICATION WAS USED. KEY FEATURES OF THAT FACTORY INCLUDE:

- FACTORY SIZE IS 100 MWp
- MANUFACTURING YEAR IS 1986
- STARTUP BEGINS IN 1985, CONSTRUCTION IN 1983
- RETURN ON EQUITY IS SET AT 21%

15th PIM Candidate Module Description

- MODULES ARE APPROXIMATELY 4 ft by 4 ft
- PACKING EFFICIENCY AND EXACT MODULE SIZE IS DIFFERENT FOR THE FOUR CELL SHAPES (5-in. ROUND, 6-in. ROUND, 4-in. SQUARE, AND 4-in. QUARTER CIRCLE (QUAD)
- ENCAPSULATION MATERIAL IS 1/8 in. ANNEALED FLOAT GLASS, EVA, AND ALUMINIZED MYLAR
- CELLS ARE ETCHED, $POCl_3$ DIFFUSED, PRINTED WITH ALUMINUM ON THE BACK SURFACE AND SILVER ON THE FRONT SURFACE

Summary of 5-in. Round Cells

INGOT TYPE: 25kg (USABLE) Cz INGOTS, 5 in. DIAMETER, 33.5 in. LONG.
5 INGOTS PULLED PER RUN

REQUIRED PRICE RANGE: \$0.81 TO \$0.83/Wp (ONLY 2 CASES RUN)

INGOT REQUIRED PRICE (\$/kg): \$25.4/kg

MODULE PACKING EFFICIENCY: 80%

CELLS PER 4 x 4 ft MODULE: 99

MODULE EFFICIENCY: 12%

Summary of 6-in. Round Cells

INGOT TYPE 1: 35 kg (USABLE) Cz INGOTS, 6-in. DIAMETER, 23 in. LONG, 4 INGOTS PULLED PER RUN

INGOT TYPE 2: 45.9 kg (USABLE) Cz INGOTS, 6-in. DIAMETER, 42.2 in. LONG, 3 INGOTS PULLED PER RUN

REQUIRED PRICE RANGE: \$0.62 TO \$0.80
(LOW PRICE CAME FROM INGOT TYPE 1, OPTIMISTIC ID SAWING. HIGH PRICE CAME FROM INGOT TYPE 2, PESSIMISTIC MBS SAWING)

INGOT REQUIRED PRICE (\$/kg): 20.0 (TYPE 1), 19.5 (TYPE 2)

MODULE PACKING EFFICIENCY: 79%

CELLS PER 4 x 4 ft MODULE: 63

MODULE EFFICIENCY: 12%

Summary of 4-in. Square Cells

INGOT TYPE: HEM CAST INGOTS (30 cm^3)

REQUIRED PRICE RANGE: \$0.58 TO \$0.80/Wp
(LOW PRICE CAME FROM OPTIMISTIC WIRE SAWING, HIGH PRICE CAME FROM PESSIMISTIC ID SAWING)

INGOT REQUIRED PRICE (\$/kg): \$14.4/kg

MODULE PACKING EFFICIENCY: 95%

CELLS PER 4 x 4 ft MODULE: 144

MODULE EFFICIENCY: 14%

Summary of 4-in. Quad Cells

INGOT TYPE: 50 kg (USABLE) Cz INGOTS, 8 in. DIAMETER, 26 in. LONG, 5 INGOTS PULLED PER RUN. INGOTS ARE CUT INTO 4-in. QUARTER-ROUND (QUAD) BOULLES BEFORE SLICING

REQUIRED PRICE RANGE: \$0.68 TO \$0.80/Wp
(LOW PRICE CAME FROM OPTIMISTIC MBS SAWING. HIGH PRICE CAME FROM CONSERVATIVE WIRE SAWING)

INGOT REQUIRED PRICE (\$/kg): \$15.0/kg

MODULE PACKING EFFICIENCY: 83%

CELLS PER 4 x 4 ft MODULE: 150

MODULE EFFICIENCY: 12%

Ingot Sizes and Ratios

PROCESS	DIAM. (inches)	USABLE INGOT WEIGHT (kg)	USABLE LENGTH (inches)	CROP PROCESS	IDEAL RATIO	SAW BOULLE LENGTH (inches)	SLICES/CM LOWER	SLICES/CM UPPER	SLICES/BOULLE LOWER	SLICES/BOULLE UPPER
Cz 1	5	29.3	39	MBS	2.45	16	20.5	23.5	833	955
				WIRE	3.25	12	19.0	25	570	[illegible]
				ID SAW	1.00	39	17.9		1783	
	6	35	32.2	MBS	2.02	16	20.5	23.5	833	[illegible]
				WIRE	2.66	12	19.0	25	570	[illegible]
				ID SAW	1.00	32.2	17.9	20	1462	[illegible]
	8 QUADS	50	26	MBS	1.625	16	20.5	23.5	833	955
				WIRE	2.167	12	19.0	25	570	750
				ID SAW	1.00	26		22.2		1466
Cz 2	6	45.9	42.2	MBS	2.638	16	20.5	23.5	833	955
				WIRE	3.517	12	19	25	570	750
				ID SAW	1.00	42.2	17.9	20	1917	2143
HEM		63	12	MBS	6.75	16	20.5	23.5	833	955
				WIRE	9.00	12	19	25	[illegible]	750
				ID SAW	9.00	12	17.9	22	[illegible]	660

15th PIM Candidate Factory Comparison Prices

REQUIRED BY THE VARIOUS INGOT GROWTH AND SLICING OPTIONS (EFFECTS OF CELL SIZE AND SHAPE ON SUBSEQUENT PROCESSING COSTS ARE INCLUDED)
(1980 $/Wpk)

	ID SAW		MBS SAW		WIRE SAW	
	CONS	OPT	CONS	OPT	CONS	OPT
5-in. Cz	[illegible]				0.83	
6-in. Cz1	0.74	0.62	0.78	0.71	0.77	0.63
6-in. Cz2	0.76	0.63	0.80	0.75	0.79	0.65
4-in. QUAD Cz	0.75		0.73	0.68	0.80	0.69
4 x 4-in. HEM	0.80	0.67	0.70	0.63	0.71	0.58

Module Fabrication Steps

	Cz(1) 6-in. (VALUE ADDED $/Wpk)	Cz(1) 8-in. QUAD (VALUE ADDED $/Wpk)
PANEL PREPARATION	0.053	0.052
INTERCONNECT CELLS	0.022	0.023
CONNECT AND TEST STRINGS	0.020	0.019
CLEAN MODULE	0.010	0.010
HEAT AND VACUUM BOND	0.005	0.005
TRIM EDGE AND SEAL	0.006	0.006
FINAL TEST AND LABEL	0.000	0.000
PACKING AND SHIPPING	0.011	0.010
TOTAL	0.127	0.125

Cell-Processing Steps
(Conservative Wire)

	Cz(1) 6-in. VALUE ADDED $/Wpk	Cz(1) 8-in. QUAD VALUE ADDED $/Wpk
CLEAN WAFER	0.003	0.005
DIFFUSE POCL	0.011	0.025
AL BACK CONTACT	0.004	0.005
CLEAN WAFER	0.003	0.005
SILVER FRONT CONTACT	0.070	0.073
AR COAT	0.008	0.010
ELECTRICALLY TEST	0.003	0.006
TOTAL	0.100	0.129

Impact of Cell Size
(Conservative Wire Saw)

	5-in. ROUND	4-in. SQUARE	6-in. ROUND	4-in. QUAD
INGOT $/kg	26	15	20	15
SHEET $/m^2 VALUE ADDED	60	48	51	56
CELL $/m^2 VALUE ADDED	15	16	14	18
MODULE $/m^2 VALUE ADDED	15	14	15	15

Impact of Cell Size
(Conservative ID Saw)

	5-in. ROUND	4-in. SQUARE	6-in. ROUND	4-in. QUAD
INGOT $/kg	25	14	20	14
SHEET $/m^2 VALUE ADDED	60	61	50	54
CELL $/m^2 VALUE ADDED	15	16	14	17
MODULE $/m^2 VALUE ADDED	15	14	14	15

Impact of Cell Size
(Conservative MBS Sawing)

	5-in. ROUND	4-in. SQUARE	6-in. ROUND	4-in. QUAD
INGOT $/kg		13	19	13
SHEET $/m^2 VALUE ADDED		52	58	52
CELL $/m^2 VALUE ADDED		15	14	16
MODULE $/m^2 VALUE ADDED		13	14	14

General Industry Assumptions for ALL SAMICS Runs

1) 100 mW INDUSTRY

2) CELL EFFICIENCY ASSUMES ENCAPSULATED CELLS OPERATING AT 28°C

3) PACKING EFFICIENCY IS BASED ON OPTIMAL PACKING OF CELLS IN A 4 x 4 ft SURFACE AREA REDUCED BY A 3/4 in. FRAME BORDER

SAMIS RELEASE 3 MODIFICATIONS

JET PROPULSION LABORATORY

Robert G. Chamberlain

OLD NAME:

SAMIS III = SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION

NEW NAME:

SAMIS = STANDARD ASSEMBLY-LINE MANUFACTURING INDUSTRY SIMULATION

- DATA FILE CHANGES
  - NEW CAPABILITIES ⇒ NEW PARAMETERS
  - THEREFORE, EXISTING PROCESS FILES WILL NOT BE COMPATIBLE
  - WE WILL PROVIDE ONE-SHOT PROGRAMS TO MODIFY THE FILES
- MODEL IMPROVEMENTS
  - MAJOR: OPERATING SCHEDULE, CONSTRUCTION CONTINGENCY, . . .
  - MINOR: TAX PART OF WORKING CAPITAL, CASH BALANCE, . . .
- REPORT IMPROVEMENTS
  - PROFIT
  - REPORT YEAR
  - EXPENSE SUMMARIES NOW GIVE $/Wp AS WELL AS $
- PROGRAM IMPROVEMENTS

Data File Changes

- EXPENSE DATA, WHICH CONTAINS THE COST ACCOUNT CATALOG
  - FORMAT IS NOT CHANGED, BUT THERE ARE NEW EXPENSE ITEM NAMES, NEW INFLATION TABLES, NEW INDIRECTS
  - YOU MUST MAKE A NEW USER-SPECIFIC CATALOG TO INCLUDE YOUR EXPENSE ITEMS
- PROCESS DATA, WHICH CONTAINS FORMAT A PROCESS DESCRIPTIONS
  - NEW ATTRIBUTES: NUMBER.OF.SHIFTS.PER.DAY
PERSONNEL.INTEGERIZATION.OVERRIDE.SWITCH
PURCHASE.COST.VS.QUANTITY.BOUGHT TABLE OF COMPONENT
- COMPANY DATA, WHICH CONTAINS FORMAT B COMPANY DESCRIPTIONS
  - NEW ATTRIBUTES HAVING TO DO WITH THE OPERATING SCHEDULE

CONTACT MURIEL HORTON (213) 354-2709 FOR INFORMATION ABOUT THE ONE-SHOT PROGRAMS TO CHANGE YOUR FILES

Model Improvements

- COMPANY OPERATING SCHEDULE NOW DEFINED BY INPUT (OLD SCHEDULE: 24 hrs/day, 345 days/yr NOW THE DEFAULT)
- FACILITIES CONSTRUCTION CONTINGENCY AND EQUIPMENT CONTINGENCY
- INTEGER NUMBERS OF MACHINE OPERATORS IN EACH SHIFT (BACKGROUND CONTROLLED BY RUN.CONTROL: INTEGER.OPERATORS.SWITCH, ALSO AVAILABLE: PROCESS: PERSONNEL.INTEGERIZATION.OVERRIDE.SWITCH)
- MACHINE COMPONENTS CAN NOW BE CHEAPER IF YOU BUY SEVERAL
- WAREHOUSE SIZE NOW DEPENDS ON WHAT'S IN IT
- A COMPANY: BETWEEN.PROCESS.INVENTORY.TIME ATTRIBUTE IS NOW AVAILABLE
- MONTHLY RESOLUTION OF DEPRECIATED VALUES, INSTEAD OF YEARLY
- WORKING CAPITAL NOW INCLUDES A CASH BALANCE
- A FRACTION OF WORKING CAPITAL IS NOW SUBJECT TO PROPERTY TAXES

Report Improvements

- COMPANY PROFIT WAS REDEFINED AND IS NOW PRINTED OUT
  DOLLARS, PERCENT OF SALES, PERCENT OF EQUITY
- EXPENSE SUMMARIES NOW INCLUDE $/Wp AS WELL AS JUST $
- RUN.CONTROL: REPORT.YEAR MAY BE MANUFACTURING.YEAR OR BASE.YEAR
- THE CURRENT.TECHNOLOGY BACKGROUND REPORT NOW LOOKS MORE LIKE FORMAT A
- NUMEROUS MINOR CHANGES TO IMPROVE READABILITY

Program Improvements

- NOW ADDITIONAL VERIFICATION OF PROCESS DESCRIPTION DATA
  - DEAD-END SUBSEQUENCES
  - SOME PROCESS MUST MAKE THE COMPANY'S PRODUCT
- IMPROVED FILE READING EFFICIENCY
- NON-INTEGER RELEASE NUMBERS

How to Get Background Reports

- BE SURE RUN.CONTROL: REPORT.OUTPUT.FILE = PRINT.FILE
  - WHILE CREATING THE RUN.CONTROL, ANSWER THE PROMPT FOR REPORT.OUTPUT.FILE BY PRINT.FILE, NOT BY TERMINAL.
  - IF THE CURRENT RUN.CONTROL: REPORT.OUTPUT.FILE = TERMINAL,

$$> \begin{bmatrix} \text{FIND} \\ \text{F} \end{bmatrix} \begin{bmatrix} \text{RUN.CONTROL} \\ \text{RC} \end{bmatrix}$$

$$\begin{bmatrix} \text{CHANGE} \\ \text{C} \end{bmatrix} \begin{bmatrix} \text{REPORT.OUTPUT.FILE} \\ \text{ROF} \end{bmatrix}$$

- TO GET THE SAMIS-PRODUCED COST ACCOUNT CATALOG

$$> \begin{bmatrix} \text{REPORT} \\ \text{RE} \end{bmatrix} \begin{bmatrix} \text{COST.ACCOUNT.STRUCTURE} \\ \text{CAS} \end{bmatrix} \begin{bmatrix} \text{ONFILE} \\ \text{INCORE} \\ \text{BOTH} \end{bmatrix}$$

- TO GET THE SAMIS-PRODUCED PROCESS DESCRIPTION REPORT

$$> \begin{bmatrix} \text{REPORT} \\ \text{RE} \end{bmatrix} \begin{bmatrix} \text{CURRENT.TECHNOLOGY} \\ \text{CT} \end{bmatrix} \begin{bmatrix} \text{ONFILE} \\ \text{INCORE} \\ \text{BOTH} \end{bmatrix}$$

- BE SURE TO PRINT IT OUT WHEN DONE WITH SAMIS
  - HAVE AN ADDRESS (SEE NCSS INSTRUCTIONS ON PADDR OR TADDR)
  - THEN, FROM OUTSIDE OF SAMIS,
    XX.XX.XX > OFFP

LIFETIME COST AND PERFORMANCE (LCP) MODEL FOR RESIDENTIAL PV SYSTEMS

JET PROPULSION LABORATORY

Chet Borden

Purpose

- THE LIFETIME COST AND PERFORMANCE (LCP) RESIDENTIAL MODEL IS DESIGNED TO EVALUATE THE PERFORMANCE, COST AND VALUE OF UTILITY CONNECTED RESIDENTIAL PHOTOVOLTAIC SYSTEMS OWNED BY THE HOMEOWNER

- LCP WILL SUPPORT SYSTEM DESIGNERS AND POTENTIAL OWNERS INTERESTED IN MAKING DESIGN AND OPERATIONS POLICY TRADEOFFS, AND POLICY PLANNERS INTERESTED IN EVALUATING ALTERNATIVE SYSTEM APPLICATIONS (FOR THE PURPOSES OF PROGRAM PLANNING AND R&D BUDGET ALLOCATION)

