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Low-Cost
Solar Array Project

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Progress Report 13

for the Period April 1979 to August 1979

and Proceedings of the 13th Project Integration Meeting

Prepared for

U.S. Department of Energy

Through an agreement with
National Aeronautics and Space Administration

by

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

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period April through August 1979. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at, the Project Integration Meeting held August 22-23, 1979.

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NOMENCLATURE

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

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

MWS	Multiwire sawing
Na	Sodium
NDE	Nondestructive evaluation
Nb	Niobium
NOCT	Nominal operating cell temperature
O	Oxygen
OTC	Optional test conditions
P	Phosphorus
PA&I	Project Analysis and Integration Area
PDU	Process Development Unit
P/FR	Problem/failure report
PIM	Project Integration Meeting
PMMA	Polymethylmethacrylate
P_{max}	Maximum power
PnBA	Poly-n-butyl acrylate
POC13	Phosphorus oxychloride
PP&E	Production Process and Equipment Area
ppba	Parts per billion atoms
ppma	Parts per million atoms
PRDA	Program Research and Development Announcement
PV	Photovoltaic
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RTR	Ribbon-to-ribbon (silicon crystal growth method)
S	Sulfur

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

SECTION I

PROJECT SUMMARY

A. INTRODUCTION

This report describes the activities of the Low-Cost Solar Array Project during the period April 1979 through August 1979, including the 13th LSA Project Integration Meeting (PIM) held August 22 and 23, 1979.

The LSA Project is assigned responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this, and the progress that has been made during the period.

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic modules at a rate greater than 500 MW/yr and at a price of less than $700 (in 1980$) per peak kilowatt by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. OVERVIEW

In cooperation with PP&E and the Large Area Silicon Sheet Task, detailed SAMIS analyses were made for candidate 1986 factories based on advanced Czochralski ingot growth and wafering, web dendritic, EFG, and HEM cast single crystal ingots. A number of SAMIS runs were made to analyze the potential of cast polycrystalline ingot technology with a variety of assumptions for the manufacturing sequence and the module performance. An advanced version of IPEG, for application to foreign manufacture of photovoltaics, is being developed.

Battelle Columbus Laboratories (BCL) is fabricating and installing the four principal items of equipment that will be required for verifying key process functions of an EPSDU. Union Carbide Corporation issued the final report on Phases I (process feasibility) and II (EPSDU process design). The Phase III process support R&D for a 100 MT/year EPSDU is proceeding. The design of a novel reactor for producing semiconductor grade silicon from the hydrogen reduction of trichlorosilane ($SiHCl_3$) was completed by Energy Materials Corp. Effort was resumed on the Westinghouse development of the arc heater process with shakedown testing in progress.

Two Mobil Tyco multiple-growth runs using five cartridges produced 90 m and 150 m of 5 cm wide ribbon at average growth rates of 3.4 cm/min and 3.75 cm/min, respectively (8 h and 14 h run times). Preliminary efficiencies were measured to be between 8 and 9% AM1. An

18-hour single-cartridge run was successfully completed. Westinghouse has demonstrated web throughput of 27 cm^2/min. Web material consistently wider than 4 cm has been produced. Honeywell has produced more than 100 SOC cells in the 4 to 10 cm^2 range with average efficiencies around 8-9% (AM1). Using the silicon-coating-by-inverted meniscus (SCIM) coating procedure with the substrate tilted upward at an angle of +20°, nearly the entire surface of 5 cm x 50 cm unslotted substrates were covered. Higher-growth-speed tests have resulted in 10 μm films at 0.15 to 0.2 cm/sec rates over almost the entire surface. Crystal Systems has cast several 8 kg HEM ingots, 15 cm on each edge with average single crystal structure equal to 80%. Crystal Systems has achieved a cutting speed of 5.7 mils/min with their multiwire saw. Hamco has successfully produced ingots weighing over 100 kg using sequential melt replenishment. The material was 85% single crystal and was grown in 86 hours. Siltec has grown 6-in-dia Cz ingots under vacuum but without recharging. Siltec has demonstrated the use of a production-type ID saw utilizing microprocessor control and ingot rotation cutting speeds of 1.3 cm/min increasing to 10 cm/min toward the center of the ingot. The kerf loss was 250 μm and the wafer thickness was 250 μm.

An improved ethylene/vinyl acetate (EVA) has been successfully formulated by Springborn for an encapsulation pottant, with production of 1000 lb now in process. SPIRE has delivered 6-in-square electrostatically bonded modules, each containing four 2 inch dia cells. A 4 x 8-ft prototype glass-fiber-reinforced concrete (GRC) substrate has been produced and tested by MB Associates. A final report draft, "Development of Accelerated Test Design for Service-Life Prediction of Solar Array at Mead, Nebraska," was delivered by Battelle. A minimodule using poly-n-butylacrylate (PnBA) as a pottant was made and successfully sent through the JPL qualifying tests.

Spectrolab reports their process sequence is complete to antireflective coating. A decision has been made to laser scribe from the back side after back-surface field formation and before front-side metallization. The RCA antireflective film produced by their spray-on titanium isopropoxide process becomes tetragonal titanium dioxide (anastase) with a refractive index of 2.22. On polished wafers a broad reflection minimum is reached at about 6,000 A. Sol/Los cells made using their molybdenum-based ink metallization have been fired at high temperatures and then annealed at lower temperatures. They exhibited the required metallization adhesion strength but also showed the electrical properties of cells that had only been fired at the lower temperatures. RCA reports that they are able to interconnect 90 cells (6 x 15 strings) in a single-pass, continuous process. The cells used were of 7.5 cm dia and had been pre-tinned and pre-tabbed. The technique is one designed by RCA in which a motorized infra-red lamp is used to heat the solder and interconnects. A hollow cathode has been operated successfully in a Freeman-type ion source. This is identical to the type used in the Extrion 200-1000 ion implanter at SPIRE Corp.

A multi-cell failure-analysis computer program was developed and used in a life-cycle cost analysis. Drafts of the final reports for the Bechtel curved-glass module structure study, the Boeing wind-loading study and the Burt Hill Kosar Rittelmann Associates residential requirements study were received. The Phase II module soiling investigation was expanded to include samples at MIT/LL and NYU. A preliminary procedure for proof-testing cells mechanically before encapsulation is under investigation as a method of minimizing broken cells in completed modules. Significant progress was made in preparation of array standards requirements/criteria and test-method drafts.

Block III module deliveries are complete except from Sensor Technology, which has been unable to purchase enough 5-cm-dia wafers. Eight contracts for the Block IV module design and test phase were executed. Ten module designs will result from these contracts, with ARCO Solar, GE, and Solarex producing modules to be qualified under the residential specifications, and ARCO Solar, Motorola, Applied Solar Energy Corp., Sensor Technology, Solar Power, Solarex, and SPIRE producing modules to be qualified under the intermediate-load specifications. The Block IV designs reviewed to date show that distinct improvements are being incorporated into these new modules. The qualification testing of 12 types of PRDA-38 modules was completed. The principal focus of field test activity centered on two areas: continuation of in-field calibration of reference cells and inspection and acquisition of data from the newly acquired JPL/Lewis remote sites.

Please read pages 3-1 to 3-8 for a summary of the 13th LSA Project Integration Meeting.

SECTION II

AREA REPORTS

A. PROJECT ANALYSIS AND INTEGRATION AREA

Planning and Integration

The LSA PA&I Area has been supporting the Technology Development and Applications Lead Center in developing an advanced version of IPEG, a version of IPEG for application to foreign manufacture of photovoltaics and an analysis of a fixed-price buy involving cast polycrystalline ingot technology.

The ongoing dialogue is continuing with the American Physical Society concerning the viability of the silicon crystal based photovoltaic technologies. An updated response has been drafted and transmitted by PA&I and the Lead Center to address concerns stated by APS and to reflect the substantial progress made by the Project since the last exchange of letters.

Array Technology Cost Analysis

SAMIS III Release 2 has been released by the Technology Development and Applications Lead Center. The inflation tables have been modified to reflect the current economic environment. Modifications of the indirect requirements have also been made, based on suggestions by PP&E, PA&I, Theodore Barry and Associates and others.

In cooperation with PP&E and the Large Area Silicon Sheet Task, detailed SAMIS analyses were made for candidate 1986 factories based on advanced Czochralski ingot growth and wafering, web dendritic, EFG and HEM cast single crystal ingots. These sheet options were combined with several cell processing options to produce seven candidate factories. The results of these analyses were presented at the Thirteenth PIM and are shown in Section III of this document.

The LSA Project Price Allocation Guidelines have been updated. The preliminary results were presented at the Thirteenth PIM and are shown in that section of this document. A document is in preparation describing the Price Allocation Guidelines in detail.

At the request of DOE and the Lead Center, a number of SAMIS runs were made to analyze the potential of cast polycrystalline ingot technology. Both near-term and large-scale production levels were investigated with a variety of assumptions for the manufacturing sequence and module performance.

Economics and Industrialization

An examination is in progress to determine what the role of the LSA project should be after silicon technical readiness has been achieved.

B. TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

The objective of the Silicon Material Task is to develop processes for producing silicon (Si) suitable for solar cells at a price of less than $14 per kilogram (1980 dollars). 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 costs 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 and produce semiconductor-grade Si. Another means of meeting this requirement is to devise a process for producing Si material that is less pure than semiconductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSA is dependent on optimization trade-offs, which concomitantly deal with the price of Si material and the effects of material properties on the performance of solar cells. Thus the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si. This structure has been presented in detail in previous LSA Progress Reports. Besides the process development mentioned above, the program includes economic analyses of silicon-producing processes and supporting efforts, both contracted and in-house at JPL, to respond to problem-solving needs.

Sixteen contracts in progress are listed in Table 2-1.

Summary of Progress

Development of Processes for Producing Semiconductor-Grade Silicon: Preparatory to developing a 50-MT/yr EPSDU (Experimental Process System Development Unit) based on their process, Battelle Columbus Laboratories (BCL) began a Process Development Unit program on April 1, 1979. This consists of the installation and operation of four principal items of equipment for the EPSDU: a zinc vaporizer, a fluidized bed reactor, a reactor effluent condenser and a $ZnCl_2$ electrolysis cell. The PDU program involves six months of procurement, fabrication, installation and startup, and four months of operation.

Table 2-1. Silicon Material Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SEMICONDUCTOR-GRADE SILICON PROCESSES	
Battelle Columbus Laboratories Columbus OH JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized bed reactor
Energy Materials Corporation Harvard MA JPL Contract No. 955269	Gaseous melt replenishment system
Union Carbide Corporation Tonawanda NY JPL Contract No. 954334	Silane/Si process
SOLAR-CELL-GRADE SILICON PROCESSES	
SRI International Menlo Park CA JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corporation Trafford PA JPL Contract No. 954589	Reduction of $SiCl_4$ by Na in arc heater reactor
IMPURITY STUDIES	
Aerospace Corporation El Segundo CA JPL Contract No. 955201	Impurity concentration measurements by analytical photon catalysis
Lawrence Livermore Labs Livermore CA NASA Defense Purchase Request No. WO-8626	Impurity concentration measurements by neutron activation analysis
Materials Research, Inc. Salt Lake City UT JPL Purchase Order No. JR-672583	X-ray analysis of silicon wafers
National Bureau of Standards Washington DC NASA Defense Purchase Request No. WO-8604	Impurity concentration measurements by neutron activation analysis and spark-source mass spectroscopy

Table 2-1. Silicon Material Task Contractors (Continuation 1)

CONTRACTOR	TECHNOLOGY AREA
IMPURITY STUDIES (Cont'd)	
Sah, C.T., Associates Urbana IL JPL Contract No. 954685	Effects of impurities on solar cell performance
Solarex Corporation Rockville MD JPL Contract No. 955307	Effects of impurities on solar cell performance
Westinghouse R&D Center Pittsburgh PA JPL Contract No. 954331	Definition of purity requirements
SUPPORTING STUDIES	
AeroChem Research Labs Princeton NJ JPL Contract No. 954777	Investigation of silicon halide/alkali metal flames
JPL Contract No. 954862	Development of model and computer code for description of silicon production processes employing silicon hydrides or halides
Lamar University Beaumont TX JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge MA JPL Contract No. 955382	Hydrogenation of $SiCl_4$ and metallurgical-grade silicon
Jet Propulsion Laboratory Pasadena CA	Silicon production process R&D

To the end of this reporting period, procurement has been on schedule, with the major exception of graphite liners for each of the four items listed above and the minor exception of condenser and heat exchanger liquid pumps. Site preparation (at BCL), isolation wall construction, structural steel work, electric circuitry, piping and instrumentation are all on schedule.

During this reporting period, R&D activity at BCL in support of the PDU has consisted solely of studies of the reactor effluent condenser, using a single-tube version. The purpose of the work is to demonstrate and to optimize the operation of a wet-wall type of condenser for the removal of $ZnCl_2$, Zn and Si dust from the gaseous effluent stream. A condenser run was made in late June, followed by a disassembly analysis. It showed that operational problems (clogging and low yield) were sufficiently alleviated by design modification and procedural changes that the condenser R&D work could be considered completed.

For the PDU, BCL is following the graphite liner situation closely and is investigating alternatives, in case a lapse of schedule is indicated. R&D support activity will continue with a study of the zinc vaporizer. BCL is expected to complete the installation part of the PDU program and to have accumulated two months of operational experience on the PDU during the next reporting period.

A program was initiated on April 17, 1979, with Energy Materials Corp. to develop a novel reactor for producing semiconductor-grade Si from the hydrogen reduction of trichlorosilane ($SiHCl_3$) and delivery of low-cost molten Si to a crystal growth apparatus. The design of the experimental apparatus and of procedures to carry out Task I (demonstration of process feasibility) was completed. Procurement of the equipment and materials for constructing the apparatus was begun.

The third effort in developing processes for producing semiconductor-grade Si is being performed by Union Carbide Corporation. The contractor issued the final report on Phases I (process feasibility) and II (EPSDU process design). The Phase III program (100-MT/yr EPSDU and its associated supporting R&D effort) started during this period. The process support R&D started in April 1979, and experimental data on the kinetics of trichlorosilane and dichlorosilane redistribution were correlated. Using these correlations as a base, the two liquid-phase redistribution reactors were properly sized. The inert fluidization gas experiments are progressing well. Capacitive heating of a 550-μm-diameter silicon particle bed shows that large particles can be heated with minimal sintering. Particle separation tests with the new boot design show that it is possible to separate larger and smaller particles. More tests are needed to optimize the design. Two bed-sintering tests, conducted using high-purity silicon, showed that the sintering rates are much lower when compared with the tests conducted with metallurgical-grade Si (mg-Si).

A concept was developed for pyrolyzing silane onto a slim rod of silicon in a reactor. The product silicon, containing over 90% newly deposited silicon, could be used to characterize the electronic contaminants in the silane. The design emphasis is on the detection of low-level impurities and on a quick and easy operation.

The EPSDU pre-engineering effort was formally begun in June. The engineering work will be based on a process design package, issued in Engineering Memorandum form on June 1, 1979. The information is based on the most recent stream catalog and on the process flow diagram. The process design is not complete in a few areas, and the support R&D effort has been directed to address these uncertainties. A small waste treatment apparatus is being assembled to learn more about control system design, materials of construction, and environmental concerns.

Development of Processes for Producing Solar-Cell-Grade Silicon. SRI International: In Task I (gas reactor), a unit was constructed of Inconel and batches of Si up to 0.5 kg were made routinely in the reactor, which is 15 cm in diameter and 120 cm high. Recent effort was devoted to improvements in the sodium (Na) feed mechanism. Shredded Na was stored in the reactor and delivered by a screw-feed mechanism. The uniform feed rate contributes to obtaining Na-free reaction product. In Task II (melt separation), one kg of reaction product yielded 0.2 kg of Si. A graphite cup 15 cm in diameter and 20 cm high was made operational. The melt separation system employing this cup and capable of holding up to 0.7 kg of Si was operated successfully with continuous feed of reaction product. The Si samples were found by emission spectroscopy to be free of impurities and more refined analyses (SSMS and resistivity) are under way. Westinghouse: Effort was resumed on the development of the arc heater process for producing solar-cell-grade Si by the Na reduction of silicon tetrachloride ($SiCl_4$). Most of the work consisted of assembly and installation of the process demonstration system. The Na and $SiCl_4$ reactant feed systems were completed, and these two systems were installed and the electrical work on them was completed. Shakedown testing is in progress preparatory to initial testing with reactants.

Impurity Studies. Aerospace Corporation: Analyses were made of a sample of Si obtained from SPEX Industries, stated to be 99.999% pure. A well-defined spectrum was obtained, showing the presence of arsenic, bismuth, gallium, and germanium as impurities. In continuing their analyses, Aerospace found high signal-to-noise ratios for copper at 5 ppm, aluminum at 1.0 ppm, and magnesium at 0.2 ppm. These data fall within the manufacturer's specifications for the material, which list copper at 4 to 8 ppm, aluminum at 0.5 to 2 ppm, and magnesium at 0.1 to 0.5 ppm. Modifications were then made to the equipment to speed sample handling techniques and to optimize conditions for analysis.

C. T. Sah Associates: The second technical report was distributed. It contains a computer study of silicon solar cell performance limited by the following factors:

(1) Interband Auger recombination.

(2) Interface recombination at the front and back surfaces.

(3) Enhanced impurity solubility in the diffused emitter and back-surface field layers.

(4) Diffusion profiles of majority or doping impurities.

(5) Recombination at the defect-impurity centers (phosphorus-vacancy pair and boron-impurity-vacancy complexes) in the diffused emitter and back surface field layers.

(6) Recombination at the titanium (Ti) recombination centers in the base and in the diffused emitter.

Comparisons are made with the Sandia high-efficiency cell (17% AM1) and the Westinghouse Ti-doped cells. The 17% Sandia cell is base-recombination or base-lifetime limited (700 μs) and is near the maximum AM1 efficiency obtainable (19%) from this cell geometry ($p+/n(10\ \Omega$-cm$/n^+$) Emitter recombination and surface recombination cannot be important in this cell. A 16% AM1 efficiency can be obtained in a $p^+/n(5\times10^{15}$ atoms/cm$^3)/n^+$ of the Westinghouse geometry if the Ti concentration is smaller than 6×10^{12} Ti/cm^3, which is again limited by base recombination at the Ti center. Emitter recombination at the Ti centers may become important when the Ti density in the starting material is greater than about 10^{14} Ti/cm^3.

A code for computing small-signal admittance as a function of forward bias, signal frequency, and sample temperature for solar cells was completed and tested against the DC differential conductance from the slope of the DC I-V characteristics.

Equilibrium capture rates at impurity recombination centers in silicon p-n junctions are being obtained from transient capacitance measurements. Preliminary measurements of the electron capture rates at the gold acceptor from 77K to 250K gave no temperature dependance, and the value is in excellent agreement with that used in Technical Reports I and II of this program.

Solarex Corporation: The detailed program plan was evolved and approved by JPL. The plan includes not only the cell processing parameters, but also the in-process inspections and tests, equipment calibration, lot traveler formats, data package formats, and quality assurance plan. Over 400 "verification cells" have been processed and evaluated. The production of these cells is now very consistent, with AM0 efficiencies mostly in the range of 12.7 to 12.9% (measured at

25°C). These are very respectable efficiencies for a "detuned" space-type cell. It is expected that by the end of August the first lot of five experimental subgroups will have been fabricated. The detuned process selected is consistent for control cells fabricated from both 111 and 100 silicon when the former is etched in CP 26 (5 parts HNO_3/3 parts HF/6 parts acetic acid) and the latter in sodium hydroxide. Earlier problems with front-contact integrity have been greatly minimized by improvements in processing, particularly with respect to the photoresist technology. A batch of verification cells was submitted to JPL for evaluation. Electrical measurements made by JPL proved to be in good agreement with those made by Solarex; currents, voltages, and maximum power outputs agreed within ±1% (noting that JPL measures at a cell temperature of 28°C).

Westinghouse R&D Center: The first measurements of the segregation coefficients of tungsten, tantalum, and cobalt during Czochralski pulling of silicon single crystals were performed. Sensitive neutron activation analysis was used to determine the metal impurity content of the silicon, while atomic absorption was used to measure the metal content of the residual liquid from which

$$k = \frac{C_s}{C_l}$$

is computed. The measured values were $k_W = 1.7 \times 10^{-8}$, $k_{Ta} = 2.1 \times 10^{-8}$, $k_{Co} = 1 \times 10^{-5}$. The preliminary value of $k_{Mo} = 4.5 \times 10^{-8}$ was confirmed.

Gettering of Ti-doped silicon wafers improves cell performance by 1 to 2% (absolute) for the highest temperatures and longest times. HCl is more effective than $POCl_3$ treatments for deactivating Ti, but $POCl_3$ and HCl produce essentially identical results for Mo or Fe. Detailed analysis by deep-level transient spectroscopy (DLTS) indicates that the performance improvement is due to a reduction in the number of active recombination centers, not to a change in the recombination energy level.

The reduction in the trap center density is not uniform through a wafer but is lowest near the junction, then rises to a value close to that in the bulk within a distance of 10 to 12 μm from the surface. The formation of the impurity profile during gettering appears to be diffusion-controlled. When a mathematical model is fitted to the Ti profile measured after gettering, it is found that the diffusion constant $D_{Ti} \approx 1.3 \times 10^{-11}$ cm^2/sec is close to extrapolated values in the literature.

Measured cell-performance data coupled with the preliminary segregation coefficients indicate that cobalt behaves much like manganese and iron, while tungsten and niobium depress cell performance about as much as molybdenum. Tantalum appears to degrade cell performance by the greatest amount at any given impurity concentration.

Supporting Studies: AeroChem Research Laboratories: In the study of silicon halide/alkali metal flames, AeroChem performed tests of the Na/$SiCl_4$ reactor, graphite collection crucible for Si, and associated heating systems. It was found that molybdenum wire heaters are not suitable for producing high-purity Si. Graphite preheaters were found to be satisfactory, and with a thick-walled graphite reactor, satisfactory runs were made for 20-minute durations. It was found that stainless steel delivery tubes were satisfactory for Na delivery, but not for $SiCl_4$ delivery, so alumina tubing is under construction for $SiCl_4$ delivery.

The AeroChem effort in development of a model and computer code for description of silicon production processes employing silicon hydrides or halides is nearing its completion date, October 20, 1979. Two computer models, CHEMPART and modified GENMIX, were developed to describe silicon processes occurring in the Westinghouse arc heater reactor and the AeroChem reactor used in the above flame study. CHEMPART is a modified version of the LAPP (Low-Altitude Plume Program) code; it describes the chemical reaction $4\ Na + SiCl_4 \longrightarrow Si + 4\ NaCl$ and the nucleation and growth of silicon particles. It is used to calculate the size distribution of Si nuclei in the core region of the Westinghouse reactor. The modified GENMIX computer model describes the condensation of Si vapor and transport of Si droplets to the reactor wall. AeroChem concluded that the Soret effect is the important mechanism in the transport of silicon droplets (0.01 μm to 1 μm) to the walls. Calculations are being performed to determine the size distribution of Si droplets (with the use of CHEMPART) and to determine Si collection efficiency of the Westinghouse reactor (with the use of modified GENMIX).

AeroChem is preparing the draft final report for the contract. Complete documentation (as a user's guide) is being prepared for the computer models CHEMPART and GENMIX. At the completion of the contract in October,1979, AeroChem will deliver the final report, card decks for the two computer models, and user's guides for the computer models.

Lamar University: Primary efforts were expended on process system properties, chemical engineering and economic analyses.

Analyses of process system properties were continued for silicon source materials involved in the processes under consideration for producing semiconductor-grade silicon. Primary efforts centered on physical and thermodynamic property data for dichlorosilane. The following property data were reported for dichlorosilane: critical temperature, critical pressure, critical volume, critical density, acentric factor, vapor pressure, heat of vaporization, gas heat capacity, liquid heat capacity, density, surface tension, gas viscosity, and liquid viscosity.

Work was initiated on a system to prepare binary gas mixtures of known proportions and to measure the thermal conductivity of these mixtures between 30° and 350°C. The binary gas mixtures will include silicon source material such as silanes and halogenated silanes used in the production of semiconductor-grade silicon. The apparatus was assembled, and calibration studies using mixtures of nitrogen and hydrogen were started.

Chemical engineering analysis of the Battelle process was continued with major efforts concentrated on the preliminary process design. Primary activities in the preliminary design were devoted to determining production labor requirements for operating the major process equipment as well as raw material, utility, and major process equipment requirements.

Massachusetts Institute of Technology: This effort, which started in April 1979, is for study of the conversion of $SiCl_4$ and metallurgical-grade silicon to $SiHCl_3$, as a supporting program for the Union Carbide contract. A program plan and baseline cost estimate were prepared and submitted to JPL, and the design of the reactor assembly was completed. Preparation of the laboratory site for the hydrogenation experiments was completed, and construction and installation of the hydrogenation reactor assembly is in progress. The apparatus for the hydrogenation studies was 85% completed at the end of July. Start-up of the reactor system is scheduled for August.

JPL In-House Studies: Two LSA Project reports (5101-105 and 5101-106) on silicon particle growth (SPG) modeling were published. These reports established the theoretical and mathematical basis for the modeling of SPG. A computer model of SPG for flow reactors was completed and is being tested. The model is applicable to circulating fluidized beds of high void fraction (0.9 or more) and to the Union Carbide Corporation free-space reactor; development of the model is being coordinated with development of UCC's model for the jet expansion zone of the free-space reactor.

Experiments (Runs 3 and 4) were conducted in the continuous-flow pyrolyzer (CFP) system using a silane flow rate of 1.4kg/h and reactor temperature of 600 to 700°C. Seed particles were used in Run 3. Silicon product from both runs appears to be of a different texture, higher bulk density, and larger particle size in comparison with the silicon-particle product obtained in previous CFP experiments. One experiment (Run 5) was conducted in the CFP system using a silane flow rate of 1.1 kg/h and reactor temperature of 810 to 870°C for a total time of 57 sec. The product particle size ranged from 0.1 to 0.4 μm.

The experiments (Runs 1-5) indicate that the product particle size increases with increasing silane concentration, increasing reaction time, and decreasing reaction temperature. The use of seed particles appears to promote the coagulation of fine product particles. Chemical-vapor deposition of silicon on seed particles, however, has not been observed.

The investigation of the clogging phenomenon in fluidized bed reactors continued. SEM examination of the clogs obtained with alumina bed particles indicate that clogging may be caused by the silicon deposited from silane. No evidence of sintering of alumina was found. SEM examination of the clogs obtained with silicon bed particles showed that the bed particles were bonded with a dense coating of silicon. The reason for the dense coating or sintering of silicon has not been identified. All fluidized bed reactor results to date show that bubbling fluidized beds would be clogged when the bed temperature and silane concentration are above 630°C and 3%, respectively. One run was conducted in a slugging mode (at a speed eight times the minimum fluidization speed) at 700°C and 7% silane concentration without clogging.

In the work on silicon chemical vapor deposition, the apparatus was completely assembled and tested for leaks, and the capability of the heaters was determined. Reactor wall temperatures of 950°C were achieved. The setup is ready for experimentation.

Large-Area Silicon Sheet Task

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several alternative 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 for 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 (e.g., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of silicon high-volume production techniques that would result in low-cost electrical energy.

Growth of crystalline silicon material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), 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 ID blade cutting, initiated in 1975-76, continues.

Organization and Coordination: At the time 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 being funded. After a period of accelerated development the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed in 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 Task Contracts: Research and development contracts awarded for growing crystalline silicon material for solar cell production are shown in Table 2-2. Preferred growth methods for further development during FY '79-80 have been selected.

Technical Background

Shaped-Ribbon Technology: Vacuum Die Casting Method--Arco Solar. 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. The Stanford Research Institute is under subcontract to 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 cm 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 of this is that the heat of fusion is radiated from a larger area. Thus the material can be solidified much faster. This project is presently a feasibility study requiring a demonstration of the technique.

Shaped-Ribbon Technology: Edge-Defined Film-Fed Growth 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 5 cm/min at a ribbon width of 10 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

Table 2-2. 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 Blcomington 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
Hamco Corporation Rochester NY JPL Contract No. 954888	Advanced Cz growth
Silicon Technology Corporation Oakland NJ JPL Contract No. 955131	ID wafering

Table 2-2. Large-Area Silicon Sheet Task Contractors (Continuation 1)

CONTRACTOR	TECHNOLOGY AREA
INGOT TECHNOLOGY (CONTINUED)	
Siltec Corporation Menlo Park CA JPL Contract No. 955282	ID wafering
Siltec Corporation Menlo Park CA JPL Contract No. 954886	Advanced Cz growth
Varian Vacuum Division Lexington MA JPL Contract No. 954374	Multiblade slurry sawing
Varian Vacuum Division Lexington MA JPL Contract No. 954884	Advanced Cz growth
DIE AND CONTAINER MATERIALS STUDIES	
Battelle Labs Columbus OH JPL Contract No. 954876	Silicon nitride for dies
Coors Porcelain Golden CO JPL Contract No. 954878	Mullite for container and substrates
Eagle Picher Miami OK JPL Contract No. 954877	CVD silicon nitride and carbide
RCA Labs Princeton NJ JPL Contract No. 954901	CVD silicon nitride
Tylan Torrance CA JPL Contract No. 954896	Vitreous carbon
University of Missouri Rolla Columbia MO JPL Contract No. 955415	Partial pressures of reactant gases

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

CONTRACTOR	TECHNOLOGY AREA
MATERIAL EVALUATION	
Cornell University Ithaca NY JPL Contract No 954852	Characterization-Si properties
Charles Evans and Associates Company San Mateo CA JPL Contract No. LK-694028	Technique for impurity and surface analysis
Applied Solar Energy Corp. City of Industry CA JPL Contract No. 955089	Cell fabrication and evaluation
Spectrolab Sylmar CA JPL Contract No. 055055	Cell fabrication and 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 technique evaluation

Shaped-Ribbon Technology: Dendritic Web--Westinghouse. Dendritic web is a thin, wide, ribbon form of single crystal silicon. "Dendritic" refers to the two wire-like dendrites on either 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 that can be fabricated from it, the excellent packing factor of the cells into subsequent arrays, and the cost-effective conversion of raw silicon into substrates.

Supported-Film Technology: Silicon-on-Ceramic Substrate--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 eliminates the need for 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-exchanger ingot casting method can be applied to the growth of large shaped silicon crystals (30-cm cube) in a form suitable for 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 eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (25-kg sapphire ingots have already been grown), and the theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

Ingot Technology: Advanced Cz--Varian, Siltec and Hamco. In the advanced Cz contracts, efforts are geared toward developing equipment and a process to achieve the cost goals and demonstrate the feasibility of continuous Cz solar-grade crystal production. Varian will modify an existing furnace for continuous growth using granular silicon for recharging (molten silicon will also be considered), and a new puller is to be designed.

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 100kg of a single crystal material using only one crucible by periodic melt replenishment.

Silicon Slicing: Fixed Abrasive Sawing Technique (FAST)--Crystal Systems; Multiblade Sawing (MBS)--Varian; Inner Diameter (ID) Sawing--Silicon Technology and Siltec. Today most silicon is sliced into wafers with an inside diameter (ID) saw, one wafer at a time being cut from the crystal. Advanced efforts in this area are continuing. The multiblade and multiwire slicing operations employ similar reciprocating blade-head motion with a fixed workpiece. Multiblade slicing is done with a slurry suspension of cutting fluid and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness. Multiwire slicing uses .125 mm wires surrounded by a 0.05 mm copper sheet, which is impregnated with diamond as an abrasive. Ingot rotation and dynamic blade control are some of the advance work being pursued in ID sawing.

Contact Material--Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, Tylan and 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. The objective of these contracts is to develop and evaluate cost-effective refractory die and container materials. The material must be mechanically stable to temperatures above the melting point of silicon, must not excessively contaminate the silicon processed through it, be amenable to the fabrication of dies and containers with close tolerances and varying geometries, and be cost-effective. Two of the contracts in this area, with RCA and Tylan, are to develop a substrate material for supported film growth and a coating for substrates, dies, and containers. UMR is investigating the effect of partial pressures on the reaction between molten silicon and the fused-silica contact.

Material Evaluation--Applied Solar Energy Corp., 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 process 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, Applied Solar Energy Corp. 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, thus permitting a correlation of impurity distributions with the defect structures.

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

Summary of Progress

Shaped-ribbon Technology. Arco Solar: SRI has cast a silicon rod in a boron nitride (BN) die. No attempt to remove the silicon from the die was made. However, large grains (200 μm by 1 mm) were measured. Initial tests using a split mold made of graphite were unsuccessful due to the silicon reacting with the mold to form silicon carbide. These experiments demonstrated the need to use coated dies. Energy Materials: Several ribbon-growth runs have been made, but small problems have prevented a definitive effort. A consultant has been retained to investigate heat flow and resulting thermal-gradient problems. Mobil Tyco: Two multiple-growth runs using five-5-cm wide cartridges produced 90 m and 150 m of ribbon at average growth rates of 3.4 cm/min and 3.75 cm/min, respectively (8 h and 14 h run times). Preliminary efficiencies were measured to be between 8 and 9% AM1. An 18-hour single-cartridge run was successfully completed. Stable growth runs using the 10-cm-wide cartridge has been achieved for over 6 m. Ribbon flatness and stress investigations continue with only minor buckling being observed in the 5 cm/min (7.5-cm wide) growth. Controlled gas-flow experiments have produced large-area (5 cm x 10 cm) cells with efficiencies greater than 11% (AM1). Motorola: Reproducible RTR material was not produced by the purgative furnace. It was observed that Si_3N_4 coating on Mo gives good nucleation sites, but CVD ribbon separation is a major problem. SO_x coating on Mo did give good isolation but poor nucleation. Westinghouse: A throughput of 27 cm^2/min has been demonstrated. Web material consistently wider than 4 cm has been produced because of the changes in the thermal environment around the lid. Development of a melt replenishment system has progressed well. A bench-model version of a melt-level sensor consisting of a reflected laser beam has demonstrated its usefulness.

Supported-Film Technology. Honeywell: More than 100 cells in the 4 to 10 cm^2 range have been produced with average efficiencies around 8-9% (AM1); the best was greater than 10% (AM1). Additionally, cells on 100- m-thick films have shown good performance. Tests indicate that boron doping in the 0.8-2-cm range is optimum for silicon on the slotted ceramic substrates. The silicon-coating-by-inverted meniscus (SCIM) coating procedure was improved by passing the substrate over the meniscus at an angle of +20°. Nearly the entire surfaces of 5 cm x 50 cm unslotted substrates were covered. Higher-growth-speed tests have resulted in 10 μm films at 0.15 to 0.2 cm/s rates over almost the entire surface. Thinner films (6 μm) have been produced at 0.2-0.3 cm/s rates. These films show directional solidification and good grain structure, but have exhibited no junction characteristics after cell processing.

Ingot Technology. Crystal Systems (HEM): Several 8-kg ingots, 15 cm^3 on each edge, have been cast with average single crystal structure equal to 80%, the best being 90%. Material cracking due to crucible attachment continues to be a major problem. Crystal Systems (FAST): A cutting speed of 5.7 mils/min has been achieved. Unfortunately, severe vibration and guide-roller instability has caused low yields. Hamco: Runs producing ingots over 100 kg have been successfully completed using sequential melt replenishment. The material was 85% single crystal and was grown in 86 hours. It has been demonstrated that the recharge material can be either polyrod or chunk silicon. Siltec (Cz): Modifications to incorporate a solid-rod feed and vacuum operation into the furnace are underway. Ingots of 6-in dia have been grown under vacuum but without recharging. A newly designed transfer tube/heater element has been fabricated and will be tested in the next quarter. Two 150-kg runs have been scheduled for January. Siltec (ID wafering): A production-type saw using microprocessor control and ingot rotation has achieved a cutting speed of 1.3 cm/min, increasing to 10 cm/min toward the center of the ingot. Kerf loss is 250 μm and a wafer thickness of 250 μm has been demonstrated. Routine cutting continues to be plagued by edge-chipping problems. Design of the rotary blade dressing fixture and the blade position sensor has been completed. Varian (Cz): The construction of the prototype advanced Cz grower continues on schedule. Varian (MBS): Several wafering demonstrations have been performed. Due to various hardware failures none of the runs was successful.

Die and Container Materials. Battelle showed that specific compositions of high-purity-silicon aluminum oxynitride (sialon) and silicon beryllium oxynitride (sibeon) solid solutions are promising refractory materials for handling and manipulating solar grade silicon into silicon ribbons. Well-controlled processing procedures were developed for fabricating high-purity sialon and sibeon materials in which the impurity content of the hot pressed ceramics was due only to impurities in the starting materials. Projected manufacturing cost estimate for 10^5 dies per year was \$5.40 per die. Evaluation of the interaction of these materials in contact with molten silicon indicates that solid solutions based upon B-Si_3N_4 are more stable than those based on Si_2N_2O. Sibeon is more resistant to molten silicon attack than sialon, and both materials should preferably be used in an inert atmosphere rather than vacuum. This is because removal of oxygen from the silicon melt as SiO enhances the dissolution of aluminum and beryllium. The wetting angles of these materials are low enough (37^o for X = 0.75B' sialon and 49^o for X = 0.35 sibeon) for these materials to be considered as both die and container materials. Eagle Picher: Recent efforts have pertained to characterizing the controlled nucleation thermal coated die (CNTD) and container test parts. Difficulties encountered in coating the die slots caused EPI to change to a two-piece die design. RCA: The difficulties in the EFG-type die development and fabrication involve die substrate/CVD coating compatibility and sufficient wetting of die surfaces. Capillary rise has been accomplished repeatedly in CVD coated dies under vacuum condition. Several dies were fabricated using reaction bonded silicon nitride and multi-phase silicon oxynitride as the substrate for subsequent CVD coatings. Excessive edge nucleation of CVD materials has caused chipping of the CVD layer to occur either upon cooling from deposition temperature or when die tips are polished. Hot pressed Si_3N_4 die substrates have been used to help eliminate this problem. Tylan: Nine samples were sent to Honeywell for silicon dip coating evaluation. All of them indicated (visually) that the Vitregraf (glassy carbon) coating provided an adequate surface wetting mechanism. University of Missouri Rolla: UMR completed work on their subcontract under the Eagle Picher Industries prime contract, JPL Contract No. 954877. This work concerned investigations of the effect of controlled partial pressures of oxygen upon reactions between molten silicon and selected coated refractories. In this work UMR used an H_2/H_2O

buffer system and a UMR-constructed thoria-yttria oxygen sensor cell to achieve and measure oxygen partial pressures below the equilibrium values for the formation of the oxides in the silicon-oxygen systems, i.e., below 10^{-18} atmospheres. This allowed the study of molten silicon-ceramic substrates systems in environments where oxides would not be present under equilibrium conditions. This work clearly demonstrated that even in this extremely low-oxygen partial-pressure range, the wetting characteristics and the degree of chemical reaction at the liquid-solid interface are dependent upon the oxygen partial pressure.

UMR was awarded a one-year study contract on May 3, 1979 (JPL Contract No. 955415) to extend the scope of previous investigations to include other refractories. Initially, these studies pertain to fused silica refractories such as the crucibles used in Czochralski crystal growth. A CO/CO_2 buffer system is being used to find the oxygen partial pressure, since the previously used H_2/H_2O buffer system would cause the silica to devitrify. This buffer system is limited to a minimum oxygen partial pressure of 10^{-16} atmospheres at 1430°C. Answers should be forthcoming whether fused silica will devitrify at low oxygen partial pressures and whether the wetting angle and degree of reaction of molten silicon in contact with fused silica will be altered.

Material Evaluation. Cornell University: EFG ribbon samples have been analyzed for molybdenum and boron concentrations using an ion microprobe. In boron-doped (10^{17} atoms/cm^3) samples variations in the boron concentration across the width of the sample were detected. Applied Solar Energy Corp.: The initial 12-month investigation of various silicon sheet materials has been completed. Some of the data from this investigation is shown in Table 2-3. More detailed results can be found in the annual report. Spectrolab: Results for various silicon-sheet materials are found in Table 2-4. UCLA: Laser-scan photoresponse measurements have been made on several solar cells of various silicon sheet materials with results still to be analyzed. A new interference length-measuring technique that mixes two slightly offset wavelengths has been developed. Several tests of this method have been performed but the results have not been reproducible. Materials Research, Inc.: Much of the effort in this contract has been in upgrading the Quantimet Image Analyzer Data Collection System, understanding and testing the system and modifying the existing silicon defect structure characterization program. Approximately 200 cm^2 of Mobil-Tyco and Motorola ribbon material have been characterized. Some of the samples have been sent to Spectrolab for cell fabrication. No results are available yet.

Table 2-3. Applied Solar Energy's Material Evaluation

MATERIAL	PERCENT EFFICIENCY		
	Std. Process	Std. Process with MLAR	BSF
Wacker Silso	8.8 - 10.2	10.6 - 10.8	8.2 - 10.2
Mobil-Tyco EFG			
(RF)	5.8 - 9.6	10.6	6.5 - 10.3
(RH)	2.9 - 7.5		
Motorola RTR			
(CVD)	3.9 (annealed)	---	---
	5.6 (unannealed)		
Single Crystal	6.6		
Westinghouse WEB	8.9 - 11.8	---	8.2 -11.0
Crystal Systems HEM	5.3 (0.5 Ω-cm)		
	10.1 (3.0 Ω-cm)	---	---
Honeywell SOC	5.1 - 11.3	---	5.5 - 6.9
Hamco (6 ingots)	6.7 - 11.4	---	---

Note: All data were taken at AMO, 25°C.

Table 2-4. Spectrolab's Material Evaluation

MATERIAL	Percent Efficiency (Curve Fill Factor)				
	Standard Process	Texturized	Non-Texturized	BSF	Non-BSF
Wacker Silso	---	12.6	11.9	9.8 (.75)	10.6 (.77)
Westinghouse WEB	10.6 (.75)	---	---	12.0 (.75)	9.6 (.76)
Mobil Tyco EFG (RH)	8.4 (.73)	---	---	---	---
Motorola RTR	7.2 (.75)	---	---	---	---
Crystal Systems HEM	11.0 (.79)	11.2 (.77)	---	10.5 (.73)	---
Hamco	11.7 (1st ingot) to 7.3 (6th ingot)	12.4 (3rd ingot) to 7.3 (3rd ingot)	---	---	---

Note: All data was taken at AMO, 25°C; these represent the highest cell efficiencies.

Procurement Status. Battelle: Work on the contract has been completed and a final report was issued in May. Crystal Systems: A unilateral modification to the existing contract has been sent to procurement. Eagle Picher: A four-month, no-cost extension was granted making the new completion date 29 July 1979. Applied Solar Energy Corp.: An add-on contract is being negotiated. RCA: A two-month, no-cost extension was granted. The scheduled due date for the draft final report is 30 July 1979. Spectrolab: An add-on contract is currently being negotiated.

JPL In-House Activities. In regard to the wafering effort, trial cut conducted on the Yasunaga YQ-100 multiwire slurry saw demonstrated that high-quality, low-kerf, 10 to 12-mil-thick wafers (25 wafers/cm) could be produced with yields greater than 95%. Detailed wire investigations have also been conducted.

Thirty-hour sessile drop tests were conducted on hot pressed sialon from Battelle and on a CNTD-SiC-coated hot-pressed SiC sample from Eagle Picher/Chemetal. Results show that the SiC material exhibited the least amount of surface dissolution of the two. The sialon material still incorporated second-phase (Al/Si) precipitates into the Si matrix which makes the photovoltaic response of this material considerably limited. Elemental analysis on Directional Solidification (DS) Sample #104 has been performed. DS104 was a glassy-carbon-coated standard (S1-SI) mullite crucible in which semiconductor grade silicon was melted and cooled. Second-phase grain-boundary precipitates were evident throughout the lower third (near the crucible base) of this sample. These grain boundary phases contained high levels of Al, S, Ca, K and Fe (in that order). Trace amounts of grain boundary Ti were found. No extrinsic materials were detected in any of the several bulk-silicon areas (away from grain boundaries) analyzed. Resistivity (4 pt) of this material had been reported at approximately 1 ohm-cm.

A computer-controlled system designed to measure minority carrier diffusion lengths and relative spectral response sequentially has been completed. The diffusion length measurements for unprocessed silicon wafers are done using a surface photovoltage (SPV) technique and for finished solar cells a short-circuit current method is used. Further improvements including high spatial resolution, even faster material turnaround, and absolute spectral response measurements are underway.

Encapsulation Task

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

The scope of the Encapsulation Task includes developing the total system required to protect the optical 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 meet the LSA Project low-cost and 20-year-life objectives. In addition, technical problems have occurred at interfaces between elements of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections.

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

The approach being used to achieve the 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 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 attaining the LSA Project 20-year-minimum-life requirement for modules by 1986. It includes the development of life-prediction methods applicable for terrestrial photovoltaic modules and their validation by application at a specific photovoltaic demonstration site. Material degradation is being studied to determine failure modes and mechanisms. This effort supports both the materials and processes development work and the life-prediction methods development.

Summary of Progress

Materials and Processes Development. An improved ethylene/vinyl acetate (EVA) has been successfully formulated by Springborn for an encapsulation pottant, with large-scale production (1000 lb) now in progress. The criteria for improvement consist of curability, thermal oxidative stability, chemical inertness and module fabricability. Compared with the baseline formulation, the revised formulation cures faster and more efficiently, is more stable to thermal oxidation, is more chemically inert, and is of equal module fabricability (i.e., handling, anti-blocking, etc.).

A quantity of small electrostatically bonded modules, approximately 6 x 6 in, each containing four 2-in-dia cells, were delivered to JPL by SPIRE. These were the first deliveries of modules demonstrating the production capability of the electrostatic-bonding equipment. Six of these were Type II modules and 24 were Type I modules. These will be assembled into 12 x 16 in minimodules (five total) for exposure at outdoor sites.

The equipment has been assembled, specimen substrates prepared, and film-forming solutions characterized by Motorola for the preparation of specimens to develop processes for forming antireflective coatings on glass by two processes: application and etching of sodium silicate coatings and acid leaching.

A design for an optimized 4 x 8-ft glass-fiber-reinforced concrete (GRC) substrate was completed by MBAssociates and a prototype produced and tested. The equipment was assembled for automated spraying of GRC and manufacture of 14 4 x 8-ft substrates, required by contract, was begun.

Life Prediction and Material Degradation. The first cut of a draft of a final report, "Development of Accelerated Test Design for Service-Life Prediction of Solar Array at Mead, Nebraska," was delivered to JPL by Battelle. This report ultimately will contain both the methods and the test designs for determining the life of the Mead array. Three tests are included in the accelerated test design: constant-temperature tests, cyclic-temperature tests, and ultraviolet radiation (UV) tests. The constant- and cyclic-temperature tests are integrated designs; the constant-temperature tests are run in advance to estimate the testing parameters for the cyclic-temperature tests. The constant- and cyclic-temperature tests are run on full-sized modules or minimodules; the UV tests are run on small one- or two-cell modules because of the size limitations of accelerated UV testing facilities.

The JPL in-house minimodule testing program has been expanded because of a decision to do the major part of the life prediction work in-house. Three sites for outdoor exposure are being readied at JPL, Goldstone, and the Coast Guard facility at Point Vicente, California. Data from these tests, to be collected for at least two years, will be used for several purposes: validation of failure-prediction models, testing of materials and materials interfaces, correlation with accelerated testing and demonstration of encapsulation systems.

A combined field survey and laboratory corrosion analysis was performed by Rockwell Science Center on the Sensor Technology and Solarex modules at Mead, Nebraska. For Sensor Technology modules, the predominant corrosion process was a staining and discoloration of the SiO_x antireflection coatings, determined by surface chemical analysis to be associated with the tin or tin oxide present in the metallization. Solarex modules show a progressive staining and corrosion of the metallizations that was analyzed as due to reaction of silver in the metallization alloy with sulfur (the source of sulfur is now being determined). An atmospheric corrosion model and test plan for Mead site test modules has been developed. This model will be used in analytical studies of accelerated aging with experimental verification will be obtained by comparative analysis of aging in Mead site modules.

In-House Activities. In-house photodegradation activities resulted in significant progress in the following areas:

1) A minimodule using poly-n-butylacrylate (PnBA) as a pottant was made and successfully sent through the JPL qualifying tests including thermal and humidity cycling. This result proved that high-molecular-weight acrylic rubbers need not be crosslinked to function as a pliable pottant with no significant creep rate.

2) Photodegradation of PnBA was studied and rates were measured. Photodegradation products under 253.7 and 300 nm radiation have been identified. It appears that this product needs screening of UV shorter than 320 nm to be fully protected.

3) A controlled-temperature UV photodegradation reactor has been built and tested for 1900 hours without failure. A new reactor with atmosphere control and provision for rain and fog has been constructed.

4) A general rule has been found: the higher the modulus, the lower the maximum UV acceleration applicable for a given material. Thus, polymethylmethacrylate (PMMA) can be accelerated far less than PnBA. This rule was found by application of flash photolysis and quantum yield measurements.

5) Techniques were developed for UV testing of whole modules. Gradients of temperature and UV intensity were applied to 1 x 4-in areas on the module surface and a corresponding gradient of darkening was obtained. Approximate values of activation parameters and the nature of the photothermal change can be determined from this work.

Table 2-5. Encapsulation Task Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Case Western University Cleveland, OH	954738	System studies of basic aging and diffusion
Dow Corning Midland, MI	954995	Encapsulation systems

Table 2-5. Encapsulation Task Contractors (Continuation 1)

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
MB Associates San Ramon CA	955281	Glass-reinforced concrete
Motorola, Inc. Phoenix AZ	955339	AR coating
Motorola Phoenix AZ	955387	AR coating
Rockwell Science Center Thousand Oaks CA	954739	Materials interface problem study
SPIRE Corp Bedford MA	954521	Electrostatic bonding process
Springborn Labs, Inc. Enfield CT	954527	Test methods and materials properties evaluation

C. PRODUCTION PROCESS AND EQUIPMENT AREA

Area Objectives

The Production Processes and Equipment area has three major objectives:

First, overseeing a wide variety of contractors' efforts to develop economical processes, designs and equipment to fabricate solar modules at levels that can be scaled up to 500 MW (by the industry) by 1986. See Table 2-6.

Second, to make the processes and designs available to the industry at large and to encourage the use of those pieces of equipment that have been found to be most cost-effective.

Third, to coordinate efforts with those of LSA Project tasks to advance the technology at the optimum rate.

A laboratory has been designed and is being constructed within the JPL complex to evaluate the processes and designs evolved by the contractors. Its function will be to duplicate the techniques evolved and, where a process is not reproducible by someone other than the originator, to assist in ascertaining the reason and in identifying the discrepancy.

Table 2-6. Production Process and Equipment Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Arco Solar, Inc. Chatsworth, CA	955278	Automated solar-panel assembly
Bernd Ross Associates San Diego, CA	955164	Thick-film solar cell contact
Kinetic Coatings Inc. Burlington, MA	955079	Ion implantation
Kulicke & Soffa Ind Morsham, PA	955287	Automated solar module assembly
MBA San Ramon, CA	954882	Phase II, process development
Motorola, Inc. Phoenix, AZ	954716	Parallel-oriented interconnects
Motorola, Inc. Phoenix, AZ	954847	Phase II, process development
Motorola, Inc. Phoenix, AZ	955324	Etch-resistant wax patterns
Motorola, Inc. Phoenix, AZ	955328	Thin substrate
Applied Solar Energy Corp City of Industry, CA	954830	Slicing
Applied Solar Energy Corp City of Industry, CA	955118	Ion implanter investigation
Applied Solar Energy Corp City of Industry, CA	955217	High-efficiency solar module
Applied Solar Energy Corp City of Industry, CA	955244	Low-cost contacts
Applied Solar Energy Corp City of Industry, CA	955423	Laboratory services
RCA Princeton, NJ	954868	Phase II, process development

Table 2-6. Production Process and Equipment Contractors (Continuation 1)

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
RCA Princeton, NJ	955342	Megasonic cleaning
Photowatt, Inc. Chatsworth, CA	954865	Phase II, production process
Photowatt, Inc. Chatsworth, CA	955265	Polysilicon solar cell
Photowatt, Inc. Chatsworth, CA	955266	Si wafer-surface texturing
Sol/Los, Inc. Los Angeles, CA	955318	Metallization
Solarex Corp Rockville, MD	954822	High-density panels
Solarex Corp Rockville, MD	954854	Phase II, process development
Solarex Corp Rockville, MD	955077	Wafer thickness evaluation
Spectrolab, Inc Sylmar, CA	954853	Phase II, process development
Spectrolab, Inc Sylmar, CA	955298	High-resolution contact development
SPIRE Corp Bedford, MA	954786	Ion implanter
TBA Los Angeles, CA	955519	Development of technical manuals & mathematical manuals
Texas Instruments Dallas, TX	954881	Cell development--tandem junction cell
Univ. of Pennsylvania Philadelphia, PA	954796	Automated array
Westinghouse Research Pittsburgh, PA	954873	Phase II, process development

Background

Figure 2-1 shows that Phase I, Technology Assessment, has been completed and that processes were identified almost two years ago. During that phase the processes were on a stand-alone basis. The questions asked were: "Did it produce cells of the required quality?" and "Was it economical enough or did it show the potential to be made economical enough to fit the goals of the project?". After processes were identified in 1977 (in some cases multiple processes were required to cover all the potential inputs to the stage being evaluated), it became necessary to develop them into reasonable sequences that could be integrated into production lines that were able to lend themselves to automation. In late 1978 these decisions were made and certain processes were selected for development into sequences. Phase II is now ending and Phase III is being initiated.

In many ways this is the most exciting phase. The efforts of hundreds of people have gone into developing the technologies that will be put into use. In Phase III the design and development of the equipment and facilities that will go into the pilot will be done.

Figures 2 and 3 show the milestones that have been attained and those toward which we are headed.

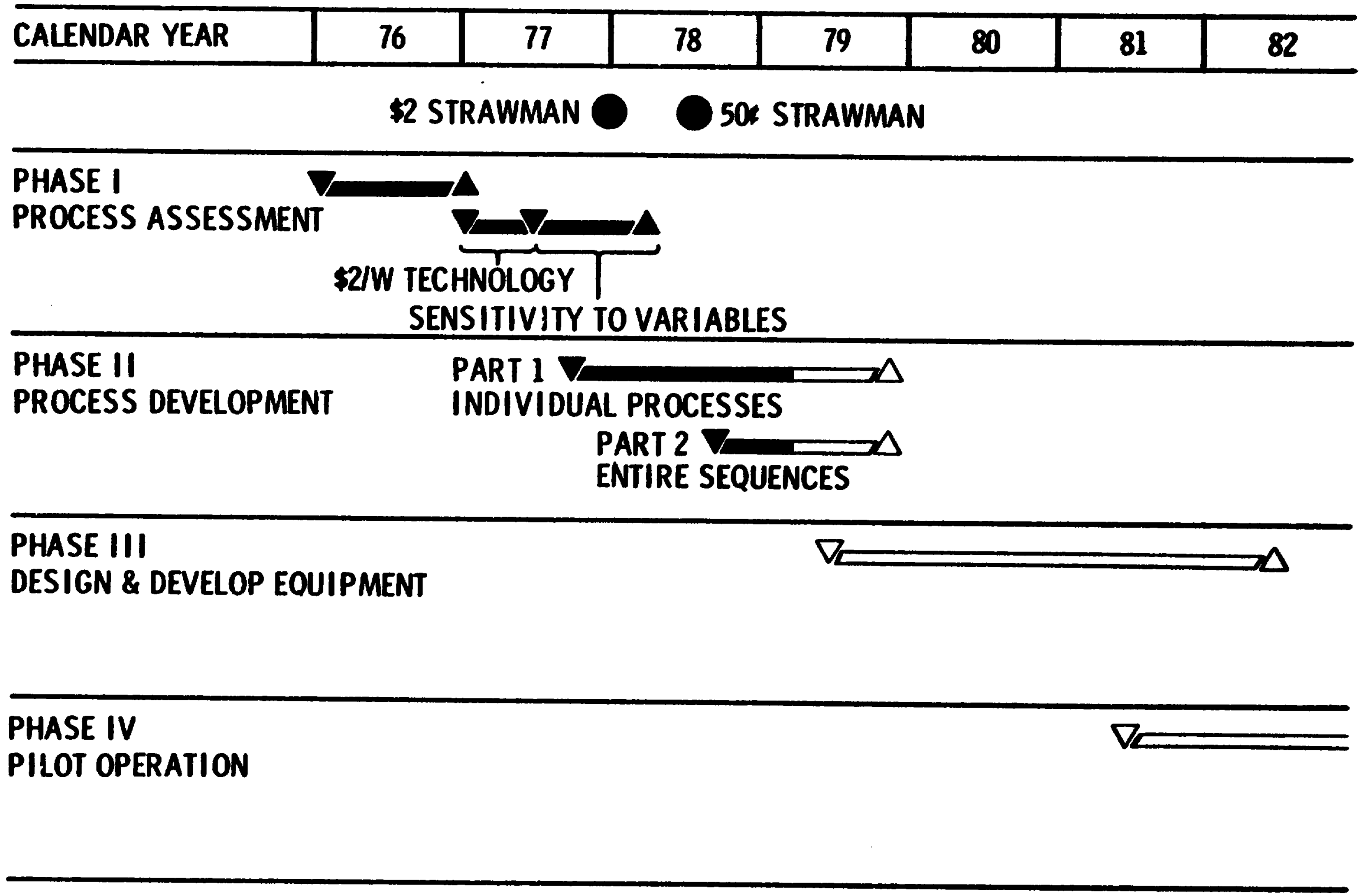


Figure 2-1. Production Process and Equipment Area Phase Schedule

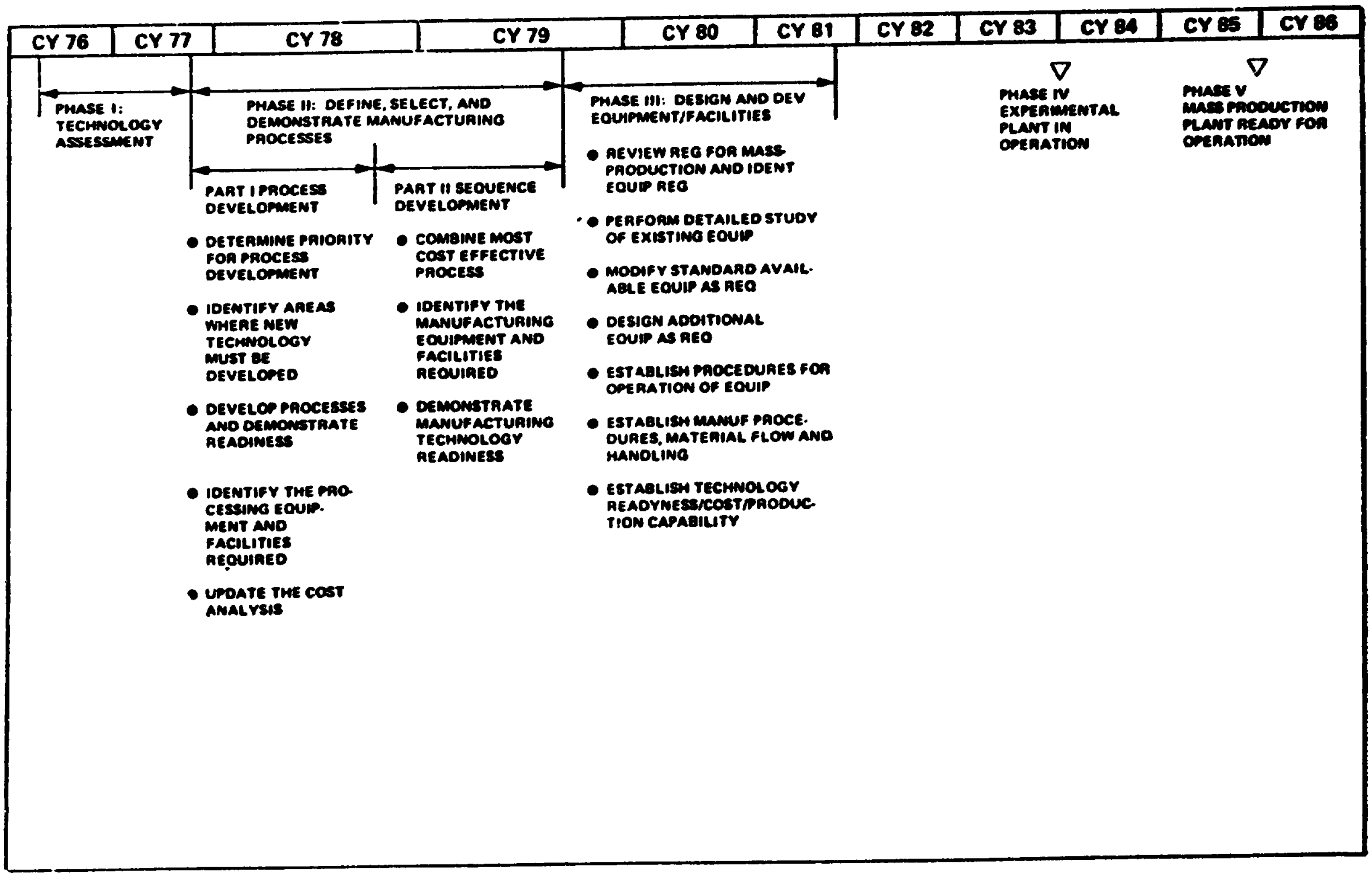


Figure 2-2. Production Process and Equipment Area Major Milestones

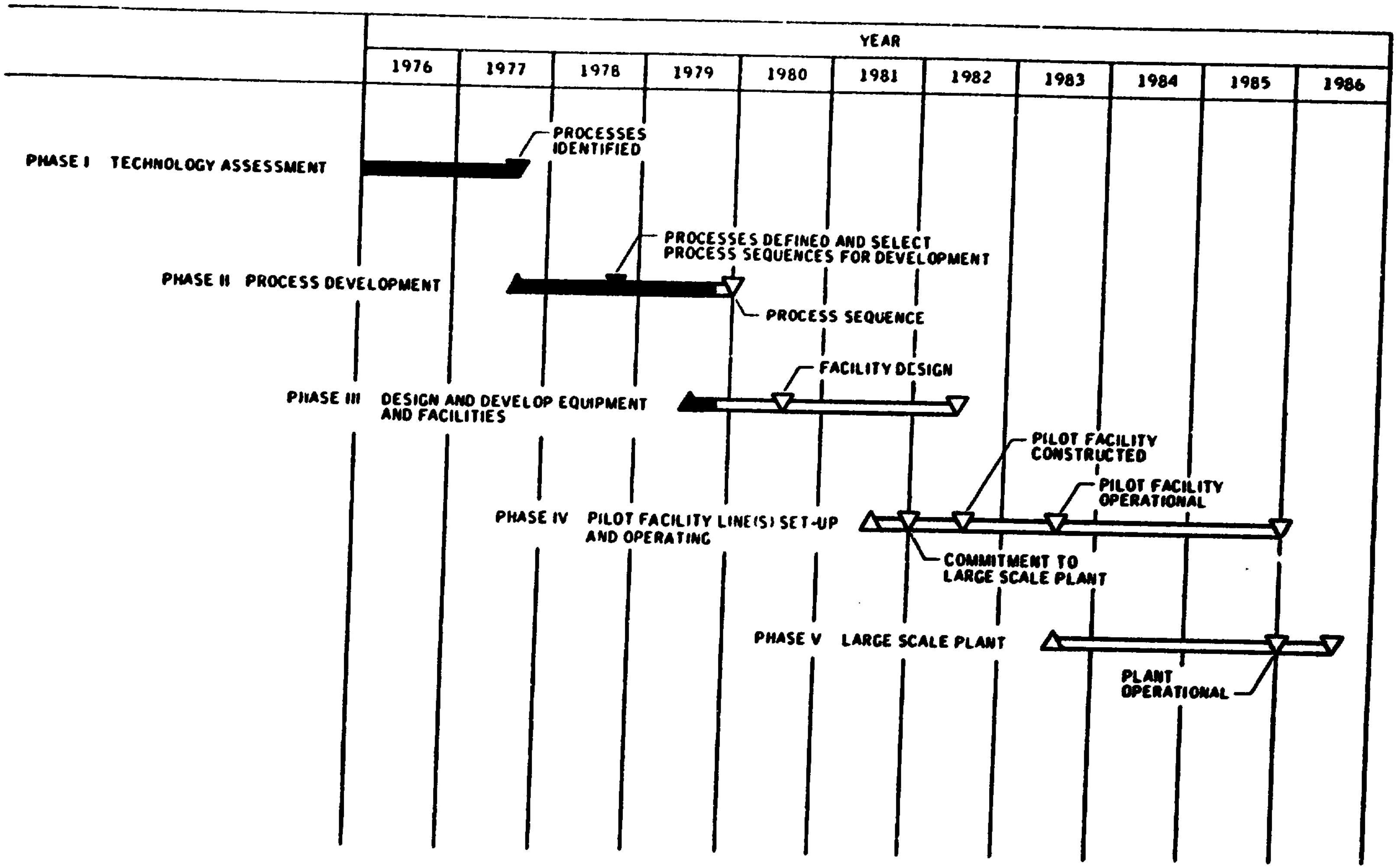


Figure 2-3. Production Process and Equipment Schedule

Summary of Progress

Process Sequence. Spectrolab reports their process sequence is complete to antireflective coating. A decision has been made to laser scribe from the back side after back-surface field formation and before front-side metallization. The module assembly phase of the process is being worked upon as a parallel effort. The fixture for lamination is complete and presently being proven.

Kinetic Coatings, Inc. has experienced additional material and equipment problems that have caused a further delay in the delivery of the first batch of evaluation cells. They currently expect to have the problems resolved soon, and to be able to deliver the cells by the end of September.

JUNCTION FORMATION

RCA reports having processed some lots of ion-implanted cells without using silicon dioxide capping to prevent out-diffusion of phosphorus. The cells averaged 90 ohms per square and the cell fill factors averaged no better than 60% when in-house metallization was used. This is in line with their discovery that an upper limit of sheet resistivity of 50 ohms per square is required for proper ohmic contact.

Spectrolab is continuing efforts in plotting time-temperature diffusion response curves. As an adjunct to this effort they are using the GFE TEGAL plasma etcher to reduce surface recombination sites. They have determined the plasma etch rates on silicon and have started the experiment thinning the front-surface layer. Initial results show an increase of from 3% to 5% in the short-circuit current. At 12 sec of etch the open-circuit voltage loss is only 0.1 of a mV. At 24 sec the cell degrades catastrophically.

There is some question about the cause of this change. It has been suggested that this type of response is caused by closer junction-surface proximity rather than by elimination of surface recombination sites. An investigation will be carried out to ascertain the cause by testing dark forward current and spectral response changes as etching is done. This will require an extension of the contract to February 1980 but at no additional cost.

Photowatt, Inc., with Advanced Concepts, has attempted to spray aluminum on wafers for formation of back-surface fields. Initial results showed that the cloud of aluminum created caused degradation of the front side, not reversible by etching. A two-layer stainless steel fixture to protect the front surface is being fabricated.

In conjunction with the above experiment, the printed and diluted/sprayed Conductrox 5504 Al samples were evaluated. Although no front-surface degradation was encountered, no appreciable back-surface field effect was created. The open-circuit voltages were

3ear 580 mV instead of the greater than 600 MV that can be expected when an effective BSF is created. Further work will be done with 15-ohm-cm material as opposed to the 1-ohm-cm units used this time.

SPIRE Corporation has completed the balance of the 500 3-in cells required on their current contract. Although they have experienced problems, the final group shows a definite improvement and SPIRE is confident that they can achieve the same level of performance as they had in the 2-in cells.

The better performance was attained by a marginal reduction in the pulsed electron beam annealing (PEBA) machine. During the scale-up from the 2-in system it was necessary to increase the voltage to produce the additional total energy required. The attendant increase in average energy of the electrons caused a reduction in cell efficiency. The final answer was a critical dimensional change.

Aluminum back-surface field studies have been completed at Westinghouse. Tests with AMPAL #631 Al powder using the Spectrolab process specification have resulted in cells equivalent to those produced using the sputtered Al method. The Al penetration was uniform and controllable. However, in Westinghouse's process sequence the dendrites remain on during junction formation; therefore sputtering is Westinghouse's preferred method due to the difficulty in silk-screening the web between the dendrites. The process sequence has been revised to use the Al BSF instead of a boron-diffused BSF.

Although resistance plots show uniform penetration and active Al, the V_{oc}s obtained are very low (560-585 mV). This points to a problem in the front junction that is now being investigated. They plan to use capacitance vs frequency measurements to sort out the I_o contributions from the junction, the back-surface field and the emitter.

Surface Preparation

RCA expects to have the megasonic cleaning process operational in the second half of August. At that time preliminary data will be collected. Delivery of the 3/32-in spacing boats also was expected in the second half of August. It was found that the laser-scanner system for cleanliness inspection could not be used on sliced-etched wafers, as hoped. It does, however, give adequate information on polished-surface wafers.

The air dryer, used in conjunction with RCA's megasonic cleaner, was found to be capable of drying two carrier loads in 5 min without the use of heat, reducing the processing costs.

Photowatt, Inc. has completed the SAMICS inputs for the cleaning process associated with their texturizing investigation. These have been included in their final monthly report but have not yet been placed into a computer run.

RCA is still studying the antireflective film produced by their spray-on titanium isopropoxide process. The layer is initially amorphous but, at elevated temperature, the coating becomes tetragonal titanium dioxide (anastase). The refractive index becomes 2.22 and remains there after 5.5 min of bake. On polished wafers a broad reflection minimum is reached at about 6000 angstroms.

METALLIZATION

Applied Solar Energy Corporation has been awarded a unilateral modification to their copper contact contract to initiate efforts toward solving the copper migration problem and developing an inexpensive but reliable plating mask. The plating sequence defined at this time is one of palladium, chromium, copper. Initial theoretical studies show that nickel should be a good barrier, however, and this is being pursued.

RCA reports that contacts applied with their thick-film metallization techniques require sheet resistances on the insolation side of less than 50 ohms/square to obtain good ohmic contact.

Motorola is pursuing the temperature-control approach to apply the wax for their patterning process. Both the printing plate and wafer will be controlled. In addition, the device being constructed will cause a more precise alignment of wafer to plate. The various waxes are being evaluated for their chemical inertness as well.

Photowatt, Inc., is working with Advanced Concepts to create a spray-on copper metallization. No data are yet available.

Sol/Los has recently reported a major breakthrough in their molybdenum-based ink metallization. Previous efforts to secure a good metallization adhesion and, at the same time, have good electrical properties had met with no success. The electrical properties were good when the firing occurred at low temperatures (e.g., 560°C), but the enhanced mechanical properties required 700° to 800°C. Recently cells have been fired at high temperatures and then annealed at lower temperatures. They exhibited the required metallization adhesion strength but also showed the electrical properties of cells that had only seen the lower temperatures. Verification of these results and establishment of working parameters are continuing.

Environmental tests (e.g., thermal shock, humidity) will also be conducted on the production cells.

Spectrolab has been working with Ferro Corporation of Independence, OH on Ferro's patented "Midfilm" process. Of the 400 wafers diffused by Spectrolab and sent to Ferro, 230 have been used. These were metallized with five different systems and are being processed so that a time/temperature/quality matrix will be generated.

Assembly and Test

RCA reports that they are able to interconnect 90 cells (6 x 15 strings) in a single pass continuous process. The cells used were of 3-in. dia and had been pre-tinned and pre-tabbed. The technique employed, designed by RCA, uses a motorized infrared lamp to heat the solder and interconnects.

During the autoclaving cycle of the RCA PVB lamination they have encountered glass breakage. The cause for this is unknown but is under investigation. Bond parameters for the ultrasonic bonding of either Cu or Al straps to the Ag (or Cu) front contact and Al back contact have been determined by Westinghouse. Back interconnects were made after the sun side of the cell has been attached to the glass superstrate.

MB Associates is using the Unimate 2000B Robot for automated interconnection and layup. During the past month a design approach for all interconnect and layup was reached. They proposed the use of a cell preparation sub-station to unload the cells from cassettes, orient them optically, and position a ribbon interconnect lead. The robot arm, equipped with an induction heating head, will then solder the lead to the cell, place the cell in the array configuration and solder the cell to the adjecent cell. Design and fabrication of elements of the sub-station have been started.

Module Development

Applied Solar Energy Corporation's contract (955217) for development of a 14% efficent module has been modified to emphasize meeting the required 16.5% cell efficiency as opposed to delivery of modules. By reducing the number of modules from 26 to 6, the original contract price has been maintained and additional efforts are possible in the cell fabrication area.

Advanced Equipment Development

More extensive evaluation of the focused induction heating technique of soldering interconnects has unveiled some problems. As a result Kulicke and Soffa has decided to return to pulsed heating. Although contactless heating was a desirable feature, the complexity and expense of the control system required to accommodate the variations in wafer and solder thicknesses found throughout the industry forced the fall-back to a less complicated system.

K&S's evaluation of both 3- and 4-in. cells from for different manufacturers has resulted in the selection of Applied Solar Energy Corporation's as being the only ones that are solderable in an automatic machine. Cells are now being procured by JPL to permit K&S to proceed with final machine development and subsequent verification of machine operation. The cells being purchased are of 3-in. dia and have the standard titanium-palladium-silver evaporated metallization.

The automated soldering machine section of ARCO Solar's automated solar panel assembly line is undergoing redesign of the cell alignment and soldering stations. The deflux cleaning and cell string taping stations remain as constructed. The redesign is being done at their Albuquerque laboratory and will result in an induction heating and roller contact system.

The automated lamination box section of the ARCO Solar system is undergoing a minor revision although the basic concept is progressing well. The contractor has found that the "lazy-susan" arrangement involving eight boxes is expensive and has been judged to be not cost effective. A "static box" system is now under study to reduce the overall labor/equipment/material cost.

Photowatt, Inc., has executed a subcontract with Cober Electronics of Stamford, CT, for the evaluation of the use of pulsed-microwave energy in solar cell processing. Data and end product requirements have been given to Cober and initial time-power curves are being generated.

Photowatt, Inc., has also designed a nozzle for use in the spray-on antireflective coating process. One of the main purposes of the nozzle is to trap particulate matter that is larger than 10 mils without clogging.

In-House Work

All equipment received has been connected to the required utilities with the exception of chilled water.

The water chiller initially ordered has not been delivered because of labor disputes at the manufacturer's facility. An alternative source has been located and the initial order has been canceled. Delivery is now expected in the first week in October. This lack of delivery has impacted the installation of three essential pieces of equipment: the diffusion furnace, the thick-film curing furnace and the evaporation system. After installation of the chiller, these pieces of equipment are expected to be tested and profiled by the end of October.

Most of the major machine tools for the machine shop have been delivered and positioned: lathes, mills, grinders, a drill press, band saw, and a metal shear. On order and expected soon are a box and pan brake, finishing machine, horizontal band saw and a cylindrical grinder. The associated tooling, fixturing and peripheral equipment is being delivered at a reasonable rate.

Overhead air lines have been installed to the location of each machine tool and drop lines will be installed after the machines are anchored and leveled.

Overhead electrical ducting and wiring is progressing and, after completion, each machine will be checked out.

A hollow cathode has been operated successfully in a Freeman-type ion source. This is identical with the type used in the Extrion 200-1000 ion implanter at SPIRE. The cathodes were run on argon, which is a typical carrier gas for these types of implanters. Two cathodes have been run for approximately 60 h each. One cathode failed because of a bad electron-beam weld between the tantalum feed tube and the tungsten cathode tip. So little erosion had occurred at the cathode tip that it can be assumed that it would have survived many hundreds of hours of usage. The failure of the other cathode was due to an overdose of low-work-function barium that plugged the tube.

The new cathodes, on order, are patterned after flight hardware and are designed to eliminate these problems.

The ion source is currently being fitted with an accelerator electrode system to test its beam extraction capability.

Documentation

A contract has been executed with Theodore Barry and Associates, a management consultant firm in Los Angeles, which submitted an unsolicited proposal to develop a solar cell production handbook. The areas to be covered are: aggregate plans and programs, production control, inventory management quality control, maintenance management, materials handling, marketing strategy, and executive summary and bibliography. The production levels that will be addressed will be 0.5, 5 and 50 MW in order to be able to make comparsions of volume vs cost to manufacture. Drafts have been completed on all sections. The entire book will be completed in draft form by the end of September. Publication is expected in mid-November.

Miscellaneous

Analysis of the cells created from Applied Solar Energy's cast material disclosed the following characteristics:

The structure is polycrystalline with crystal sizes in the 1-to-5 mm range. Resistivity is about 0.1 ohm-cm and P-type. They are cracked extensively (as disclosed by examination after polish etching). Electrical measurements under a light source showed all cells to be shorted. This is possibly due to diffusion along cracks.

ASEC is now analyzing the cells and process to ascertain the reason or reasons for the cracks and shorting. Other cast wafers are being sliced preparatory to processing on the basis of the analysis.

Photowatt, Inc., has reported the inability to slice polycrystalline material from Exotic Materials in a cost-effective way. The material is too brittle. Some modified techniques will be attempted but there is limited expectation of success.

The HEM material from Crystal Systems has been fabricated into cells by Photowatt, Inc., and is presently undergoing performance testing.

Motorola has completed processing on their previously reported thin cells. On this series of lots no back surface field was included. Test data on one lot of each of the test samples are shown in Tables 2-7, 2-8, and 2-9.

Table 2-7. Wafer Data for Test Lot No. A2

1	17.82	0.89	17.28	32.4	1220	1290	607
2	17.68	0.88	17.22	32.0	1210	1300	605
3	17.82	0.87	17.41	33.5	1200	1310	605
4	17.67	0.88	17.35	33.7	1200	1310	605
5	17.58	0.89	17.32	32.9	1200	1300	603
6	17.63	0.87	17.39	33.9	1190	1300	603
7	17.51	0.88	17.27	31.9	1190	1300	603
8	17.50	0.88	17.28	34.6	1190	1310	605
9	17.68	0.89	17.28	32.0	1180	1300	602
10	17.89	0.88	17.43	34.0	1200	1300	604
11	17.77	1.09	17.55	31.1	1200	1300	599
12	17.96	1.12	17.70	32.0	1200	1310	600
13	18.10	1.11	17.68	34.0	1220	1320	601
14	17.79	1.12	17.48	31.5	1200	1320	600
15	17.58	1.09	17.35	31.3	1200	1310	600
16	17.94	1.10	17.71	32.7	1200	1310	599
17	18.07	1.10	17.79	29.8	1190	1300	599
18	17.65	1.08	17.43	30.3	1200	1300	598
19	17.59	1.10	17.38	31.0	1210	1310	600
20	17.62	1.04	17.35	28.4	1210	1310	600
21	17.59	1.09	17.37	31.7	1200	1310	600
22	17.60	1.08	17.35	28.9	1200	1310	601
23	17.70	1.12	17.38	28.6	1220	1310	600
24	18.13	1.10	17.75	28.0	1200	1310	599
	17.74	1.01	17.44	31.8	1201	1306	602
	0.19	0.11	0.17	1.8	10	7	3
	1.1%	10.9%	1.0%	5.6%	0.8%	0.5%	0.4%
	N.A.	N.A	100%	100%	100%	---	100%

Table 2-8. Wafer Data for Test Lot No. A5

1.	7.15	1.36	7.00	34.8	1340	1270	596
2	7.29	1.35	7.05	35.7	1280	1270	594
3	7.10	1.41	6.93	37.1	1280	1270	593
4	7.18	1.41	7.02	36.4	1320	1280	593
5	7.10	1.36	6.97	37.2	1300	1290	594
6	7.16	1.39	6.98	38.3	1280	1280	594
7	7.17	1.67	7.00	39.5	1290	1280	588
8	7.14	1.68	6.99	38.4	1300	1290	588
9	7.01	1.18	6.82	39.6	1270	---	---
10	7.18	1.69	6.93	38.2	1280	1280	588
11	7.17	1.24	6.98	41.1	1260	1280	594
12	7.16	1.21	6.98	41.8	1240	1280	595
13	7.12	1.25	6.95	38.8	1250	1280	594
14	7.35	1.42	7.18	41.6	1240	1290	593
15	7.49	1.73	7.16	44.9	1260	1290	588
16	7.39	1.68	7.21	43.0	1250	1290	590
17	7.26	1.64	7.10	43.2	1260	1290	588
18	7.25	1.64	7.09	43.9	1270	1290	588
19	7.22	1.68	7.05	45.3	1260	1300	588
20	7.23	1.37	7.05	46.6	1260	1290	592
21	7.36	1.37	7.09	44.4	1280	1290	592
22	7.22	1.32	7.05	51.9	1270	1300	593
23	7.26	1.20	7.08	52.7	1260	1300	593
24	7.29	1.25	7.00	44.6	1230	1290	593
	7.22	1.44	7.03	41.5	1272	1286	592
	0.11	0.19	0.09	4.7	25	9	3
	1.5%	12.9%	1.2%	11.4%	2.0%	0.7%	0.5%
	N.A.	N.A.	100%	100%	100%	---	95.8%

Table 2-9. Wafer Data for Test Lot No. A4

1	4.35	1.37	4.13	39.1	1220	1170	575
2	4.38	1.19	4.16	43.6	1280	---	---
3	4.36	1.24	4.12	41.4	1280	---	---
4	4.39	1.20	4.17	39.4	1240	1180	579
5	4.40	1.20	4.20	39.2	1240	1180	578
6	4.41	1.20	4.20	36.5	1250	1180	578
7	4.39	1.17	4.17	40.8	1300	1190	578
8	4.40	1.20	4.16	38.2	1270	1190	577
9	4.43	1.18	4.22	39.2	1260	1200	578
10	4.37	1.20	4.18	42.3	1220	1190	577
11	4.47	1.20	4.25	38.0	1230	1180	578
12	4.50	1.18	4.29	36.8	1260	1180	579
13	4.50	1.17	4.23	37.7	1230	---	---
14	4.36	1.17	4.15	36.5	1220	1180	578
15	4.33	1.18	4.19	37.2	1220	1180	576
16	4.39	1.21	4.19	35.7	1220	1190	578
17	4.32	1.20	4.12	36.1	1240	1190	577
18	4.40	1.23	4.19	35.8	1210	1190	576
19	4.34	1.24	4.14	35.0	---	---	---
20	4.43	1.18	4.20	33.0	1230	1190	578
21	4.43	1.20	4.23	---	---	---	---
22	4.28	1.18	4.09	29.6	1240	---	---
23	4.42	1.23	---	---	---	---	---
24	4.39	1.19	---	---	---	---	---
	4.39	1.20	4.18	38.1	1243	1185	578
	0.05	0.04	0.05	2.6	25	7	1
	1.2%	3.4%	1.1%	6.7%	2.0%	0.6%	0.2%
	N.A.	N.A.	91.7%	87.5%	83.3%	---	66.7%

13th Project Integration Meeting

In a departure from the previous formats, the PP&E area conducted a four-hour poster session on August 22 and another one-hour session on August 23. Twenty-five contractors displayed in pictorial and graphic form the results of their efforts. This technique allowed information interchange on a one-on-one basis.

During this session JPL presented a composite of alternative techniques to fabricate solar modules. Among the many alternative methods seven were displayed as Strawmen. These were randomly chosen to illustrate some of the many manners in which modules can be built.

JPL also displayed a summary of the recent in-house work on hollow cathode and non-mass-analyzed ion implantation.

The PP&E Area sponsored a Process Sequence Development Report Period during which the three contractors that are developing entire sequences (RCA, Spectrolab and Westinghouse) reported on their progress.

D. ENGINEERING AREA

During this reporting period work has been directed toward array design/engineering, reliability-durability requirement development and array standards.

Array Design/Engineering

Series/Parallel Computer Program development during this period concentrated on modifications required to perform analysis of multi-cell failures, especially emphasizing application of the program to a larger intermediate load-center systems. The results of these analyses were successfully employed in a life-cycle cost analysis optimization for intermediate-sized array fields. Variable parameters of the life-cycle analyses include numbers of parallel strings per branch circuit, numbers of series blocks per branch circuit, numbers of bypass diodes and cell characteristics such as fill factor and shunt resistance.

The supporting program for analysis of insolation data was modified significantly to make spectral analysis for multiple sites possible. Spectrum parameters are air mass value, water vapor content, ozone content and atmospheric turbidity.

Sensitivity studies were initiated to evaluate the possibility of using one year's data for a meteorological site comparable in quality to a SOLMET site to replace the 10 years of actual data currently used when insolation analyses are performed.

Final-report review drafts were recieved for the Bechtel curved-glass module structure study, the Boeing wind-loading study and the Burt Hill Kosar Rittelman Associates Residential requirements study. Preliminary results of these studies were provided to the photovoltaic community during technical sessions of the 13th PIM.

Motorola continued work on the module termination requirements study with distribution of industry survey questionnaires and extensive contacts with hardware producers and users.

During this period a contract was initiated with Underwriters Laboratory to develop safety-related module design criteria and test methods. Representative samples of Block II and III modules were shipped to UL for exploratory tests.

Reliability/Durability

The Phase II module-soiling investigation has continued throughout the period. Emphasis was placed on the expansion of field-site deployment to include samples at MIT/LL and NYU. A very large statistical base for soiling-rate studies is becoming available through this program that includes frequent sample rotation, transmission measurements, and materials representing likely candidates for low-cost encapsulation materials for 1986 designs.

A report was issued describing the results of two interconnect investigations: fatigue failure of module interconnects due to a number of years' exposure to wind effects, and stress on, and life expectancy of, various interconnect designs. The results confirm that fatigue-related failures will probably not be a factor in module lifetime performance.

An interim draft report on the first phase of the investigation of solar cell fracture mechanics was prepared. Redesign of the 4-point twist test fixture was completed to accept alternatively sized and shaped cells. Cell fracture parameters have been demonstrated to be a function of cell processing sequence. A preliminary procedure for proof testing cells mechanically before encapsulation is under investigation as a method of minimizing broken cells in completed modules.

Block II and III minimodule testing at the JPL High-Voltage Test Site and at DSET Laboratories continued throughout the reporting period. Significant progress has been made in improving thermal control and monitoring capability of the Super-MAQ Facility, I-V curve data collection and characterization of acceleration factors.

The Clemson University cell-reliability accelerated-stress testing continued with three cells types with different metallization systems. Improved testing procedures based on Phase I experience are now in use. An additional task using a JPL-supplied high-pulse-current fixture obtained preliminary cell operating and breakdown characteristic data for reverse-bias conditions of the sample cells.

Array Standards

The Photovoltaic Interim Performance Criteria Task Group I (Array Subsystem) met monthly during the period. Review of the European Document on PV measurements was completed by the group and comments were sent to SERI. The Draft IPC document implementation plan in support of the January 1980 release date was prepared. Significant progress was made in preparation of requirements criteria and test-method drafts during this period.

Active participation continued on the ASTM E44 Photovoltaic Standards Committee, and Engineering Area personnel contributed papers and presentations at a variety of seminars conferences and work shops including the PV standards meeting of SEMI (Semiconductor Equipment Manufacturers Institute).

Table 2-10. Engineering Area Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Bechtel National Columbus, OH	954698	Curved-glass module
Boeing Co. Seattle, WA	954833	Feasibility study--solar dome encapsulation
Burt Hill Association Butler, PA	955149	Residential module requirements study
Clemson University Clemson, SC	954929	Solar cell reliability test
DSET Laboratories, Inc. Phoenix, AZ	681934	Accelerated sunlight testing of modules
Motorola, Inc. Phoenix, AZ	955367	Study of termination design requirements
Underwriters Lab Melville, NY	955392	Solar array and module safety requirements

E. OPERATIONS AREA

Introduction

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

(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 the coming year are:

(1) To 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 modules 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 ongoing field and endurance tests at the 16 outdoor test sites

(5) To determine the causes of and recommend corrective action for, test and field module failures including those from flat-panel PRDA experiments

(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. The status of the Block III contracts through the month of July is displayed below. During this reporting period, Motorola completed delivery of modules and Sensor Tech continued to be unable to meet its delivery schedule because of a shortage of 2-in wafers. Prospects at both Sensor Tech and at Solarex for completing the work on the glass-faced modules and the high-density modules respectively appeared to improve; however, actual hardware deliveries were minimal.

Contractor	Allocation kW	Shipped April-July kW	Shipped Total kW	Complete %
ARCO Solar, Inc.	37.15	0	37.28	100
Motorola, Inc.	52.02	8.13	51.95	100
Sensor Technology	42.73	5.60	30.04	70
Solar Power Corp.	53.07	0	53.51	100
Solarex Corp.	31.91	0	31.71	100
Totals	216.88	13.73	204.49	94

Block IV. Eight contracts for the Block IV module design and test phase were executed during this reporting period. Ten module designs will result from these contracts, with ARCO Solar, G.E. and Solarex producing modules to be qualified under the residential specifications and ARCO Solar, Motorola, OCLI, Sensor Tech, Solar Power, Solarex and SPIRE producing modules to be qualified under the intermediate-load specifications.