Capabilities

- SIMULATE HOURLY PERFORMANCE OF ALTERNATIVE PV RESIDENTIAL SYSTEM DESIGNS IN VARIOUS LOCATIONS
- CALCULATE LONG TERM CHANGES IN PV SYSTEM PERFORMANCE AND RELIABILITY (IN TERMS OF REDUCTIONS DUE TO DEGRADATION, AND INCREASES DUE TO OPERATIONS/MAINTENANCE (O/M) ACTIVITIES)
- CAUSALLY RELATE PV SYSTEM DESIGN AND O/M STRATEGIES TO SYSTEM PERFORMANCE, COST AND VALUE OVER TIME
- EVALUATE TIME OF DAY ELECTRICITY PURCHASES AND SELL-BACK (IN kWh AND DOLLARS)
- PERFORM SENSITIVITY ANALYSES
- GENERATE TECHNICAL AND FINANCIAL INFORMATION FOR USE BY ECONOMIC MODELS AND MARKET PENETRATION MODELS

WHEN LINKED WITH AN ECONOMIC MODEL, LCP CAN PROVIDE VALUABLE INFORMATION:

<u>FOR POLICY PLANNERS:</u>

- DETERMINE APPLICATION-SPECIFIC SYSTEM AND SUBSYSTEM BREAKEVEN COSTS
- IDENTIFY APPLICATION-SPECIFIC SYSTEM DESIGN PREFERENCE

<u>FOR SYSTEM DESIGNERS AND OWNERS:</u>

- HELP DETERMINE OWNER-SPECIFIC OPTIMAL PV SYSTEM DESIGN AND SIZE
- CALCULATE COST-EFFECTIVE OPERATIONS/MAINTENANCE POLICIES
- CALCULATE FINANCIAL EFFECTS OF HOURLY HOMEOWNER ELECTRICAL DEMAND (AND CHANGES TO THAT DEMAND) WITH, AND WITHOUT, THE PV SYSTEM INSTALLED

Inputs

SYSTEM DESIGN
- SYSTEM SIZE AND ELECTRICAL DESIGN
- ARRAY CONFIGURATION AND TILT ANGLE
- COMPONENT EFFICIENCIES AND COSTS
- SUPPORT EQUIPMENT

POWER PLANT LOCATION
- LATITUDE/LONGITUDE
- HOURLY WEATHER DATA (SOLMET)
- CLIMATIC CONDITIONS (RAIN, WIND, DIRT ACCUMULATION)

PHOTOVOLTAIC MODULE CHARACTERISTICS
- SHORT CIRCUIT CURRENT AND OPEN CIRCUIT VOLTAGE AT STC
- AREA (A)
- EFFICIENCY (η_{MOD}) AT NOCT
- DISTRIBUTION OF INITIAL MODULE QUALITIES
- DEGRADATION AND FAILURE RATES (TIME-VARYING)
- MODULE PRICE (SAMIS)

SYSTEM CONSTRUCTION, STARTUP, AND TEST
- SCHEDULE AND COSTS

OPERATIONS AND MAINTENANCE (O&M)
- CLEANING FREQUENCY AND EFFECTIVENESS
- REPLACEMENTS, REPAIRS, AND BOS O&M
- O&M COSTS

FINANCIAL ATTRIBUTES
- CAPITAL EXPENDITURES AND EXPENSES OVER TIME
- TIME-VARYING FINANCIAL RATES

UTILITY GRID
- TIME OF DAY ELECTRICITY PRICES
- TIME OF DAY BUY-BACK RATES

HOURLY CUSTOMER DEMAND BY APPLIANCE TYPE (E.G., SOLOPS)

Compute Hourly Energy Output for Month (at PCU Level)

$$\sum_{\substack{\text{BRANCH} \\ \text{CIRCUITS}}} S \times A \times \eta_{MOD} \times \eta_{TEMP} \times \eta_{PCU} \times \eta_{DEG} \times \eta_{INT} \times \eta_{CLEAN} \times \eta_{BOS}$$

WHERE S = HOURLY INSOLATION ADJUSTED FOR ARRAY ORIENTATION AND SHADOWING

A = MODULE AREA

η_{MOD} = MODULE EFFICIENCY

η_{TEMP} = HOURLY TEMPERATURE FACTOR

η_{PCU} = HOURLY PCU EFFICIENCY FACTOR

η_{DEG} = { MODULE POWER DEGRADATION; ELECTRICAL MISMATCH IN BRANCH CIRCUIT }

η_{INT} = { MODULE FAILURE/FAILURE REPLACEMENT; BALANCE OF SYSTEM FAILURE/REPLACEMENT }

η_{CLEAN} = DIRT ACCUMULATION/CLEANING

η_{BOS} = BALANCE OF SYSTEM EFFICIENCY

EVALUATE ALTERNATIVE REPLACEMENT SCENARIOS

PERFORM HOURLY HOMEOWNER ELECTRICITY PURCHASE AND SELL-BACK ANALYSIS

EVALUATE EFFECT OF LOAD SHIFTING AND CHANGES IN DEMAND LEVELS (TBD)

COMPUTE REVENUES, CAPITAL EXPENDITURES, EXPENSES, AND ENERGY OUTPUT

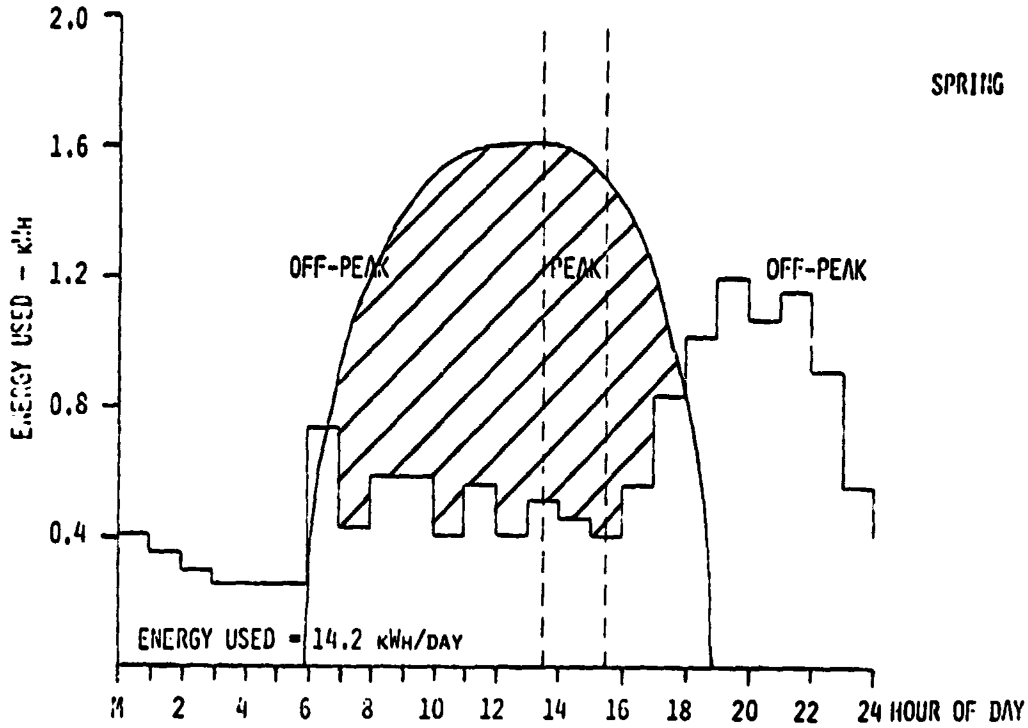
INCREMENT MONTH UNTIL END OF PLANT LIFETIME

Value of PV Electricity Generation

VALUE OF PV ELECTRICITY GENERATION

- UTILITY ELECTRICITY PURCHASE ALTERNATIVES
  - HOMEOWNER SELLS ALL PV OUTPUT TO THE GRID AND PURCHASES ALL ELECTRICITY FROM THE GRID
  - HOMEOWNER SELLS ALL OUTPUT IN EXCESS OF HIS OWN DEMAND
- NON-DISCRIMINATORY RATES TO ALL CUSTOMERS
  - UTILITY'S NET AVOIDED COST PAID TO PV OWNER
  - UTILITY RELIABILITY REQUIREMENTS SATISFIED
  - SELL BACK RATES FROM UTILITY GRID SIMULATION (E.G., SYSGEN)
- CHANGES IN PV OWNER TIME OF DAY DEMAND

Representative Residential Energy Demand



SOURCES: G.E. RESIDENTIAL STUDY, P. 6-11 (DEMAND)
MIT/EL.(PEAK PERIOD TIMING)

Model Outputs

PERFORMANCE

- HOURLY ENERGY OUTPUT OVER SYSTEM LIFETIME
- SOLAR/LOAD COMPARISONS FOR PEAK, SHOULDER, OFF-PEAK PERIODS
- POWER REDUCTION EFFECTS OF DEGRADATION, FAILURE, ELECTRICAL MISMATCH AND DIRT ACCUMULATION (MONTHLY)
- POWER OUTPUT EFFECTS OF O/M POLICIES AND MINIMUM SYSTEM PERFORMANCE LEVELS (MONTHLY)

COSTS

- MONTHLY (NOMINAL, PRE-TAX) CAPITAL COSTS AND EXPENSES
- BASED ON SYSTEM DESIGN AND INPUT (AND DERIVED) O/M ACTIVITIES
- ELECTRICITY PURCHASES
- HOMEOWNER AVOIDED COSTS (E.G., ROOF CREDIT)

VALUE

- BASED ON UTILITY PURCHASE STRATEGY AND TIME OF DAY PRICES
- INCLUDES POSSIBLE CHANGES IN ELECTRICITY DEMAND
- TOTAL REVENUES FROM PV ELECTRICITY GENERATION (FOR TAX PURPOSES)

Economic Analysis

- LCP TECHNICAL AND FINANCIAL OUTPUTS GO TO THE ALTERNATIVE POWER SYSTEM ECONOMIC ANALYSIS MODEL (DEVELOPED BY RICHARD B. DAVIS OF JPL) WHICH PERFORMS AN OWNER-SPECIFIC INVESTMENT ANALYSIS.

- FIGURES OF MERIT FOR THE INVESTMENT ANALYSIS INCLUDE SYSTEM NET PRESENT VALUE, LEVELIZED ENERGY COST, LIQUIDITY REQUIREMENTS, FRACTIONAL RETURN ON INVESTMENT, AND PAYBACK PERIOD.

- A DECISION-MAKER'S INVESTMENT CHOICE IS BASED ON THESE FIGURES OF MERIT, ANY FINANCIAL REQUIREMENTS, CURRENT INVESTMENT PORTFOLIO, AND SUBJECTIVE/ BEHAVIORAL FACTORS.

Usefulness of Economic Model

- ASSESS PV SYSTEMS UNDER THE NEW PURPA RULES
- IDENTIFY AREAS FOR FURTHER TECHNOLOGY DEVELOPMENT
- IDENTIFY COST-EFFECTIVE PV APPLICATIONS
- PROVIDE INFORMATION (INCLUDING EFFECTS OF GOVERNMENT INCENTIVES) FOR MARKET PENETRATION MODELS
- LEARN ABOUT PV SYSTEM LONG TERM PERFORMANCE (USING A SCENARIO APPROACH)
- INVESTIGATE THE VALUE OF HOMEOWNER (AND PV SYSTEM OWNER) LOAD MANAGEMENT

Residential Application Investment Decision Factors

- NEW CONSTRUCTION
  - BUILDER AND PURCHASER DECISION CRITERIA
  - OPTIMAL TIMING
  - REGIONAL SYSTEM DESIGN PREFERENCE
- RETROFIT
  - CURRENT AVAILABILITY OF PROPERLY DESIGNED HOMES
  - OPTIMAL TIMING OF INSTALLATION
  - OPTIMAL SYSTEM SIZE AND DESIGN
- TIME OF DAY (NON-DISCRIMINATORY) ENERGY PRICES (PURCHASE AND/OR SELL BACK) AND TIME OF DAY METERING
- TIME OF DAY DEMAND AND POSSIBLE CHANGES WITH TOD PRICING AND PV
- EXPECTED PERFORMANCE, COST AND VALUE OVER TIME
- FINANCING AND TAX IMPLICATIONS

Status

- LCP MODEL FOR UTILITY OWNED PV SYSTEMS IS COMPLETED AND ANALYSES ARE UNDERWAY
- LCP RESIDENTIAL MODEL IS CURRENTLY BEING CODED AND TESTED
- RESULTS FROM THE RESIDENTIAL ANALYSIS ARE ANTICIPATED BY NEXT PIM

ENGINEERING AREA
OPERATIONS AREA

JOINT TECHNOLOGY SESSION

R. G. Ross Jr. and
Larry Dumas, Chairmen

Engineering Area

Ron Ross, Engineering Area Manager, presented a brief overview of Engineering Area Activities. Recently published reports describing completed array design requirement study contracts and in-house design optimization studies were enumerated. Distribution of the listed reports has been made to the photovoltaic community. Continuing activities within the Engineering Area included module and array design requirements studies, safety considerations, module reliability and durability requirements development, and active participation in the SERI-Sponsored PV Standards Criteria Development. Of particular note, as part of the ongoing module and array series/parallel circuit analysis task, was a workshop on module and array circuit-design optimization conducted by the Engineering Area at JPL immediately preceding this PIM. Several recently initiated activities include design studies for integrated residential arrays, a study of building codes for commercial applications, and reliability-durability studies to support development of electrical isolation design guidelines and to support investigation of the effect of cell fracture strength on module production yields. An important reliability engineering study contract, just initiated, was described in detail during this PIM (see below). The status of two other engineering activities that have provided significant results recently, module soiling and low-cost array structures design, were also discussed.

Carl Maag reviewed the current status of module soiling studies. These studies have been conducted in two phases. The objectives of the task are to collect actual field data on loss of electrical performance caused by deposition of airborne particulates, investigate the mechanisms contributing to soil retention on various top cover materials, develop procedures for determining relative soiling affinities with respect to material compositions and site-dependent variables, and set preliminary guidelines for selection of module optical surface materials exposed to dirt and dust. Various test deployment sites and materials selected for evaluation were described. The soiling measurement procedures that have been developed were described. The soiling data, for up to nine months' deployment for a variety of materials and sites, was presented. This data allows, for the first time, continuous direct comparisons of soiling rates with respect to site-development variables for the most promising encapsulant surface materials currently under consideration. Advanced cleaning strategies are being investigated as part of this study.

P. A. Mihalkanin, IIT Research Institute, presented an overview of the Engineering Area study contract with IITRI, which was initiated the week before the 15th PIM, to support reliability engineering analyses of photovoltaic modules. The objective of the study is to develop engineering-oriented reliability data to support design of improved PV modules and arrays. The approach to the task includes development of reliability prediction tools, reliability design handbooks and guidelines, and actual data assessment. Based on a sequence of data collection, analysis, and determination of module and module component failure rates and distributions, a conceptual strawman module reliability engineering model was described. The proposed model considers application and environmental factors.

Abe Wilson, Cognizant Engineer for the Engineering Area array structure cost reduction study, presented an update of recent progress in identifying means of reducing the cost of flat-plate array structures for large industrial and central-station arrays. The study considers cost parameters of the panel frame, array structure, and foundations. Actual prototype panel and struture design, fabrication and load testing was accomplished. Cost estimates for the proposed structure designs were made by Kaiser Steel, which demonstrate that significant cost reductions are possible from previous estimates. Of particular note was the success of a unique buried-truss approach that yields array panel, foundation, and structure costs of only $18.70/m^2 (1980 $). The prototype of this design was displayed at the 15th PIM. Future work will investigate panel mounting arrangements, relationship of field and factory assembly costs, and impact of module installation sequence.

Operations Area

Gil Downing, Lead Engineer for the LSA module performance measurements effort, presented an overview of the facilities available and activities under way. Two related tasks are carried out. The first is the development and maintenance of measurement standards used for flat-plate module characterization. Methods and equipment for cell and module spectral response measurement, reference cell fabrication, and reference-cell calibration are available for this purpose. The second area is the application of these standards for routine I-V curve determination for large numbers of modules under evaluation. The Large-Area Pulsed Solar Simulator (LAPSS) is the facility used for this purpose. A second LAPSS with minicomputer data processing capability and a high-current dynamic load capacity has recently been installed at JPL. The evaluation of modules having cells with a response time too long for measurement by this pulsed technique (e.g., cadmium sulfide) was flagged as a problem to be addressed.

An update on the status of Block IV design and test contracts was given by Dan Runkle, LSA Production Task Manager. Prototype modules for test have been received from Motorola, General Electric, Applied Solar Energy, and Spire. Two of the remaining contractors have incurred schedule delays as a result of redesigning their modules with round rather than polygonal cells.

John Griffith, LSA Environmental Test Director, presented an update on recent test results. Block III exploratory testing has been completed, and the humidity-heat and humidity-freeze tests, in particular, have proven to be considerably more likely to induce module degradation than the standard qualification test sequence. Early results from the Block IV qualification testing indicate the need for some design changes in the tested modules. Little electrical degradation has been observed, but some problems with cell cracking and insulation integrity have occurred.

ENGINEERING AREA STATUS

(MARCH 1980)

JET PROPULSION LABORATORY

R.G. Ross Jr.

Recently Completed Activities

- RESIDENTIAL BUILDING CODE FINAL REPORT (BURT-HILL)
- RESIDENTIAL O&M COST STUDY (BURT-HILL)
- CURVED GLASS MODULE/INSULATION FINAL REPORT (BECHTEL)
- ELECTRICAL TERMINATION FINAL REPORT (MOTOROLA)
- WIND LOAD ANALYSIS FINAL REPORT (BOEING)
- CELL FRACTURE TESTING - PHASE I FINAL REPORT (JPL)
- GLASS STRUCTURAL SIZING FINAL REPORT (JPL)
- SOILING STUDY FINAL REPORT (JPL)

Recently Initiated Activities

- INTEGRATED RESIDENTIAL ARRAY DESIGN STUDIES (RFP - PROPOSALS DUE APRIL 1)
- COMMERCIAL BUILDING CODE STUDY (BURT-HILL)
- MODULE RELIABILITY ANALYSIS (IITRI)
- SOLAR POWER CELL FRACTURE TESTING (JPL)
- ELECTRICAL INSULATION REQUIREMENTS DEFINITION (JPL)

Continuing Activities

- MODULE SAFETY - PHASE II (UL)
- WIND LOAD TESTING (BOEING)
- CELL RELIABILITY TESTING (CLEMSON)
- RESIDENTIAL ARRAY INDUSTRIAL DESIGN (T&E)
- LOW-COST STRUCTURES DEVELOPMENT (JPL/KAISER)
- PV-THERMAL MODULE DEVELOPMENT (JPL)
- SERIES/PARALLEL ANALYSIS (JPL-WORKSHOP ON MARCH 31, APRIL 1)
- ENVIRONMENTAL REQUIREMENTS STUDIES
  - UV WEATHERING (DSET)
  - MODULE SOILING (JPL)
  - HOT-SPOT ENDURANCE (JPL)
- SERI STANDARDS SUPPORT (JPL)

MODULE SOILING UPDATE

JET PROPULSION LABORATORY

Carl R. Maag

Introduction

- ONE OF THE MOST SIGNIFICANT CAUSES OF ELECTRICAL PERFORMANCE DEGRADATION OF PHOTOVOLTAIC MODULES HAS BEEN THE ACCUMULATION OF AIRBORNE PARTICULATES

- JPL LOW-COST SOLAR ARRAY PROJECT INSTITUTED A STUDY TO CHARACTERIZE AND UNDERSTAND THE DIRT PROBLEM AND TO MINIMIZE ITS IMPACT ON ARRAY LIFE CYCLE COSTS

- PROJECT DEVELOPED NATURALLY INTO TWO PHASES

Phase I LSA Project Study Objectives

- DEVELOP A DATA BASE FROM FIELD EXPOSED MODULES AND MATERIALS

- IDENTIFY KEY PHYSICAL PROPERTIES OF OPTICAL MATERIALS WHICH GOVERN SOIL RETENTION

- IDENTIFY KEY ENVIRONMENTAL FACTORS WHICH GOVERN SOILING LEVELS

- DEVELOP SIMPLE LABORATORY TESTS FOR ESTIMATING AFFINITY OF PARTICLES TO VARIOUS ENCAPSULANT MATERIALS

- INITIATE FIELD EXPERIMENTS AND STUDIES TO PINPOINT ARRAY RELATED FACTORS INFLUENCING CONTAMINANT ATTRACTION AND RETENTION

Example of Module Soiling Data

MODULE DESCRIPTION AND LOCATION	TILT ANGLE	EXPOSURE DURATION	CHANGE IN I_{SC} (%)	
			BEFORE CLEANING	AFTER CLEANING
OUTER COVER: RTV615				
- CLEVELAND, OHIO	40^0	83d	-14	-7
- NYC, NEW YORK	45^0	6mo	-47	-8
OUTER COVER: GLASS				
- CLEVELAND, OHIO	40^0	83d	-3	+3
- NYC, NEW YORK	45^0	6mo	-11	+3
OUTER COVER: SYLGARD 184				
- CLEVELAND, OHIO	40^0	90d	-26	-5
- NYC, NEW YORK	45^0	6mo	-69	-15

Phase II LSA Project Study Objectives

- DEPLOY MATERIALS FOR OUTDOOR EXPOSURE
- DEVELOP TECHNICALLY SOUND TEST METHODS FOR EVALUATION OF ENCAPSULANT MATERIALS
- ASSESS DUST SPECIES, PROPERTIES AND ACCUMULATION AT VARIOUS SITES
- CORRELATE SITE UNIQUE DUST WITH MODULE POWER CHANGES
- DEVELOP UNDERSTANDING OF SOILING MECHANISMS (RETENTION)
- SET PRELIMINARY GUIDELINES FOR SELECTION OF MATERIALS EXPOSED TO DIRT/DUST

Phase II LSA Outdoor Exposure Materials

MATERIAL	MANUFACTURER	TYPE
METHYL SILICONE	GENERAL ELECTRIC	RTV 615
PROPRIETARY SILICONE	DOW CORNING	QI-2577
SODA LIME FLOAT GLASS	FORD MOTOR GLASS DIV	1/8 in. WINDOW GLASS
BOROSILICATE GLASS	CORNING GLASS	7070
ALUMINO SILICATE GLASS	CORNING GLASS	0317
POLYVINYL FLUORIDE	DUPONT	TEDLAR 400xRB160SE
ACRYLIC	XCEL CORP	KORAD 212

Phase II LSA Project Outdoor Exposure Locations

- JPL/PASADENA, CALIFORNIA (5 LOCATIONS)
  - 45^0 SOUTH
  - 34^0 SOUTH
  - -1500 volts
  - GROUND
  - +1500 volts
- TABLE MOUNTAIN/WRIGHTWOOD, CALIFORNIA
- GOLDSTONE/BARSTOW, CALIFORNIA
- PT. VICENTE (USCG/PALOS VERDE, CALIFORNIA)
- SCAQMD (2 LOCATIONS)
  - PASADENA, CALIFORNIA
  - TORRANCE, CALIFORNIA
- NYU/NEW YORK, NEW YORK
- MIT/LINCOLN LABS/LEXINGTON, MASSACHUSETTS
- SANDIA LABS/ALBUQUERQUE, NEW MEXICO
- BATTELLE, PNL/RICHLAND, WASHINGTON

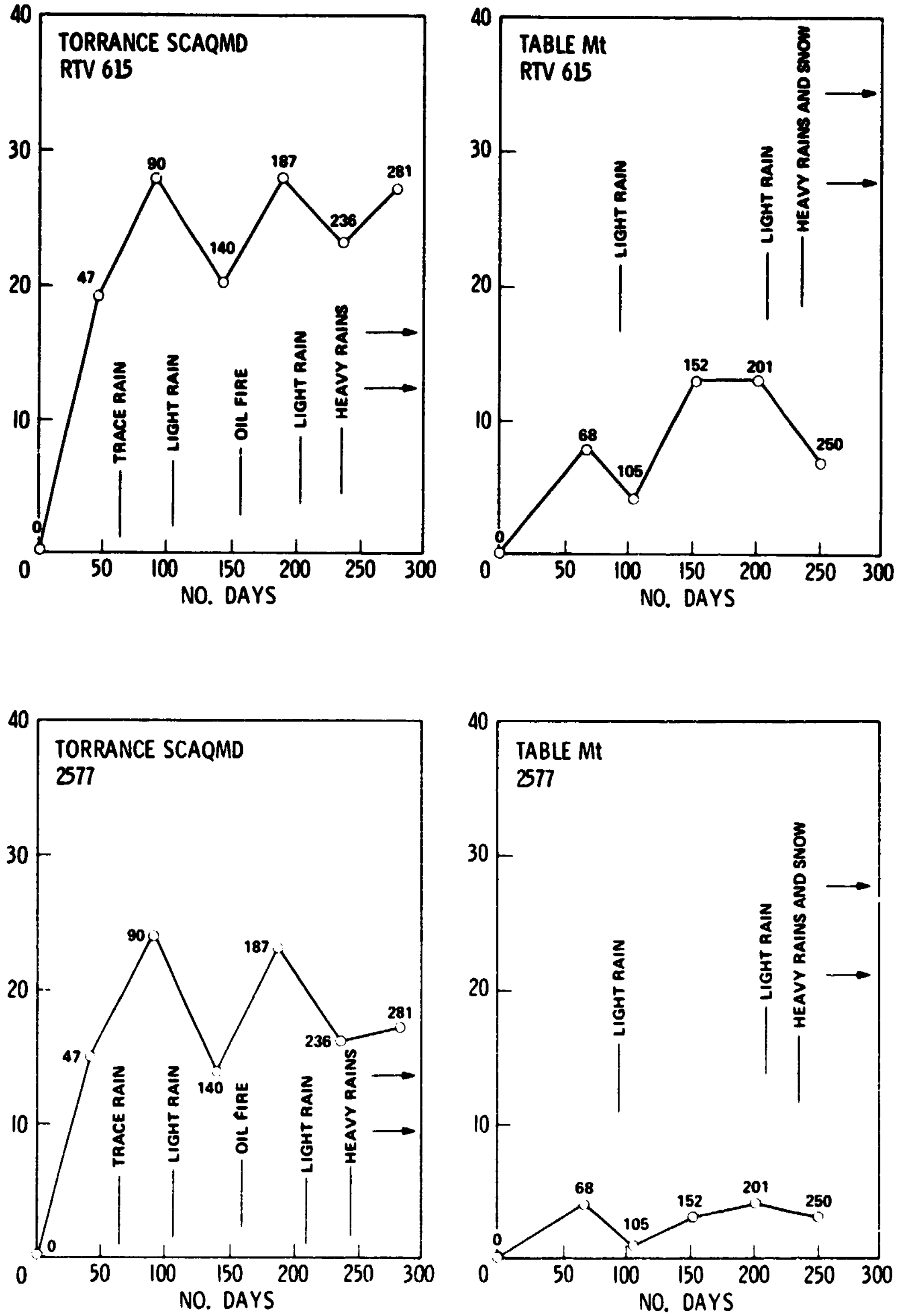
Measurement Techniques

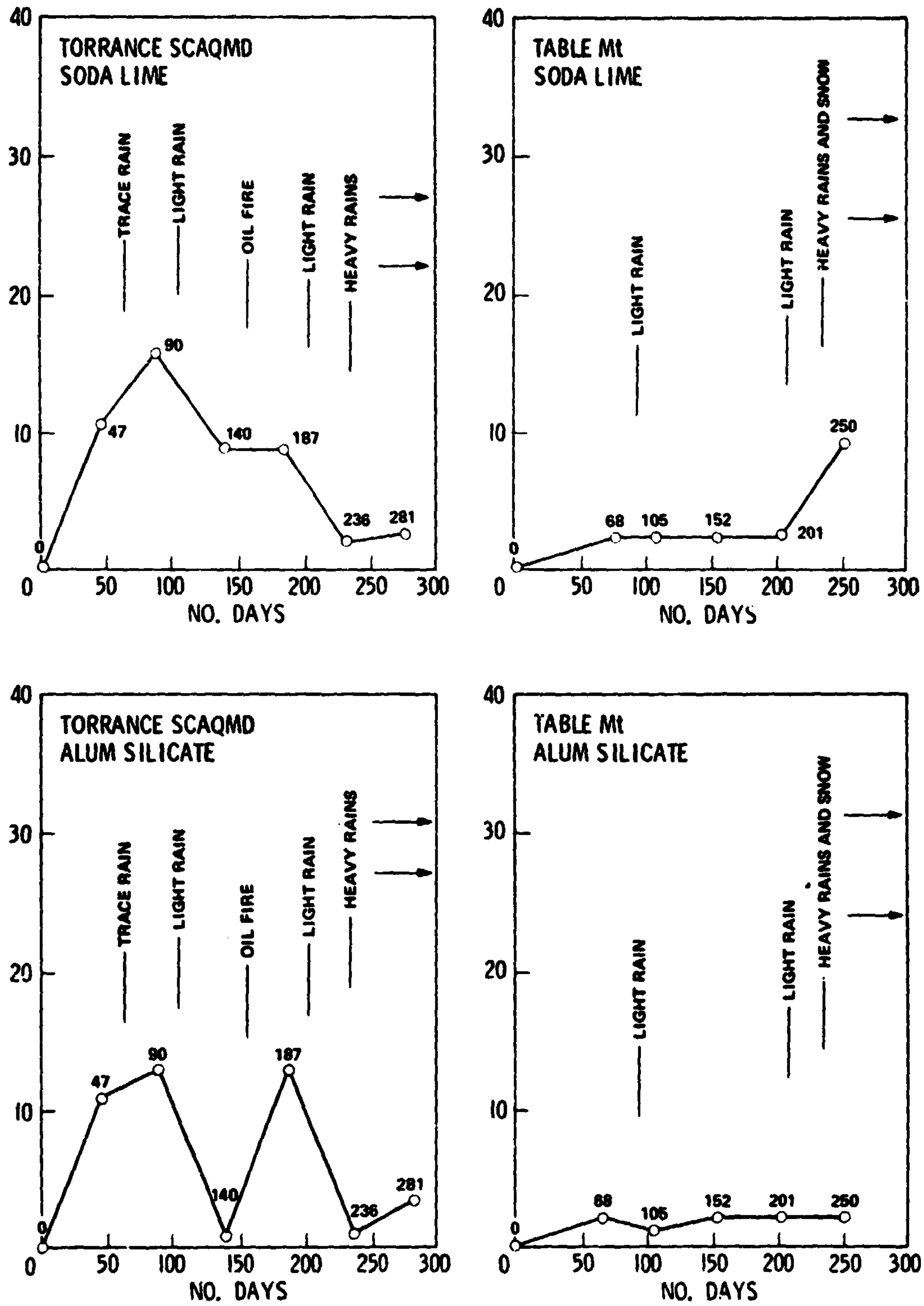
- RNHT (COMPARATIVE)
- SPECTRAL TRANSMITTANCE
  - NORMAL HEMISPHERICAL
  - NORMAL NORMAL (7^0)
- SPECTRAL REFLECTANCE
  - NORMAL HEMISPHERICAL
- SCATTERING
  - SPECULAR TRANSMITTANCE