Preliminary design reviews for the modules to be made by Motorola, OCLI, Sensor Tech, Solar Power and SPIRE were held during the reporting period. Delivery of modules to JPL for environmental testing will start in September.

Trends reflected in the Block IV designs reviewed to date include:

(1) Laminated encapsulation systems are replacing poured silicon rubber encapsulation systems.

(2) Shaped cells are supplanting round cells.

(3) Cells are being manufactured with back-surface fields.

(4) Low-iron glass is the favored top surface, but both tempered and annealed glass are used.

(5) The terminal voltage preferred by the manufacturers is usually 15 volts rather than a multiple or submultiple of this level.

(6) There is no discernible favorite series-parallel module wiring scheme.

(7) Bypass diodes are being included in the module designs.

(8) Module areas are increasing, with a resultant increase in power produced per module.

(9) A few designs have such innovative features as a vitreous insulation on a sheet-metal substrate, acrylic top sheet on laminate using metal substrate, and semi-crystalline silicon cells.

Comparison of certain of the factors used to characterize modules between Blocks I, II, III, and IV show some of the progress made since the inception of the project. These comparisons, shown graphically for all four blocks in the PIM Proceedings, are tabulated here for Block I and for the present estimates of Block IV. The conditions under which this tabulation was made are as follows:

(1) Cells are single-crystal silicon.

(2) Power is measured at 28°C and at 100 mV/cm^2.

(3) Power numbers for Blocks I, II and III are based upon measured values, corrected for all known reference-cell anomalies. Power numbers for Block IV are projected values.

	Block I	Block IV
Numbers of Module Designs	4	5
Power--Watts	4.7 - 13.2	37.0 - 90.4
Packing Factor	0.49 - 0.62	0.77 - 0.96
Encapsulated Cell Efficiency (%)	9.2 - 11.6	12.4 - 17.1
Module Efficiency (%)	4.9 - 6.6	9.9 - 13.5

These data indicate that the efficiency of the module at 28°C has effectively doubled since the inception of the project. Efficiencies at actual operating temperatures will be somewhat lower, but do not alter the conclusion regarding improvement.

Module Test and Evaluation

Environmental Testing. The qualification testing of 12 types of modules from 11 Flat Panel Experiments (PRDA 38) suppliers was completed during this period. These tests were more comprehensive than those for previous LSA block procurements. The changes in monitoring and additional tests are underlined below:

(1) Temperature cycling, +90°C, -40°C, 100°C/hr, 50 cycles. Monitor for open circuits and lowered electrical isolation from the frame during cycling.

(2) Humidity cycling, +23, +40.5°C, 90%RH, 5 cycles. Monitor for opens and isolation from frame.

(3) Mechanical Integrity (cyclic pressure loading), pressure loads application-dependent, 10,000 cycles (formerly 100 cycles), monitor for opens and isolation from frame.

(4) Hail test, hailstone size application-dependent.

(5) Measurement of NOCT (Nominal Operating Cell Temperature) and rating of modules at this temperature.

(6) Other tests--determination of thermal coefficients, twist test, LAPSS test, hi-pot test at application-dependent voltage.

Table 2-11 presents a brief summary of the results of the tests.

Two exploratory tests on Block III modules have been completed --heat-rain and mechanical integrity (10,000 cycles). The latter is a change from the previous 100 cycles and has been adopted as a standard test for both PRDA and Block IV testing. Results to date are:

R Some discoloration of the metallization on 3 of the 8 modules.

U Cracks occurred near the mounting holes on 4 of 5 modules during MI

V Satisfactory

Y Satisfactory

Z Delamination at interconnects, surface of encapsulant showed minor wrinkling, splitting on 1 of 3 modules tested.

Performance Measurements. Fabrication of Block IV reference cells has been initiated. Construction of the second LAPSS facility is complete, and final checkout of the second LAPSS is in progress.

Table 2-11. PRDA-38 Environmental Test Results

MODULE CODE	CONSTRUCTION, TOP TO BOTTOM	SPECIAL TEST CONDITIONS	RESULTS
A	1/8-in tempered glass, silicone gel encapsulant, series/parallel cells, polymide/copper interconnects, glass scrim, epoxy varnish on sheet stainless steel inverted pan	Special subarray closely matched proposed field installation	Satisfactory
B	Tempered glass, silicone rubber adhesive, approx. square high-density cells, white silicone rubber back surface, anodized aluminum frame.	Close simulation of field mounting	Isolation-to-gnd failure, 1 mod (T~). Marginal elect degrad 2 mods (H~ & MI). Delam on 3 mods.
C	Tempered glass, clear silicone rubber adhesive to bond cells to glass, silicone encapsulant, white Mylar film; frame is bolted-together Al with weather-resistant enamel coating	Vendor frame modified for fair simulation of field mounting	Unsupported end gaskets loose after T~ for 4 mods, 1 cell crack, 2 mods with frame seal delam (T~). All 4 had frame seal delam after H~.
D	Same as C		2 mods with marginal elect degrad (H~), 4 with frame seal delam (H~).
E	Tempered Glass, PVB, cells, PVB, white Tedlar sheet; frame is 2 extruded Al pieces attached to long sides of module with separate metal edge on ends		3 mods failed isolation to gnd (T~ & H~) & 1 in H~ only. 1 cell crack (T~) & cell cracks in 2 mods (H~). Wrinkling and browning of Tedlar near frame & melting & distortion of J-box, 4 mods (T~).

Table 2-11. PRDA-38 Environmental Test Results (Continuation 1)

MODULE CODE	CONSTRUCTION, TOP TO BOTTOM	SPECIAL TEST CONDITIONS	RESULTS
F	Top conformal Dow Corning Q1-4177 coating on Sylgard 184, cells mounted in depressions in a molded polyester substrate		7 cell cracks in 3 of 4 mods (3 T~, 2 H~, 2 MI). 1 of these elec degrad 18% (T~) & 10% more in H~ and showed open during test. Other 2 degraded 5 to 6%. Observed delam of interconnects, frame seal on 4 mods (T~), encap splits on 2.
G	Tempered glass superstrate, PVB, cells, PVB, clear Mylar, white paint; Al pan back surface & bezel; back surface not bonded to laminate		2 mods failed isolation to gnd from T~ & all 4 failed after H~. 1 mod failed gnd cont. test after H~ and 2 others after MI. Gasket extrusion & white paint yellowing/crazing/-blistering during T~, progressed during H~.
H	Same as G		2 mods rec., both failed receiving isolation to gnd & dropped to only 2 to 5 ohms in test chamber. 50 to 75% of frame seals delam; gaskets were extruded; white substrate paint was yellowed, crazed & blistered.

Table 2-11. PRDA-38 Environmental Test Results (Continuation 2)

MODULE CODE	CONSTRUCTION, TOP TO BOTTOM	SPECIAL TEST CONDITIONS	RESULTS
I	Tempered glass superstrate, 94 mm approx square polysilicon cells bonded with clr silicone cement, white silicone rubber, U-shaped rubber edge gasket that also serves as a dam for encapsulant; internal bypass diode on uninsulated heat sink plate imbedded in encapsulant	No frames supplied. Frames made by JPL of small Al channels for handling	As rec, mods had various power levels from 9.2 to 13.5 W. After tests, power levels erratic, both ± and unreliable as a meas. of degrad. Mods failed 2-in hailstone test when struck near edge. Vis. changes incl. intrusion of black mat'l toward cells & delam under 1 cell.
J	2 submods per mod consisting of glass, RTV-615, shingled rectangular EFG cells, glass, riveted Al frames.		1 mod failed hi-pot & another failed gnd cont. at receiving insp. 2 more failed res. to gnd & 3 failed gnd continuity at H~. H~ produced 6.4% loss of power in 1 mod with power recovery later. 3 mods were given MI test & all showed mech. failure of mounting rails. 1 had a large cover glass crack.
K	Temp. glass, approx square cells bonded to glass with clear RTV adhesive, white silicone rubber back coating, U-shaped neoprene edge gasket.	Same as I	All mods had corrosion inside & outside the J-box after humidity test. All other tests were passed satisfactorily. A resistance to gnd test between the

Table 2-11. PRDA-38 Environmental Test Results (Continuation 3)

MODULE CODE	CONSTRUCTION, TOP TO BOTTOM	SPECIAL TEST CONDITIONS	RESULTS
			cell string & the JPL handling frame was made on 1 or more mods. On 1 the resistance was too low during temp. cycling.
L	Tempered glass, RTV-615 bonding cells to glass, a polychloroprene white compound with TiO_2, weatherized cardboard back cover; the hex solar mod is attached to an approx rect. flexible laminate sandwich of closed cell rubber foam between 2 layers of white plastic reinforced with polyester scrim.	10 mods mounted shingle fashion on building-paper-covered piece of plywood to simulate a roof section; special blank shingles and edging materials were used as in a real application	After T~ all blank shingles had blistered; 2 mods were lifted from the plywood base; 6 mods had cells with collector discoloration. After H~ warping and lifting of blank shingle was observed & 5 exhibited backing separation. After completion of tests, the roof section was disassembled revealblistering of the flexible white mat'l on the mods. During a 3-wk NOCT determination the white mat'l between cells & at edge turned lt brn or tan. No measurable change in power or NOCT was observed due to the discoloration.

Field Tests. The principal focuses of activity this period centered on two areas: continuation of in-field calibration of reference cells and inspection and acquisition of data from the newly acquired JPL/Lewis remote sites. Over a period of several weeks the 10 active reference cells were recalibrated in the field using recently LAPSS-flashed modules as references. The resultant calibration numbers were found to differ by up to 10% from the original values. It was also found that the values varied by as much as 4%, depending upon the sky condition. Using the new calibration numbers an analysis designed to provide tracsability of the current I-V signature of each module with its pre-installation LAPSS signature was undertaken. The purpose was to provide traceable electrical degradation data. A first observation from the analysis was that the silicon-encapsulated modules, particularly those of the soft-surfaced type, had acquired an imbedded dirt layer that decreased the transmittance and masked the true (below encapsulant) I-V level. Subsequent cleaning with scouring powder increased their performance by more than 20% in some cases, but did not raise their I-V levels to the preinstallation values. An investigation of the I-V curves suggests that, in general, the modules were still healthy and that the differences were probably still due to remaining imbedded dirt. Another factor that clouded the issue was the discovery by JPL inspectors that many of the Block II Sensor Tech modules had experienced impact cell damage, probably due to a hailstorm in March.

An inspection of the newly acquired Lewis remote sites continued during this period with an inspection of the Canal Zone, Key West and New Orleans sites in June, the Crane (IN), Houghton (MI), and New London (CT) sites in July, and the Fort Lewis (WA) and Fort Greely (AK) sites in August. Electrical-performance data, including short-circuit current, open-circuit voltage and peak power readings, and physical-condition data were obtained on each module. Generally the modules are enduring well at all sites.

Failure Analysis. The major activity during this reporting period centered on the analysis of the 85 Problem/Failure Reports (P/FRs) filed for PRDA-38 environmental test modules. These results are reported in the PIM Proceedings.

The JPL Failure Analysis Lab has devised a new technique for determining whether cell cracks existed at the time of encapsulation in silicone rubber. The technique requires micro-sandblasting of the cell away, leaving a telltale trace (groove) along the crack location in the encapsulant if the crack was present at encapsulation. If the technique proves to be generally applicable, it will provide a useful tool for distinguishing between manufacturing and design problems that lead to cracked cells.

P/FR activity for the period from 4/6/79 to 8/7/79 is summarized in Table 2-12.

Table 2-12. Summary of P/FR Activity

Procurement Block	New P/FRs	Closed P/FRs	Environmental Test*	Field Test*	Application Centers*
I		3			
II	2	17		2	
III	5				5
Task 5	5	10	5		
PRDA	31	43	31		

* New P/FRs

SECTION III

PROCEEDINGS OF THE 13TH PROJECT INTEGRATION MEETING

A. SUMMARY

Three innovative ideas were introduced during the 13th PIM: a panel discussion by industry executives, a Production Process and Equipment poster session, and the showing of a new display depicting the entire LSA Project. All three, especially the panel, were well received by the PIM participants. Compliments were received on the PIM hand-out document and on the fact that it was received by the PIM participants well in advance.

Panel:

The panel, consisting of Bill Gregory, plant manager of Hemlock Semiconductor Company; Jim Hendrix, manager of market development of Arco Solar; Bob Lorenzini, president of Siltec; Doug O'Conner, president of Applied Solar Energy Corp. (formerly OCLI); Leo Rogers, president of Great Western Silicon Company, and Paul Tierney, director of R&D at Monsanto, presented their viewpoints regarding their perception of the silicon PV industry, today and tomorrow.

Panel Conclusions:

A polysilicon shortage starting between 1981 and 1983 for both the semiconductor and photovoltaic industries was independently predicted by each representative from Great Western Silicon, Hemlock, Monsanto and Siltec. The existing poly production capacity plus planned expansions can bve stretched to supply the demands anticipated (for the semiconductor industry) until 1981-93. Decisions to build new poly plants that would eliminate this shortage should have already been made or must be made soon because of the three-to-four-year lead time required for new poly plants. Production expansion beyond the 1981-82 period is uncertain because of high business risks. These risks are created by the new process technologies under development but not yet verified by large enough scale operation and by the large uncertainties in photovoltaic silicon requirements. The unknowns regarding the new poly are not only the price but also the quality and the influence that different poly could have on solar cell performance. The situation is exacerbated by the lack of a reliable government plan.

The capital-intensive poly industry, with large up-front capital requirements, possibly would have to sell poly from new conventional plants, if these were to be built, for more than $100/kg. The semiconductor industry could afford this price, but it would severely limit PV industry growth. In addition to the above factors, the total dollar value of the poly required by the PV industry will be small until major PV expansion can occur (possibly not until after 1984 or 1986). Consequently there is little incentive for the poly producers to invest in plants for producing low-cost silicon until there is good visibility (as perceived by industry) of a major PV expansion, of when it will occur, and of the new poly processes verification.

Thus actions of the U.S. government regarding verification of new silicon processes, the initiation of low-cost silicon production plants, and the maintenance of competitive efforts in these activities will be instrumental in determining when major expansion of the PV industry will occur. Good progress in other cell/module technology development, and in the ability to increase production capacity incrementally for the manufacturing steps from silicon growth through module assembly, permits these steps to be taken more readily and quickly.

O'Conner (ASE) underscored the problem in poly availability and cost: "We (the PV industry) are not going to get where we think we are going unless this poly problem is addressed, and the lead time required to address the problem demands that it be dealt with now."

Bob Chambers, president of Arco Solar, recognized the polysilicon problem and was concerned about the need for quick action. Participating industrial companies, from raw materials to finished product, as represented by the panel, were unanimous for the need to define and implement a poly plan quickly, if photovoltaics use is to grow as projected by DOE plans.

B. OTHER PLENARY SESSION PRESENTATIONS

- A summary of the PV Program's residential efforts was presented: MIT/LL's planned activities, the status of the BOS work by Sandia and MIT, and the module/array activities at JPL.

- Investigations of module/array design and performance requirements (with emphasis on residential) by JPL analytical and testing activities were presented.

- Block IV module design features and expected functional performance were compared with earlier LSA procured modules. Most of the Block IV modules will use glass as a superstrate, shaped (closely packed) cells, and laminated encapsulation systems. The high cell-packing factors and the higher-efficiency cells will result in module efficiencies of 9 to 14% as projected by the manufactures, a marked improvement as compared to previous designs.

Polysilicon:

Union Carbide Silane/Silicon Process

- EPSDU detailed engineering design under way; scheduled to meet FY82 Technology Readiness

- Phase III R&D (100-MT/yr EPSDU) started April 1979

  - Improvements made in free-space reactor

  - In fluidized bed reactor, demonstrated large-particle segregation and acceptably low bed-sintering rates

- Economic analysis, 1000 MT/yr plant (1980$)

• Plant Cost	$9,375,000
• Total manufacturing cost	$6.52/kg
• Price at 20% DCF	$10.58/kg (1980 $ goal: $14.00/kg)

Battelle: Si production by ZN reduction of $SiCl_4$

- Started PDU construction April 1979

- Support R&D

  - Demonstrated efficient recovery of $ZnCl_2$

- Product cost estimate: $10.25/kg to $12.19/kg (1980 $, 1000 MT/yr plant)

Westinghouse: Arc heater process for Na reduction of $SiCl_4$

- Demonstrated operation of process demonstration system in gas-only ($Ar-H_2$) power tests

- Brough system near completion (98%)

SRI- SiF_4 Reduction by Na

- Results from threefold reactor scale-up

  - No Na left in product
  - tenfold increase in rate
  - 0.5 kg Si/batch

Silicon Sheet:

Ingot Technology

- Hamco has achieved 13-cm-dia, 108-kg Cz ingot growth (Present goal: 100 kg; TR82 requirment: 150 kg)
- Siltec has demonstrated 15-cm-dia Cz ingot growth from CLF furnace (TR requirement: 150 kg)
- CSI has cast ingots up to 15 X 15 X 15 cm by the heat exchanger method (TR requirement: 30 X 30 X 30 cm)
- Siltec has cut 10-cm-dia ingot at 22 wafers/cm and 15-cm-dia ingot at 15 wafers/cm (TR requirements: 15-cm dia; 25 wafers/cm)
- CSI has demonstrated multi-wire sawing of 10-cm-dia ingot at an equivalent rate of 1.4 wafers/min, exceeding the TR requirements of 1 wafer/min.

Shaped-Sheet Technology

- MTSEC has demonstrated long-term (15 h) operation of the five-ribbon EFG system, 10-cm-wide ribbons and 11% AM1 cell efficiencies. (TR requirements: 10-ribbon system, 10-cm-wide ribbons, 12% AM1)
- MTSEC has shown a potential breakthrough in ribbon structure (larger grain size, 1 X 10 cm)
- Westinghouse has demonstrated 27.1 cm^2/min web ribbon throughput (TR requirements: 25 cm^2/min)
- Westinghouse has achieved 12% AM1 cell efficiency on web ribbon grown from Task 1 Battelle silicon material
- Honeywell has demonstrated SOC coating on 5 cm x 50 cm substrate by the SCIM technique.

Encapsulation

- Demonstrated material systems meet cost goals.
- Ethlene vinylacetate, pottant/adhesive, as candidate undergoing extensive optimization and evaluation

- Optimized formulation covers
    - Cure cycle
    - Sheet extrusion
    - Corrosion control
    - Adhesion
    - Photodegradation

- Use of flexible laminates of aluminum foil and mylar offers low-cost electrical and moisture barrier.

- Use of glass-fiber scrim increases module ruggedness and stability.

- Long-life UV screens under development to provide 20-year life for low-cost pottants.

- Glass-reinforced concrete substrate developed and demonstrated.

- Poly-n-butylacrylate has been developed as a solvent-free castable pottant.

    - Minimodule passed qual testing

    - Photodegredation mechanisms defined

    - In-situ polymerization developed

    - Electrostatic bonding process optimization favorable
    - Good yields

    - Advanced concepts explored--mesh-back contacts.

    - Low-cost bonder and lower-cost glass

- See page 3-216 for candidates.

Manufacturing Sequences

- Selected from a matrix with more possible sequences

- Original strawman left mistaken impression that JPL preferred certain processes

- Costs vary with processes and sheet form

Candidate Factory Costs

The most recent SAMICS calculations indicate that by 1986 photovoltaic modules could be manufactured and sold for (FOB, 1980$)

$0.56/$W_p$	if EFG ribbons were used
$0.57/$W_p$	if heat exchange method (HEM) ingot and multiblade sawing were used
$0.58/$W_p$	if web dendritic ribbons were used
$0.68/$W_p$	if advanced Czochralski ingot and multiblade sawing were used

Assumptions: 250 MW/year production of each design; 3 shifts/day; $14/kg silicon; 20% return on investment after taxes; start-up costs included.

Process Sequence Development

- RCA
  - Material perfection/ion implantation relationship
  - Web processing starting
- Spectrolab
  - Surface preparation/spray-on dopant relationship
  - Waffle-pattern BSF reduces warpage
- Westinghouse
  - 5-cm web to 2.5-cm web increases process cost 7¢/watt
  - U.S. ribbon bonding only .002 in above surface

Module Life Prediction and Material Degradation

- Three-year plan for modeling and verification
- Failure models being developed and experimentally verified
  - Photodegradation of polymers and total systems
  - Thermomechanical stress failures
  - Corrosion of metallization and interconnects

- Testing technology being developed
    - Testing strategies and techniques for life prediction
    - Testing facilities for long-term environmental simulation
    - Testing instrumentation and diagnostics
        - Corrosion monitor
        - AC impedance
        - Auger
- Cell reliability study (Clemson)
    - Recent measurements of reverse-bias characteristics of cell types undergoing stress tests

Module Design

- The results of wind-tunnel testing of flat solar panels conducted by Sandia Labs at Colorado State University indicated that screening can effectively lower maximum wind pressures on modules and hence reduce array structure costs.
- Investigation of the effect of lifetime wind loading on cell interconnects has demonstrated that cyclic wind loading will not result in fatigue failure of a variety of interconnect designs.
- The latest results of the ongoing series/parallel studies, which related life-cycle energy cost to module size and circuit design for various failure replacement strategies, were described.
- Bechtel's presentation covered analysis of array costs for a curved-glass superstrate and described high-voltage stress design requirements for module encapsulation systems.

Module Testing

- Flat-Panel Experiments (PRDA-38) module qualification test program: The tight delivery schedule for the qualification test modules led to a number of design and workmanship deficiencies that were manifested by test problems. JPL problem/failure analysis indicates that these problems are all corrigible by straightforward improvements in design, workmanship, and quality assurance.

- Survey of the LeRC-installed endurance test sites: To date, 132 Block II modules have been inspected at nine sites. Two modules have failed and four have shown significant electrical degradation. Embedded dirt in silicone rubber encapsulant is a common problem, but the modules are in generally good condition after one and a half years in the field. The marine environment of Key West is producing the worst physical degradation; the alpine environment of Mines Peak appears to be the least harmful.

- Module performance at MIT/LL test sites: The cumulative failures at all sites to date stand at 1.5%; the largest installation, at Mead, Nebraska, has shown 1.6% failures after two years of operation. The physical condition of the modules is less encouraging, with cracked cells and encapsulant degradation increasingly prevalent. The degree to which present physical degradation portends future functional degradation remains to be established. An apparently progressive type of cell cracking failure has been observed at the University of Texas test site; a simple single crack led to massive cracking and "bulginmg" of that cell over a six month period, presumably as a result of reverse-bias overheating. (JPL engineers reported that a similar phenomenon at the Mount Laguna site has been observed and is under study.) Some power was delivered even with 2 in snow coverage on modules.

- Accelerated sunlight aging of equipment at DSET Laboratories has been modified for temperature control and natural sunlight spectral measurements in support of performance standards.

C. PRESENTATIONS

1. Technology Development Area
a. Silicon Material Task

TECHNOLOGY SESSION

Tony Briglio, Chairman

Significant progress was reported by contractors engaged in developing silicon production processes and in various supporting efforts of the Silicon Materials Task.

Union Carbide Corporation (UCC) started their Phase III program to design, construct and operate a 100-MT/yr EPSDU (Experimental Process System Development Unit). In the UCC Supporting Research and Development program, improvements were made in both reactor concepts (free-space reactor and fluidized bed reactor) that are being developed and evaluated for use in the EPSDU. In support of the UCC work, the Massachusetts Institute of Technology undertook a study of the conversion of metallurgical-grade silicon and silicon tetrachloride to trichlorosilane, which is to be used as the feedstock for the UCC process. The apparatus for the investigation was designed, and construction and installation are near completion.

The Battelle Columbus Laboratories (BCL) reported on their progress in building a Process Development Unit (PDU), which consists of the four critical units (fluidized bed reactor, by-product condenser, zinc vaporizer, and electrolytic cell, all fullscale) of BCL's 50-MT/yr EPSDU. The site was prepared and structural steel installed. In the support studies, work with the zinc chloride condenser showed that the by-product zinc chloride can be recovered very efficiently (97%).

In their effort in developing a process for producing silicon by the sodium reduction of silicon tetrafluoride, SRI International reported results from tests of a threefold scaled-up reactor. The reaction rate was increased from 0.1 to 1.2 kg of silicon per hour, and the amount of unreacted sodium was reduced from 10% to essentially zero.

Westinghouse successfully conducted the initial tests of their process demonstration system in gas-only operation (no reactants being present). The system was brought to a state of near completion (98%) in preparation for the process demonstration tests with reactants.

In the silicon impurity studies, the Westinghouse R&D Center showed data on effects of impurity concentration on solar cell performance, representing better fits of data and including information for certain elements (tantalum, niobium, tungsten, and cobalt) which have not been reported on previously. It was also reported that the electrically active concentrations are linear with total concentrations for titanium, chromium, vanadium, and molybedenum. The Aerospace Corporation reported on their study to determine the applicability of Metastable Transfer Emission Spectrometry to analysis of trace impurities in silicon. Data were presented that established that spectral analysis of vaporized silicon samples will yield the composition of the bulk sample.

In the area of Supporting Studies, AeroChem Research Laboratories described progress in their studies of silicon halide/alkali metal flames. Separation of silicon from gaseous sodium chloride by-product was accomplished by jet impingement. Lamar University presented results of their chemical engineering analysis of the Battelle process for producing silicon. Product silicon price was estimated to be $17.53/kg (20% DCF, 1980 dollars) for a 1000-MT/yr plant (fixed capital investment of $17,450,000).

UNION CARBIDE SILANE/SILICON PROCESS

- EPSDU DETAILED ENGINEERING DESIGN UNDERWAY
  SCHEDULE TO MEET FY82 TECHNOLOGY READINESS
- ECONOMIC ANALYSIS - 100 MT/YR PLANT (1980 $)
  - PLANT COST $9,375,800
  - TOTAL MFG COST $6.52/KG
  - PRICE AT 20% DCF $10.58/KG (1980 $ GOAL: $14.00/KG)
- STARTED R&D SUPPORT PROGRAM FOR PHASE III (100-MT/YR EPSDU) IN APRIL 1979
  - IMPROVEMENTS MADE IN FREE-SPACE REACTOR
  - IN FLUIDIZED BED REACTOR DEMONSTRATED LARGE-PARTICLE SEGREGATION AND ACCEPTABLY LOW BED SINTERING RATES

BATTELLE - SI PRODUCTION BY ZN REDUCTION OF $SICL_4$

- STARTED PDU CONSTRUCTION, APRIL 1979
- SUPPORT R&D
  - DEMONSTRATED EFFICIENT RECOVERY OF $ZNCL_2$
- PRODUCT COST ESTIMATE: $10.25/KG TO $12.19/KG
  (1980 $, 1000 MT/YR PLANT)

- REACTOR AND COLLECTOR HEATING TO 1700°K ACCOMPLISHED IN SHORT (15 MIN) TESTS

AEROSPACE CORP - IMPURITY CONCENTRATION MEASUREMENT IN PPB RANGE (METASTABLE TRANSFER EMISSION SPECTROSCOPY)

- DESIGNED AND BUILT EXPERIMENTAL APPARATUS
- DEMONSTRATED FEASIBILITY OF METHOD
- ANALYZED STANDARD SI SAMPLES FOR SEVERAL ELEMENTS

WESTINGHOUSE - ARC HEATER PROCESS FOR NA REDUCTION OF $SICL_4$

- DEMONSTRATED OPERATION OF PROCESS DEMONSTRATION SYSTEM IN GAS-ONLY ($AR-H_2$) POWER TESTS
- BROUGHT SYSTEM TO STATE OF NEAR-COMPLETION (98%)

SRI - SIF_4 REDUCTION BY NA

- RESULTS FROM 3-FOLD REACTOR SCALE-UP
  - NO NA LEFT IN PRODUCT
  - 10-FOLD INCREASE IN RATE
  - 0.5 KG SI/BATCH

WESTINGHOUSE - IMPURITY EFFECTS STUDIES

- ELECTRICALLY ACTIVE CONCENTRATIONS LINEAR WITH TOTAL CONCENTRATIONS FOR TI, CR, V, MO
- NO EFFECT OF RESISTIVITY OF BASE MATERIAL ON IMPURITY EFFECTS

AEROCHEM - SILICON HALIDE/ALKALI METAL FLAMES STUDIES

- SEPARATION OF SI FROM GASEOUS NACL ACCOMPLISHED BY JET IMPINGEMENT
- REACTOR AND COLLECTOR HEATING TO>1700°K ACCOMPLISHED IN SHORT (~15 MIN) TESTS

SILANE/SILICON PROCESS

UNION CARBIDE CORP.

PHASE I AND II: ACCOMPLISHMENTS

- CONTINUOUS INTEGRATED PRODUCTION OF SILANE FROM SI AND HYDROGEN
- LONG TERM FREE-SPACE REACTOR PYROLYSIS RUN
- DENSE PLATE GROWTH ON SI SEED PARTICLE IN FLUID BED REACTOR
- POWDER TRANSPORT AND MELTING TECHNIQUE
- CAPACITIVE HEATING OF FLUID BED FOR PYROLYSIS
- VAPOR-LIQUID EQUILIBRIUM DATA IMPACTS PROCESS DESIGN
- CHEMICAL EQUILIBRIUM AND KINETIC DATA USED IN EPSDU DESIGN
- ECONOMIC ANALYSIS OF LARGE SCALE OPERATION

SILANE PRODUCT FROM PROCESS DEVELOPMENT UNIT

CYLINDER	1	2
HYDROGEN & HELIUM	36%	36%
NITROGEN	2.03	2.56
DISILANE, ppm	66 ppm	53 ppm
TRISILANE	83	75
TETRA SILANE	71	144
SILOXANE	35	53
MONOCHLOROSILANE	51	31
DICHLOROSILANE	< 8	< 8
TRICHLOROSILANE	217	81
SILICON TETRACHLORIDE	70	60
METHYL SILANE	99	91
METHANE	< 50	< 50
EPITAXY FILM	20 Ω cm	120 Ω cm
RESISTIVITY, TYPE	N	N
FLOAT ZONED POLY SI		
FROM SILANE		
RESISTIVITY	3 Ω cm, N	
LIFE TIME	500 μsec	
BORON	0.2 ppba	
PHOSPHOROUS	5 - 12 ppba	
CARBON	24 ppma	
OXYGEN	220 ppma	

PRODUCT PRICE FROM A 1000-MT/YR SEMICONDUCTOR-GRADE SILICON PLANT

	1975	1980
PLANT COST	6,697,000	9,375,800
RAW MATERIALS	1.80/Kg	2.52
UTILITIES	.65	.91
LABOR	.97	1.36
MAINTENANCE	.21	.29
CONSUMABLES	.26	.36
OTHER CHARGES	.73	1.02
TOTAL MANUFACTURING COST	4.66/Kg	6.52

DISCOUNTED CASH FLOW RATE, %	SILICON PRODUCT PRICE 1975	1980
10	6.08/Kg	8.51/Kg
15	6.77	9.48
20	7.56	10.58
25	8.45	11.83
30	9.41	13.17

PRODUCT FORM MOLTEN SILICON

SILICON PRODUCT FROM FREE—SPACE REACTOR

PARTICLE SIZE	~1 μm
SURFACE AREA	4 - 10 m^2/GM

BULK DENSITY	0.12 G/CC
COLOR	LIGHT GRAY
BORON	8 ppba
PHOSPHOROUS	1 ppba
RESISTIVITY	38 Ωcm

PHASE III ACTIVITIES

OBJECTIVES

DESIGN, INSTALL AND OPERATE AN EPSDU SIZED FOR 100 MT/YR

PERFORM SUPPORTING R & D

PERFORM ITERATIVE ECONOMIC ANALYSIS

TO PROVIDE DATA BASE AND ESTABLISH VIABILITY FOR LARGE-SCALE PRODUCTION (1000 MT/YR)

PHASE III ENGINEERING ACTIVITIES—CURRENT AND PLANNED

PROCESS EQUIPMENT SPECIFICATION

INSTRUMENTATION AND CONTROL SYSTEMS

ENVIRONMENTAL AND SAFETY DESIGN

SITE AND UTILITIES DESIGN

DETAILED COST AND SCHEDULE ANALYSIS

SUPPORTING RESEARCH AND DEVELOPMENT

FREE-SPACE REACTOR

OBJECTIVE: TO PROVIDE RECOMMENDATIONS FOR THE DESIGN, ASSEMBLY, OPERATION AND EVALUATION OF A FREE SPACE REACTOR FOR EPSDU

- CONDUCT LONG DURATION PERFORMANCE RUNS TO VERIFY CAPACITY AND SCALE-UP PARAMETERS
- PERFORM THEORETICAL ANALYSIS TOWARD OPTIMIZING REACTOR CONFIGURATION AND OPERATING CONDITIONS

RECENT ACTIVITIES

REPLACED CORRODED MONEL REACTOR WITH INCOLOY 800

REVISED SILANE INJECTOR

LARGER HOPPER FABRICATED

REMOTE OPERATION PROVIDED

IMPROVED INSTRUMENTATION FOR LONG-TERM OPERATION

FUTURE PLANS

COMPLETE INSTALLATION IN HYDROGEN RATED TEST CELL

BEGIN EXPERIMENTAL OPERATION

FLUIDIZED BED REACTOR

OBJECTIVE: DETERMINE THE TECHNICAL FEASIBILITY OF A FLUID-BED SILANE PYROLYSIS REACTOR SUITABLE FOR EPSDU

- **FIXED BED STUDIES:** TO DETERMINE SILANE DECOMPOSITION RATES
- **FLUIDIZATION STUDIES:** TO DEFINE METHOD FOR SELECTIVE REMOVAL OF LARGER PARTICLE

  TO EVALUATE THE USE OF CAPACITIVE PARTICLE HEATING
- **OPERABILITY:** DESIGN, CONSTRUCT AND OPERATE A PDU REACTOR
- **ECONOMIC/TECHNICAL ANALYSIS:**

  TO DETERMINE THE ECONOMIC POTENTIAL FOR FLUID BED PYROLYSIS

FLUIDIZED BED PARTICLE SEPARATION

OBJECTIVE: TO DETERMINE THE CONDITIONS BY WHICH LARGE SILICON PARTICLES CAN BE SELECTIVELY REMOVED FROM A BED OF MIXED SIZE PARTICLES

RESULTS TO DATE

CRITICAL DIAMETER RATIO	=	2.5
FLUIDIZATION RATE U/U_{MF} (BASED ON COARSE FRACTION IN BOOT SECTION)	=	.7
SEPARATION RATE, %/HR	=	4.4
MEAN BED PARTICLE SIZE,		215

CAPACITIVE HEATING

OBJECTIVE: TO DEVELOP METHOD FOR HEATING FLUIDIZED BED OF SILICON WITHOUT HEATING THE REACTOR WALL

RESULTS: SINTERING OF BED PARTICLES INCREASES WITH

- LOAD IMPEDENCE (CONDUCTIVE PATH LENGTH)
- DECREASING PARTICLE SIZE
- CONDUCTIVITY OF SILICON

AVERAGE SINTERING RATE FOR HIGH PURITY SILICON WAS .5%/DAY AT 5.4 Ω IMPEDENCE, 375 μ PARTICLES. THIS IS ACCEPTABLE FOR PRACTICAL OPERATION

FLUID BED REACTOR

STATUS

FIXED BED STUDIES: EXPERIMENTAL APPARATUS HAS BEEN ASSEMBLED

FLUIDIZATION STUDIES: PARTICLE SEGREGATION DEMONSTRATED
ACCEPTABLY LOW SINTERING RATES ACHIEVED

FUTURE PLANS

COMPLETE EXPERIMENTAL DECOMPOSITION KINETICS STUDY

DESIGN A PDU SCALE FLUID-BED REACTOR

POWDER MELTING AND CONSOLIDATION

OBJECTIVE: TO DEVELOP A WORKABLE TECHNIQUE FOR MELTING AND CONSOLIDATING SILICON POWDER PRODUCT FROM EPSDU

- PREPARATION OF SUBCONTRACT WORK STATEMENT
- SUBCONTRACTOR'S PROPOSAL EVALUATION AND AWARDING OF SUBCONTRACT
- SUBCONTRACT MONITORING AND EVALUATION OF TEST DATA
- EPSDU MELTER SYSTEM BID PACKAGE
- REQUEST FOR MELTER SYSTEM QUOTES
- HYDROGEN ATMOSPHERE STUDIES

QUALITY ASSURANCE

OBJECTIVE: PROVIDE FOR ON-SITE QUALITY ASSURANCE AT EPSDU

- SLIM ROD REACTOR
- EPITAXY REACTOR
- CHROMATOGRAPHIC METHODS
- EQUIPMENT PREPARATION AND ASSEMBLY STANDARDS

STATUS

- **FEASIBILITY ESTABLISHED AND METHOD DEVELOPED FOR DETERMINING METHANE, ETHANE, ETHYLENE IN SILANE AT ~100 ppb LEVEL**
- **LABORATORY STYLE SLIM ROD REACTOR DESIGNED FOR SILANE PYROLYSIS**

FUTURE PLANS

- **DIBORANE AND PHOSPHINE IN SiH_4 TEST DEVELOPMENT**
- **EPITAXY REACTOR DESIGN**
- **CONSTRUCTION OF SLIM ROD UNIT**

HYDROGENATION OF $SiCl_4$

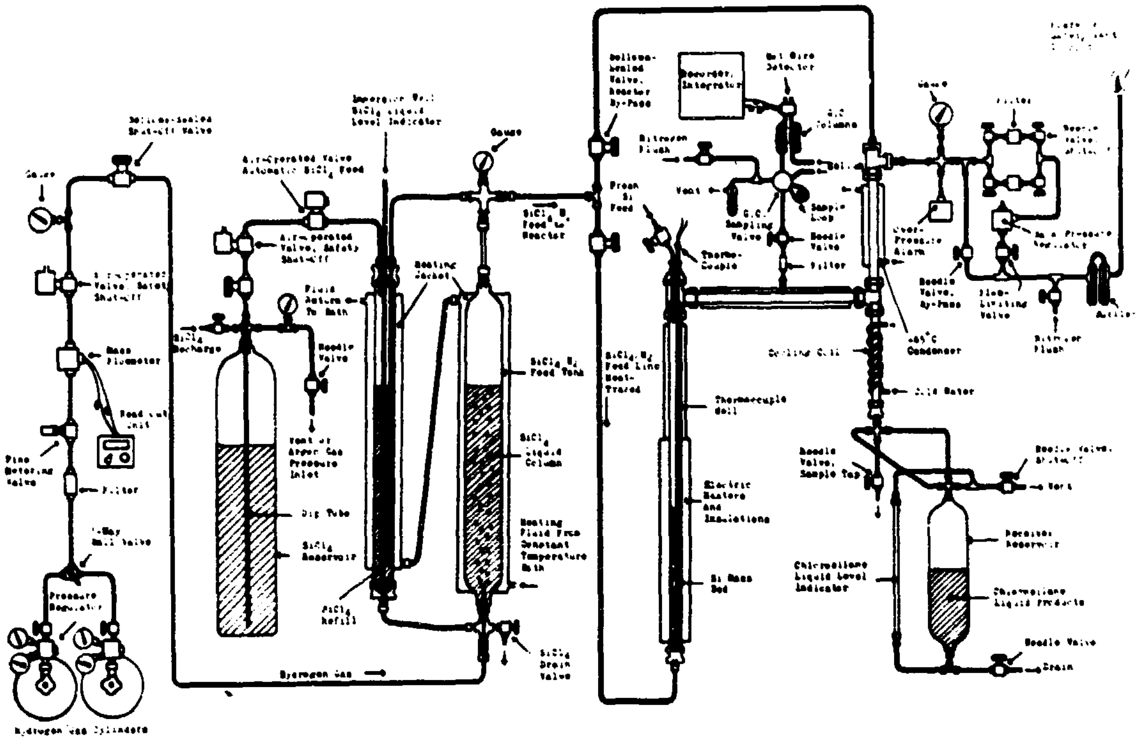
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

INVESTIGATION OF THE HYDROGENATION OF $SiCl_4$

Year	1979	1980	1981
Month of Year	4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3
Month of Contract	1 2 3 4 5 6 7 8 9	10 11 12 13 14 15 16 17 18 19 20 21	22 23 24
I Program Plan, Laboratory Site Preparation	1		
II Finalize Reactor Design, Order Equipment	1 2		
III Construct Hydrogenation Apparatus	2 3 4 5		
IV Safety Review, Start-Up, Standardization	5		
V **Process Studies**	▲	▲ ▲	
A. Reaction Kinetics			
(1) Function of $T, P, H_2/SiCl_4$: with no Catalyst	5 6 7 8		
(2) Establish Rate Equation, Reaction Order	8 9		
(3) Copper Catalyst Studies: $T, P, H_2/SiCl_4$	8 9	10 11 12 13	
(4) Particle Size Distribution, Surface Area		13 14 15	
(5) Different Grade of MG Si		14 15 16	
B. Mass Life Studies			
(1) With no Catalyst Added		16 17 18	
(2) With Cu Catalyst Added		18 19 20	
(3) Different Grade of MG Si		20 21	22
VI **Research and Development**	▲	▲ ▲	
A. Method of Preparing Cu/Si Mass			
(1) Literature Studies	1 2 3 4 5 6 7 8		
(2) Prepare Cu/Si Mass	5 6 7 8		
(3) Evaluation and Optimization	8 9	10 11 12 13	
B. Reaction Mechanism Studies			
(1) Literature Studies	1 2 3 4 5 6 7 8		
(2) Identify Reaction Intermediates: HCl, etc.	6 7 8 9	10 11 12 13 14 15 16 17 18 19 20 21	
(3) Identify Intermediate Reaction Steps	6 7 8 9	10 11 12 13 14 15 16 17 18 19 20 21	
(4) Nature of the Equilibrium Reactions	6 7 8 9	10 11 12 13 14 15 16 17 18 19 20 21	
(5) The Role of Copper Catalyst			
a. Nature of the Catalytic Sites	8 9	10 11 12 13 14 15	
b. Copper Transport Mechanism	8 9	10 11 12 13 14 15	
c. Copper Distribution on Solid Si Surfaces	8 9	10 11 12 13 14 15	
(6) Kinetic Isotope Effect		▲	22 23
C. Other Hydrogenation Catalysts		▲	22 23
VII **Reports**			
A. Recomendation on Optimun Reaction Conditions	9	14 19	23
B. Recomendation for Additional Development Work	9	14	23
C. Final Report			23 24

▲ Milestone Check Points

APPARATUS FOR THE HYDROGENATION OF $SiCl_4$ TO $SiHCl_3$



THE HYDROGENATION OF $SiCl_4$ to $SiHCl_3$

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

A. KINETIC STUDIES AS FUNCTIONS OF

- PRESSURE (UP TO 500 psig)
- TEMPERATURE
- $H_2/SiCl_4$ RATIO
- CATALYST CONCENTRATION
- SURFACE AREA
- MASS LIFE
- FLUIDIZATION MECHANICS

B. REACTION MECHANISM STUDIES

- CATALYST PREPARATION
- REACTION INTERMEDIATES
- INTERMEDIATE REACTION STEP
- NATURE OF THE CATALYST
- SOLID SURFACE
- SPECTROSCOPIC STUDIES

SILICON HALIDE-ALKALI METAL FLAMES AS A SOURCE OF SOLAR-GRADE SILICON

AEROCHEM RESEARCH LABORATORIES, INC.

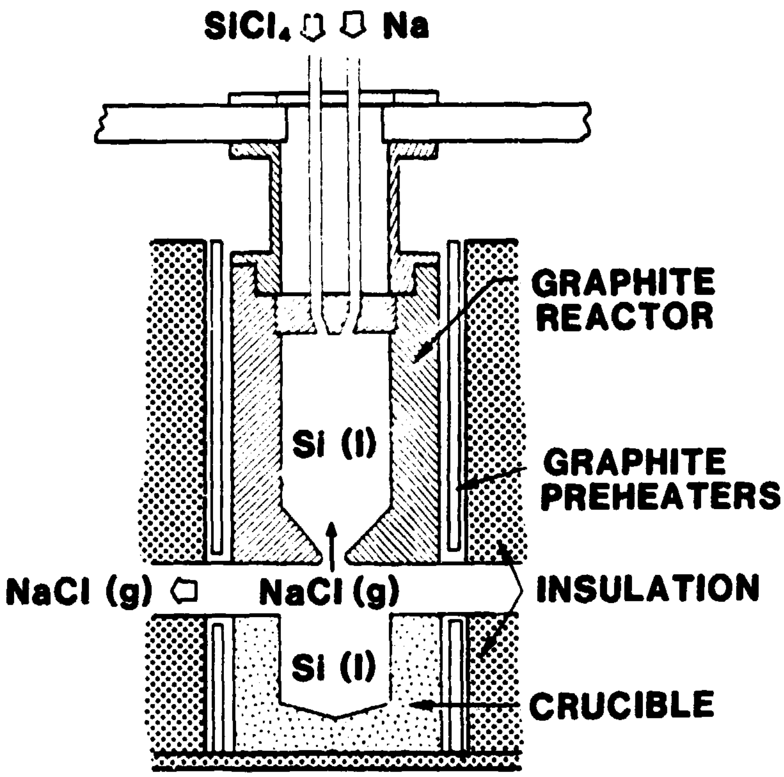
OBJECTIVES

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

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

CURRENT WORK

1. TEST 0.5 KG/HR SILICON FACILITY
2. USE FACILITY TO DETERMINE RATE OF OVERALL REACTION-COMPLETENESS, HEAT RELEASE
3. TEST EFFECTS OF WALL TEMPERATURE REGIME
4. DEVELOP SEPARATION-COLLECTION TECHNIQUES



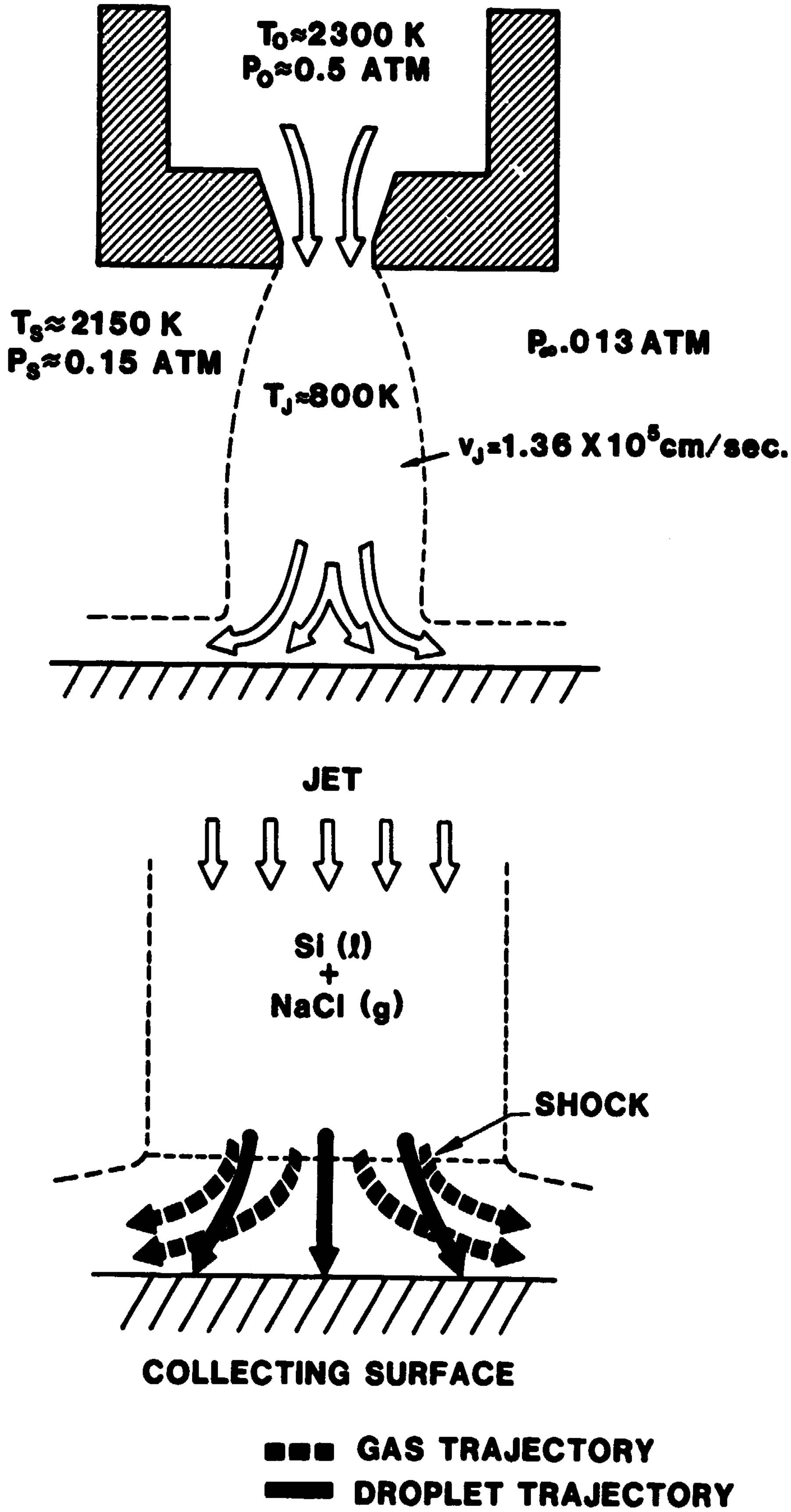
RESULTS

1. REACTOR AND COLLECTOR HEATING TO > 1700 K HAS BEEN ACCOMPLISHED.

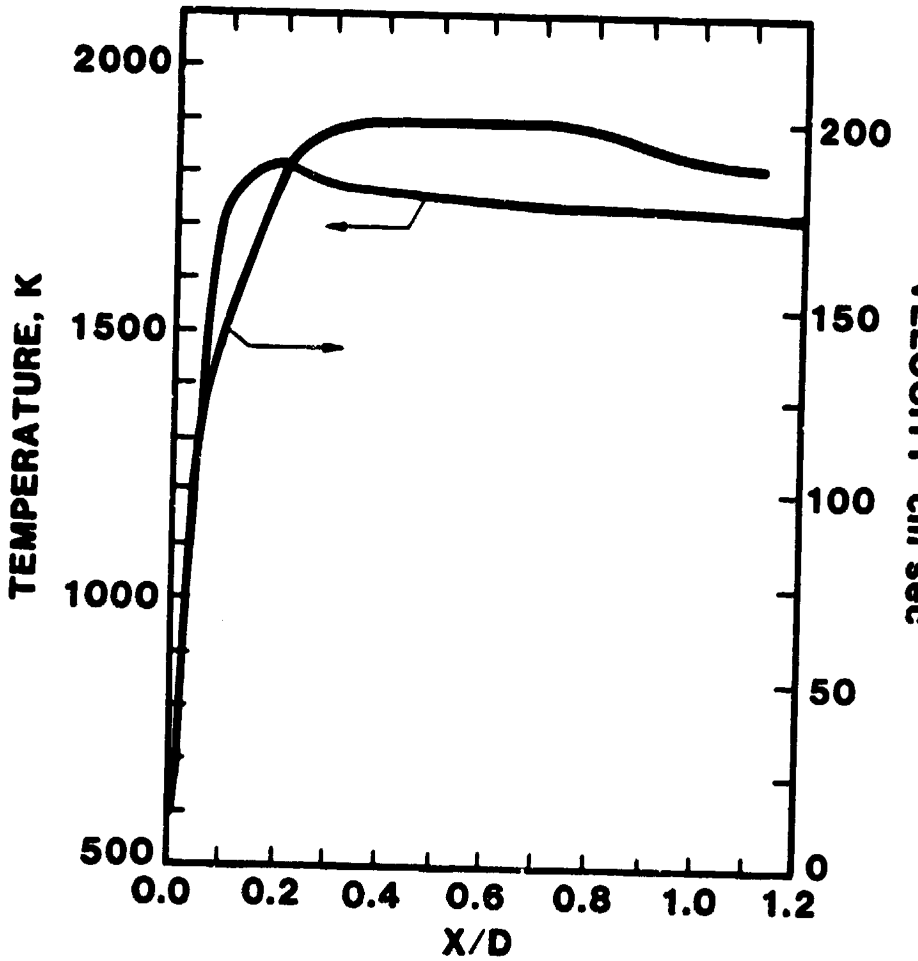
2. SHORT ($\approx$15 MIN) TESTS WITH REACTANTS HAVE BEEN MADE

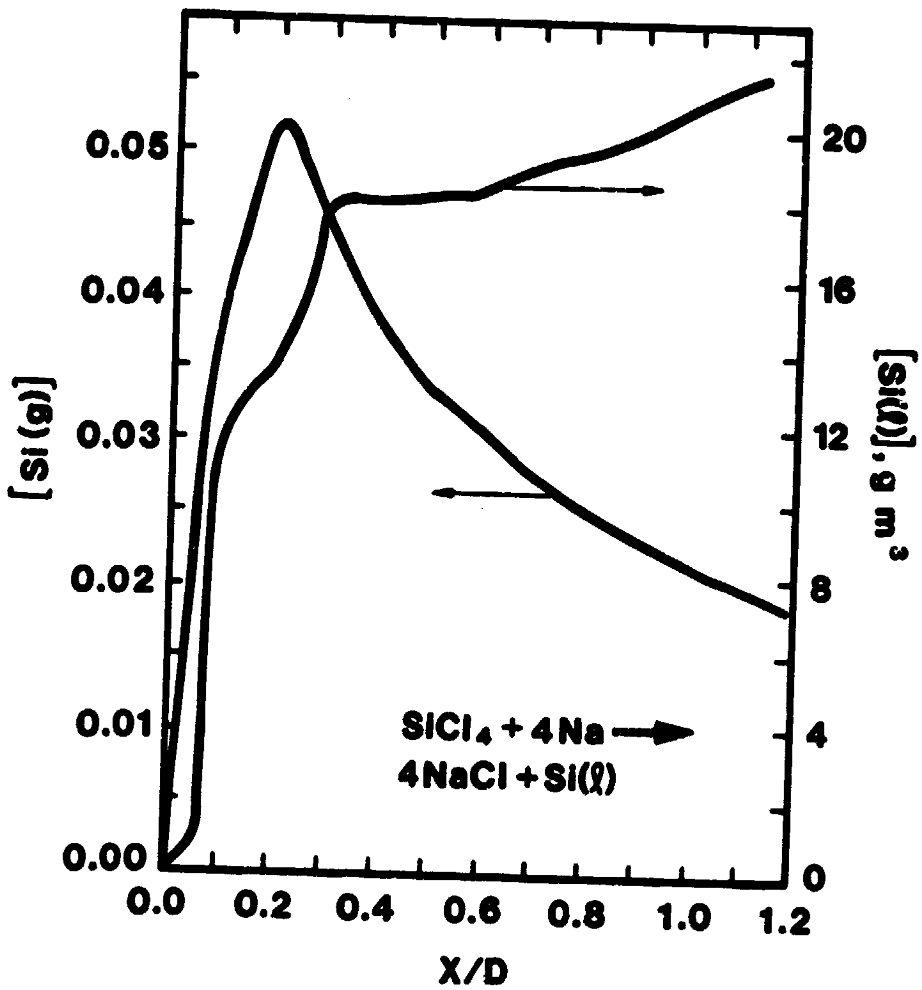
3. FAILURE OF $SiCl_4$ AND NA INJECTION LINES HAS BEEN EXPERIENCED--PROBLEMS APPEAR SOLVED.

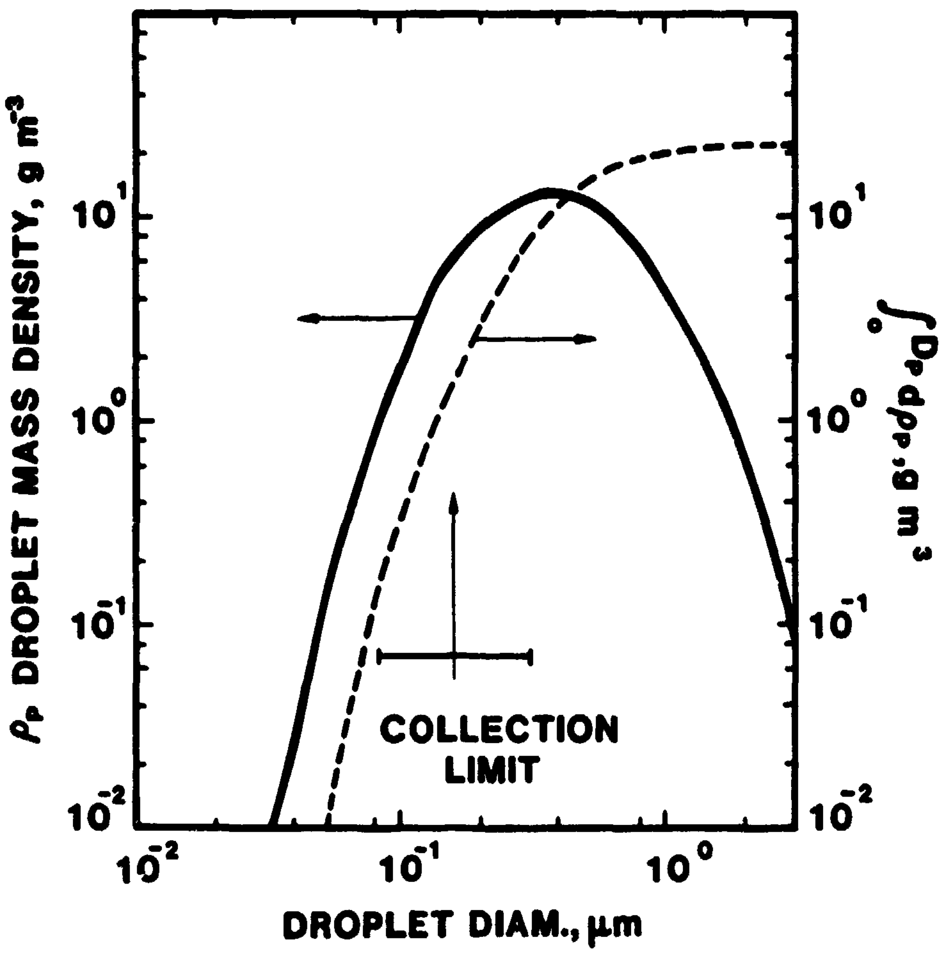
4. DEVELOPMENT OF IMPROVED MEANS OF REGULATING $SiCl_4$ AND NA(G) FLOWS IS NEEDED. PRESSURE CONTROLS FOR THIS PURPOSE ARE BEING ACQUIRED.



T₀≈2300 K
P₀≈0.5 ATM
Tₛ≈2150 K
Pₛ≈0.15 ATM
P∞.013 ATM
T_J≈800K
v_J=1.36 X 10⁵cm/sec.
JET
Si (ℓ)
+
NaCl (g)
SHOCK
COLLECTING SURFACE
GAS TRAJECTORY
DROPLET TRAJECTORY


2000
1500
1000
500
TEMPERATURE, K
200
150
100
50
0
VELOCITY' cm sec⁻¹
0.0
0.2
0.4
0.6
0.8
1.0
1.2
X/D


0.05
0.04
0.03
0.02
0.01
0.00
[Si (g)]
20
16
12
8
4
0
[Si(ℓ)], g m⁻³
SiCl₄ + 4Na ⟶
4NaCl + Si(ℓ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
X/D



PLANS

TESTS AT VARIOUS PRESSURES AND FLOW RATES WILL BE CONDUCTED DETERMINE:

1. RATE OF REACTION
2. COMPLETENESS OF REACTION
3. SILICON DROPLET SIZES
4. COLLECTION EFFICIENCIES

CONCLUSIONS

1. THE 0.5 KG/HR $SiCl_4$/NA TEST FACILITY HAS BEEN TESTED AT OPERATING TEMPERATURE (> 1700 K).

2. FAILURES DUE TO DESIGN INADEQUACIES OF THE NA(G) AND $SiCl_4$ INJECTION PORTS HAVE BEEN ENCOUNTERED.

3. RECENT TESTS SHOW THESE INJECTION PROBLEMS TO HAVE BEEN SOLVED.

4. COMPUTER SIMULATION PREDICTS SI DROPLET SIZES OF 0.1 TO ONE MICRON. COLLECTION EFFECIENCIES ARE CALCULATED TO BE HIGH FOR THESE DROPLETS.

C-2

PROCESS FEASIBILITY STUDY
SILICON MATERIAL TASK 1

BCL PROCESS (BATTELLE COLUMBUS LABORATORIES)

LAMAR UNIVERSITY

C. S. FANG
K. Y. LI
CARL L. YAWS

STEP 1

1. Plant Size
   -silicon produced from silicon tetrachloride (TET)
   -1000 metric tons/yr
   -silicon
   -solid phase product form (granules)
2. Light End Distillation
   -purification of TET by distillation
   -remove 4% chlorosilanes as the light end
   -80°C, 10 psig

3. Heavy End Distillation
   -purification of TET by distillation
   -remove 4% impurities as the heavy end
   -92% over-all yield of TET from both distillations
   -80°C, 10 psig

4. TET Vaporizer
   -to supply TET vapor for deposition reactor
   -by power input (resistance heater)
   -hold at constant level and constant pressure
   -164°F

5. Deposition Reactor
   -reduce TET by zinc to produce silicon
   -deposit on pure silicon seed
   -fluid bed
   -927°C (1700°F, 1 atm)
   -63% conversion of TET to silicon

6. Reactor Condenser
   -to condense gases from reactor ($ZnCl_2$, unreacted Zn and $SiCl_4$ gases)
   -partial condensation
   -using therminol 66 as the coolant
   -927°C inlet temperature and 350°C outlet temperature

7. Reactor $ZnCl_2$ Stripper
   - work as partial condenser
   - to condense $ZnCl_2$ gas from $SiCl_4$ gas
   - operating at the temperature right above $ZnCl_2$ melting point (318°C), 350°C
   - using therminol 66 as the coolant

8. Cell $ZnCl_2$ Stripper
   - operates as partial condenser
   - to condense $ZnCl_2$ gas from Cl_2 and $SiCl_4$ gases
   - operating at the temperature right above $ZnCl_2$ melting point (318°C), 350°C
   - using therminol 66 as the heat exchange medium

9. Reactor $SiCl_4$ Condenser
   - condense $SiCl_4$ gas for recycle
   - antifreeze as the coolant
   - 350°C inlet temperature, 20°F outlet temperature.

10. Electrolysis
    - electrolytic recovery of Zn from $ZnCl_2$
    - Cl_2 gas is by product
    - 95% Zn recovery
    - 500°C, approx. 1 atm

11. Zinc Vaporizer
    - to vaporize Zinc
    - by induction heating
    - 927°C, approx. 1 atm.

12. Wastes Treatment
    - to scrub and neutralize $SiCl_4$ and chlorosilane gases
    - caustic solution used to neutralize

13. Operating Ratio
    - approximately 80% utilization (on stream time)
    - approximately 7,000 hr/yr production

14. Storage Considerations
    - feed material (two week supply)
    - product (two shifts storage)
    - process (several hours)

STEP 2

REACTION CHEMISTRY FOR BCL PROCESS

1. Silicon Deposition

$$2Zn + SiCl_4 \rightarrow Si\downarrow + 2ZnCl_2$$

2. Electrolysis

$$ZnCl_2 \xrightarrow{\text{electroly.}} Zn(l) + Cl_2\ (g)$$

3. Waste Treatment

$$SiCl_4 + 2H_2O \xrightarrow{aq} SiO_2 + 4HCl(aq)$$

$$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O$$

or

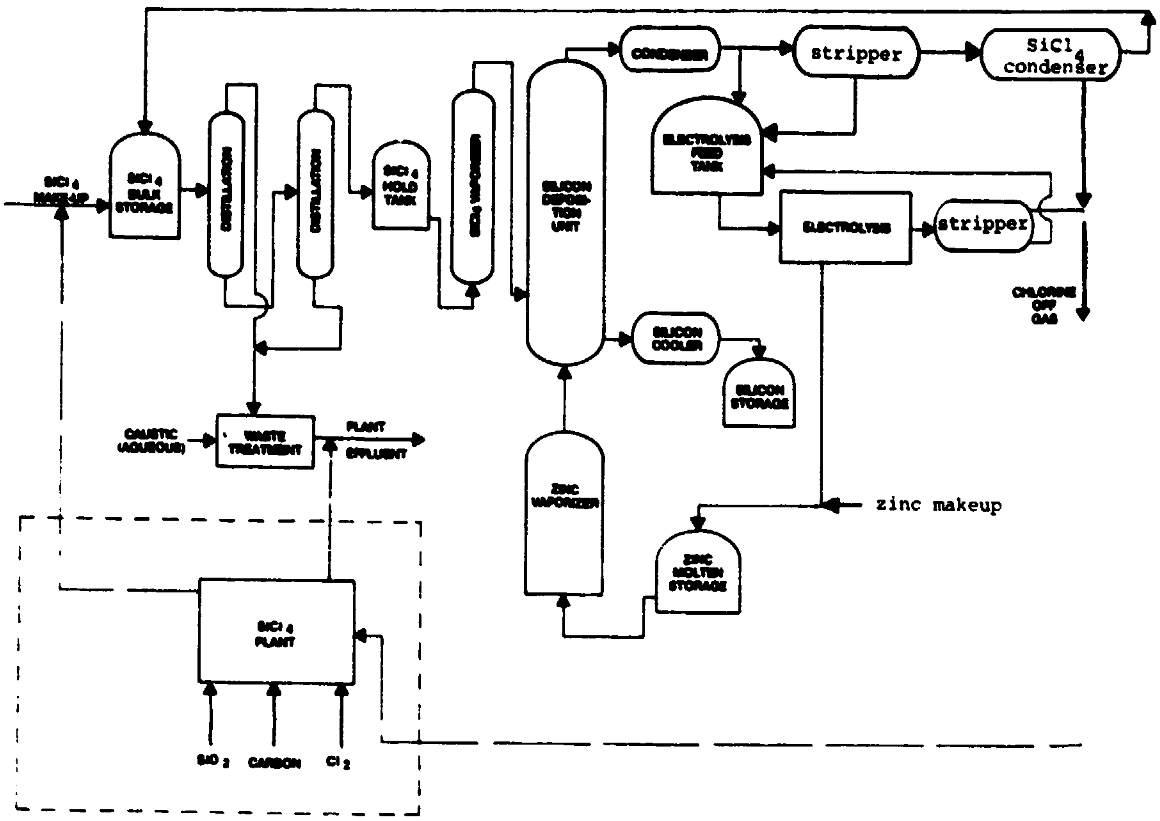
$$Ca(OH)_2(aq) + 2HCl(aq) \rightarrow CaCl_2(aq) + 2H_2O$$

3a. <u>Waste Treatment (50 MT/yr unit)</u>

$Cl_2(g) + 2NaOH(aq) \rightarrow NaOCl(aq) + NaCl(aq) + H_2O$

PROCESS FLOW SHEET FOR BCL PROCESS

STEP 3



STEP 5

UTILITY REQUIREMENTS FOR BCL PROCESS

Utility/Function		Requirements/Kg of Si Product
1. Electricity		30.92 Kw-hr
1. Low Volatage D.C. for Electrolysis	(20.51)	
2. Zinc Vaporizer Induction Heated	(5.62)	
3. Preheat Section of Deposition Unit Induction Heated	(1.39)	

Utility/Function		Requirements/Kg of Si Product
4. Electrolysis Feed Tank Heater	(0.24)	
5. Molten Zinc Storage Heater	(0.10)	
6. $SiCl_4$ Vaporizer	(0.53)	
7. Pumps, Blowers	(2.53)	
2. Steam (50 PSIA)		9.67 pounds
1. #1 Purification Column Reboiler	(4.59)	
2. #2 Purification Column Reboiler	(4.30	
3. Caustic Storage Heating	(0.29)	
4. #1 Purification Column Preheater	(0.49)	
3. Cooling Water		37.88 Gallons
1. #1 Purification Column Condenser	(16.94)	
2. #2 Purification Column Condenser	(15.88)	
3. Purified Tet Cooler	(1.67)	
4. Chlorination Cooler (H-17)	(0.53)	
5. Cell Gas Cooler (H-18)	(2.86)	
4. Process Water		24.20 Gallons
1. Diluent for Waste Treatment	(24.20)	
5. Refrigeration		2.38 MBtu
1. Reactor $SiCl_4$ Condenser (H-11)	(1.28)	
2. $SiCl_4$ Vent Condenser (H-07)	(1.10)	

PRELIMINARY ECONOMIC ANALYSIS ACTIVITIES FOR BCL PROCESS

Prel. Process Economic Activity	Status
1. Process Design Inputs	●
1. Raw Material Requirements	●
2. Utility Requirements	●
3. Equipment List	●
4. Labor Requirements	●
2. Specify Base Case Conditions	●
1. Base Year for Costs	●
2. Appropriate Indices for Costs	●
3. Additional	●
3. Raw Material Costs	●
1. Base Cost/Lb. of Material	●
2. Material Cost/Kg of Silicon	●
3. Total Cost/Kg of Silicon	●
4. Utility Costs	●
1. Base Cost for Each Utility	●
2. Utility Cost/Kg of Silicon	●
3. Total Cost/Kg of Silicon	●
5. Major Process Equipment Costs	●
1. Individual Equipment Cost	●
2. Cost Index Adjustment	●

Prel. Process Economic Activity	Status
6. Production Labor Costs	●
1. Base Cost Per Man Hour	●
2. Cost/Kg Silicon Per Area	●
3. Total Cost/Kg Silicon	●
7. Estimation of Plant Investment	●
1. Battery Limits Direct Costs	●
2. Other Direct Costs	●
3. Indirect Costs	●
4. Contingency	●
5. Total Plant Investment (Fixed Capital)	●
8. Estimation of Total Product Cost	●
1. Direct Manufacturing Cost	●
2. Indirect Manufacturing Cost	●
3. Plant Overhead	●
4. By-Product Credit	●
5. General Expenses	●
6. Total Cost of Product	●

O Plan
◐ In Progress
● Complete

BASE CASE CONDITIONS FOR BCL PROCESS

STEP 2

1. **Capital Equipment**

   -January 1975 Cost Index for Capital Equipment Cost
   -January 1975 Cost Index Value = 430

2. **Utilities**

   -Electrical, Steam, Cooling Water, Nitrogen
   -January 1975 Cost Index (U. S. Dept. Labor)
   -Values determined by literature search and summarized in cost standardization work

3. **Raw Material Cost**

   -Chemical Marketing Reporter
   -January 1975 Value
   -Raw Material Cost Index for Industrial Chemicals
   -1975 Cost Index Value = 206.9 (Wholesale Price Index, Producer Price Index)

4. **Labor Cost**

   -Average for Chemical Petroleum, Coal and Allied Industries (1975)
   -Skilled $6.90/hr

5. **Update to 1980**

   -historically cited 1975 dollars (LSA project)
   -DOE decision to change to 1980 dollars (JPL, 6/22/79)
   -reports to reflect both 1975 and 1980 dollars (JPL, 6/22/79)
   -inflation factor of 1.4 to be used (JPL, 6/22/79)

STEP 3

RAW MATERIAL COST FOR BCL PROCESS

	Raw Material	Requirement lb/KG of Si	$/lb of Material	Cost $/KG of Si
1.	Silicon Tetrachloride ($SiCl_4$)	15.68	0.135	2.117
2.	Zinc (Zn)	0.54	0.38	0.205
3.	Hydrate Lime ($Ca(OH)_2$)	2.85	0.015	0.043
4.	Argon (Ar)	3.1 SCF	0.016/SCF	0.050
5.	Nitrogen (N_2)	7.6 SCF	0.003/SCF	0.023
			Sub Total	2.438
6.	Chlorine (Cl_2)	-10.46[1]	0.0332	-0.347
			TOTAL	2.091 (1975 dollars)
				x 1.4 inflation
				2.927 (1980 dollars)

Note:

[1] This number is the result of by-product rate minus reactor chlorination rate, i.e., 11.12 - 0.66 lb. of Cl_2/KG Si.

UTILITY COST FOR BCL PROCESS

STEP 4

	Utility	Requirement/KG of Silicon	Cost of Utility	Cost $/KG of Silicon
1.	Electricity	30.92 KW-HR	0.0324 $/KW-HR	1.0018
2.	Steam	9.67 pounds	1.35 $/Mlb	0.0131
3.	Cooling Water	37.88 Gallons	0.09 $/Mgal	0.0034
4.	Process Water	24.20 Gallons	0.405 $/Mgal	0.0098
5.	Refrigerant	2.38 MBtu	10.50 $/MMBtu	0.0250
			TOTAL	1.0531 (1975 dollars) x 1.4 inflation 1.4743 (1980 dollars)

PRODUCTION LABOR COST FOR BCL PROCESS

STEP 6

	Section	Labor Man-Hr/Kg Si	Labor Cost $/Man-Hr	Cost $/Kg Si
1.	Purification	0.01402	6.90	0.0968
2.	Deposition	0.01402	6.90	0.0968
3.	Electrolysis	0.02103	6.90	0.1451
4.	Waste Treatment	0.00701	6.90	0.0484
5.	Product Handling	0.00701	6.90	0.0484
			TOTAL	0.4355 (1975 dollars) x 1.4 inflation 0.6097 (1980 dollars)

Note: Costs are 1975 Dollars

ESTIMATION OF PLANT INVESTMENT FOR BCL PROCESS

STEP 7

	Investment $1000
1. DIRECT PLANT INVESTMENT COSTS	
1. Major Process Equipment Cost	2,177.7
2. Installation of Major Process Equipment	936.4
3. Process Piping, Installed	1,611.5
4. Instrumentation, Installed	413.8
5. Electrical, Installed	217.8
6. Process Buildings, Installed	217.8
1a. SUBTOTAL FOR DIRECT PLANT INVESTMENT COSTS (PRIMARILY BATTERY LIMIT FACILITIES)	5,574.9

2.	OTHER DIRECT PLANT INVESTMENT COSTS	
	1. Utilities, Installed	1,045.3
	2. General Service, Site Development, Fire Protection, etc.	261.3
	3. General Buildings, Offices, Shops, etc.	304.9
	4. Receiving, Shipping Facilities	457.3
2a.	SUBTOTAL FOR OTHER DIRECT PLANT INVESTMENT COSTS (PRIMARILY OFFSITE FACILITIES OUTSIDE BATTERY LIMITS)	2,068.8
3.	TOTAL DIRECT PLANT INVESTMENT COST, 1a + 2a	7,643.7
4.	INDIRECT PLANT INVESTMENT COSTS	
	1. Engineering, Overhead, etc.	1,197.7
	2. Normal Cont. for Floods, Strikes, etc.	1,546.2
4a.	TOTAL INDIRECT PLANT INVESTMENT COST	2,743.9
5.	TOTAL DIRECT AND INDIRECT PLANT INVESTMENT COST, 3 + 4a	10,387.6
6.	OVERALL CONTINGENCY, % of 5	2,077.5
7.	FIXED CAPITAL INVESTMENT FOR PLANT, 5 + 6	12,465.2 (1975 dollars)
		x 1.4 inflation
		17,451.2 (1980 dollars)

ESTIMATE OF TOTAL PRODUCT COST

STEP 8

		$/KG of Si
1.	Direct Manufacturing Cost (Direct Charges)	
	1. Raw Materials	2.091
	2. Direct Operating Labor	0.436
	3. Utilities	1.053
	4. Supervision and Clerical	0.065
	5. Maintenance and Repairs	1.247
	6. Operating Supplies	0.249
	7. Laboratory Charge	0.065
2.	Indirect Manaufacturing Cost (Fixed Charges)	
	1. Depreciation	1.247
	2. Local Taxes	0.249
	3. Insurance	0.125
3.	Plant Overhead	0.675
4.	By-Product Credit	-----
4a.	Total Manufacturing Cost, 1 + 2 + 3 + 4	7.501
5.	General Expenses	
	1. Administration	0.450
	2. Distribution and Sales	0.450
	3. Research and Development	0.225
6.	Total Cost of Product, 4a + 5	8.626 (1975 dollars)
		x 1.4 inflation
		12.076 (1980 dollars)

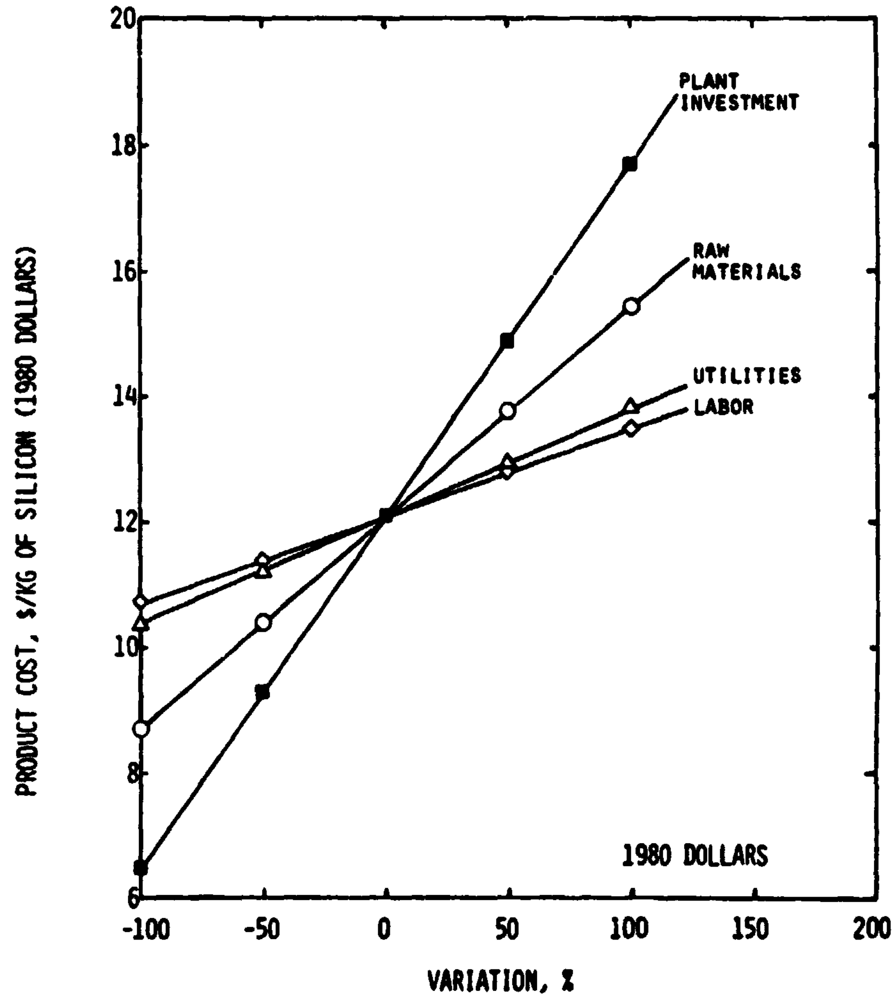
STEP 1 BASE CASE CONDITIONS FOR BCL PROCESS

1. Process.............................BCL process
2. Plant Size..........................1,000 Metric Tons/year
3. Plant Product.......................Silicon
4. Product Form........................Silicon Granules
5. Plant Investment....................$14,340,000/$20,070,000 (1975 dollars) (1980 dollars)

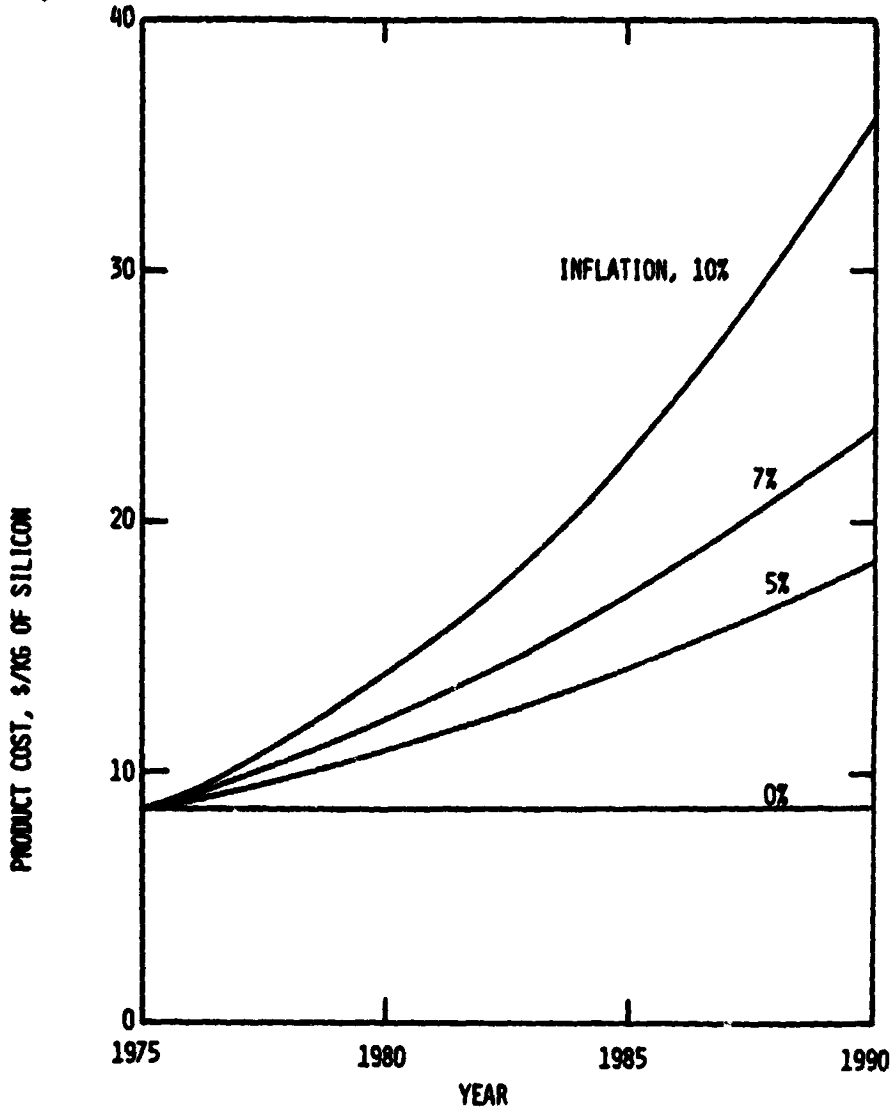
		(1975 dollars)	(1980 dollars)
Fixed Capital		$12.47 Mega	$17.45 Mega
Working Capital (15%)		1.87 Mega	2.62 Mega
	Total	$14.34 Mega	$20.07 Mega

6. Product Cost (No Profit)............8.63 $/kg/12.1 $/kg (1975 dollars) (1980 dollars)
7. Inflation Factor (1975 to 1980).....1.4

STEP 1-7 COST SENSITIVITY ANALYSIS OF BCL PROCESS



STEP 8 INFLATION EFFECT



STEP 9 COST AND PROFITABILITY ANALYSIS

1. Process..BCL Process
2. Plant Size.......................................1,000 Metric Tons/year
3. Plant Product....................................Silicon
4. Product Form.....................................Silicon Granules
5. Plant Investment.................................$14,340,000/$20,070,000
(1975 dollars) (1980 dollars)

		1975 dollars	1980 dollars
Fixed Capital		$12.47 Mega	$17.45 Mega
Working Capital (15%)		1.87 Mega	2.62 Mega
	TOTAL	$14.34 Mega	$20.70 Mega

6. Product Cost.....................................8.63 $/Kg (1975 dollars)
7. Tax Rate (Federal)...............................46%
8. Return on Original Investment, after taxes (%ROI)

	Sales Price \$/Kg of Silicon (1975 dollars)	Sales Price \$/Kg of Silicon (1980 dollars)
0% ROI..............	8.63	12.08
5% ROI..............	9.96	13.94
10% ROI..............	11.28	15.80
15% ROI..............	12.61	17.65
20% ROI..............	13.94	19.51
25% ROI..............	15.27	21.37
30% ROI..............	16.59	23.23
40% ROI..............	19.25	26.95

9. Discounted Cash Flow Rate of Return, after taxes (%DCF)

	Sales Price \$/Kg of Silicon (1975 dollars)	Sales Price \$/Kg of Silicon (1980 dollars)
0% DCF..............	8.63	12.08
5% DCF..............	9.48	13.28
10% DCF..............	10.42	14.59
15% DCF..............	11.44	16.01
20% DCF..............	12.52	17.53
25% DCF..............	13.65	19.11
30% DCF..............	14.83	20.76
40% DCF..............	17.27	24.18

Based on 10 year project life and 10 year straight line depreciation.