Severity of Dust and Dirt Accumulation at Pasadena AQMD Site

MATERIAL	HEMISPHERICAL TRANSMITTANCE DAY 0	HEMISPHERICAL TRANSMITTANCE DAY 150	SPECULAR TRANSMITTANCE DAY 150
RTV 615	0.930	0.585	0.303
QI-2577	0.870	0.564	0.251
SODA LIME GLASS	0.870	0.681	0.581
BOROSILICATE GLASS	0.910	0.730	0.613
ALUMINO SILICATE GLASS	0.914	0.783	0.642
TEDLAR	0.892	0.741	0.585
KORAD	0.912	0.718	0.564

Percent Loss in RNHT for Materials Exposed at 2 Locations




TORRANCE SCAQMD
SODA LIME
TRACE RAIN
LIGHT RAIN
OIL FIRE
LIGHT RAIN
HEAVY RAINS
0
47
90
140
187
236
281
NO. DAYS
TABLE Mt
SODA LIME
LIGHT RAIN
LIGHT RAIN
HEAVY RAINS AND SNOW
0
68
105
152
201
250
NO. DAYS
TORRANCE SCAQMD
ALUM SILICATE
TRACE RAIN
LIGHT RAIN
OIL FIRE
LIGHT RAIN
HEAVY RAINS
0
47
90
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281
NO. DAYS
TABLE Mt
ALUM SILICATE
LIGHT RAIN
LIGHT RAIN
HEAVY RAINS AND SNOW
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NO. DAYS
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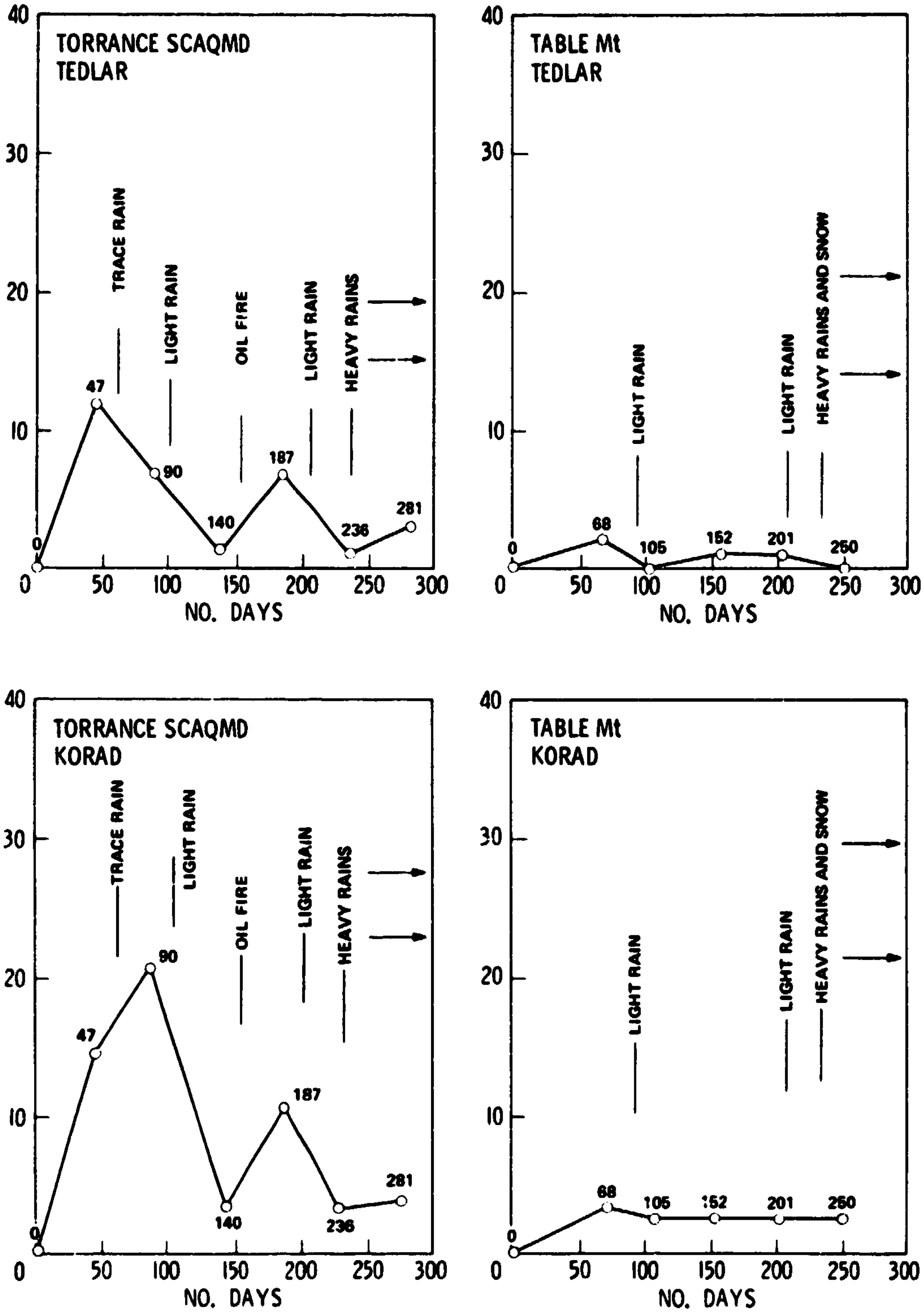
300


TORRANCE SCAQMD
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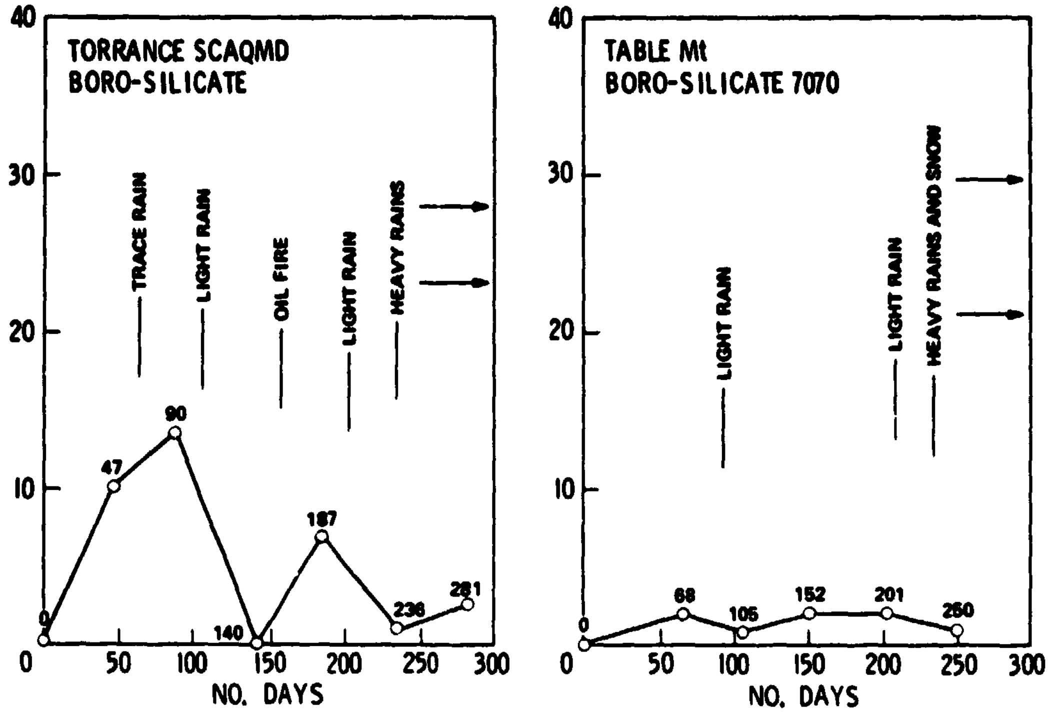
NO. DAYS


TORRANCE SCAQMD
BORO-SILICATE
TRACE RAIN
LIGHT RAIN
OIL FIRE
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HEAVY RAINS
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150
200
250
300
NO. DAYS
TABLE Mt
BORO-SILICATE 7070
LIGHT RAIN
LIGHT RAIN
HEAVY RAINS AND SNOW
0
68
105
152
201
250
NO. DAYS

ENGINEERING and OPERATIONS AREAS

Summary and Observations

- DUST/DIRT ACCUMULATES ON MATERIALS EXPOSED TO OUTDOOR ENVIRONMENT
- ELECTRICAL PERFORMANCE DEGRADATION OF MODULES RESULTING FROM ACCUMULATION OF PARTICULATE MATTER ON OPTICAL SURFACES SHOWS SIGNIFICANT TIME-AND SITE-DEPENDENCE RANGING FROM 2% to 60% POWER LOSS
- DUST/DIRT ATTENUATES INCIDENT FLUX BY OBSCURATION AND SCATTERING PHENOMENA
- NATURAL REMOVAL (WIND, RAIN) MECHANISMS NOT SUFFICIENT TO TOTALLY CLEAN SURFACES
- DURING PERIODS WHEN NATURAL REMOVAL PROCESSES DO NOT DOMINATE, THE RATE OF PARTICULATE ACCUMULATION APPEARS TO BE LARGELY MATERIAL INDEPENDENT, WHEREAS THE AFFINITY/RETENTION OF PARTICULATE MATTER IS MATERIAL DEPENDENT
- ADVANCED CLEANING TECHNIQUES MUST BE DEVELOPED TO REMOVE CONTAMINANTS FROM SURFACES

Status

• DEPLOY MATERIALS FOR OUTDOOR EXPOSURE	COMPLETE
• DEVELOP TECHNICALLY SOUND TEST METHODS FOR EVALUATION OF ENCAPSULANT MATERIALS	COMPLETE
• ASSESS DUST SPECIES, PROPERTIES AND ACCUMULATION AT VARIOUS SITES	IN PROGRESS
• CORRELATE SITE UNIQUE DUST WITH MODULE POWER CHANGES	IN PROGRESS
• DEVELOP UNDERSTANDING OF SOILING MECHANISMS (RETENTION)	IN PROGRESS
• SET PRELIMINARY GUIDELINES FOR SELECTION OF MATERIALS EXPOSED TO DIRT/DUST	GUIDELINES ESTABLISHED

RELIABILITY ENGINEERING ANALYSIS SUPPORT

IIT RESEARCH INSTITUTE

P. A. Mihalkanin

Objectives

TO DEVELOP ENGINEERING-ORIENTED RELIABILITY DATA TO SUPPORT THE DESIGN OF IMPROVED PHOTOVOLTAIC MODULES/ARRAYS

Module Analysis Outputs

SUPPORT TO ENGINEERING AREAS FOR MODULE/ ARRAY DESIGN IMPROVEMENTS (i.e.)

- RELIABILITY PREDICTIONS
- RELIABILITY ALLOCATIONS/APPORTIONMENTS
- DESIGN TRADE OFFS
- TEST DESIGN
- RELIABILITY/DURABILITY STANDARDS
- RELIABILITY DESIGN HAND BOOKS, GUIDELINES & PRACTICES
- WORKSHOPS
- DATA ANALYSIS PROCEDURES

Work Sequence/Flow

DATA GATHERING

- DATA SOURCE IDENTIFICATION
  - (P/FR)
  - OTHER
- DATA REDUCTION ANALYSIS

DETERMINATION OF MODULE FAILURE RATES & MODULE FAILURE DISTRIBUTIONS

- MODULE FAILURE MODES (FM)
- APPLICATION/ ENVIRONMENTAL FACTORS
- λ/FM
- λ/DESIGN TECH
- λ/MECHANISMS
- λ/TEST ACTIVITY

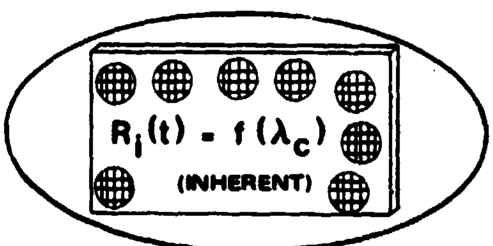
DETERMINATION OF MODULE COMPONENT FAILURE RATES

- CELL
- INTERCONNECTS (SOLDER JOINT)
- ENCAPSULANT
- CONNECTOR/ EXTERNAL
- STRUCTURE

LSA MODULE RELIABILITY ENGINEERING MODEL DEVELOPMENT

- DESIGN FACTORS
- ENVIRONMENTAL FACTORS
- APPLICATION FACTORS

Strawman Module Reliability Engineering Model (Conceptual)



$R_M(t) = F[\lambda_c, K_i, \Theta_j]$

$$\lambda_C = \sum_{i=1}^{n} \lambda_{C_i}$$

λ_{C_1} = CELL FAILURE RATE

λ_{C_2} = INTERCONNECT FAILURE RATE

λ_{C_3} = ENCAPSULANT FAILURE RATE (OR ADJUSTMENT FACTOR)

λ_{C_4} = CONNECTOR FAILURE RATE

λ_{C_5} = STRUCTURE FAILURE RATE (OR ADJUSTMENT FACTOR)

APPLICATION MODIFIERS

- REMOTE STAND ALONE
- RESIDENTIAL
- INTERMEDIATE LOAD
- CENTRAL STATIONS

ENVIRONMENTAL/ LOCATION MODIFIERS

- TEMPERATURE
- HUMIDITY
- HAILSTONE
- SOILING
- SOLAR WEATHERING

ARRAY STRUCTURE COST REDUCTION STUDY

JET PROPULSION LABORATORY

Abe Wilson

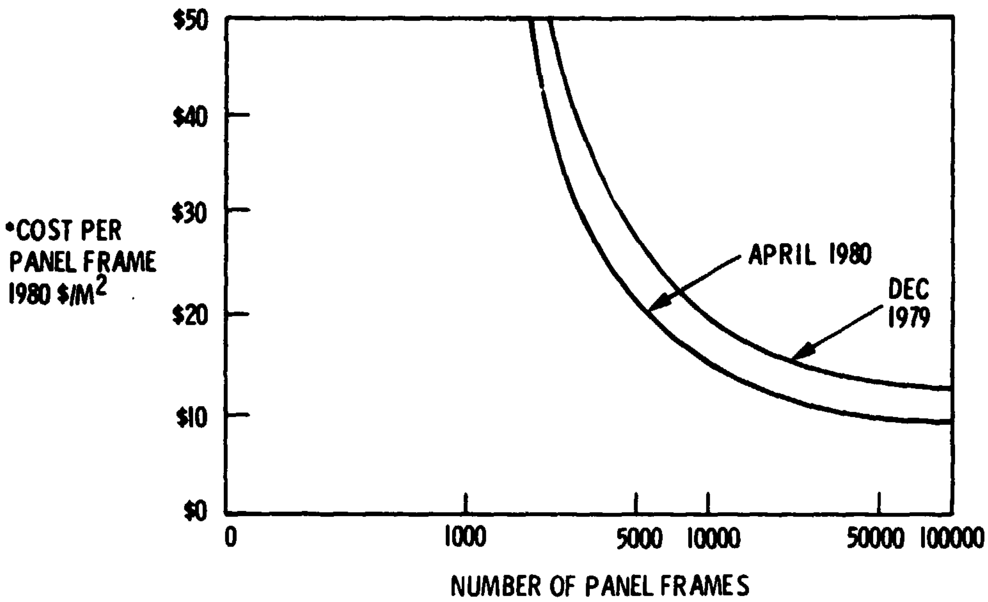
OBJECTIVE

- IDENTIFY MEANS FOR REDUCING THE COST OF FLAT/PLATE ARRAY STRUCTURES FOR LARGE INDUSTRIAL/CENTRAL STATION ARRAYS
  - PANEL FRAME (8 x 16 FOOT)
  - ARRAY STRUCTURE
  - ARRAY FOUNDATION

APPROACH

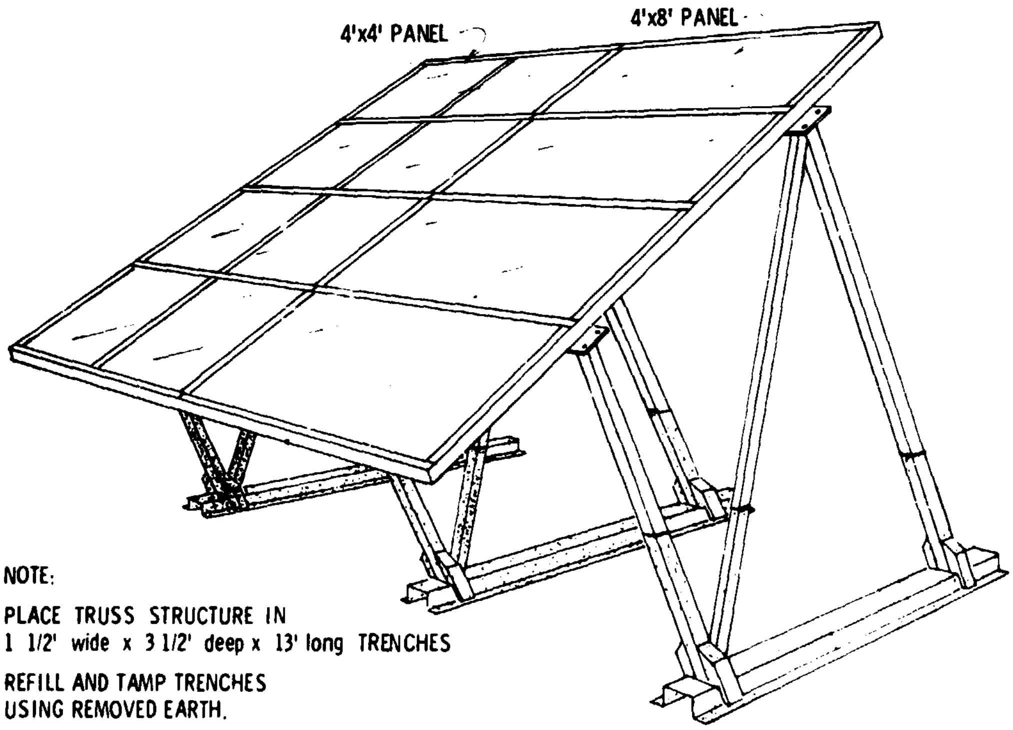
- DESIGN AND FABRICATE LOW-COST PANEL FRAME AND PROOF TEST TO FAILURE
- DISCUSS DESIGN WITH MASS PRODUCTION VENDORS AND OBTAIN COST ESTIMATES ON EQUIVALENT DESIGN
- FABRICATE EQUIVALENT PANEL AND PROOF TEST
- DESIGN AND FABRICATE LOW-COST FOUNDATION AND STRUCTURE
- PROOF TEST DESIGN FOR SEVERAL SOIL CONDITIONS
- DISCUSS DESIGN WITH VENDORS:
  - HOLE DRILLING, PILE DRIVING, TRENCHING
  - WOOD TREATING, GALVANIZING
- DISCUSS ARRAY FOUNDATION AND STRUCTURE WITH MASS PRODUCTION VENDORS AND OBTAIN COST ESTIMATES ON EQUIVALENT DESIGN

Panel Frame Cost/Quantity Sensitivity



•PER QUOTE BY KAISER STEEL

Solar Array Structure



NOTE:

PLACE TRUSS STRUCTURE IN
1 1/2' wide x 3 1/2' deep x 13' long TRENCHES

REFILL AND TAMP TRENCHES
USING REMOVED EARTH.

SHADED PORTION OF STRUCTURE
IS BELOW GROUND LEVEL.

Preliminary Study Results (1980 $/m²)

SIGNIFICANT COST REDUCTIONS ARE POSSIBLE

DATE OF ESTIMATE	(1) BARE PANEL FRAME	(2) * PANEL FRAME	(3) ARRAY FOUNDATION MATERIAL	(4) ARRAY FOUNDATION AND STRUCTURE	(5) TOTAL (1) + (4)
AUG'78	$18.90	$28.42	CONCRETE	$40.32	$59.22
NOV'79	$13.45	$22.97	EARTH	$ 7.56	$21.01
APR'80	$ 9.80	RESTUDY	EARTH	$ 8.90	$18.70

* BARE PANEL FRAME COST PLUS $9.52 FOR GASKET, GROUND CONNECTORS ASSEMBLY LABOR, FREIGHT AND INSTALLATION LABOR, PER BECHTEL STUDY.

Future Work

- ARRAY STRUCTURE
  - NEED FOR CROSS BRACES
- ARRAY FOUNDATION
  - SPECIAL TRENCHERS & COMPACTORS
  - EFFECT ON PERFORMANCE OF:
    - DEPTH OF TRENCH, BASE AREA, SOIL TYPE, COMPACTION
- BETTER MEASURE OF ASSEMBLY AND SHIPMENT COSTS
  - FACTORY ASSEMBLE STRUCTURE, HIGHER SHIPMENT COST
  - FIELD ASSEMBLE STRUCTURE, LOWER SHIPMENT COST
  - COMBINATION OF ABOVE
- INTERFACE WITH MODULE SUPPLIER
  - ASSEMBLE MODULES IN FRAME AT MODULE SUPPLIERS PLANT
  - ASSEMBLE MODULES IN FRAME AT FIELD SITE

ELECTRICAL PERFORMANCE MEASUREMENTS AND STANDARDS AT JPL

JET PROPULSION LABORATORY

Gil Downing

Measurements and Standards Objectives

- ESTABLISH, OPERATE, AND MAINTAIN LABORATORY FACILITIES FOR THE PERFORMANCE EVALUATION OF PHOTOVOLTAIC CELLS AND MODULES
- PROVIDE REFERENCE CELLS AND CONSULTATION FOR PERFORMANCE MEASUREMENTS ACTIVITIES

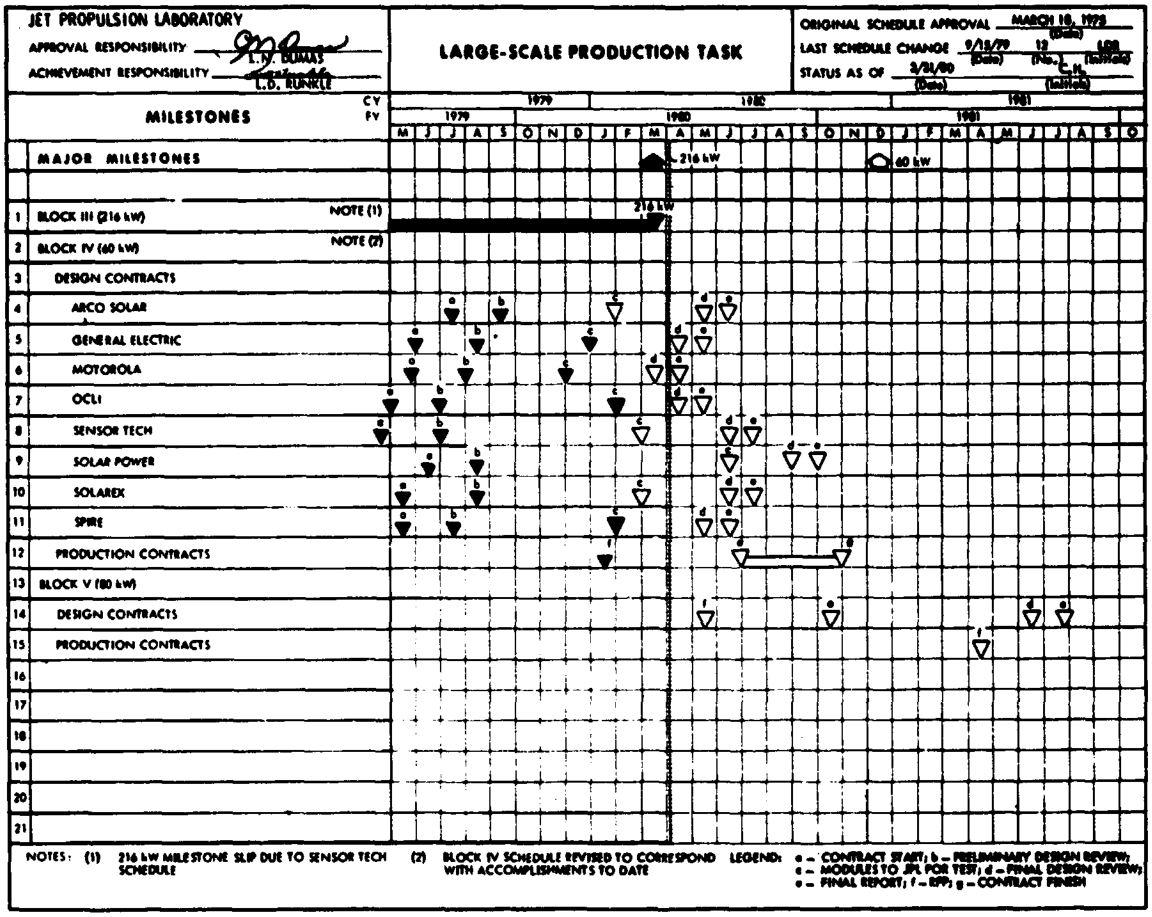
Measurements and Standards Approach

- EXPAND LAPSS FACILITY THROUGH INSTALLATION OF SECOND LAPSS AND INTEGRATION OF BOTH LAPSS's INTO CENTRAL CONTROL AND DATA PROCESSING COMPUTER
- OPERATE AND MAINTAIN NECESSARY LABORATORY FACILITIES AND INSTRUMENTATION FOR THE ELECTRICAL PERFORMANCE MEASUREMENTS OF CELLS AND MODULES, CALIBRATION OF REFERENCE CELLS, AND MONITORING OF TERRESTRIAL ATMOSPHERIC AND INSOLATION PARAMETERS
- DEVELOP MEASUREMENT FACILITIES PROCEDURES AND STANDARDS FOR TESTING OF NON-SINGLE-CRYSTAL SILICON CELLS AND MODULES
- FABRICATE, CALIBRATE, AND MAINTAIN REFERENCE CELLS FOR LSA AND PRDA TESTING BOTH IN-HOUSE AND AT CONTRACTORS FACILITIES
- REVIEW LSA AND PRDA CONTRACTORS MEASUREMENT FACILITIES AND PROCEDURES AND IMPLEMENT APPROPRIATE STANDARDS IN COOPERATION WITH MANUFACTURERS
- PROVIDE CONSULTATION TO PROJECT AND CONTRACTORS PERFORMANCE MEASUREMENT ACTIVITIES AND PARTICIPATE IN NATIONAL CONSENSUS STANDARDS PROGRAM WITH SERI AND ASTM

LARGE-SCALE PRODUCTION TASK

JET PROPULSION LABORATORY

L.D. Runkle



RECENT ENVIRONMENTAL TEST RESULTS

JET PROPULSION LABORATORY

John S. Griffith

Contents

- EXPLORATORY TESTS OF BLOCK III MODULES
- QUALIFICATION TESTS OF BLOCK IV MODULES TO DATE
    - TWO TYPES OF MODULES HAVE COMPLETED QUAL TESTS
    - TWO OTHERS HAVE COMPLETED TEMPERATURE CYCLING ONLY

Block III Exploratory Environmental Tests

MECHANICAL CYCLING* (WIND SIMULATION)

CYCLIC ALTERNATING PRESSURE LOAD ON MODULES, 50 psf, 10,000 cycles

SOLAR-RAIN

MODULES ALLOWED TO REACH MAXIMUM TEMPERATURE ON A CLEAR, WARM DAY (OVER 27°C, 80°F), THEN SPRAYED WITH DEIONIZED WATER. 10 cycles

HUMIDITY-HEAT*

MODULES ARE MOISTURE SATURATED AT 70°C, 95% RH FOR 6 hours OR MORE; THEN THEY ARE REMOVED AND IRRADIATED AT FULL SIMULATED SOLAR HEAT WITH IR LAMPS. 10 cycles

HUMIDITY-FREEZE*

TEN CYCLES AS FOLLOWS:

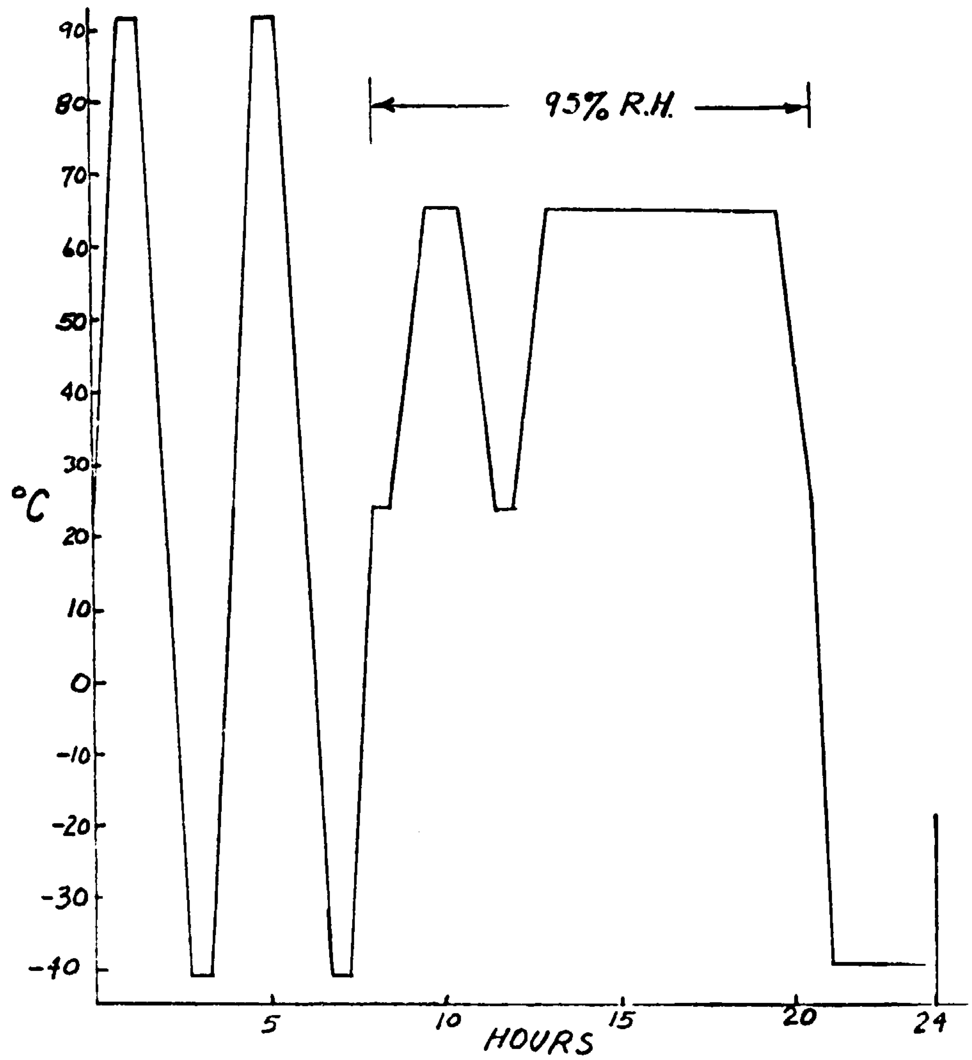
a. TWO TEMPERATURE CYCLES, +90, -40°C, 100°C/hr
b. TWO HUMIDITY CYCLES, 23°, 40°C, 95% RH, THE LAST 40° EXPOSURE FOR 6 hours
c. -40°C FOR 3 hours

SALT FOG

SIMULATE METAL FIELD SUPPORTS ON MODULES. NOMINAL REVERSE BIAS VOLTAGE, WITH ONE SIDE OF SUPPLY GROUNDED TO THE METAL FIELD SUPPORT. 5 days, 35°C, 95% RH IN SALT FOG CHAMBER PER MIL-STD-810B, METHOD 509.1