PURE SILICON PROCESS

SRI INTERNATIONAL

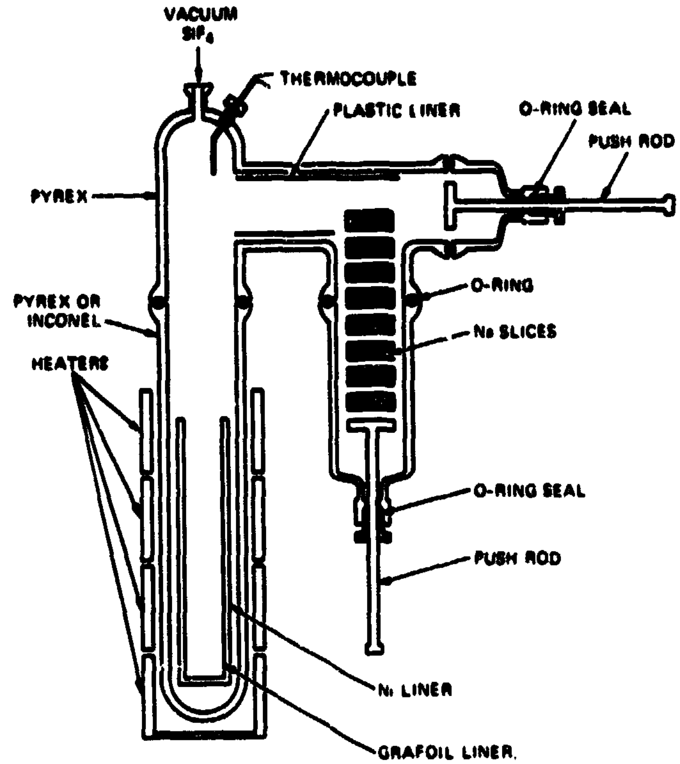
TASK I: $SiF_4 + 4\,Na \rightarrow Si + 4\,NaF$

TASK II: MELT SEPARATION OF Si AND NaF

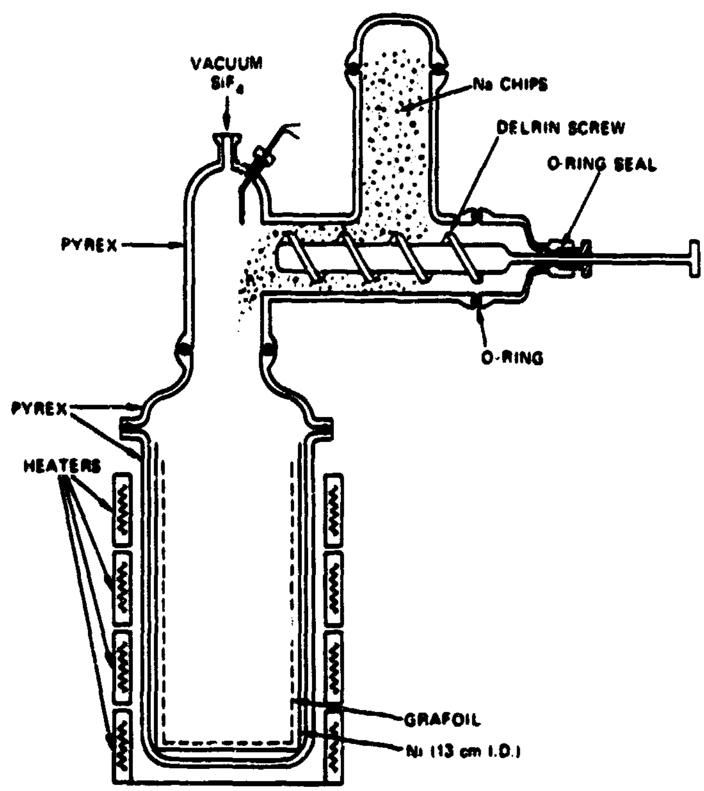
EFFECT OF REACTOR SCALE-UP (X3) ON REACTION $SiF_4 + 4Na \rightarrow Si + 4\,NaF$

Objectives	Accomplishments 7-Cm Reactor	Accomplishments 13-Cm Reactor
• Increase Si Production (kg Si/batch)	0.15	0.5
• Decrease Unreacted Na (wt% Na)	10	0
• Increase Reaction Rate (kg Si/hr) At 0 wt% Na unreacted.	0.1	1.2

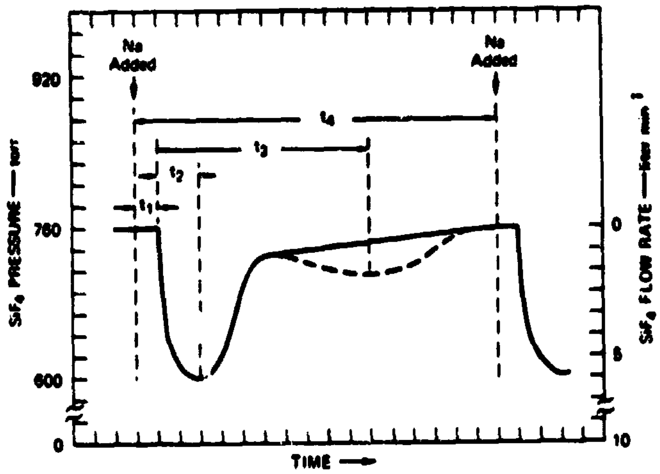
SMALL REACTOR FOR THE SiF_4-Na REACTION: SOLID Na FEEDING TECHNIQUE



LARGE REACTOR FOR THE SiF_4-Na REACTION: SOLID Na FEEDING TECHNIQUE

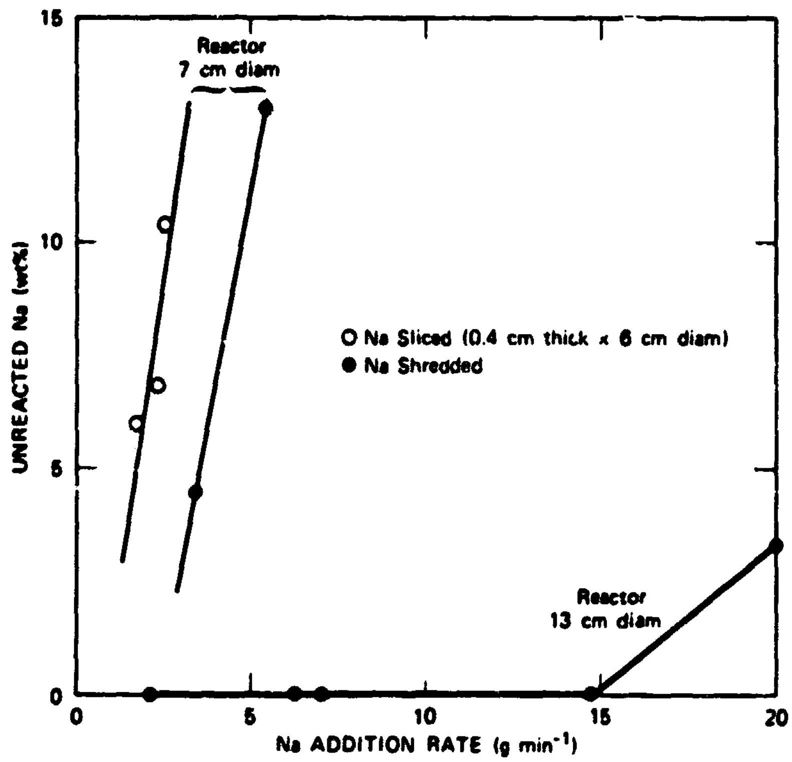


SCHEMATIC REPRESENTATION OF FOUR REACTION PERIODS ASSOCIATED WITH SiF_4-Na REACTION

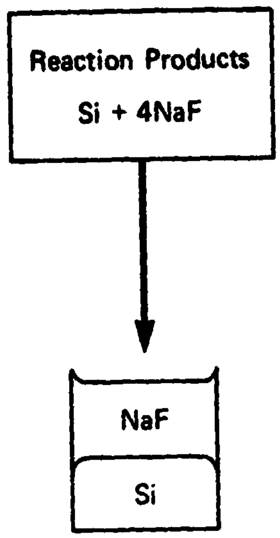


EFFECT OF Na ADDITION RATE AND REACTOR DIAMETER ON AMOUNT OF UNREACTED Na

Reactor temperature 400–450°C.



TASK 2: MELT SEPARATION



MAIN ACTIVITIES IN TASK 2, MELT SEPARATION

Scale Up Experiments

Batch Melt, batch Load

Total Cap. = 3 kg RP* (0.3 kg Si)

↓

Continuous Feed, batch melt.

Total Cap. = 7 kg RP (0.7-1.0 kg Si)

↓

Continuous feed, continuous melt

Intermittent discharge

Production rate = 0.6 kg/h of Si

Auxiliary Experiments

Coalescence

Wetting behavior

Design Testing

*RP = reaction product.

SUMMARY OF COALESCENCE EXPERIMENTS

Melt Composition	Coalescence of Si on Cooling
Si + NaF + 0% NaOH	Complete
Si + NaF + 5% NaOH	Complete
Si + NaF + 10% NaOH	Incomplete
Si + NaF + 20% NaOH	Incomplete
Si + NaF + 10% Na_2SiO_3	Incomplete
Si + NaF + 10% SiO_2	Incomplete

SUMMARY OF WETTING BEHAVIOR EXPERIMENTS

	C	Si	SiC
Si	Reacts (SiC)		Wets
NaF	Does not wet	Wets	Wets
NaOH	Wets	Wets & Reacts	
NaF + SiO_2	Does not wet	Wets	
NaF + Na_2SiO_3	Does not wet	Wets	Wets

ARC HEATER PRODUCTION OF SILICON

WESTINGHOUSE ELECTRIC CORP.

P.C.B. DIVISION

REACTION

$SiCl_4 + 4Na \rightarrow Si(l) + 4NaCl(v)$

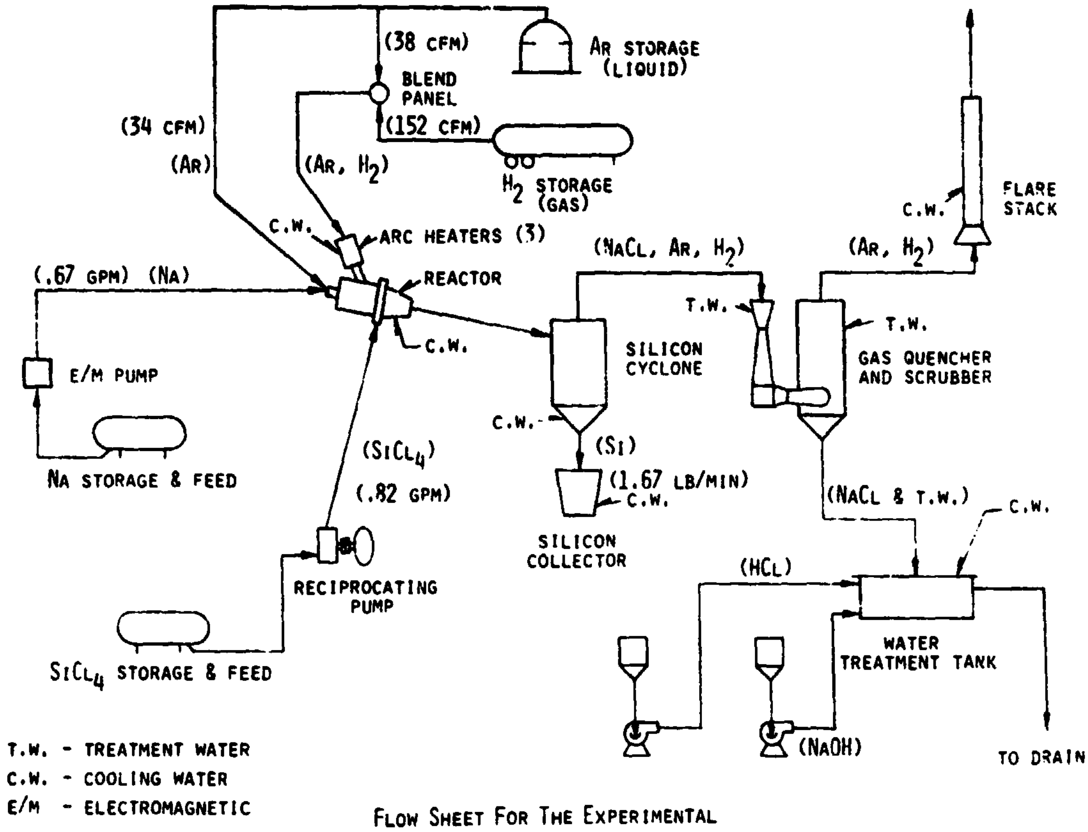
- At Temperature Of 3000°K Or Higher
- Reducing Atmosphere: H_2/Ar
- Molar Input Ratio:
  $SiCl_4 : Na : H_2 : Ar$
  1 : 4 : 6.62 : 1.66

EXPERIMENTAL VERIFICATION PROGRAM

OBJECTIVE

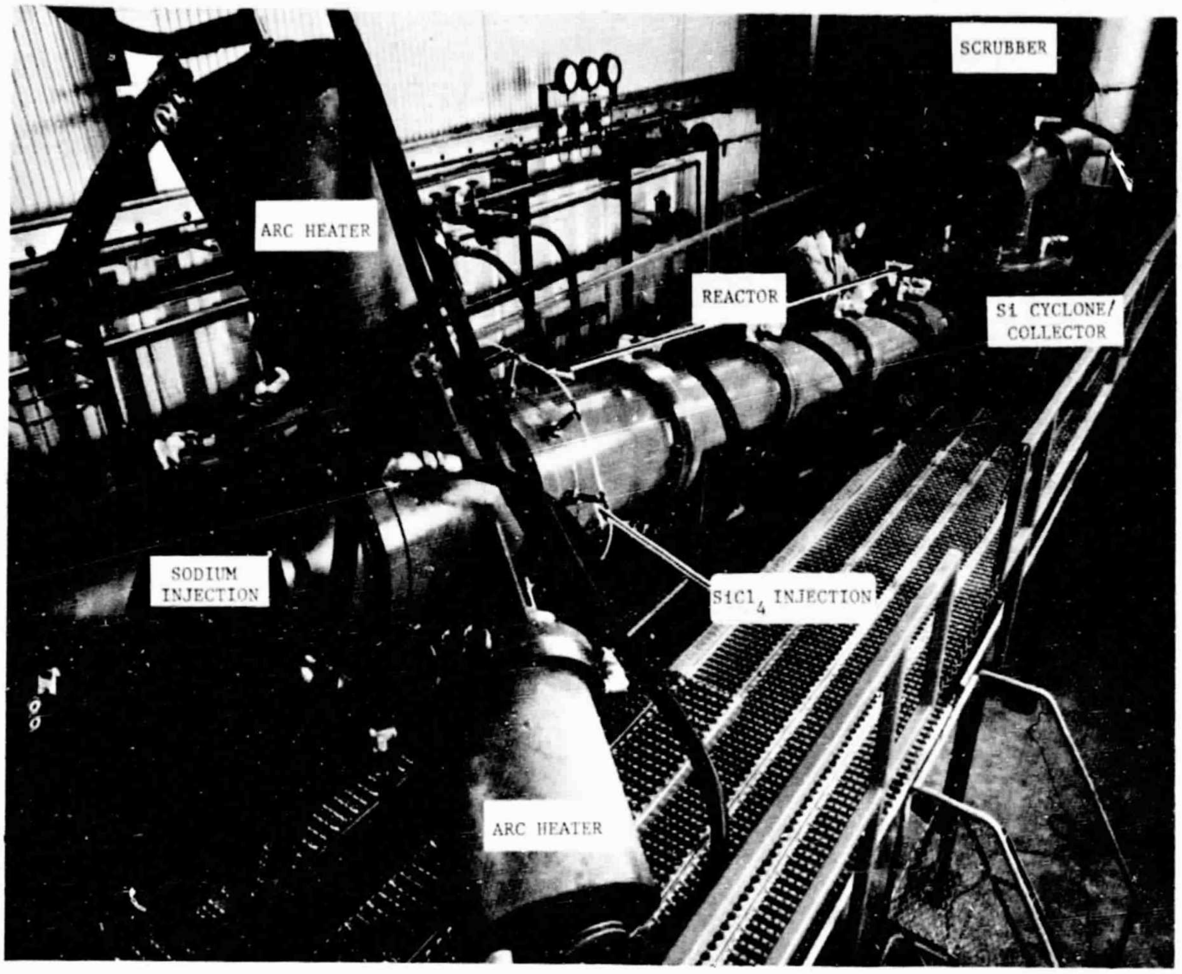
- Demonstrate reduction of $SiCl_4$ with Na to produce Si.
- Achieve effective product separation via Si(v) condensation.
- Achieve a production rate of 100 lb_m/hr. based on effective continuous operation.
- Develop preliminary information relevant to process economics.
- Produce representative silicon product samples exceeding 1 kg each.

FLOW SHEET FOR THE EXPERIMENTAL VERIFICATION SYSTEM



FLOW SHEET FOR THE EXPERIMENTAL VERIFICATION SYSTEM

ARC HEATER-REACTOR FOR EXPERIMENTAL SILICON PRODUCTION



EXPERIMENTAL SYSTEM SHAKEDOWN AND GAS POWER TESTS

- SHAKEDOWN TESTS
  - Reactor & Arc Heaters
  - Electrical Power System
  - Gas, Cooling Water, & Stack
  - Instrumentation & Control
  - $SiCl_4$ System

ORIGINAL PAGE IS OF POOR QUALITY

- GAS ONLY POWER TESTS
  - Ar-H_2 Gas Mixture (200 scfm, $4H_2$:1Ar)
  - Power Input - 30 Equivalent 1500 kW (Arc Heaters)
  - Successful System Operation

EXPERIMENTAL VERIFICATION TEST SYSTEM

STATUS

Test System Installation 98% Complete

- Reactor
- Arc Heaters
- Na System
- $SiCl_4$ System
- Water System
- Gas System
- Power System
- Effluent System
- I&C System

System Shakedown

All Systems Of The Test Unit Have Completed Shakedown, Except Na, $SiCl_4$ Systems & Respective I&C.

Power Tests

6 Gas Only Power Tests Completed, 10 Tests Remain To Be Completed.

PLANNED ACTIVITY

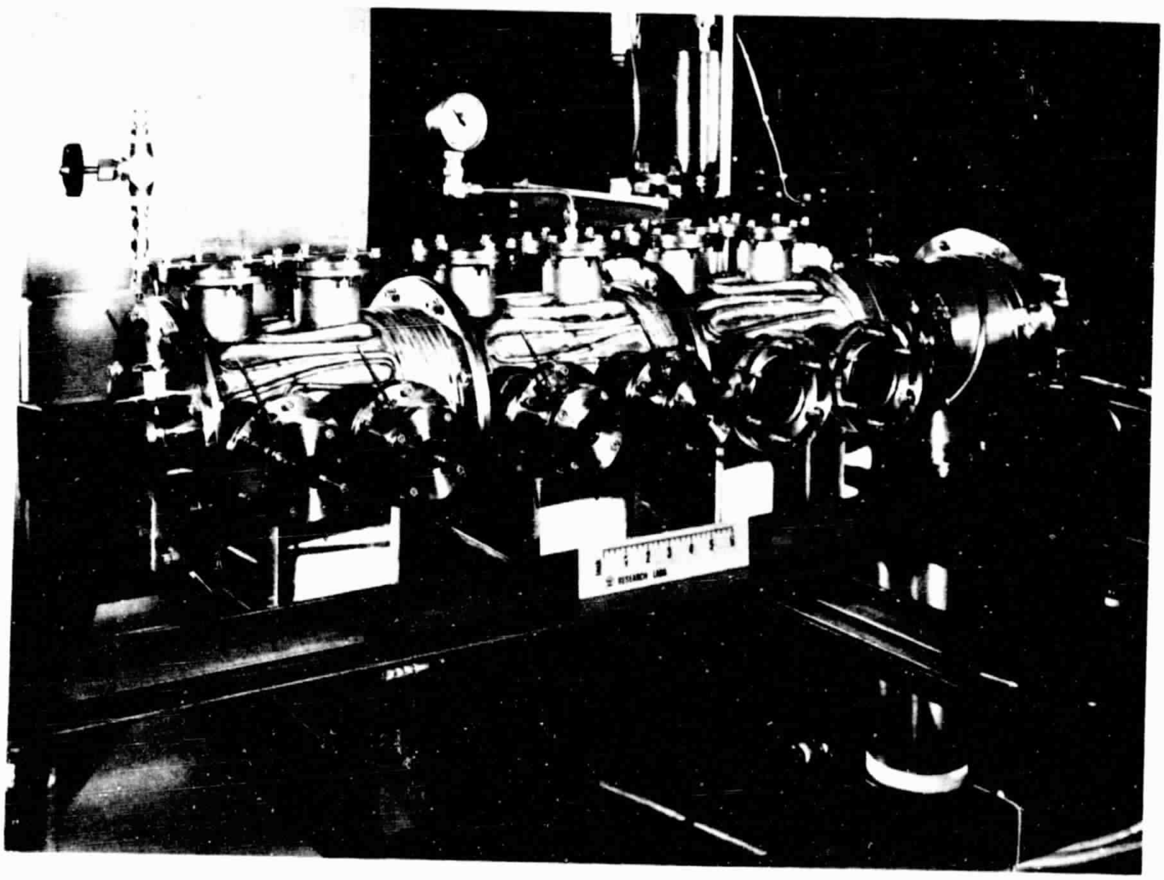
- Complete Installation & Shakedown Of Na & $SiCl_4$ Systems
- Complete Shakedown Of I&C System
- Complete Gas Only - Power Test Series
- Conduct Demonstration Tests For Si Production
- Characterize Si Product & Evaluate Reaction Parameters
- Submit Si Samples To JPL For Evaluation

OBJECTIVE OF LABORATORY EXPERIMENT

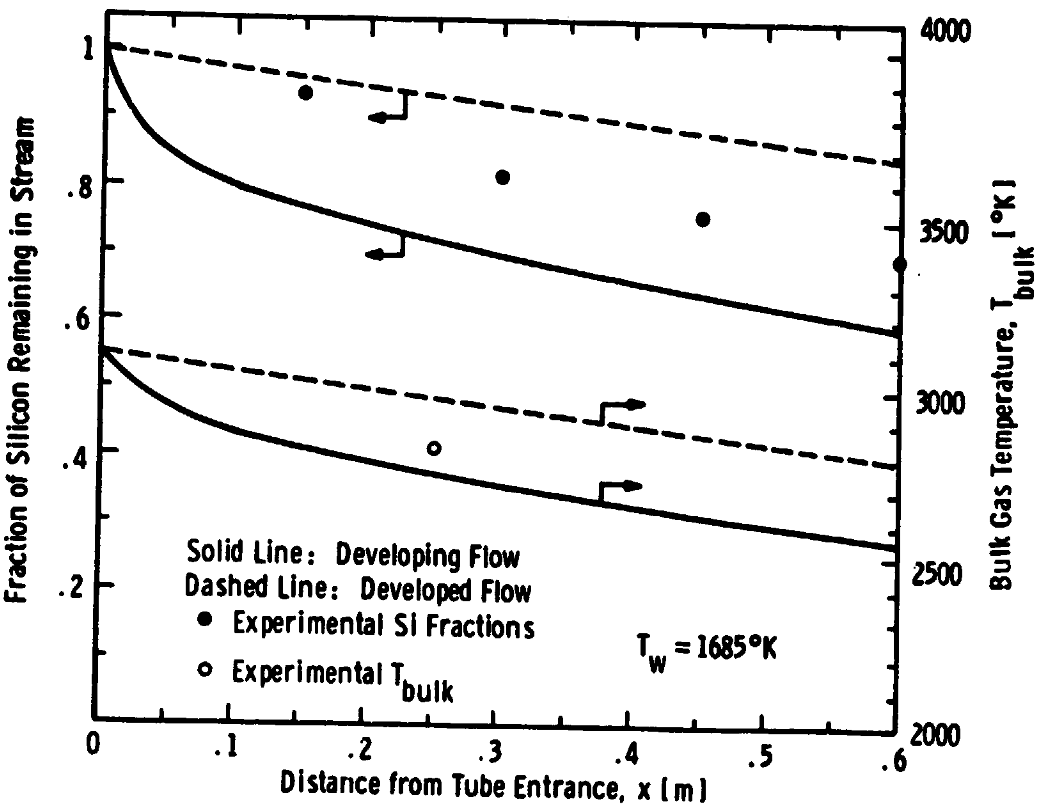
Provide Input For Process Development

- Study Reaction Rates
- Verify Product Separation Analysis

TEST CHAMBER



AXIAL Si/TEMPERATURE DISTRIBUTION



Theoretical and experimental axial distribution of the fraction of silicon remaining in the gas stream, and axial bulk temperature distribution

CONCLUSIONS

- Reaction Proceeds Rapidly
- Reaction Product Si Can Be Separated And Collected By Wall Condensation As Predicted
- Differences Between Laboratory Experiment And Process Verification Reactor Point Towards Even More Favorable Operation Of Latter

LOW-COST SILICON PROCESS

BATTELLE COLUMBUS LABORATORIES

THE REACTION

- O ZINC REDUCTION OF SILICON TETRACHLORIDE

  $SiCl_4(G) + 2Zn(G) = Si(S) + 2ZnCl_2(G)$

  PRESSURE = 1 ATM

  TEMPERATURE = 927 C

  ABOVE - EFFICIENCY DROPS OFF
  BELOW - DANGER OF ZINC CONDENSATION

- O REACTION USED BY DU PONT TO SUPPLY SILICON TO INFANT SILICON SEMICONDUCTOR INDUSTRY (BATCH PROCESS, DENDRITIC PRODUCT, VARIABLE QUALITY)

THE REACTOR

- O FLUIDIZED BED OF SEED PARTICLES
  - -- CONTINUOUS PROCESS, UNIFORM PRODUCT
  - -- PARTICLES GROW FROM (E.G.) 200 µM TO 600 µM (4 PERCENT SEED)
  - -- HIGH PRODUCTION RATE -- 15.6 KG/HOUR PER SQUARE FOOT OF REACTOR CROSS SECTION
  - -- HIGH EFFICIENCY -- 60 TO 65 PERCENT
  - -- CONTINUOUS PRODUCT WITHDRAWAL

THE PRODUCT

- O FREE-FLOWING GRANULES
  - -- EASILY LOADED INTO MELTING UNIT
- O COST = \$10.29/KG TO \$12.19/KG (1980 DOLLARS) AT 1,000,000 KG/YR DEPENDING UPON SIZE AND MULTIPLICITY OF PLANT COMPONENTS
- O UNIFORM HIGH PURITY ANTICIPATED BECAUSE OF CONTINUOUS PROCESS

THE TECHNOLOGY

- O $SiCl_4$ PRODUCTION
  - -- ESTABLISHED COMMERCIAL TECHNOLOGY

    $SiC(S) + 2Cl_2(G) = SiCl_4(G) + C(S)$

- o $SiCl_4$ PURIFICATION
  - — BY DISTILLATION, TECHNOLOGY IN HAND
- O FLUIDIZED BED REDUCTION
  - — WIDELY USED TECHNOLOGY
  - — REACTOR FOR PRESENT PROCESS BEING DEVELOPED
- O ZINC REDUCTANT
  - — HIGH PURITY, 99.99%, (DISTILLED) AVAILABLE COMMERCIALLY
  - — PURIFICATION IN BY-PRODUCT $ZnCl_2$ ELECTROLYSIS AND IN VAPORIZATION
  - — MOST IMPURITIES MUCH LESS VOLATILE THAN ZINC. CADMIUM (EXCEPTION), LIKE ZINC, IS NOT RETAINED BY SILICON ON MELTING
- O ZINC CHLORIDE BYPRODUCT
  - — $ZnCl_2$/Zn/Si (MINOR, SUBMICRON) CONDENSATION FROM $SiCl_4$ BEING DEVELOPED
  - — $ZnCl_2$ ELECTROLYSIS (~50M/O IN KCL, 500 C)
    - — APPROACHING COMMERCIAL STATUS BUREAU OF MINES, RENO, TREATMENT OF ZnS ORES ALTERNATIVE TO ROASTING
    - — 6000-AMP GRAPHITE CELL OPERATED IN ENGLAND 16 MO IN 1915-1916 WITH NEGLIGIBLE DETERIORATION

THE STATUS

- O EXPERIMENTAL WORK HAS DEMONSTRATED FEASIBILITY
- O 50,000 KG/YR EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (EPSDU) DESIGNED
  - — PRELIMINARY BIDS FOR CONSTRUCTION OBTAINED. AWAITING GO-AHEAD
- O PROCESS DEVELOPMENT UNIT (PDU) BEING CONSTRUCTED
  - — FOUR CRITICAL UNITS OF FULL SCALE EPSDU DESIGNED TO BE OPERATED BATCH-WISE (8-HR)
    - — FLUIDIZED BED
    - — BY-PRODUCT CONDENSER
    - — ZINC VAPORIZER
    - — ELECTROLYTIC CELL
- O INITIATION OF OPERATION, OCTOBER 1, 1979

THE PROBLEMS

- o RESIDUAL ZINC IN PRODUCT
  - — ~1000 PPM ZN, REMOVED ON SILICON MELTING
  - — NO PROBLEM IN ISOLATED MELTING
  - — MAY NOT BE A PROBLEM IN DIRECT MELTING
- o PURITY OF PRODUCT NOT WELL ESTABLISHED
  - — FULL PURITY STUDY DEFERRED
  - — MASS SPECTROMETRIC AND NEUTRON ACTIVATION ANALYSIS REVEAL NO IMPURITIES OF GREAT CONCERN
  - — DUPONT PRODUCT ACCEPTABLE
- o UNUSUAL BY-PRODUCT CONDENSATION/CIRCULATION
  - — CONDITIONS FOR CONDENSING AND CIRCULATING $ZnCl_2$(L)/ZN(S)/SI(S) SLURRY MAY BE CRITICAL
    - — WET-WALL CONDENSER BEING STUDIED
  - — ZINC(S) AND SI(S) HELD IN SUSPENSION IN $ZnCl_2$ AT 350 C
  - — ZN(S) COALESCES FOR COLLECTION AT 500 C (ELECTROLYTIC CELL TEMPERATURE)
  - — SI(S) CHLORINATED IN ELECTROLYTIC CELL TO $SiCl_4$ FOR RECYCLE

THE PROSPECTS

- o PDU OPERATION EXPECTED TO CONFIRM EPSDU DESIGN WITH MINIMUM OF MODIFICATION
- o EPSDU CONSTRUCTION, INITIATION ANTICIPATED IN APRIL 1980
- o EPSDU OPERATION ANTICIPATED - 1981
- o TRANSFER OF TECHNOLOGY TO INDUSTRY ANTICIPATED - 1982
  - — ONE COMPANY IN RELATED TECHNOLOGY SHOWING CONTINUED INTEREST
  - — OTHER INQUIRIES ANSWERED
  - — ADDITIONAL PROSPECTS IN MIND WITH MESHING TECHNOLOGY

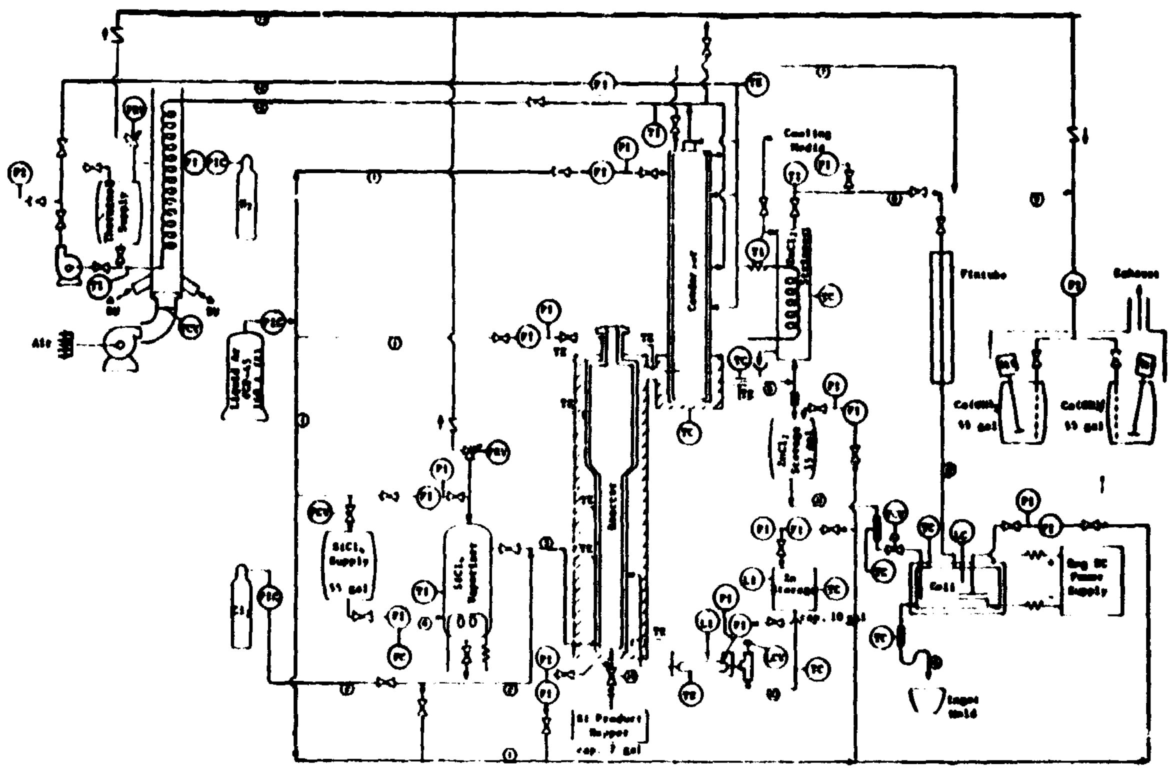
SUPPORT STUDIES

- ZINC VAPORIZATION
  - DESIGN
  - PURITY
- FLUIDIZED-BED MODELLING
- ELECTROLYTIC CELL DESIGN
- REACTOR-CONDENSER DESIGN

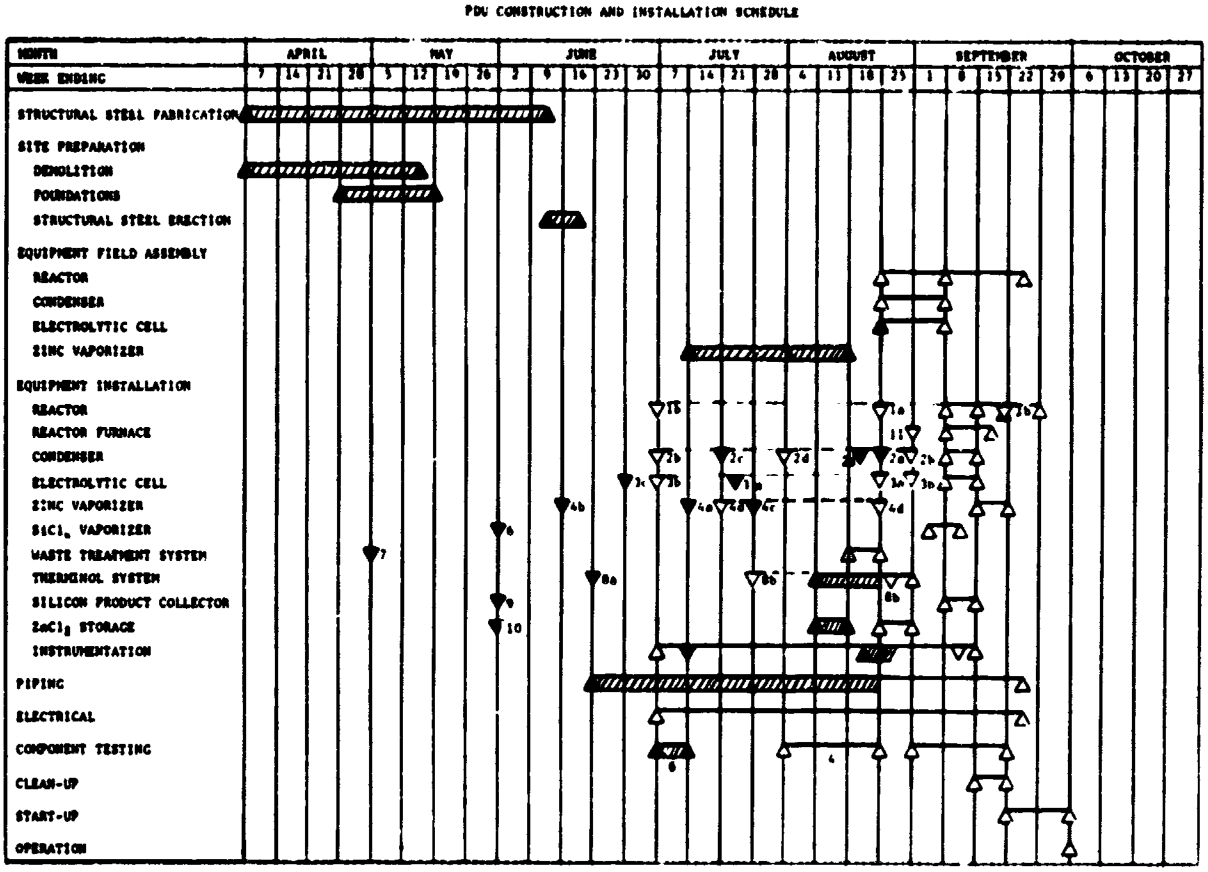
HANDLING $SiCl_4$ SPILLS

- CATAGORIES:
  - MOSTLY VAPOR OR <1 GALLON/HOUR
  - SEVERAL GALLONS/HOUR, SUDDEN RELEASE
  - SPILLAGE OF MAJOR PORTION OF $SiCl_4$ INVENTORY

PROCESS FLOW SHEET FOR PDU



PDU CONSTRUCTION AND INSTALLATION SCHEDULE

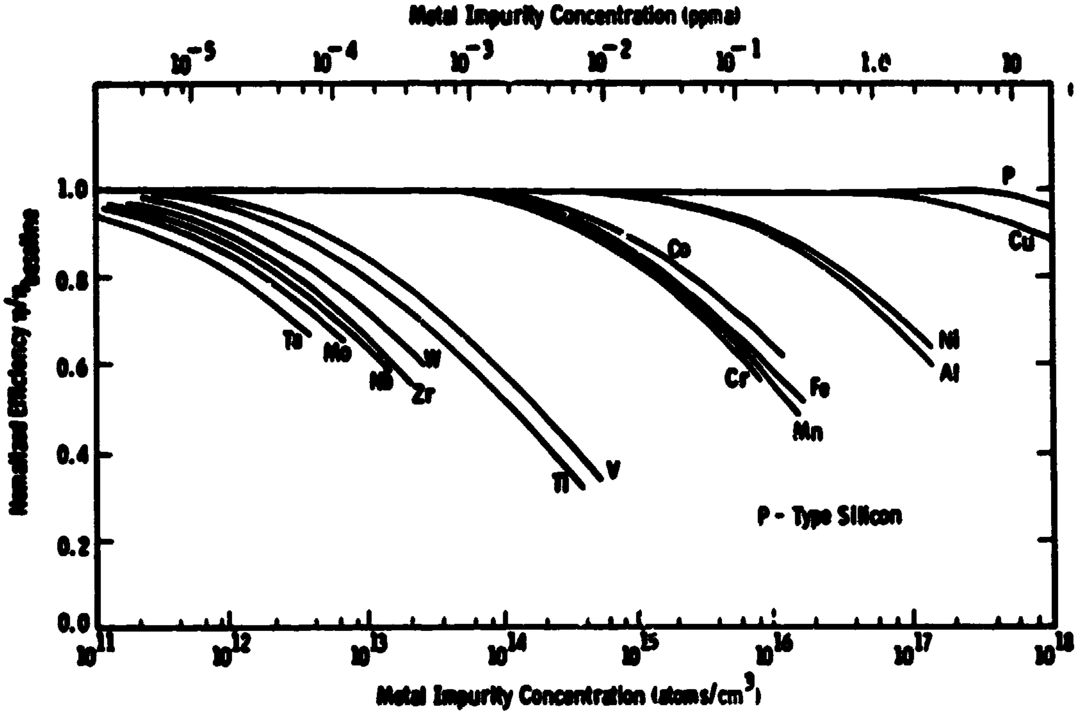


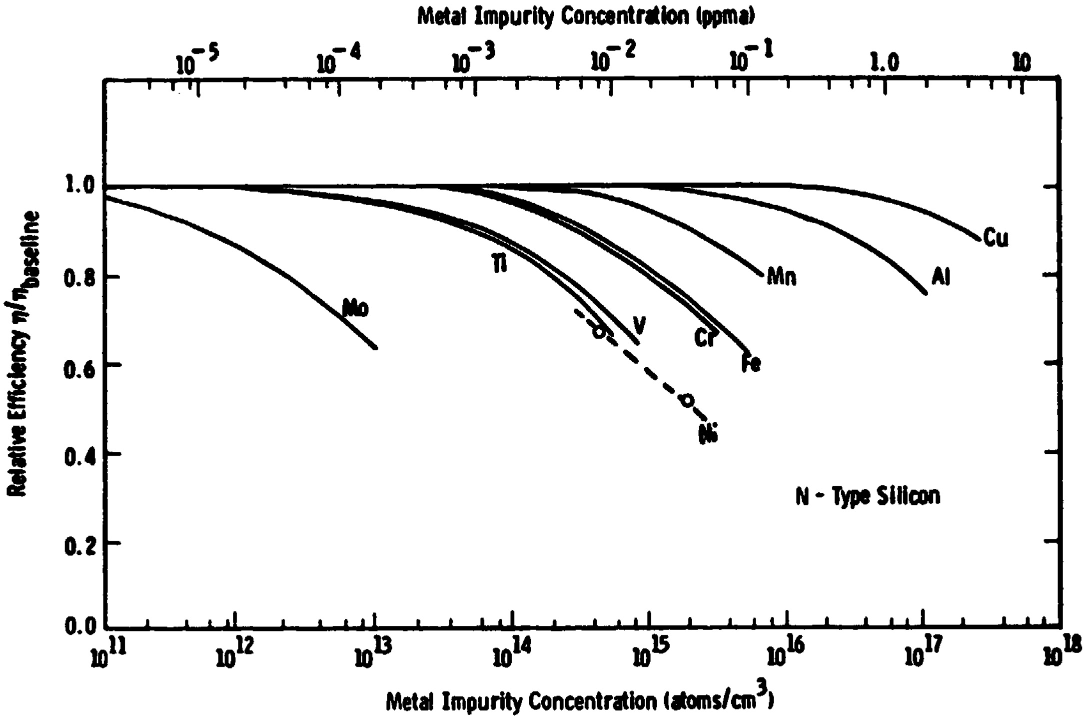
▼ = EQUIPMENT DELIVERY MILESTONE; △ = CURRENT ACTIVITY; ▲ = CONCLUDED ACTIVITY; --- = CHANGE IN SCHEDULE.

1. REACTOR COMPONENTS: (a) SHELL, (b) GRAPHITE LINER
2. CONDENSER COMPONENTS: (a) SHELL, (b) GRAPHITE LINER, (c) SUMP TANK, (d) PUMP
3. ELECTROLYTIC CELL COMPONENTS: (a) SHELL, (b) GRAPHITE LINER, (c) POWER SUPPLY
4. ZINC VAPORIZER SYSTEM: (a) QUARTZ SHELL, (b) CONTROL VALVE, (c) MELT/STORAGE TANK, (d) GRAPHITE CRUCIBLE
5. INSTRUMENTATION
6. $SiCl_4$ VAPORIZER
7. WASTE TREATMENT SYSTEM
8. THERMINOL SYSTEM: (a) COMPONENTS, (b) PUMP
9. SILICON PRODUCT COLLECTOR
10. $ZnCl_2$ STORAGE
11. REACTOR FURNACE

EFFECTS OF IMPURITIES AND PROCESSING ON Si SOLAR CELLS

WESTINGHOUSE R&D CENTER

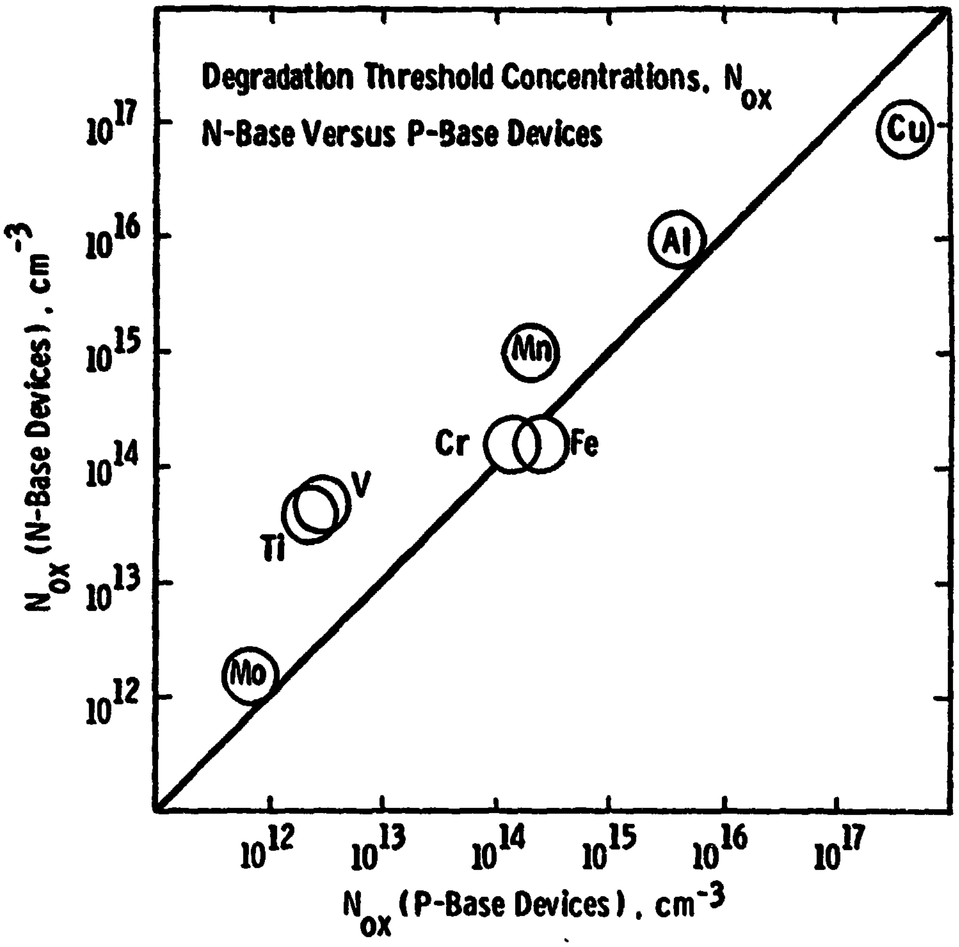




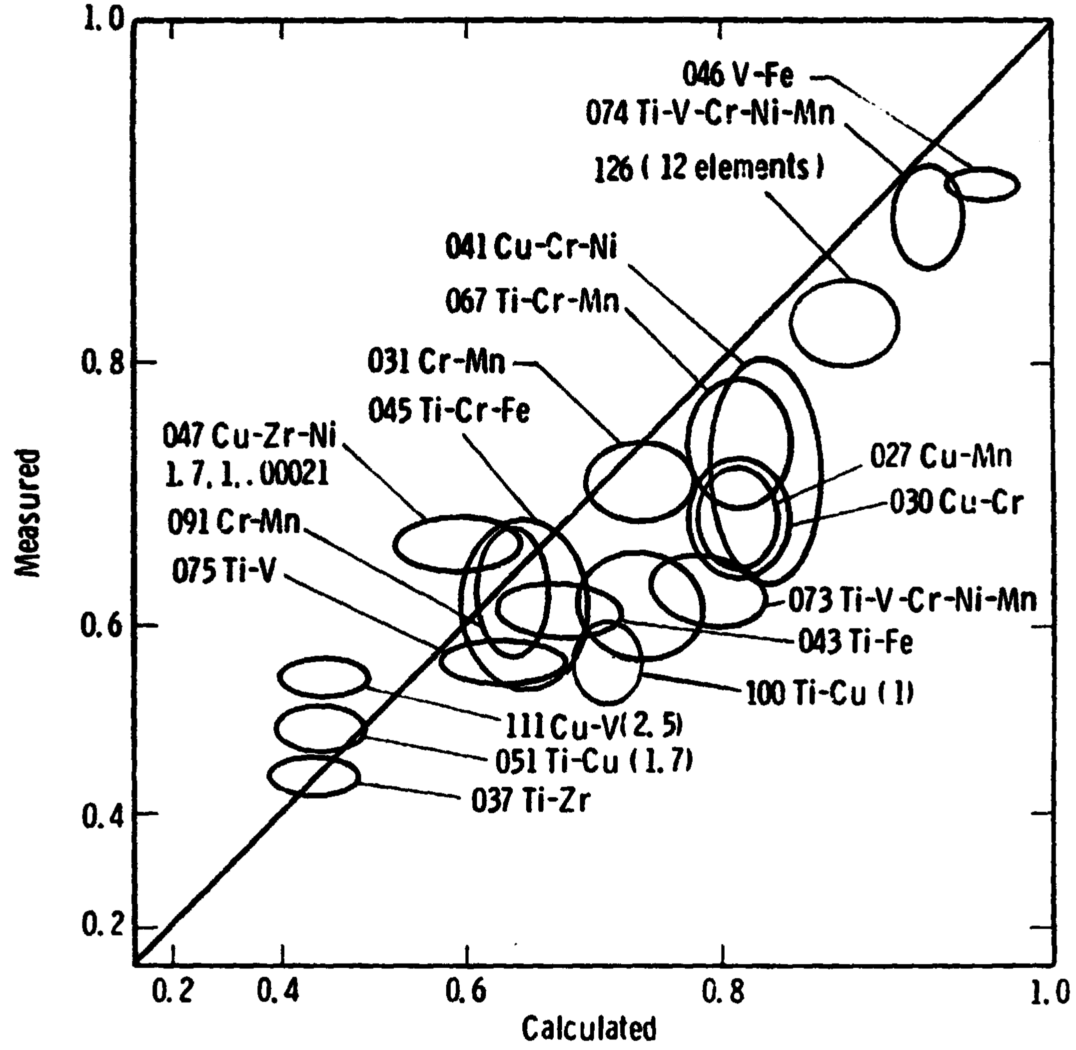
SEGREGATION COEFFICIENTS

Element	Effective Segregation Coefficient*
Al	3×10^{-2} (2.8×10^{-3})
B	0.8
C	0.05
Ca	?
Cu	8.0×10^{-4}
Cr	1.1×10^{-5}
Fe	6.4×10^{-6}
Mg	3.2×10^{-6}
Mn	1.3×10^{-5}
Mo	4.5×10^{-8}
Ni	3.2×10^{-5}
Ph	0.35
Ta	2.1×10^{-8}
Ti	2.0×10^{-6}
V	4×10^{-6}
Zn	10^{-5}
Zr	$<1.5 \times 10^{-7}$
W	1.7×10^{-8}
Co	1.0×10^{-5}
Nb	$\sim 10^{-7}$

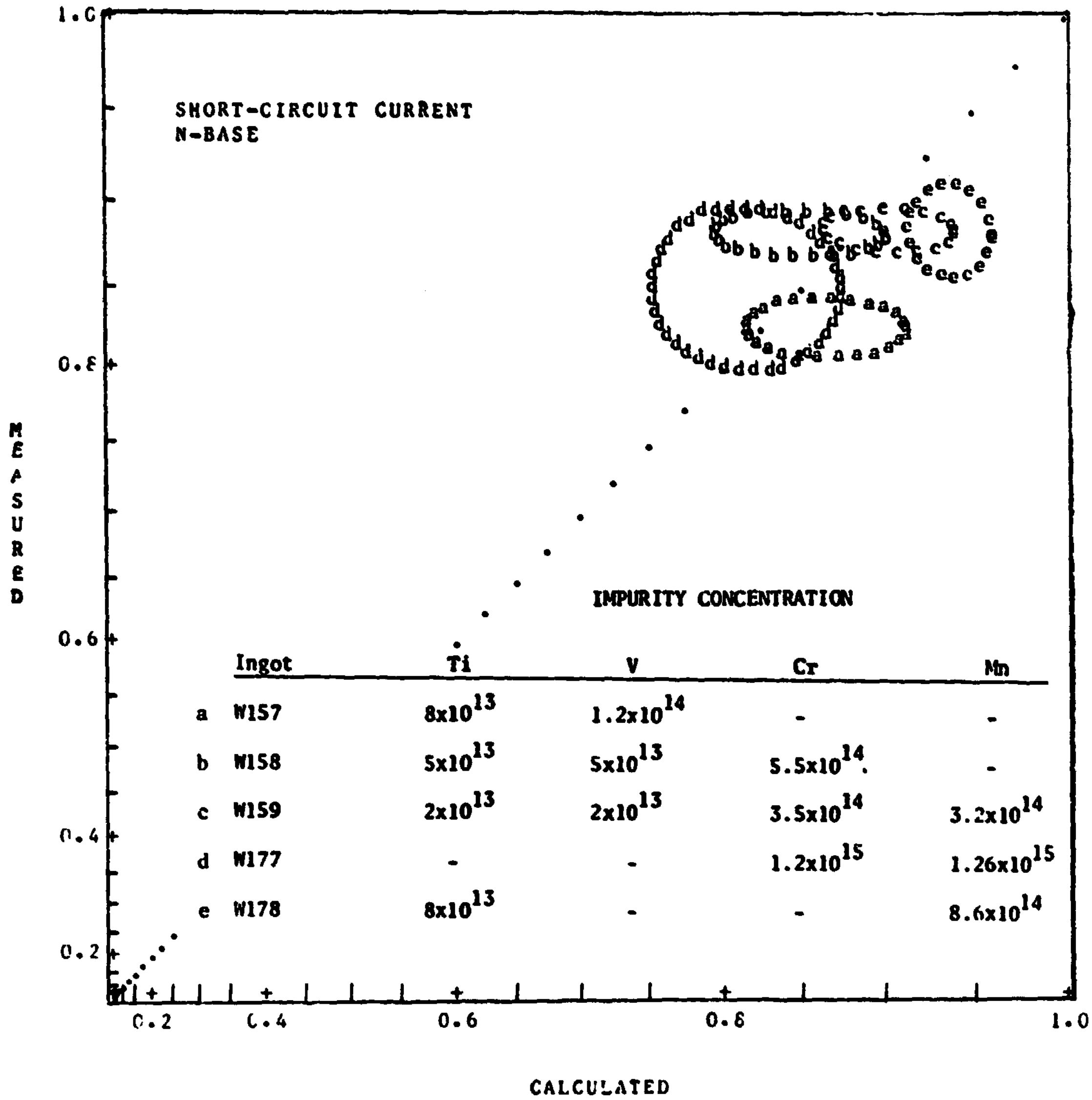
*k_{eff} = ingot impurity concentration/melt impurity concentration



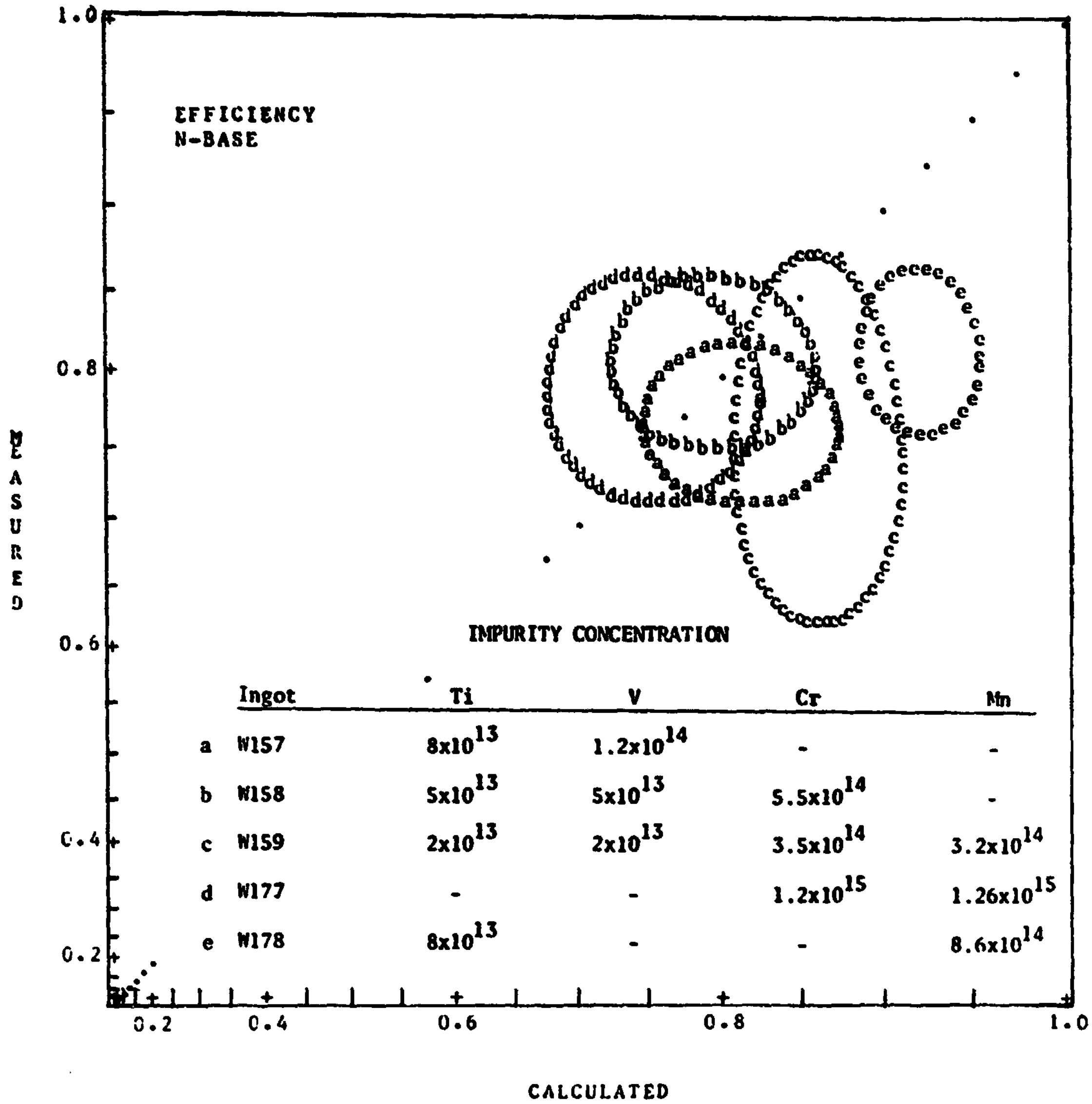
Comparison of the Threshold Impurity Concentration (N_{ox}) for Cell Efficiency Degradation in N and P-base Silicon Solar Cells.



Normalized efficiencies for multiply doped, 4-ohm-cm, P-base solar cells

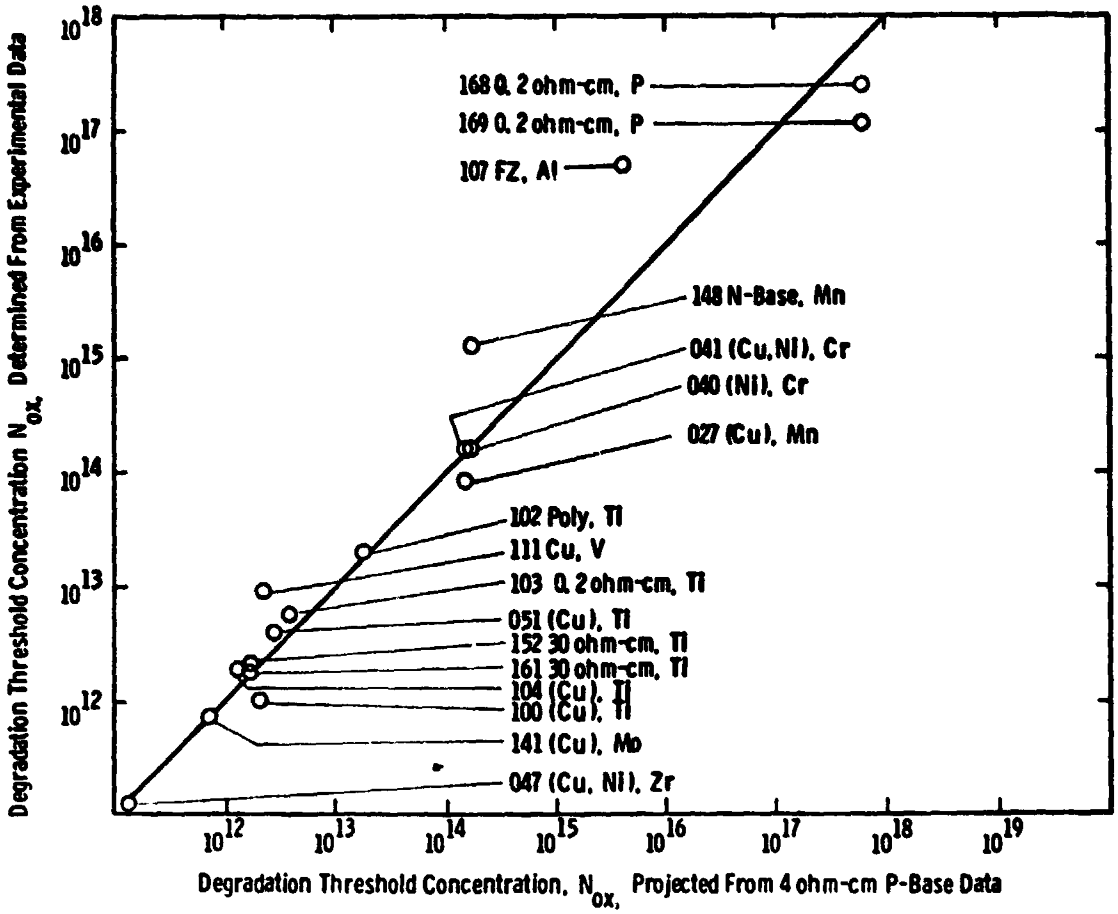


	Ingot	Ti	V	Cr	Mn
a	W157	$8x10^{13}$	$1.2x10^{14}$	-	-
b	W158	$5x10^{13}$	$5x10^{13}$	$5.5x10^{14}$	-
c	W159	$2x10^{13}$	$2x10^{13}$	$3.5x10^{14}$	$3.2x10^{14}$
d	W177	-	-	$1.2x10^{15}$	$1.26x10^{15}$
e	W178	$8x10^{13}$	-	-	$8.6x10^{14}$

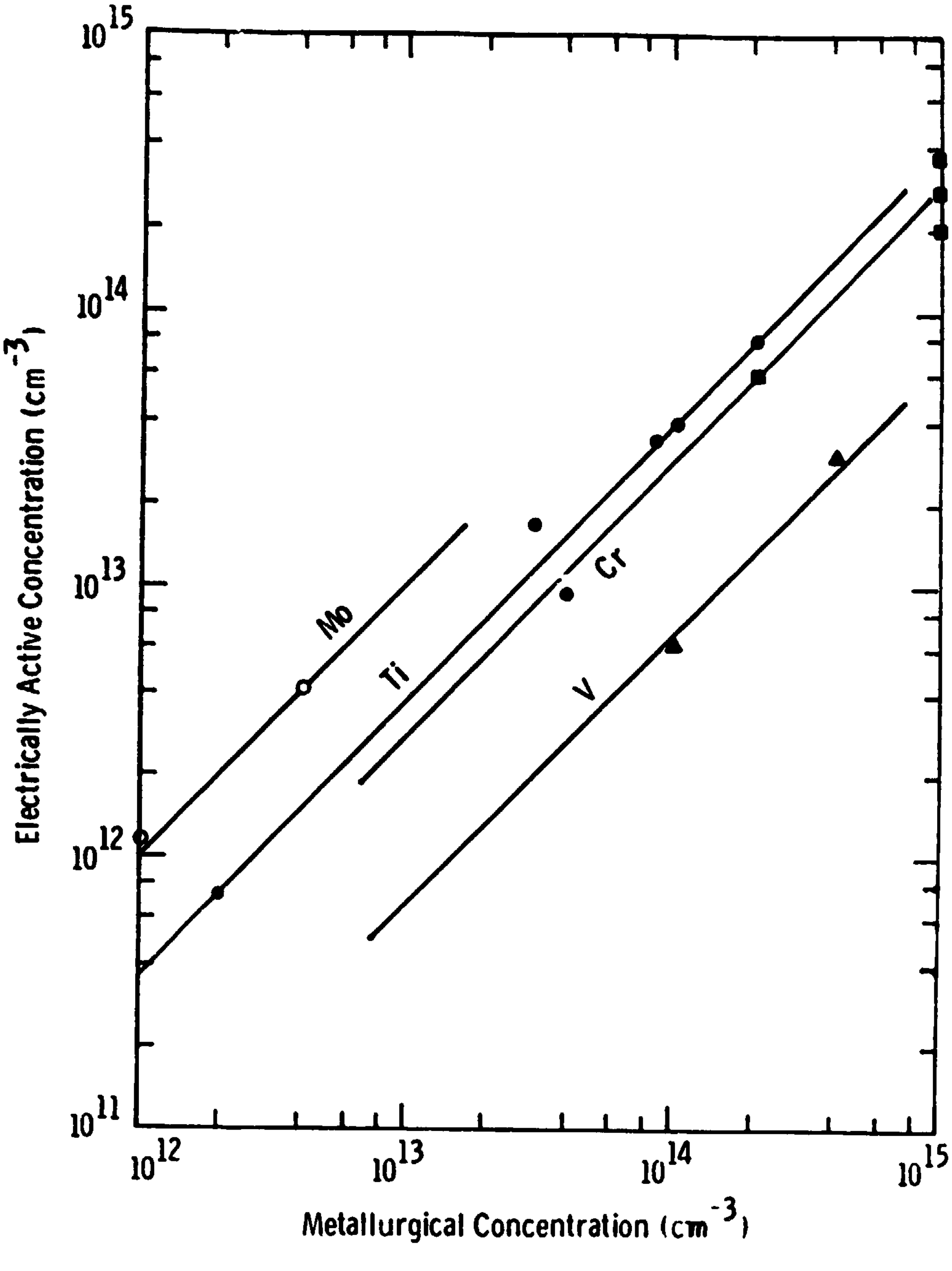


IMPURITY CONCENTRATION

	Ingot	Ti	V	Cr	Mn
a	W157	$8x10^{13}$	$1.2x10^{14}$	-	-
b	W158	$5x10^{13}$	$5x10^{13}$	$5.5x10^{14}$	-
c	W159	$2x10^{13}$	$2x10^{13}$	$3.5x10^{14}$	$3.2x10^{14}$
d	W177	-	-	$1.2x10^{15}$	$1.26x10^{15}$
e	W178	$8x10^{13}$	-	-	$8.6x10^{14}$



168 0.2 ohm-cm, P
169 0.2 ohm-cm, P
107 FZ, Al
148 N-Base, Mn
041 (Cu, Ni), Cr
040 (Ni), Cr
027 (Cu), Mn
102 Poly, Ti
111 Cu, V
103 0.2 ohm-cm, Ti
051 (Cu), Ti
152 30 ohm-cm, Ti
161 30 ohm-cm, Ti
104 (Cu), Ti
100 (Cu), Ti
141 (Cu), Mo
047 (Cu, Ni), Zr
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
Degradation Threshold Concentration N_{ox}, Determined From Experimental Data
Degradation Threshold Concentration, N_{ox}, Projected From 4 ohm-cm P-Base Data

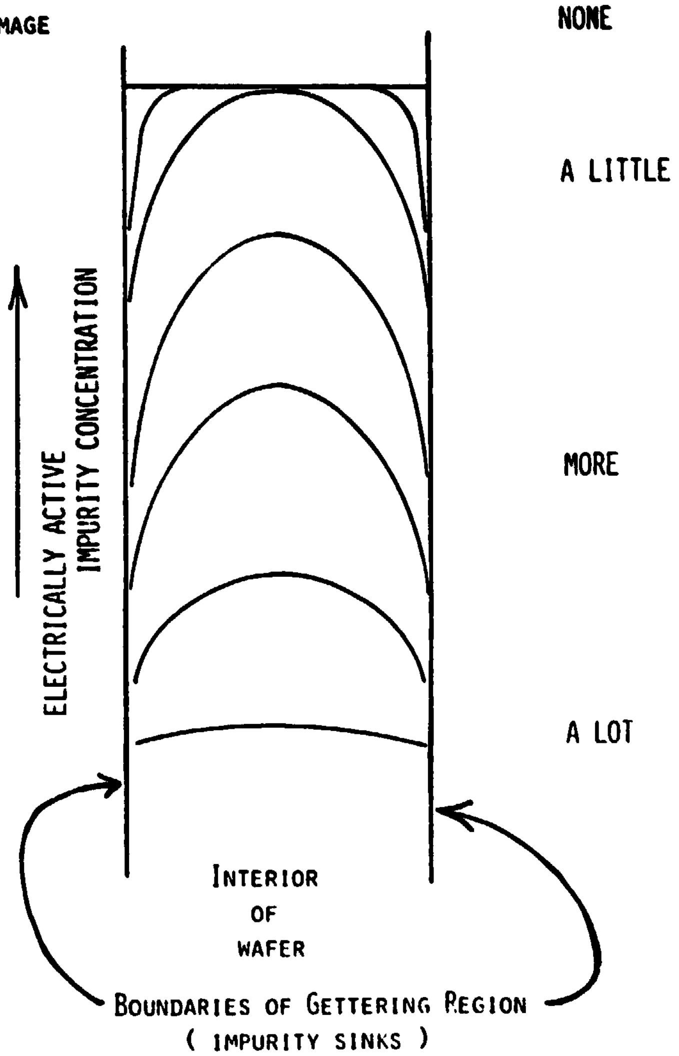


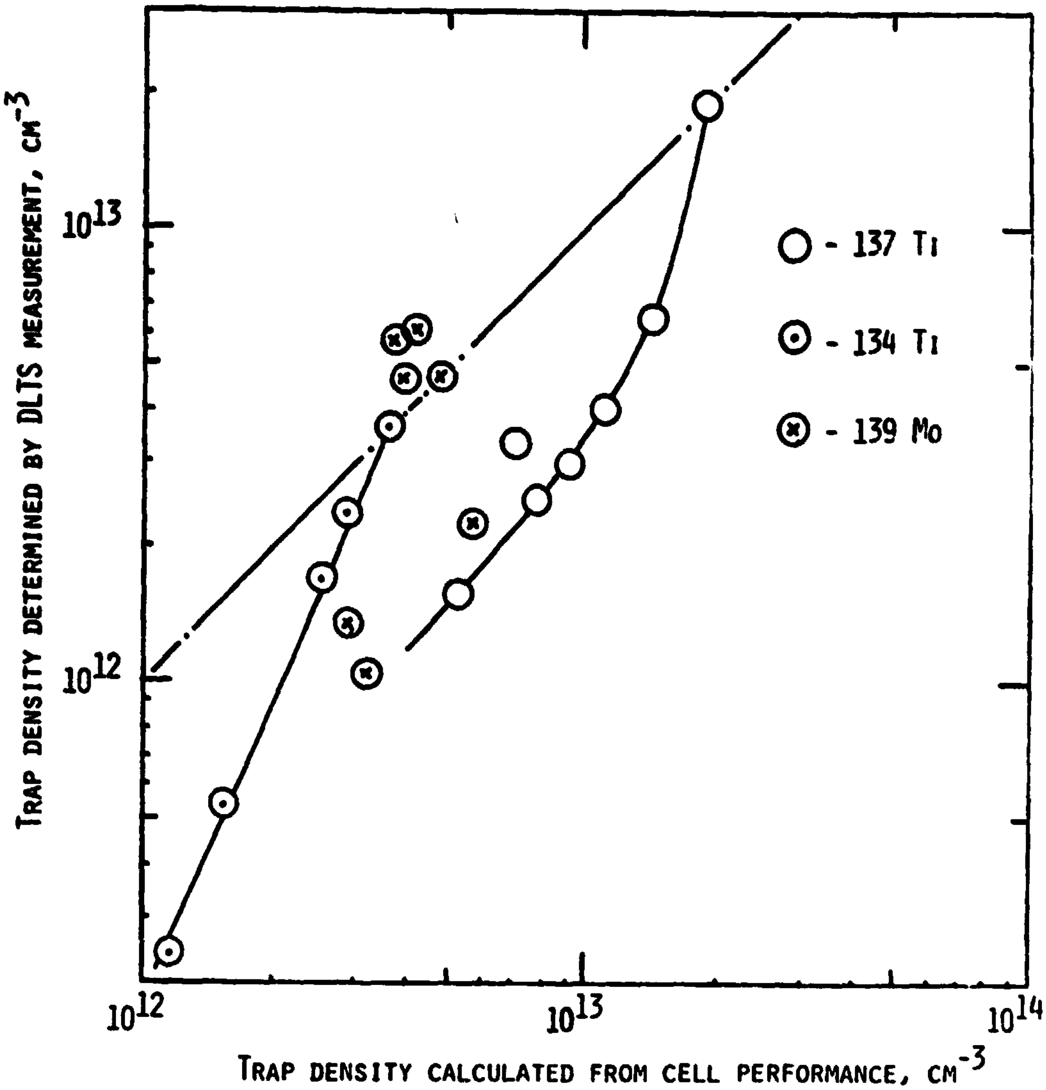
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
Electrically Active Concentration (cm^{-3})
Mo
Ti
Cr
V
10^{12}
10^{13}
10^{14}
10^{15}
Metallurgical Concentration (cm^{-3})

GETTERING

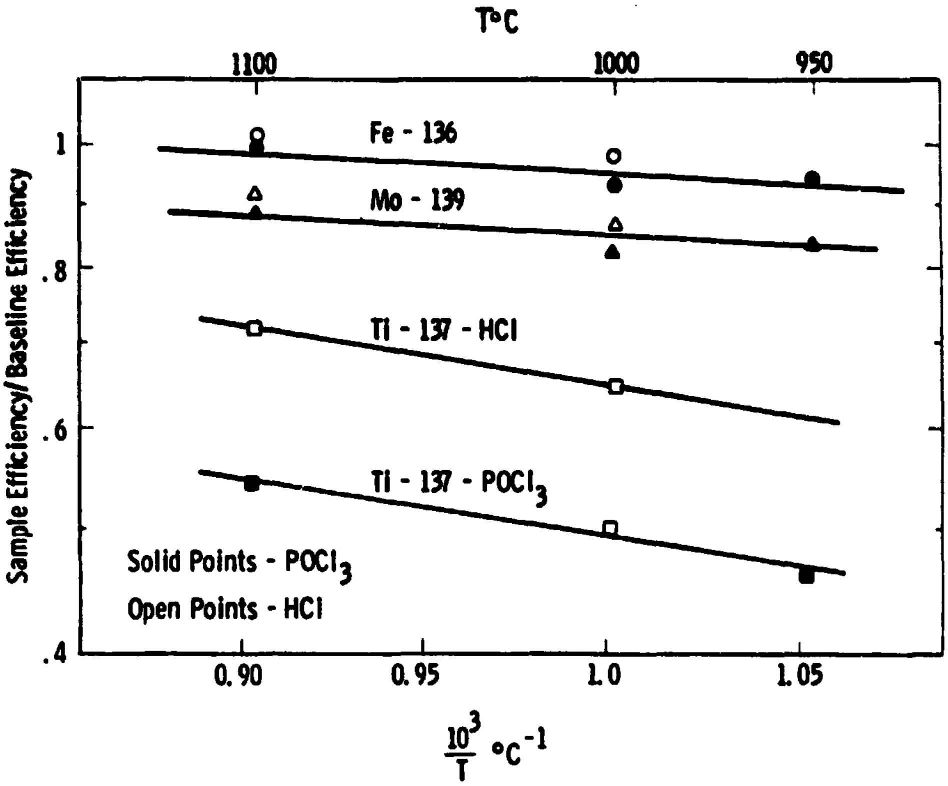
GETTERING

- + PHOSPHORUS
- + HCL
- + DAMAGE

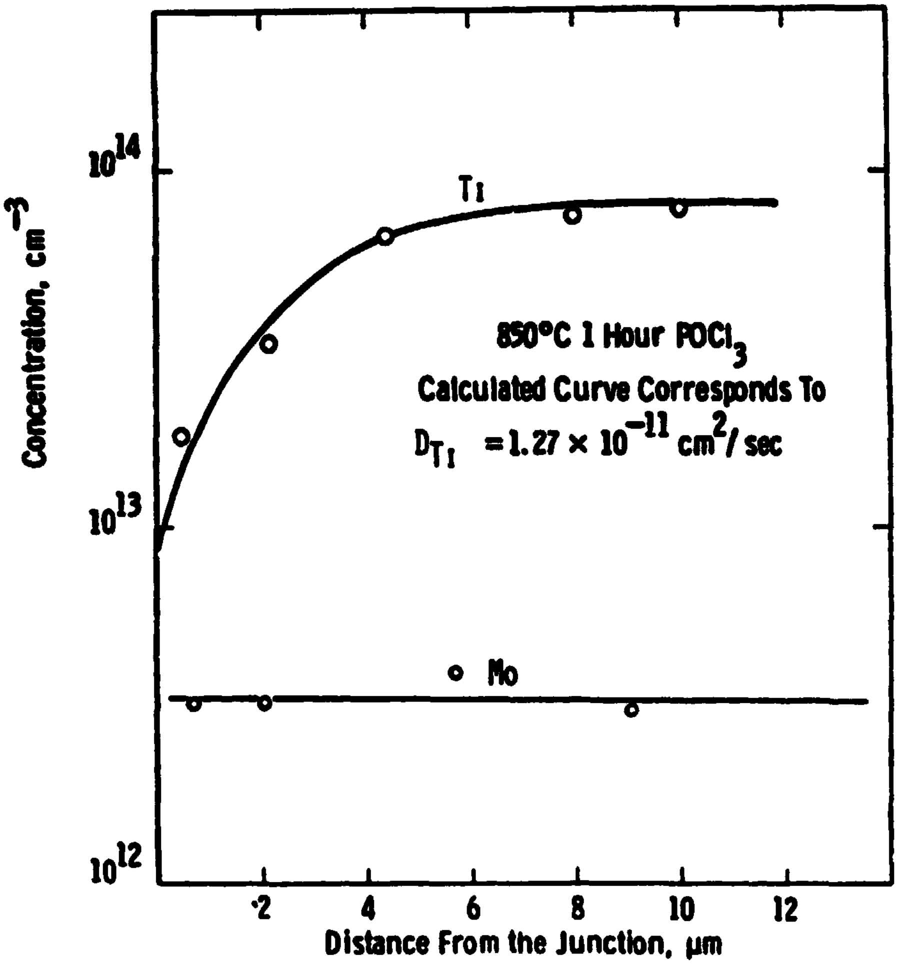




TRAP DENSITY DETERMINED BY DLTS MEASUREMENT, CM-3
10^13
10^12
O - 137 Ti
⊙ - 134 Ti
⊗ - 139 Mo
10^12
10^13
10^14
TRAP DENSITY CALCULATED FROM CELL PERFORMANCE, CM-3


T°C
1100
1000
950
Fe - 136
Mo - 139
Ti - 137 - HCl
Ti - 137 - POCl3
Solid Points - POCl3
Open Points - HCl
Sample Efficiency/Baseline Efficiency
1
.8
.6
.4
0.90
0.95
1.0
1.05
10^3/T °C^-1

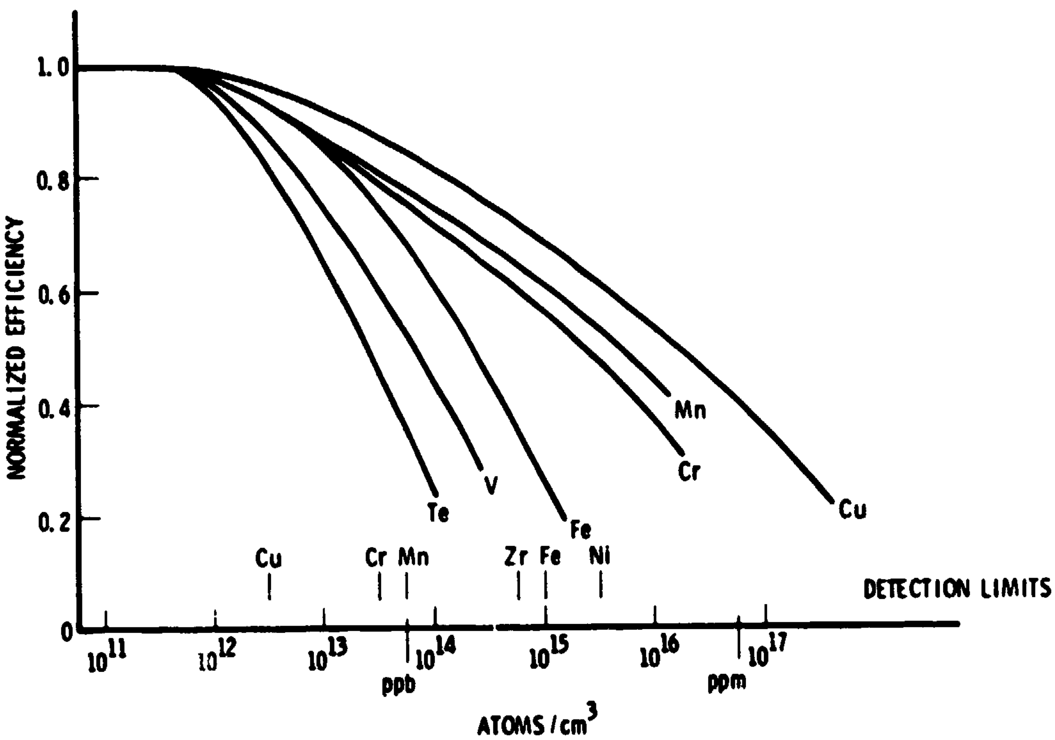
PROFILES FOR Mo AND TI AFTER 850° $POCl_3$ GETTERING



MULTIELEMENT DETECTION OF TRACE IMPURITIES IN SILICON BY METASTABLE TRANSFER EMISSION SPECTROMETRY

AEROSPACE CORP.