*MONITOR FOR OPEN CIRCUIT IN CELL STRING AND REDUCED RESISTANCE TO GROUND

Block III Humidity-Freeze, 10 Times



Block III Environmental Testing

VENDOR	No. MDLS TESTED	RESULTS OF EXPLORATORY TESTS			RESULTS OF QUALIFICATION TEST		
		TEST	No. MDLS AFFECTED	RESULTS	TEST	No. MDLS AFFECTED	RESULTS
R R CELLS	4	SR	1	4% EL DEGRAD	T~	4	AIR BUBBLES
		HH	1	5% EL DEGRAD, DSCN NEAR EDGE	T~	4	AIR BUBBLES
		HF	3	AIR BUBBLES			DECREASED
		SF	1	CELL CRACK			
R M CELLS	4	MI-10K	1	OPEN ALL CYCLES OVER 730	T~	3	ENCAP LEAK
		SR	4	DISCOLORED METALLIZATION	H~	2	BUBBLES
		HF	3	BUBBLES		1	BUBBLES DECREASED
		SF	1	INTERMITTENT OPEN, TERM CORR			
U	5	MI-10K	4	RAILS CRACKED AT MOUNTING HOLES	T~	5	END CHANNELS SHRINKING, LIFTING
		HH	5	FRAME SEAL DELAMINATION		1	EL DEGRAD, 4%
		HF	5	END CHANNELS SHRUNK, SEPARATION	H~	1	CELL CRACK
		HF	3	FURTHER FRAME SEAL DELAM			
		SF	3	CELL DSCN, FRAME CORROSION			
		SF	4	TERMINAL CORROSION			
		SF	1	EL DEGRAD, FRAME DELAM			

VENDOR	No. MDLS TESTED	RESULTS OF EXPLORATORY TESTS			RESULTS OF QUALIFICATION TEST		
		TEST	No. MDLS AFFECTED	RESULTS	TEST	No. MDLS AFFECTED	RESULTS
V	8	HH	8	TERM CORROSION, YELLOW DSCN	H~	8	TERM CORROSION
		HF	4	ENCAP DELAM OVER CELLS			
		SF	5	MORE TERMINAL CORROSION			
		SF	1	INTERCON CONTAM, DELAM, CR CELL			
Y	4	HH	4	J BOX HARDWARE CORROSION	T~, H~	4	SATISFACTORY
		SF	2	MORE J BOX CORROSION			
Z	3	MI-10K	1	DELAM INTERCONS, ENCAP WRINKLING, SPLITTING	T~	3	SATISFACTORY
		HH	1	8% EL DEGRAD, 3 CELL CRACKS	H~	3	INTERCON DELAM
		HH	2	DELAM AT CELL EDGES		3	FRAME SEAL DELAM
		HH	1	YELLOW DSCN, 2 CELL CRACKS		2	1 CELL CRACK
		HF	3	FRAME SEAL DELAM, EL DEGRAD-21%, 9%, 15%, RESP			
		HF	2	ONE CELL CRACKS			
		HF	1	2 CELL CRACKS, ENCAP SPLIT			
		SF	2	REPAIR PLUGS LOOSE			
		SF	1	DELAM FRAME SEAL, INTERCONS; CORROSION J BOX			

T~ - TEMPERATURE CYCLING
H~ - HUMIDITY CYCLING
MI - MECHANICAL INTEGRITY

SR - SOLAR - RAIN
HH - HUMIDITY - HEAT
HF - HUMIDITY - FREEZE
SF - SALT FOG

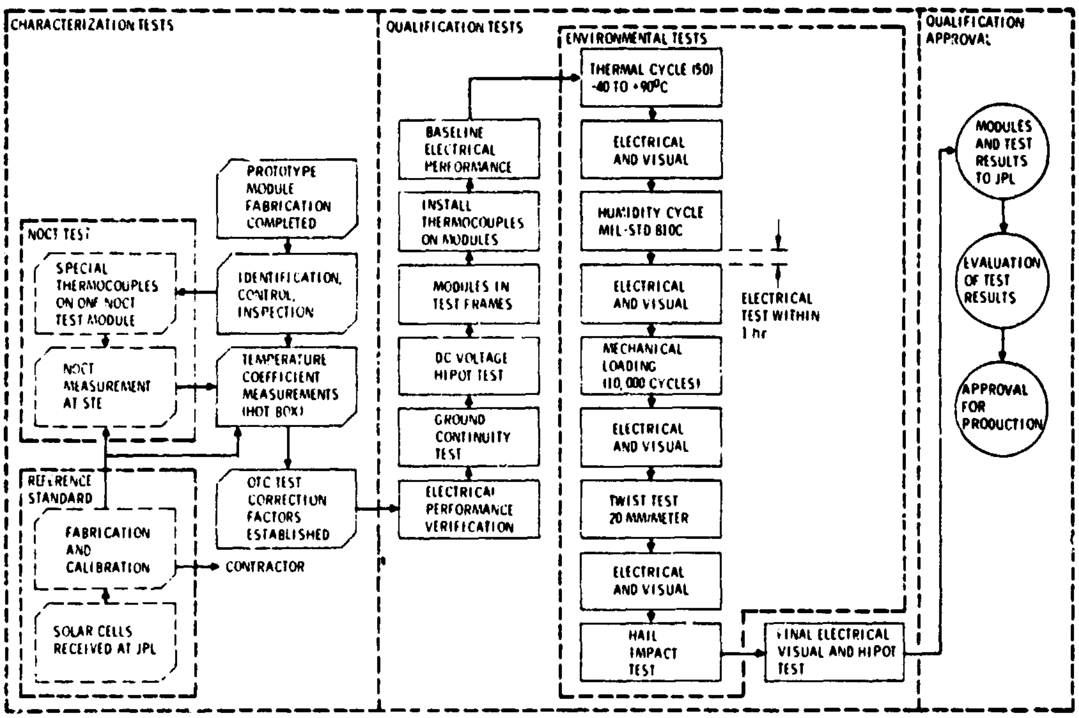
BLOCK IV QUALIFICATION TESTS

INITIAL RESULTS

JET PROPULSION LABORATORY

John S. Griffith

Block IV Qualification Test Flow Plan



Intermediate Module, RS
Qual Tests Completed

TEST	RESULTS
TEMPERATURE CYCLING	SEALANT BETWEEN GLASS AND FRAME EXTRUDED
HUMIDITY CYCLING	TWO CELLS CRACKED
MECHANICAL INTEGRITY	ONE CELL CRACK. ONE FRAME CORNER BROKEN OFF AT MOUNTING HOLE
POST TESTS EVALUATION	3 OF 5 MODULES FAILED HIPOT TEST. ONE FAILED GROUND CONTINUITY TEST

Residential Module, GR
Qual Tests Completed

TEST	RESULTS
TEMPERATURE CYCLING	OPEN CIRCUIT, AS YET UNEXPLAINED. APPLICATION OF FORWARD CURRENT OF 2A CORRECTED THIS CONDITION. SOME DELAMINATION AT INTERCONNECTS AND ADJACENT CELLS. GREEN DISCOLORATION OF CELL BUS ON TWO MODULES
HUMIDITY CYCLING	ALL DUMMY SHINGLES WARPED

Intermediate Modules, MS and SS
Temperature Cycling Only

MS IN FOUR MODULES, 3, 7, 9, and 15 CELLS CRACKED, RESP. NO APPARENT ELECTRICAL DEGRADATION

SS SMALL J-BOX SCREWS STRIPPED THREADS IN PLASTIC BOX. BLISTERS ON MODULE BACKSIDE

Conclusions

- BLOCK III EXPLORATORY TESTS — REVISED EXPLORATORY PROCEDURES ARE MORE EFFECTIVE AND REALISTIC THAN QUALIFICATION TESTS IN DUPLICATING FIELD EXPERIENCE AND IN SCREENING ENVIRONMENTALLY WEAK MODULES
- BLOCK IV EARLY QUALIFICATION TEST RESULTS
  - GR RESIDENTIAL MODULE — SOFT PLASTIC PORTION OF SHINGLE WARPS
  - RS INTERMEDIATE — HIPOT AND GROUND CONTINUITY PROBLEMS. ALSO, MOUNTING CORNER STIFFENING NEEDED. MODERATE PROBLEM WITH CELL CRACKING
  - MS INTERMEDIATE — NUMEROUS CELL CRACKS
  - SS INTERMEDIATE — MINOR J-BOX SCREW THREAD PROBLEM

OPERATIONS AREA

MODULE APPLICATIONS

TECHNOLOGY SESSION — Larry Dumas, Chairman

The Thursday afternoon session on module applications provided an opportunity for system-oriented users to comment on their field experience. Dr. Steve Forman of MIT/LL noted that overall failure rates for modules at their sites remain below 1% per year, despite serious problems at their University of Texas (Arlington) residential test site. Two new techniques under development by MIT/LL for the detection and tracking of module degradation were presented. A scanning infrared microscope system is showing promise for the detection of cracked cells, and an acoustic digitizer is being used for the characterization of encapsulant delamination.

Elmer Christensen of JPL spoke on behalf of Bill Bifano of LeRC on village photovoltaic power systems, using the Schuchuli, Arizona, installation as an illustration. LeRC calculations indicate that photovoltaic systems are currently cost-competitive with diesel generators for such applications. A large market potential for these systems is foreseen.

Dr. Larry Partain of Lawrence Livermore Laboratory (LLL) explored some possibilities in solar-powered transportation, and gave the results of a small experiment carried out by LLL in such an application. In an 18-month, 1600-mile test, a PV-powered "solar surrey" was provided with 70% of its power from a 200 W array of Block II modules. Dr. Partain proposed a scale-up of such a system to a 40-mile-per-day, 55-mph commuter vehicle powered by a housetop array.

PHOTOVOLTAIC MODULE PERFORMANCE AT VARIOUS MIT/LL TEST SITES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORIES

S.E. Forman

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)

Natural Bridges National Monument (NBNM) PV System

SYSTEM

- STAND-ALONE LOAD CENTER WITH DIVERSIFIED LOADS (170 MWh)

ARRAY

- 100 kW PEAK ($60^{o}C$)
- 1700 M^2 PANEL AREA (18,000 ft^2 ON 1.4 ACRE PLOT)
- GLASS-COVERED MODULES ($11/W)

STORAGE

- LEAD-ACID (CALCIUM) BATTERIES
- 700 kWh TOTAL CAPACITY, 600 kWh USABLE CAPACITY
- COST $119/kWh (TOTAL CAPACITY BASIS)

POWER CONDITIONING

- 50 kVA MAIN INVERTER (SINGLE-PHASE, $380/kVA)
- 3 kVA UPS INVERTER ($970/kVA)
- 50 kW BATTERY CHARGER ($310/kW)

OPERATIONS AREA

BUILDING

- 1440 ft^2 (INCLUDES STORAGE AREA)

BACKUP

- DIESEL-POWERED GENERATOR, 40 KW/50 kVA - SINGLE-PHASE
- PROJECTED TO SUPPLY 5-10% OF ENERGY CONSUMPTION

Module Distribution at NBNM

MFG	NO. OF MODULES	TOTAL POWER
SPECTROLAB (II)	720	18 KW
ARCO SOLAR (III)	1740	31 KW
MOTOROLA (III)	2256	47 KW
SENSOR TECH (III)*	500	4 KW

*To be added after turn-on in June 1980

Module Failures at MIT/LL Test Sites

DATA UP TO 10/79

MANUFACTURER STARTING DATE	NEB (7/77)	RTB (11/78)	RTTB (5/77)	UTA (8/78)	CHICAGO (7/77)	TOTALS	%
A (I)	--	--	15/945	--	0/288	15/1233	1.21
B (II)	--	--	5/64	63/240	--	68/304	22.4
C (II)	28/1512	13/720	0/36	--	--	41/2268	1.8
D (II)	20/728	--	--	--	--	20/728	2.74
					TOTAL	144/4533	3.18%

NOTE: ROMAN NUMERALS I AND II REFER TO JPL-LSA BLOCK PURCHASES OF MODULES FOR DOE.

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.

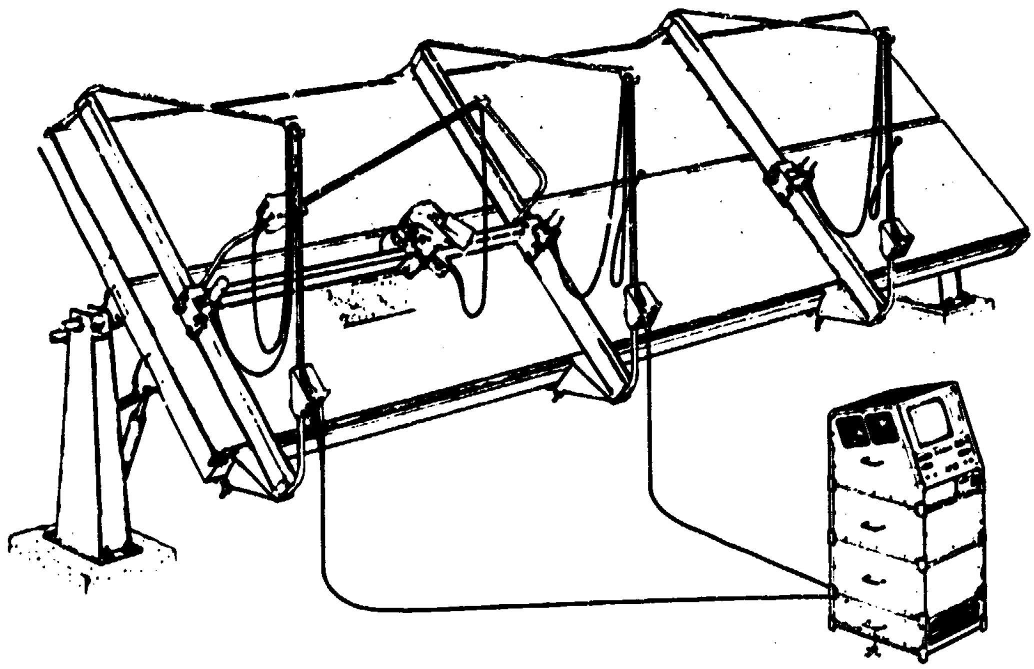
Nebraska Field Inspection Results for Cracked Cells - 7/77 to 10/79

MFG	MODULES INSPECTED	MODULES WITH CRACKED CELLS	TOTAL NO. OF CRACKED CELLS	NO. OF IMPACT CRACKED CELLS	TOTAL NO. OF CELLS
C	1404	856	1596	758	61,776
D	676	188	425	397	28,392
TOTAL	2080	1044	2021	1155	90,168