EFFECT OF IMPURITIES ON SOLAR CELL EFFICIENCY



METASTABLE TRANSFER EMISSION SPECTROMETRY (MTES)

FORMERLY PHOTON CATALYSIS

1. METHOD:

   MEASURES TRACE AMOUNTS OF VARIOUS MOLECULES IN A GAS FLOW

   (10^6 - 10^{12} molecules / cm^3)

   (to 10^4 atoms / cm^3)

2. TECHNIQUE:

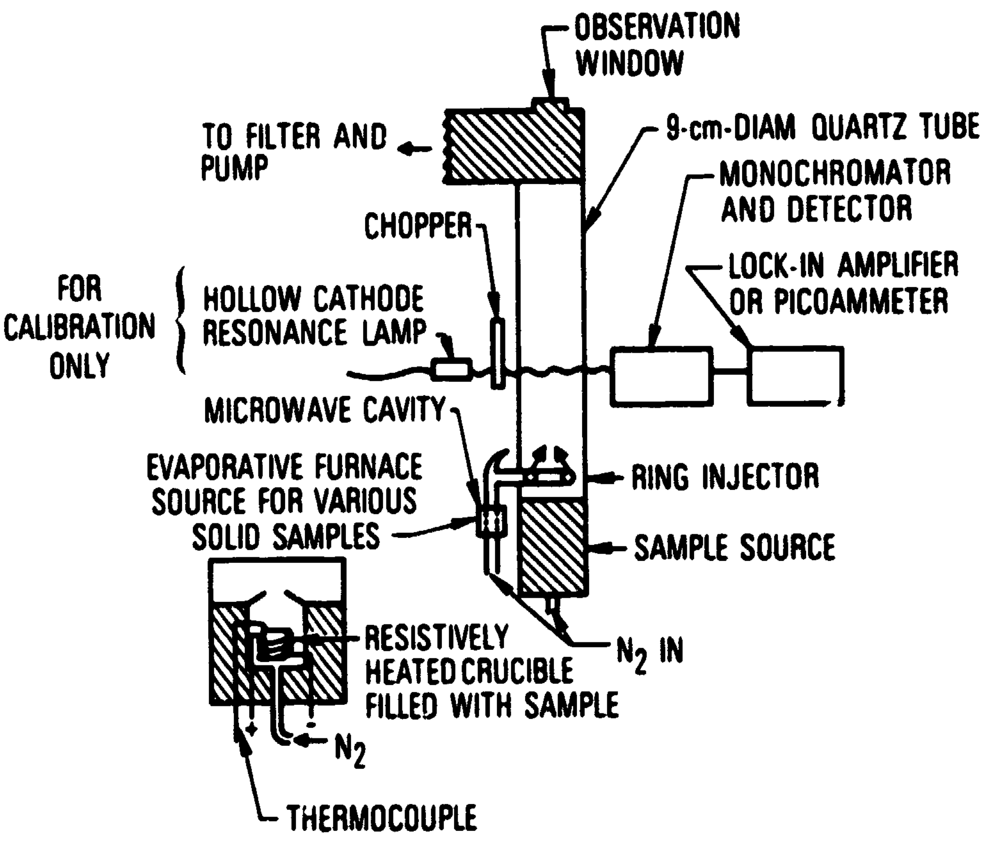
   CREATE GAS FLOW OF ACTIVE NITROGEN

   COMBINE WITH VAPORIZED SAMPLE AND OBSERVE EMISSION

   USE EMISSION INTENSITY AS MEASURE OF CONCENTRATION OF SAMPLE CONSTITUENTS PRESENT

   CALIBRATE FOR QUANTITATIVE MEASUREMENTS

MTES SCHEMATIC



ACTIVE NITROGEN

$N_2 \xrightarrow{\text{ENERGY}} N + N$

$N + N + M \longrightarrow N_2^* + M$

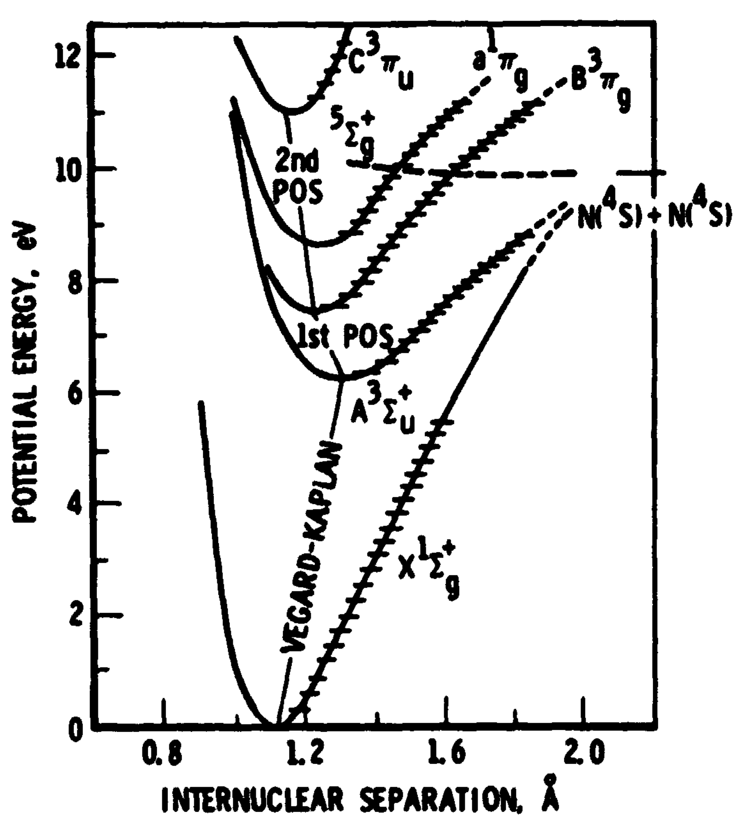
N_2^* IS $N_2\,(A^3\Sigma)$ (electronically excited)

AND/OR $N_2\,(X^1\Sigma,\ v > 0)$ (vibrationally excited)

BOTH N_2 (A) AND N_2 (v) ARE METASTABLE

NEITHER RADIATE

N_2, PARTIAL GILMORE DIAGRAM



MTES KINETICS

$$S + N_2^{*} \xrightarrow{k} S^{*} + N_2$$

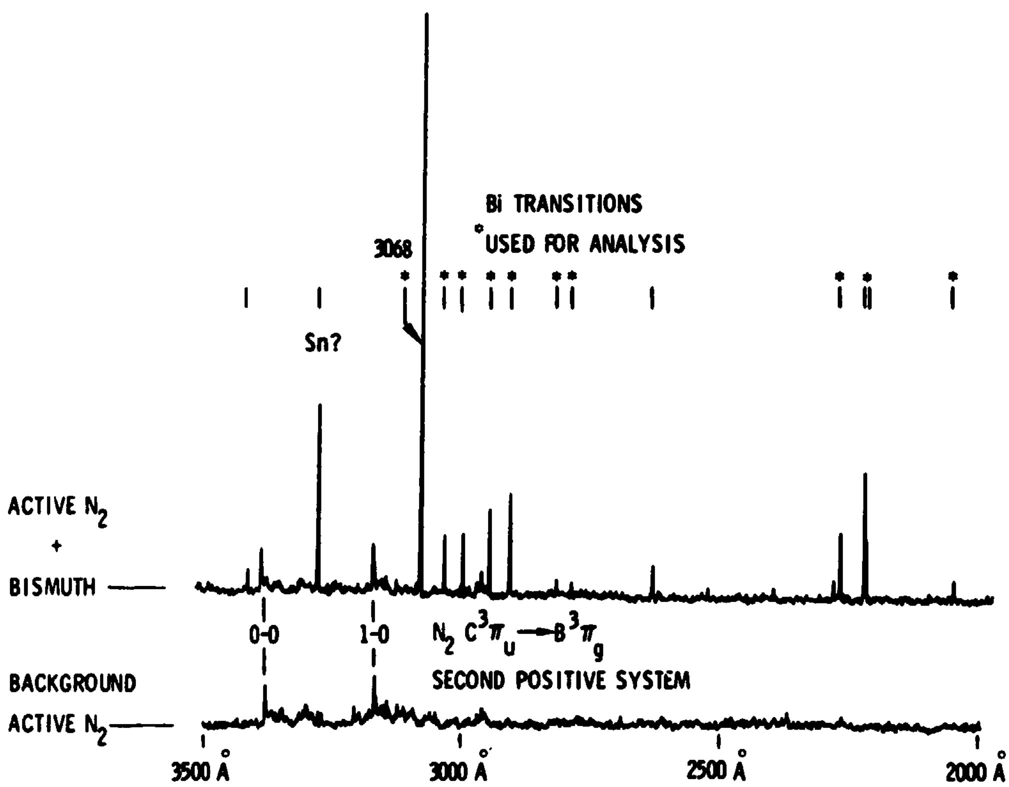
(S = "sample," N_2^{*} = metastable)

$$S^{*} \xrightarrow{1/\tau} S + h\nu$$

$$I = \underbrace{K[N_2^{*}]}_{\text{CONSTANT}}[S]$$

(if N_2^{*} in large excess, intensity proportional to [S]; calibrate, then measurement of I gives [S])

SPECTRA SHOWING HIGH SIGNAL AND LOW BACKGROUND AVAILABLE WITH ACTIVE NITROGEN EXCITATION



CONTRACT MILESTONES

1. DEMONSTRATE RESPONSE TO APPROPRIATE ELEMENTS

   Al, Cr, Mn, Fe, Ti, V, Mo, W

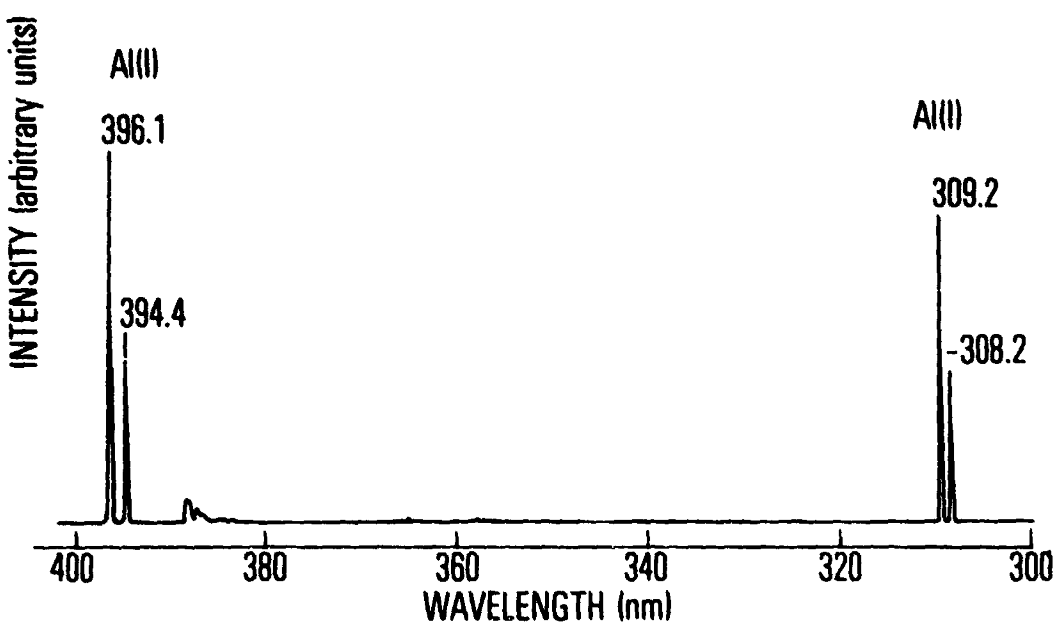
2. PROVE EFFICACY OF EVAPORATION TECHNIQUE

   CONGRUENT EVAPORATION

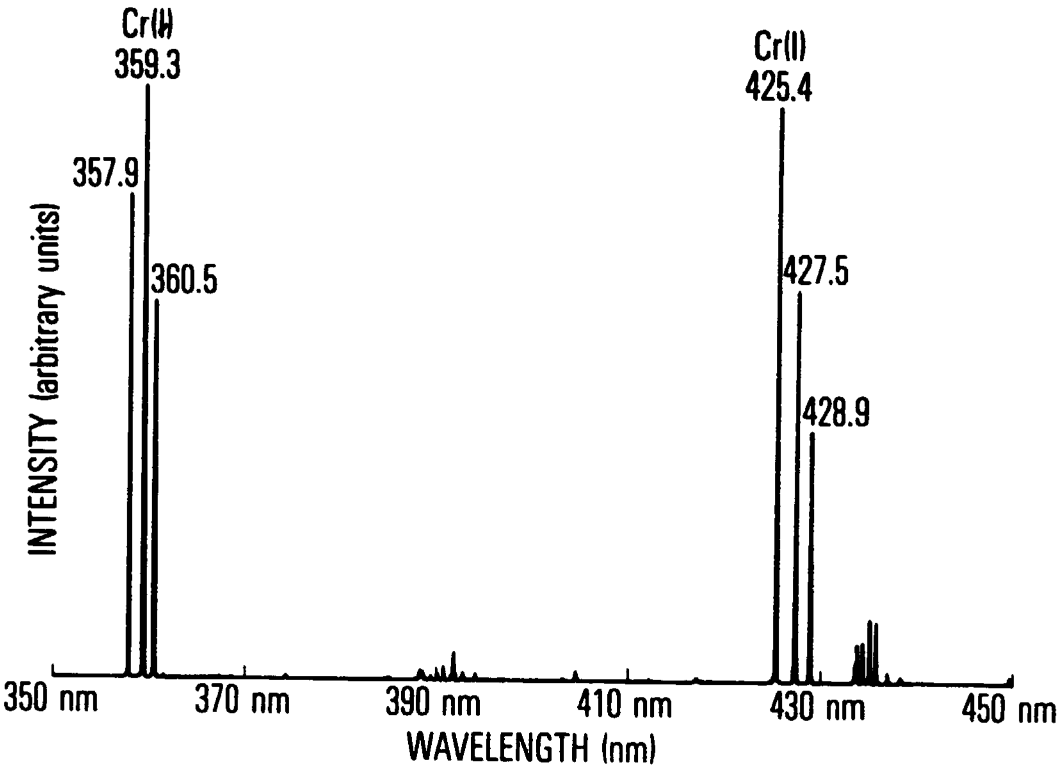
   NO BACKGROUND CONTAMINATION

3. DETECT IMPURITIES IN SILICON AT 10 ppb

ALUMINUM MTES SPECTRUM



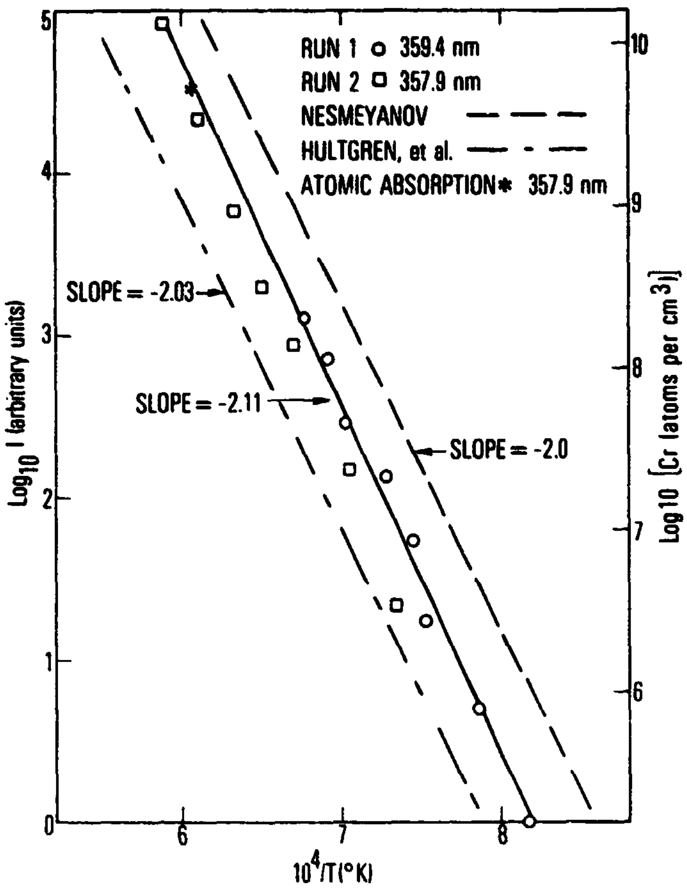
CHROMIUM MTES SPECTRUM

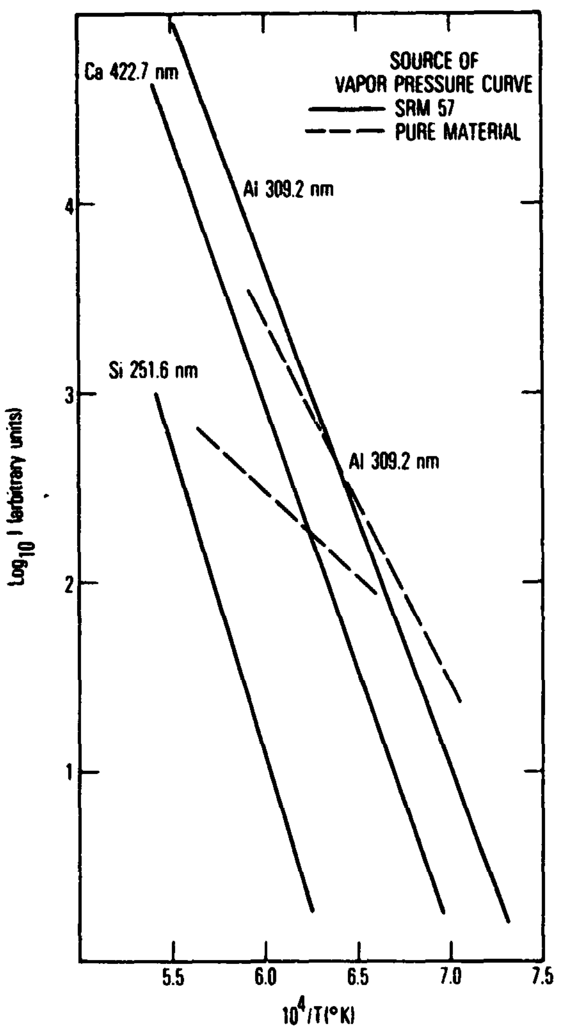


SUMMARY OF FIRST-QUARTER RESULTS

ELEMENT	Al	Cr	Fe	Mn
BEST MTES LINES (nm)	309.2, 396.1	359.4	344.1	279.5
ANCILLARY LINES (nm)	308.2, 394.4	347.9, 425.4	358.1, 372.0	403.1
GAS PHASE SENSITIVITY (cm^{-3})	3×10^5	2×10^5	10^7	5×10^4
PROJECTED SOLID PHASE SENSITIVITY IN Si MATRIX (ppb)	30	20	1000	5

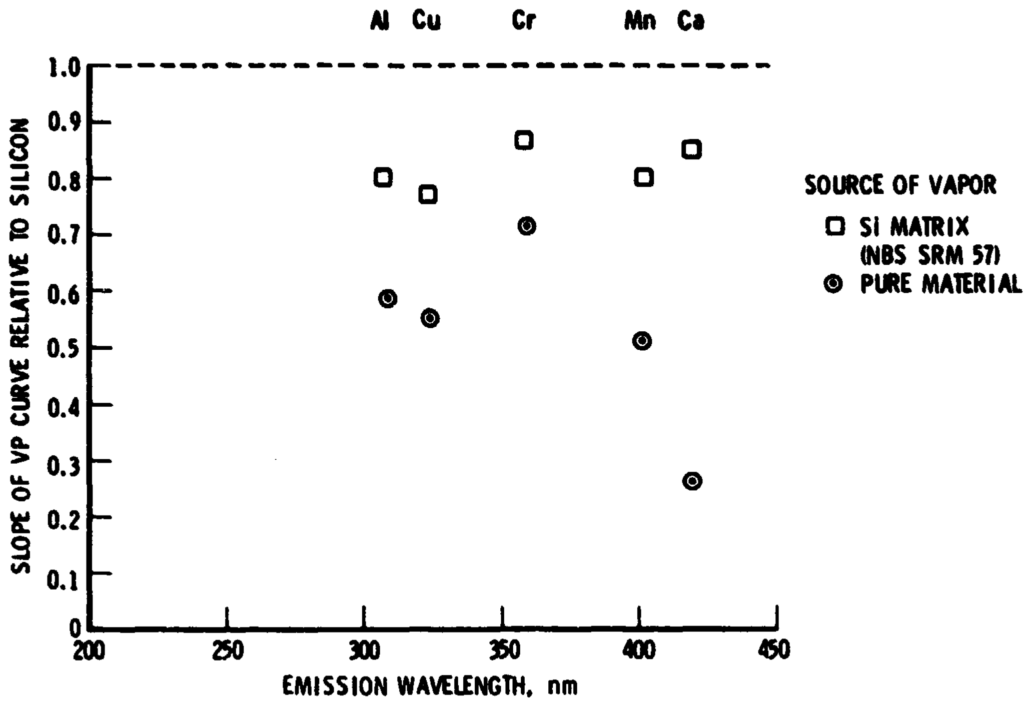
CHROMIUM MTES VAPOR PRESSURE CURVE

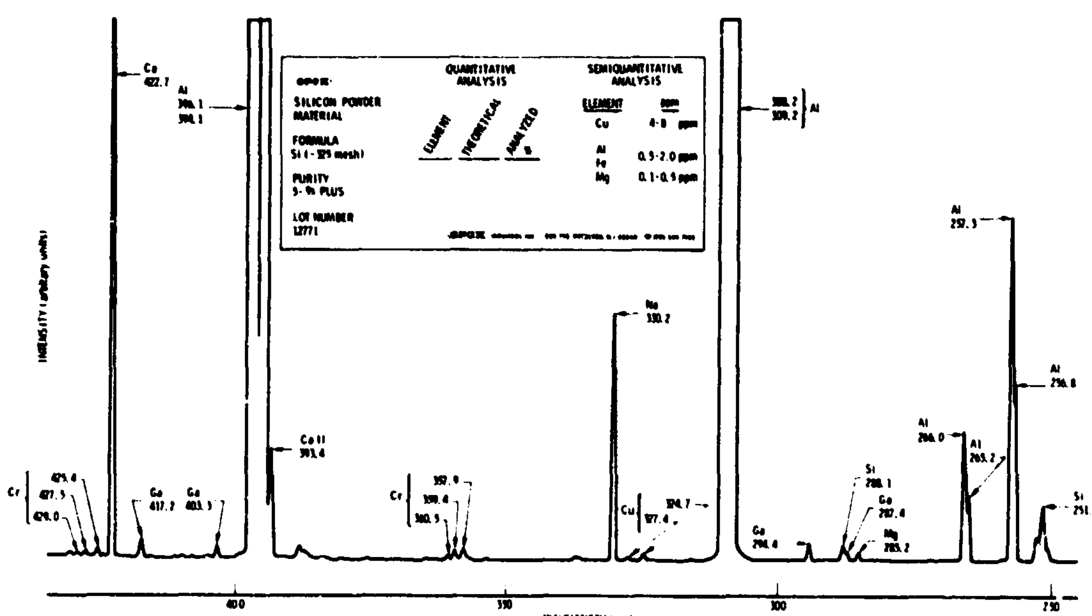




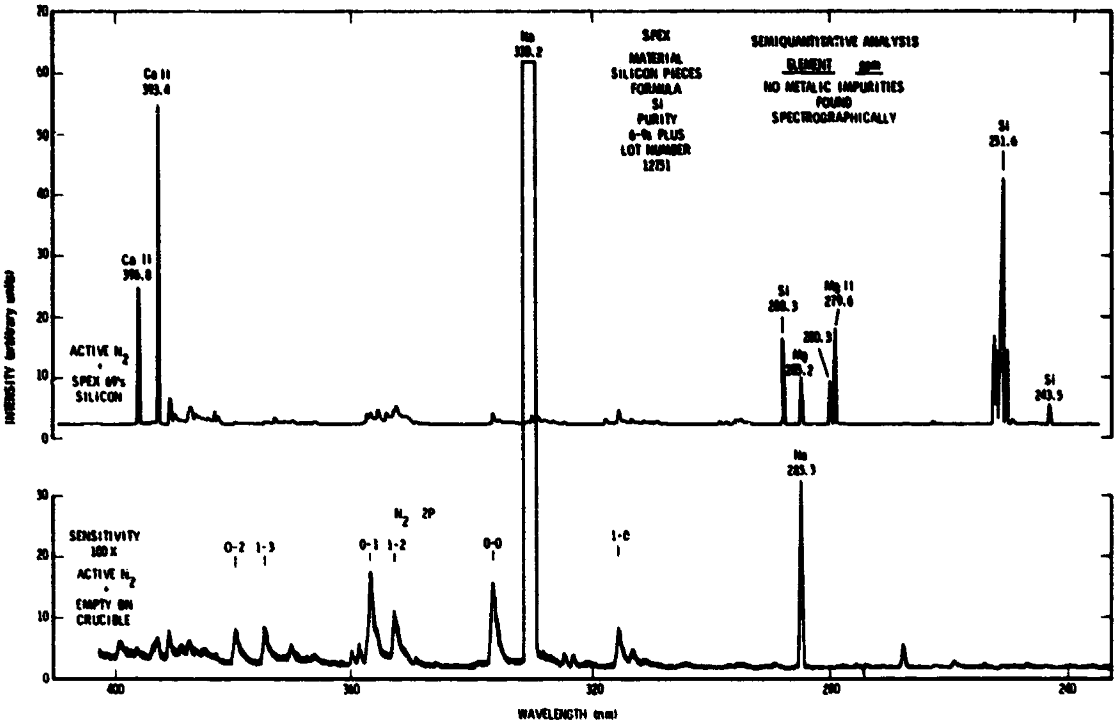
VAPOR PRESSURE CURVES OF IMPURITIES IN SILICON

EVIDENCE FOR CONGRUENT EVAPORATION OF SI

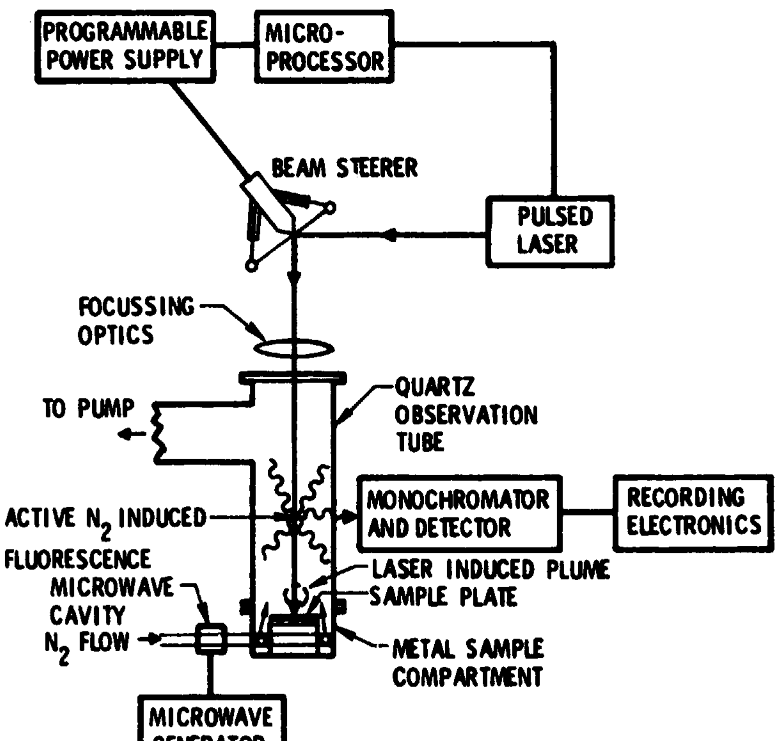




MTES SPECTRUM OF 6—9's SILICON



ACTIVE NITROGEN LASER MICROPROBE



b. Large-Area Silicon Sheet Task

TECHNOLOGY SESSION

INGOT TECHNOLOGY

- HAMCO HAS ACHIEVED 13 CM DIAMETER, 108 KG CZO INGOT GROWTH
  (PRESENT GOAL: 100 KG
  TR'82 REQUIREMENT: 150 KG)
- SILTEC HAS DEMONSTRATED 15 CM DIAMETER CZO INGOT GROWTH FROM CLF FURNACE
  (TR REQUIREMENT: 150 KG)
- CSI HAS CAST INGOTS UP TO 15 x 15 x 15 CM BY THE HEAT EXCHANGER METHOD
  (TR REQUIREMENT: 30 x 30 x 30 CM)
- SILTEC HAS CUT 10 CM DIAMETER INGOT AT 22 WAFERS/CM AND 15 CM DIA. INGOT AT 15 WAFERS/CM
  (TR REQUIREMENTS: 15 CM DIA; 25 WAFERS/CM)
- CSI HAS DEMONSTRATED MULTI-WIRE SAWING OF 10 CM DIA. INGOT AT AN EQUIVALENT RATE OF 1.4 WAFERS/MIN EXCEEDING THE TR REQUIREMENTS OF 1 WAFER/MIN.

SHAPED-SHEET TECHNOLOGY

- MTSEC HAS DEMONSTRATED LONG TERM (15 HRS) OPERATION OF THE 5 RIBBON EFG SYSTEM, 10 CM WIDE RIBBONS AND 11% AM1 CELL EFFICIENCIES (TR REQUIREMENTS: 10 RIBBON SYSTEM, 10 CM WIDE RIBBONS, 12% AM1)
- MTSEC HAS SHOWN A POTENTIAL BREAKTHROUGH IN RIBBON STRUCTURE (LARGER GRAIN SIZE, 1 x 10 CM).
- WESTINGHOUSE HAS DEMONSTRATED 27.1 CM^2/MIN WEB RIBBON THROUGHPUT (TR REQUIREMENTS = 25 CM^2/MIN).
- WESTINGHOUSE HAS ACHIEVED 12% AM1 CELL EFFICIENCY ON WEB RIBBON GROWN FROM TASK I BATTELLE SILICON MATERIAL
- HONEYWELL HAS DEMONSTRATED SOC COATING ON 5 CM x 40 CM SUBSTRATE BY THE SCIM TECHNIQUE.

CONTINUOUS CZ INGOT GROWTH

HAMCO DIVISION OF KAYEX CORP.

APPROACH

- PERIODIC MELT REPLENISHMENT BETWEEN SUCCESSIVE INGOT GROWTH CYCLES USING ROD OR LUMP POLYSILICON.
- 100 KILOGRAMS FROM ONE CRUCIBLE

SOLAR CELL EVALUATION ON RUN NO. 30

EFFICIENCY IN AM-1

	1	2	3	4	5	6
TOP	15.9		15.5	15.8	15.5	14.8
	(SINGLE)		(SINGLE)	(SINGLE)	(SINGLE)	(SINGLE)
MIDDLE	16.1	11.3 10.9		10.8 12.2		10.3
	(SINGLE)	(POLY)		(POLY)		(POLY)
BOTTOM	11.7	12.2	11.5	12.0	10.9	12.6
	(DISLOCATED CELL QUALITY QUESTIONABLE)	(POLY)	(POLY)	(POLY)	(POLY)	(POLY) (1.9 - 3.1 OHM-CM)

CONTROL 14.7 14.8 14.8 (7 - 14 OHM-CM)

MEASUREMENTS TAKEN AT AM-0 AND CONVERTED TO AM-1.

COST UPDATE FOR CZ NO. 2*

OPERATION		PROJECTED TIME (HR)	ACTUAL TIME (RUN #49) (HR)	UPDATED PROJECTION (HR)
MELT DOWN		4	2	2
SEED AND CROWN GROWTH		10.6	23	10.2
		(4 INGOTS)	(9 INGOTS)	(4 INGOTS)
STRAIGHT GROWTH		30.4	50	30.4
		(10 CM/HR)	(6.8 CM/HR)	(10 CM/HR)
RECHARGE		12.5	11	11
		(3 TIMES)	(5 TIMES)	(3 TIMES)
		57.5	86	53.6
ADD-ON CZ	1975 $	17.91	22.16	16.47
COST	(1980 $)	(25.07)	(31.0)	(23.06)

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

NET TIME CYCLES OF RUN 49

OPERATION	TIME (HOURS)	COMMENTS
GROWING PREPARATION	23	9 CRYSTALS
1. STABILIZING TEMP.		
2. GROWING SEED		
3. CROWN GROWTH		
INGOT GROWING (STRAIGHT SECTION)	50	2.12 KG/HR
RECHARGE CYCLE (LUMP ONLY)	13	8.3 KG/HR AVERAGE
1. REMOVAL OF CRYSTAL		ACTUAL MELTBACK
2. LOAD HOPPER		EXCEEDED 11 KG/HR
3. HOT FILL		7 RECHARGE
4. MELT DOWN		CYCLES
TOTAL TIME	86	

SUMMARY OF RUN NO. 49

CRYSTAL INGOT DIAMETER	13.3 CM
INITIAL MELT CHARGE	30 KG
CRUCIBLE DIAMETER	35.5 CM
TOTAL CRYSTAL PULLED	108 KG 95%
TOTAL SINGLE CRYSTAL	92.3 KG 84%
NUMBER OF INGOTS	9
THROUGHPUT	1.25 KG/HR
TOTAL RUN TIME	86 HOURS
RECHARGE MATERIAL	100% LUMP

SUMMARY OF THREE LONG RUNS

RUN NO.	TOTAL PULLED (KG)	% SINGLE CRYSTAL
30	99.1	27
47	60.2	88 - CRUCIBLE FAILURE
49	108.0	84

STATUS OF CONTINUOUS CZ INGOT GROWTH

PHASE I RESULTS
- 100 KG FROM ONE CRUCIBLE DEMONSTRATED
- >14% EFFICIENCY (AM-1) ACHIEVED
- MELT REPLENISHMENT (ROD OR LUMP) DEMONSTRATED

PROBLEMS
- QUALITY OF CRYSTAL STRUCTURE

PHASE II GOALS
- IMPROVE QUALITY OF GROWN INGOT
- PERFORM SIX 100 KG RUNS
- REDUCE PROCEDURES FOR CONTINUOUS CZ GROWTH TO ROUTINE TECHNOLOGY
- MAINTAIN GOOD EFFICIENCY AND LOW COST

SUMMARY AND CONCLUSIONS

1. 100 KILOGRAMS CAN BE PULLED OUT OF ONE CRUCIBLE WITH ACCEPTABLE YIELDS.
2. SOLAR CELL EFFICIENCY DOES NOT APPEAR TO DETERIORATE THROUGH THE RUN.
3. LUMP RECHARGING IS PREFERABLE TO ROD.
4. IN ORDER TO FURTHER REDUCE COST, PULL SPEEDS MUST IMPROVE, SINCE THIS REPRESENTED 60% OF THE CYCLE TIME.

ADVANCED CZ

NEAR-TERM COST REDUCTION

HAMCO DIVISION OF KAYEX CORP.

PROGRAM INTRODUCTION

THE PROGRAM REQUIRES PROCESS IMPROVEMENT CONCEPTS AIMED AT:

1. LOWERING THE COSTS OF THE MELT-DOWN AND GROWTH PROCESSES.
2. REDUCING LABOR COSTS AND IMPROVING YIELDS BY PROCESS AUTOMATION.

A COMBINATION OF THE ABOVE WILL REDUCE THE CONTINUOUS CZ ADD-ON COSTS BY AN ESTIMATED 34%.

PROGRAM DISCUSSION

THE PROCESS GOALS ARE AS FOLLOWS:

1. DEMONSTRATE THE GROWTH OF 150 KILOGRAMS OF 6" DIAMETER, SINGLE CRYSTAL SILICON FROM ONE CRUCIBLE.
2. MODIFY A CG 2000 HAMCO CRYSTAL PULLER TO ALLOW PERIODIC MELT REPLENISHMENT OF EITHER 5" DIAMETER POLYCRYSTALLINE SILICON RODS OR POLYCRYSTALLINE SILICON CHUNK.
3. DEMONSTRATE A GROWTH RATE OF 15+ CMS/HR FOR 6" GROWTH, UTILIZING A HEAT SINK ARRANGEMENT TO REMOVE ENERGY RELEASED BY HEAT OF FUSION.
4. INSTALL A MICROPROCESSOR CONTROL SYSTEM TO AUTOMATE THE GROWTH CYCLE.

EQUIPMENT DESIGN AND MODIFICATION STATUS

	GOAL	STATUS
1.	CONCEPTUAL DESIGN APPROVAL	COMPLETE 5/29/79
2.	H.F. COIL AND HEAT SINK DESIGN	COMPLETE 5/28/79
3.	MODIFIED GROWTH CHAMBER DESIGN	COMPLETE 7/5/79
4.	COLD CRUCIBLE PREMELTER DESIGN	ONGOING
5.	MICROPROCESSOR CONTROLS	ONGOING

EQUIPMENT DESIGN ANALYSIS

1. H.F. COIL AND HEAT SINK

GOAL	STATUS	COMPLETION DATE
PURCHASE R.F. HEATING GENERATOR	COMPLETE	7/26/79
DESIGN R.F. FEED-THRU AND VACUUM SEAL	COMPLETE	7/10/79
DESIGN R.F. WORK COIL/ HEAT SINK	COMPLETE	5/28/79
SUB-CONTRACT DELIVERY OF WORK COIL/HEAT SINK	COMPLETE	8/17/79
SUB-CONTRACT DELIVERY OF FEED-THRU AND SEAL SYSTEM	ONGOING	9/1/79

2. MODIFIED GROWTH CHAMBER

GOAL	STATUS	COMPLETION DATE
TANK COVER ASSEMBLY MODIFICATION DESIGN	COMPLETE	7/5/79
SUB-CONTRACT DELIVERY OF MODIFIED TANK COVER	ONGOING	9/7/79
RE-DESIGN OF POLY ROD RECHARGE MECHANISM	COMPLETE	7/26/79
SUB-CONTRACT DELIVERY OF RECHARGE MECHANISM	ONGOING	10/1/79

3. COLD CRUCIBLE SILICON PREMELTER

GOAL	STATUS	COMPLETION DATE
CONCEPTUAL DESIGN	COMPLETE	5/28/79
COLD CRUCIBLE DESIGN AND SUB-CONTRACTOR DISCUSSION	ONGOING	9/7/79
ANCILLARY EQUIPMENT DESIGN	ONGOING	10/12/79
R.F. MULTI-TURN WORK COIL FABRICATION	ONGOING	11/30/79
R.F. FEED-THRU AND VACUUM SEAL SYSTEM	ONGOING	11/30/79

4. MICROPROCESSOR CONTROLS

THE MICROPROCESSOR SYSTEM HAS BEEN PURCHASED AND WILL BE INTERFACED WITH A CONTRACTOR OWNED HAMCO CG 2000 RC CRYSTAL PULLER.

THE MICROPROCESSOR SYSTEM IS CURRENTLY UNDERGOING PROGRAM AND SOFTWARE EVALUATION UNDER LABORATORY CONDITIONS.

ALL INTERFACE CIRCUITS HAVE BEEN RECEIVED.

CONCEPTUAL DESIGN CONSIDERATIONS

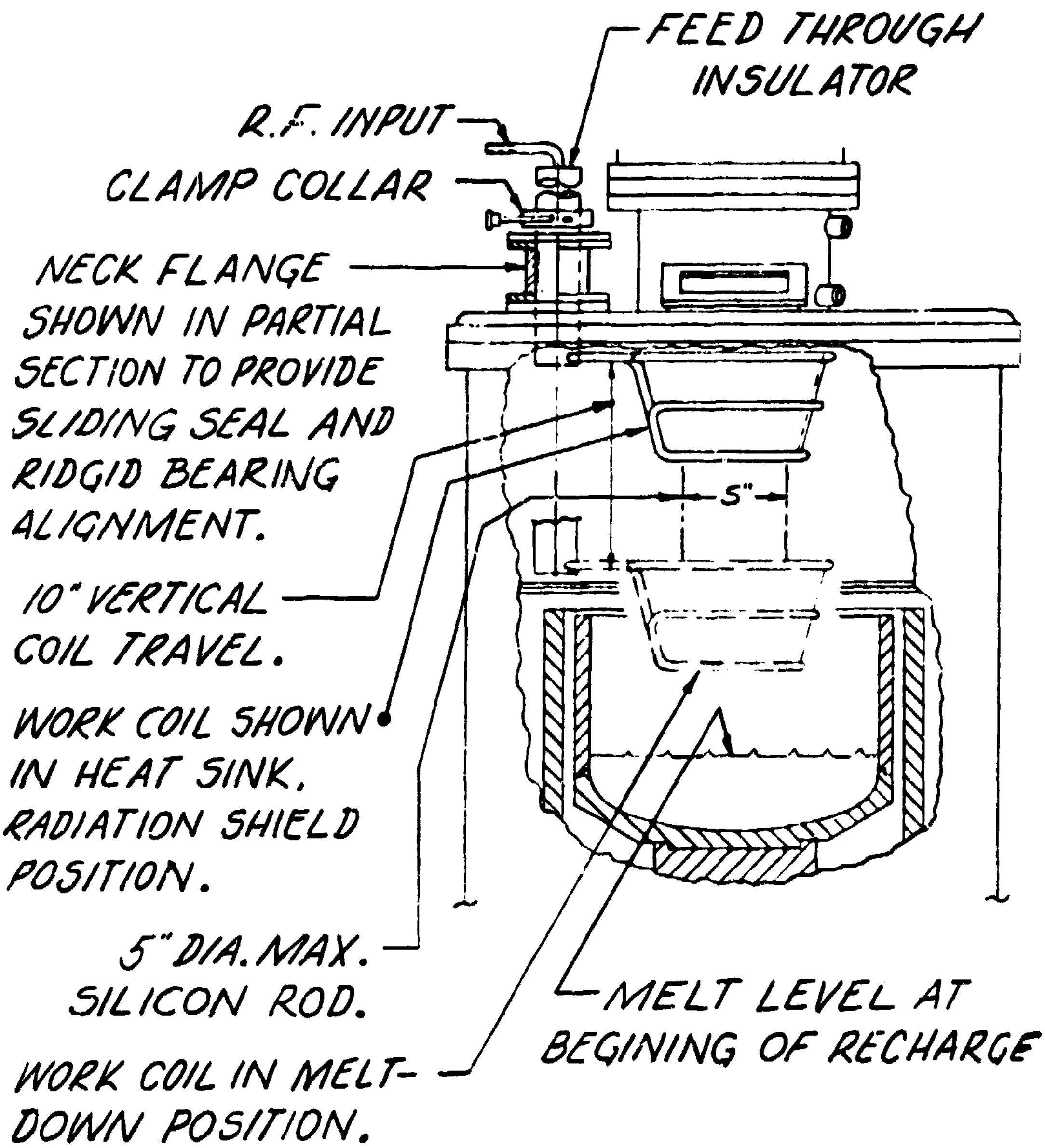
ACCELERATED MELT AND GROWTH PROGRAMS

1. R.F. WORK COIL WATER LEAKAGE - LOW VOLTAGE SINGLE BAND WORK COIL WILL BE UTILIZED. THICK WALL MACHINED COPPER CONSTRUCTION WILL ELIMINATE LEAKAGE DUE TO ARCING, ETC.
2. CRUCIBLE DEVITRIFICATION - UTILIZE HIGH PURITY HALOGEN TREATED GRAPHITE PIECE-PARTS FOR FURTHER IMPROVEMENT ABOVE ACCELERATED MELT PROGRAM.
3. OXIDE BUILD UP ON WORK COIL - SYSTEM WILL OPERATE UNDER REDUCED PRESSURE. ARGON FLOW PATTERN MAY REQUIRE RE-DESIGN. MELT/COIL POSITION CAN BE VARIED THRU VERTICAL PLANE.

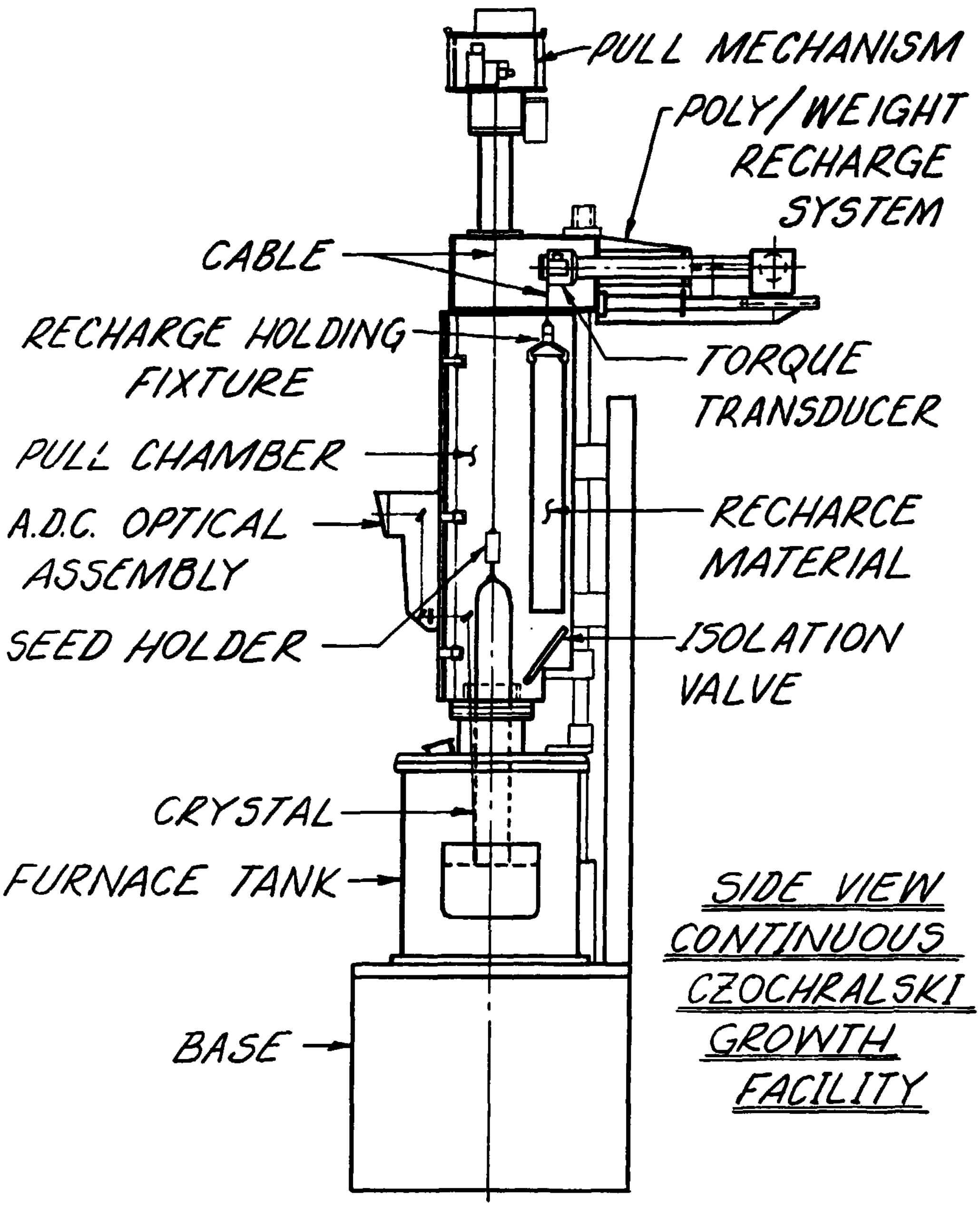
COLD CRUCIBLE PROGRAM

1. MELT TRANSFER - AN EXTENSION OF THE R.F. COIL AROUND THE TRANSFER TUBE WILL PROBABLY BE NECESSARY TO MAINTAIN THE TEMPERATURE OF THE MOLTEN SILICON SUCH THAT IT WILL FLOW INTO THE CRUCIBLE.
2. OXIDE BUILD UP ON TRANSFER TUBE - THE TRANSFER TUBE HAS BEEN DESIGNED WITH A BELLOWS SYSTEM WHICH WILL ALLOW RETRACTION FROM THE CRUCIBLE AREA.

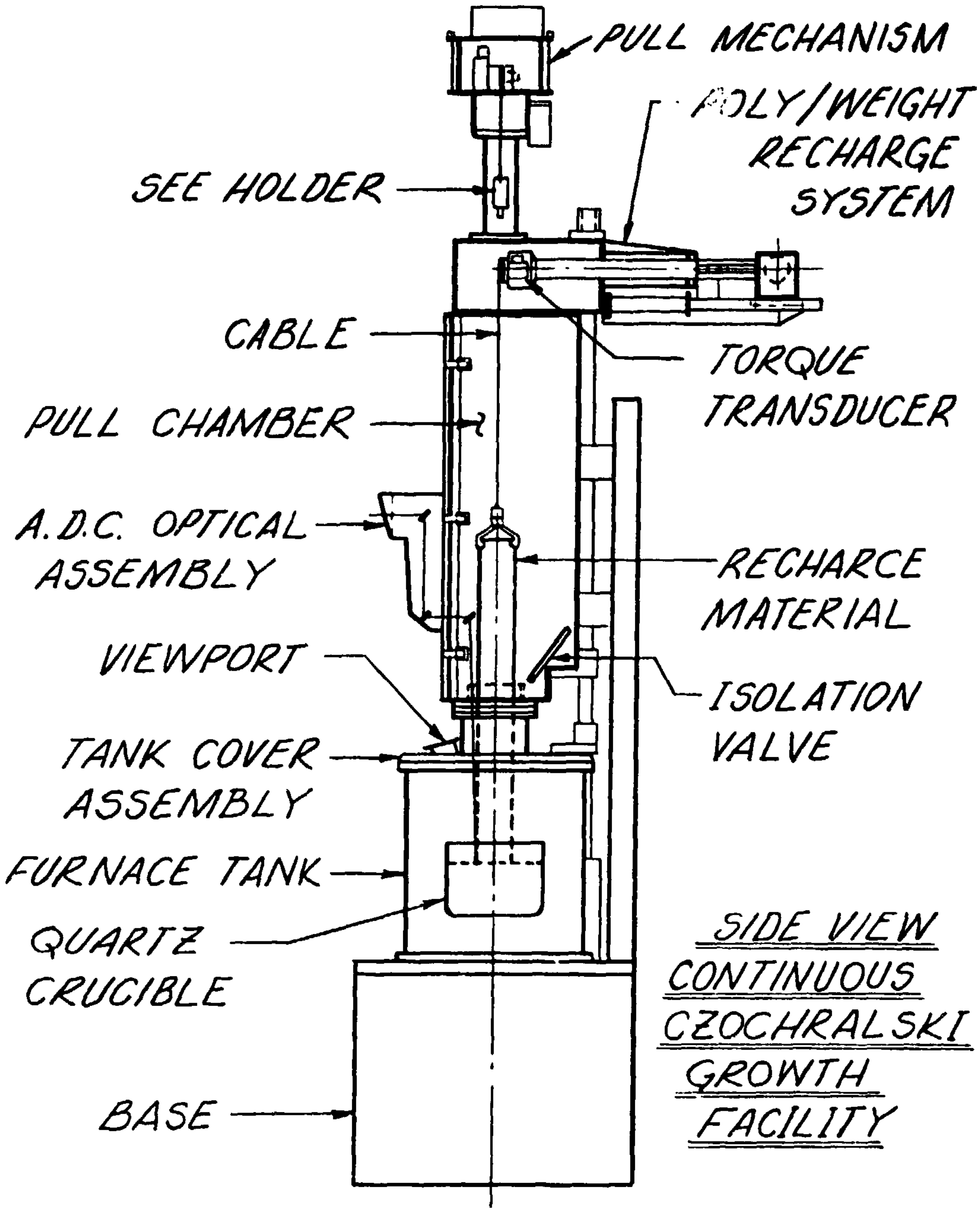
CONCEPTUAL DESIGN SCHEMATIC FOR COLD CRUCIBLE DEVELOPMENT PROGRAM



GROWTH MODE


PULL MECHANISM
POLY/WEIGHT RECHARGE SYSTEM
CABLE
RECHARGE HOLDING FIXTURE
TORQUE TRANSDUCER
PULL CHAMBER
A.D.C. OPTICAL ASSEMBLY
RECHARCE MATERIAL
SEED HOLDER
ISOLATION VALVE
CRYSTAL
FURNACE TANK
BASE
SIDE VIEW CONTINUOUS CZOCHRALSKI GROWTH FACILITY

RECHARGE MODE



SIDE VIEW CONTINUOUS CZOCHRALSKI GROWTH FACILITY

OVERALL PROCESS AND COST ANALYSIS

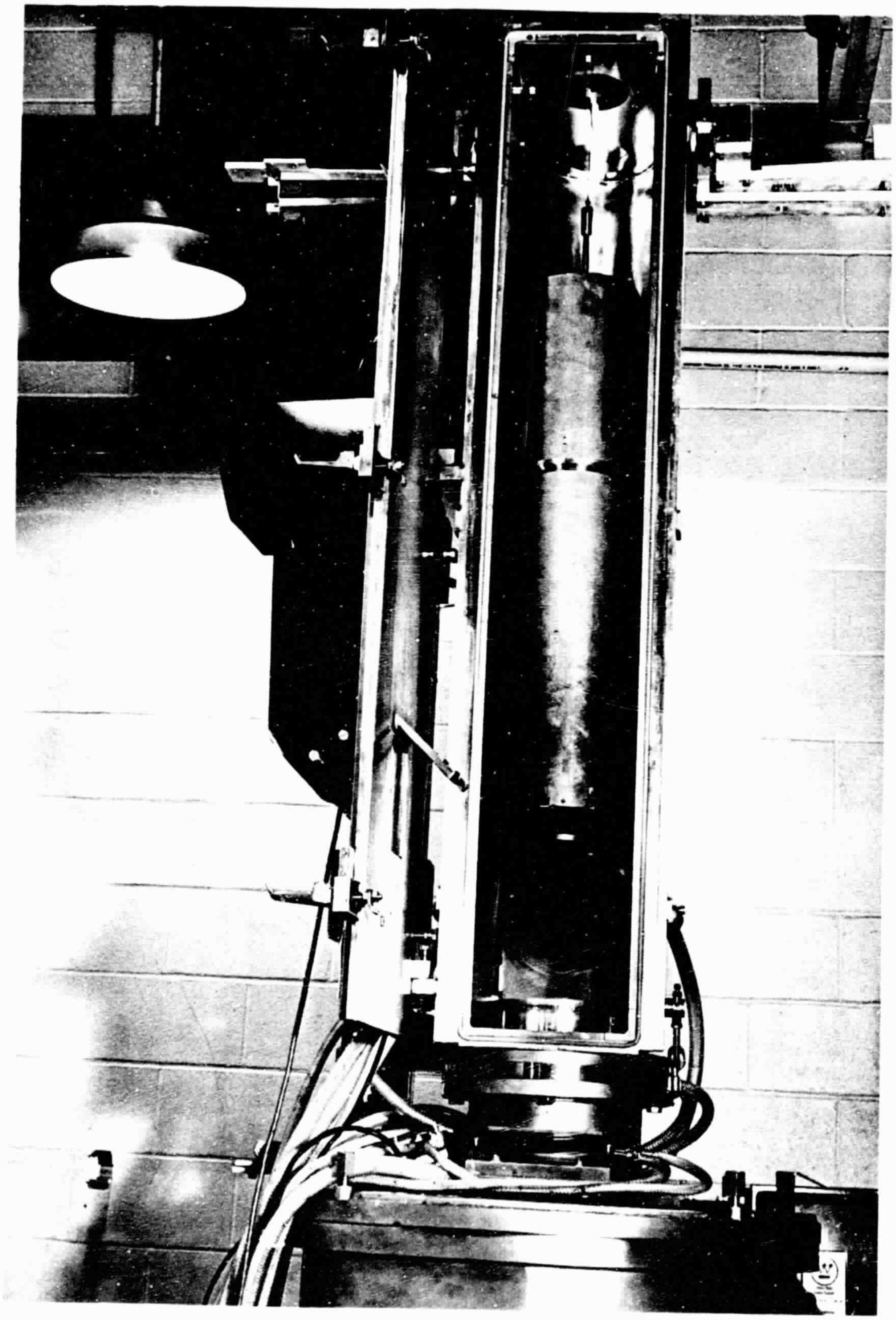
PROGRAM	PROCESS IMPROVEMENT	COST SAVINGS
ACCELERATED MELT	DECREASED CRUCIBLE DEVITRIFICATION INCREASED MELT-BACK, I.E. UP TO 40 KG/HR	$ 0.72/KG
ACCELERATED GROWTH	INCREASE GROWTH RATE FROM 10 CMS/HR TO 15+ CMS/HR	DECREASE ADD-ON COST BY 18%, I.E. $ 2.16/KG
COLD CRUCIBLE	MAINTAIN MELT PURITY LEVEL INTO CRUCIBLE AND PREVENT CRUCIBLE DEVITRIFICATION	
MICROPROCESSOR	REDUCE LABOR COSTS IMPROVE YIELD	DECREASE CZ ADD-ON COSTS BY 10%, I.E. $ 1.2/KG

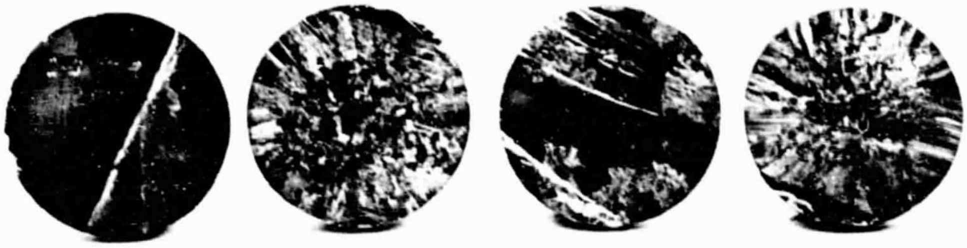
OVERALL: TOTAL COST REDUCTION ESTIMATED AT 34% OF PRESENT CZ

ADD-ON COSTS OF $ 12.00 (1975) / $ 16.80 (1980) PER KILOGRAM

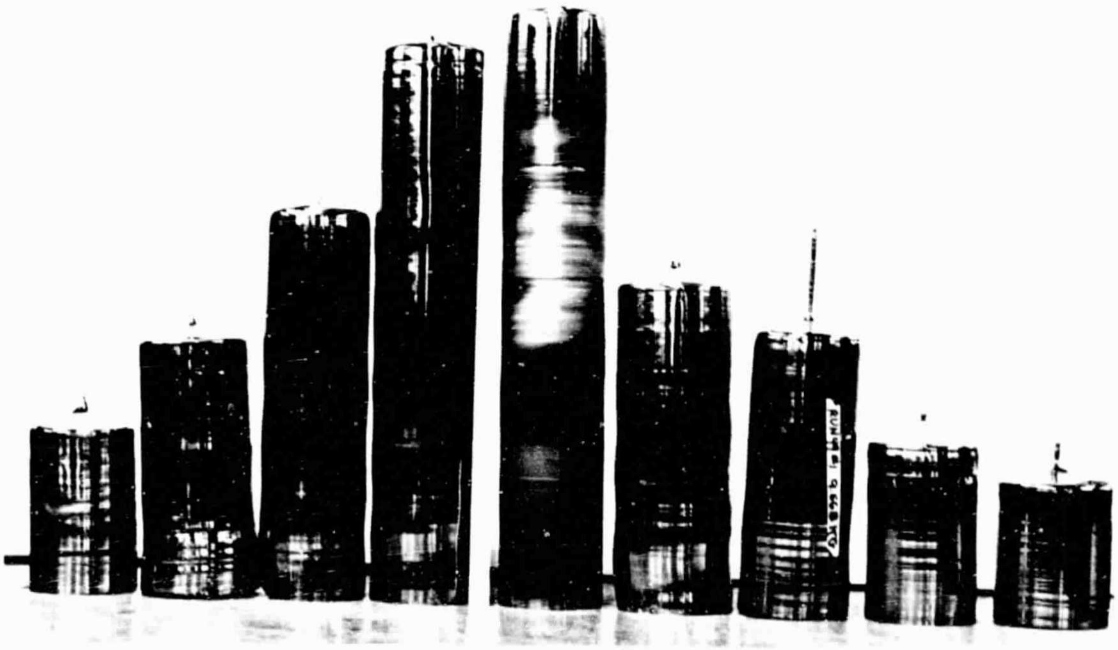
= 4.08¢ (1975) / 5.71¢ (1980) PER KILO.

HAMCO CONTINUOUS CZ GROWER





CONTINUOUS CZ CRYSTAL GROWTH: ETCHED SECTIONS OF INGOTS



CONTINUOUS CZOCHRALSKI INGOT GROWTH: RUN 49--108-kg INGOT PULLED, 86 hr
84% SINGLE CRYSTAL, 1.25 kg/hr THROUGHPUT

ACHIEVABLE ECONOMIC GOAL FOR 1986

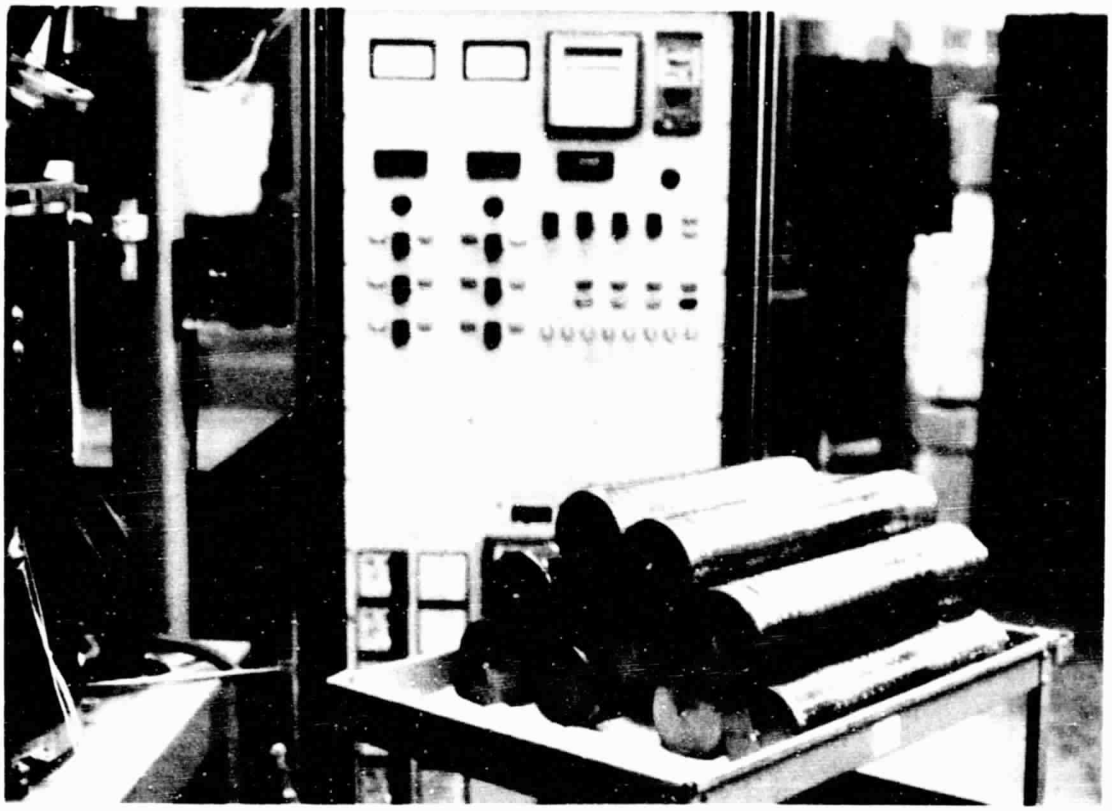
CRYSTAL ADD-ON COST \$13.89/M^2 IN 1980 DOLLARS

KEY ASSUMPTIONS

FURNACE RUN SIZE	150 KG
CRYSTAL DIAMETER	150 MM
CRYSTAL GROWTH VELOCITY	100 MM/HR
INGOTS PER RUN	3
CRYSTAL YIELD	85%
RUN CYCLE TIME	52 HRS
PULLERS PER OPERATOR	3
DIRECT LABOR COST	\$6.94/HR
OPERATING SUPPLIES COST	\$635.00/RUN
EQUIPMENT COST	\$160,000
EQUIPMENT FLOOR SPACE	150 SQ FT
EQUIPMENT UTILIZATION	90%
ENERGY REQUIREMENTS	3552 KWH/RUN
ENERGY COST	\$0.05/KWH
SILICON/SLICE CONVERSION	25 SLICES/CM

CONTINUOUS LIQUID-FEED CZ GROWTH

SILTEC CORP.



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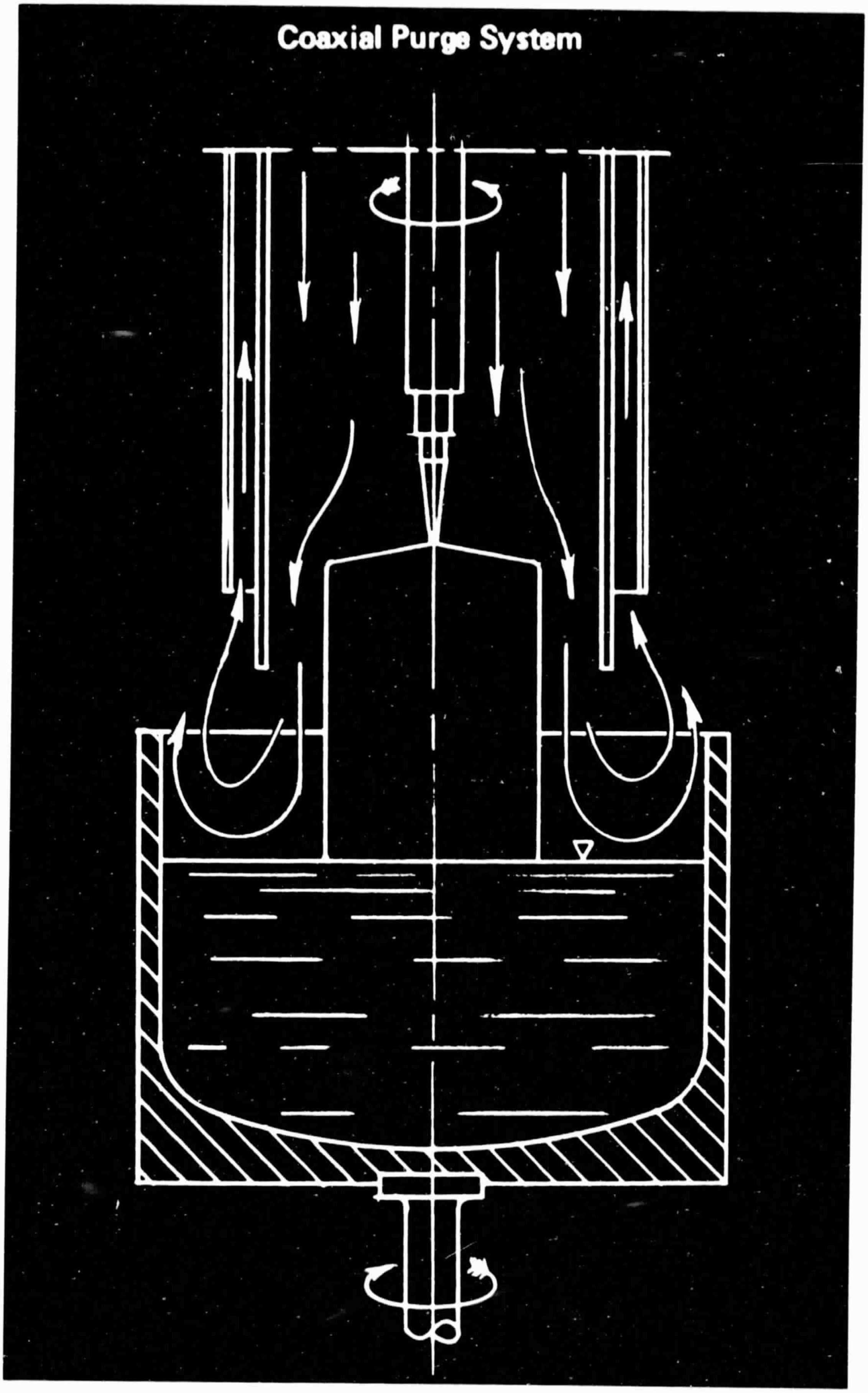
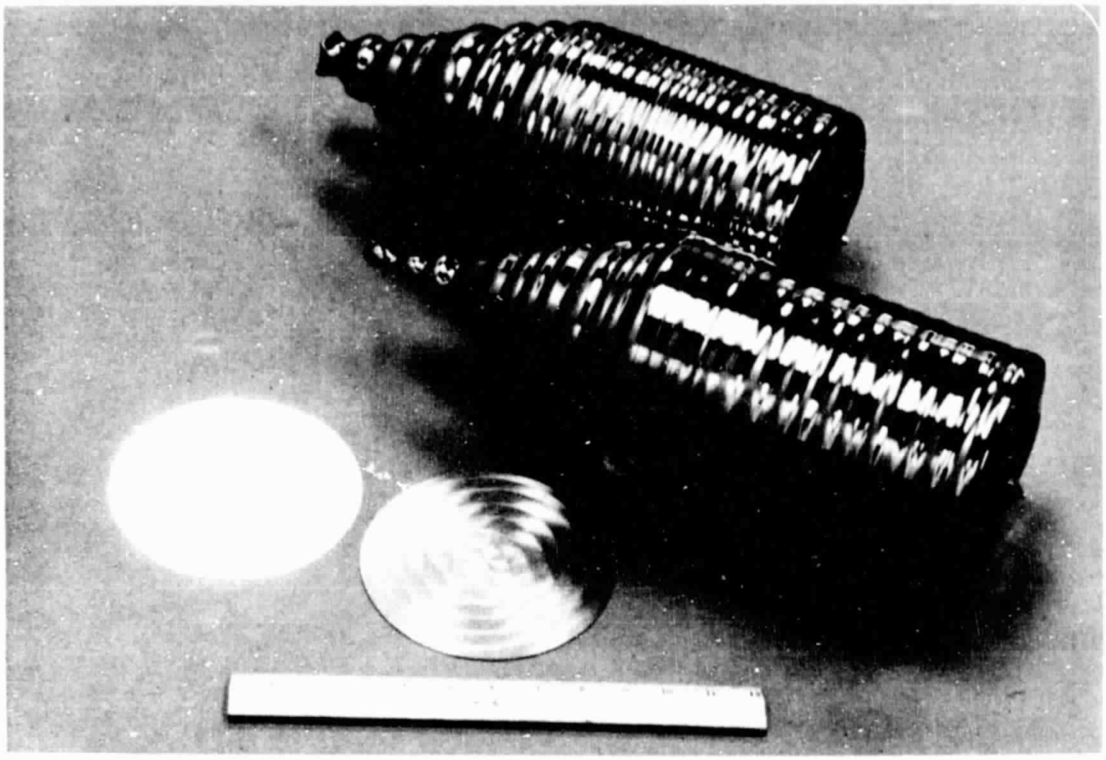
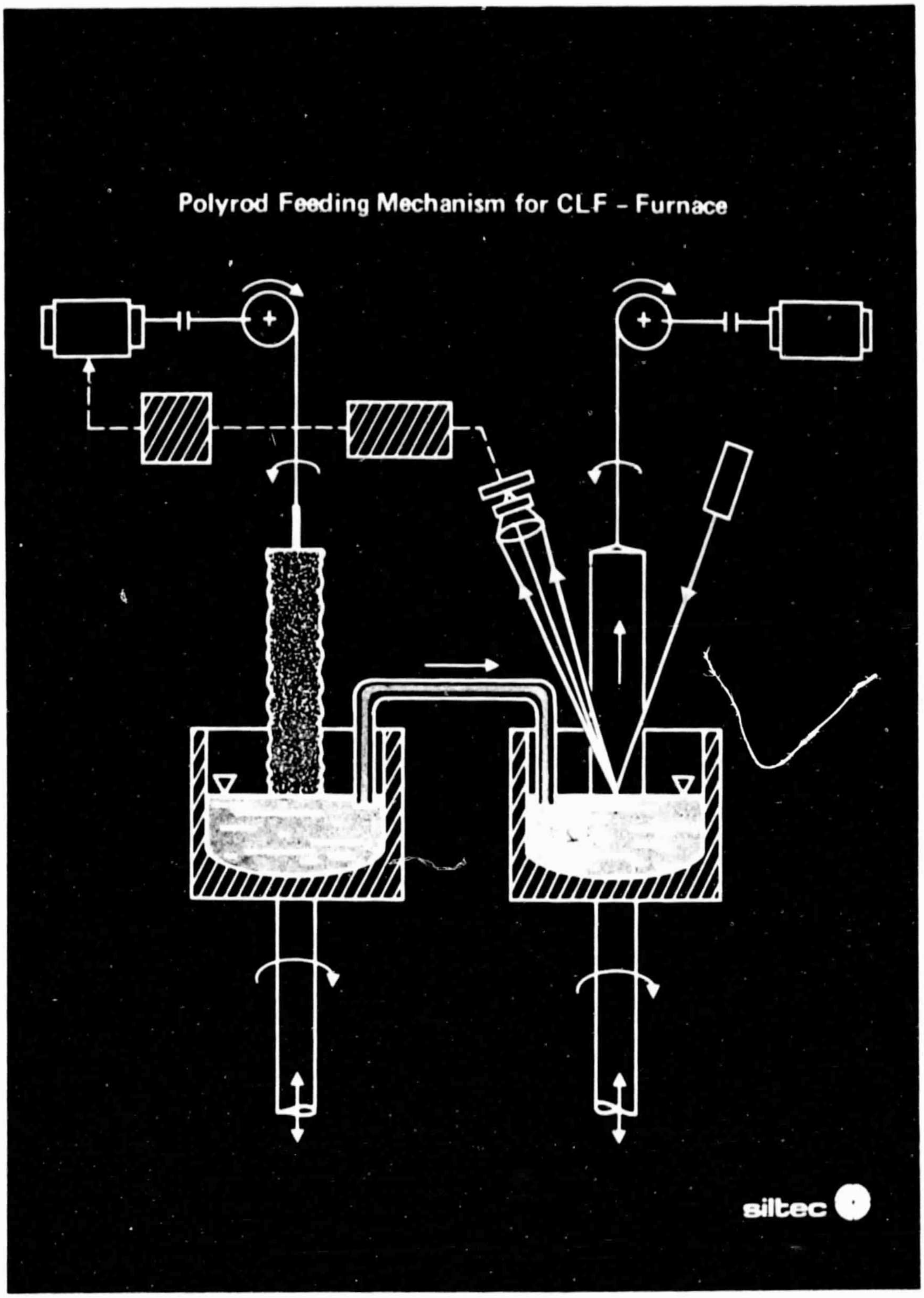
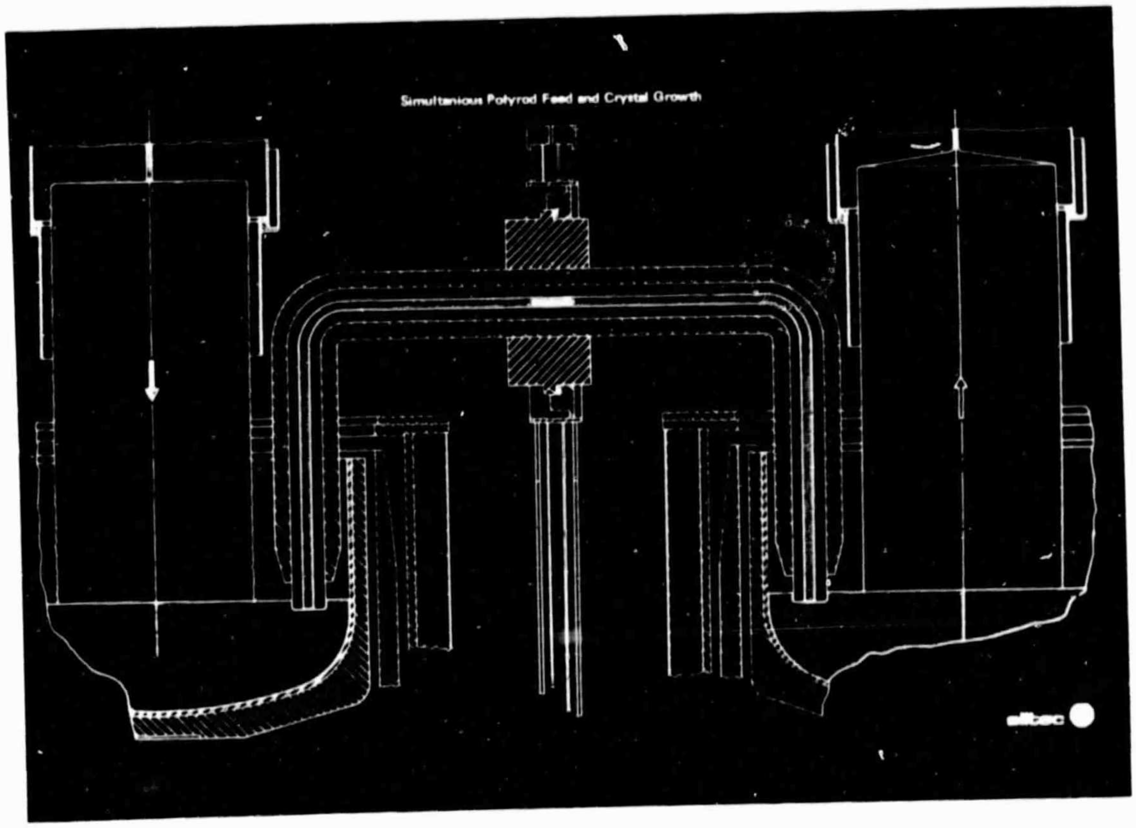

Coaxial Purge System




Polyrod Feeding Mechanism for CLF - Furnace
siltec



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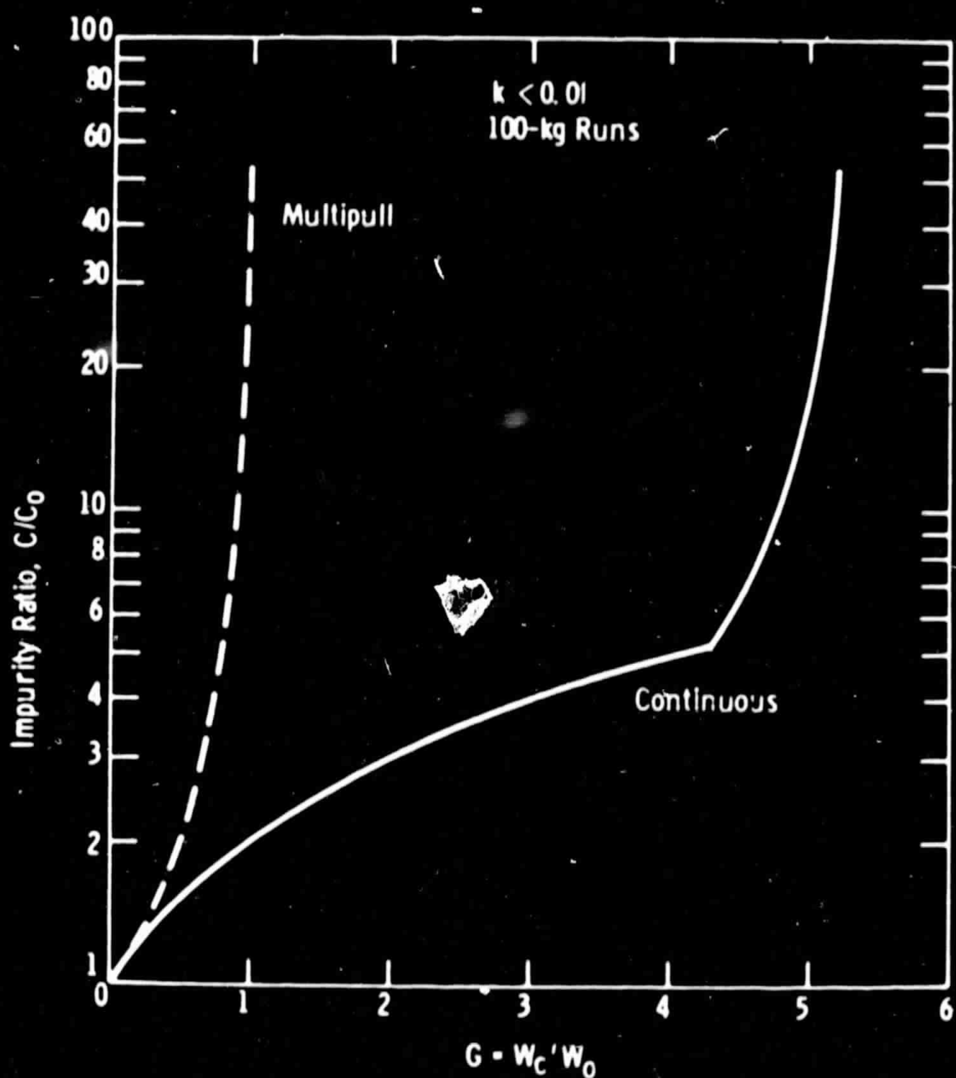
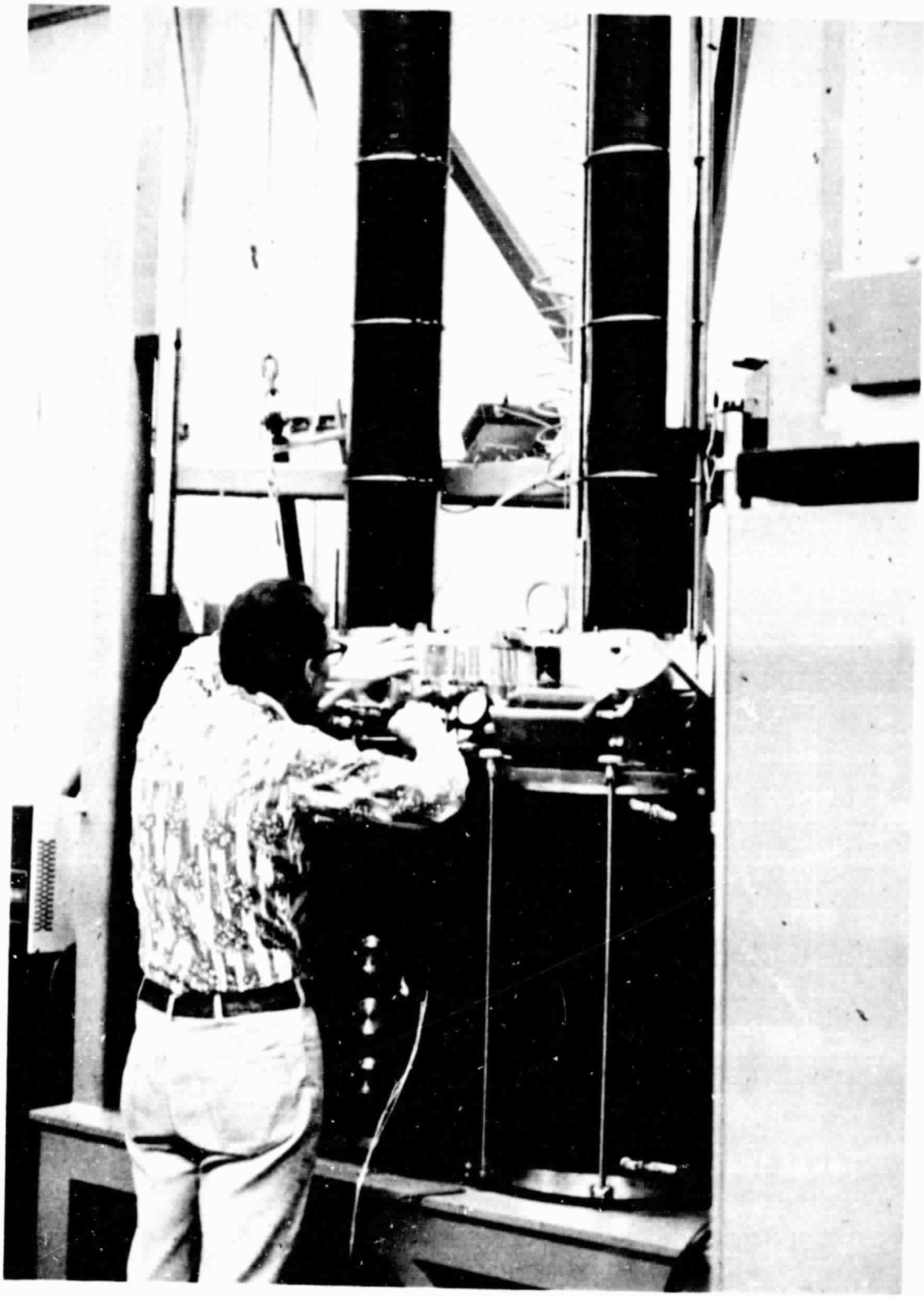
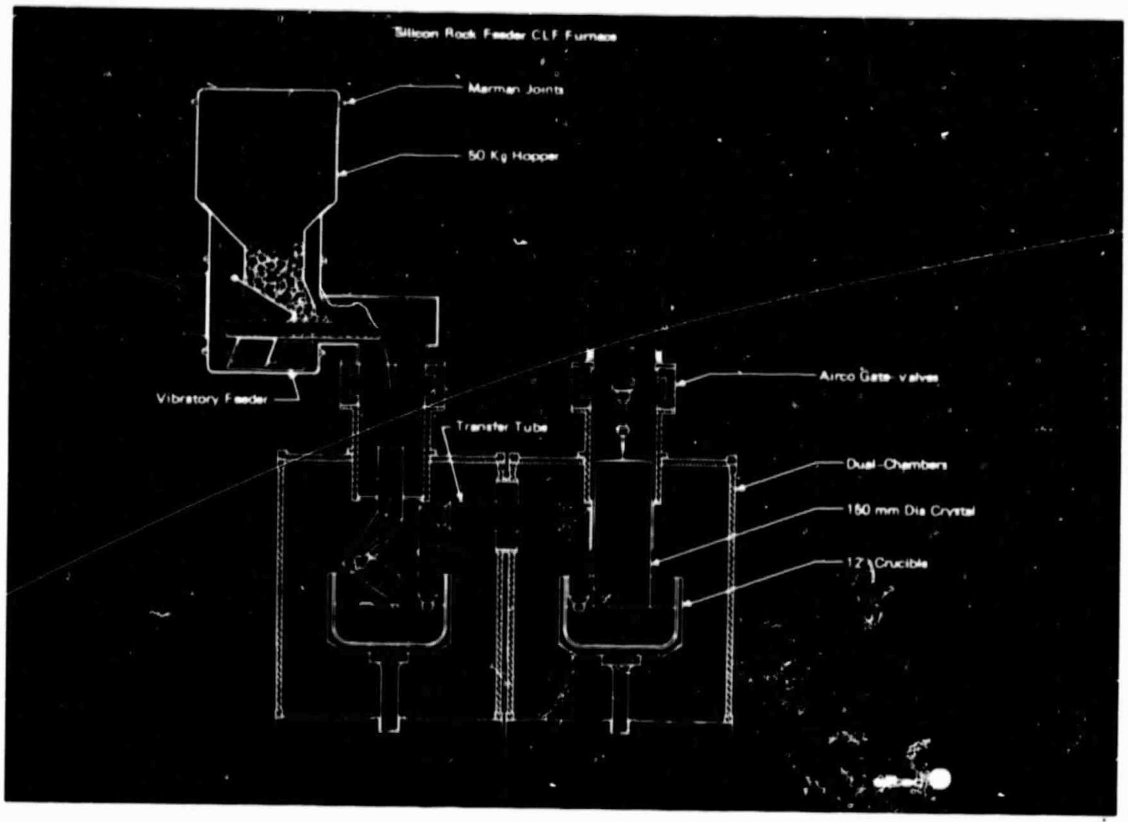
Impurity Buildup for Czochralski Growth*

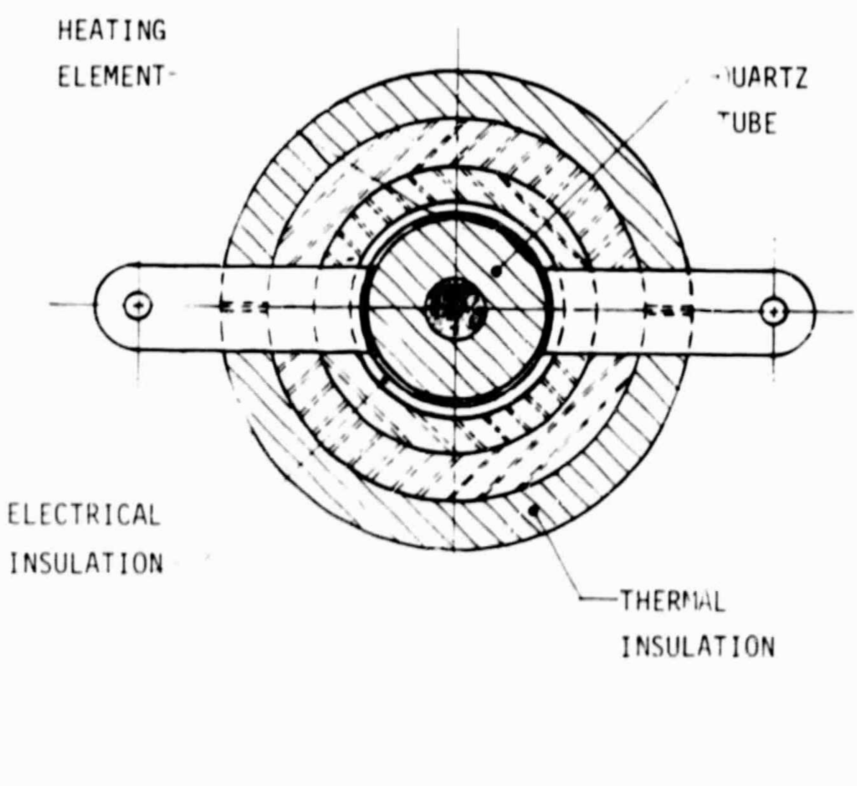


*Texas Instruments Final Report, JPL Contract 954887

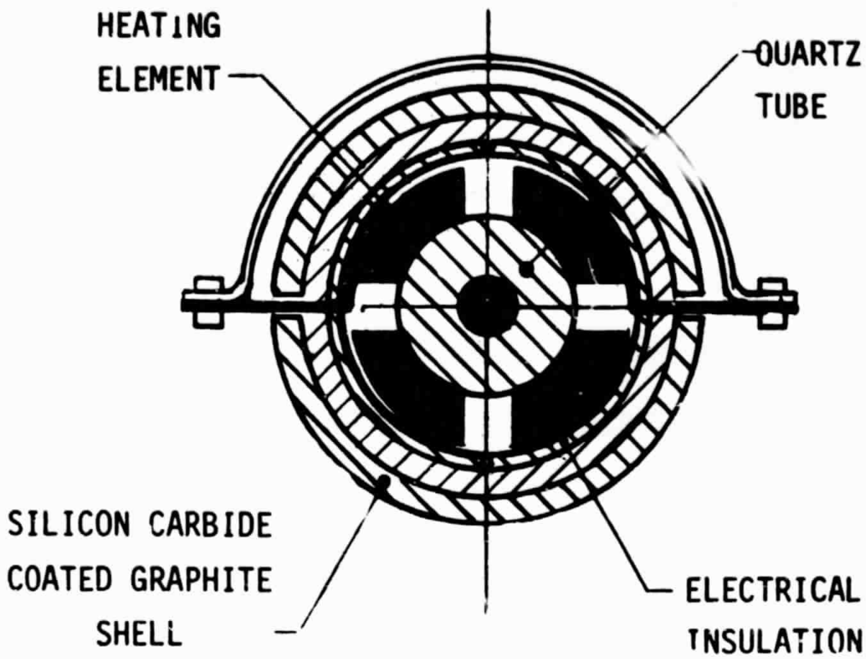




GRAFOIL STRIP HEATER



RIGID GRAPHITE HEATER



INGOT CASTING—HEAT EXCHANGER METHOD

CRYSTAL SYSTEMS, INC.

C. P. KHATTAK

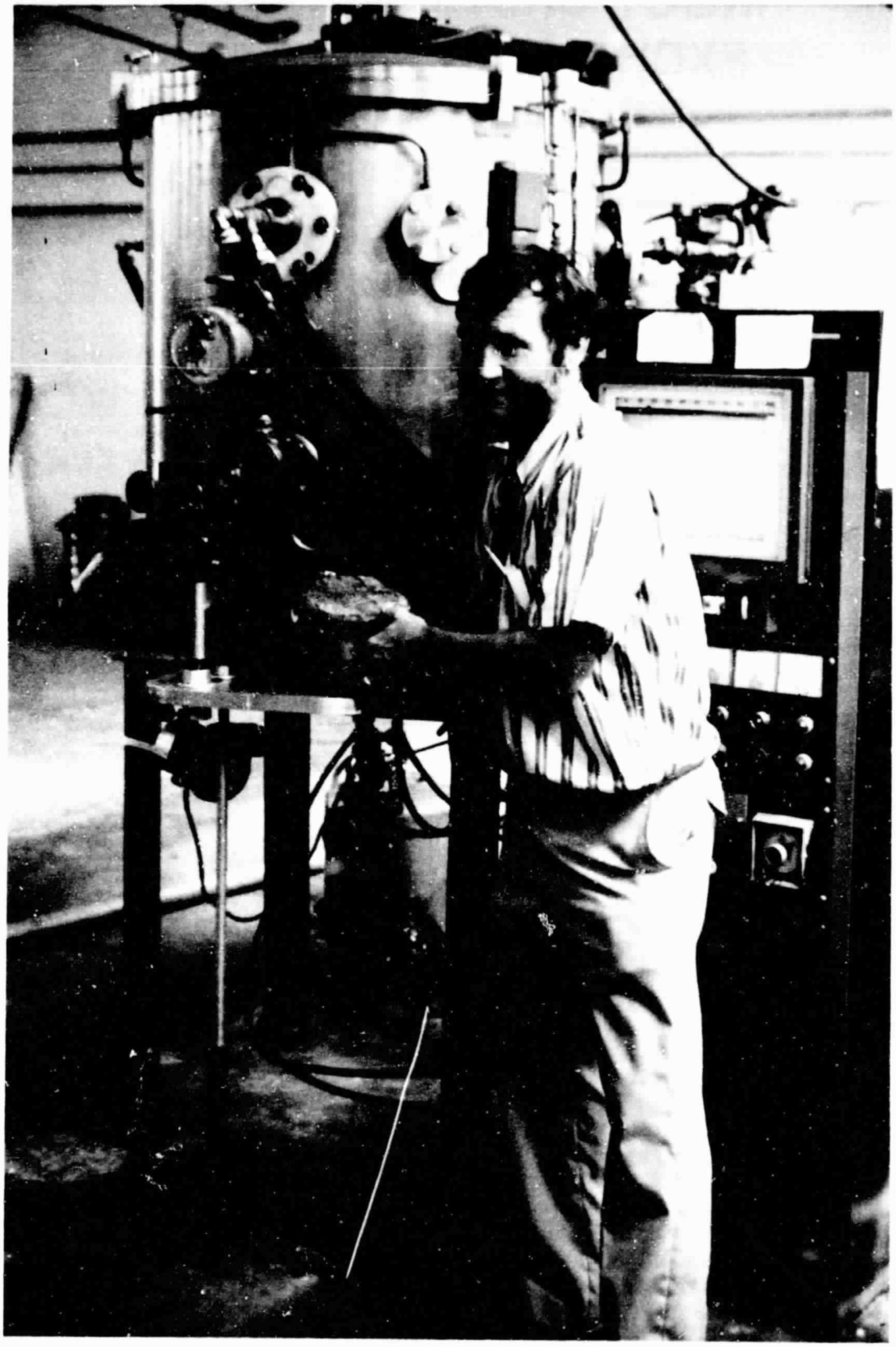
F. SCHMID

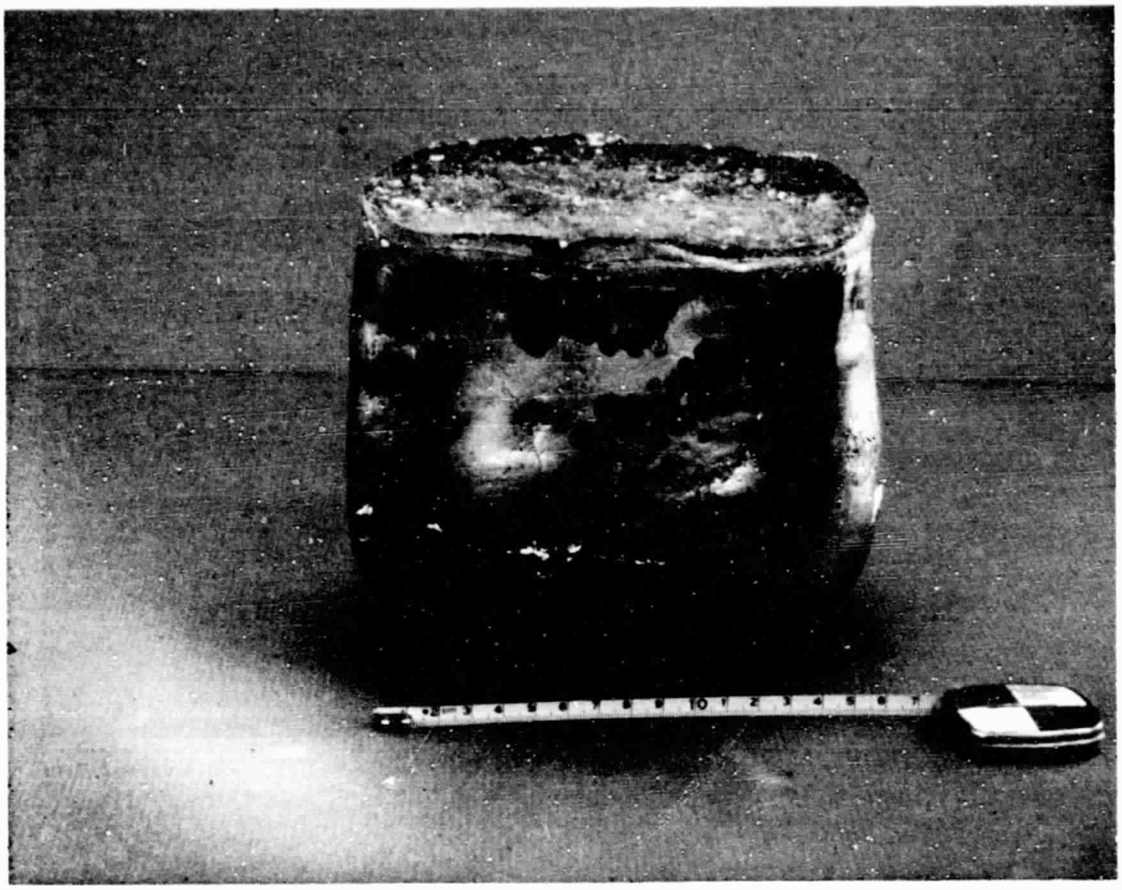
It has been demonstrated that silicon produced by Heat Exchanger Method (HEM) is comparable to that produced by the Czochralski process for photovoltaic applications. Further, the projected costs of the HEM are significantly lower. The emphasis of the present program is on scale-up to large-size ingots so that economies of the process are realized.

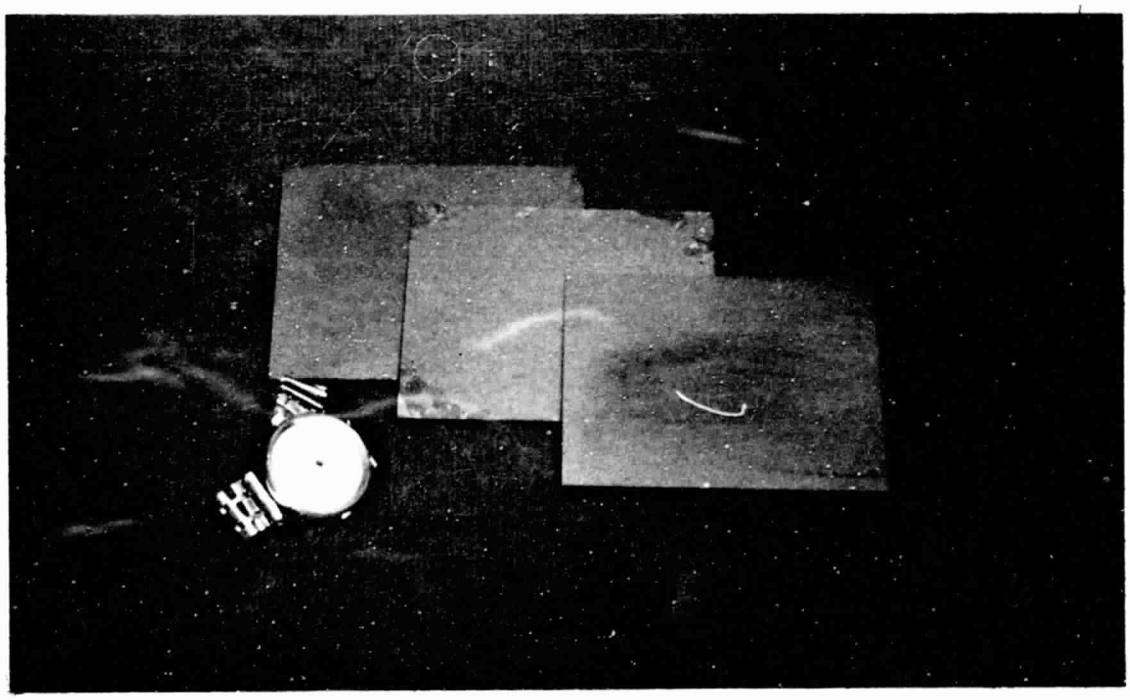
During the current period ingots have been scaled up from 10 cm cubes weighing about 2.8 kg to 16 cm x 16 cm x 16 cm sizes weighing up to 8.3 kg as shown in accompanying pictures. Examination of the surface of some of these ingots shows that there is chipping on the surface in localized areas. This behavior is attributed to non-uniformity in the graded structure of the crucible. At the present time the heat treatment of the crucible is carried out manually. It is, therefore, very difficult to achieve uniformity in heat treatment for such large sizes. The non-uniformity causes attachment of the crucible to the ingot and thus the resultant chipping. Efforts are being made to mechanize the heat treatment process.

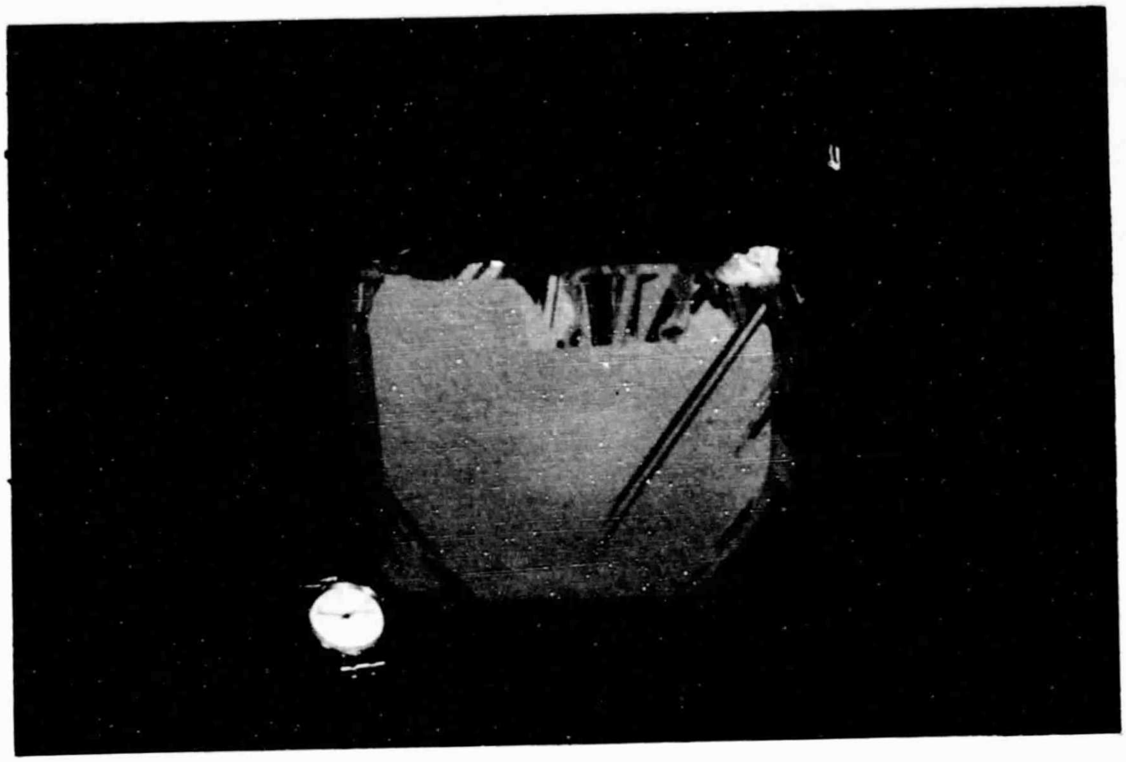
Also shown is a cross-section of a 8.1 kg, 16 cm x 16 cm square silicon ingot. It can be seen that most of the material solidified as a single crystal in the central area. The breakdown in single crystallinity near the top of the ingot was due to the trapping of a silicon dendrite from the surface of the melt onto the interface. This occurred while physically probing for the interface position with a quartz rod. It also reveals that the last material to freeze is near the crucible wall. This could be important when low purity melt stock is used. The directional solidification during HEM growth will reject most impurities in the last material to freeze which in this case is near the crucible wall. This portion has to be sectioned to maintain dimensional accuracy of the cast ingots.

It is, therefore, concluded that scale-up of ingot size by HEM is not a major problem. A high degree of single crystallinity is achieved. Even in areas where breakdown occurs, the grain sizes are large (1 cm), which may not deteriorate the solar cell performance.









MULTI-WIRE SLICING (FAST)

CRYSTAL SYSTEMS, INC.

F. SCHMID

C. P. KHATTAK

The emphasis in the area of multi-wire slicing by Fixed Abrasive Slicing Technique (FAST) was in two areas - - Machine Development and Testing.

Machine Development

It has been demonstrated that high surface speeds are essential for effective slicing with fixed diamond abrasive. In a reciprocating type of motion high speeds can be achieved by reducing the weight of the bladehead. Initial work with the modified Varian 686 slicer showed that the massive 220 lbs. bladehead was not necessary for the FAST approach. With this machine only 100 surface feet per minute was achieved. In the design of the high-speed slicer the weight of the bladehead was reduced in half with twice the stroke length. With this machine 200 feet per minute surface speed was achieved. Modification of the bladehead reduced its weight to 37 lbs. and gave 400 ft/min. Other modifications made in rocking and feed mechanism reduced the hysteresis and vibrations in the machine. Figure 1 shows two views of the high-speed slicer after these modifications.

Testing

Initial slicing after the recent modification of the high-speed slicer showed significant improvement in cutting effectiveness. The average slicing rate for 10 cm dia silicon ingot using commercially impregnated wires was 5.7 mils/min, 0.145 mm/min. This is a big improvement from 2.33 mils/min, 0.059 mm/min achieved before the modification and is also more than 40% higher than estimated in the projected economic analysis to meet 1986 cost goals. The increased cutting rates will increase the throughput of the slicer significantly.

Another essential economic feature is the life of the wires. The goal of the present Phase III is to show a bladepack slice through two ingots of 10 cm dia. This goal was demonstrated with commercially impregnated wires during runs 328-SX and 329-SX. Figure 2 shows a plot of the depth of cut as a function of the slicing time for these runs. It can be seen that rocking of the workpiece during slicing minimizes the effect of the changing kerf length during most of the ingot. Further, the average cutting rate for the second test (4.82 mils/min, 0.122 mm/min) was also higher than the estimated value used in projected economic analysis. Also shown in Figure 2 is the slicing performance in run 2-002-SX at 200 ft/min surface speed, average cutting rate 2.33 mils/min, 0.059 mm/min.

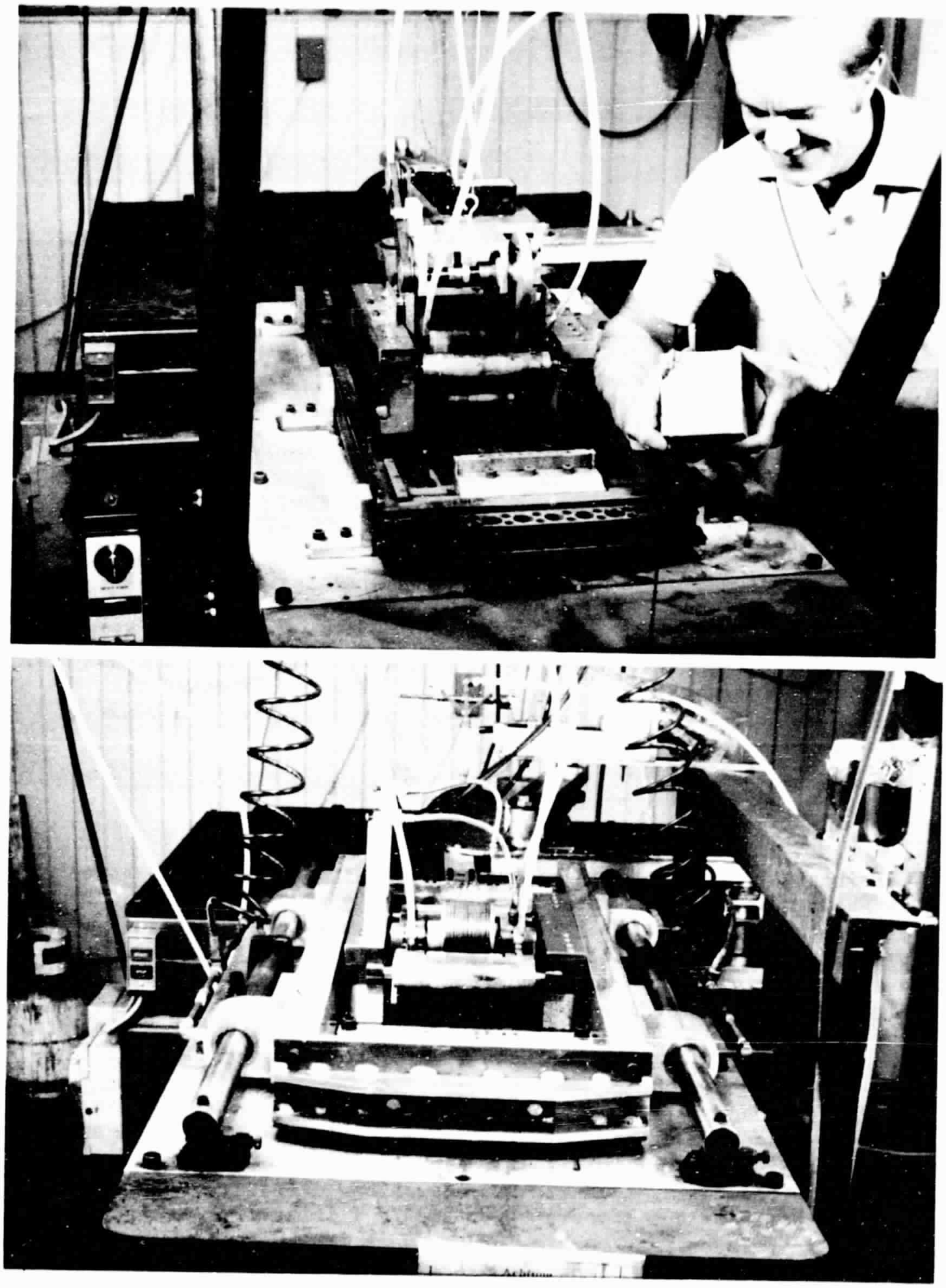


Figure 1. Two views of the modified Varian 686 high-speed slicer

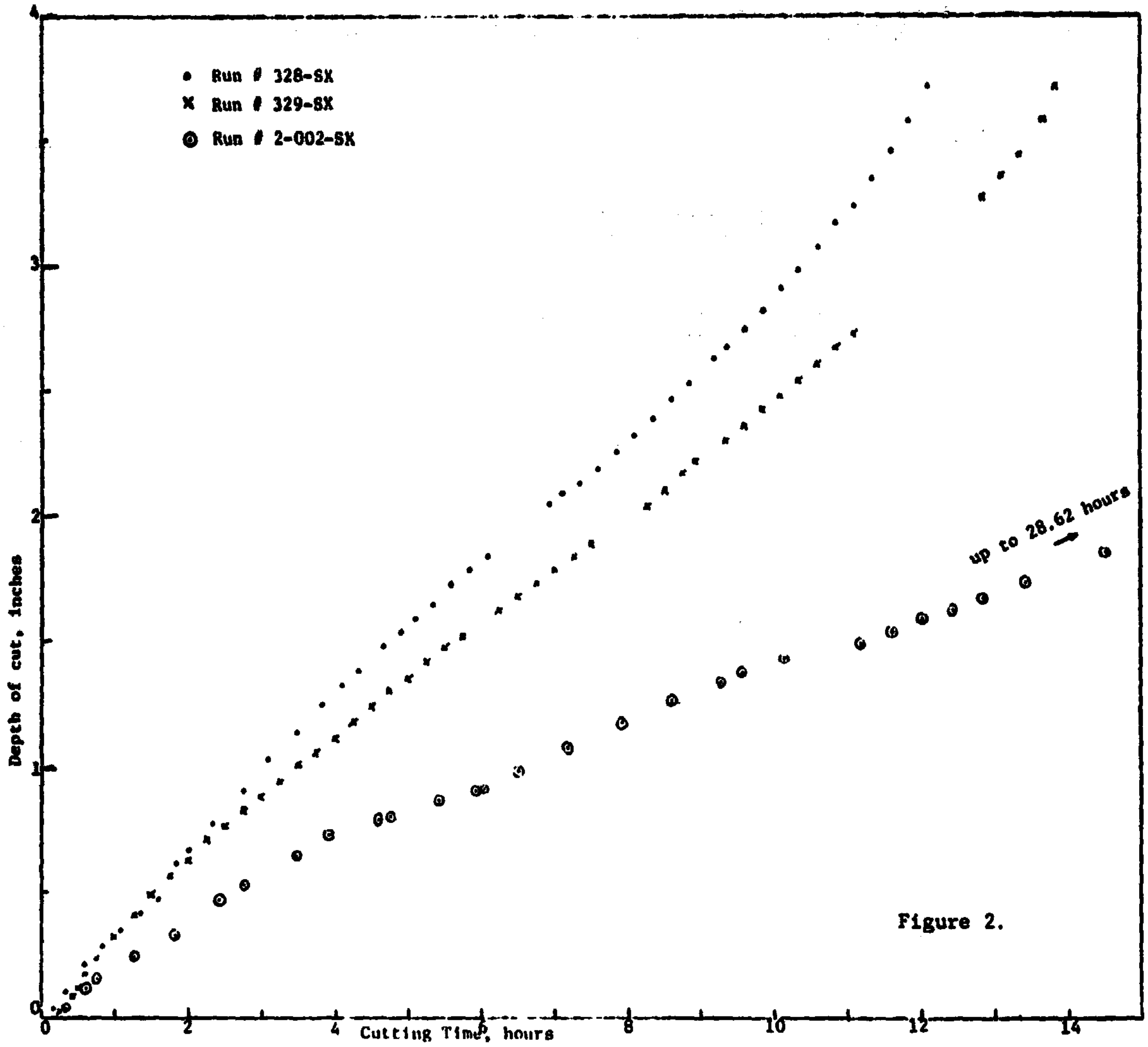

Run # 328-SX
Run # 329-SX
Run # 2-002-SX
up to 28.62 hours
Depth of cut, inches
Cutting Time, hours
0
1
2
3
4
0
2
4
8
10
12
14

Figure 2.

MULTIBLADE SLURRY SAWING

VARIAN ASSOCIATES, INC.

PROGRESS

RECYCLED ABRASIVE

- SEPARATION ACHIEVED
- TESTED AT 33% RECYCLING
- EXCELLENT RESULTS

LARGE SAW REBUILD/REVISE

- IMPROVED SLURRY GUARDING INSTALLED ON CARRIAGE AND DRIVE SYSTEM BEARINGS
- ELECTRONICS REBUILT (LVDT, FORCE CONTROL MODULES)
- MACHINE FULLY REALIGNED

LARGE SAW OPERATION

- RUNS MADE AT 20, 22, 25 WAFERS/CM
- SOME MECHANICAL PROBLEMS AFFECTING OPERATION
- EVEN SLURRY DISTRIBUTION DIFFICULT
- LATEST RUN PARTIALLY SUCCESSFUL (22 WAFERS/CM, .94 M^2/KG)

ECONOMIC EVALUATION

COST REDUCTION HIGHLIGHTS (CUMULATIVE)

DATES ARE 2 YEARS PRIOR TO NEED

1979 CURRENT EQUIPMENT, PROCESS, SLURRY
- 300 SLICES PER CYCLE
- PURCHASED BLADE PACKS
- 100 MM DIAMETER
- 3.5 MM PER HOUR CUT RATE
- 0.67 SQUARE METER PER KG

1980
- IN-PLANT BLADE PACK FABRICATION
- LOW-COST SLURRY VEHICLE
- 0.80 SQUARE METER PER KG

1982
- 900 SLICES/CYCLE
- 125 MM DIAMETER
- 0.81 SQUARE METER PER KG
- PARTIAL SLURRY RECLAMATION

1984
- 1000 SLICES/CYCLE
- LOW-COST BLADE STOCK
- 150 MM DIAMETER
- 4.6 MM PER HOUR CUT RATE
- 1.0 SQUARE METER PER KG
- MORE SLURRY RECLAMATION, VERY LOW COST VEHICLE

COST BY YEARS*

YEAR	VALUE ADDED ($/M^2)	GOAL**
1980	63.7 (89.2)	122.5 (171.5)
1982	29.1 (40.75)	64.0 (89.6)
1984	13.7 (19.2)	19.0 (26.6)
1986	13.7 (19.2)	9.1 (12.74)

* **1975 DOLLARS**: 1980 DOLLARS IN PARENTHESIS (1975 $ TIMES 1.4)

** 1/2 OF SHEET GENERATION ALLOCATION

ENHANCED I.D. SLICING

SILTEC CORP.

CURRENT CONTRACT GOALS

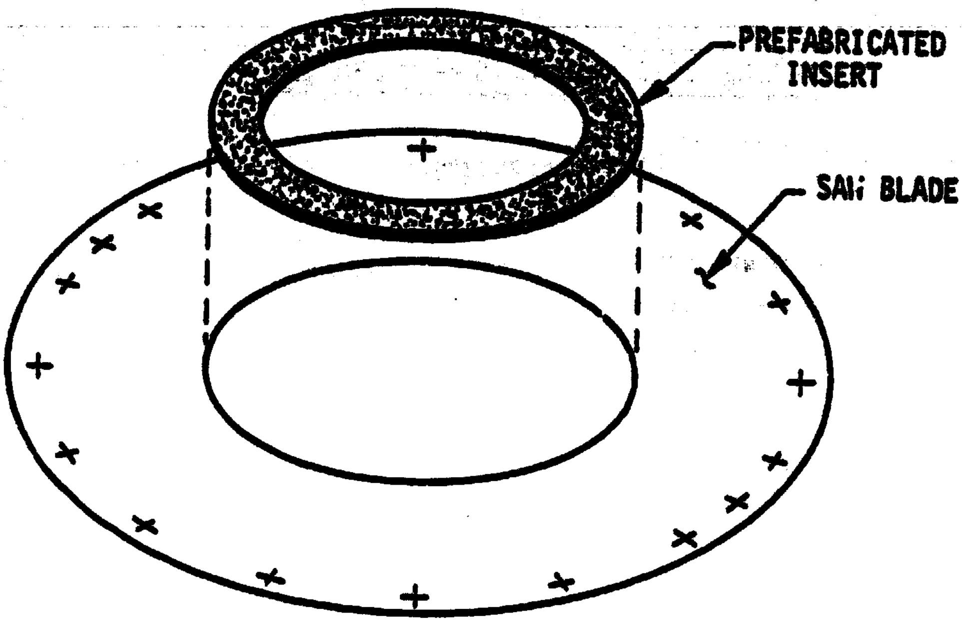
DEVELOP PROCESSES TO DEMONSTRATE ENHANCED I.D. SLICING TECHNOLOGY THAT WILL SIGNIFICANTLY INCREASE THE NUMBER OF USABLE SLICES PER CENTIMETER OVER CURRENT I.D. SLICING TECHNOLOGY.

SPECIFICATION	CURRENT PRACTICE (IN MICRONS)	PROJECT GOAL (IN MICRONS)
MATERIAL LOSS	305 - 381	<140
SLICE THICKNESS	432 - 610	250
KERF & SLICE THICKNESS	737 - 991	<390
SLICING YIELD	88% - 97%	>95%
BLADE COST	$42	$30
PRODUCTIVITY/MACHINE/24 HRS.	500 - 900	1250
BLADE MAINTENANCE/CUTS/DRESS	150 - 400	600
BLADE LIFE /CUTS	2500 - 4000	2500 - 4000
NO. SAWS/OPERATOR	3	6

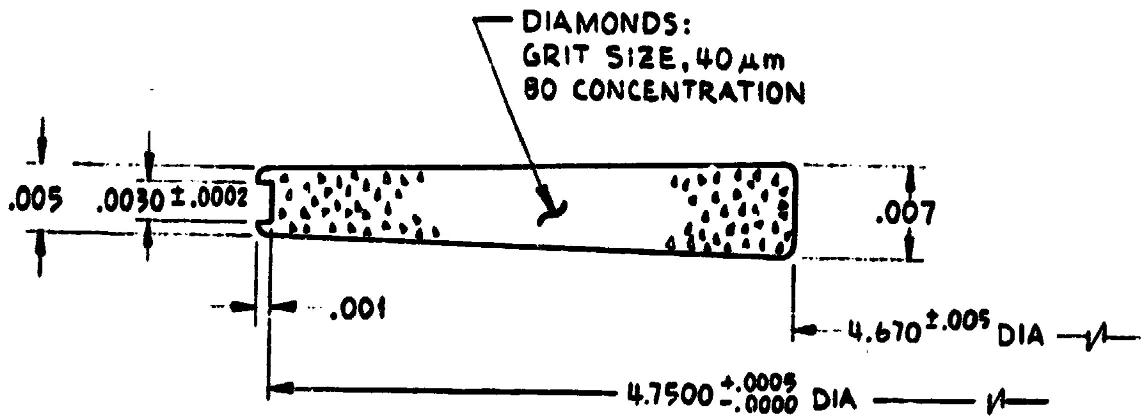
APPROACH TO ACHIEVE THESE GOALS

- INGOT ROTATION WITH MINIMUM EXPOSED BLADE AREA
- DYNAMIC CUTTING EDGE CONTROL
- PRE-FABRICATED INSERT BLADES

PERSPECTIVE VIEW: PREFABRICATED INSERT BLADE



INSERT, I.D. BLADE PRE-FAB



ACHIEVABLE ECONOMIC GOAL FOR 1986

SLICE ADD-ON COST $9.76/$M^2$ IN 1980 DOLLARS

KEY ASSUMPTIONS

EQUIPMENT COST	$42,560
SPACE REQUIREMENT	30.0 SQ FT
EQUIPMENT UTILIZATION	90%
POWER REQUIREMENTS	1.5 KW
LABOR RATE	$5.38
SLICING YIELD	95%
CRYSTAL DIAMETER	150 MM
ENERGY COST	$0.05/KWH
CUTS/BLADE	2,000
PRODUCTIVITY/MACHINE/24 HRS	900
BLADE COST	$40

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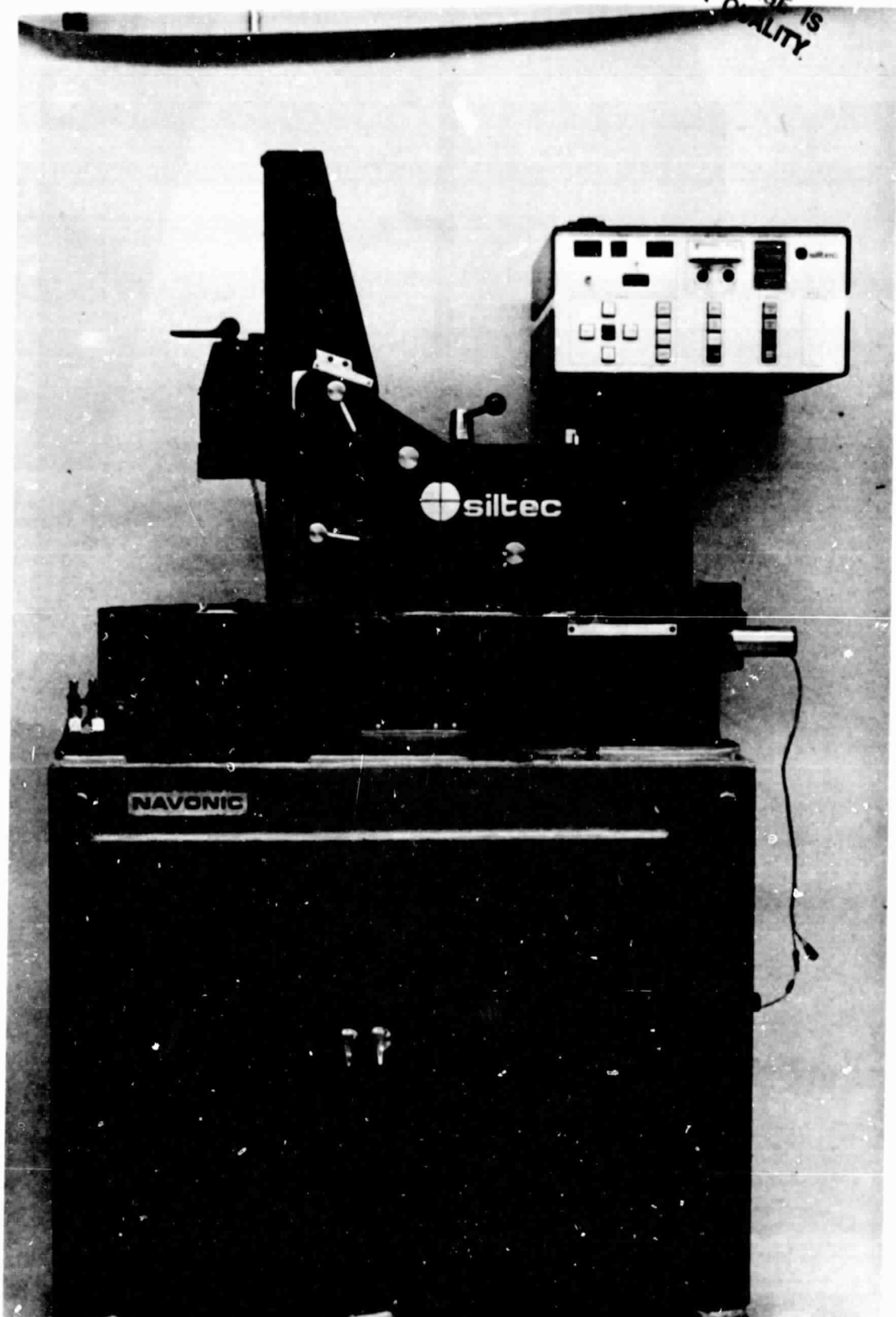
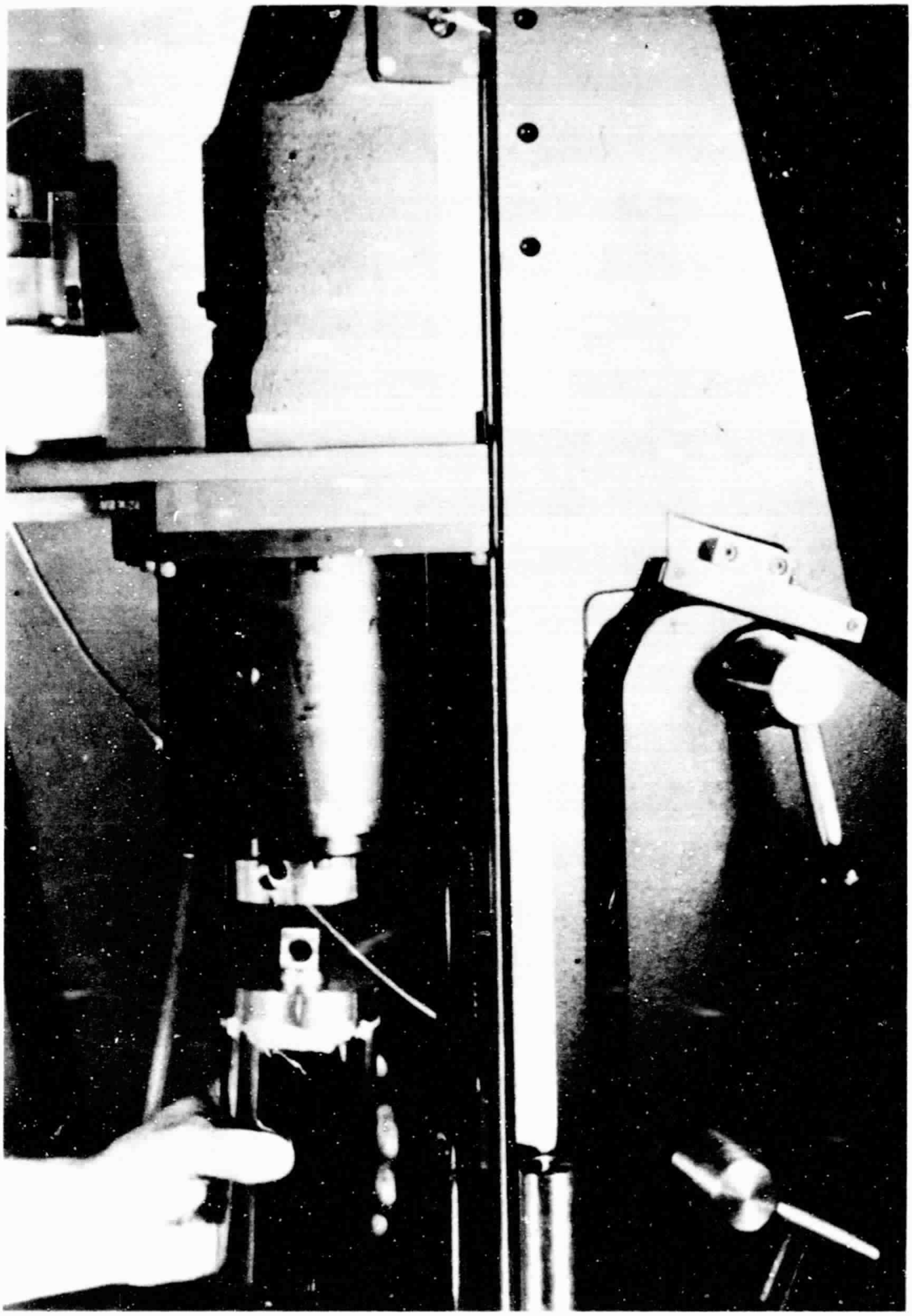
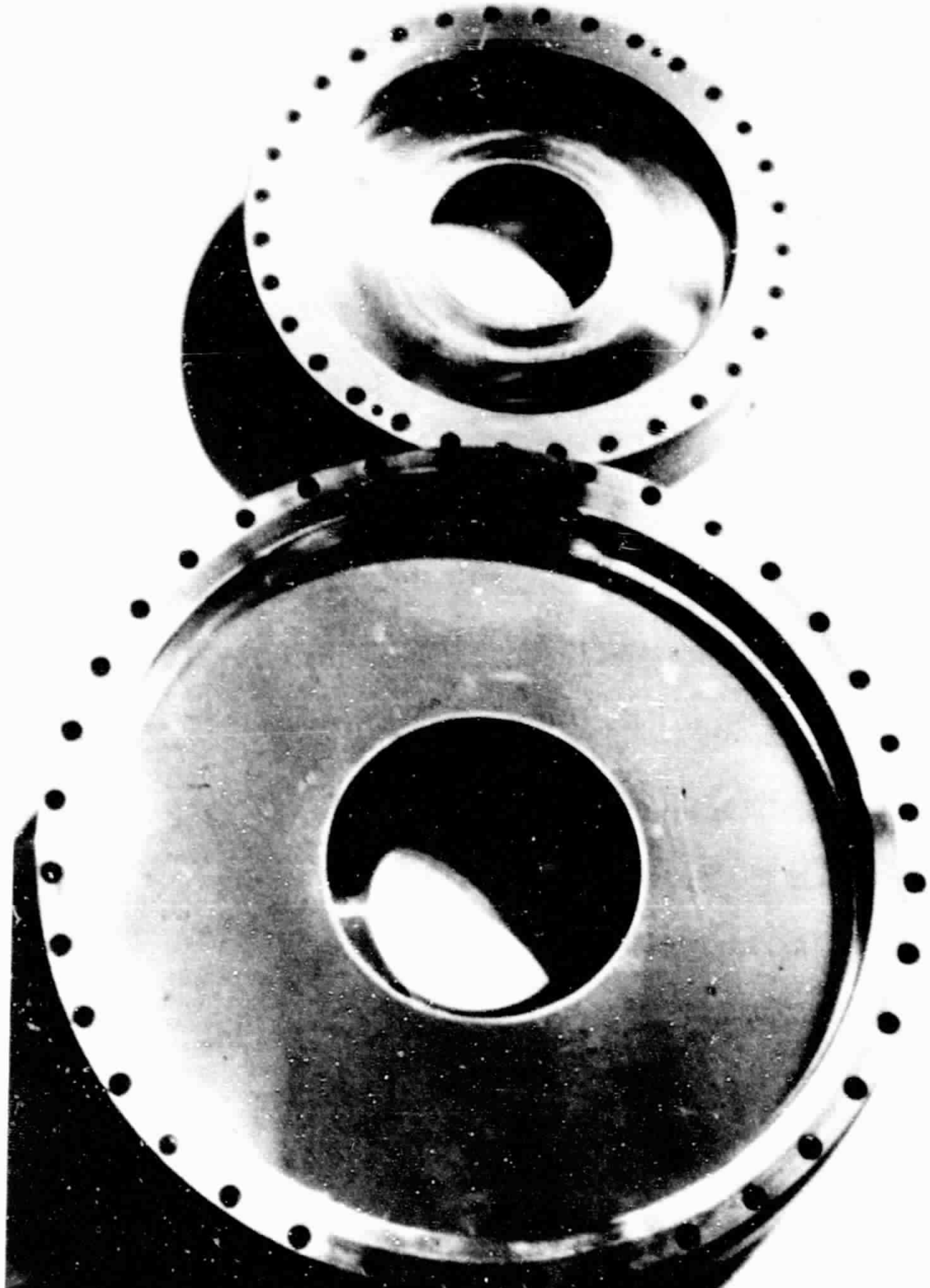




LOADING OF SILICON CRYSTAL INTO INGOT ROTATION ASSEMBLY



COMPARISON OF SMALL AND LARGE DIAMETER BLADE AND HEAD ASSEMBLIES

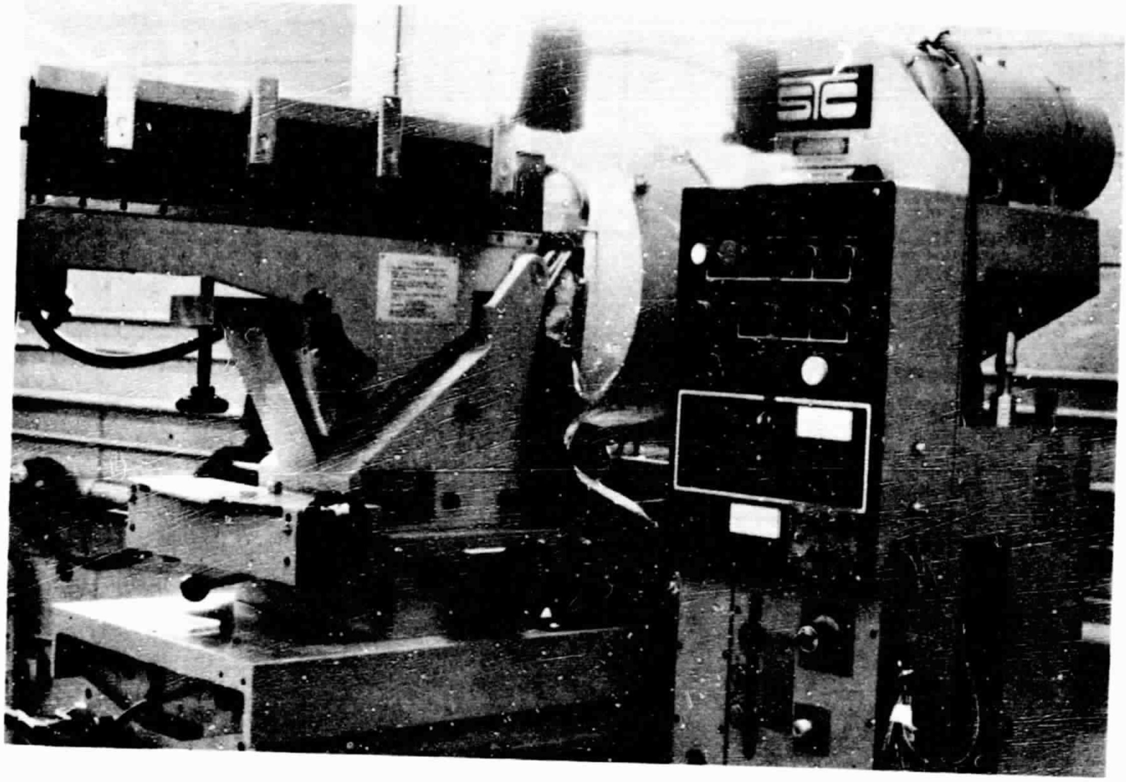
SILICON TECHNOLOGY CORP.

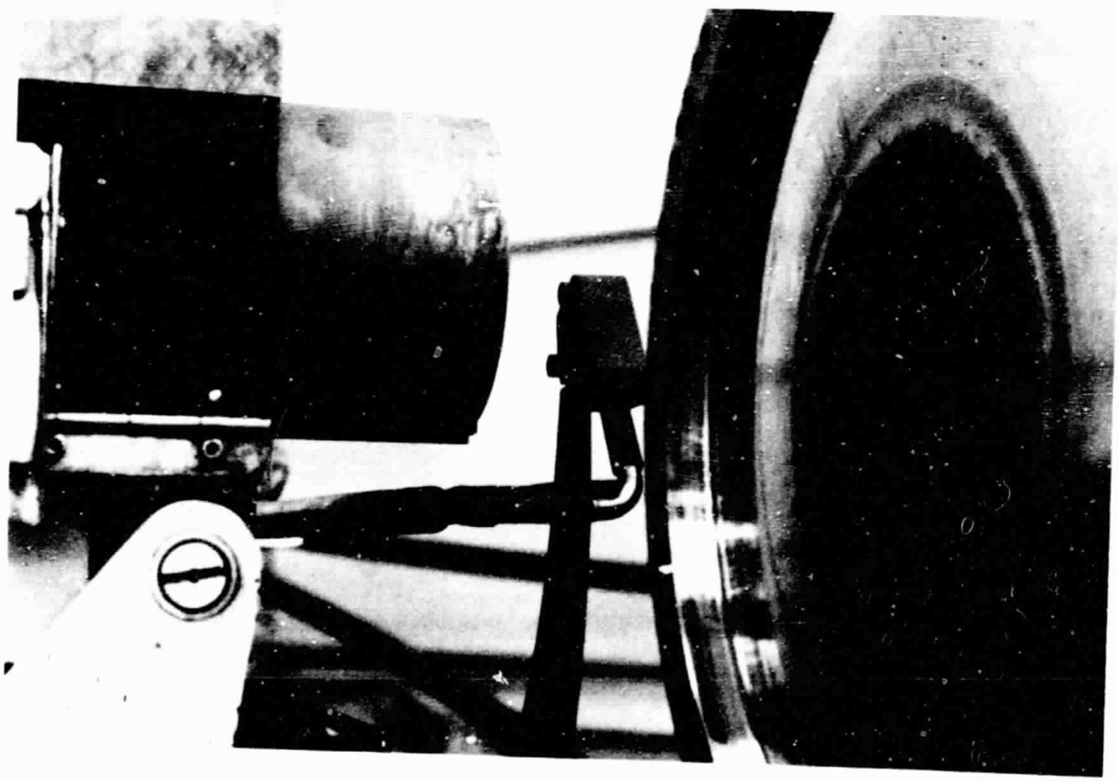
CONTRACT OBJECTIVES

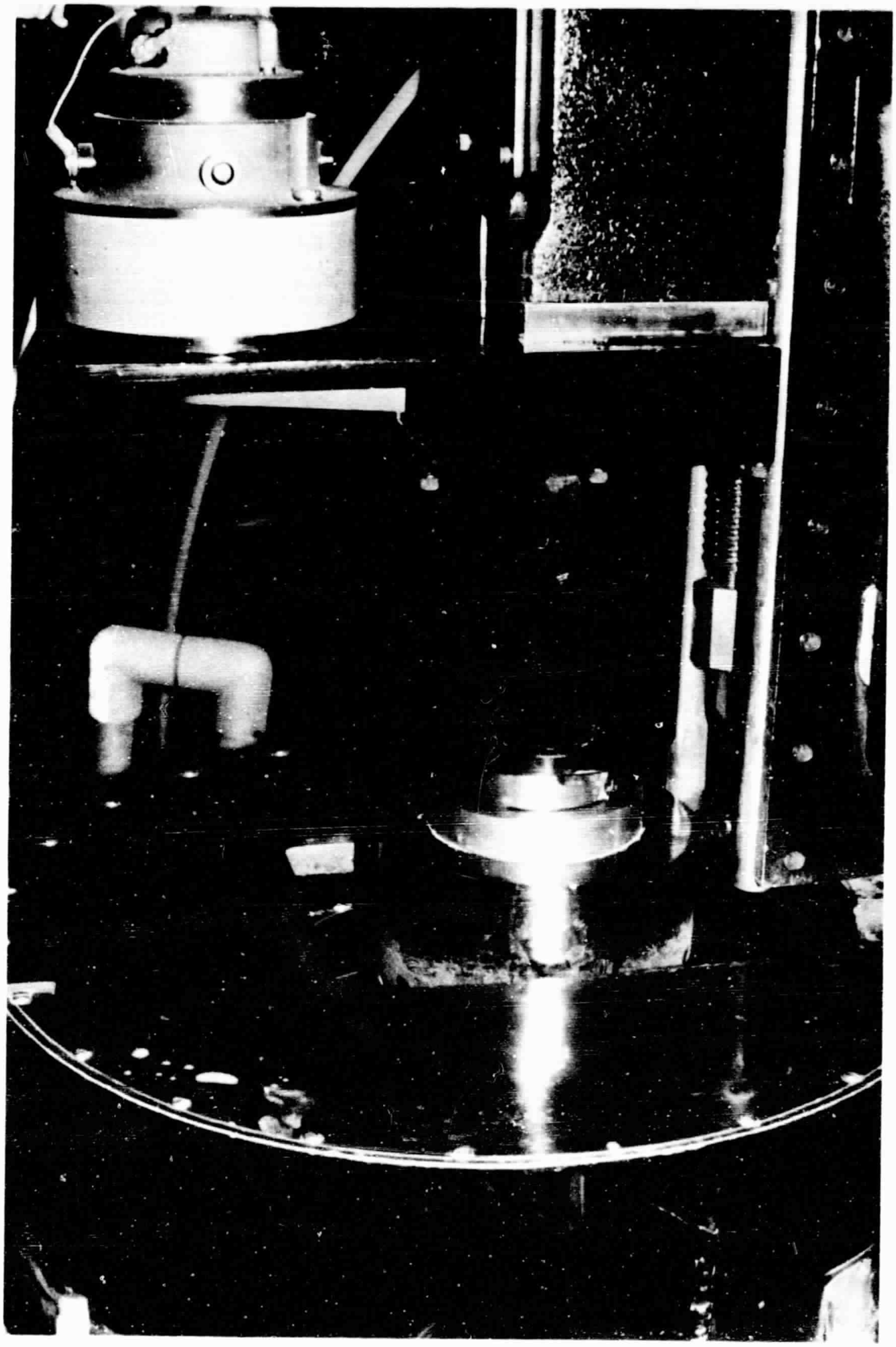
1. Development of low kerf I.D. diamond blades.
2. Modification of an STC 16 inch I.D. Slicing Machine to allow crystal rotation of 4 inch diameter silicon.
3. Slicing experiments to test blades and equipment.
4. Achievement of 18-19 mils total material consumption on 100 mm wafers.

I.D. SLICING EQUIPMENT

1. STC 16" I.D. Slicing Machine Model SMA-4400
2. Single Slice Recovery System
3. Crystal Rotation System
4. Programmable Feed System







ELECTRIC FEED ACTUATOR SYSTEM

SEA 4298

Cutting Speed Variable .02-1.3 in./min.
Return Speed Variable to 1.3 in./min.
Stroke 6 in.; Zero backlash in actuator drive train.
Speed Regulation 1% of set speed or better
Overload slipclutch protection (80 in.# Torque Drive Train)
Preprogrammed cam shaped to suit
Drip oiler lubrication; Sealed drive train against dust, etc.
1/8 H.P. D.C. Servo Motor Drive
Actuator Assembly Drawing SEA 4302

CONTROLS LOCATED ON MAIN CONTROL PANEL AND CONSIST OF:

- Toggle switch for manual feed or programmed feed
- Potentiometer for manual feed control
- Potentiometer for return speed control
- Potentiometer for programmed minimum speed setting
- Potentiometer for programmed maximum speed setting
- Dual Range feed rate meter 0 -.5 x 1 or x 10

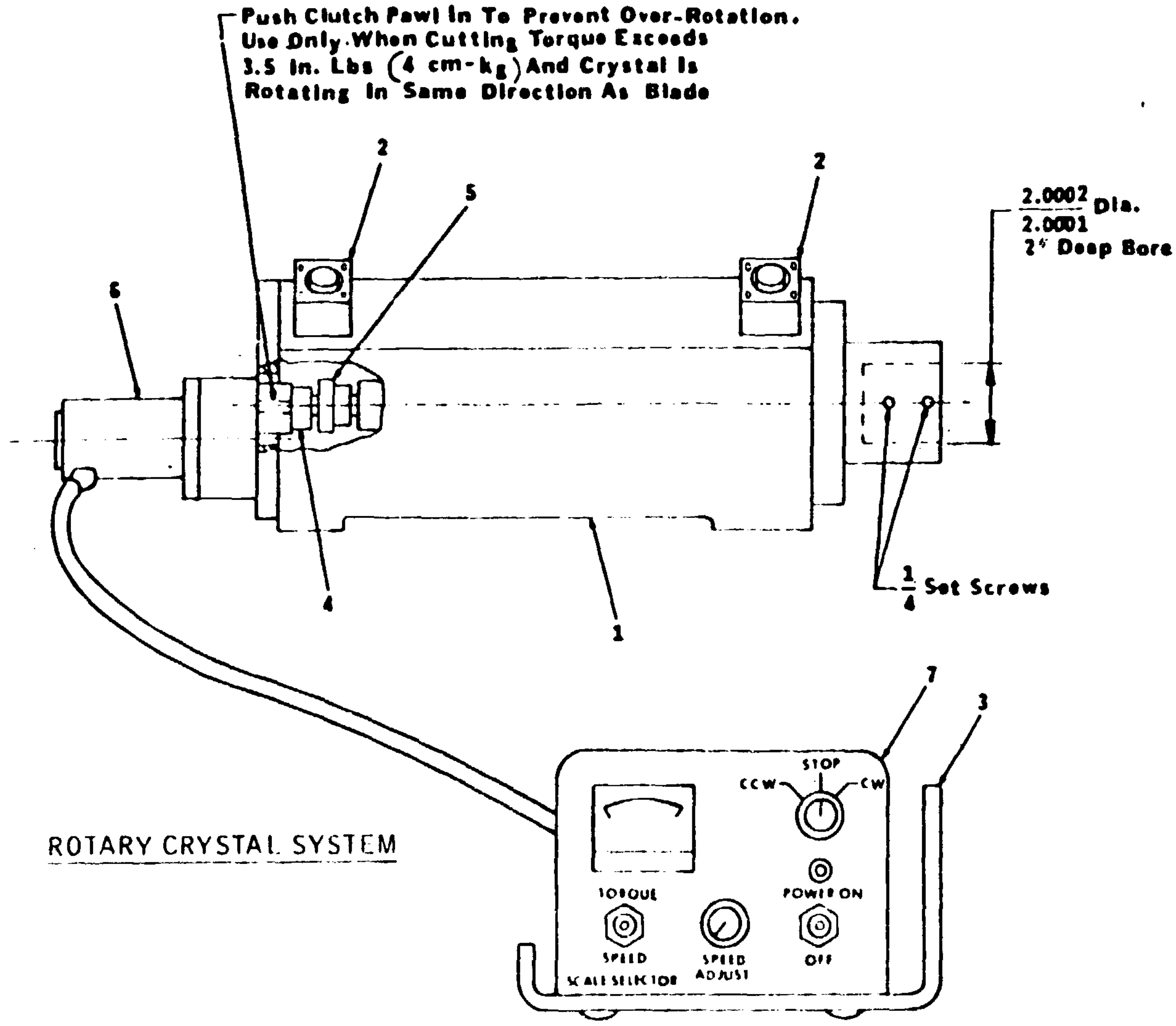
ROTARY CRYSTAL SYSTEM - SEA 4286

Rotation speed .15 to 150 RPM
Crystal capacity to 5" diameter on 16"/22" machines
Crystal length to 16"
Precision spindle and gear motor integral with mounting block; fits into ingot box in normal spring loaded manner. Gear motor provides full torque 20 in-# even at lowest speed; cogging free output torque; speed regulation better than 1% of set speed over full load variation; overload protection; CW and CCW Rotation Preprogrammed cam shaped to suit; over rotation protection. Crystal rotates only during down stroke.

CONTROLS LOCATED ON MAIN CONTROL PANEL AND CONSIST OF:

- **Toggle switch for manual feed or programmed feed**
- **Potentiometer for RPM control on gear motor control box**

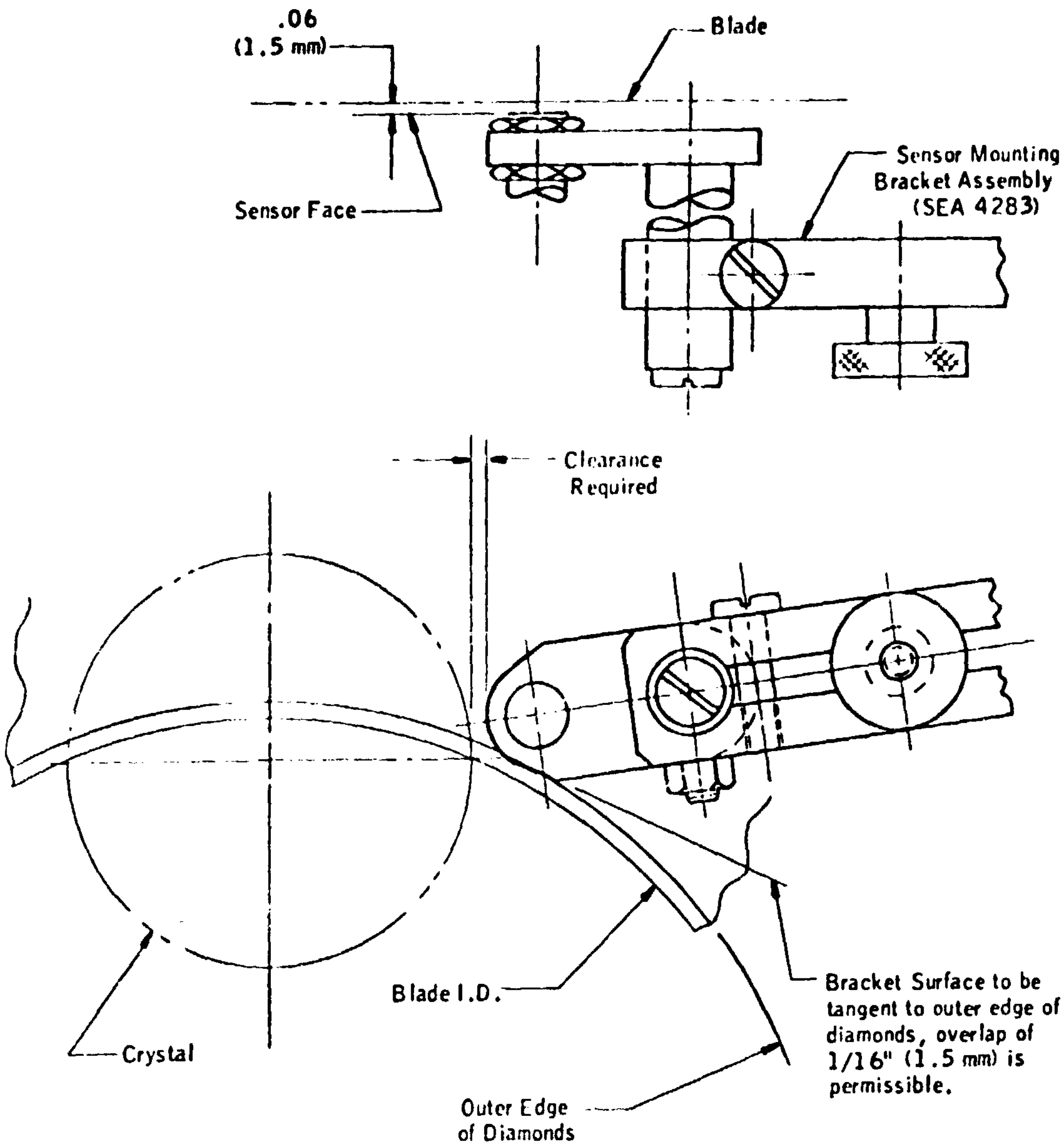
ROTARY CRYSTAL SYSTEM



ROTARY CRYSTAL SYSTEM

Item	Description
1	Rotary Crystal Assembly
2	Plunger Assembly
3	Controller Mounting Bracket
4	Slip Clutch
5	Coupling Assembly
6	Motor
7	Motomatic Control

DYNATRACK SENSOR ALIGNMENT



I.D. BLADE DEVELOPMENT

TECHNIQUES FOR LOW-KERF I.D. BLADES:

1. GRINDING OF THE I.D.
2. CONTROLLED PLATING TO MINIMIZE THICKNESS.
3. STANDARD SINGLE PLATING OPERATION WITH REDUCED PLATING TIMES.
4. STANDARD DOUBLE PLATING OPERATION WITH REDUCED PLATING TIMES.

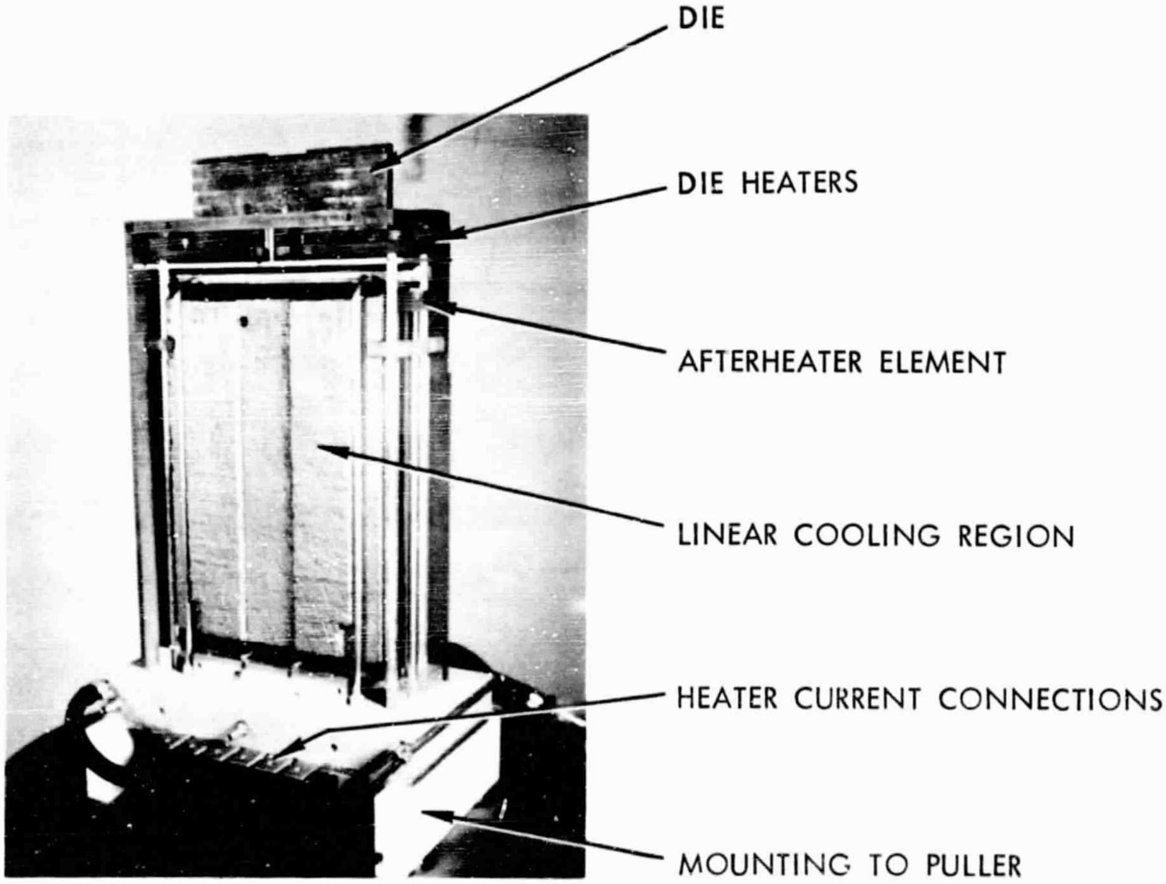
PLANNED WORK

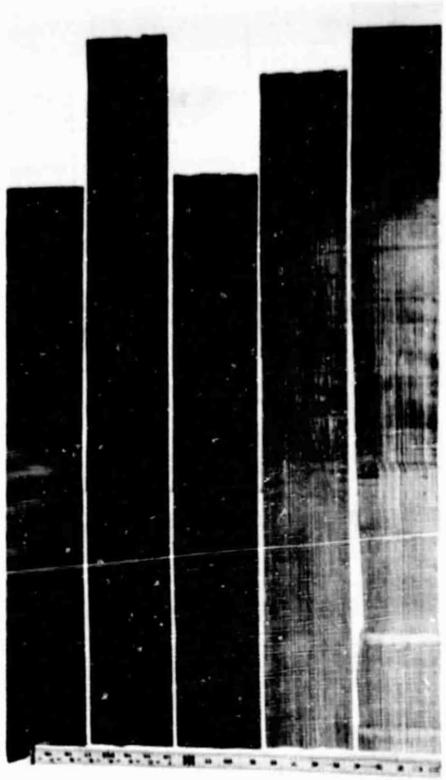
1. ROTATIONAL SLICING RUNS TO OPTIMIZE FEED AND ROTATION PROGRAMS.
2. LOW-KERF, LOW-THICKNESS RUNS DURING CRYSTAL ROTATION.

LARGE-AREA SILICON SHEET BY EFG

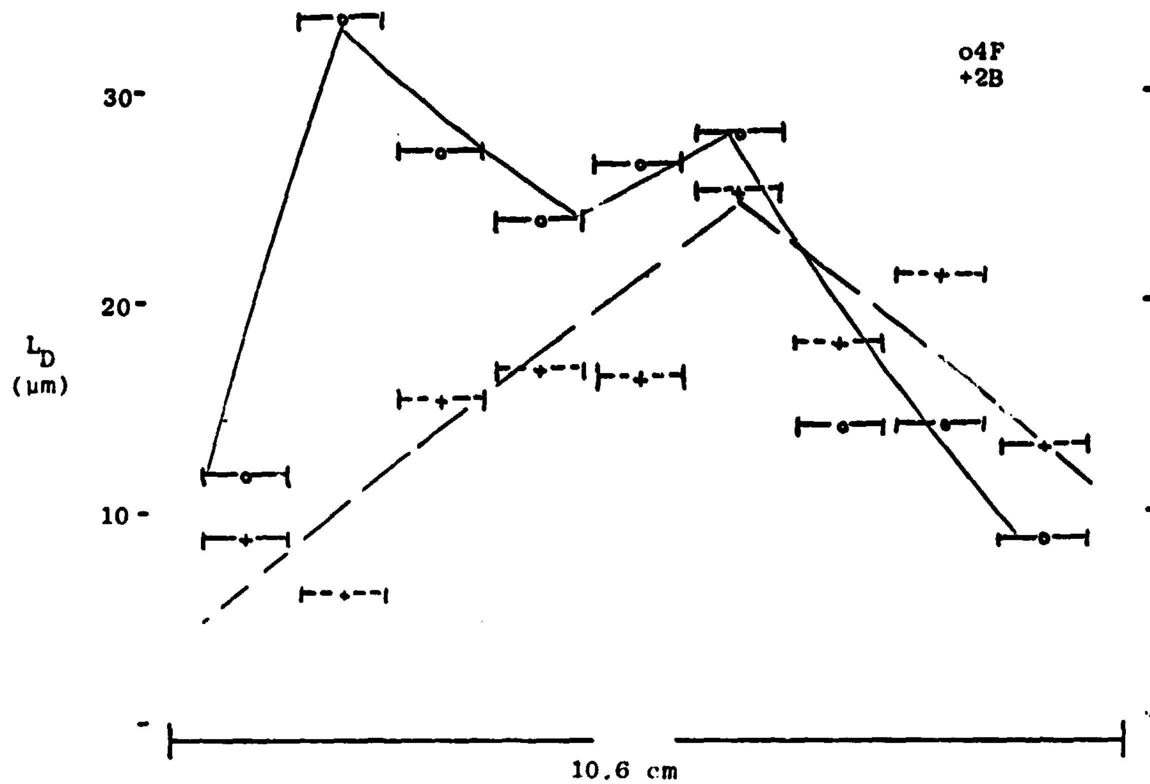
MOBIL TYCO SOLAR ENERGY CORP.

10-cm CARTRIDGE WITH SIDE WALL AND COVER REMOVED





Ten meters of 10-cm-wide EFG ribbon segments. These ribbons were grown from the newly designed cartridge setup in Machine JPL No. 3A using continuous melt replenishment and a growth speed of 3.5 cm/min



Distribution of diffusion length values across the width of a 10 cm cartridge grown EFG ribbon. Second clean run with the newly designed 10 cm growth cartridge. Growth speed 3.5 cm/min. ├─ ─┤ indicates the width of the Schottky barrier which was measured. Between the 2B and 4F segments of the ribbon, gas flow to the cartridge was decreased by 50% and the die top temperature, and thus the ribbon thickness was changed.

FURNACE DESIGN AND CRYSTAL GROWTH VARIABLES STUDIED IN JPL No. 1

Materials of Construction

a. Graphite vs. quartz crucibles

b. Cold shoe removal

c. Molybdenum shield (main zone and die top) replacement by graphite.

Die Design Studies

a. Central capillary vs. distributed multi-capillary

b. Saw cut with constriction (channel width) vs. central capillary

c. Melt feed channel size

d. Displaced die top

e. Side channel die

f. Radius displaced dies with uniform and nonuniform die top flats

Speed Effect Studies

a. Cold shoe vs. no cold shoe growth over a comparable speed range

b. Effect of cold shoe thickness, spacing and height above die on speed

Atmosphere Studies

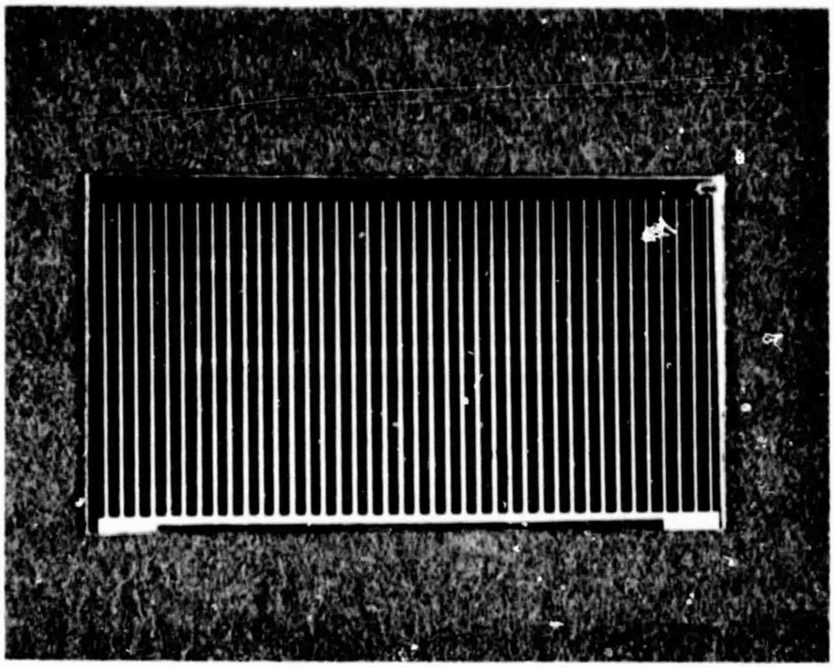
a. Graphite vs. quartz crucibles

b. Oxygen influence on growth stability and SiC particle formation

c. Main zone argon purge rate effects.

Summary of Solar Cell Data for Ribbons Grown from Furnace No. 1. All Cell Areas ≈ 45 cm^2. ELH Light 100 mW/cm^2. 28°C.

Cell No.	Growth Conditions	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)	L_n (μm)	Note
18-117-1	Graphite Crucible	18.04	.530	.686	6.56	26	
-2	Displaced Die	17.04	.515	.612	5.37		
-3	Central Channel	17.70	.506	.694	6.22		
Average		17.59	.517	.664	6.05		
18-118-1	Graphite Crucible	17.70	.523	.681	6.30	25	
-2	Displaced Die	17.31	.520	.638	5.74		
-3	Central Channel	17.59	.530	.70	6.52		
Average		17.53	.524	.673	6.19		
18-119-1	Graphite Crucible	17.92	.521	.633	5.91	19	
-2	Flat Die	15.93	.512	.650	5.30		
	Central Channel						
Average		16.93	.517	.642	5.61		
18-121-1	Graphite Crucible	17.50	.503	.651	5.73	22	No AR Coating
-2	Displaced Die	16.74	.501	.686	5.76		
-3	Open Channel	15.24	.496	.710	5.37		
-4		17.74	.510	.662	6.00		
Average		16.81	.503	.677	5.72		
18-123-1	Quartz Crucible	15.95	.524	.664	5.55	24	
-2	Displaced Die	17.34	.506	.550	4.83		
-3	Open Channel	17.34	.526	.633	5.77		
-4		17.97	.531	.669	6.38		
Average		17.15	.522	.629	5.63		
18-125-1	Graphite Crucible	18.81	.501	.683	6.43	26	
-2	Displaced Die	16.48	.525	.666	5.76		
-3	Open Channel	17.56	.492	.644	5.56		
Average		17.62	.506	.664	5.92		
18-126-1	Quartz Crucible	16.79	.522	.642	5.33	24	
-2	Displaced Die	18.07	.531	.674	6.47		
-3	Open Channel	17.46	.531	.683	6.33		
Average		17.44	.528	.666	6.14		
18-133-1	Graphite Crucible	26.92	.552	.646	9.61	32	AR Coated
-2	Displaced Die	26.08	.549	.651	9.32		
-3	Open Channel	26.97	.551	.650	9.65		
-4		26.01	.545	.606	8.58		
Average		26.50	.549	.638	9.29		



The standard 5 x 10 cm^2 solar cell configuration used to evaluate material grown in both Furnace No. 1 and No. 3A

CONTRIBUTION OF VARIOUS METALLIZATION LOSS MECHANISMS TO DECREASED SOLAR CELL PERFORMANCE IN LARGE AREA CELLS.

	Design				Actual	
	2.5 x 10 cm^2		5 x 10 cm^2		5 x 10 cm^2	
Loss Mechanism	(mW)	(%)	(mW)	(%)	(mW)	(%)
Finger Resistivity	0.6	0.3	6.4	1.3	13.2	2.6
Bus Bar Resistivity	0.2	0.1	1.0	0.2	6.0	1.2
Shadowing	24.0	10.9	43.5	8.7	~70	~14.0

PROPERTIES OF SURFACE FILMS GENERATED ON EFG RIBBON IN JPL NO. 1 DURING RECENT AMBIENT GAS EXPERIMENT

I-R Spectrophotometry:

Absorption peaks at: 790 cm^{-1} → Si-C bond.
1100 cm^{-1} → Si-O bond.

After removal of film by etching, 790 cm^{-1} peak disappears, 1100 cm^{-1} peak diminishes.

Etching in HF:

Removes part of the film to make a very fine grained dendritic structure visible.

X-Ray Diffraction:

Film fragments undercut during etching process reveal cubic and hexagonal SiC.

General Conclusions:

The film formed is a mixture of SiC and SiO or SiO_2. Once this film is solidly established on the growing ribbon surface, discrete SiC particles are no longer present.

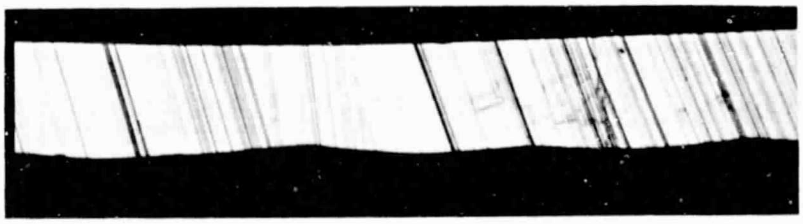
C-3

STRUCTURE OF RIBBON

1(a)

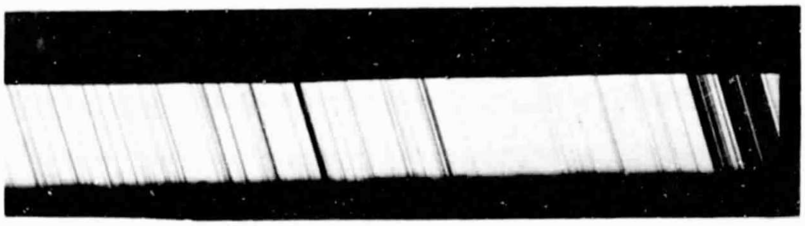
1(b)

1. Surface view of ribbon: (a) typical "equilibrium defect structure" of EFG ribbon, and (b) large-grained structure obtained under sharply reduced inert gas flows. 0.7X



2(a)

2(b)



2(c)

2. (a) Typical cross-sectional "equilibrium defect structure" obtained in ribbon from Machine 18. (b) Cross-sectional structure in large-grained material. (c) "Best" cross-sectional structure obtained under "normal" conditions. 45.2X

Summary of Solar Cell Data for Ribbons Grown from Furnace 18 During Rece[illegible] Ambient Gas Experiments. Cells are Nominally 5 cm x 10 cm, Areas in cm^2 are Given in Table.

Cell No.	Area (cm^2)	I_{rv} (mA/cm^2)	V_{oc} (V)	I_p (mA)	I_{sc} (mA/cm^2)	FF	P (mW/cm^2)
143-2	44.48	0.166	0.548	888.2	22.38	0.741	9.10
-4	44.48	0.203	0.552	969.8	24.00	0.751	9.94
-5	44.48	0.535	0.550	1041.9	25.54	0.763	10.72
-7	44.48	0.350	0.561	1082.9	26.19	0.778	11.43
148-3	44.48	0.203	0.555	1010.5	25.74	0.750	10.72
-4	44.48	0.147	0.553	1030.5	24.88	0.792	10.91
-5	44.48	0.147	0.549	1035.1	25.21	0.762	10.54
-5	44.48	0.004	0.556	1066.3	25.77	0.778	11.15
-6	44.48	0.004	0.556	1078.3	25.85	0.781	11.21
150-1	57.71	0.753	0.559	1342.3	25.94	0.731	10.59
-2	57.71	2.330	0.553	1158.0	23.30	0.705	9.08
-3	57.71	1.023	0.569	1334.4	26.27	0.712	10.63
-4	46.73	0.281	0.565	1131.1	27.36	0.744	11.49
-5	46.90	0.472	0.561	1117.7	26.68	0.712	10.65
-6	57.71	0.298	0.564	1298.6	25.64	0.730	10.54
-7	57.71	0.398	0.570	1374.9	26.13	0.744	11.07
-8	57.71	0.469	0.565	1383.1	26.99	0.707	10.79
-9	57.71	0.824	0.566	1369.4	26.39	0.716	10.68
-10	57.71	1.577	0.568	1297.5	26.51	0.704	10.60
-11	57.71	0.426	0.570	1382.7	26.51	0.746	11.28
-12	57.71	1.876	0.564	1230.8	24.95	0.700	9.84
-13	57.71	1.165	0.563	1270.7	25.72	0.715	10.35
-14	57.71	0.455	0.558	1350.0	25.92	0.729	10.54
-15	57.71	0.199	0.558	1198.0	25.34	0.648	9.16

MULTIPLE GROWTH DEMONSTRATION RUN 16-187

May 21, 1979; 9:20 a.m. - 12:40 a.m.; 1 Operator

Station No.	1	2	3	4	5
Total Quantity (meters)	30.4	29.6	29.9	31.1	27.7
Total Duration of Growth (mintues)	910	890	825	919	829
Percentage of 15.5-Hour Run Period* Actually Growing	97.8	95.7	88.7	98.8	89.1
Number of Freezes	3	5	6	3	4
Longest Duration of Continuous Growth (mintues)	692	331	505	490	508
Average Growth Rate (cm/minute)	3.34	3.33	3.62	3.38	3.34

*The run period begins when the operator starts pulling the first ribbon and ends when the five growth stations run out of silicon more or less simultaneously when replenishment ceases. Three-hour heat-up time preceding first start (could be automated).

Summary of Solar Cell Data for Ribbons Grown from Furnace 16 During Multiple Demonstration Run. All Cell Areas = 44.1 cm^2.

Cell No.	J_{sc} (mA/cm^2)	V_{oc} (Volt)	FF	η (%)	Note
187-1-1	23.30	0.527	0.699	8.63	
-2	23.20	0.531	0.695	8.56	
-3	22.79	0.531	0.673	8.15	
-4	23.26	0.536	0.687	8.56	
-5	24.43	0.545	0.713	9.49	
-6	22.97	0.534	0.730	8.96	Cartridge No. 1
-7	23.00	0.538	0.718	8.89	
-8	23.75	0.533	0.651	8.24	
-9	23.18	0.532	0.700	8.63	
Average	23.32	0.534	0.696	8.68	
187-3-1	23.37	0.531	0.731	9.06	
-2	23.89	0.536	0.705	9.03	
-3	23.67	0.541	0.711	9.12	Cartridge No. 3
-4	23.90	0.535	0.694	8.86	
-5	23.14	0.542	0.729	9.54	
Average	23.79	0.537	0.714	9.12	
187-4-1	22.64	0.523	0.689	8.15	
-2	23.14	0.528	0.684	8.37	
-3	23.54	0.530	0.701	8.74	
-4	22.77	0.534	0.736	8.96	
-5	23.39	0.526	0.665	8.19	Cartridge No. 4
-6	22.74	0.529	0.716	8.62	
-7	23.41	0.536	0.706	8.86	
-8	22.56	0.536	0.706	8.53	
Average	23.02	0.534	0.70	8.55	
187-5-1	23.74	0.534	0.672	8.52	Cartridge No. 5

SILICON WEB

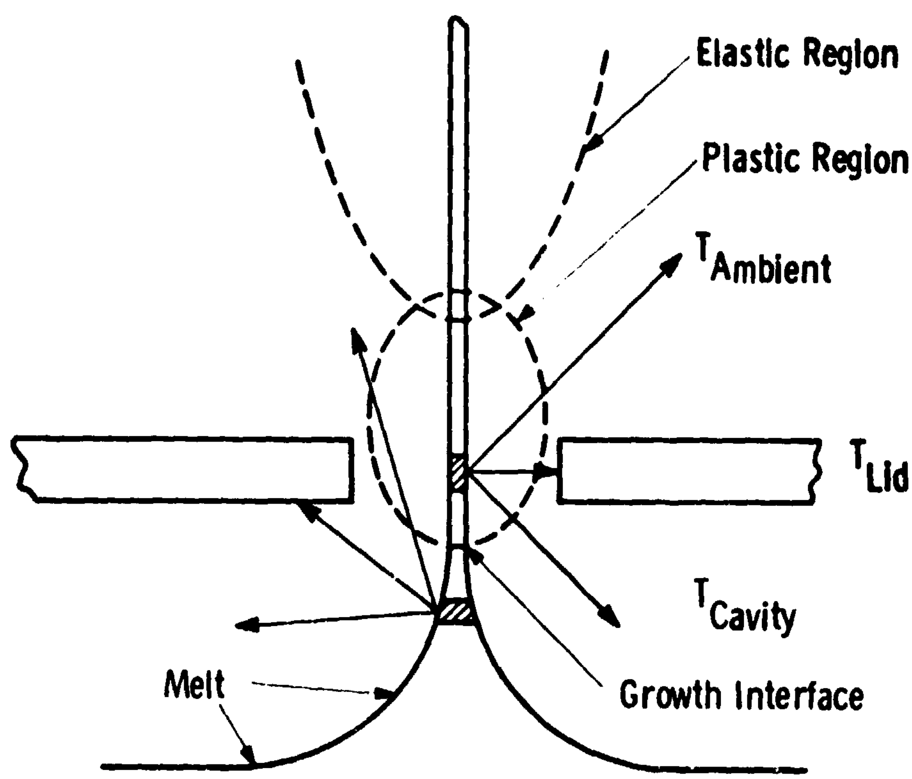
WESTINGHOUSE R&D CENTER

TECHNOLOGY STATUS

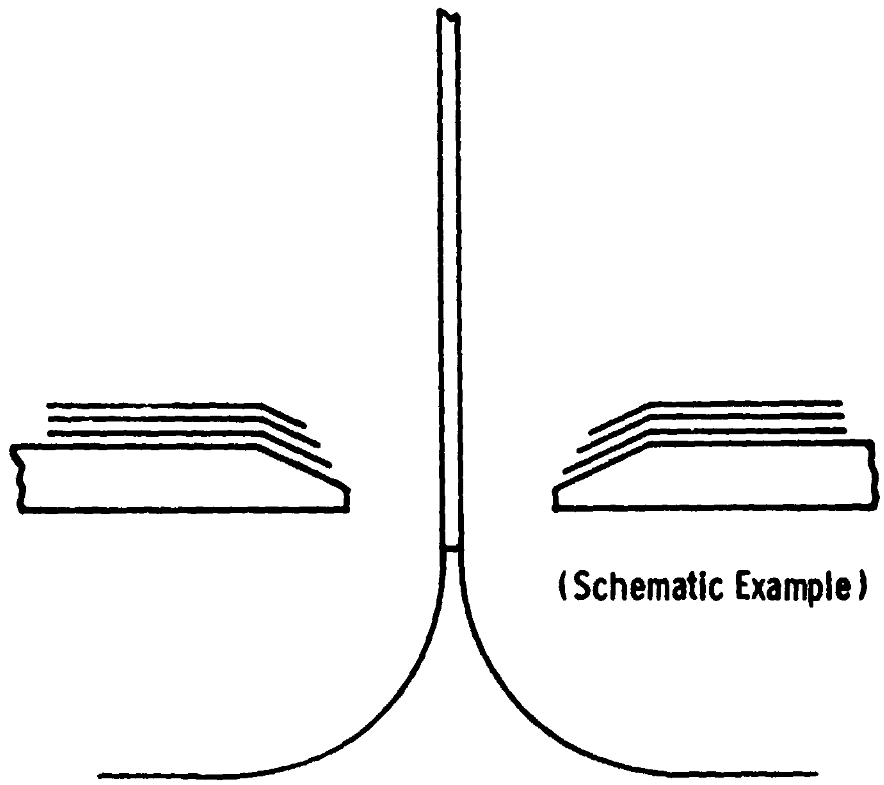
Area Throughput - Maximum Demonstrated 27. 1cm^2/minute

Melt Replenishment - Polysilicon Mechanically Fed Simultaneously With Growth Of High Quality Web Without Interruption For Periods Up To Two Hours.
- Melt Level Sensor Operated In Bench Test Version

Cell Efficiency - Average ~ 13% AM1
- Maximum 15.5% AM1



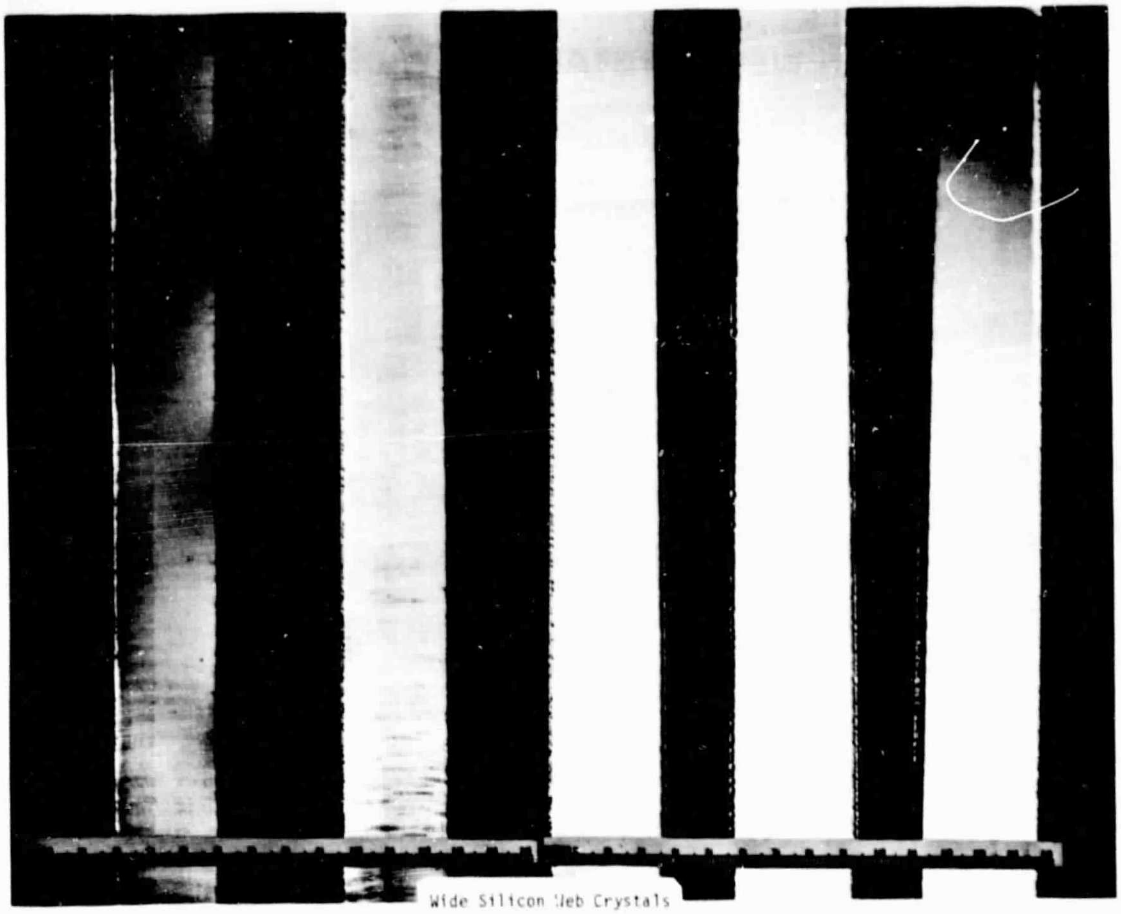
Silicon Web Area Growth Rate and Quality Are Controlled By the Thermal Environment Near the Growth Interface



Silicon Web Improved Area Growth Rate Is Attained By Passive Thermal Shields Designed To Provide Better Combined Conditions For Width, Speed And High Quality. This Method Is An Alternative To Water Cooled After-Trimmers And The Associated Problems. With This Method Web Has Been Grown Wider And Faster With High Quality Than Ever Before.