Remote Solar Cell Inspection Device

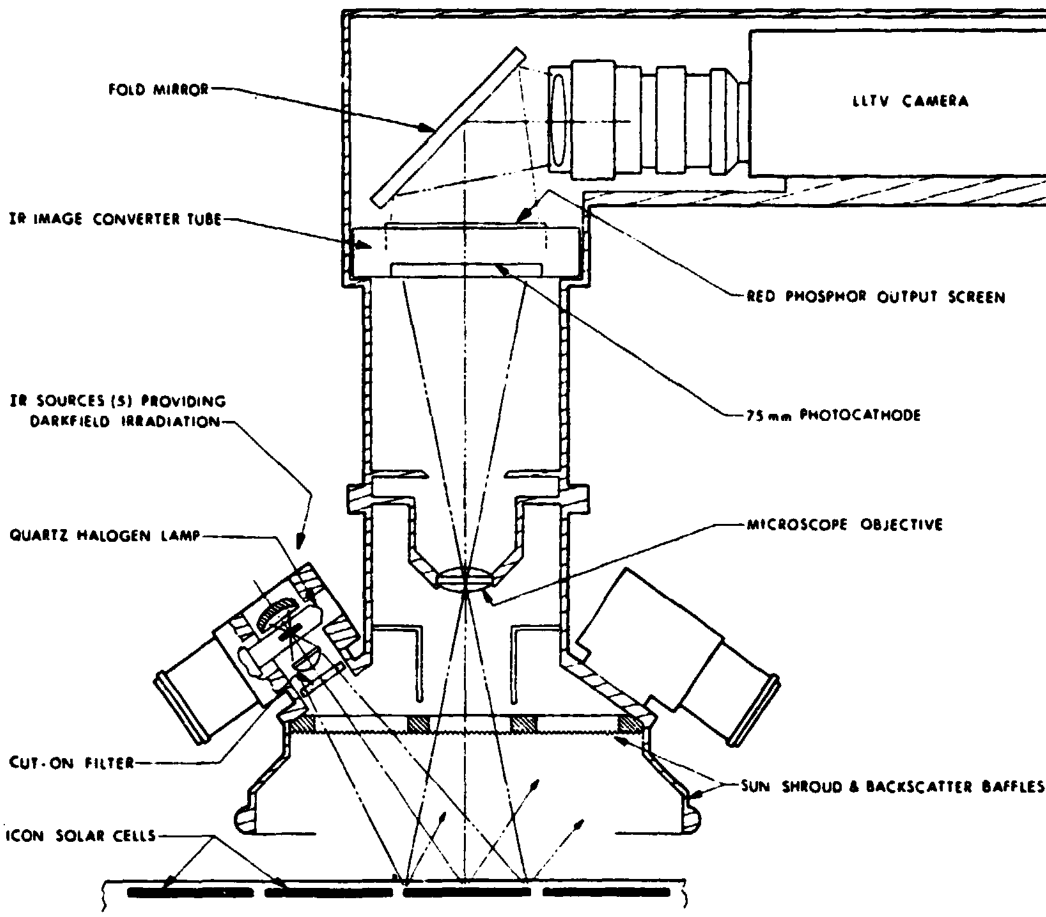
FEATURES:

- INFRARED MICROSCOPE OPERATING AT 1 MICRON, WITH A 3 INCH FIELD OF VIEW AND MAGNIFICATION OF 5X TO 15X.
- TV CAMERA ATTACHED TO MICROSCOPE
- PORTABLE X-Y TRANSLATOR WHICH CAN MOVE THE MICROSCOPE OVER AN 8 FOOT BY 8 FOOT AREA.
- VIDEO DISPLAY AND REMOTE CONTROL CONSOLE PROVIDES A 14 INCH VIEWING SCREEN, CONTROLS FOR X AND Y MOTION OF MICROSCOPE AND CAN BE 500 FEET REMOVED FROM MICROSCOPE.

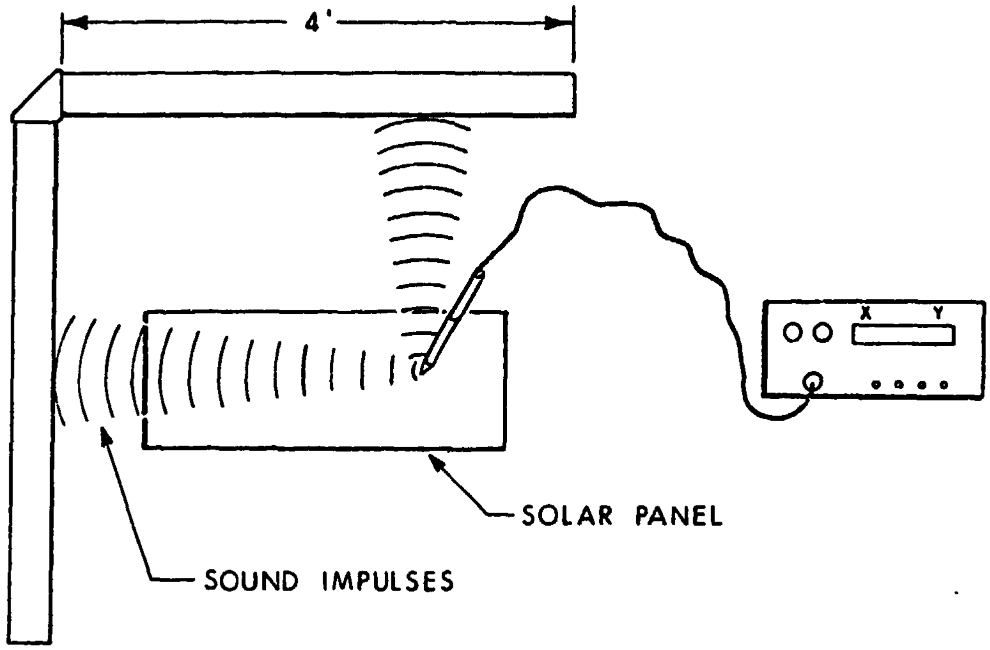


SOLAR CELL INSPECTION DEVICE

IR Microscope System

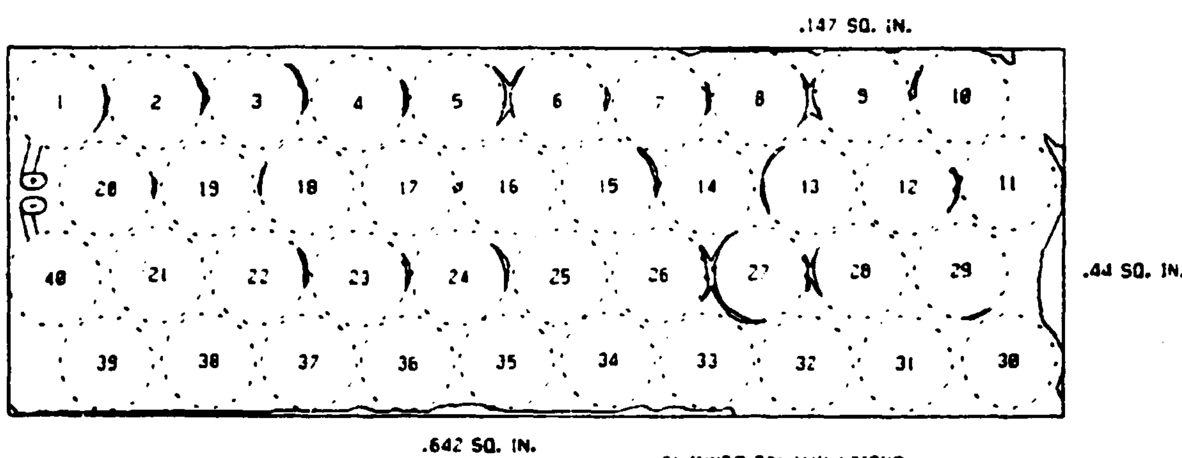


Acoustic Digitizer Concept



Rooftop Test Site Module

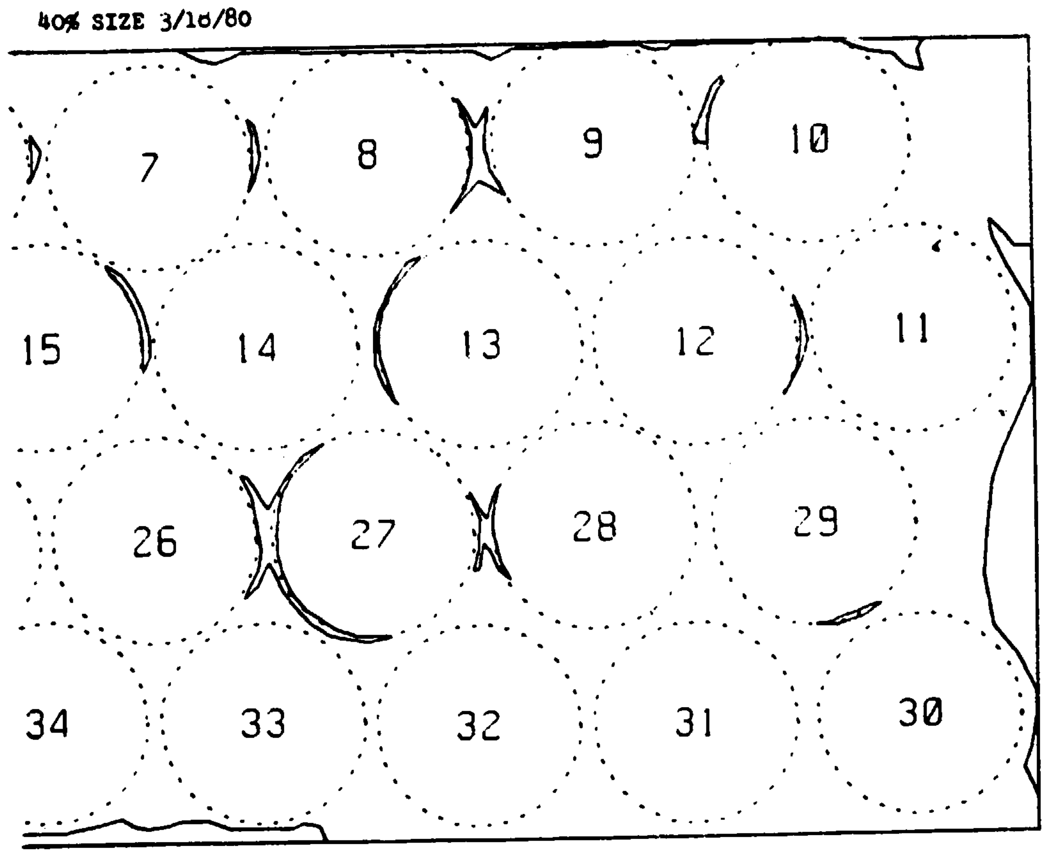
SOLAR MODULE # SP 4558
MIT LINCOLN LAB ROOF TOP EXPERIMENTAL STATION
INSTALLED DEC. 1977
REMOVED MAR. 1980 TOTAL EXPOSURE 28 MONTHS



21 INNER DELAMINATIONS

TOTAL EDGE DELAMINATION = 1.229 SQ. IN.
EBM 3/17/80

Delamination Profile of SP 4558



VILLAGE PV POWER: SCHUCHULI AZ

JET PROPULSION LABORATORY

Elmer Christensen

Schuchuli Village Power System

- VILLAGE OF 15 FAMILIES (95 PEOPLE)
- OPERATIONAL SINCE DECEMBER 16, 1978

- PROVIDES POWER FOR
  - 1 WATER PUMP (UP TO 5000 GALLONS/DAY)
  - 15 REFRIGERATOR/FREEZER UNITS
  - 44 LIGHTS, 20 WATTS FLUORESCENT - DISTRIBUTED AMONG THE HOMES AND COMMUNITY BUILDINGS
  - 1 CLOTHES WASHER
  - 1 SEWING MACHINE

- PROJECT MANAGEMENT - NASA, LEWIS RESEARCH CENTER
- PRINCIPAL PARTICIPANTS:
  - PAPAGO TRIBE
  - DOE
  - US PUBLIC HEALTH SERVICE

OPERATIONS AREA

- PEAK OUTPUT OF PV ARRAY — 3.5 KW
  (24 MODULE STRINGS - PARALLEL CONNECTED)
  (EACH MODULE STRING - 8 MODULES IN SERIES)
- NOMINAL SYSTEM VOLTAGE — 120 V DC
- BATTERY STORAGE CAPACITY — 2380 AH
  52 LEAD ACID CELLS IN SERIES
- LOAD MANAGEMENT SUBSYSTEM — 4410 Watts (max)
  SEQUENTIALLY DISCONNECTS LOADS AS BATTERY CAPACITY/DECREASES
- SYSTEM VOLTAGE IS REGULATED BY ARRAY STRING SWITCHING
- POWER SYSTEM IS INSTRUMENTED

Schuchuli Village Power Project Experiment Costs

• MODULES (JPL BLOCK II PROCUREMENT) $15.36/WATT OR	$54,850
• PV PANEL ASSEMBLY AND STRUCTURE & INSTALLATION	15,850
• C&D BATTERIES (2380 AMPERE HOURS)	15,600
• CONTROL AND INSTRUMENTATION	20,000
• ELECTRICAL EQUIPMENT BUILDING	18,700
• INSTALLATION OF EQUIPMENT AND LOADS	5,200
• DATA ACQUISITION SYSTEM/WEATHER STATION	7,500
• APPLIANCES	
PUMP MOTOR AND STARTER	1,150
REFRIGERATORS (15)	4,250
WASHING MACHINE	280
SEWING MACHINE	160
LIGHT FIXTURES AND INVERTERS	3,015
	$146,555
• TECHNICAL SUPPORT & SYSTEM DESIGN	$140,000

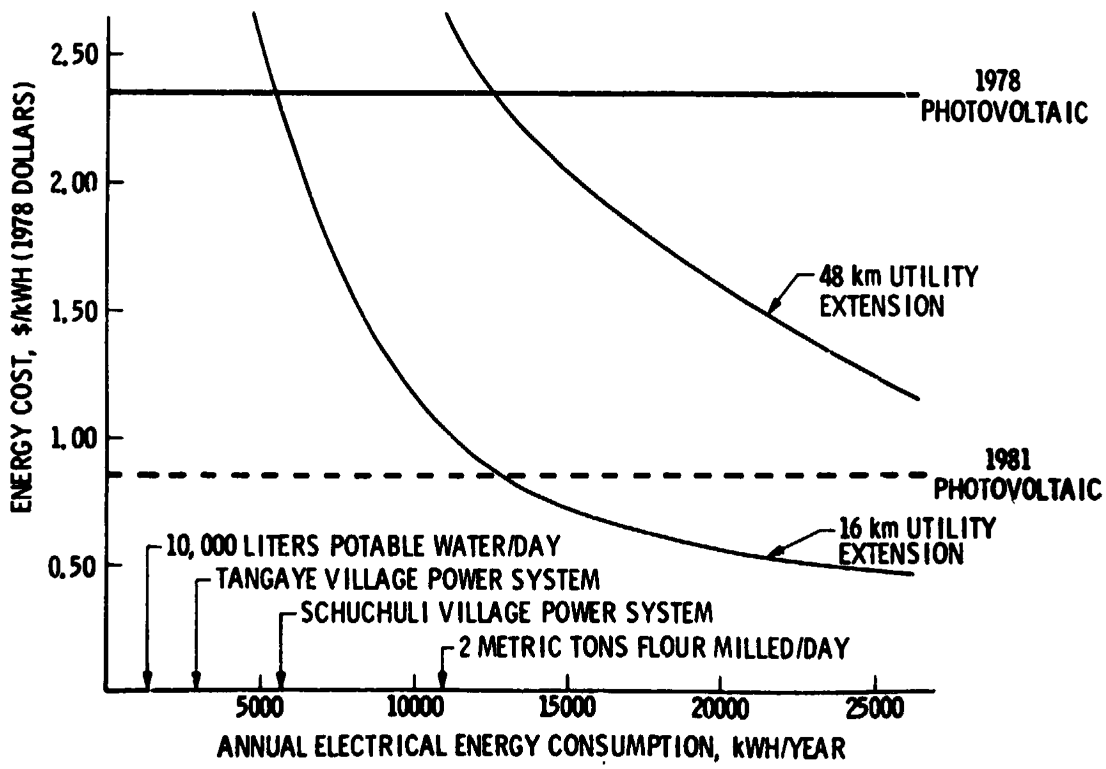
Life-Cycle Cost Comparisons

SYSTEM	CAPITAL COSTS	ENERGY PRICE[1]
PHOTOVOLTAICS - 3.5KW (20-YEAR LIFE)	\$108,483[2]	\$1.76/kWh
DIESEL GENERATORS 4 UNITS @ 3.5 KVA (BACK-UP FOR MAINTENANCE, EACH UNIT FIVE YEAR LIFE)	7,849	\$1.73/kWh (FUEL COST OF \$1/GAL)
UTILITY LINE EXTENSION		
BY PTUA	\$ 90,000	\$1.55/kWh (27 km OR 17 MILES)
BY POWER COMPANY	\$112,500	\$1.91/kWh (27 km OR 17 MILES)