THROUGHPUT PROGRESS

- Maximum Demonstrated Area Growth Rate, 27.1 cm^2/min (37% Increase)
- Maximum Demonstrated Width Of Growth Without Deformation, > 44 mm (25% Increase)

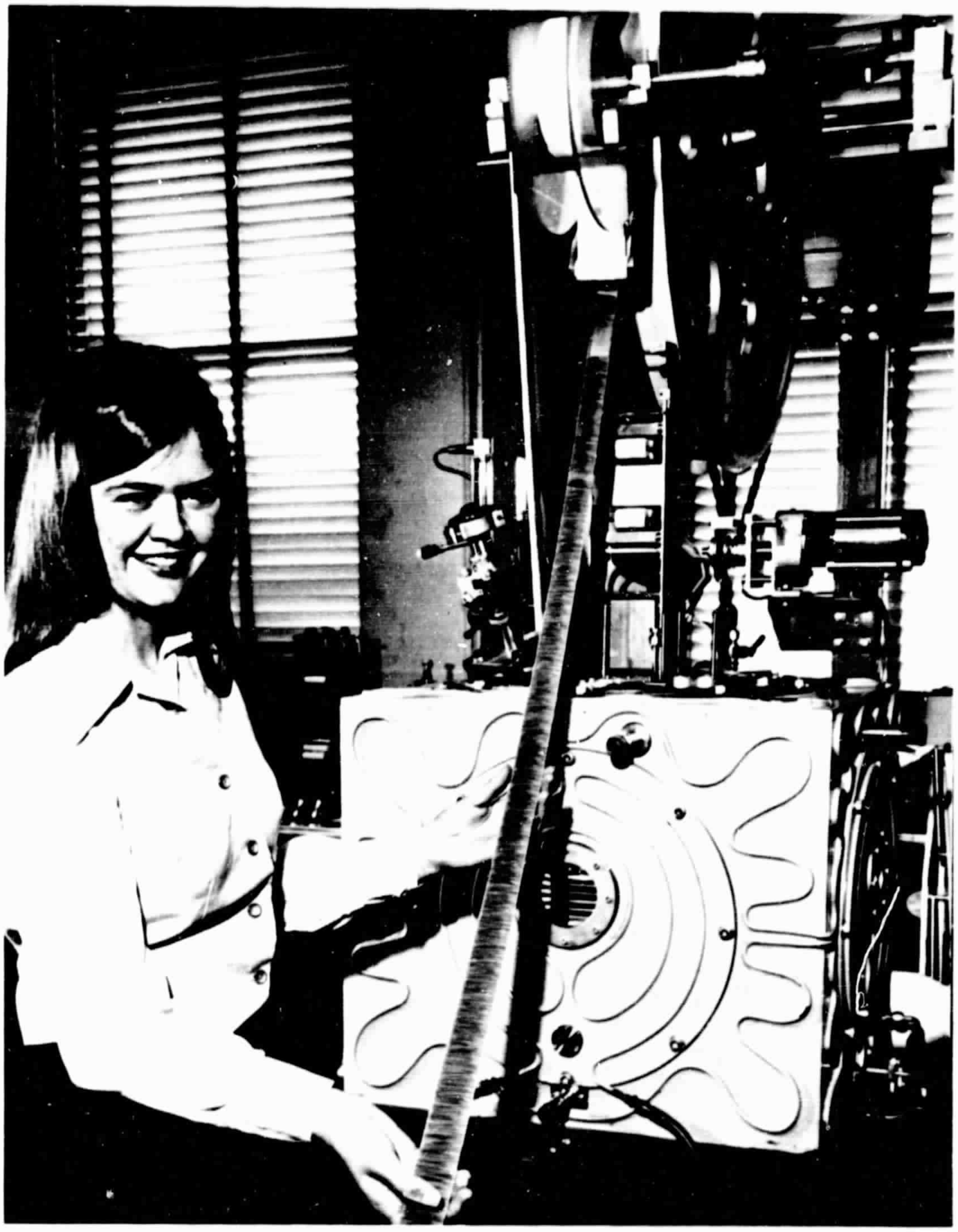


Wide Silicon Web Crystals

CONTINUOUS MELT REPLENISHMENT IS ESSENTIAL

- To Provide Long Periods Of Uninterrupted Growth
- To Obtain Thermal Conditions For Maximized Throughput
- To Sustain Growth At Maximized Throughput
- To Satisfy Economic Requirements

SILICON WEB CRYSTAL 4 cm WIDE



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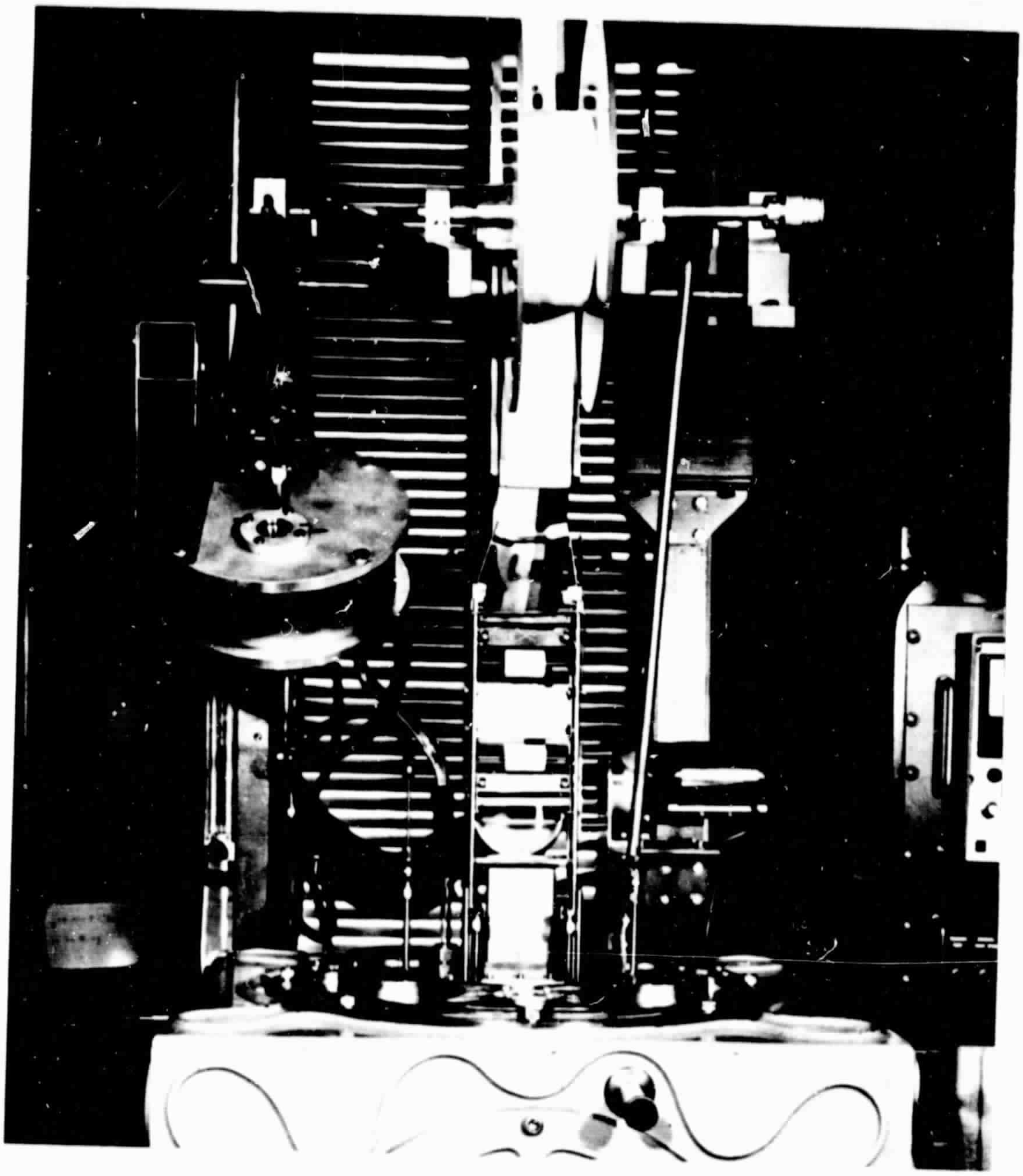
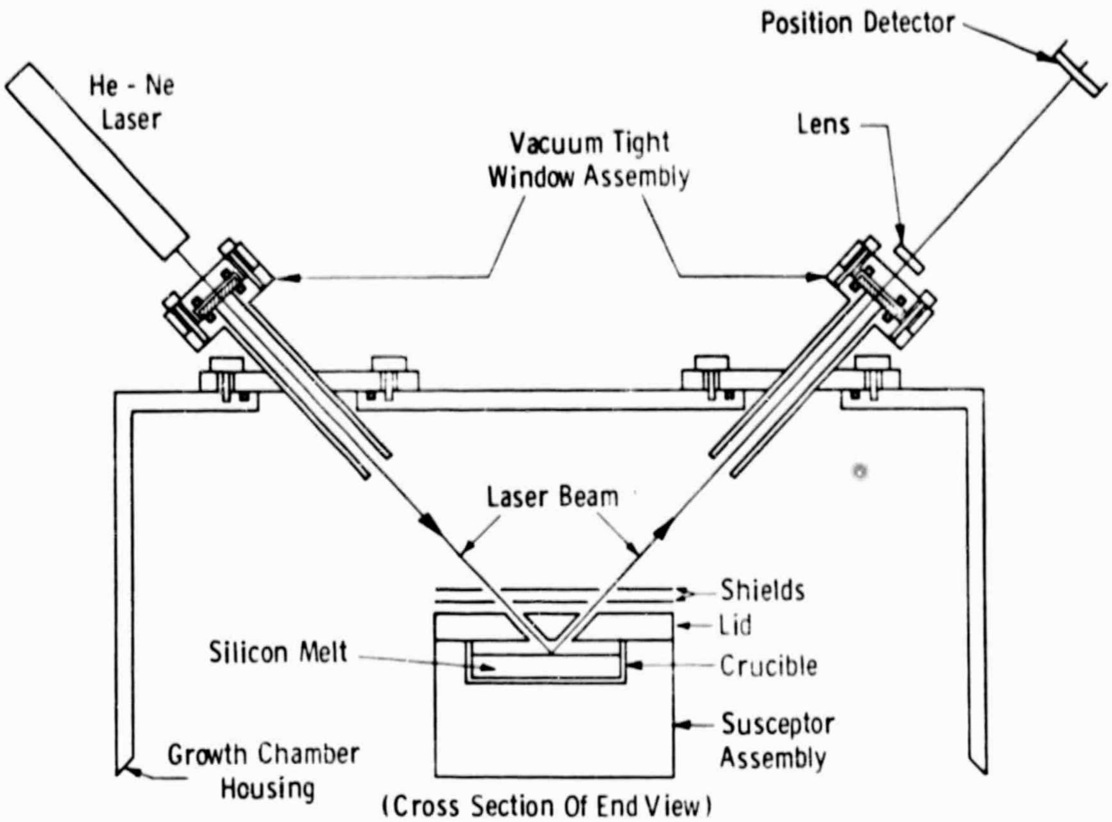
MECHANIZED PELLET FEEDER MOUNTED ON RE SILICON WEB SURFACE



SCHEMATIC OF MELT LEVEL SENSOR

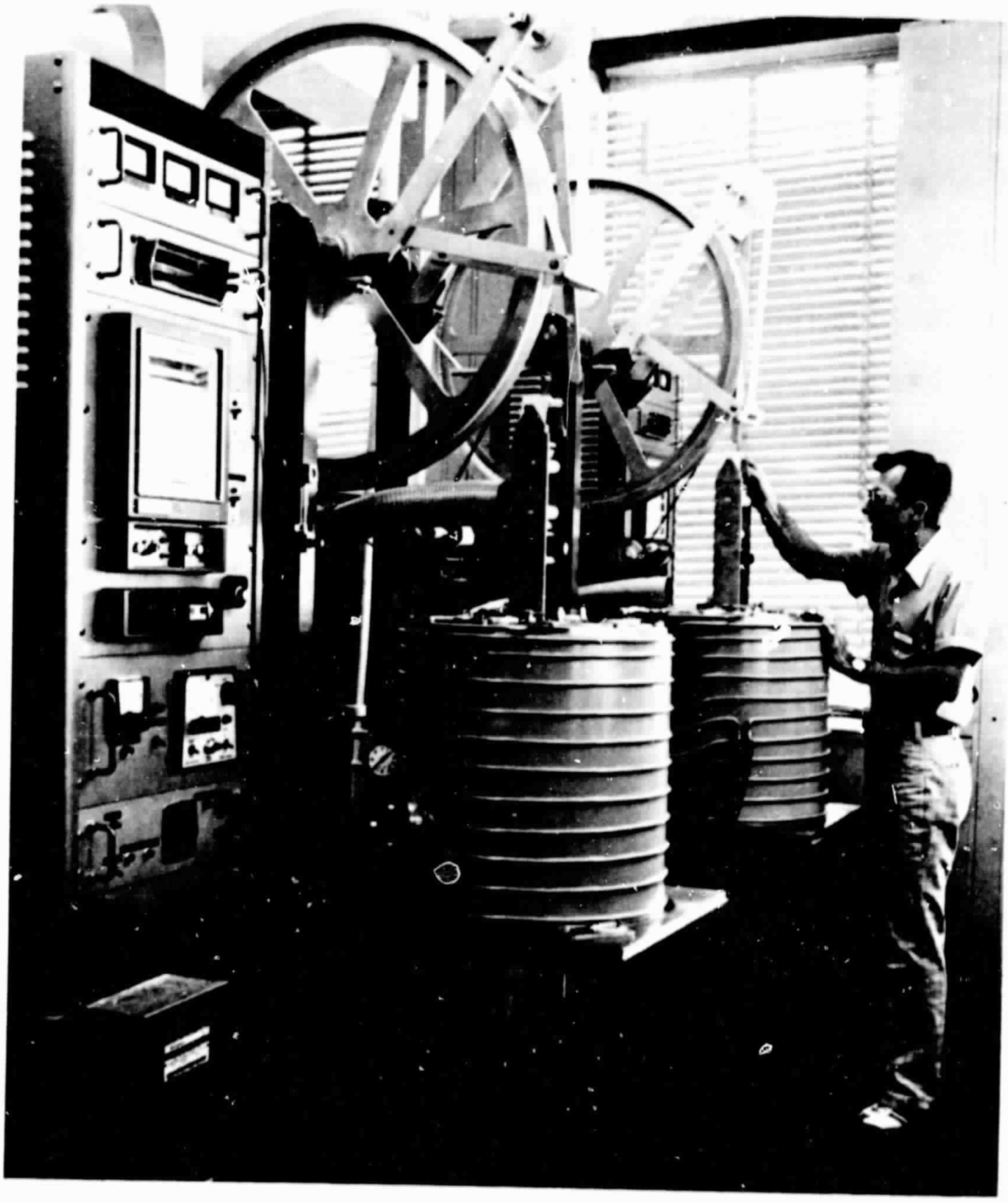


(Cross Section Of End View)

MELT REPLENISHMENT PROGRESS

- Uninterrupted Simultaneous Melt Replenishment And Growth With Mechanized Pellet Feeder, 2 Hours Demonstrated
- **Melt Level Sensing Under Development. Concept Selected And Demonstrated In Bench Test Version. Assembly And Installation On Schedule**

NEW WESTINGHOUSE SILICON WEB GROWTH FURNACES



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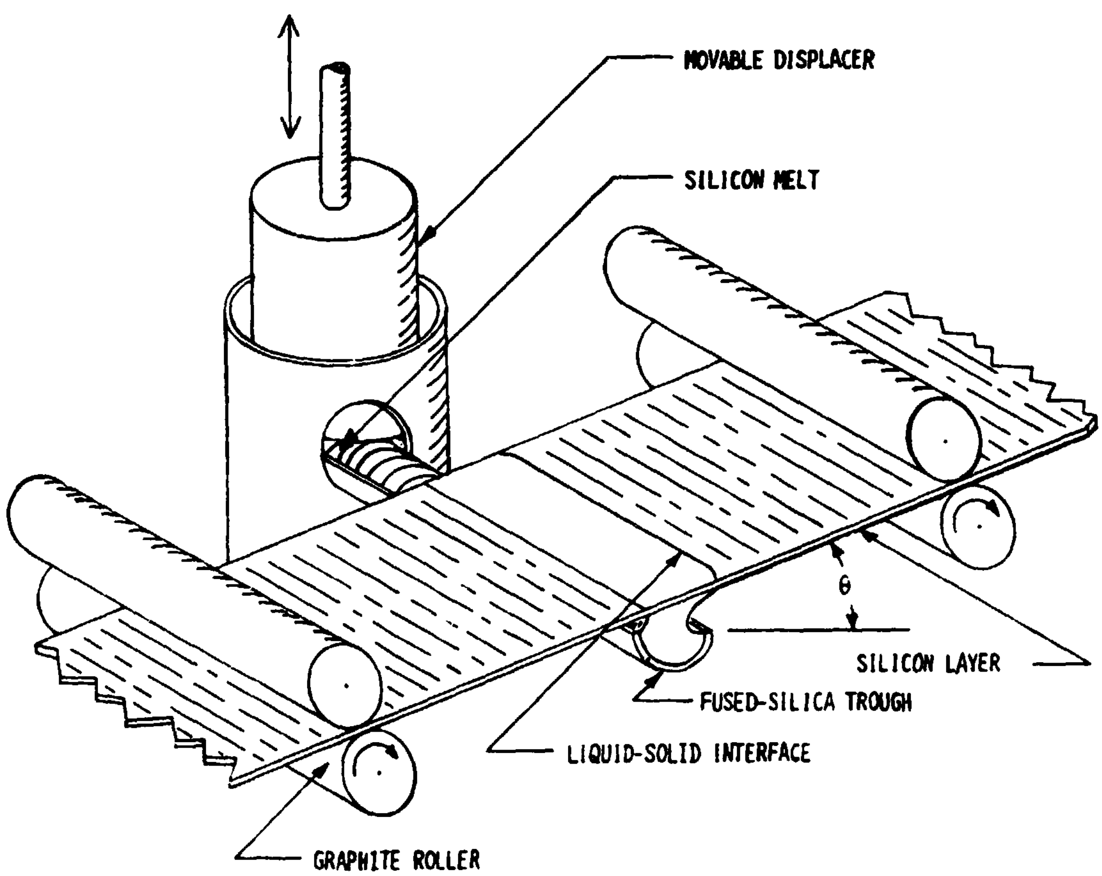
SUMMARY

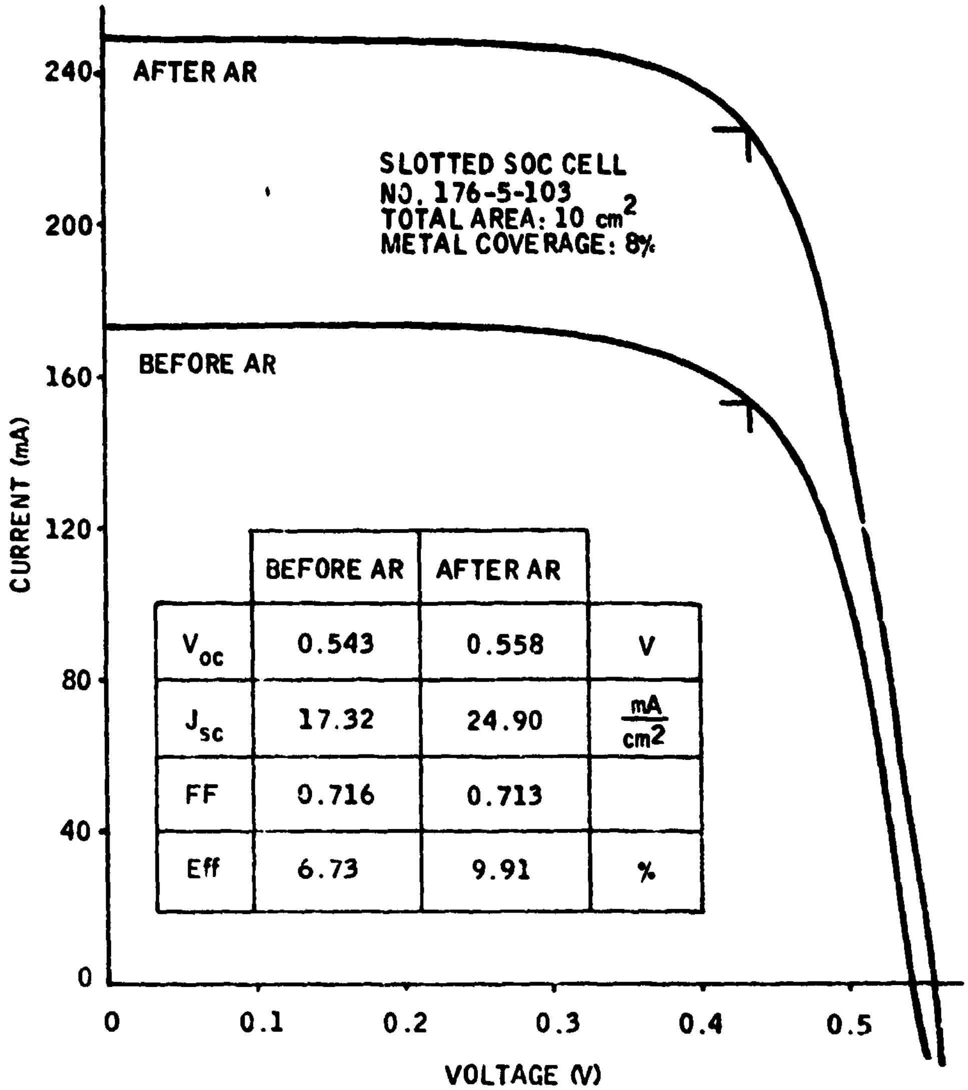
- Area Throughput Rate Increased To 27.1 cm^2/min., Maximum Demonstrated
- Width Without Deformation Increased To 44 mm, Maximum Demonstrated
- Simultaneous Melt Replenishment And Web Growth Increased To 2 Hours, Maximum Demonstrated
- Liquid Level Sensor Assembly And Installation In Progress
- Two New Westinghouse Built Web Growth Furnaces Placed In Service

SILICON ON CERAMIC

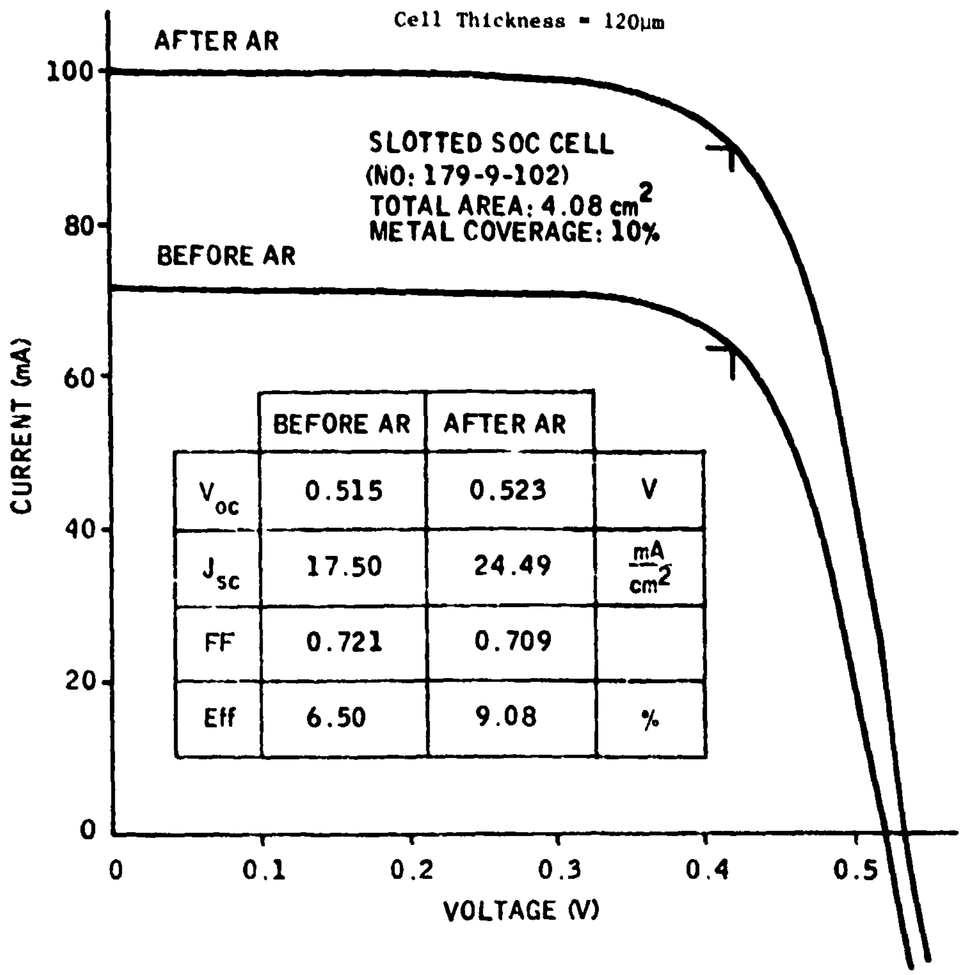
HONEYWELL CORPORATION

GOAL	STATUS
CONTINUOUS COATING	SCIM PRINCIPLE DEMONSTRATED LARGE GRAINS $L_N \sim 30$ μM.
11% CELL EFFICIENCY	9.91% ON 10 CM^2 CELL 9.08% ON ~ 120 μM THICK CELL.
0.2-0.3 CM/SEC GROWTH SPEED	100 μM THICK AT 0.15 CM/SEC (NORMALLY ~ 15 μM WITHOUT COOLING)

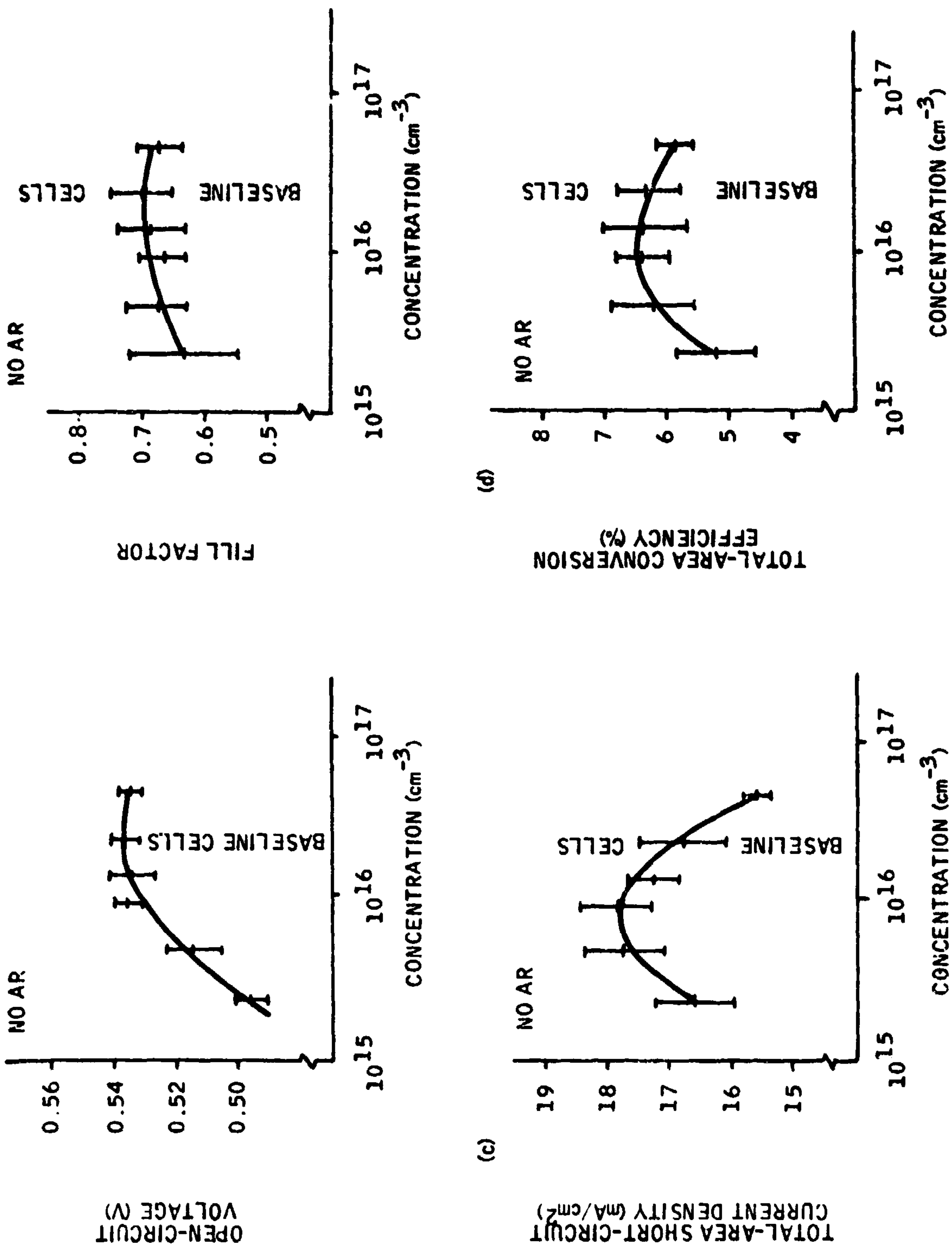


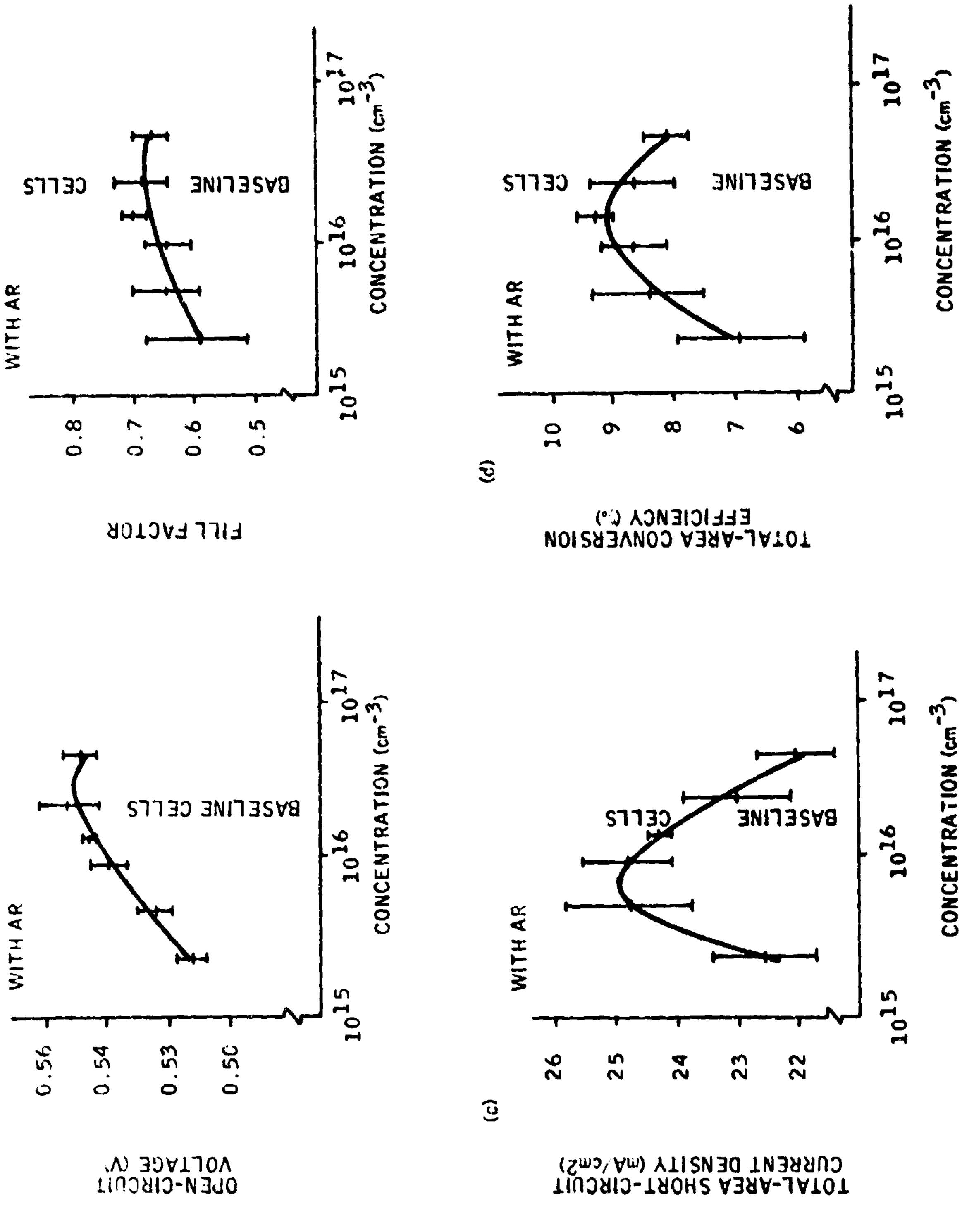


	BEFORE AR	AFTER AR	
V_{oc}	0.543	0.558	V
J_{sc}	17.32	24.90	$\frac{mA}{cm^2}$
FF	0.716	0.713	
Eff	6.73	9.91	%

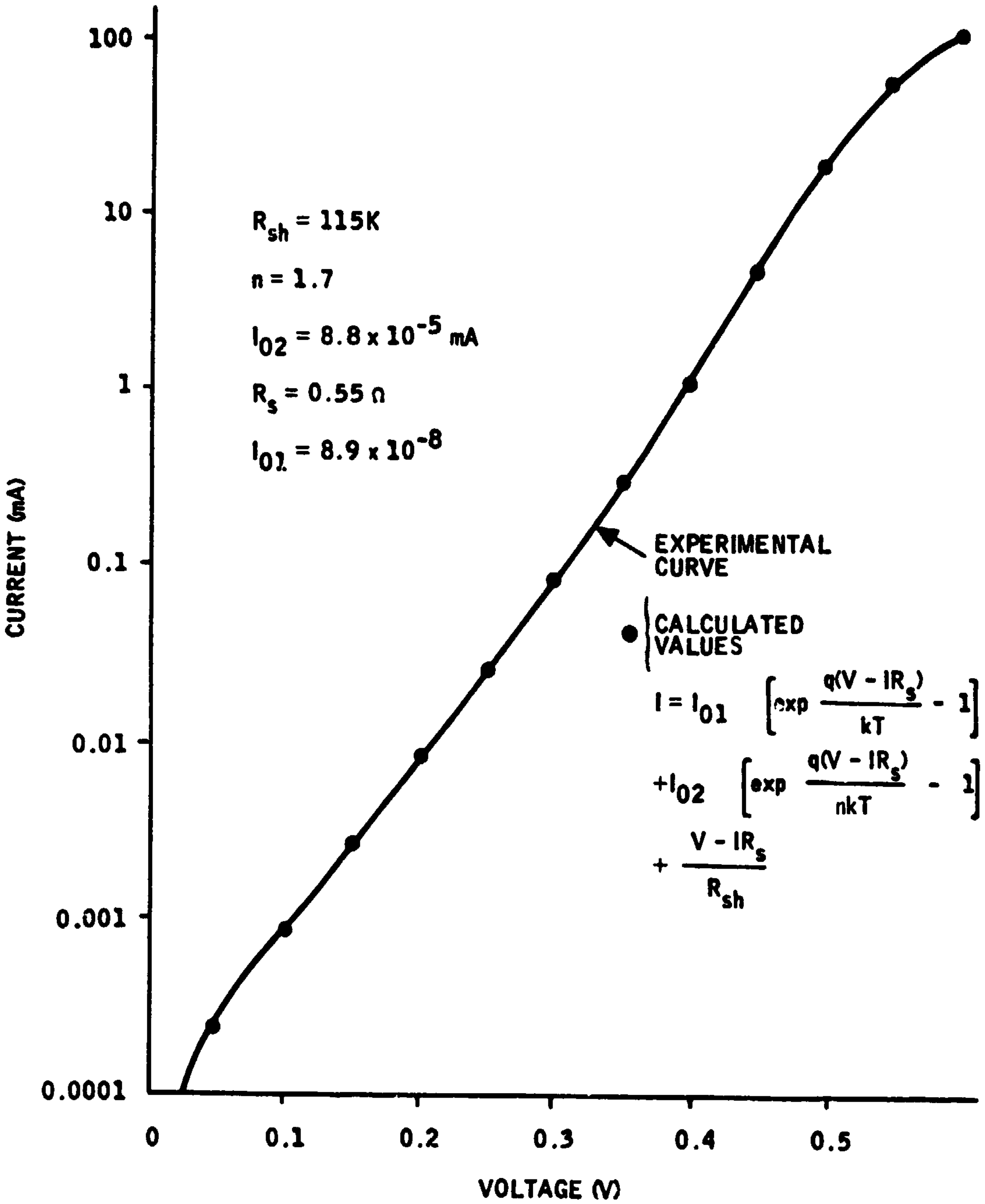


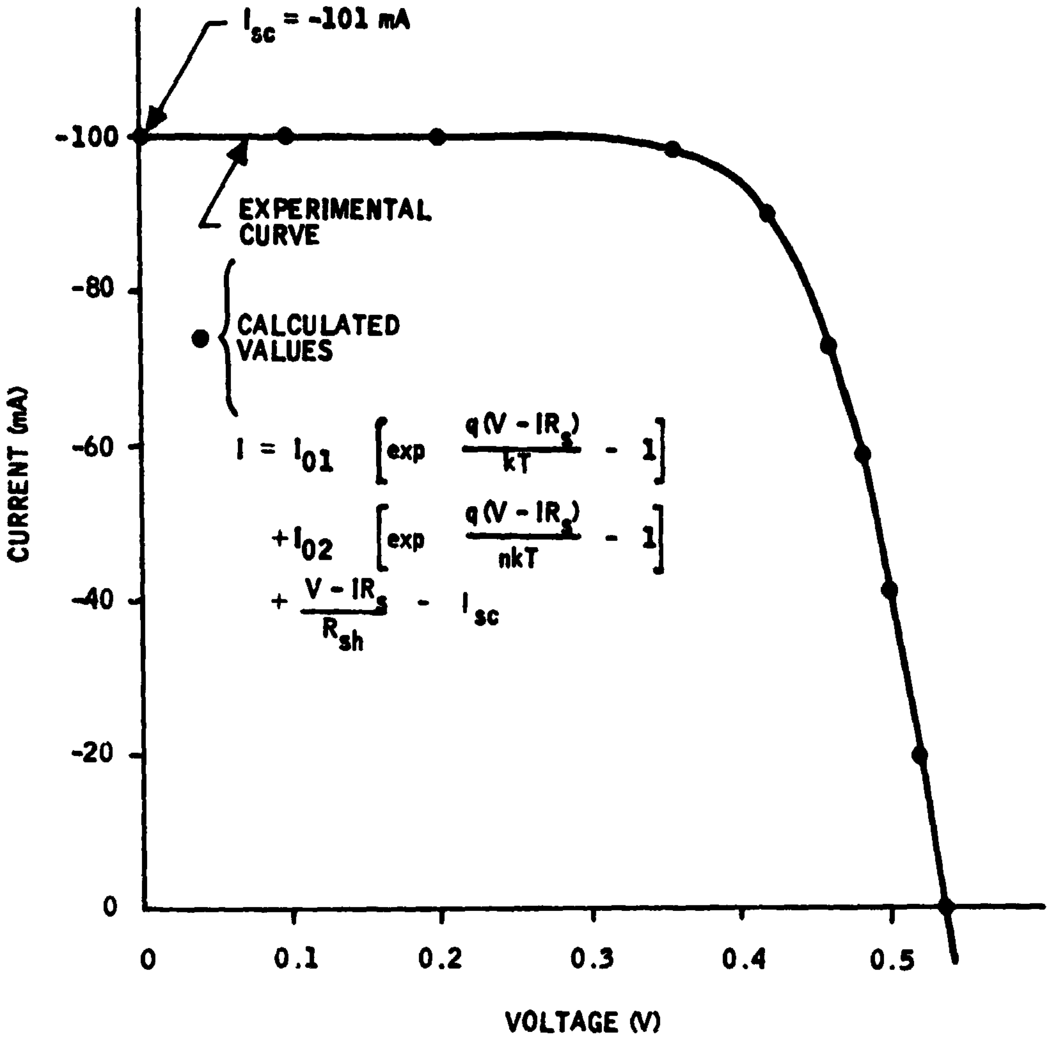
	BEFORE AR	AFTER AR	
V_{oc}	0.515	0.523	V
J_{sc}	17.50	24.49	$\frac{mA}{cm^2}$
FF	0.721	0.709	
Eff	6.50	9.08	%


FILL FACTOR
0.8
0.7
0.6
0.5
NO AR
BASELINE CELLS
10^15
10^16
10^17
CONCENTRATION (cm^-3)
TOTAL-AREA CONVERSION
EFFICIENCY (%)
(d)
8
7
6
5
4
OPEN-CIRCUIT
VOLTAGE (V)
0.56
0.54
0.52
0.50
TOTAL-AREA SHORT-CIRCUIT
CURRENT DENSITY (mA/cm2)
(c)
19
18
17
16
15

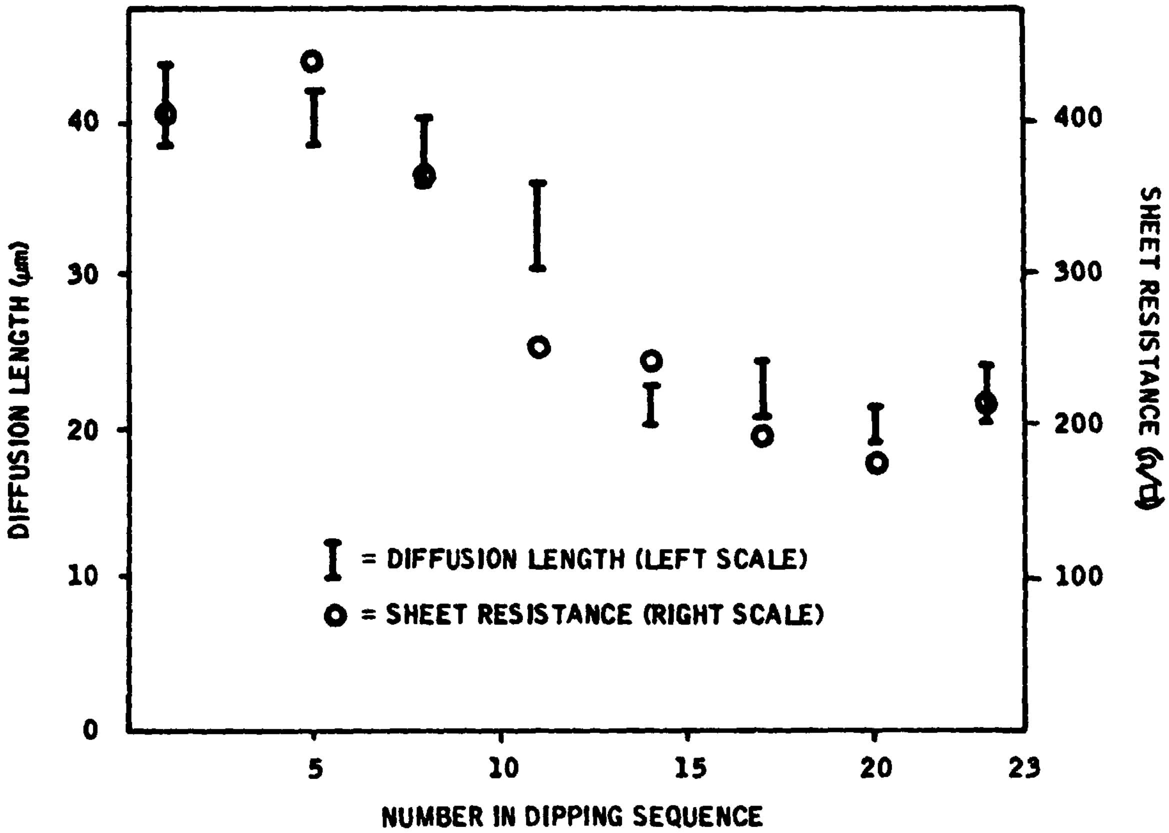


OPEN-CIRCUIT VOLTAGE (V)
FILL FACTOR
WITH AR
BASELINE CELLS
CONCENTRATION (cm-3)
(c)
TOTAL-AREA SHORT-CIRCUIT CURRENT DENSITY (mA/cm2)
(d)
TOTAL-AREA CONVERSION EFFICIENCY (%)

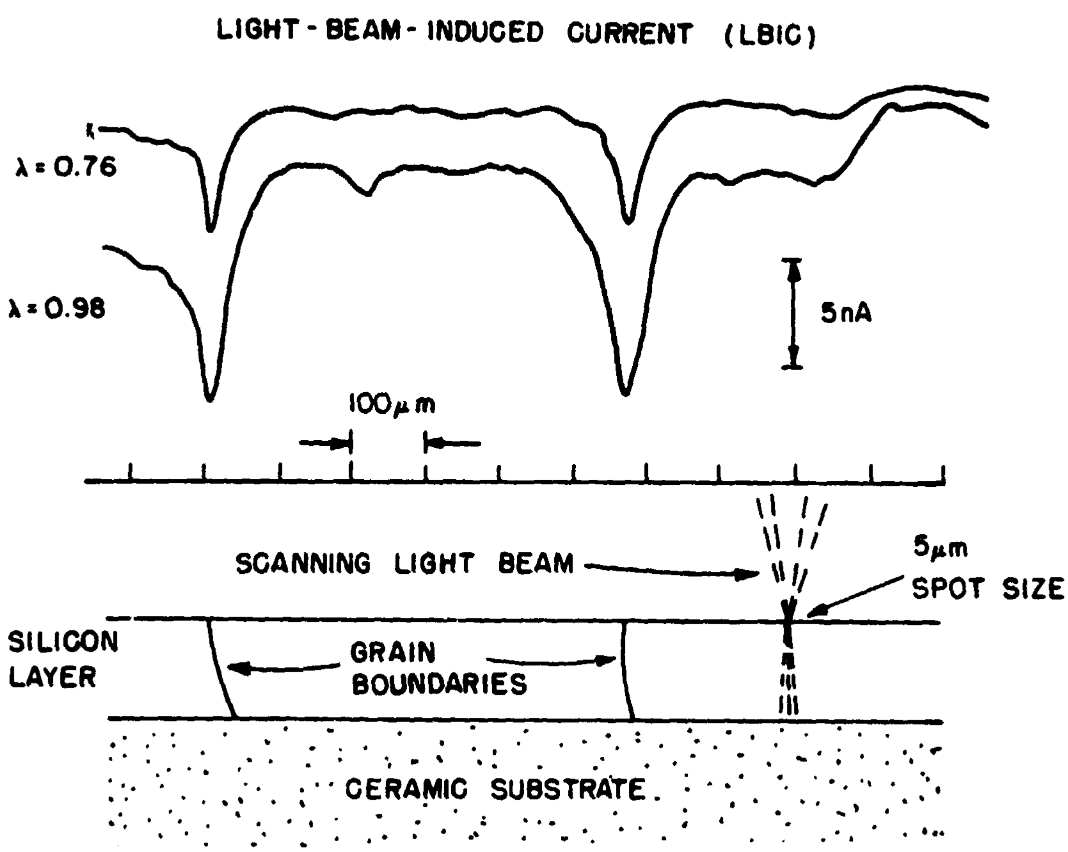

100
10
1
0.1
0.01
0.001
0.0001
CURRENT (mA)
0
0.1
0.2
0.3
0.4
0.5
VOLTAGE (V)
R_{sh} = 115K
n = 1.7
$I_{02} = 8.8 \times 10^{-5}$ mA
$R_s = 0.55\ \Omega$
$I_{01} = 8.9 \times 10^{-8}$
EXPERIMENTAL CURVE
CALCULATED VALUES
$I = I_{01}\left[\exp\frac{q(V-IR_s)}{kT} - 1\right] + I_{02}\left[\exp\frac{q(V-IR_s)}{nkT} - 1\right] + \frac{V-IR_s}{R_{sh}}$



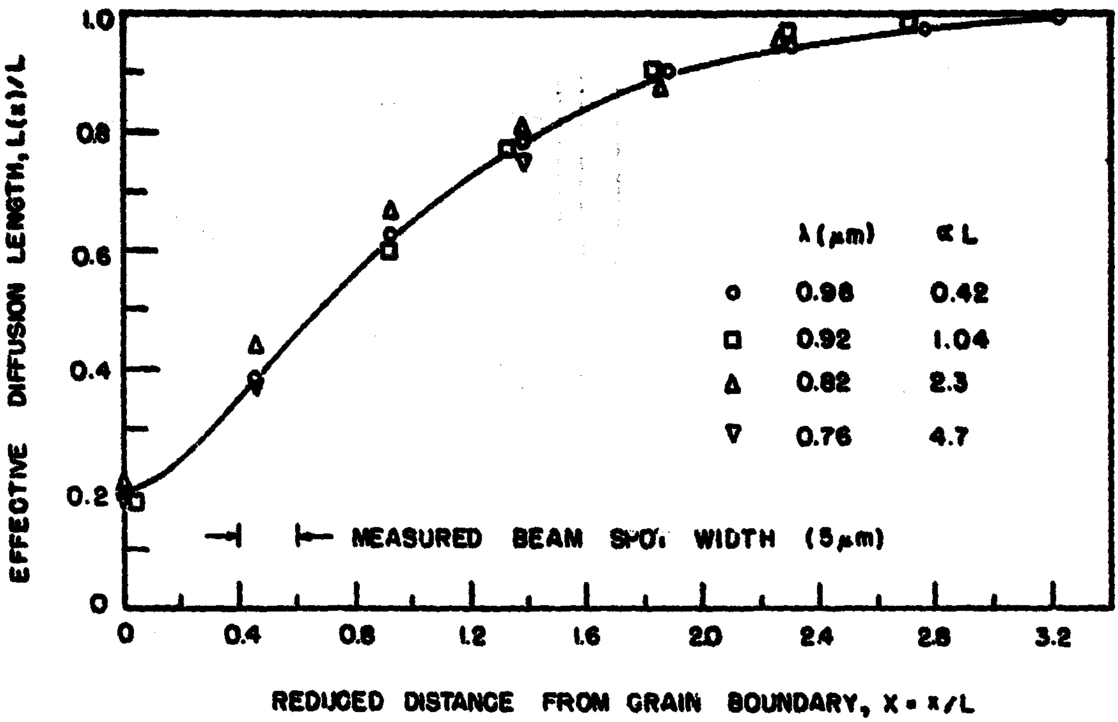
$I_{sc} = -101$ mA
-100
-80
-60
-40
-20
0
EXPERIMENTAL CURVE
CALCULATED VALUES
$I = I_{01}\left[\exp\frac{q(V-IR_s)}{kT} - 1\right] + I_{02}\left[\exp\frac{q(V-IR_s)}{nkT} - 1\right] + \frac{V-IR_s}{R_{sh}} - I_{sc}$
CURRENT (mA)
0
0.1
0.2
0.3
0.4
0.5
VOLTAGE (V)



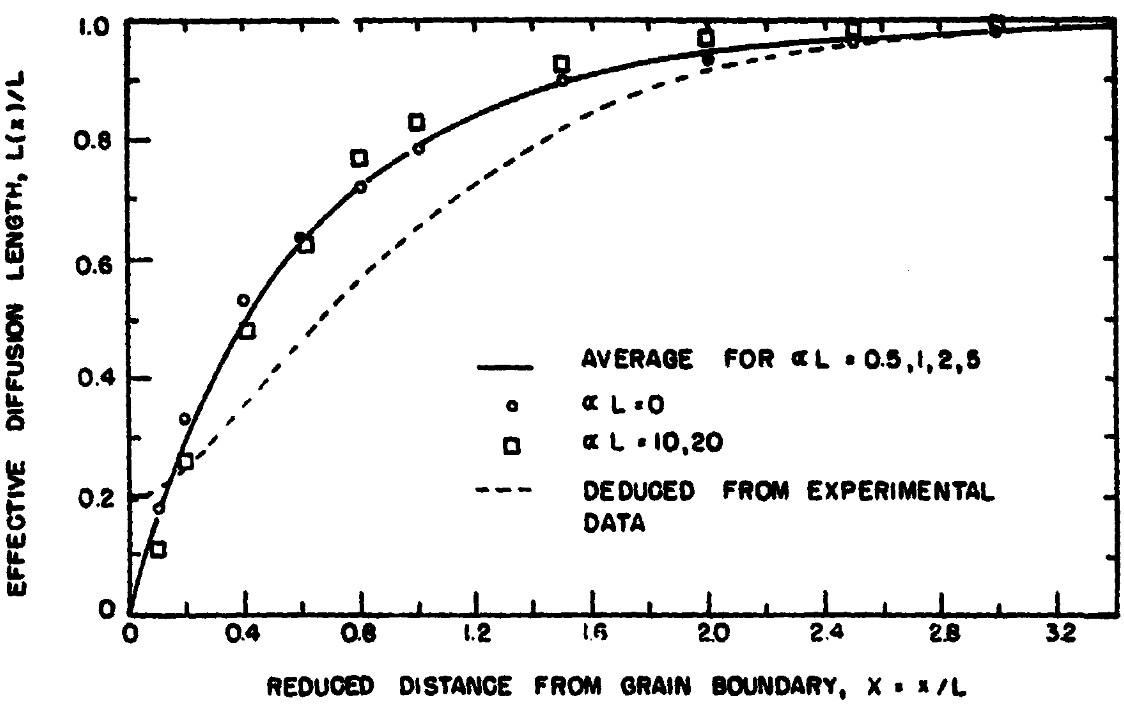
DIFFUSION LENGTH (μm)
SHEET RESISTANCE (Ω/□)
NUMBER IN DIPPING SEQUENCE
= DIFFUSION LENGTH (LEFT SCALE)
= SHEET RESISTANCE (RIGHT SCALE)



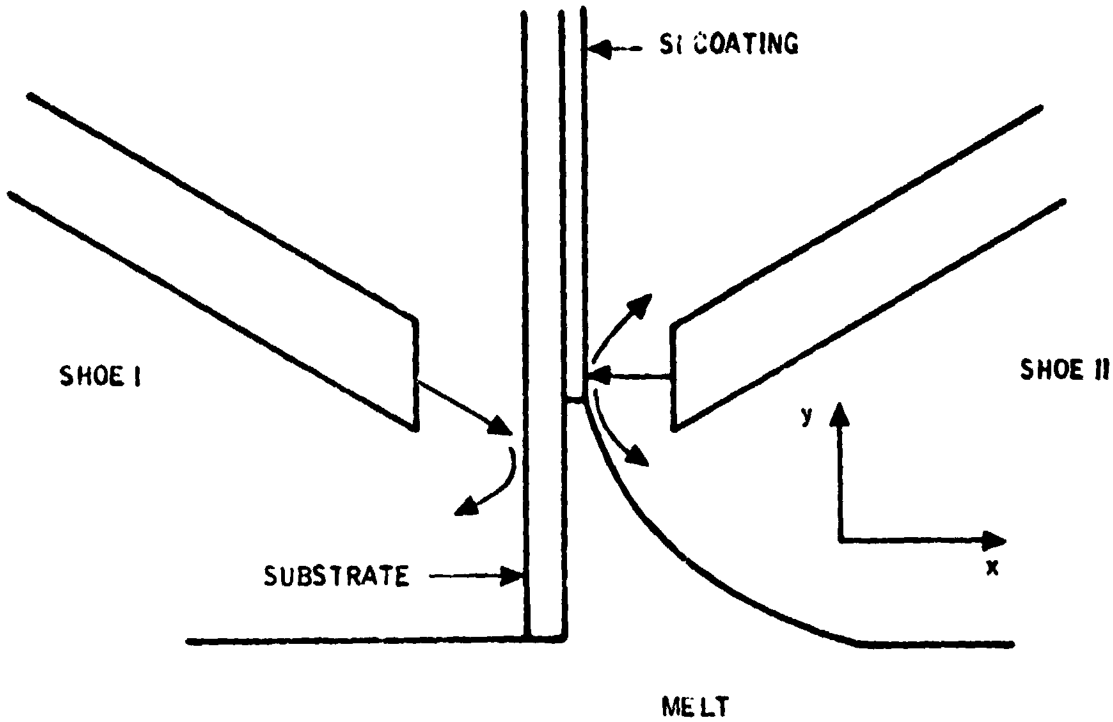
LIGHT-BEAM-INDUCED CURRENT (LBIC)
λ = 0.76
λ = 0.98
5nA
100μm
SCANNING LIGHT BEAM
5μm
SPOT SIZE
SILICON
LAYER
GRAIN
BOUNDARIES
CERAMIC SUBSTRATE

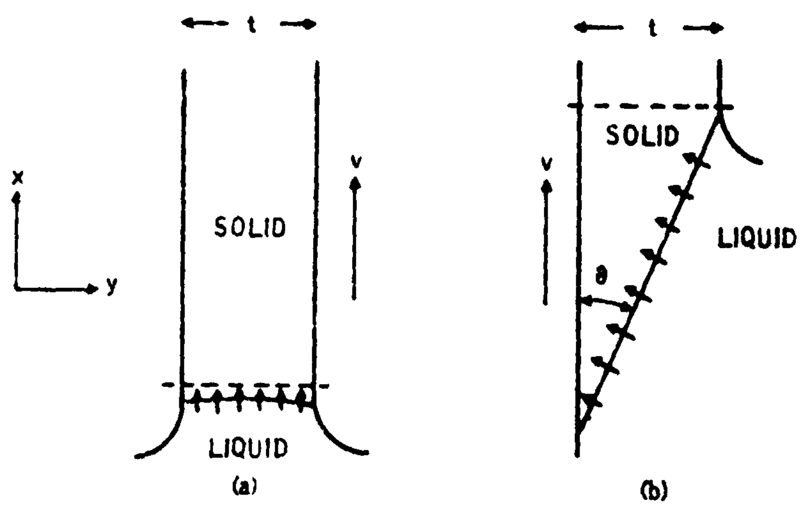


Effective diffusion length at a grain boundary deduced from LBIC results.



Comparison of theory and experiment for diffusion length near a grain boundary.





Growth Models. a) Symmetric mode
b) Asymmetric mode

HONEYWELL SCIM COATER FOR SOC PROCESS

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VACUUM DIE CASTING

ARCO SOLAR, INC.

C. GAY

G. TURNER

SRI INTERNATIONAL

R. BARTLETT

D. ROWCLIFFE

SRI

DEVELOP VACUUM DIE
CASTING PROCESS

SHEETS 2.5 CM X 10 CM

ARCO SOLAR

DEVELOP LOW COST
CELL PROCESS FOR
POLYCRYSTALLINE MATERIALS

DIE CAST
12 % AM1
2 CM X 2 CM

↓

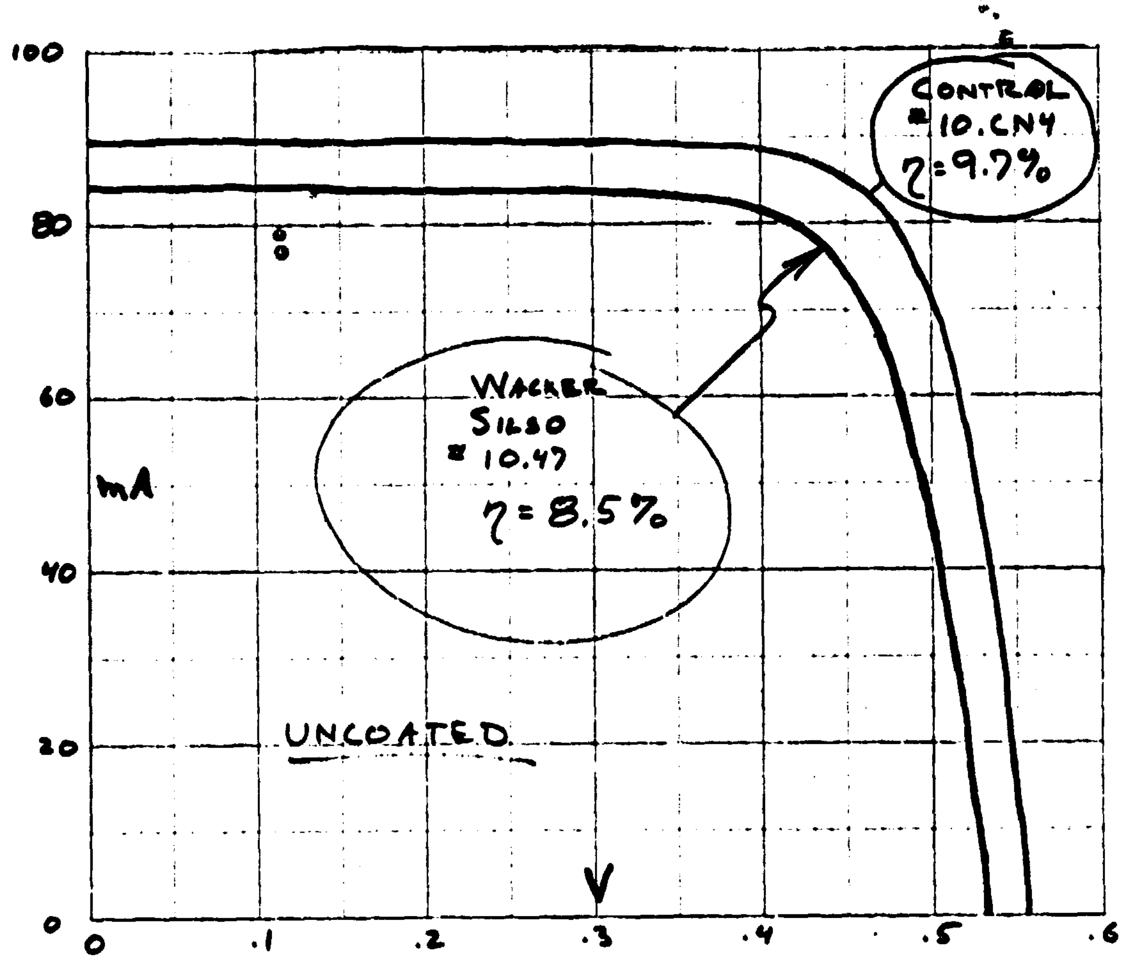
SCALE UP
(2ND YEAR)
7.9 M^2/HR/MACHINE

MATERIALS

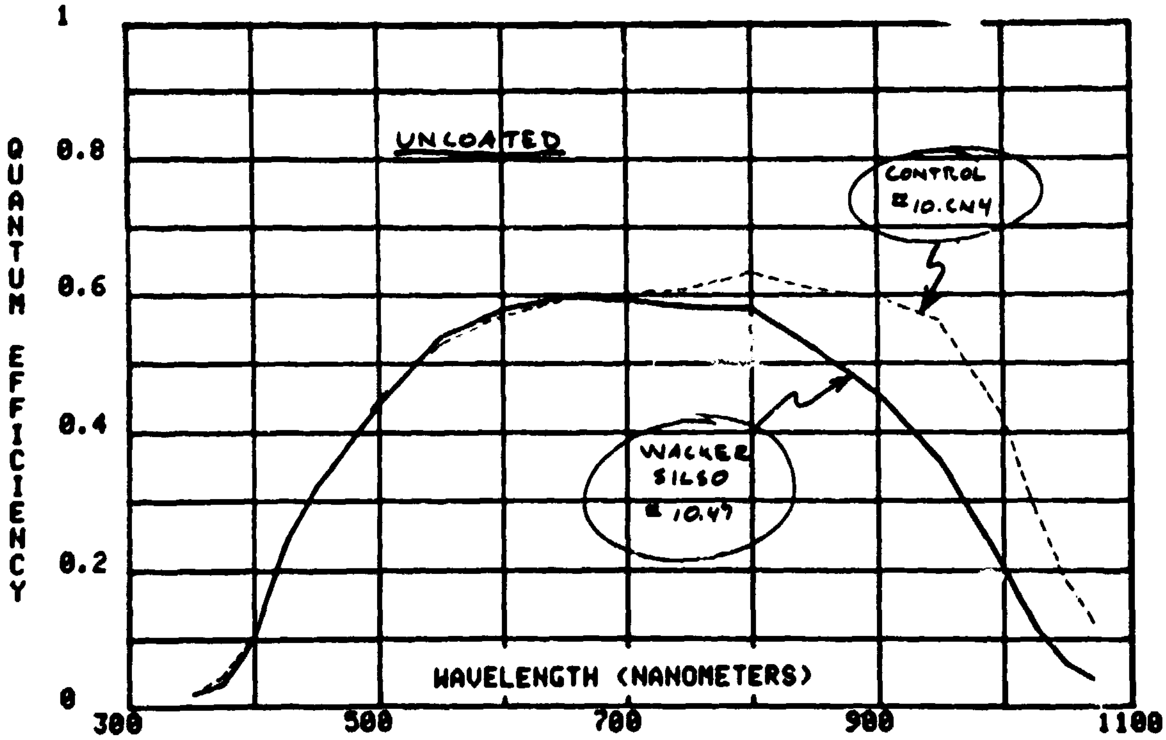
- o WACKER SILSO
- o IN-HOUSE CZ POLY
  SEMICONDUCTOR GRADE
  DIE MATERIAL CONTAMINATED
- o HEM CAST
- o EFG RIBBON

PROCESSES

- o BASELINE
- o P+
- o LOW COST
- o PASSIVATED



QUANTUM EFFICIENCY OF TEST CELL LOT 10 #47
CALIBRATION DATA UPDATED 8-21-79



VACUUM DIE CASTING OF Si SHEET

SRI INTERNATIONAL

D. J. ROWCLIFFE

R. W. BARTLETT

PROGRAM GOALS

- DEVELOP A VACUUM DIE-CASTING PROCESS TO PRODUCE SOLAR CELL GRADE SILICON SHEET

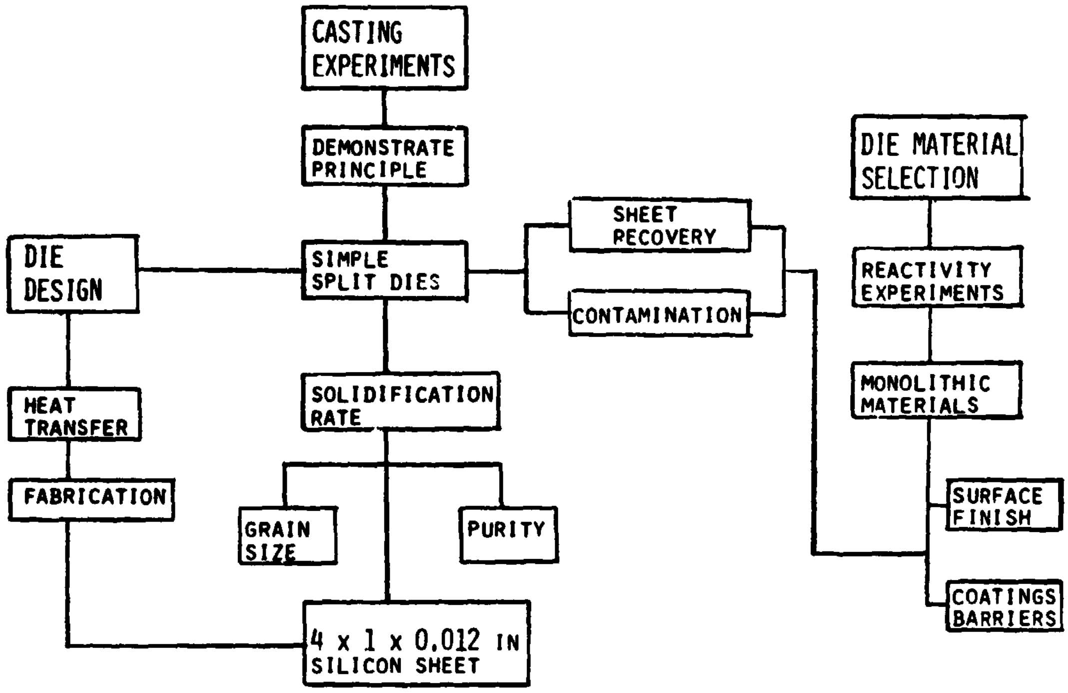
  EXPERIMENTAL GOAL: SILICON SHEET 4 x 1 x 0.012 INCHES

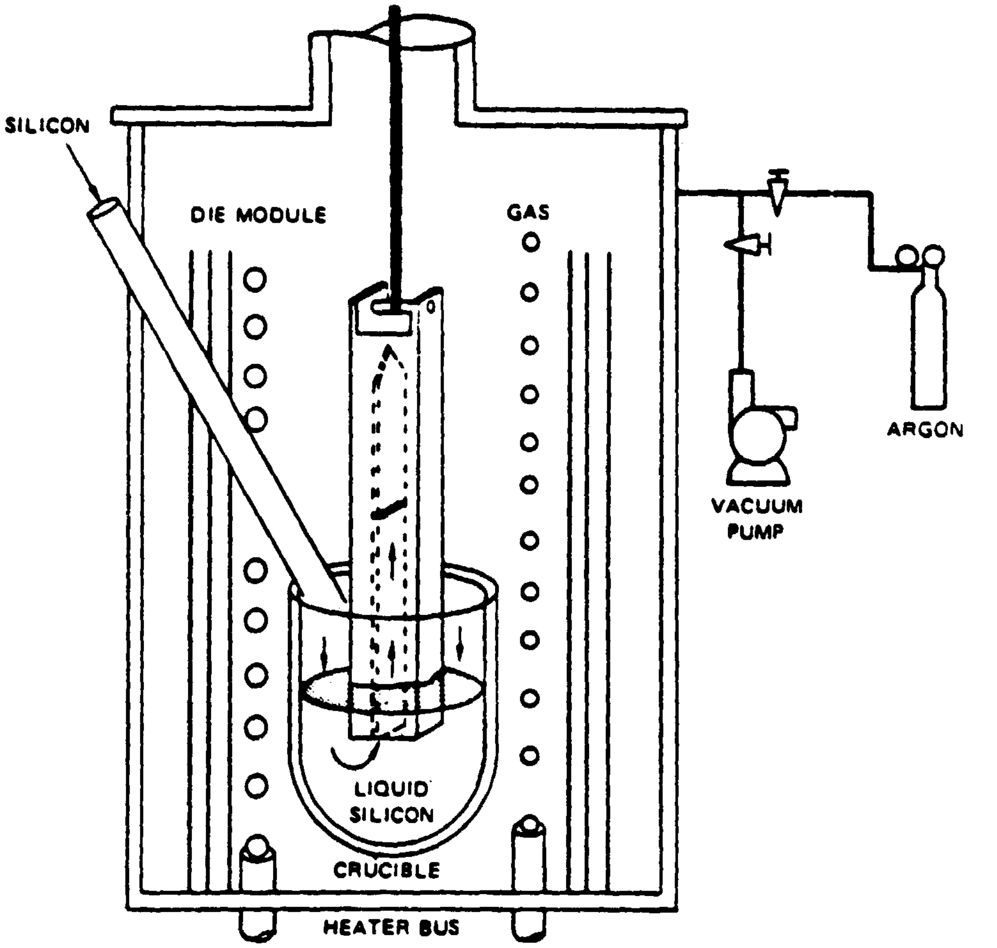
- PROVIDE TECHNOLOGY ASSISTANCE FOR SCALE UP

SCHEDULE

- 5 SHEET CASTINGS 4 x 1 x 0.012 INCHES BY 31 DEC 1979
- 10 MORE CASTINGS BY 31 JAN 1980
- TECHNOLOGY TRANSFER TO BEGIN JAN 1980
- LABORATORY DEVELOPMENT TO BE COMPLETED BY JULY 1980

BASIC APPROACH



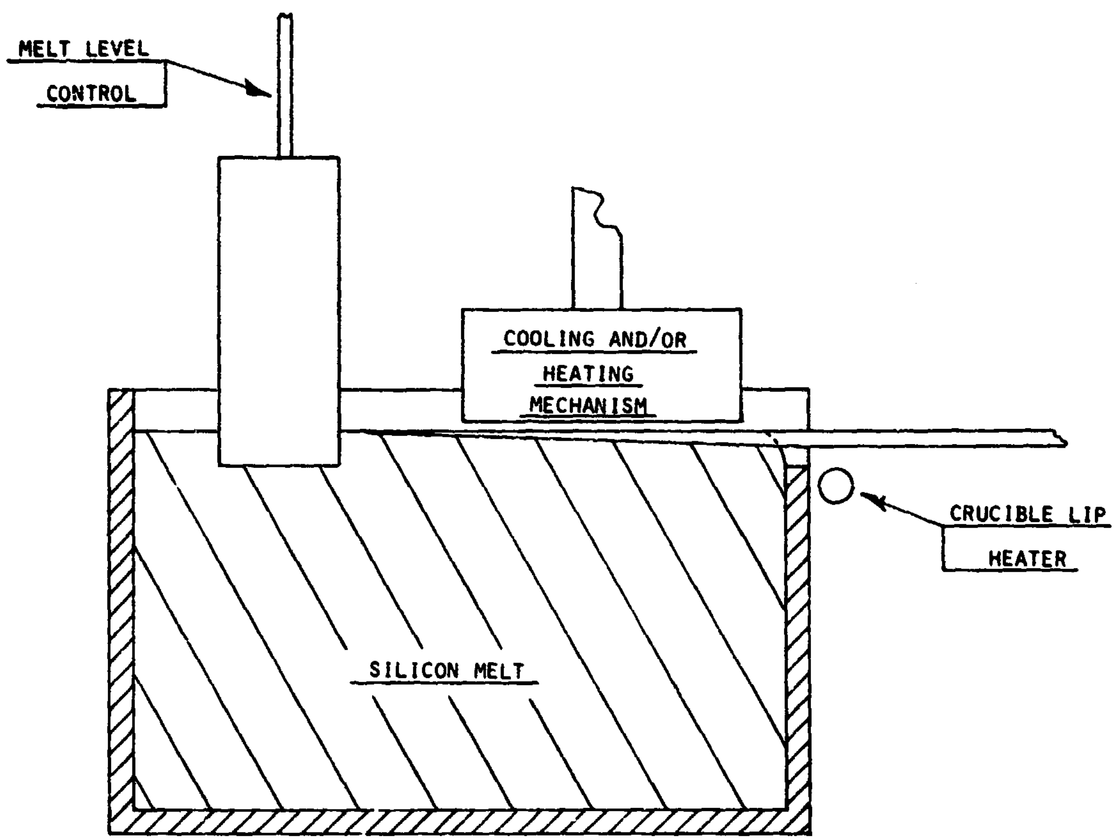


ARGON PRESSURE INJECTION OF LIQUID SILICON INTO THE DIE CAVITY

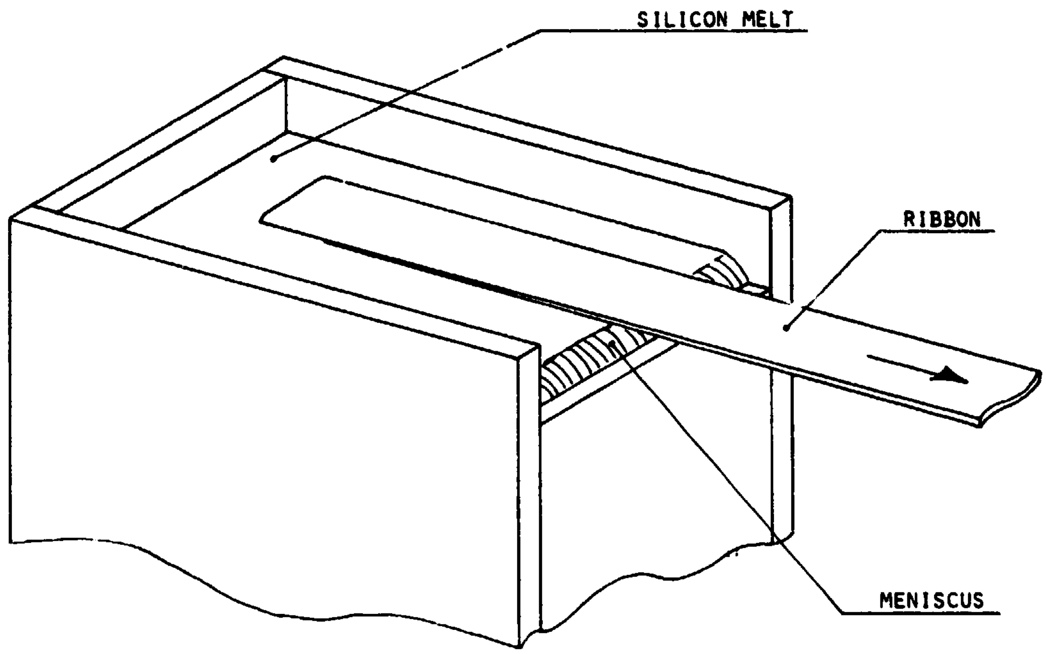
LOW-ANGLE RIBBON

ENERGY MATERIALS CORP.

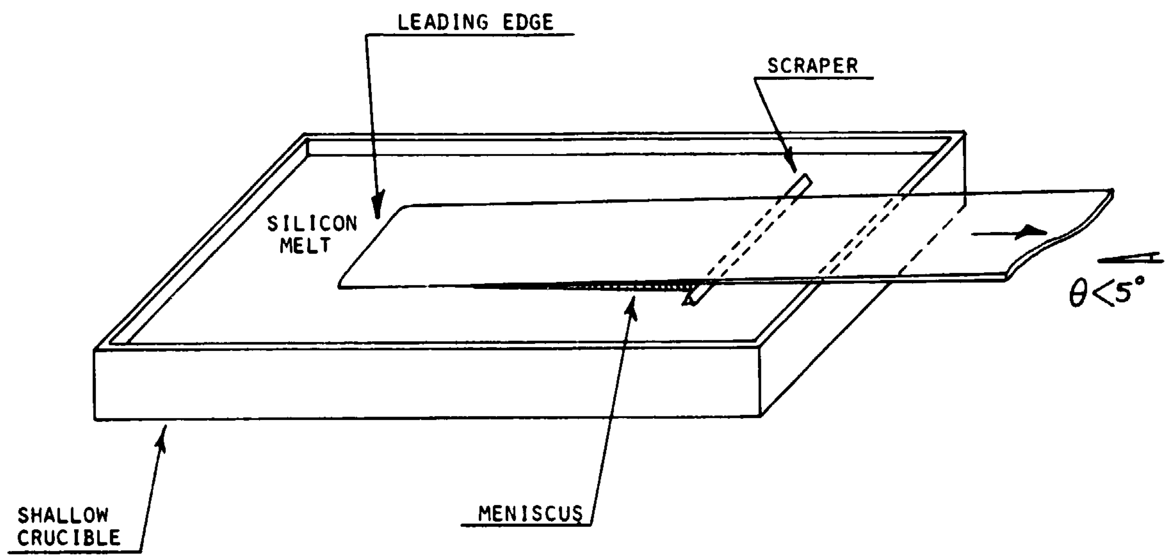
SCHEMATIC OF HORIZONTAL GROWTH SYSTEM



SCHEMATIC OF HORIZONTAL RIBBON GROWTH



SCHEMATIC OF LOW-ANGLE RIBBON GROWTH



BASIC FEATURES

1. MAIN GROWTH INTERFACE PARALLEL TO RIBBON PULL DIRECTION.

2. TWO CRYSTAL GROWTH REGIONS TO CONTROL: LEADING EDGE AND MAIN GROWTH ZONE.

3. LEADING EDGE GROWTH RATE DETERMINES RIBBON PULL RATE. HIGH GROWTH RATE REPORTED. (30 CM/MIN SINGLE CRYSTAL)

4. MAIN GROWTH ZONE DETERMINES RIBBON THICKNESS.

$$\text{THICKNESS} = \text{GROWTH RATE} \times \frac{\text{ZONE LENGTH}}{\text{PULL RATE}}$$

5. HEAT LOSS THROUGH THE RIBBON THICKNESS RATHER ALONG LENGTH. THEREFORE RELATIVELY SHALLOW GRADIENTS.

6. COOLING TEMPERATURE PROFILE INDEPENDENT OF GROWTH CONDITIONS.

BASIC APPROACH

1. LOW ANGLE AND SCRAPER
2. GEOMETRIC SEPARATION OF THE KEY GROWTH/CONTROL AREAS
    A. LEADING EDGE - PULL SPEED
    B. MAIN GROWTH ZONE - BULK CRYSTAL & RIBBON THICKNESS
    C. LATERAL EDGES - PREVENTION OF EXCESS WIDTH
    D. SCRAPER REGION - PREVENTION OF EXCESSIVE THICKNESS
3. SUBSURFACE STRUCTURE TO DEFINE TEMPERATURE GRADIENTS
4. SHALLOW TROUGH TO LIMIT CONVECTIVE HEAT TRANSFER

RESULTS TO DATE

1. SCRAPER AND LOW-ANGLE PULLING
2. SUBSURFACE STRUCTURES TO CONTROL TEMPERATURE GRADIENTS
3. GROWTH RESULTS
4. CONVECTION EFFECTS

PLANS FOR THE NEXT FOUR MONTHS

1. ACTIVE COOLING
2. NON-TRANSPARENT SUBSURFACE ELEMENTS
3. EXPERIMENTAL TEST OF THE SEPARATE GROWTH CONTROL ELEMENTS
4. MELT LEVEL EFFECTS
5. GUIDANCE AND SUPPORT REQUIREMENTS

QUANTITIVE ANALYSIS OF DEFECTS IN SILICON

MATERIALS RESEARCH, INC.