[1]ASSUMES:
- 20-YEAR LIFE CYCLE COST CALCULATION
- 10% DISCOUNT FACTOR
- ENERGY CONSUMPTION OF 6255 kWh/yr.
- FUEL DELIVERY AND STORAGE FOR DIESEL IS \$1000 PER ANNUM

[2]CONSISTS OF THE FOLLOWING ELEMENTS:
- SOLAR CELL MODULES - PRICE - \$12.79/WATT OR \$45,660 TOTAL (BLOCK III)
- BALANCE OF SYSTEM - HARDWARE COSTS \$15.58/WATT OR \$55,659 TOTAL
- ONE BATTERY REPLACEMENT AFTER 10 YEARS - \$7164
- EXCLUDES ENGINEERING AND EXPERIMENT-RELATED COSTS

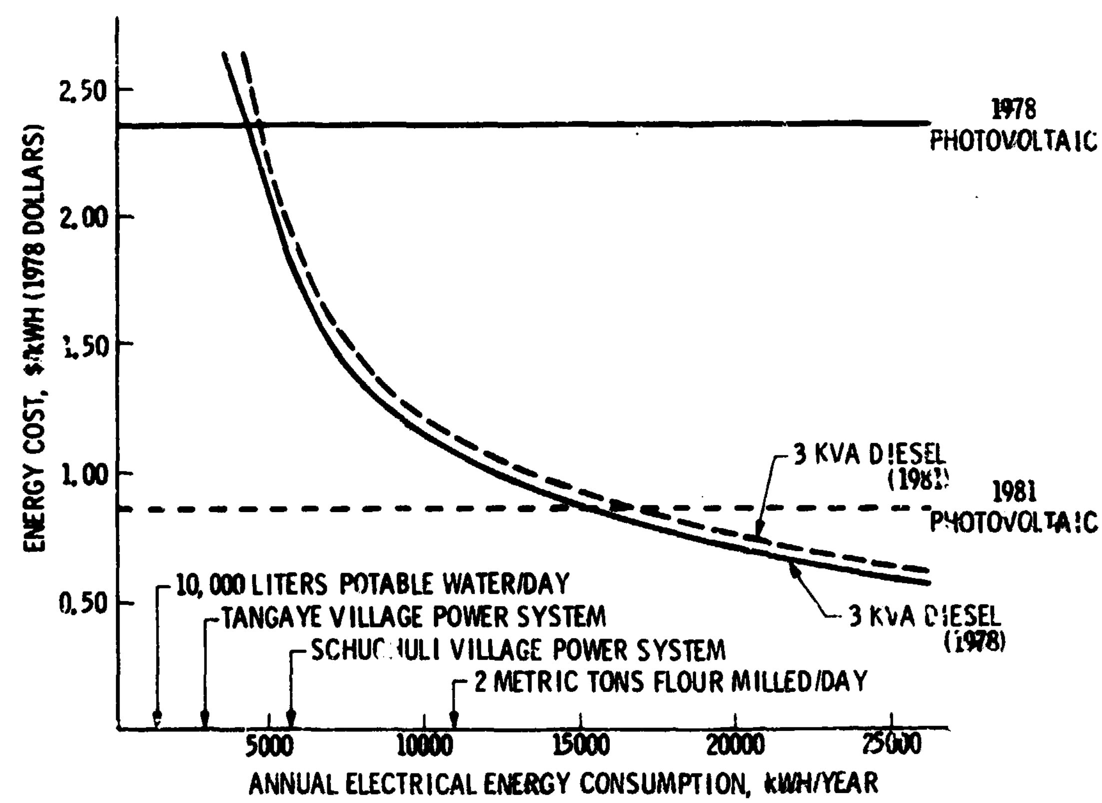
PV and Diesel Energy Cost Comparisons



Installed OV System Cost Projections (1978 $/Wp)

YEAR	MODULE COST	BOS COST	TOTAL FIRST COST	AVERAGED ANNUAL CAPITAL COST	AVERAGED ANNUAL REPLACEMENT AND MAINTENANCE	ENERGY COST $/kWh
1978	13.00	15.00	28.00	3.29	.44	2.33
1979	9.00	12.00	21.00	2.46	.31	1.73
1980	5.00	10.00	15.00	1.76	.23	1.24
1981	2.45	8.00	10.45	1.22	.17	.86
1986	.61	5.00	5.61	.66	.10	.47

PV and Utility Extension Energy Cost Comparisons



SOLAR POWERED TRANSPORTATION

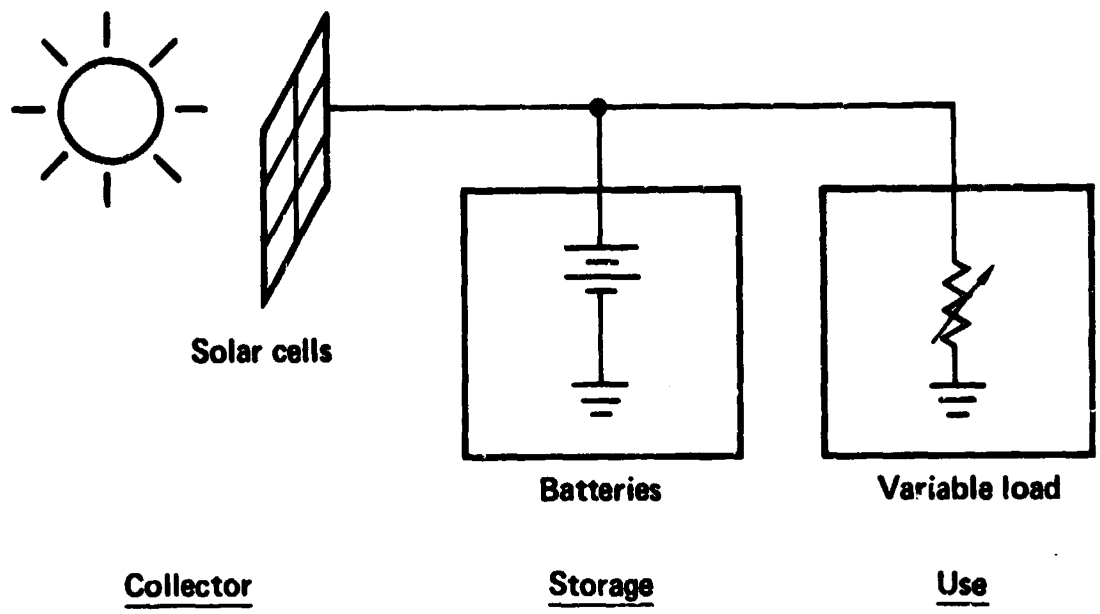
LAWRENCE LIVERMORE LABORATORY

Larry Partain

THE FEASIBILITY OF SOLAR CELL POWERED TRANSPORTATION IS BEING DEMONSTRATED

- Technical feasibility shown in 18 months test
- Scale up will provide a commuting performance vehicle
- First major energy area for cost competition because of escalating fuel prices

SOLAR SURREY SYSTEM



SOLAR SURREY DEMONSTRATES FEASIBILITY OF SOLAR POWERED TRANSPORTATION

- 18 months test
- 1600 miles traveled in daily use
- Over 70% power provided directly by the sun

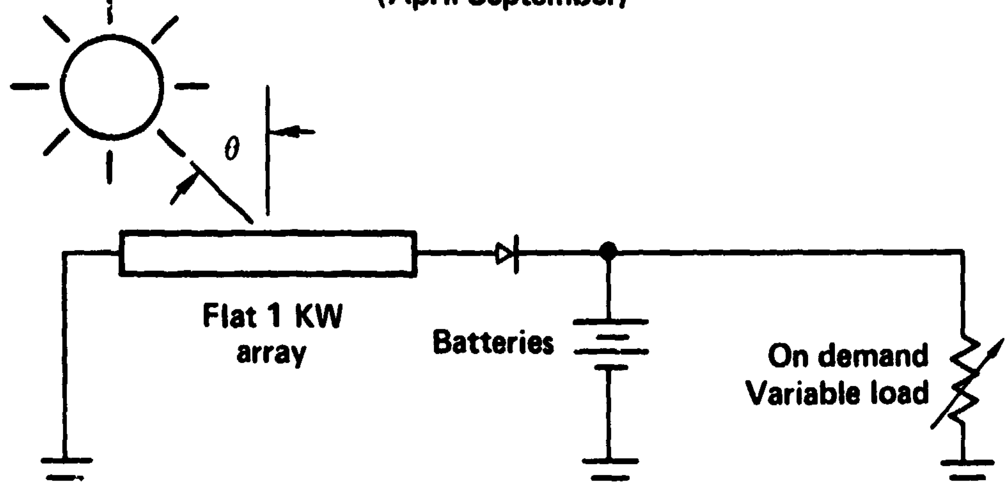
SOLAR SURREY SPECIFICATIONS

- **200 watt (peak) silicon cell array 4′ X 10′**
- **Six 6 V, 170 ampere-hour, lead-acid batteries**
- **11 mile/hour speed, 30 mile range/charge**
- **4 mile range per sunny day of charging**
- **Cost $5480 in 1977**
- **Energy available from 1 KW (peak) array-battery system:**

$$2.3 \frac{\text{KW - hr}}{\text{sunny day}} \quad \text{(April-Sept)}$$

THE ENERGY OBTAINED IS WHAT ONE WOULD REASONABLY EXPECT

(April-September)



$$1 \text{ KW} \times \cos 40^\circ \times 5 \frac{\text{hours}}{\text{sunny day}} \times 0.6 \text{ battery storage efficiency}$$
$$= 2.3 \frac{\text{KW-hr}}{\text{sunny day}}$$

NEXT OBVIOUS STEP IS TO SCALE UP TO A LARGER SYSTEM

- 7 KW (peak) array
- Roof-top size at 10% panel efficiency measures 20′ X 40′
- 16 KW-hour/day energy (70% of time throughout year)

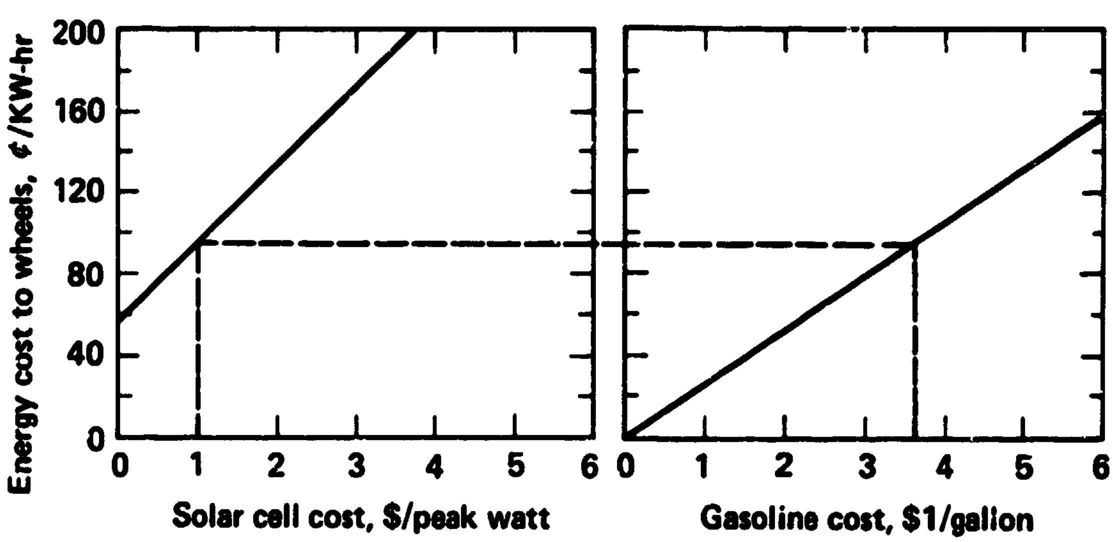
ELECTRA VAN PROVIDES COMMUTER LEVEL VEHICLE PERFORMANCE

- 55 mile per hour speed
- 40 mile per charge range
- Sixteen 6 V, 220 amp-hour, lead acid batteries
- Weight 3250 pounds
- 17 KW-hr output energy per charge capacity

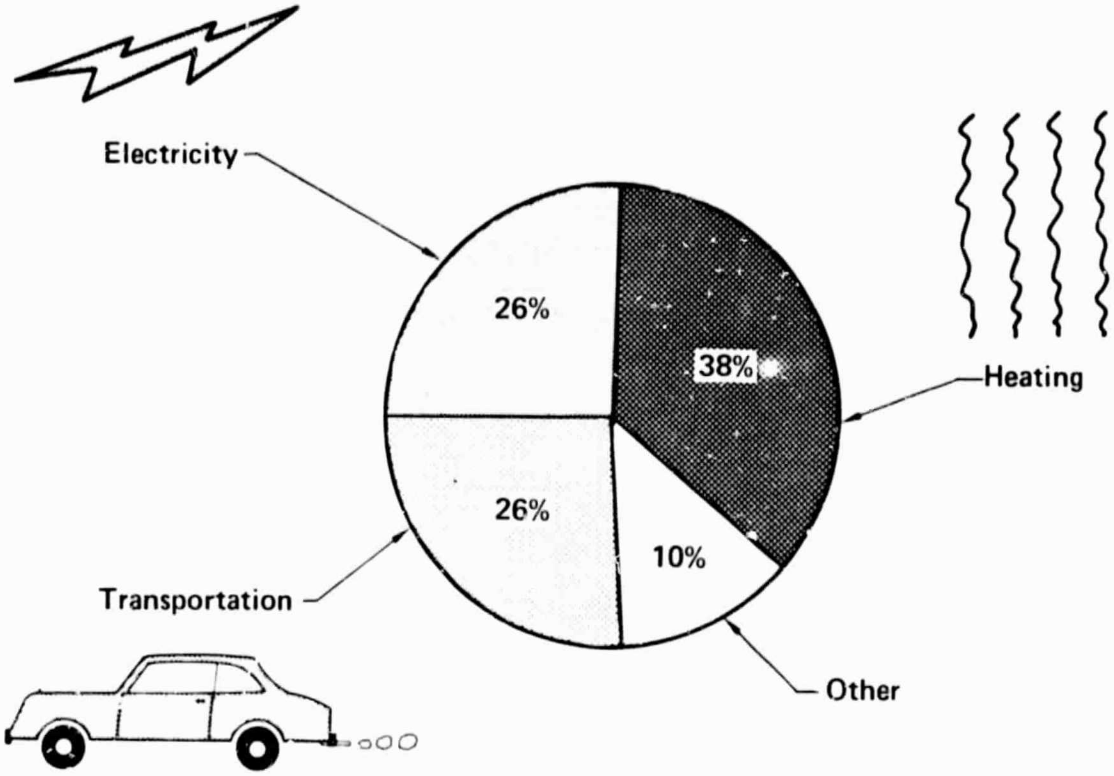
RESIDENTIAL ARRAY – COMMUTER CAR APPLICATION IS VERY PROMISING

- $1-2/peak watt cells compete with gasoline at $2-4/gallon
- Energy costs for transportation fuels rising most rapidly
- Solar-electric system twice as efficient as internal combustion engine
- Transportation accounts for large share of energy consumption
- Excess array energy can power 10-20% of home electric load

TIME VALUE OF MONEY CALCULATION SHOWS PRICE COMPETITION AT $1/PEAK WATT AND $3.70/GALLON GAS



US ENERGY CONSUMPTION IS DISTRIBUTED INTO 3 MAIN AREAS



SOLAR CELL POWERED TRANSPORTATION CAN PROVIDE A LARGE AND EARLY MARKET FOR PHOTOVOLTAICS

- **Demonstration of 70% sun powered vehicle for 1600 miles**
- **Vehicle with 40 mile/day, 55 mile/hour capability can be powered by roof-top array**
- **Economics is promising due to escalating fuel prices and combustion engine inefficiency**
- **Transportation accounts for large fraction of energy fuel consumption (26 percent)**