MOBIL TYCO No. 53, FIELD No. 1

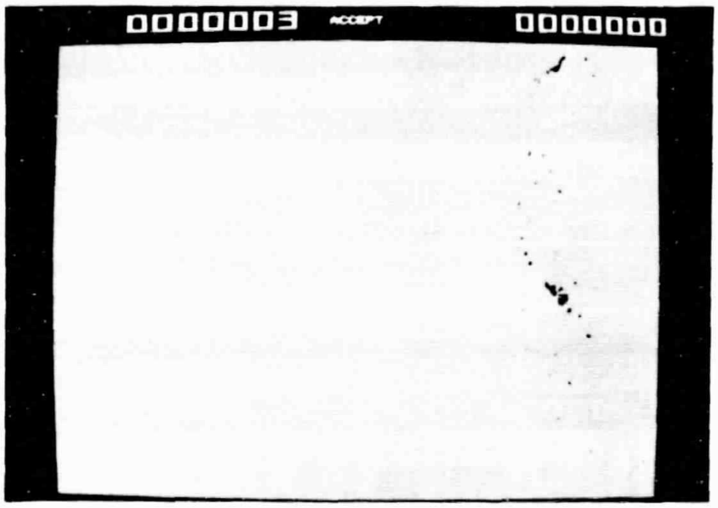


Photo from QTM display screen. 800X

Photo from QTM display screen showing only the area of the of the sample that has been accepted. 800X

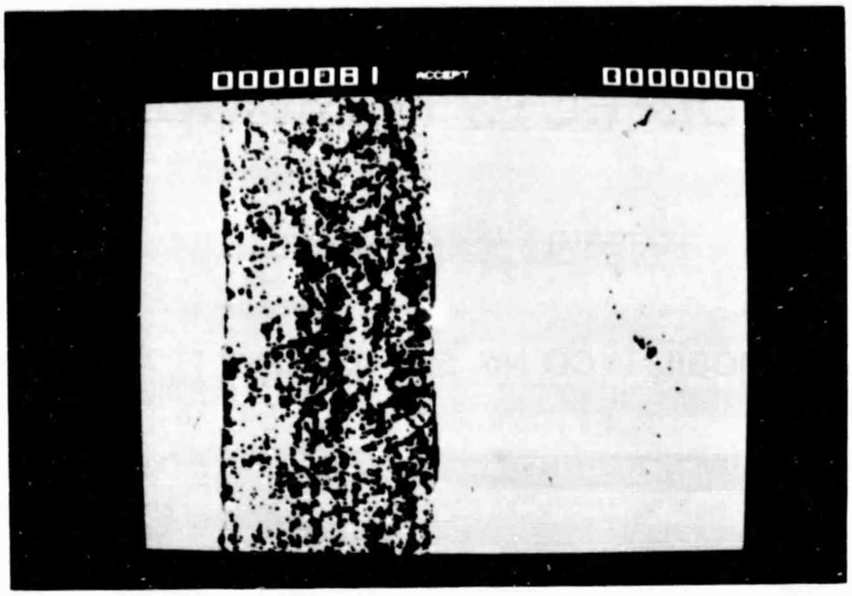


Photo from QTM display screen showing dislocation pits only. 800X

Photo from QTM screen with area being circled by light pen. 800X

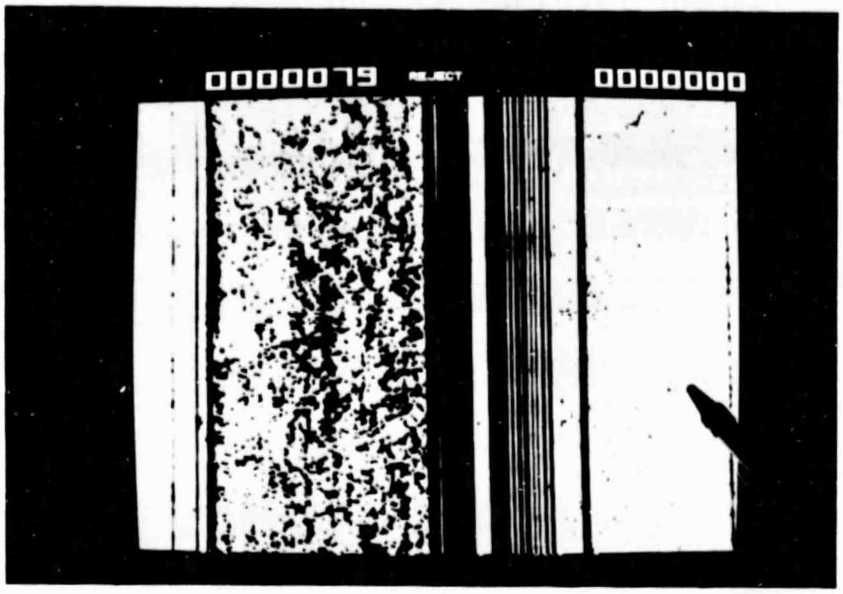


Photo from QTM display screen showing small region that has been rejected. 800X

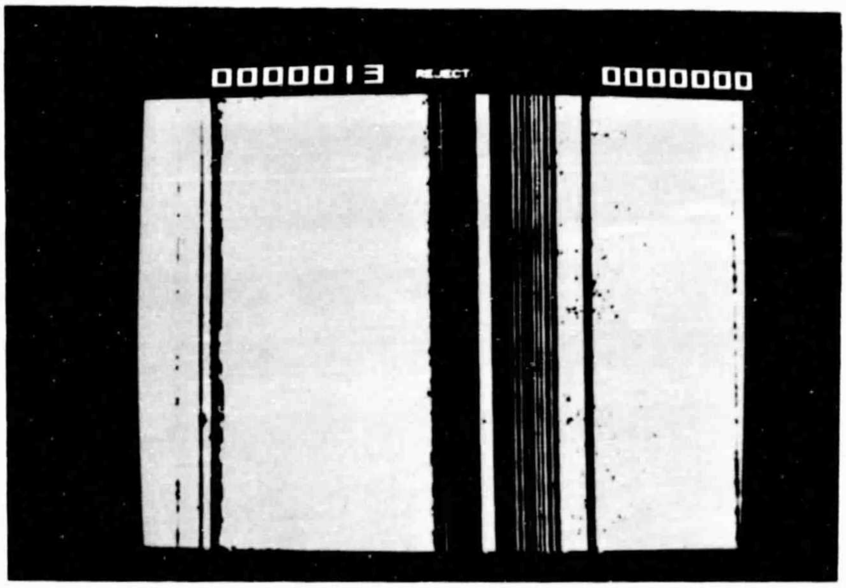


Photo from QTM display screen showing only the twins. The dislocation pits have been rejected. 800X

MOBIL TYCO No. 53, FIELD No. 2

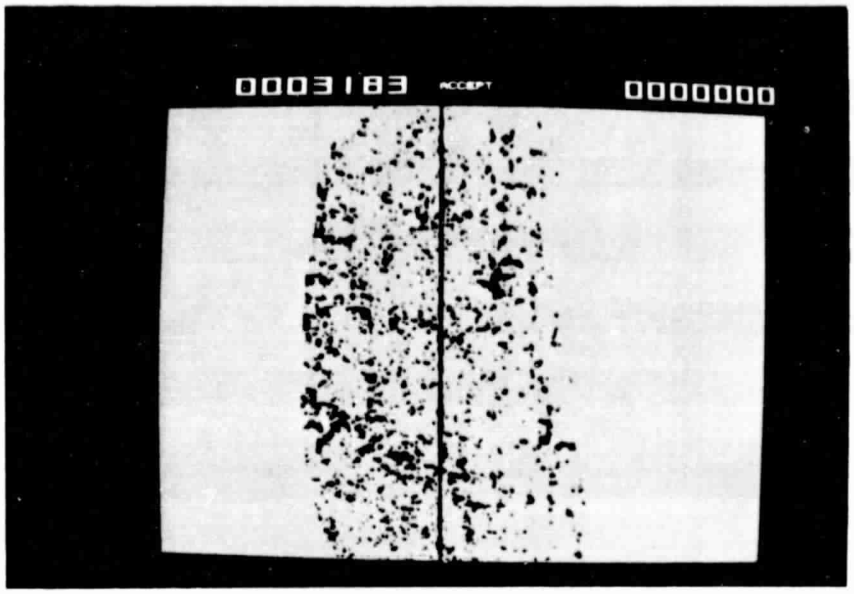


Photo from QTM display screen showing an area of dislocation pits with one twin boundary

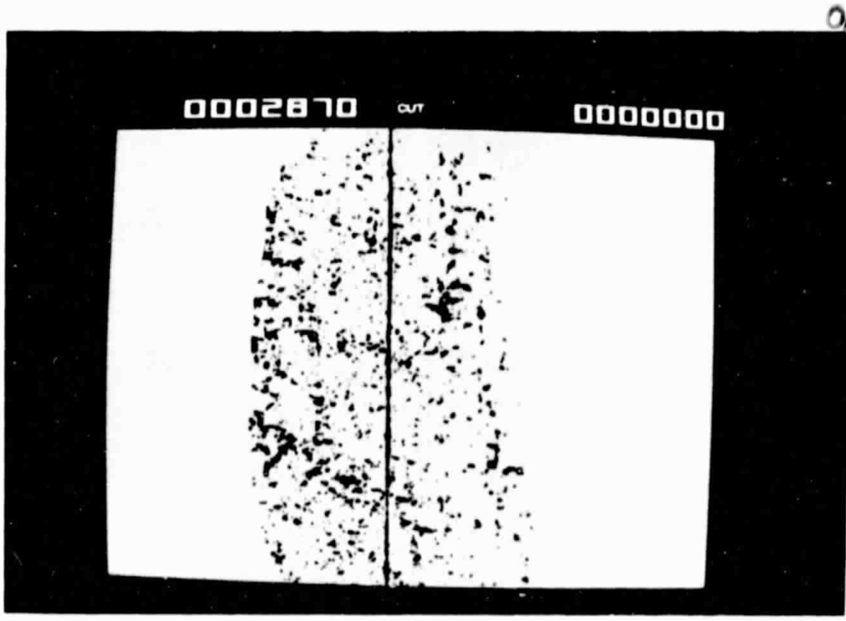
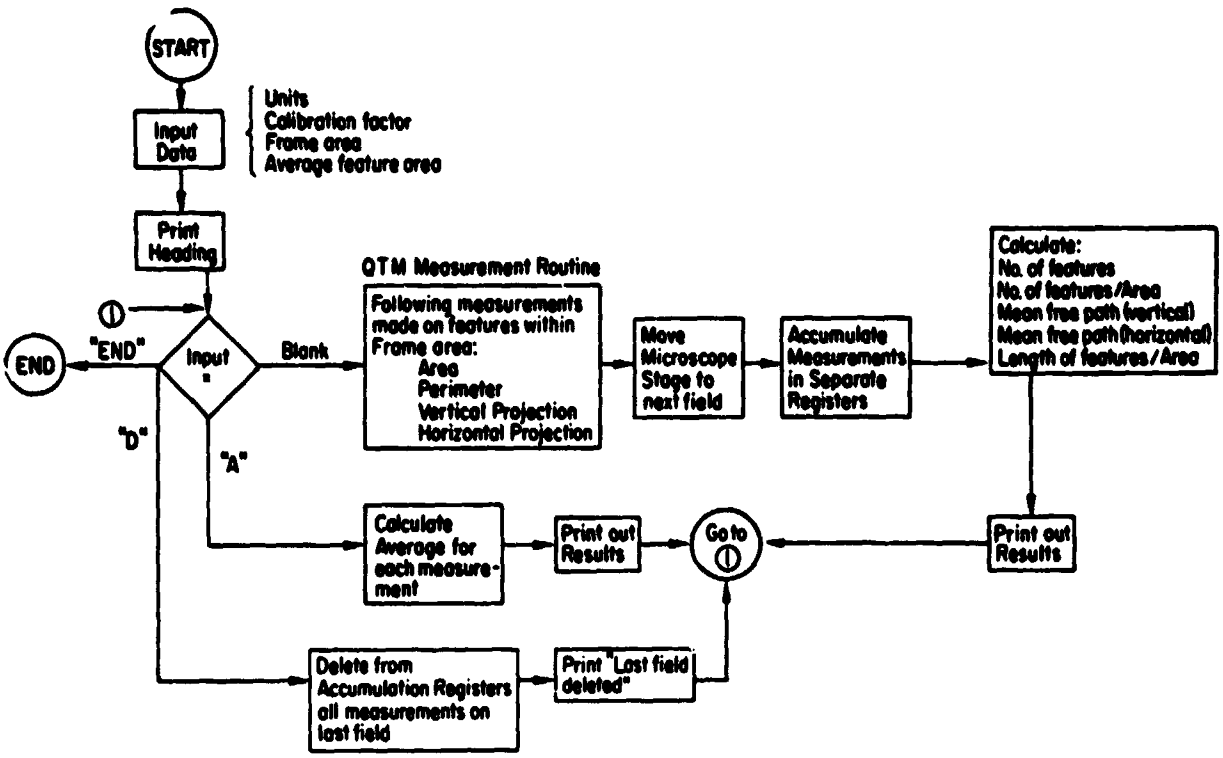


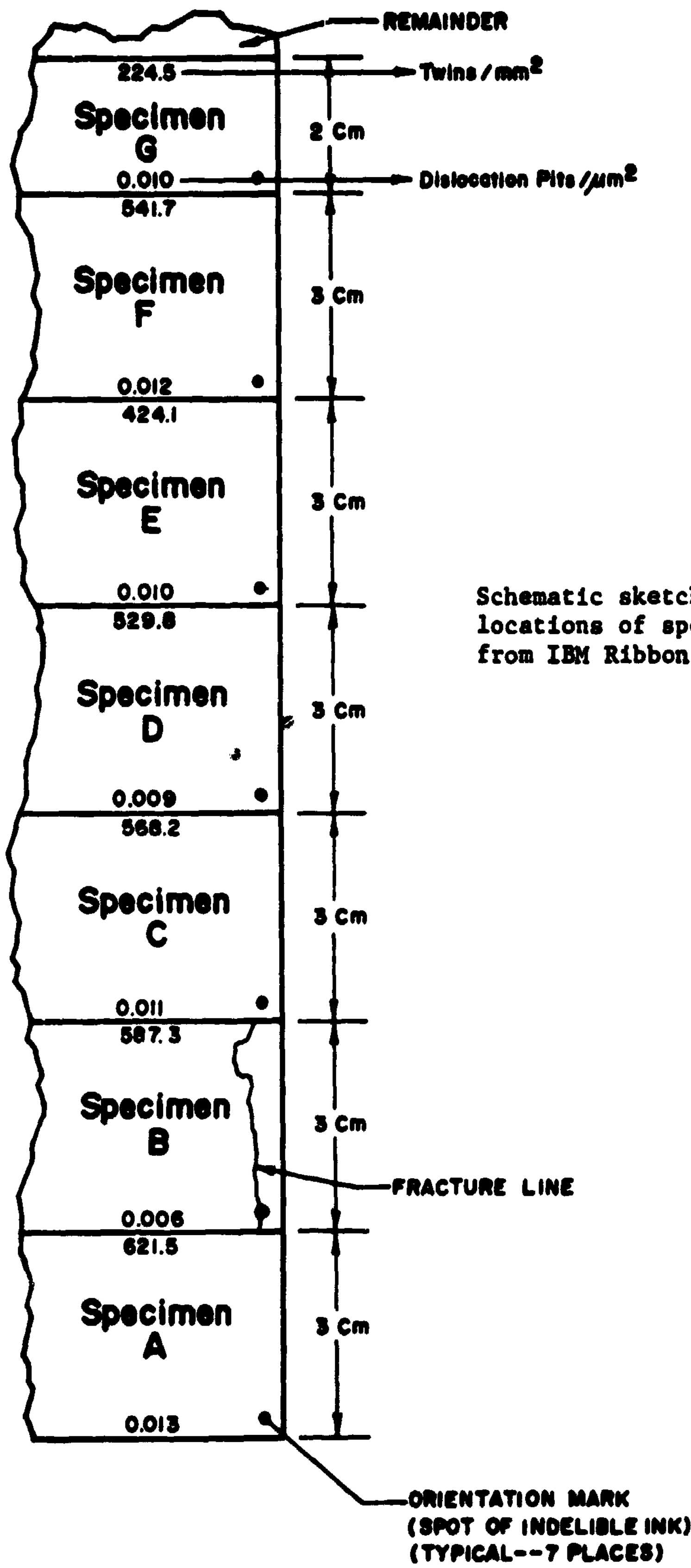
Photo from QTM display screen showing the same area as above. The twin has been separated from the dislocation pits by use of the image editor

FLOW CHART OF BASIC QTM OPERATION AND DATA REDUCTION

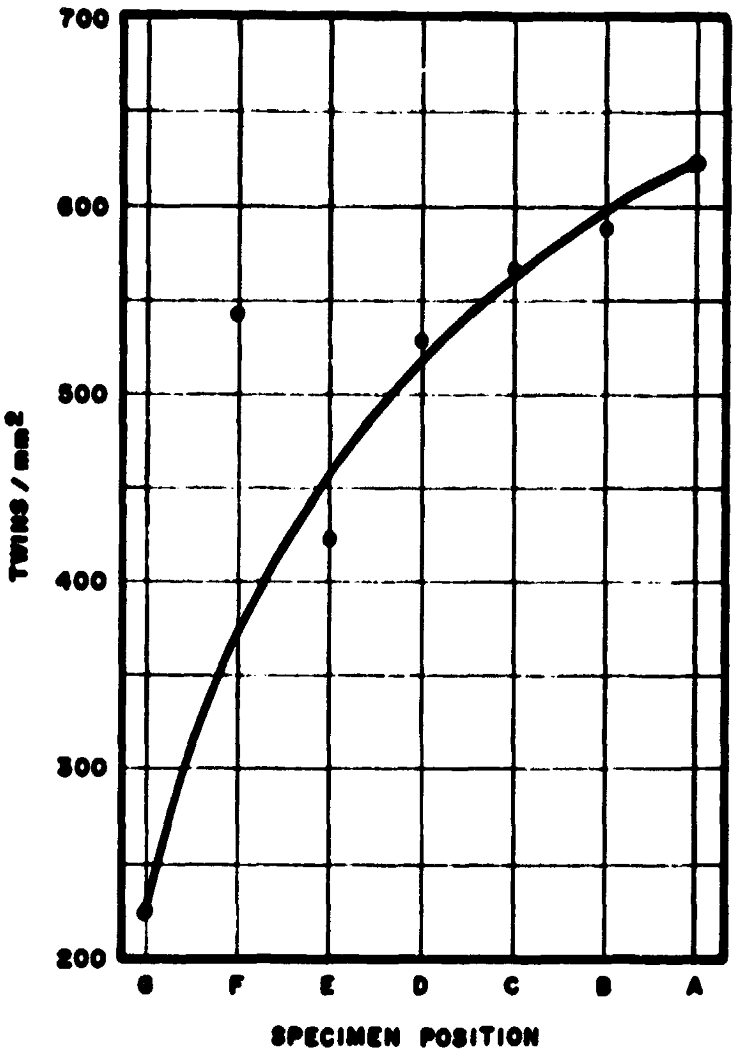


ANALYSIS OF IBM SAMPLES

MRI Sample No.	JPL No.	Avg. No. of Twins/ field	Avg. No. of Twins/mm^2	Grain boundary length/cm^2	Avg. No. of Dislocation Pits/field	Avg. No. of Dislocation Pits/μm^2
1	4-457 A	43.70	621.581	1.3	460.56	0.013
2	4-457 B	41.30	587.374	1.5	205.37	0.006
3	4-457 C	39.96	568.254	1.12	373.20	0.011
4	4-457 D	37.25	529.826	0.51	302.98	0.009
5	4-457 E	29.82	424.114	0.52	328.91	0.010
6	4-457 F	38.09	541.730	1.33	405.75	0.012
7	4-457 G	15.79	224.585	1.5	342.75	0.010



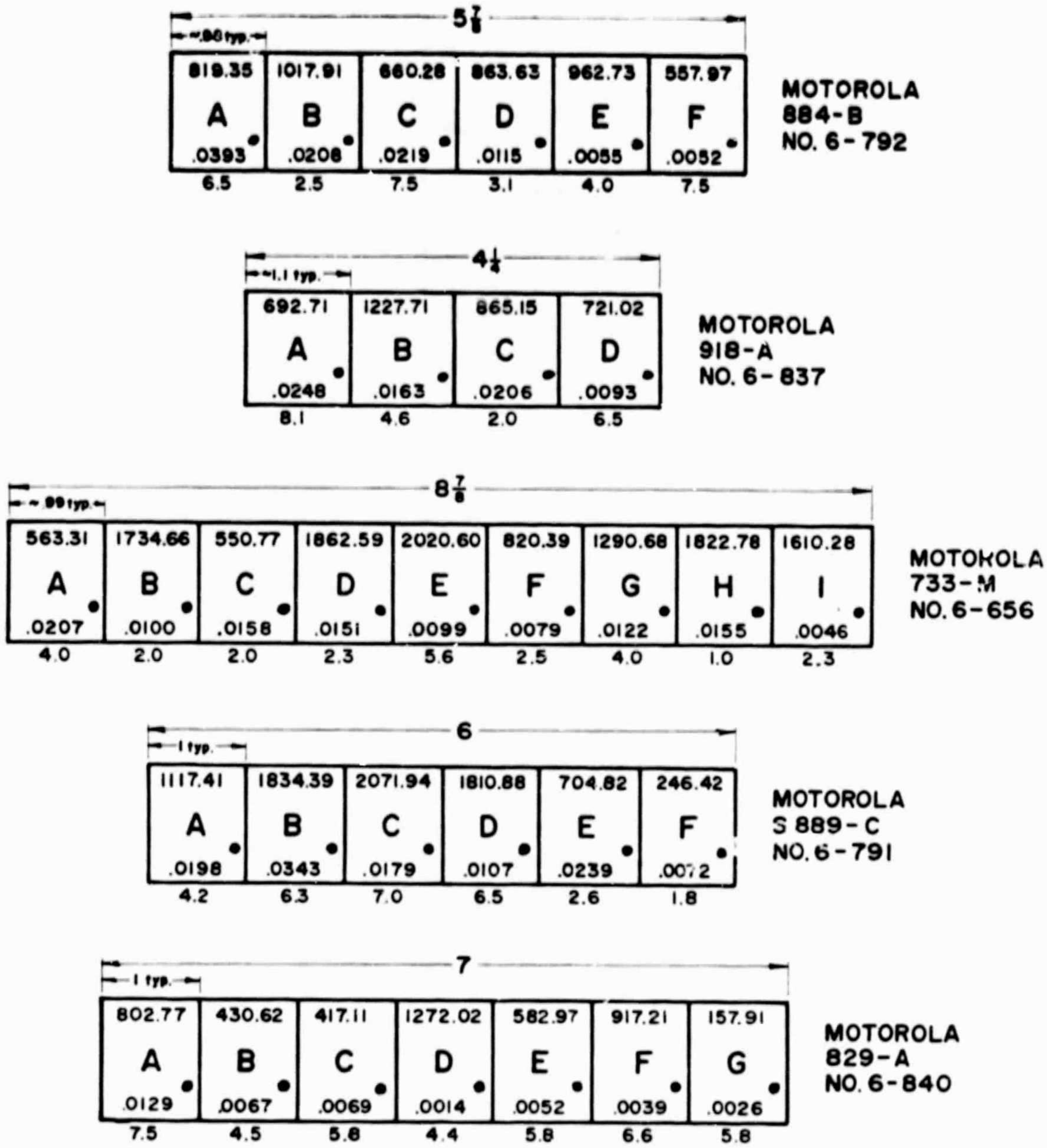
Schematic sketch showing locations of specimens from IBM Ribbon No. 4-457



Graphical plot showing systematic variation in twin density with respect to specimen location in IBM Ribbon No. 4-457

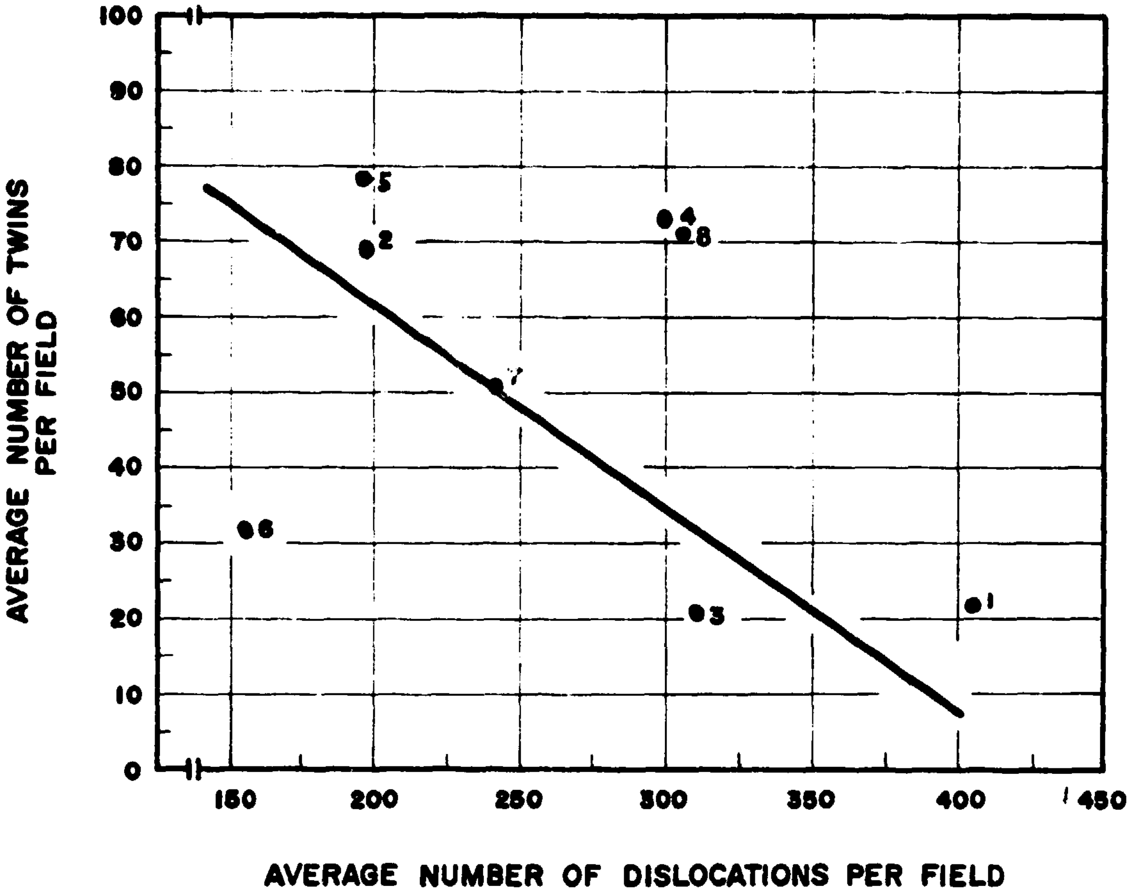
ANALYSIS OF MOTOROLA SAMPLES

MR I Sample #	JPL Sample #	No. of Twins/field	No. of Twins/mm^2	Grain boundary length/cm^2	No. of Dislocation Pits/field	No. of Dislocation Pits/μm^2
1	6-656 A	21.02	563.31	0.48	406.58	.0207
2	6-656 B	67.99	1734.66	0.7	196.17	.0100
3	6-656 C	21.59	550.77	2.12	310.58	.0158
4	6-656 D	73.01	1862.59	1.25	300.47	.0151
5	6-656 E	79.20	2020.60	2.05	195.65	.0099
6	6-656 F	32.16	820.39	3.12	155.85	.0079
7	6-656 G	50.59	1290.68	2.96	240.21	.0122
8	6-656 H	71.45	1822.78	3.07	305.25	.0155

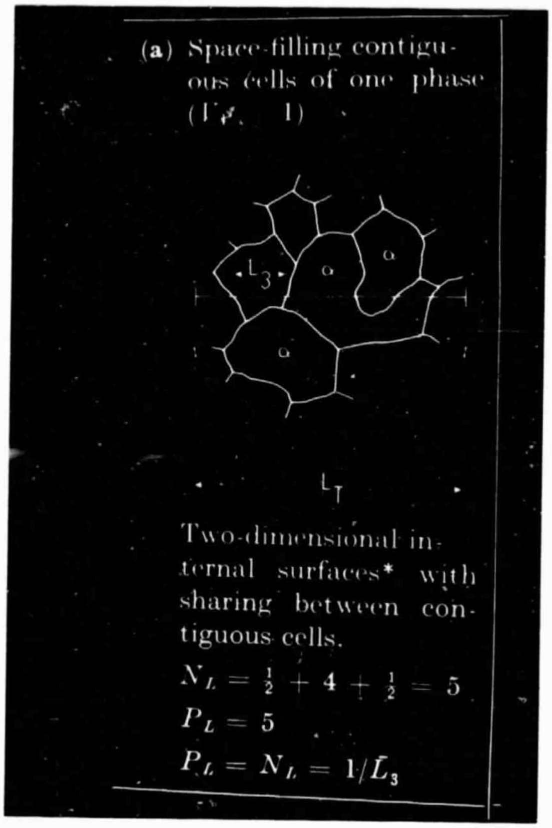


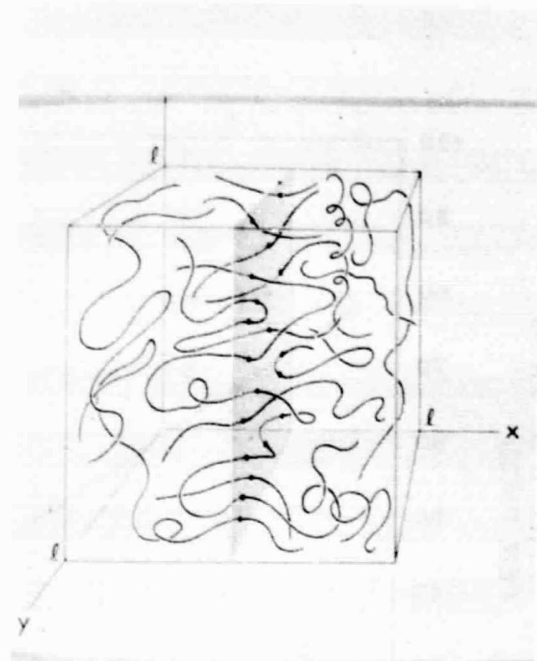
Schematic sketch showing location of 32 Motorola samples from five ribbons. In each square (representing a sample), the number at top represents average twin density/mm^2 and the number at bottom represents dislocation density/microns^2.

● These dots maintain proper orientation of the specimens during QTM analysis and also during solar cell fabrication to be done at a future date.

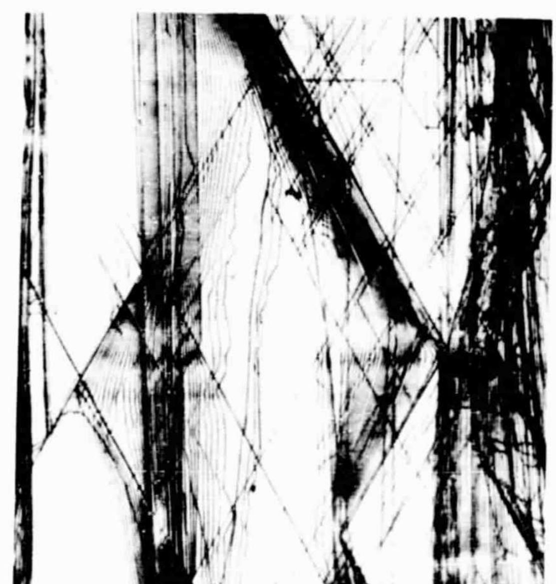


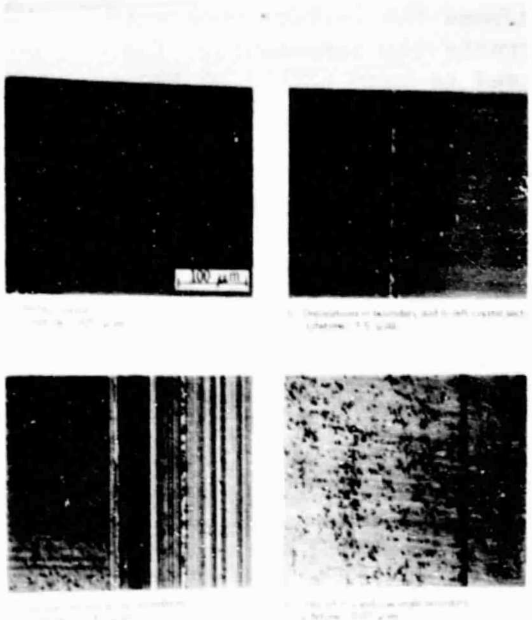
Graphical plot showing relationship between twin boundary density and dislocation density for Motorola silicon wafers. The identity of these test samples are given in Table 2, and the location of these test samples with respect to the Motorola Ribbon are given in Figure 1.

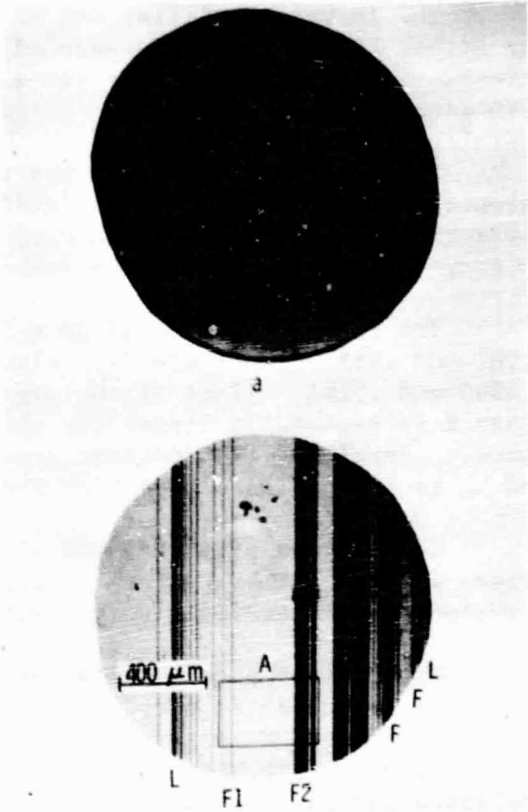

(a) Space-filling contiguous cells of one phase
L_3
α
α
α
L_T
Two-dimensional internal surfaces* with sharing between contiguous cells.
$N_L = \frac{1}{2} + 4 + \frac{1}{2} = 5$
$P_L = 5$
$P_L = N_L = 1/L_3$


ℓ
ℓ
ℓ
X
Y


A







MULTIWAVELENGTH ANALYZER FOR SOLAR CELL CHARACTERIZATION

UNIVERSITY OF CALIFORNIA, LOS ANGELES

O. STAFSUDD

The simplest form of the multi-wavelength analyzer (MWA) is shown in Figure 1. Two LEDs (light emitting diodes) operating at different wavelengths are square-wave modulated 180° out of phase with one another. The output energies of the diode are combined in a beam splitter and then focused with an optical system on the surface of the solar cell to be tested. The solar cell is effectively operating into a short circuit by means of a Kiethley 480 picoammeter. The output of the current to voltage converter of the picoammeter is sent to a P.A.R. 124A lock-in amplifier. The intensities of each of the LEDs are independently adjustable.

The lock-in amplifier can be used to read the current generated by either LED or the difference of the currents (AC component). The Kiethley digital picoammeter can also be used to read either of the LED-generated currents.

The governing equations are shown in Equation 1-8 below. In the simplest mode of operation the diffusion length L_n can be found by measuring the ratio of the AC component of the cell current to the average (DC) component of the cell current as shown in Equation 6.

The ratio R is plotted as a function of L_n for two IR LEDs at .907 and .955 in Figure 2A. Figure 2B shows a similar curve for .4880 and .5145 lines of the argon ion laser. It should be noted that R is reasonably linear for changes in L_n of a factor of two or more. Therefore, even without precise calibration the relative values of L_n as a function of position are easily obtained.

Calibration of the system simply requires matching the photon flux, using a calibrated PIN diode, or the powers at the two different wavelengths. Therefore, no absolute power calibration is necessary.

Errors in the calculation of L_n that result from various possible experimental errors are shown in Figures 3A to 6B.

If one calibrates the absolute photon flux as well as the relative photon flux it is possible to obtain both L_n and d (the junction depth) as a function of position on the cell non-destructively.

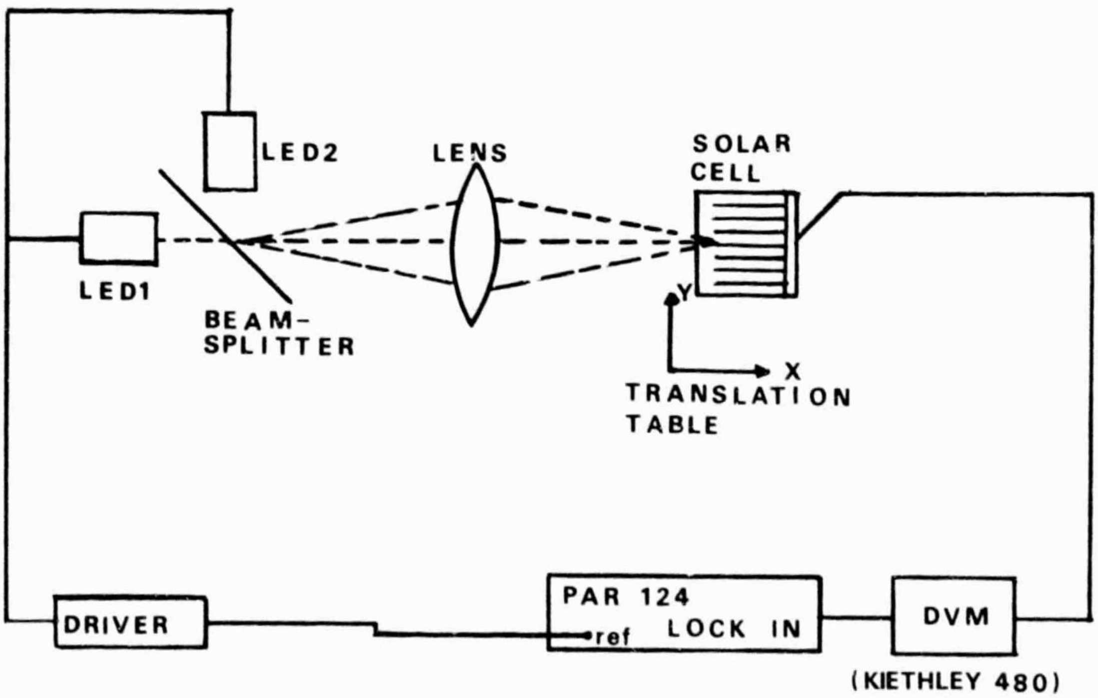


FIG 1 - EXPERIMENTAL SETUP

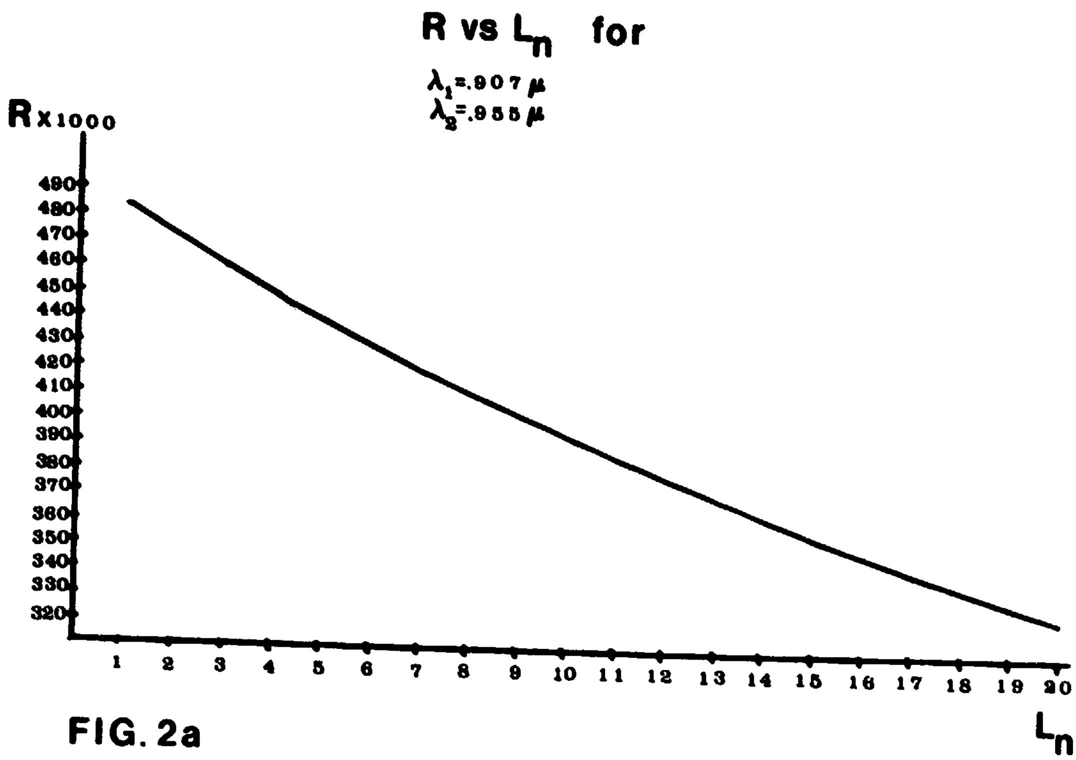

R vs L_n for
λ_1=.907 μ
λ_2=.955 μ
R x1000
490
480
470
460
450
440
430
420
410
400
390
380
370
360
350
340
330
320
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
L_n

FIG. 2a

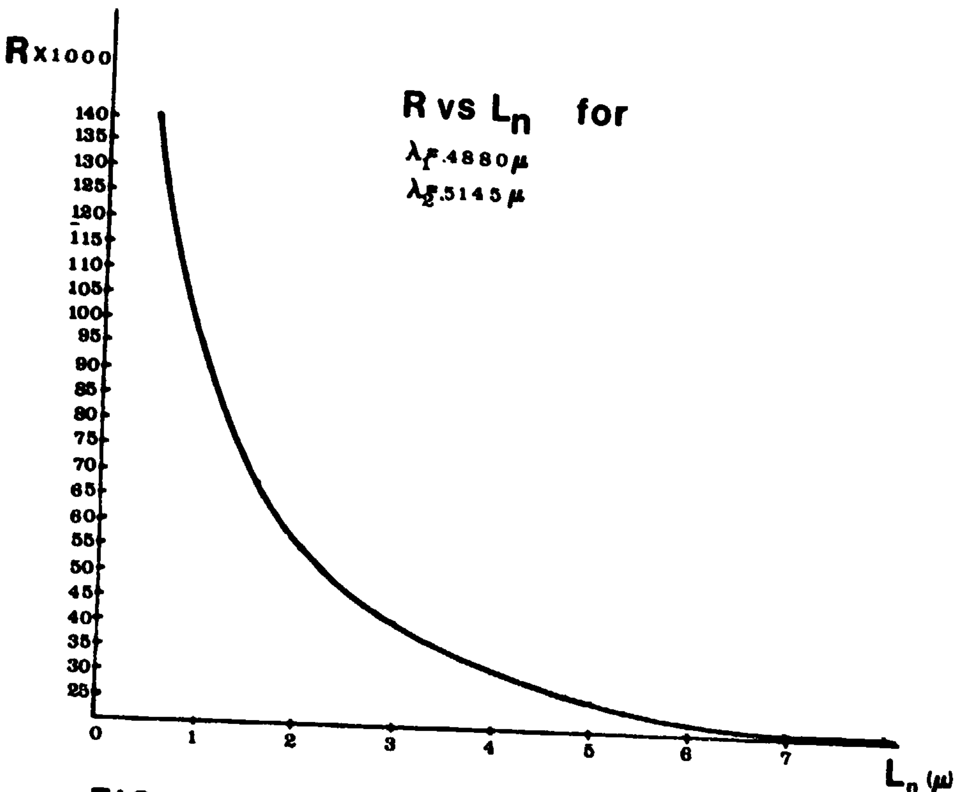

R x1000
R vs L_n for
λ_1=.4880μ
λ_2=.5145 μ
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
0 1 2 3 4 5 6 7
L_n (μ)

FIG 2b -

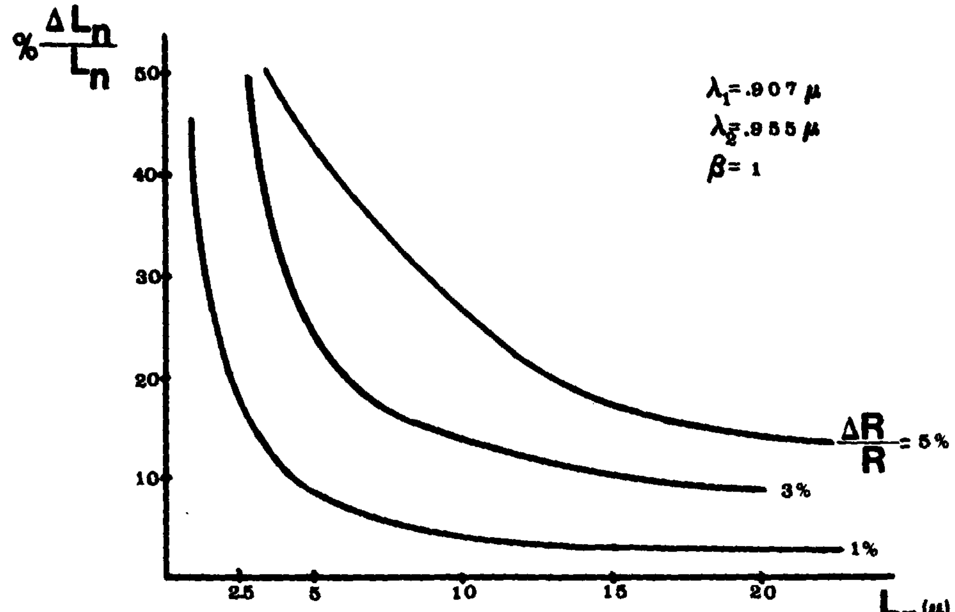


FIG.3a Errors in L_n Due to Errors in Current Ratios

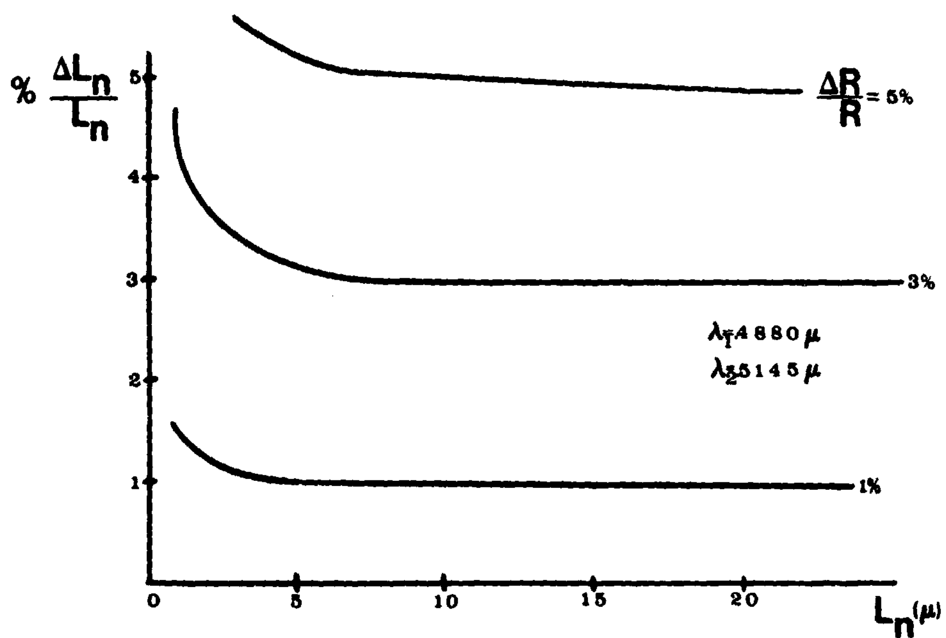


FIG. 3b Errors in L_n Due to Errors in Current Ratios

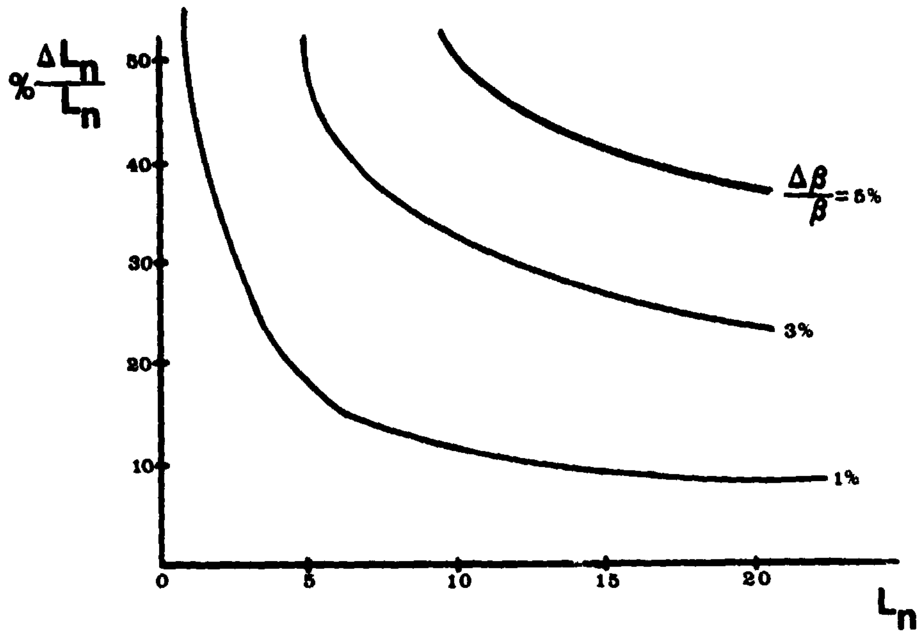


FIG.4a Errors in L_n Due to Errors in β

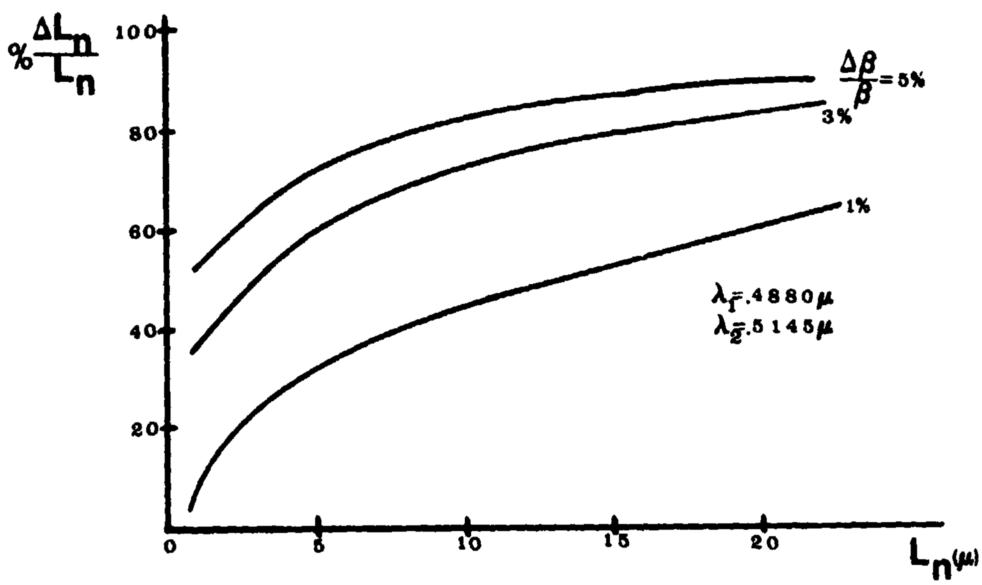


FIG.4b Errors in L_n Due to Errors in β

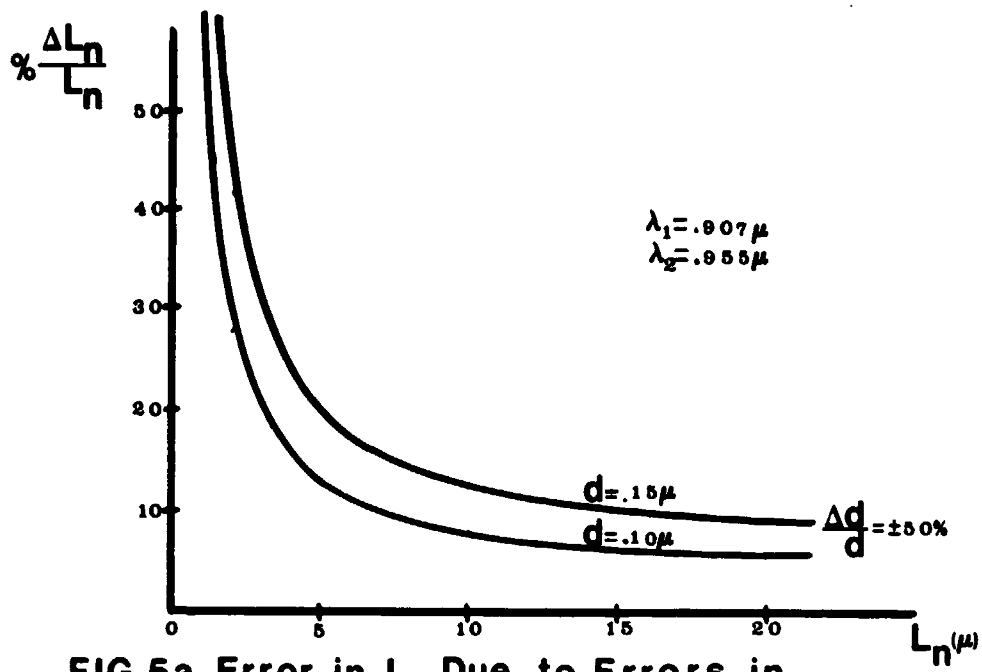


FIG.5a Error in L_n Due to Errors in Junction Depth

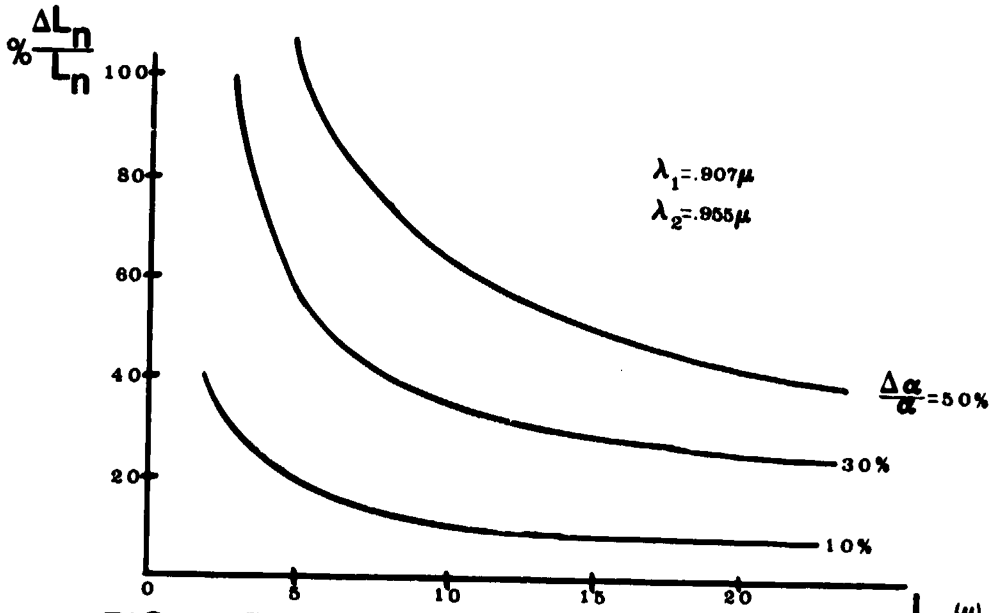


FIG.6a Error in L_n Due to Changes in α from Nonstress to Stress Relieved Values

GRAIN SIZE, D

$D = 1.5\bar{L}$ WHERE $\bar{L}$ IS THE AVERAGE INTERCEPT LENGTH.

$S_V = 2P_L$ WHERE S_V IS THE GRAIN BOUNDARY AREA PER UNIT VOLUME & P_L ARE NUMBER OF INTERSECTIONS PER UNIT LENGTH OF TEST LINE.

VOLUME FRACTION, V_V

$$V_V = P_P = L_L = A_A$$

WHERE P_P IS POINT FRACTION

L_L IS LINEAL FRACTION

AND A_A IS AREAL FRACTION.

$$P_T = \left[\frac{200\,\sigma(P_P)}{(\%\,ACC)\,P_P}\right]^2$$

WHERE P_T ARE TOTAL NO. OF POINTS AND

$\sigma(P_P)$ IS THE STANDARD DEVIATION.

DISLOCATION DENSITY

RANDOM ORIENTATION: $L_V = 2 P_A$

PARTIAL ORIENTATION: $L_V = (P_A)_\perp + (P_A)_\parallel$

WHERE L_V IS THE LENGTH OF LINE PER UNIT VOLUME AND P_A ARE NUMBER OF POINTS PER UNIT AREA

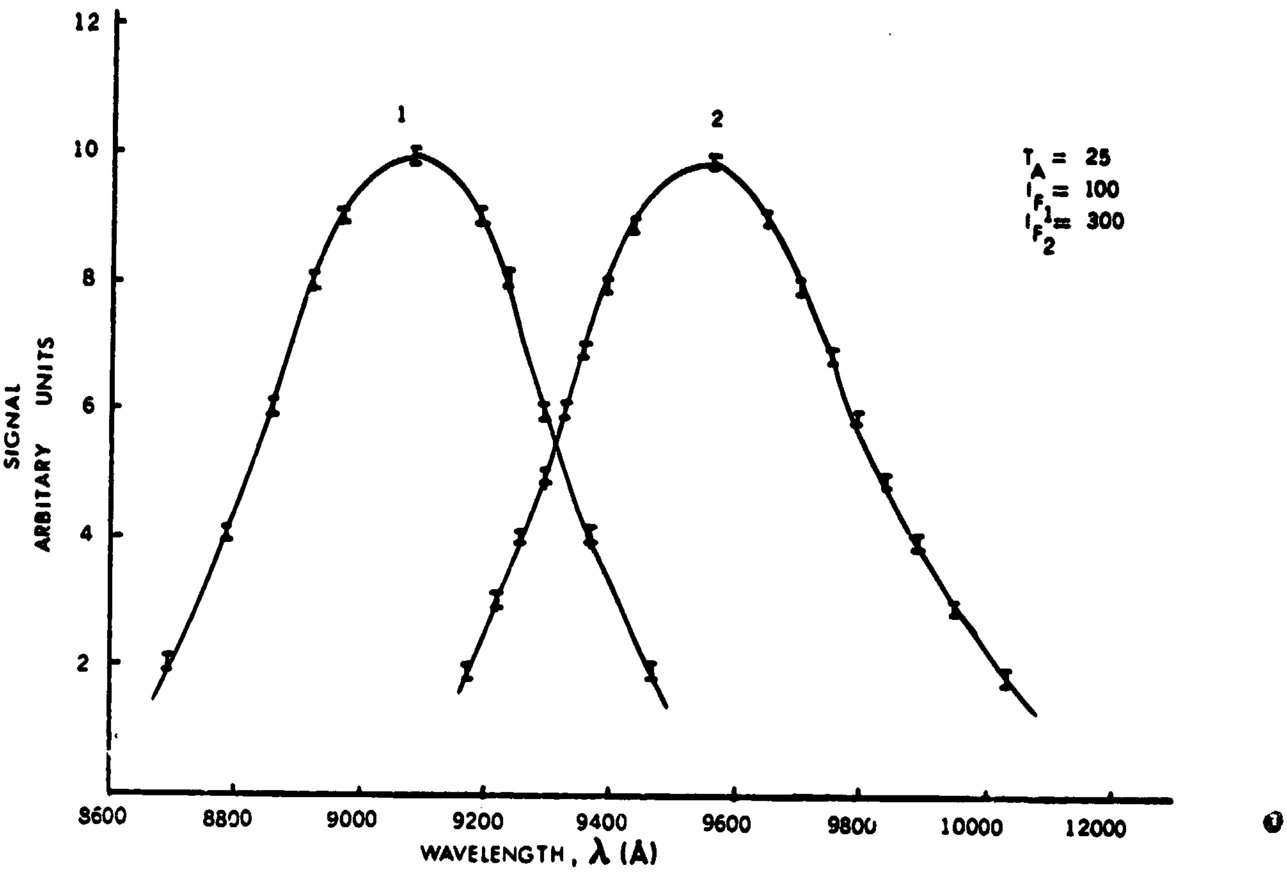
TWIN BOUNDARIES

RANDOM ORIENTATION: S_V IS RELATED TO P_L

PARTIAL ORIENTATION: $S_V = 1.571(P_L)_\perp + 0.429(P_L)_\parallel$

WHERE $(P_L)_\perp$ AND $(P_L)_\parallel$ ARE MEASUREMENTS MADE ON A LONGITUDINAL SECTION, PERPENDICULAR AND PARALLEL TO THE ORIENTATION AXIS, RESPECTIVELY.

LED RELATIVE SPECTRAL CHARACTERISTICS



FORMULAS

$$I_{sc_1} = \frac{\Phi_1 \alpha_1}{\alpha_1 - \frac{1}{L_p}} \left[e^{-\frac{d}{L_p}} - e^{-\alpha_1 d} \right] + \frac{\Phi_1 \alpha_1 e^{-\alpha_1 d}}{\alpha_1 + \frac{1}{L_n}} \qquad 1.$$

$$I_{sc_2} = \frac{\Phi_2 \alpha_2}{\alpha_2 - \frac{1}{L_p}} \left[e^{-\frac{d}{L_p}} - e^{-\alpha_2 d} \right] + \frac{\Phi_2 \alpha_2 e^{-\alpha_2 d}}{\alpha_2 + \frac{1}{L_n}} \qquad 2.$$

$$I_{sc_1} = \frac{\Phi_1 \alpha_1 e^{-\alpha_1 d}}{\alpha_1 + \frac{1}{L_n}} \qquad 3.$$

$$I_{sc_2} = \frac{\Phi_2 \alpha_2 e^{-\alpha_2 d}}{\alpha_2 + \frac{1}{L_n}} \qquad 4.$$

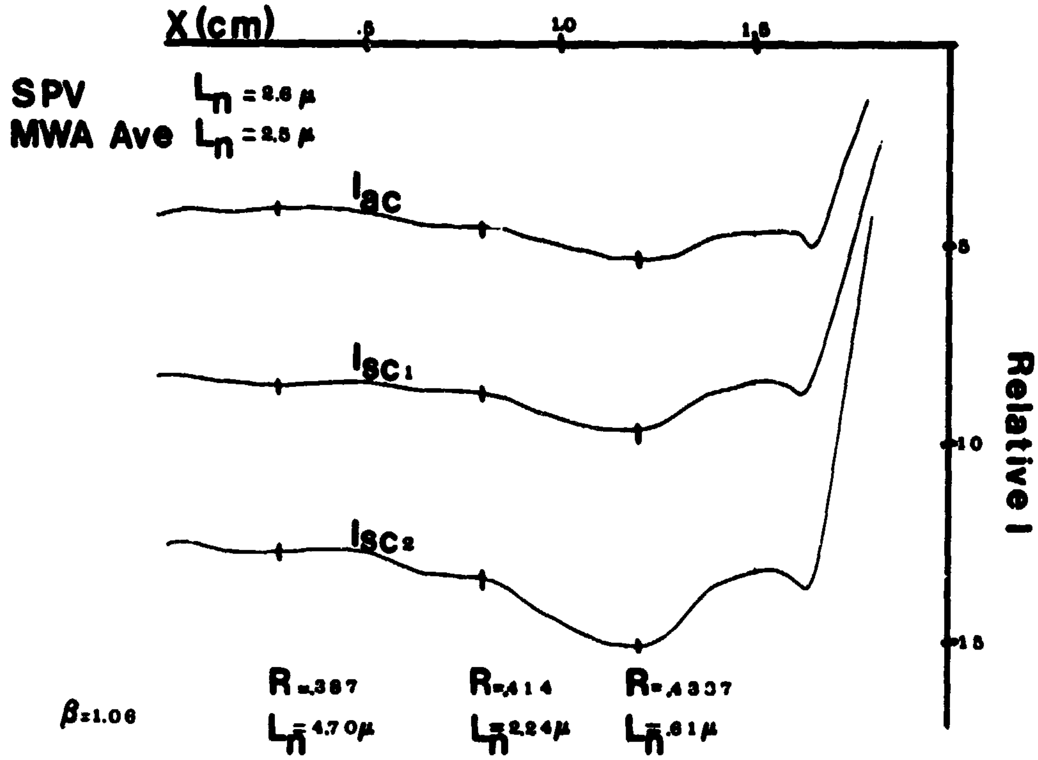
$$R = 2 \times \frac{I_{sc_1} - I_{sc_2}}{I_{sc_1} + I_{sc_2}} \qquad 5.$$

$$L_n = \frac{1}{\alpha_1 \alpha_2} \left[\frac{\alpha_1 (2 - R) - \alpha_2 \beta (2 + R)}{R - 2 + \beta (2 + R)} \right] \qquad 6.$$

$$\beta = B \frac{1 - r_2}{1 - r_1} e^{-(\alpha_2 - \alpha_1) d} \qquad 7.$$

$$B = \frac{\text{flux at } \lambda_1}{\text{flux at } \lambda_2} \text{ at the surface} \qquad 8.$$

LED Scan of Cell #869-1 Along Finger

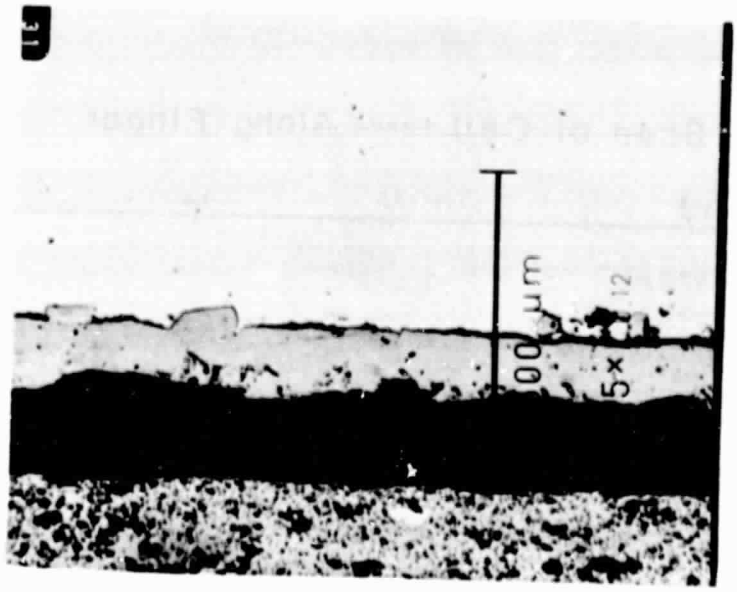


DIE AND CRUCIBLE DEVELOPMENT

• EFFECT OF VERY LOW OXYGEN PARTIAL PRESSURES ON SOME CANDIDATE DIE AND CONTAINER MATERIALS

UNIVERSITY OF MISSOURI ROLLA

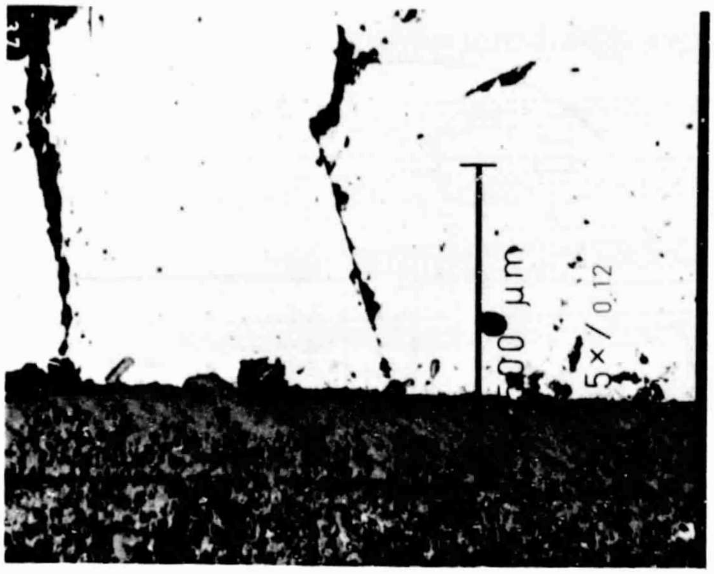
P. D. OWENBY



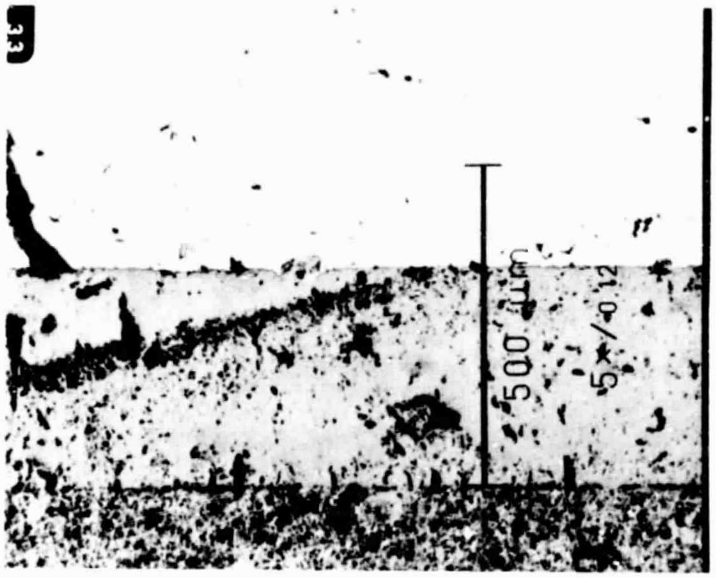
$P_{O_2} = 4.0 \times 10^{-19}$ ATM

$P_{O_2} = 2.3 \times 10^{-19}$ ATM

PHOTOMICROGRAPHS OF POLISHED SECTIONS OF THE SILICON-CNTD SILICON NITRIDE COATING INTERFACE AFTER 5 HOURS AT 1700°K SHOWING THE EFFECT OF THE OXYGEN PARTIAL PRESSURE AT TEMPERATURE.

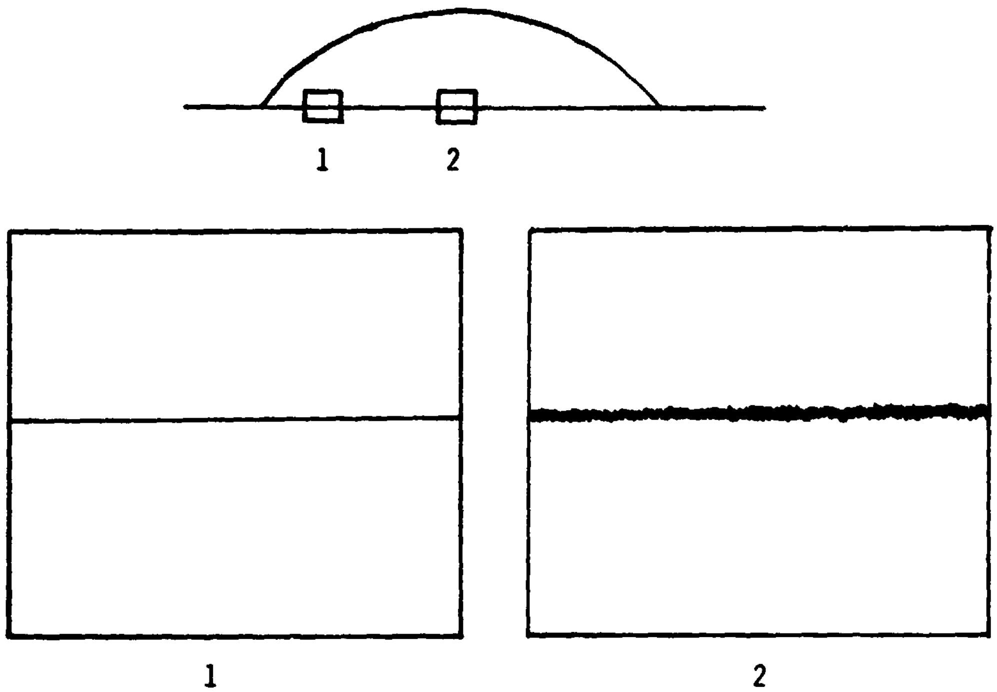


$P_{O_2} = 1.1 \times 10^{-19}$ ATM

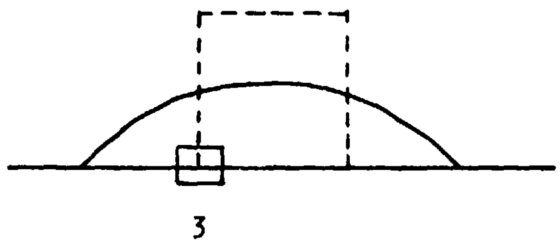


$P_{O_2} = 3.8 \times 10^{-20}$ ATM

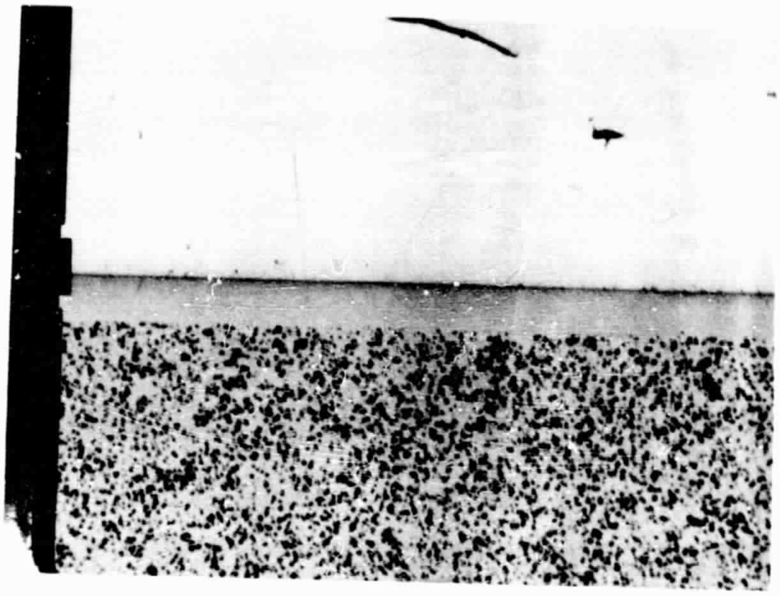
PHOTOMICROGRAPHS OF POLISHED SECTIONS OF THE SILICON-CNTD SILICON NITRIDE COATING INTERFACE AFTER 5 HOURS AT 1700^{O}K SHOWING THE EFFECT OF THE OXYGEN PARTIAL PRESSURE AT TEMPERATURE.



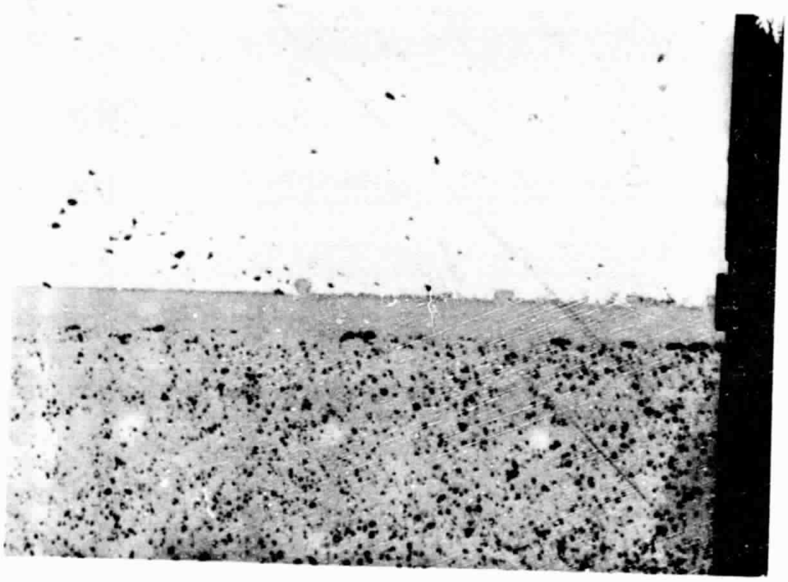
SCHEMATIC DIAGRAM OF A TYPICAL POLISHED SECTION OF THE SILICON-CNTD COATING SHOWING THE ENHANCED INTERACTION NEAR THE CENTER OF THE SESSILE DROP COMPARED TO THAT NEAR THE EDGE.



SCHEMATIC DIAGRAM OF THE POSITION OF THE PHOTOMICROGRAPH SHOWN ON FIGURE 5 WITH RESPECT TO THE SESSILE DROP (SOLID CIRCULAR SEGMENT) AND THE PRECURSOR SILICON CUBE BEFORE MELTING (DOTTED SQUARE).

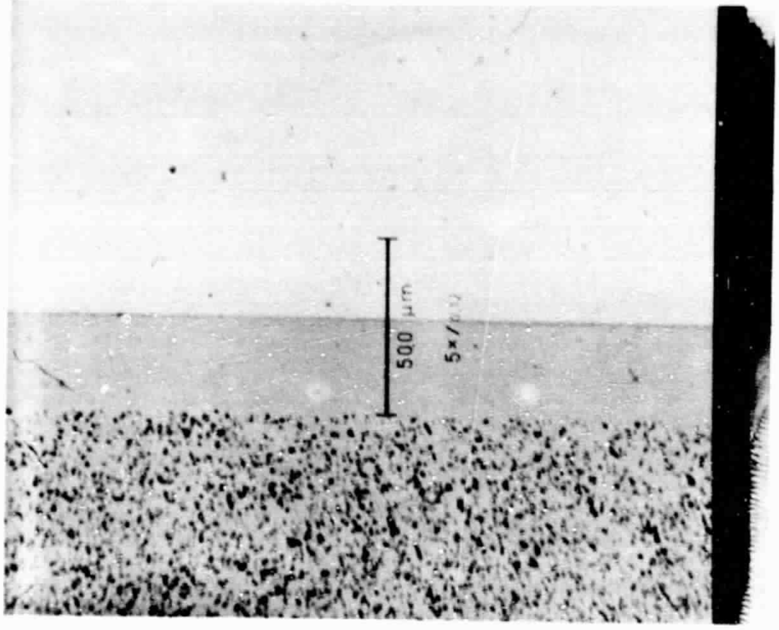


2 HOURS

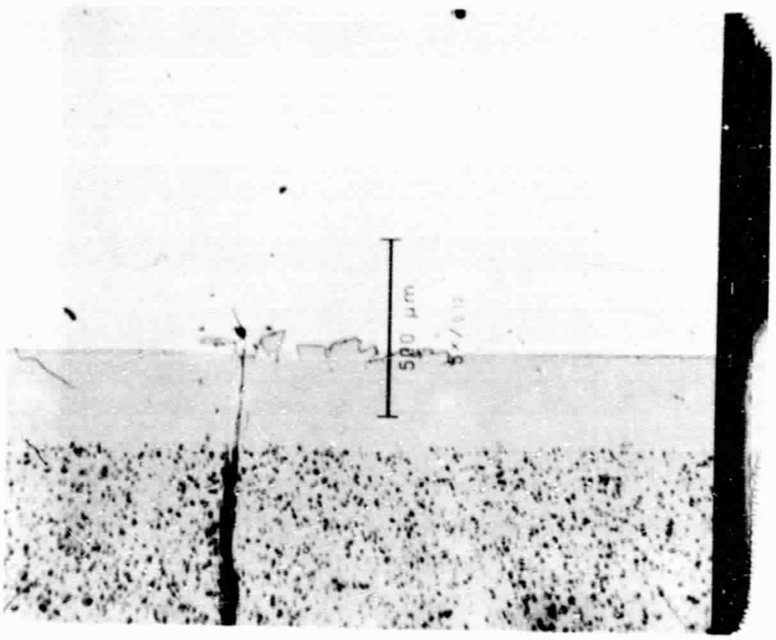


8 HOURS

PHOTOMICROGRAPHS OF POLISHED SECTIONS OF THE SILICON-CNTD SILICON CARBIDE COATING INTERFACE SHOWING THE ABRUPT CHANGE FROM PRACTICALLY NO INTERACTION ON THE LEFT SIDE TO APPRECIABLE INTERACTION ON THE RIGHT BEGINNING PRECISELY AT THE POSITION OF THE ORIGINAL SILICON CUBE EDGE AFTER A $1700^{o}K$ ANNEAL AT $P_{O_2} = 1.8 \times 10^{-20}$ ATM.

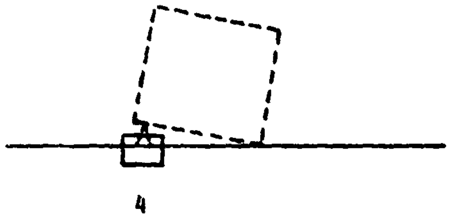


TYPICAL

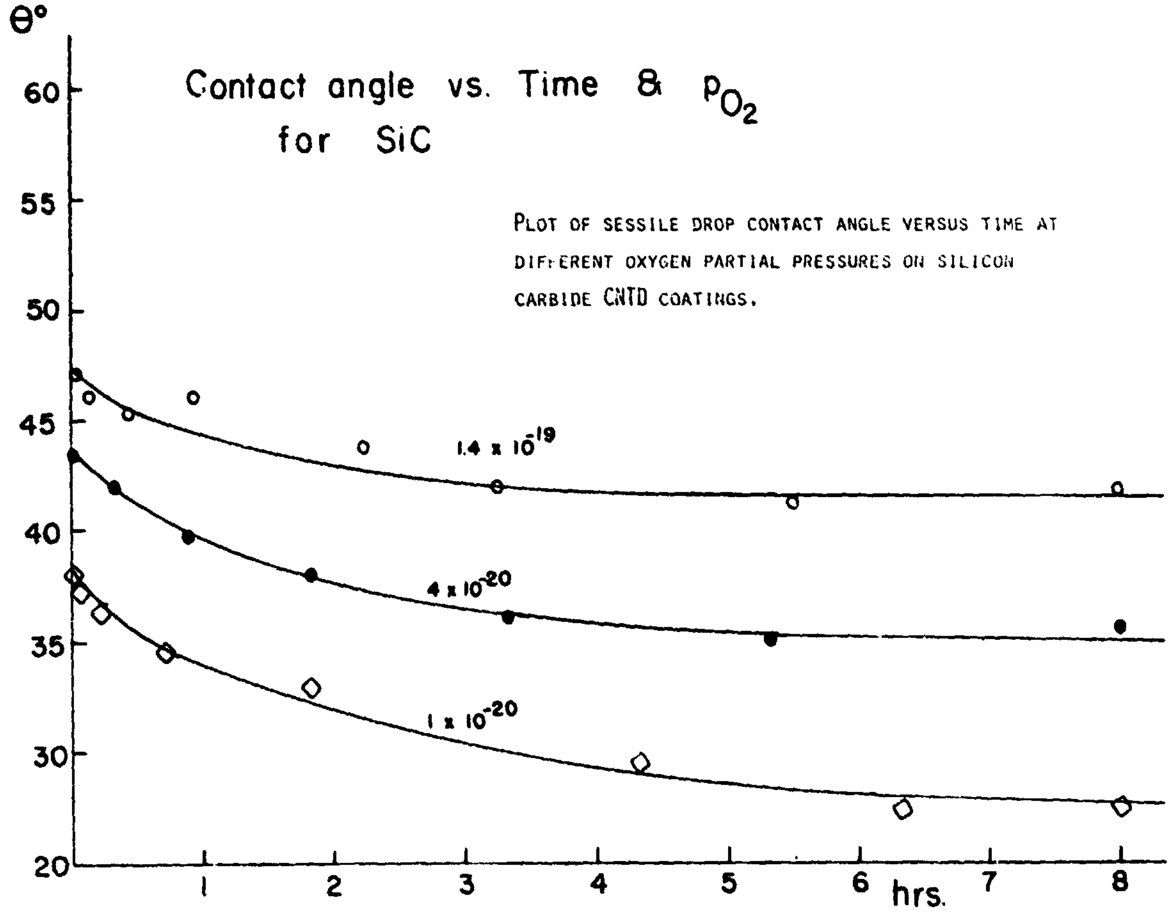


POSITION 4

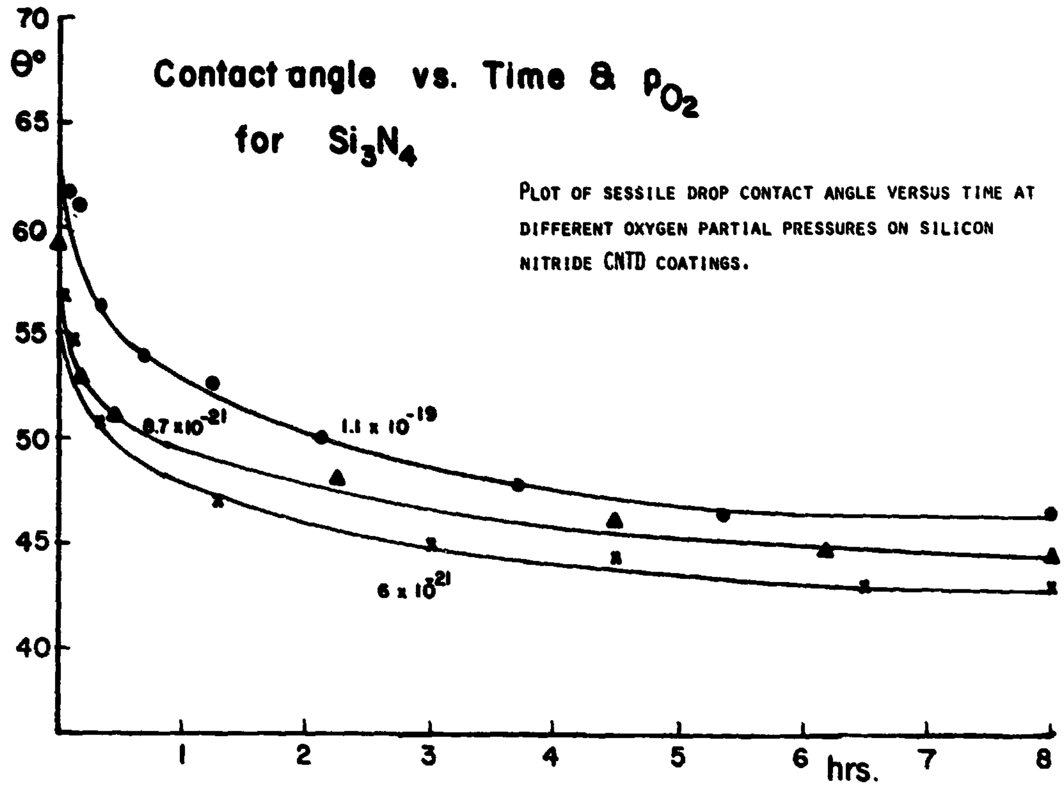
PHOTOMICROGRAPHS OF POLISHED SECTION OF THE SILICON-SILICON CARBIDE INTERFACE AFTER TILT CONFIGURATION EXPERIMENT, CLEARLY VERIFYING THE ADSORBED OXYGEN ON UNEQUILIBRATED SURFACES HYPOTHESIS.



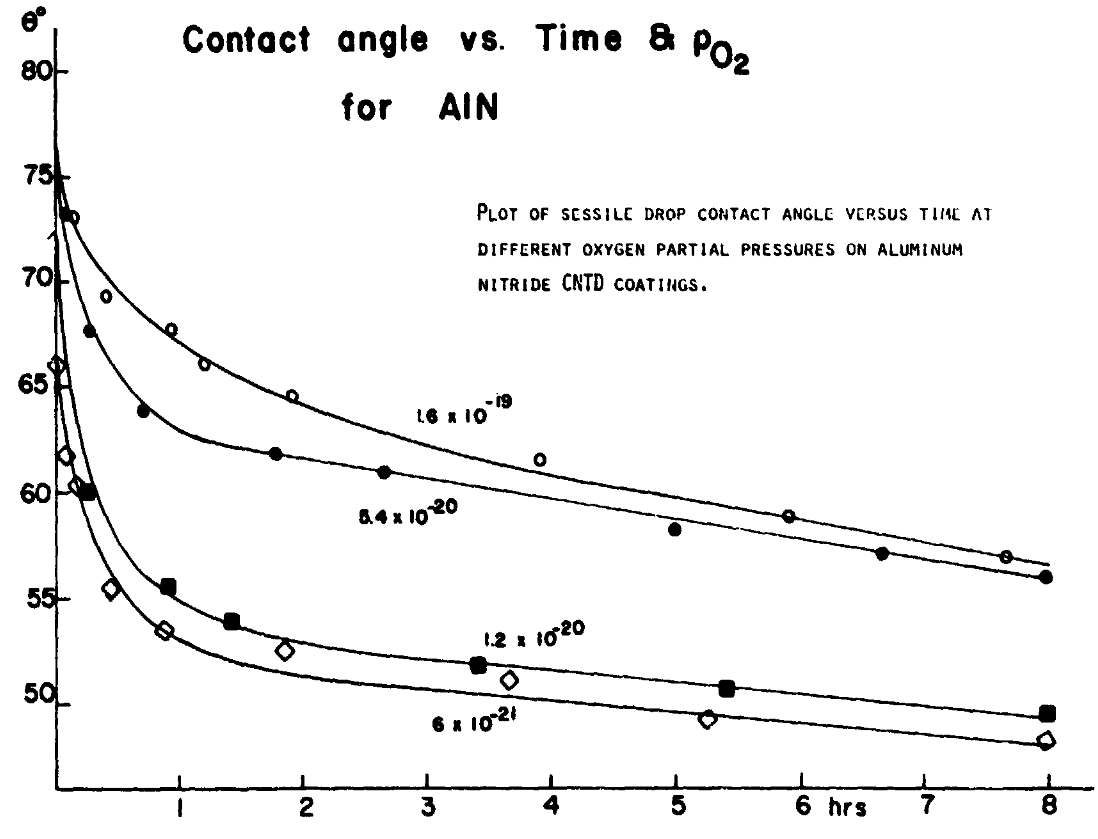
SCHEMATIC DIAGRAM OF THE EXPERIMENT DESIGNED TO TEST THE HYPOTHESIS THAT ADSORBED OXYGEN, WHICH COULD NOT EQUILIBRATE WITH THE LOW P_{O_2} ENVIRONMENT, WAS RESPONSIBLE FOR THE ENHANCED INTERACTION AT THE INTERFACE. THE PRECURSOR SILICON CUBE (DOTTED TILTED SQUARE) WAS PROPPED UP WITH A SILICON CHIP TO ALLOW THE FLOWING BUFFERED GAS TO COME IN CONTACT WITH THE SURFACES WHICH WERE HERETOFORE UNEXPOSED IN THE NORMAL UNTILTED CONFIGURATION.



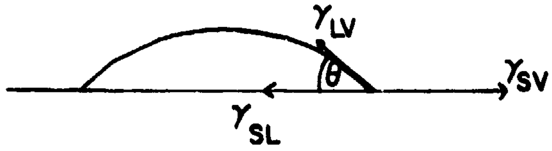
PLOT OF SESSILE DROP CONTACT ANGLE VERSUS TIME AT DIFFERENT OXYGEN PARTIAL PRESSURES ON SILICON CARBIDE CNTD COATINGS.



PLOT OF SESSILE DROP CONTACT ANGLE VERSUS TIME AT DIFFERENT OXYGEN PARTIAL PRESSURES ON SILICON NITRIDE CNTD COATINGS.



PLOT OF SESSILE DROP CONTACT ANGLE VERSUS TIME AT DIFFERENT OXYGEN PARTIAL PRESSURES ON ALUMINUM NITRIDE CNTD COATINGS.



$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos\theta$$

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$$

SCHEMATIC DIAGRAM OF A SESSILE DROP WITH VECTORS REPRESENTING THE INTERFACIAL FREE ENERGIES IN THE SYSTEM WITH THE YOUNG EQUATION RELATING THE CONTACT ANGLE TO THESE ENERGIES.

$$\left(\frac{\partial \gamma}{\partial \mu_i}\right)_T = -\Gamma_i$$

γ = interfacial energy

μ_i = chemical potential of adsorbed species

Γ_i = atoms of adsorbed species per unit area

For ideal gas:

$$d\mu_i = kT \ln p_i$$

where p is the partial pressure of the species i. For oxygen we have

$$\left(\frac{\partial \gamma_{sv}}{\partial \ln p_{O_2}}\right) = -kT\Gamma_O/2$$

Integrating gives

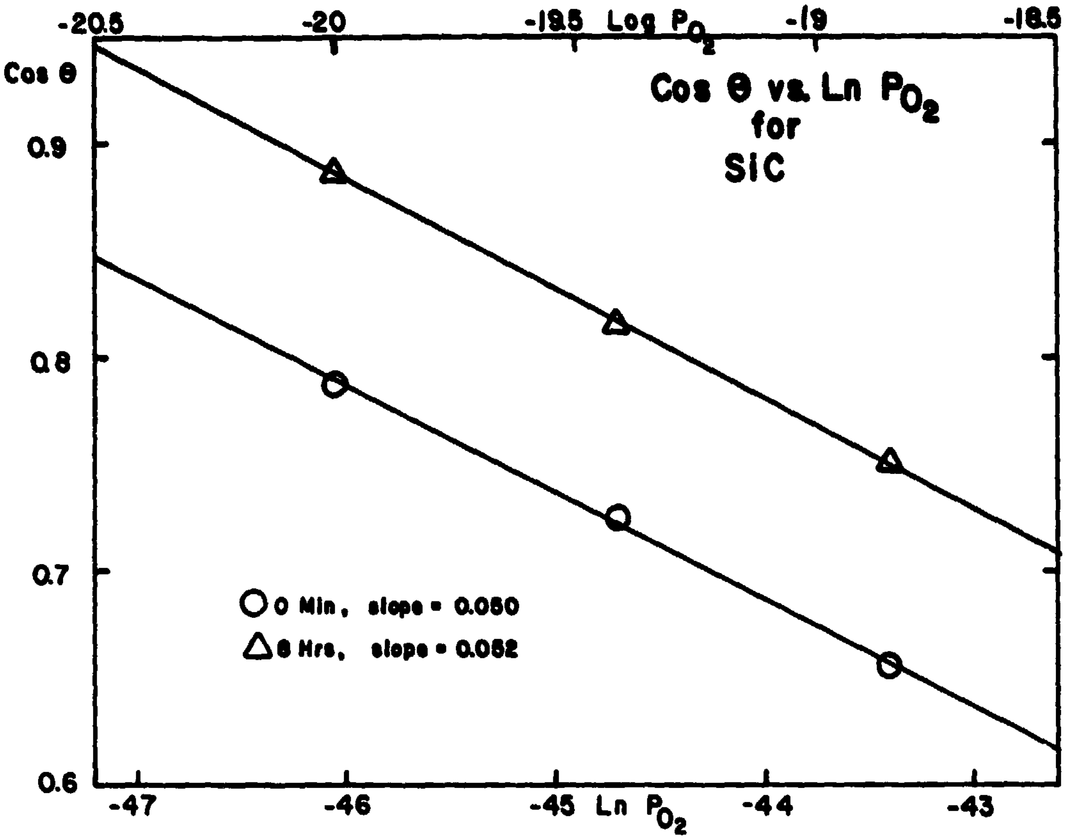
$$\gamma_{sv} = -kT\Gamma_O \ln p_{O_2}/2 + K$$

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cos\Theta \qquad \text{(Young's equation)}$$

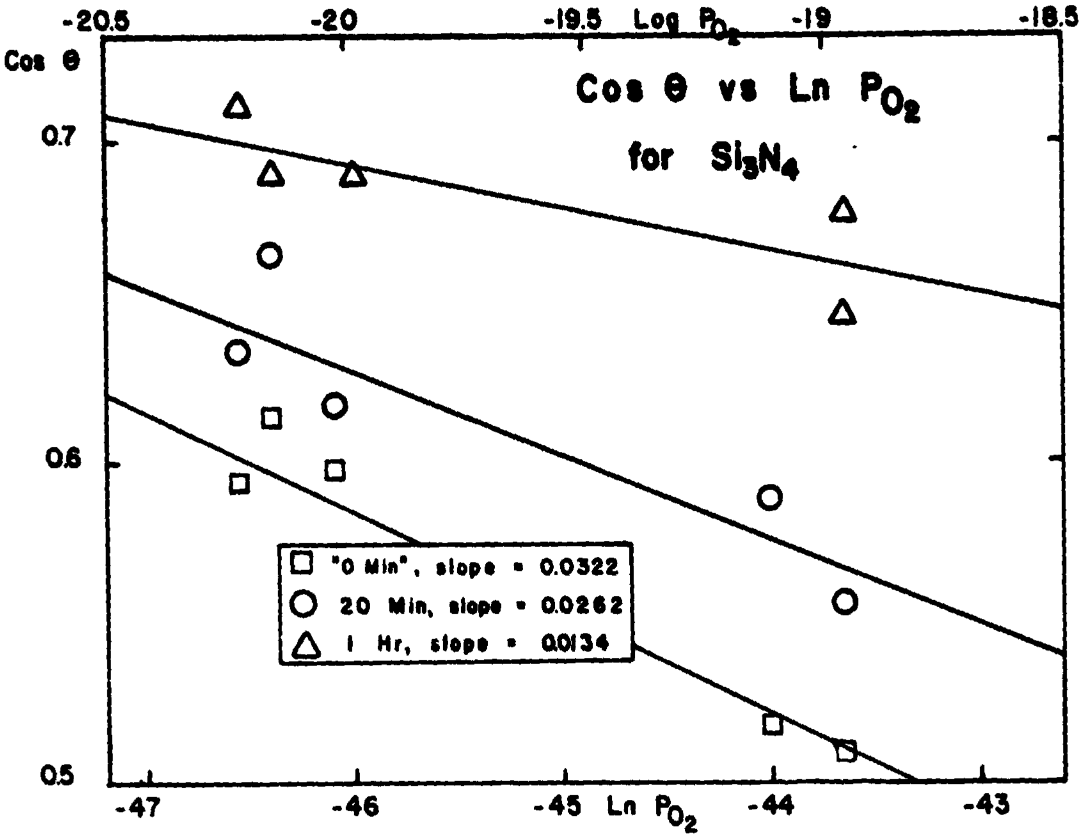
$$\cos\Theta = -\frac{kT\Gamma_O \ln p_{O_2}}{2\gamma_{lv}} - \frac{\gamma_{sl}}{\gamma_{lv}}$$

Assuming γ_{sl} & γ_{lv} constant and K = 0, the slope of $\cos\Theta$ vs. ln p_{O_2} will give a value for Γ_O

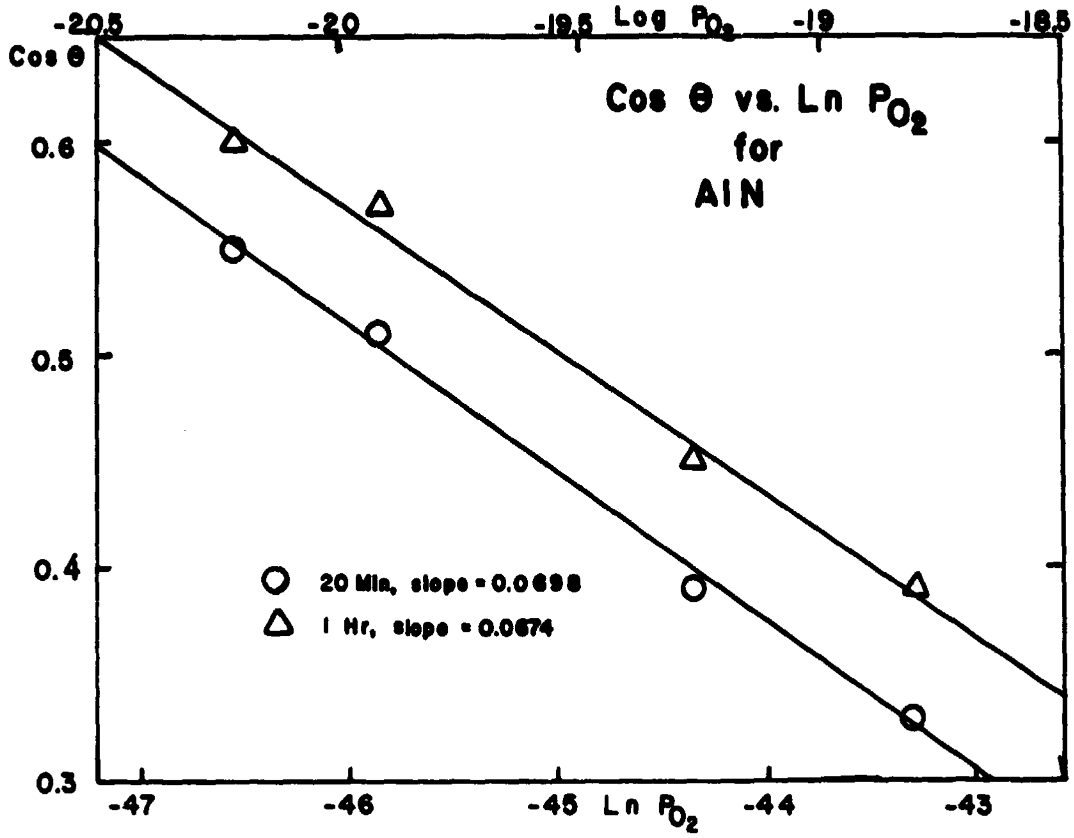
THE GIBB'S ADSORPTION ISOTHERM WHERE MONATOMIC OXYGEN IS THE ONLY SIGNIFICANT ADSORBING SPECIES COMBINED WITH THE YOUNG EQUATION.



PLOT OF THE COSINE OF THE SESSILE DROP ANGLE VERSUS THE NATURAL LOGARITHM OF THE OXYGEN PARTIAL PRESSURE AT DIFFERENT TIMES ON CNTD SILICON CARBIDE COATINGS.



PLOT OF THE COSINE OF THE SESSILE DROP CONTACT ANGLE VERSUS THE NATURAL LOGARITHM OF THE OXYGEN PARTIAL PRESSURE AT DIFFERENT TIMES ON CNTD SILICON NITRIDE COATINGS.



PLOT OF THE COSINE OF THE SESSILE DROP CONTACT ANGLE VERSUS THE NATURAL LOGARITHM OF THE OXYGEN PARTIAL PRESSURE AT DIFFERENT TIMES ON CNTD ALUMINUM NITRIDE COATINGS.

Calculated values for adsorbed monatomic oxygen population, Γ_0, for each material investigated using $T = 1700\,°K$, $\gamma_{LV} = 800\ erg/cm^2$, and the equation $\Gamma_0 = 2m\gamma_{LV}/kT$ where m is the slope of the graph of $\cos\theta$ vs. $\ln p_{O_2}$. k = Boltzmann constant

Material	Time	Slope	$\Gamma_0 \times 10^{14}$ atoms/cm^2	$\ln p_{O_2}$	$\gamma_{SV} = -kT\Gamma_0 \ln p_{O_2}/2$ ergs/cm^2	γ_{SL}
SiC	0 min	0.050	3.41	-46.1	1844	~1200
	8 hrs	0.052	3.55	"	1920	
	0 min	0.050	3.41	-43.4	1736	
	8 hrs	0.052	3.55	"	1807	
AlN	20 min	0.070	4.77	-46.5	2602	~2100
	1 hr	0.067	4.57	"	2493	
	20 min	0.070	4.77	-43.3	2423	
	1 hr	0.067	4.57	"	2321	
Si_3N_4	"0 min"	0.032	2.18	-46.5	1190	~700
	20 min	0.026	1.77	"	965	~500
	"0 min"	0.032	2.18	-43.3	1107	~700
	20 min	0.026	1.77	"	899	~500

SUMMARY OF PROGRESS TO DATE

QUALITATIVE RELATIONSHIPS BETWEEN P_{O_2} AND THE DEGREE OF INTERACTION OF MOLTEN SILICON AND SOME CANDIDATE DIE AND CONTAINER MATERIALS HAVE BEEN SHOWN. THE LOWER THE P_{O_2}, THE LESS THE INTERACTION IN THE RANGE 10^{-18} TO 10^{-22} ATMOSPHERES.

THE IMPORTANCE OF RESIDUAL ADSORBED OXYGEN ON THESE MATERIALS AND/OR ON SOLID SILICON FEED MATERIAL IN PROMOTING REACTION WITH MOLTEN SILICON HAS BEEN DEMONSTRATED.

QUANTITATIVE CONTACT ANGLE DATA ON THESE MATERIALS AS A FUNCTION OF TIME AND OXYGEN PARTIAL PRESSURE HAVE BEEN GENERATED.

A NEW TECHNIQUE FOR DETERMINING SOLID-VAPOR AND SOLID-LIQUID INTERFACIAL ENERGIES HAS BEEN PROPOSED AND APPLIED TO THE ABOVE DATA.

WORK IN PROGRESS

EQUIPMENT IS BEING MODIFIED TO CONDUCT SILICON SESSILE DROP EXPERIMENTS OVER A WIDER RANGE OF P_{O_2}'S USING DIFFERENT BUFFER SYSTEMS. SUBSTRATES OF SIBEON AND OTHER PROMISING MATERIALS WILL BE SUPPLIED BY JPL.

A PORTABLE YTTRIA-THORIA OXYGEN SENSOR CELL IS BEING CONSTRUCTED TO MEASURE THE P_{O_2} IN EXISTING SILICON BOULE, SHEET AND RIBBON PRODUCTION FACILITIES.

SOLAR CELL PROCESS DEVELOPMENT

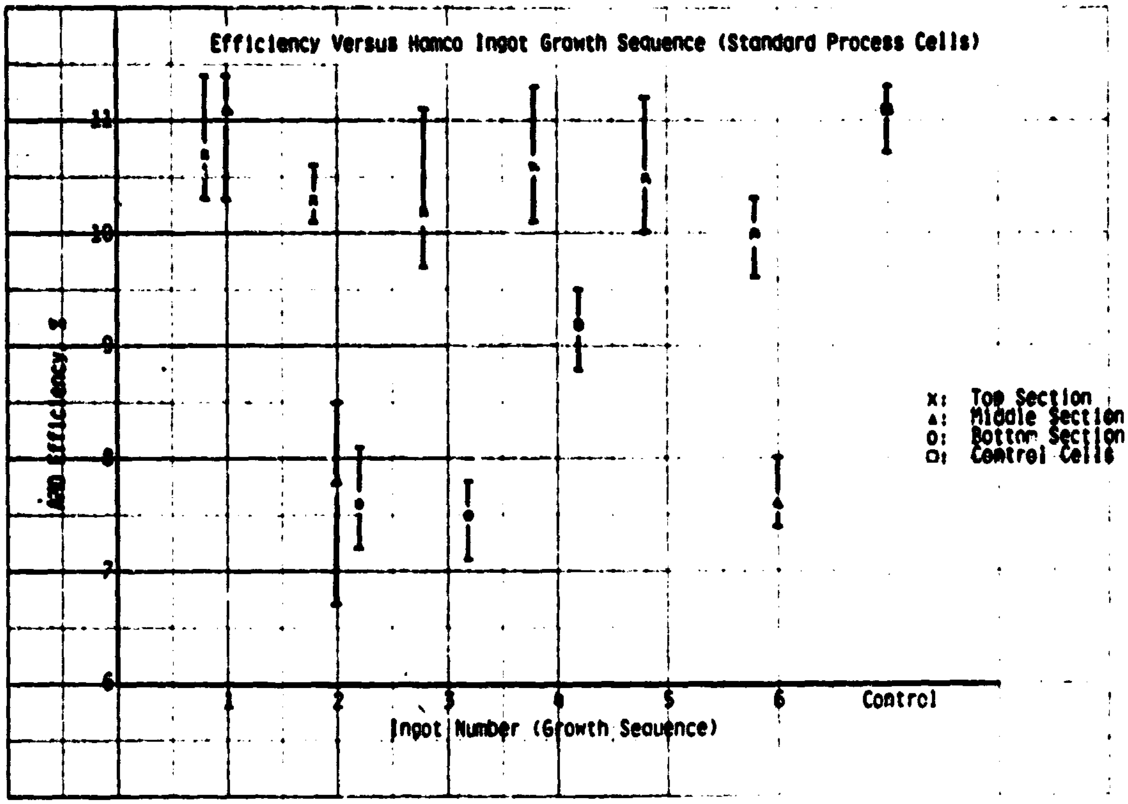
APPLIED SOLAR ENERGY CORP.

OBJECTIVE

To evaluate and develop solar cells fabricated from unconventional silicon sheets; RTR (Motorola), EFG RH and RF (Mobil Tyco), dendritic web (Westinghouse), Silso (Wacker), HEM (Crystal Systems), SOC (Honeywell) and continuous CZ wafers (JPL Contract No. 955089).

SCOPE

1. Performance of Continuous CZ Solar Cells
   - Hamco
   - Varian
2. Performance Summary of Standard Solar Cells
   - Illumination Characteristics (AMO, 25°C)
   - Dark I-V Characteristics
   - Spectral Response
   - Minority Carrier Diffusion Length
   - Defects Influencing Cell Performance
3. Process Summary


Efficiency Versus Hamco Ingot Growth Sequence (Standard Process Cells)
AMO Efficiency, %
11
10
9
8
7
6
1
2
3
4
5
6
Control
Ingot Number (Growth Sequence)
x: Top Section
▲: Middle Section
o: Bottom Section
□: Control Cells

Summary of Parameters of Standard
Solar Cells Fabricated From Varian Continuous CZ Wafers

PARAMETER		TOP	MIDDLE	BOTTOM	CONTROL
V_{OC}, mV	Average	573	575	574	592
	Standard Deviation	1.2	3	1.7	2
	Range	571-574	570-580	572-576	590-594
J_{SC}, mA/cm^2	Average	34.3	34	34.0	34.7
	Standard Deviation	0.2	0.4	0.3	0.3
	Range	34-34.8	33.5-34.8	33.5-34.3	34.5-35
CFF, %	Average	74	74	74	72
	Standard Deviation	2	2	1	2
	Range	71-76	71-77	73-76	70-74
η, %	Average	10.7	10.7	10.7	10.9
	Standard Deviation	0.3	0.4	0.2	0.4
	Range	10.3-11.1	10.1-11.3	10.4-10.9	10.5-11.3

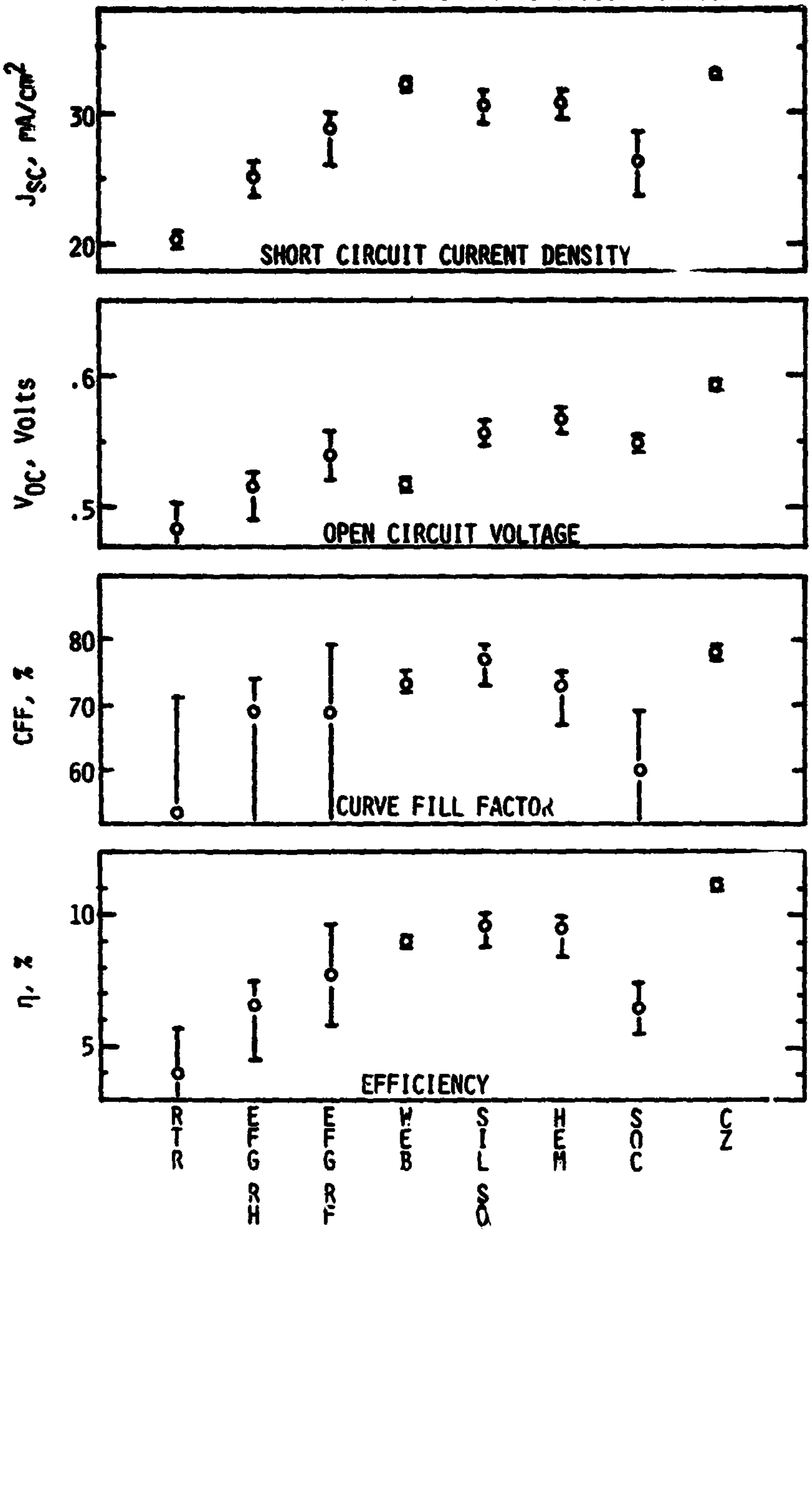
NOTES:

1. Varian Ingot Identification Run 191, Ingot No. 3
2. Measured Under AMO Condition at 25°C.
3. Cells (2x2 cm) With SiO AR Coating.
4. Number of Samples:

Varian: Top: 9 Cells
Middle: 10 Cells
Bottom: 5 Cells

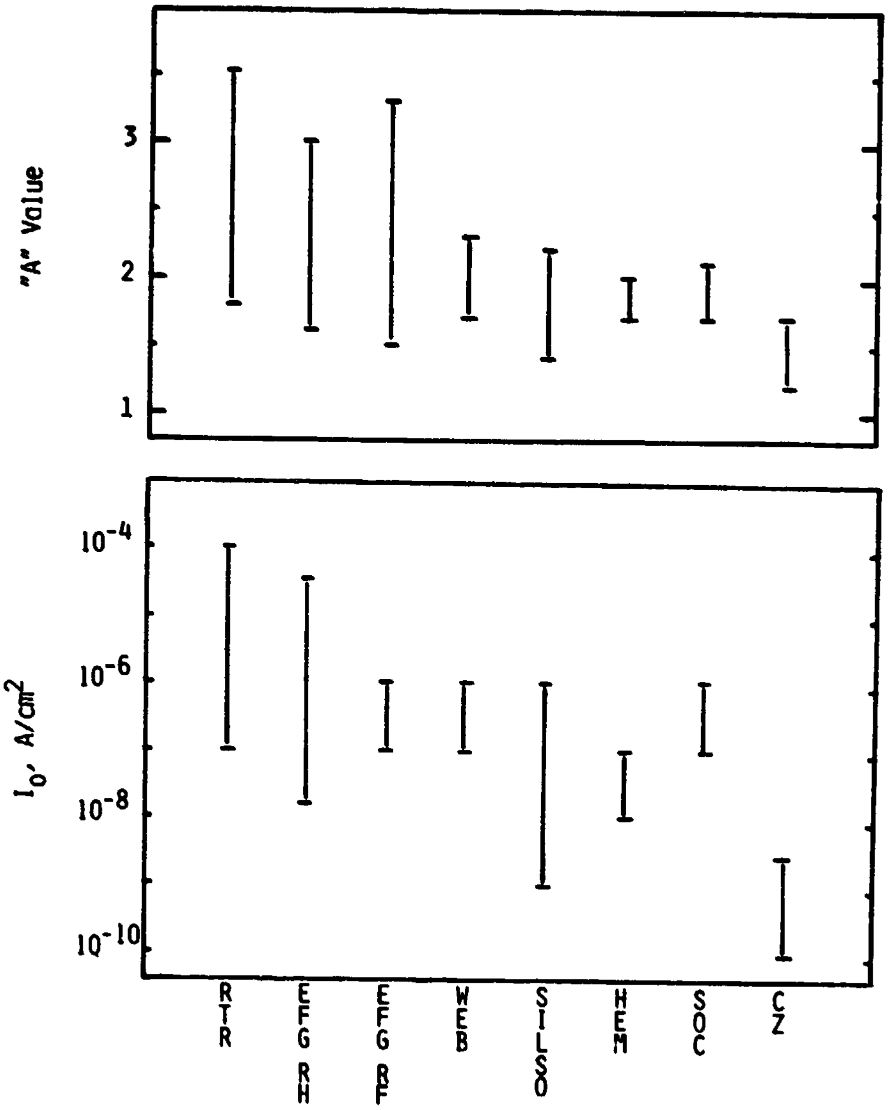
Control: 3 Cells

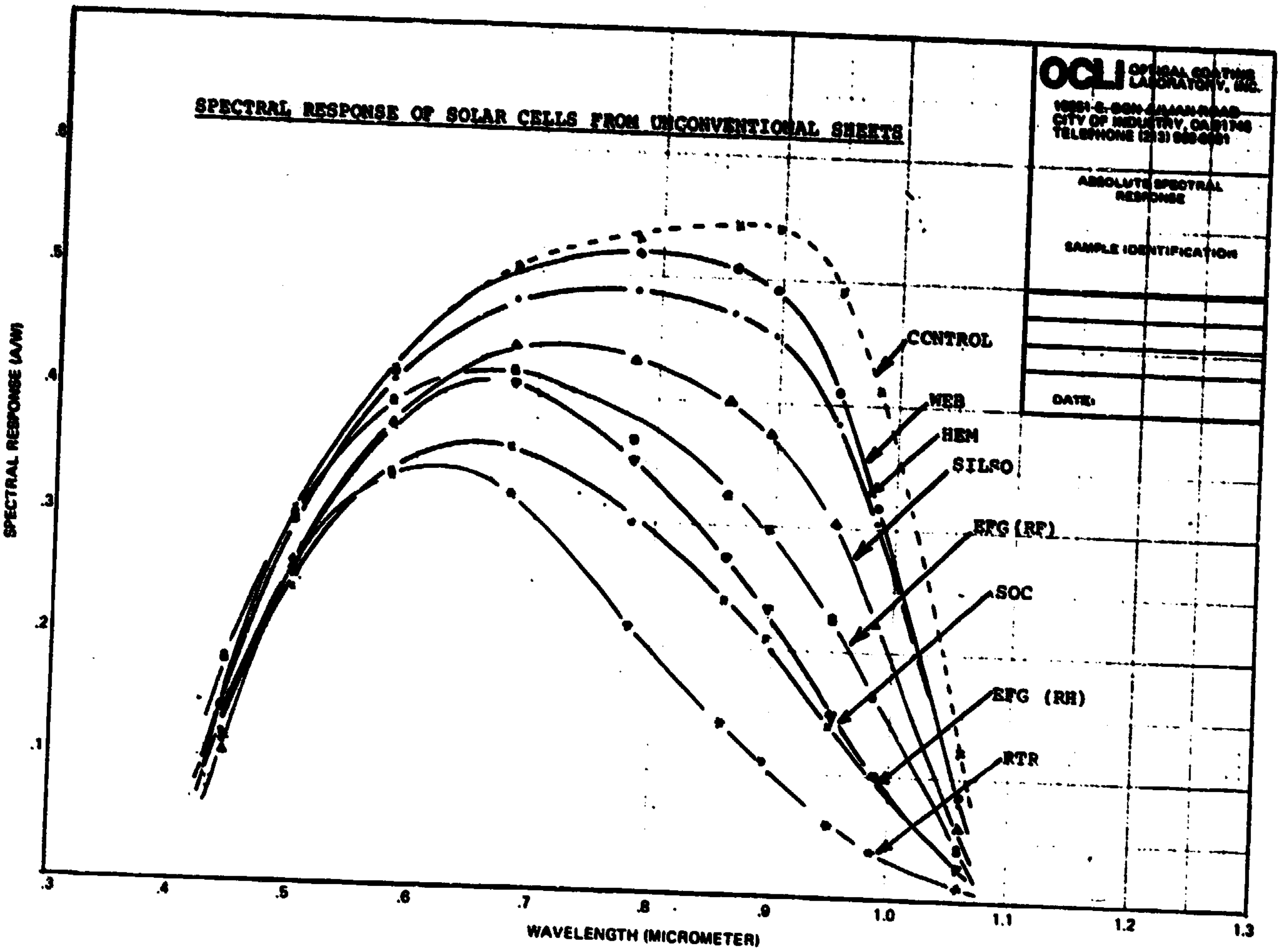
A Summary of Illumination Characteristics of the Solar Cells From the Unconventional Silicon Sheets



A Summary of Forward Dark I-V Characteristic Parameters of Solar Cells From the Unconventional Silicon Sheets

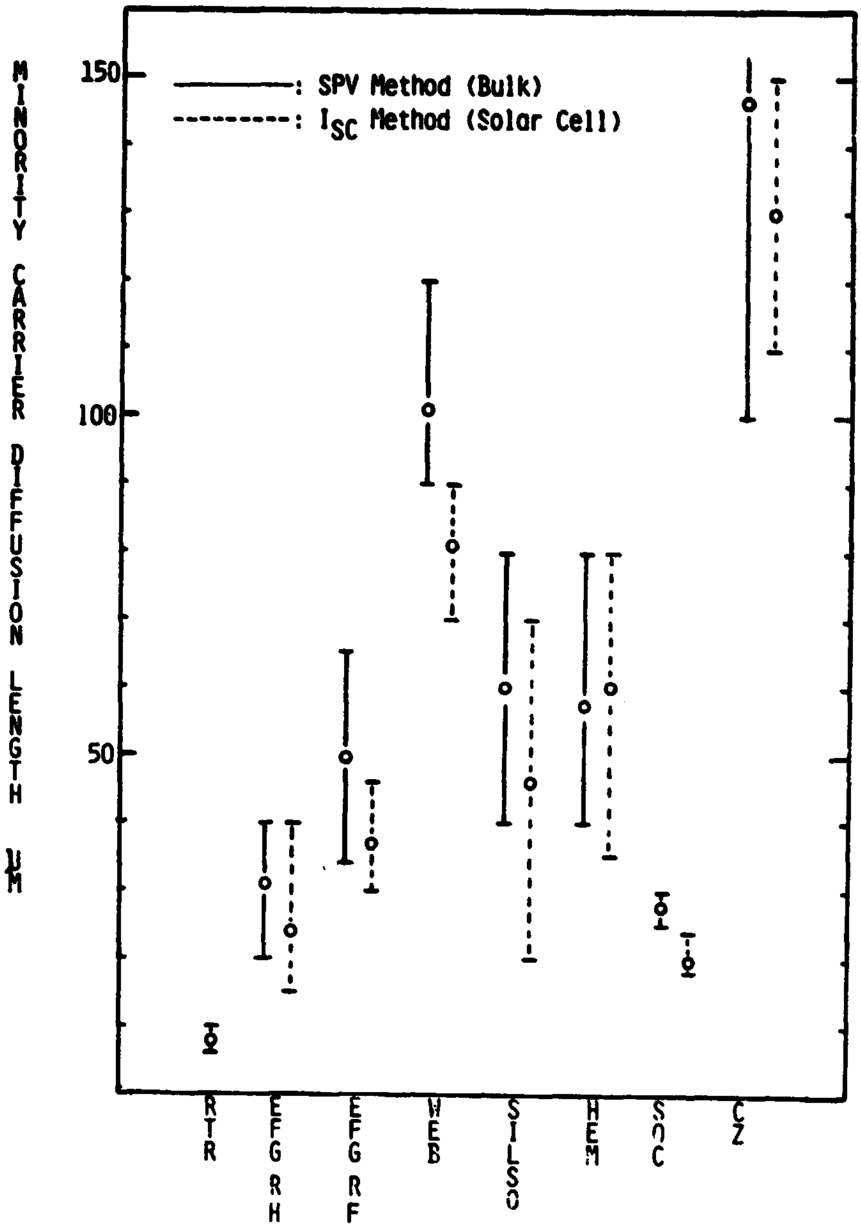
$$I_D = I_0 \left(\text{Exp} \frac{qV}{AKT} - 1\right)$$



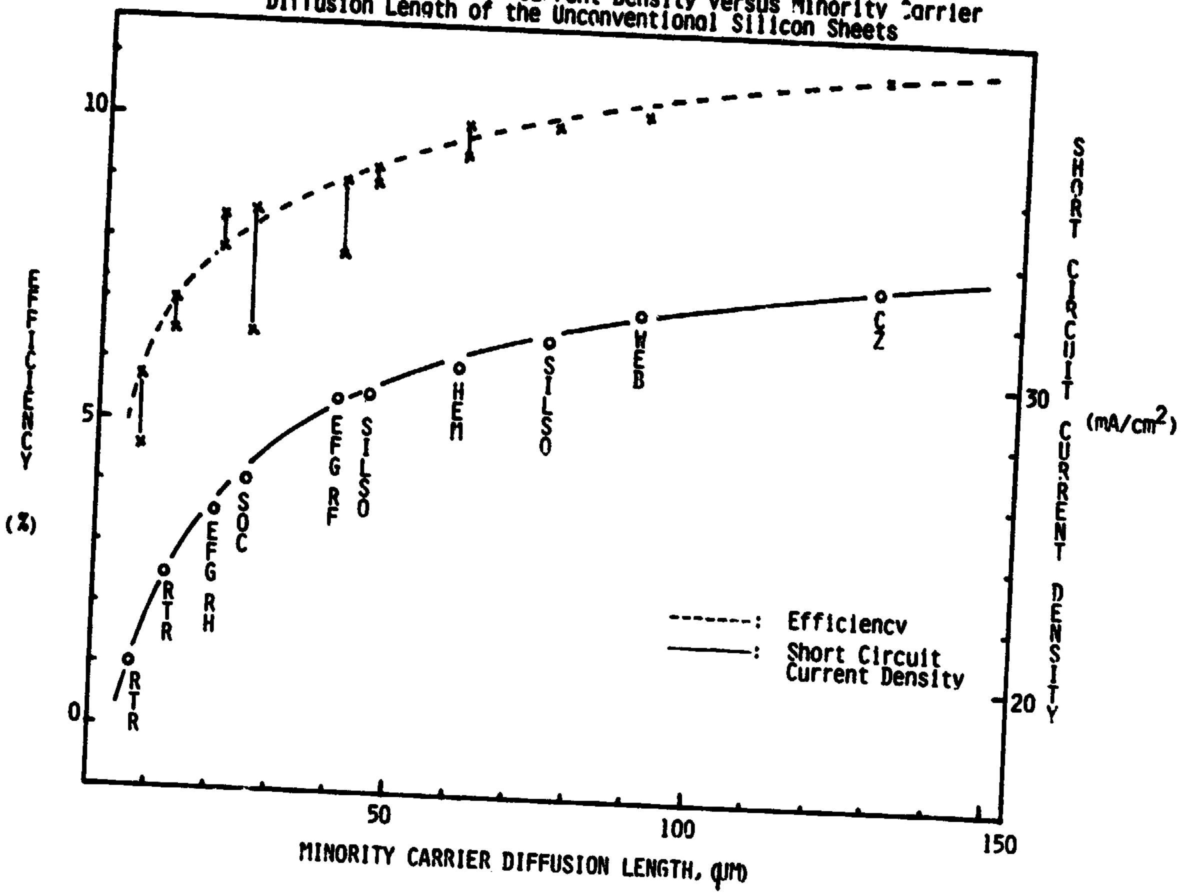


SPECTRAL RESPONSE OF SOLAR CELLS FROM UNCONVENTIONAL SHEETS
SPECTRAL RESPONSE (A/W)
WAVELENGTH (MICROMETER)
CONTROL
WEB
HEM
SILSO
EFG (RF)
SOC
EFG (RH)
RTR
ABSOLUTE SPECTRAL RESPONSE
SAMPLE IDENTIFICATION
DATE:

Minority Carrier Diffusion Length
of the Unconventional Silicon Sheets



Efficiency and Short Circuit Current Density Versus Minority Carrier Diffusion Length of the Unconventional Silicon Sheets



DEFECTS AND THEIR INFLUENCE ON CELL PERFORMANCE

	SHEETS	DEFECTS	CELL PERFORMANCE
RIBBONS	RTR	G.B. Twins Stress Induced Defects	Low I_{SC}; + Contamination Low V_{OC} Low CFF
	EFG (RH & RF)	G.B. Twins Inclusions (SiC)	Low I_{SC} (EFG RH); + Contamination Low V_{OC} Low CFF
	DENDRITIC WEB	Twins	Low V_{OC}; Low Doping Level
CAST	SILSO	G.B. Inclusions	Low CFF
	HEM	G.B. Inclusions Microcracks	Low CFF
COATED	SOC	G.B. Twins Inclusions	Low I_{SC}; + Contamination Low CFF; + High Series Resistance

PROBLEM AREAS RELATED TO STANDARD PROCESS

SHEETS	PROCESS	MECHANICAL YIELD (%)
EFG (RF and RH)	Metallization & Measurement; Non-Flat & Non-Uniform Thickness	55 (RF) 80 (RH)
RTR	Metallization & Measurement; Wavy Surface Handling; Fragile	50
DENDRITIC WEB	Removal of Surface Deposit (SiO) Handling; Fragile (Thin Web)	50* 90**
SILSO (WACKER) WAFER	No Major Problem	94
CAST SILICON BY HEM	No Major Problem	>90
SOC	Metallization & Measurement; Warpage & Back Slot Keep the Substrate Free From Moisture Before High Temperature Treatment	60
CONTINUOUS CZ (HAMCO)	No Major Problem	>90

* Thin webs, 5-6 mils
**Thick webs, 8-10 mils

MAJOR PROBLEM AREAS

GEOMETRY

Non-Uniform and Non-flat Thickness

A. Metallization

- Metal Shadow Masking
  Metal Smearing and Breakage
- Photoresist Techniques
  Spinning Photoresist (Possible solution could be spray-on technique)

B. Measurement

- Electrical Contact; Series Resistance
- Thermal Contact; Cell Temperature

THERMAL

Thermal Stress; Excessive Breakage (?)

SUMMARY

- Minority carrier diffusion (Le) is the parameter limiting the solar cell efficiency and the causes of the reduced Le-values were from grain boundaries, impurity contamination, and stress induced defects.
- Secondary losses results from low V_{OC} or CFF, caused by shunting of the voltage barrier. These shunt paths were mainly due to surface inclusions from die material, crucible and growing atmosphere, etc.
- Some sheet samples gave difficulty in processing because of increased breakage caused by warpage and thickness variation, or from apparent high stresses in the sheets.
- The evaluation technique used provided accurate and reliable information on sheet performance, and self-consistent results were obtained from the various measurement techniques used.

SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION AND ANALYSIS

SPECTROLAB, INC.

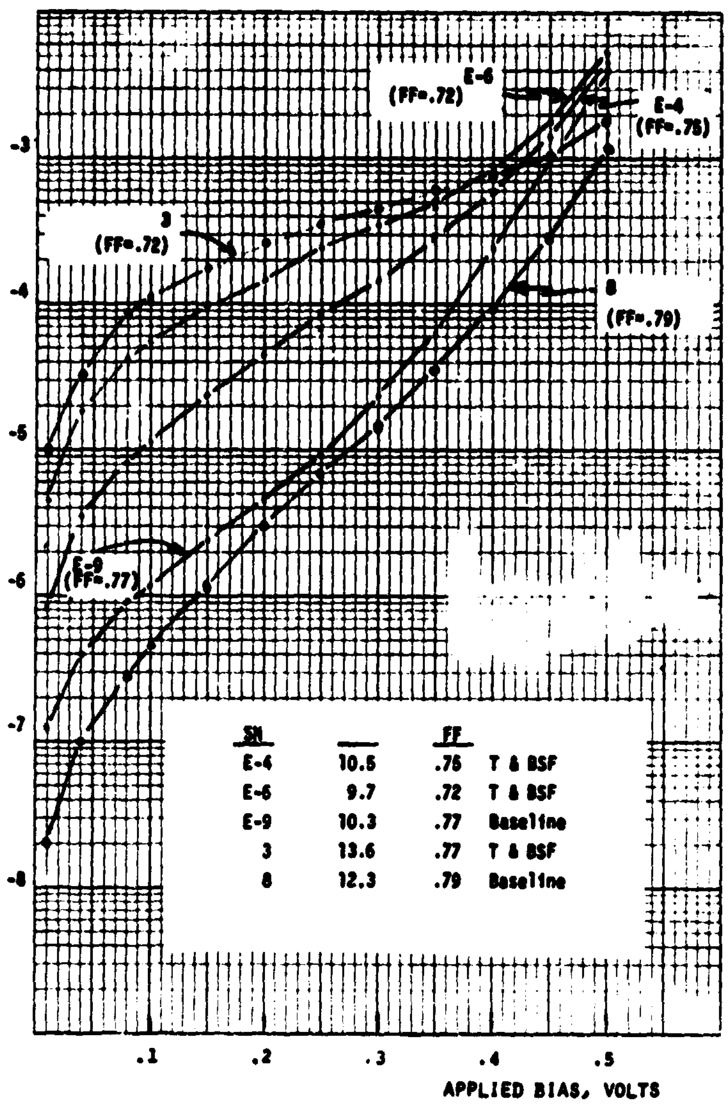
JOSEPH A. MINAHAN

CURRENT - VOLTAGE
WACKER SILSO OPTIMIZED
2 CM x 2 CM CORNER MATERIAL AMO 28°C

S/N	I_{sc}	V_{oc}	FF	η	
C1	135	547	.74	10.1%	T & BSF
C2	131	536	.65	8.4	"
C3	132	542	.74	9.8	"
C4	132	542	.73	9.6	"
C5	133	545	.73	9.8	"
C6	134	546	.71	9.6	"
C7	134	547	.73	10.0	"
Avg.	133	544	.72	9.6	"
C9	128	545	.76	9.9	BASELINE
C11	127	545	.77	9.9	"
1	159	606	.76	13.5	T & BSF
2	158	605	.75	13.2	"
3	158	607	.77	13.6	"
4	156	601	.67	11.6	"
5	143	589	.78	12.1	
6	141	584	.78	11.9	
7	144	591	.79	12.4	
8	143	587	.79	12.3	

CURRENT - VOLTAGE
WACKER SILSO OPTIMIZED
2 CM X 2 CM - EDGE MATERIAL & CENTER MATERIAL

S/N	I_{SC}	V_{OC}	FF	η	
E1	134	546	.73	9.8	T & BSF
E2	136	552	.74	10.3	"
E3	137	552	.73	10.2	"
E4	137	553	.75	10.5	"
E5	136	545	.74	10.1	"
E6	134	546	.72	9.7	"
E7	135	548	.74	10.1	"
E8	135	550	.73	10.0	"
E9	131	552	.77	10.3	BASELINE
E10	132	551	.77	10.3	"
E11	131	554	.77	10.3	"
I1	137	555	.69	9.7	T & BSF
I2	139	552	.72	10.3	"
I3	137	551	.69	9.6	"
I4	136	548	.69	9.6	"
I5	134	559	.76	10.5	BASELINE
I6	131	556	.76	10.3	"



DARK FORWARD CURRENT DENSITY, WACKER SILCO WO-1

CURRENT - VOLTAGE
RTR AMO 28°C
RTR-1 BASELINE

S/N	I_{sc} MN	V_{oc} MA	FF	η%	
2	91	556	.75	7.0	
3	140	552	.73	6.5	
4	139	560	.77	6.8	
5	82	551	.72	6.0	
Avg	113	555	.74	6.6	
Controls					
Avg	143	591	.78	12.1	
End piece	77	271	.38	1.5	
		RTR - 2 BASELINE			
4	152	557	.70	6.8	
5	95	559	.74	7.2	
6	89	543	.66	5.9	
Avg	112	553	.70	6.6	Avg
Controls					
Avg	144	586	.73	11.4	

CURRENT - VOLTAGE
RTR AMO 28°C
ExR - 1

S/N	I_{sc}	V_{oc}	FF	η%	
3	89	528	.54	4.7	T
12	86	498	.46	3.7	T
5	91	547	.69	6.3	BSF
11	91	481	.41	3.3	Baseline
Avg	89	514	.53	4.5	Avg

CONTROLS

Avg	147	581	.72	11.4	T
Avg	151	611	.76	13.0	BSF
Avg	143	588	.77	12.0	Baseline

CURRENT - VOLTAGE
EFG (RF) 2 cm x 2 cm
BASELINE EFG-3

S/N	I_{sc}	V_{oc}	FF	η%
33	121	561	.67	8.4
35	117	560	.74	8.9
36	125	568	.74	9.7
37	118	555	.64	7.7
38	116	544	.63	7.3
39	118	554	.66	8.0
40	116	532	.55	6.3
42	114	558	.61	7.2
43	109	539	.64	7.0
45	97	494	.53	4.7
46	125	567	.75	9.8
47	127	561	.68	8.9
48	122	477	.39	4.2
52	122	566	.74	9.4
54	118	563	.65	8.0
55	123	567	.71	9.2
56	124	563	.75	9.7
57	123	564	.70	8.9
AVG.	229	550	.65	8.0
MAX	125	568	.75	9.8

CURRENT - VOLTAGE
EFG (RH) 2 cm x 2 cm
AMO 28°C EFGB-1 BASELINE

S/N	I_{sc}	V_{oc}	FF	η%	
B	90	487	.60	4.9	(184-9)
C	108	519	.67	7.0	
D	116	537	.73	8.4	(184-36)
E	104	519	.71	7.2	(184-46)
F	91	451	.42	3.2	
G	83	445	.43	2.9	(184-53)
H	92	491	.61	5.1	
I	102	513	.69	6.7	(184-219)
J	98	499	.73	6.6	
L	97	515	.69	6.4	(184-275)
AVG	97	495	.62	5.7	AVG
MAX	116	537	.73	8.4	MAX
<u>CONTROLS</u>					
AVG	140	584	.76	11.4	AVG
MAX	144	591	.78	11.9	MAX

Current - Voltage
Web Material - 2 cm x 2 cm
AMO 28°C

S/N	I_{sc}	V_{oc}	FF	η%
B	134	508	.72	9.0
C	131	513	.72	9.0
D	129	510	.74	9.0
E	132	515	.73	9.0
F	131	512	.73	9.2
Avg.	132	513	.73	9.1

Controls

Avg.	143	588	.75	11.6
Max	144	590	.78	12.2

Current - Voltage
Web Material 2 cm x 2 cm
AMO 28°C Web-6 Strip Re 30-1.5

S/N	I_{sc}	V_{oc}	FF	η%	
A	142	529	.75	10.5	
C	143	529	.73	10.3	
E	143	524	.73	10.2	
G	141	519	.75	10.1	
I	140	524	.75	10.2	
K	141	531	.74	10.3	
M	140	528	.77	10.5	
O	142	527	.73	10.1	
Avg.	142	526	.74	10.3	
Avg.	144	590	.77	12.0	Controls
B	146	517	.67	9.3	825°C diffusion
D	145	525	.69	9.7	"
F	145	530	.75	10.6	"
H	145	526	.75	10.6	"
N	143	523	.75	10.3	"
Avg.	145	524	.72	10.1	"
Avg.	146	587	.76	12.1	" Control

CURRENT-VOLTAGE
WEB MTL. AMO 28^{o}C
WEB 0-1

S/N	I_{sc}	V_{oc}	FF	η%
4-B	133	519	.76	9.6% BASELINE RE33-3.5
5-B	131	520	.76	9.6 BASELINE RE33-3.5
6-B	145	581	.70	10.9 BSF RE33-3.5
7-B	141	581	.70	10.6 BSF RE33-3.5
8-B	144	585	.43	6.7 BSF RE33-3.5
3-C	145	589	.73	11.5 BSF, 850^{o}C RE33-4.4
2-C	140	581	.73	10.9 BSF, 800^{o}C RE33-4.4
1-C	142	551	.68	9.9 BSF, 800^{o}C RE33-4.4
		CONTROLS		
AVG	142	580	.61	9.2 BASELINE

CURRENT - VOLTAGE
DENDRITIC WEB MATERIAL
2 CM X 2 CM - STRIP RE 25-2.3

S/N	I_{sc}	V_{oc}	FF	η	
1	141	478	.72	8.9	BASELINE
3	139	499	.74	9.4	"
9	141	477	.72	8.9	"
11	146	473	.69	8.8	"
13	141	493	.70	8.9	"
AVG	142	484	.71	9.0	"
2	149	584	.75	12.0	BSF
4	149	575	.74	11.8	"
6	149	579	.75	12.0	"
8	149	569	.68	10.7	"
10	145	579	.75	11.6	"
12	145	573	.76	11.6	"
AVG	148	577	.74	11.6	"
AVG. CONT.	143	561	.77	11.4	
AVG. CONT.	147	596	.78	12.6	

CURRENT - VOLTAGE
HEM MATERIAL X-TAL 857
AMO 28°C HEM-2

S/N	I_{sc}	V_{oc}	FF	η %
1	205	567	.77	10.2
3	172	565	.65	7.2
4	206	568	.73	9.8
7	194	565	.70	8.8
6	189	565	.77	9.4
10	197	568	.77	9.9
16	192	564	.75	9.3
AVG.	194	566	.73	9.2
		CONTROLS		
AVG.	142	586	.77	11.9

CURRENT-VOLTAGE
HEM MTE-XTL 850
2 CM x 2 CM AMO 28°C

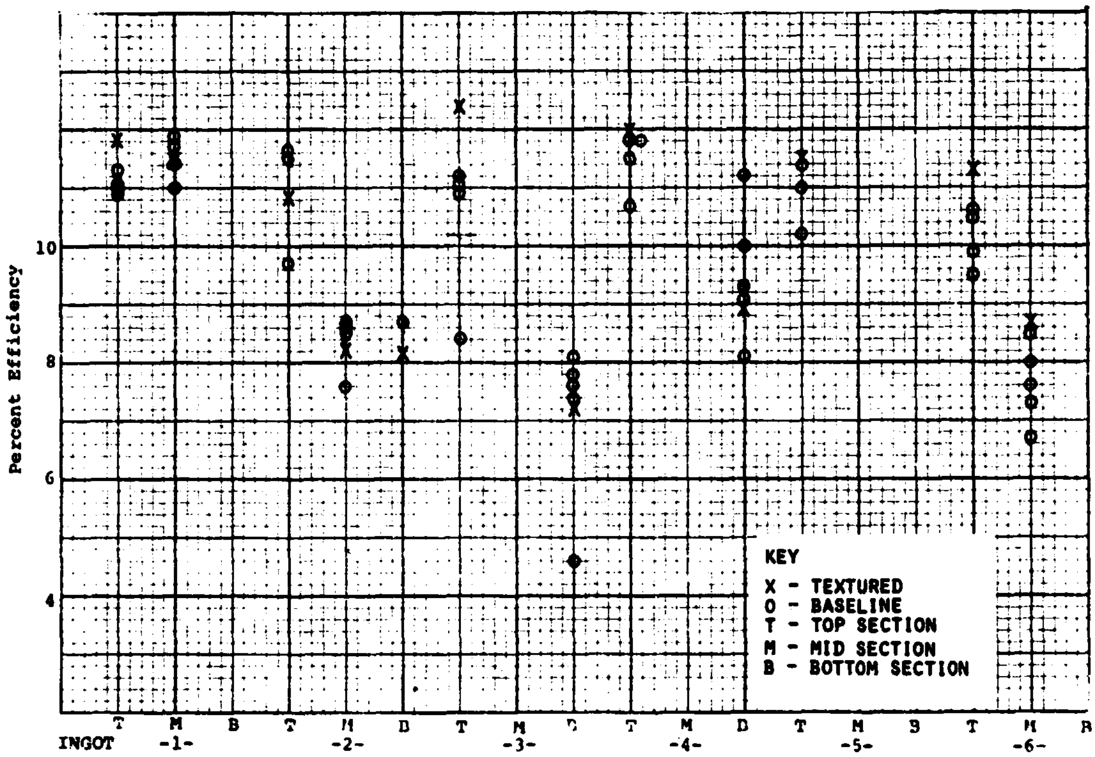
S/N	I_{sc}	V_{oc}	FF	η %
11	131	570	.76	10.5
21	128	595	.75	10.5
27	126	589	.76	10.4
36	130	590	.76	10.7
73	129	589	.74	10.4
86	116	550	.76	9.0
88	130	579	.77	10.7
		CONTROLS		
AVE	127	580	.76	10.3

CURRENT-VOLTAGE
HEM MTL 2 CM x 2CM
AMO 28oC
HEM-3

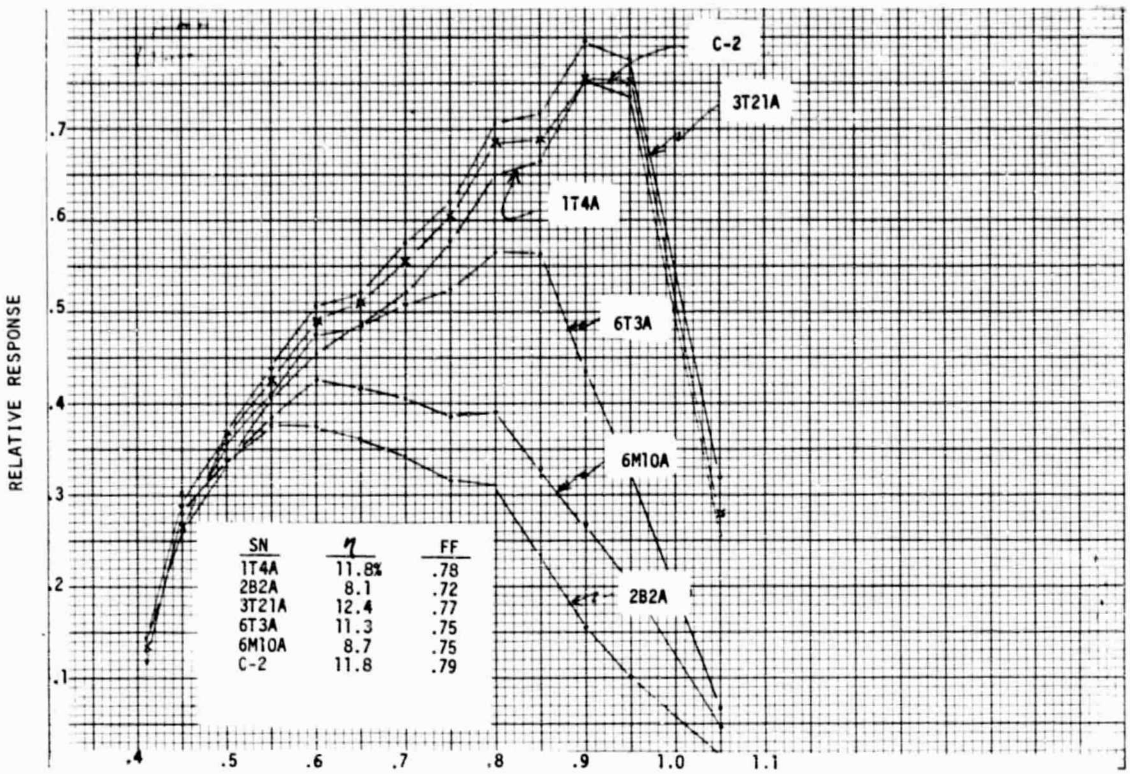
S/M	I_{SC}	V_{OC}	FF		REMARKS
A17	129	567	.75	10.1	X-TAL 857
-18	239	563	.77	10.4	
-19	124	563	.77	9.9	
-20	131	567	.77	10.6	
-21	129	560	.75	10.0	
-23	128	562	.80	10.6	
-24	131	571	.78	10.8	
-25	131	567	.78	10.7	
-26	128	591	.79	11.0	
AVE	129	568	.77	10.5	
B-9	132	567	.77	10.7	X-TAL 850
-10	124	590	.78	10.6	
-13	126	591	.78	10.7	
-14	132	576	.77	10.8	
-15	130	577	.79	10.9	
-16	131	580	.76	10.6	
-18	131	586	.77	11.0	
-20	128	581	.63	8.6	
-24	130	589	.76	10.7	
AVE	129	582	.76	10.5	

CURRENT - VOLTAGE
HAMCO TEXTURIZATION
2 CM X 2 CM AMO 28°C

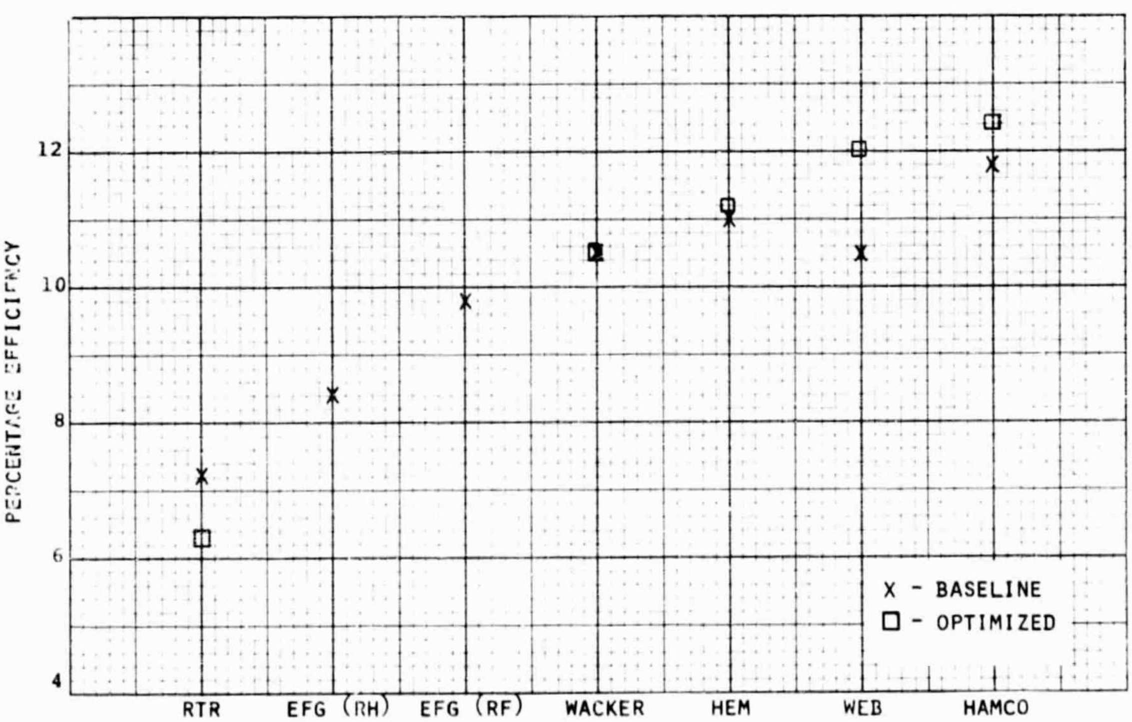
S/N	I_{sc}	V_{oc}	FF	η	
4B35A	116	558	.74	8.9	T
4B35B	115	563	.76	9.1	
5T16A	140	581	.77	11.5	T
5T16B	136	579	.75	11.0	
6M10A	117	539	.75	8.7	T
6M10B	113	535	.76	8.5	
1T4A	140	579	.78	11.8	T
1T4B	143	583	.72	10.8	
2T19A	135	575	.76	10.8	T
2T19B	141	571	.65	9.7	
3T21A	150	583	.77	12.4	T
AVG.	138	582	.78	11.6	CONTROL, T



HAMCO MATERIAL



SPECTRAL RESPONSE
FOR HAMO-1 (TEXTURIZED)



MAXIMUM EFFICIENCIES AMO 28°C

MT'L	HANDLING	TESTING	EFFICIENCY
WACKER	COMPARABLE TO CZ	COMPARABLE TO CZ	9-10.5%
RTR	SOME BRITTLENESS PROBLEMS	COMPARABLE TO CZ	LOW~6-7%
EFG (RH)	DIFFICULT, FRACTURE CUTTING PROBLEMS	DIFFICULT, UNDULATING SURFACE BREAKAGE	~6-8%
EFG (RF)	DIFFICULT, FRACTURE CUTTING PROBLEMS	DIFFICULT, UNDULATING SURFACE BREAKAGE	~6-10%
HEM	COMPARABLE TO CZ	COMPARABLE TO CZ	~9-11%
WEB	FRACTURE PROBLEMS W/ VERY THIN MT'L.	COMPARABLE TO CZ	~9-12%
HAMCO	CZ	CZ	CONSIDERABLE VARIATION W/ X-TAL & POSITION~6-12.4%
SOC	SPECIAL REQUIREMENTS	REQUIRES SPECIAL FIXTURING	

c. Encapsulation Task

TECHNOLOGY SESSION: Encapsulation Material Systems

C.D. Coulbert, Chairman

Candidate solar module encapsulation material systems and processes that meet the 1986 cost and performance goals have been identified and are being demonstrated in module hardware. Two basic encapsulation design configurations are being extensively evaluated and characterized relative to their durability for a 20-year life and to establish design optimization criteria relative to optical, thermal, electrical and structural performance. The two module design concepts are the structural superstrate (glass cover) design and the structural substrate (hardboard, concrete, or metal) design.

Several low-cost polymeric pottants are undergoing continuing development and evaluation; the two candidate pottants being most extensively evaluated by industry at this time are polyvinyl butyral (PVB) and ethylene vinylacetate (EVA). These two materials have been selected by several companies for incorporation in the LSA Block IV module procurement. The PVB selected is the Monsanto safety glass laminating material (Saflex) with the technical and processing data being supplied directly from Monsanto.

The EVA sheet material development by Springborn Labs (Enfield, CT) with LSA project funding will be supplied by Springborn with processing and assembly recommendations. Characterization and photodegradation studies on EVA and on protective covers for EVA are continuing at JPL and at supporting contractors. A photodegradation rate model for EVA as a function of UV radiation spectrum and intensity in the presence and absence of water and oxygen is being developed. The results of this study will be the basis for predicting the long-term module degradation and will provide criteria for developing and selecting module covers for UV screening and exclusion of moisture and oxygen.

The corrosion resistance of metals encapsulated with EVA appears excellent. Coupling agents or primer systems suitable for EVA in superstrate and substrate designs have been defined. These give excellent adhesion within the encapsulated module even when exposed to excessive moisture.

Other advanced encapsulant materials and processes are under development and continue to show the potential for cost-effective application. Flexible laminates of aluminum foil and polyester show potential for an excellent low-cost moisture and oxygen barrier with good electrical isolation properties. Glass-fiber scrim cloth between cells and substrate may provide increased module ruggedness and stability. Long-life UV screens based on copolymers with bound stabilizers are being developed and evaluated. Glass-reinforced concrete (GRC) module substrate panels have been developed and demonstrated. Active minimodules on the GRC substrate are currently being qualification tested.

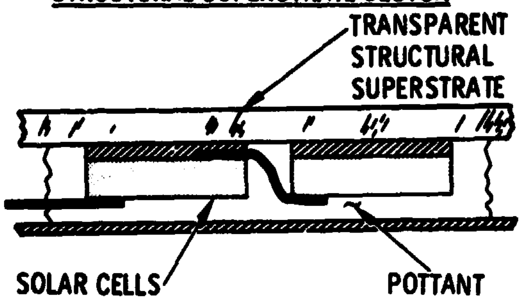
Poly-N-butyl acrylate has been developed as a solvent-free castable pottant. It has the potential of an elastomeric acrylic with improved weatherability. Design and fabrication studies with this new material will be started during FY 1980.

An advanced concept in low-cost electrostatic bonding for large panels has been explored and will be experimentally demonstrated in FY 1980. It would use very thin silicon sheet and a back-contact cell design.

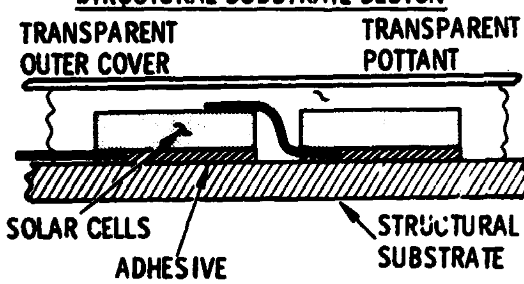
In the area of life prediction modeling, failure models and experimental techniques are being formulated for three specific failure mechanisms: photodegradation of polymers, thermomechanical stress failure, and corrosion of metallization and interconnects. To provide a long-term verification data base of field exposure and material aging experience on advanced encapsulation systems, mini-modules using these new materials are being fabricated and will be deployed at different field sites within the next three months.

1986 LOW-COST ENCAPSULANT SYSTEM CANDIDATES

STRUCTURAL SUPERSTRATE DESIGN



STRUCTURAL SUBSTRATE DESIGN



CANDIDATE MATERIALS/PRICES

SUPERSTRATES - GLASS	
LOW-IRON, SODA LIME, BOROSILICATE	$3.0 - 8/m^2$
POTTANTS/ADHESIVES	
ETHYLENE VINYLACETATE (EVA), POLVINYL BUTYRAL (PVB), SILICONES, ACRYLICS	
POTTANTS	$1.0 - 2.0/m^2$
ADHESIVES	$0.5 - 1.0/m^2$
COVER FILMS - FRONT OR BACK	
MYLAR, TEDLAR, ALUM. FOIL, ACRYLIC	$0.5 - 1.0/m^2$
STRUCTURAL SUBSTRATES	
HARDBOARD, STEEL, CONCRETE	$1.5 - 4.0/m^2$
COMPLETE SYSTEMS - MAT'L PRICE	$3.0 - 10.0/m^2$

STATUS SUMMARY

- DEMONSTRATED MATERIAL SYSTEMS MEET COST GOALS
- ETHYLENE VINYLACETATE, POTTANT/ADHESIVE, AS CANDIDATE UNDERGOING EXTENSIVE OPTIMIZATION AND EVALUATION
  - OPTIMIZED FORMULATION COVERS
    - CURE CYCLE
    - SHEET EXTRUSION
    - CORROSION CONTROL
    - ADHESION
    - PHOTODEGRADATION
- USE OF FLEXIBLE LAMINATES OF ALUMINUM FOIL AND MYLAR OFFERS LOW COST ELECTRICAL AND MOISTURE BARRIER
- USE OF GLASS FIBER SCRIM INCREASES MODULE RUGGEDNESS AND STABILITY.
- LONG LIFE UV SCREENS UNDER DEVELOPMENT TO PROVIDE 20 YEAR LIFE FOR LOW COST POTTANTS.
- GLASS REINFORCED CONCRETE SUBSTRATE DEVELOPED AND DEMONSTRATED.
- POLY-N-BUTYLACRYLATE HAS BEEN DEVELOPED AS A SOLVENT-FREE CASTABLE POTTANT.
  - MINIMODULE PASSED QUAL TESTING
  - PHOTODEGREDATION MECHANISMS DEFINED
  - IN-SITU POLYMERIZATION DEVELOPED
- ELECTROSTATIC BONDING PROCESS OPTIMIZATION FAVORABLE
  - GOOD YIELDS
  - ADVANCED CONCEPTS EXPLORES, - MESH-BACK CONTACTS
  - LOW COST-BONDER AND LOWER-COST GLASS

LIFE PREDICTION AND MATERIAL DEGRADATION

- THREE YEAR PLAN FOR MODELING AND VERIFICATION

- FAILURE MODELS BEING DEVELOPED AND EXPERIMENTALLY VERIFIED
  - PHOTODEGRADATION OF POLYMERS AND TOTAL SYSTEMS
  - THERMOMECHANICAL STRESS FAILURES
  - CORROSION OF METALLIZATION AND INTERCONNECTS

- TESTING TECHNOLOGY BEING DEVELOPED -
  - TESTING STRATEGIES AND TECHNIQUES FOR LIFE PREDICTION
  - TESTING FACILITIES FOR LONG TERM ENVIRONMENTAL SIMULATION
  - TESTING INSTRUMENTATION AND DIAGNOSTICS
    - CORROSION MONITOR
    - A.C. IMPEDANCE
    - AUGER

EVOLUTION OF EVA REFORMULATION

ELVAX	100	100	100	100
SARTOMER SR 350	3.5	-	-	-
LUPERSOL 101	1.5	1.5	-	1.5
LUPERSOL 231	-	-	1.5	-
TINUVIN	0.1	0.1	0.1	0.1
UV 531	0.25	0.25	0.25	0.25
IRGANOX 1076	0.5	0.5	-	-
GOODRITE 3114	-	-	0.2	-
NAUGARD P	-	-	-	0.2
PROBLEMS	POSSIBILITY OF EXUDATION; THERMAL YELLOWING	THERMAL YELLOWING	BUBBLING	NONE ⇧ FINAL FORMULATION AUGUST 1979

LOW-COST ENCAPSULATION SYSTEMS

SPRINGBORN LABORATORIES, INC.

B. Baum

CORROSION TESTING

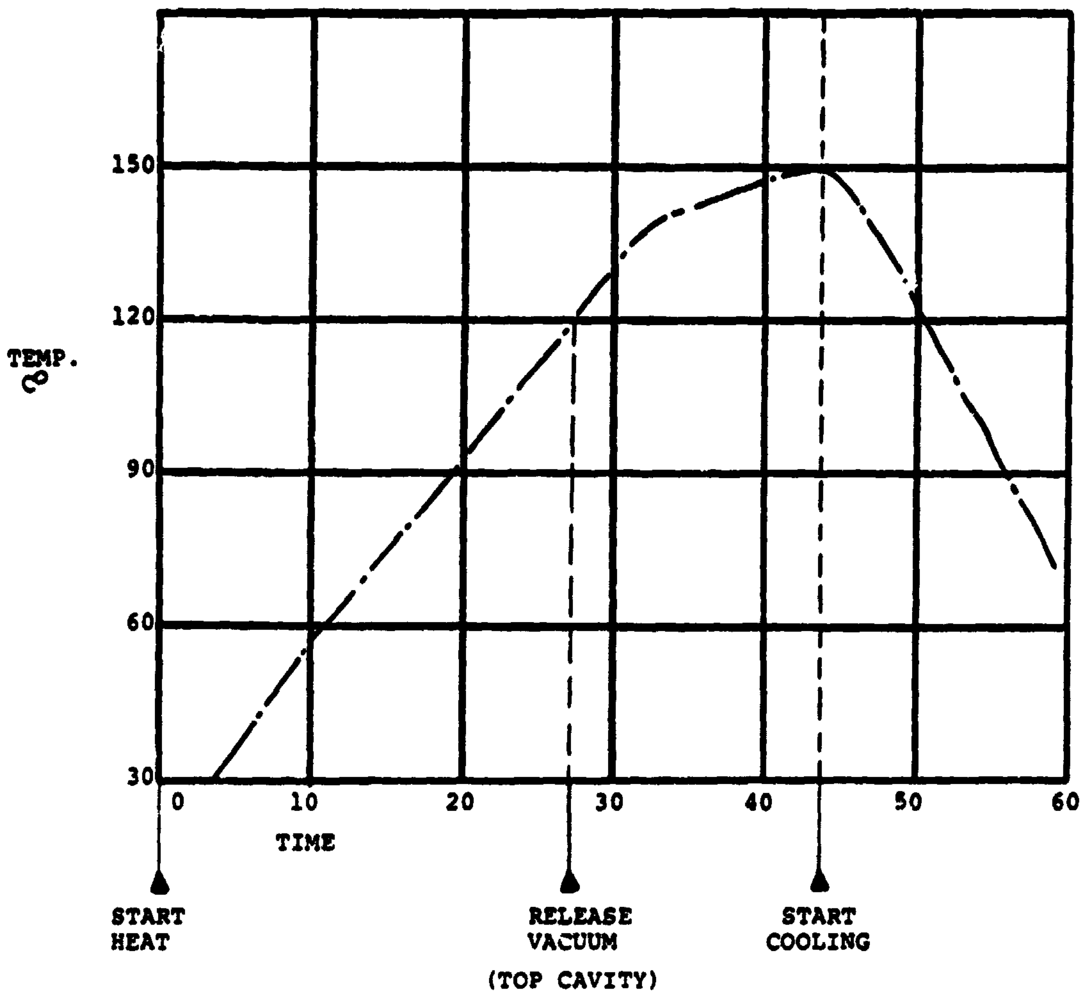
	SALT SPRAY 24 HRS.	SALT SPRAY 450 HRS.	SALT SPRAY 1600 HRS.
COMPLETELY ENCAPSULATED			
ALUMINUM-EVA			
COPPER - EVA		UNAFFECTED	UNAFFECTED
GALVANIZED - EVA			
CELL - EVA			
WITH EDGE EXPOSED			
ALUMINUM - EVA		C	C
COPPER - EVA		C	C
GALVANIZED - EVA	C	C	C
CONTROLS			
ALUMINUM		C	C
COPPER	C	C	C
GALVANIZED	C	C	C
CELL		C	C

4600 HOURS RS 4 SUNLAMP EXPOSURE

MATERIAL	CLEAR	CURED	STABILIZED	RESULT
A. ELVAX 150 (EVA)	✓	NO	NO	CHEESY
B. EVA	✓	YES	NO	SOFT
C. EVA	✓	YES	YES	TOUGH
D. EVA	WHITE	YES	YES	TOUGH
E. EVA, BETWEEN TWO PIECES OF KORAD 201-R	✓	YES	YES	LITTLE CHANGE
F. EVA, COATED WITH NATIONAL STARCH, ACRYLIC UV ABSORBING SOLUTION	✓	YES	YES	LITTLE CHANGE
G. EVA, BETWEEN TWO PIECES OF SODA-LIME GLASS, SS4179 PRIMER	✓	YES	YES	LITTLE CHANGE
H. EVA, BETWEEN GLASS AND KORAD 201-R, SS4179 PRIMER TO GLASS	✓	YES	YES	NO APPARENT DEGRADATION BUT BOND FAILURES

ETHYLENE VINYLACETATE
TIME/TEMPERATURE PRESSURE
CYCLE-SOLAR MODULES

(DOUBLE VACUUM BAG TECHNIQUE)



1. ASSEMBLE MODULE, LOAD INTO DOUBLE VACUUM BAG.
2. EVACUATE BOTH CAVITIES FOR 20 MINUTES, START HEATING.
3. RELEASE TOP CAVITY VACUUM AT 120°C POINT.
4. ALLOW 10 MINUTES HEATING AT 140 - 150°C.
5. COOL, REMOVE MODULE.

EVA PHOTODEGRADATION

PROPOSED MECHANISM (SOLAR UV)

$$\text{POLYMER} \xrightarrow[\text{PEROXIDES, } O_2]{h\nu\ (\geq 300nm)} PO_2H \longrightarrow \underset{\text{CARBONYLS}}{P = O} + P - OH \sim \text{PHOTO-OXIDATION}$$

$$P = O \xrightarrow{h\nu\ (\geq 300nm)} \text{CHAIN SCISSION}$$

ADDITIVES DETERMINE CRITICAL CARBONYL CONCN. TO BE REACHED BEFORE CHAIN SCISSION CAN OCCUR

UV SCREENING COVERS

STATUS

- LEACH OUT RATE OF UV SCREENS FROM ACRYLICS MEASURED ⟶ RATE UNACCEPTIBLY HIGH
- COPOLYMER PREPARED WHICH HAS CHEMICALLY BOUND STABILIZER MOLECULES
- DEGRADATION MECHANISM OF THESE COPOLYMER FILMS DETERMINED/RATES MEASURED*
- 15 DIFFERENT COPOLYMER SAMPLES RECEIVED FROM PROF. VOGL (U. MASS, LSA CONTRACTOR)

* SUBMITTED FOR PUBLICATION

PNBA STATUS

- PRODUCTION

  IT CAN BE MADE INTO A HIGH POLYMER BY HEATING
  (NO INITIATOR NEEDED)

- PROCESSING

  * IT CAN BE MADE INTO PREPOLYMER WHICH CAN BE INSITU POLYMERIZED TO HIGH MOLECULAR WT. POLYMER

- PERFORMANCE

  1 MINIMODULE WAS MADE: IT PASSED JPL TESTS; I.E.
  DID NOT FLOW EVEN WITHOUT CROSSLINKING: MOL. WT. = 10^6

- PHOTODEGRADATION

  STEADY STATE AND FLASH PHOTOLYSIS STUDIES
  ARE UNDER WAY

* RECENT RESULT/PRELIMINARY

SEEN AS TRUELY REDUNDANT ALTERNATE TO EVA

SCRIM MATERIAL SURVEY

Manufacturer	Cell Size (Mils x Mils)	Scrim Thickness (Mil)	Cost $/ft^2)
Burlington Glass Fabrics (Glass Fiber)	50 x 50	4	$.017
	50 x 100	4.7	$.014
Bay Mills (Bayex) (Polyester)	125 x 125	10	$.022
Apex Mills Corp. (Nylon)	50 x 50	5	$.028
	125 x 125	12	$.042

LIFE PREDICTION METHODOLOGY

OBJECTIVE:

DEVELOPMENT AND VALIDATION OF A SOLAR MODULE LIFE PREDICTION METHODOLOGY BY 1982

APPROACH:

- OUTLINE A GENERAL COMPREHENSIVE PLAN OF SEQUENTIAL TASKS AND SUPPORTING TASKS REQUIRED
- DEFINE SPECIFIC TASK PARAMETERS (STRESS, DESIGN, RESPONSE, PERFORMANCE, TESTING)
- OUTLINE EXISTING TASKS WITH INPUTS AND OUTPUTS
- DEFINE TASKS AND INPUTS REQUIRED FROM OUTSIDE TASK III
- IDENTIFY VOIDS (PARAMETERS AND STEPS NOT COVERED)
- DEFINE VITAL INTERFACES BY INTERACTIONS AND DATA REQUIRED
- INTEGRATE THE SCHEDULES AND LEVELS OF EFFORT
- DEFINE RESOURCES AND PROCUREMENTS REQUIRED

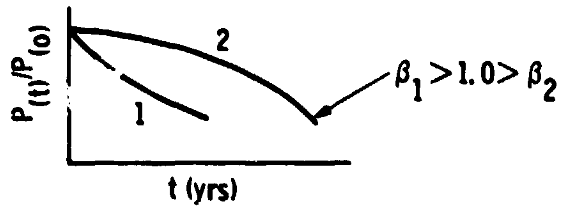
LIFE PREDICTION MODELS

FAILURE/DEGRADATION MODE

	SOURCE OF STRESS		RESPONSE	CONTROLLED SIMULATION? MODEL?
WIND	ENVIRONMENT	LOAD	PANEL	YES / YES
HAIL	ENVIRONMENT	LOAD	COVER AND CELL	YES / YES
DIRT	ENVIRONMENT		MATERIAL AND MODULE	YES / NO
HIGH VOLTAGE	ENVIRONMENT		MODULE	YES / NO
BROKEN CELLS	CAUSE?		MODULE	VARIES / NO
OPEN INTERCONNECTS	CAUSE?		MODULE	--- / ?
ABRASION	ENVIRONMENT		COVER	YES / YES
UV RADIATION	ENVIRONMENT		MATERIAL	YES / YES
CORROSION	ENVIRONMENT		CELL AND MODULE	IN PROCESS

LIFE PREDICTION MODEL: BATTELLE

MODULE POWER $\frac{P_{(t)}}{P_{(o)}} = (1-Kt)^{1/\beta}$



P = POWER
K = CONST
t = TIME
β = CONST

COMBINED STRESS CONST $K = f(T, H_2O, SO_2, UV \text{ etc})$

CONST TEMP TEST $K = A e^{-\beta/T} (1+R)^{C-D/T} (1+S/S_0)^{E-F/T}$

CYCLIC TEMP TEST $K = A f_T f_R f_M f_\omega$

T = TEMPERATURE
R = REL HUMIDITY
S = SO_2 CONCENTR
f_ω = CYCLE FREQ AND ΔT
f_M = ΔT MECH STRESS

2. Production Processes and Equipment Area

TECHNOLOGY SESSION

CONTRACTOR POSTER SESSION

FAVORABLE COMMENTS

- ABILITY TO INTERCHANGE EXPERIENCES
- OPPORTUNITY FOR DISCREET QUESTIONS
- VIEWER MAY VARY HIS TIME SCHEDULE
- COMPLEX DATA CAN BE PRESENTED
- EASIER TO CROSS REFERENCE
- MORE TIME FOR QUESTIONS

UNFAVORABLE COMMENTS

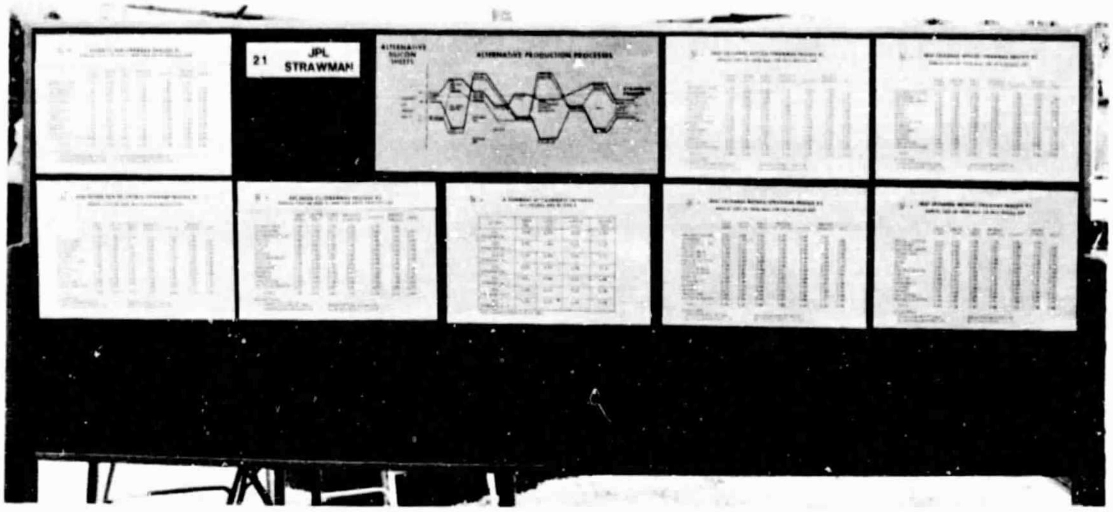
- FULL AUDIENCE INVOLVED DURING ORAL PRESENTATON
- ORAL PRESENTATION EASIER TO HIGHLIGHT
- REQUIRES ART WORK

FOUR NEW STRAWMAN MFG. SEQUENCES

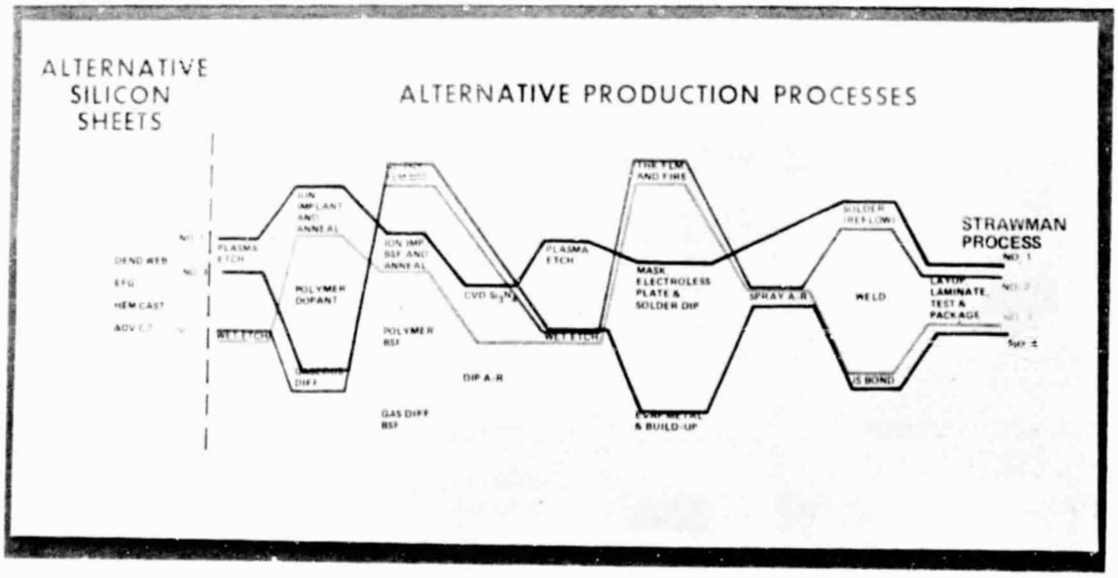
- SELECTED FROM A MATRIX WITH MORE POSSIBLE SEQUENCES
- ORIGINAL STRAWMAN LEFT IMPRESSION THAT JPL PREFERRED THE PROCESSES
- COSTS VARY WITH PROCESSES AND SHEET FORM

ORIGINAL -- $.64/W ($.46 1975)

LATEST -- $.676/W TO $1.031/W



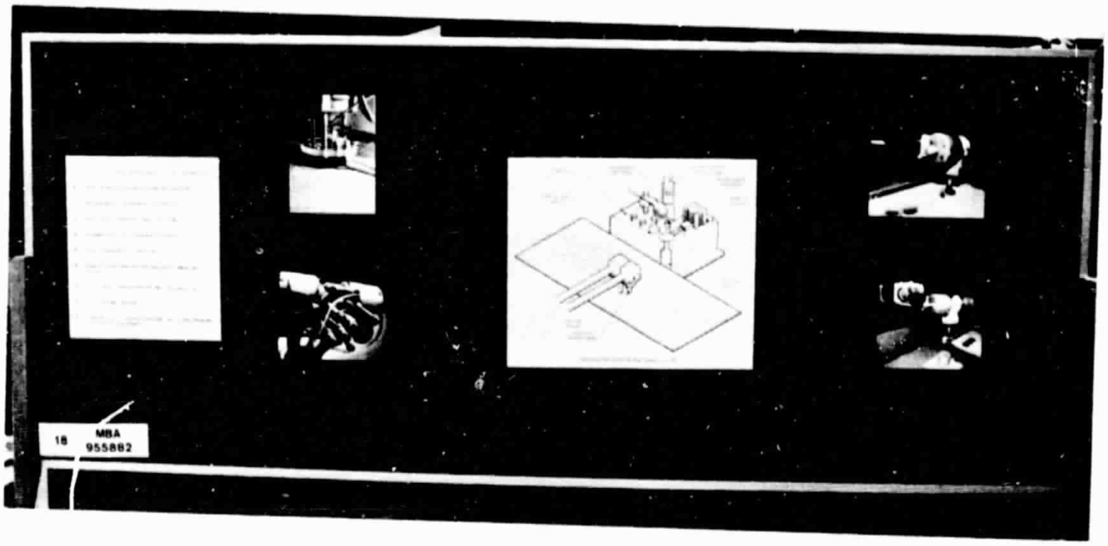
The JPL Strawman Summary Display at the Production Process and Equipment Poster Session.



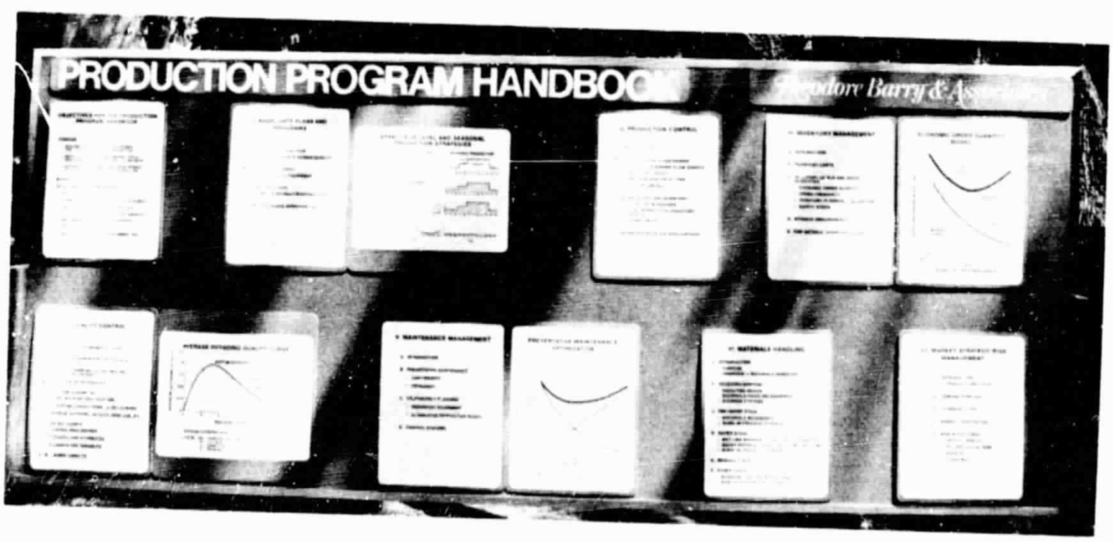
JPL Strawman Summary Display (Detail): Alternative Production Sequences Associated with the Strawman.

ORIGINAL PAGE IS
OF POOR QUALITY

Dennis Fitzgerald of JPL Explains the Equipment Associated With Ion Implantation Sources Being Developed by JPL as an Extension of Space Technology.



Typical Poster Display



Typical Poster Display

Typical Poster Display

PROCESS SEQUENCE DEVELOPMENT

RCA
- MATERIAL PERFECTION/ION IMPLANTATION RELATIONSHIP
- WEB PROCESSING STARTING

SPECTROLAB
- SURFACE PREPARATION/SPRAY ON DOPANT RELATIONSHIP
- WAFFLE PATTERN BSF REDUCES WARPAGE

WESTINGHOUSE
- 5cm WEB TO 2 1/2 cm WEB INCREASES PROCESS COST 7¢/WATT
- US RIBBON BONDING ONLY .002 INCH ABOVE SURFACE

TASK IV:
AUTOMATED ARRAY ASSEMBLY

PHASE II

RCA LABORATORIES

WILLIAM E. TAYLOR

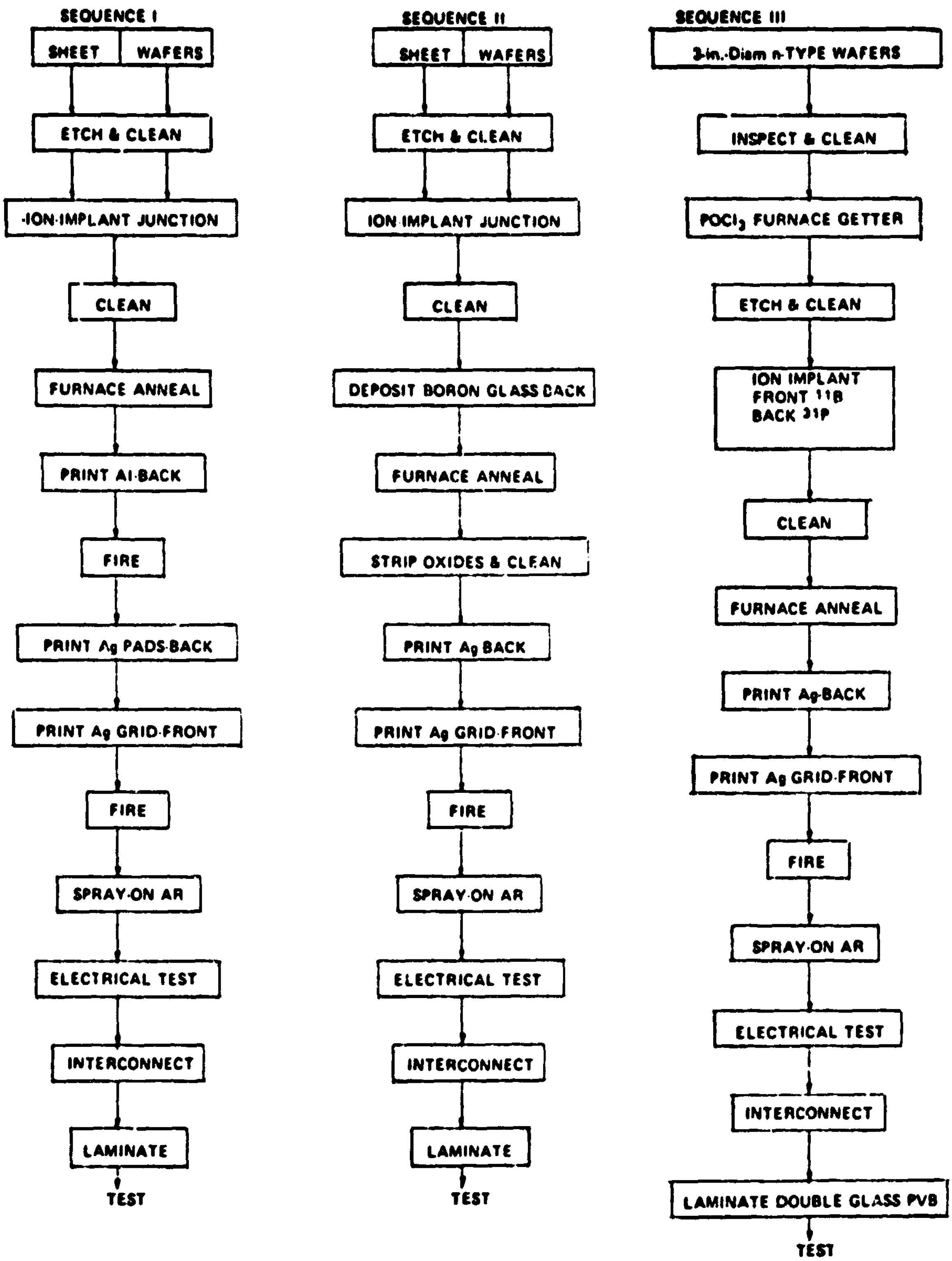
OBJECTIVE OF THE CURRENT PROGRAM

TO ASSESS THREE SOLAR-CELL MANUFACTURING SEQUENCES WITH REGARD TO PROCESS COMPATIBILITY, ACCOMMODATION TO THE FORM OF STARTING SILICON, AND TO PERFORM AN OVERALL COST/PERFORMANCE EVALUATION AND COMPARISON FOR THESE SEQUENCES.

OUTLINE

1. REVIEW OF MANUFACTURING SEQUENCES.
2. EQUIPMENT QUALIFICATION
   - A. SCREEN-PRINTER
   - B. SPRAY-ON AR AUTOCOATER
   - C. AUTOMATIC ELECTRICAL TEST-SET
3. MAJOR PRELIMINARY FINDINGS
   - A. ION IMPLANTATION
   - B. SOLAR-GRADE WAFERS
4. RESULTS OF PROCESSING SEQUENCES
   - A. $N/P/P^+$ CELLS
   - B. $P^+/N/N^+$ CELLS
5. PANEL ASSEMBLY
   - A. DOUBLE-GLASS LAMINATION
   - B. RADIANT-HEAT MASS REFLOW SOLDER ASSEMBLY

MANUFACTURING SEQUENCES



Performance of 25 Screen-Printed Cells With $POCl_3$ Junctions. No AR Coating

$\overline{J_{sc}}$* (mA/cm²)	σ_j (mA/cm²)	$\overline{V_{oc}}$ (mV)	σ_v (mV)	$\overline{FF}$ -	σ_F -	$\overline{\eta}$ (%)	σ_η (%)	$J_{sc\ max}$ (mA/cm²)	$V_{oc\ max}$ (mV)	FF_{max} -	η_{max} (%)
20.7	0.35	579	2.1	0.761	0.007	9.23	0.15	21.5	586	0.772	9.66

*Cell area = 42 cm², no AR coating.

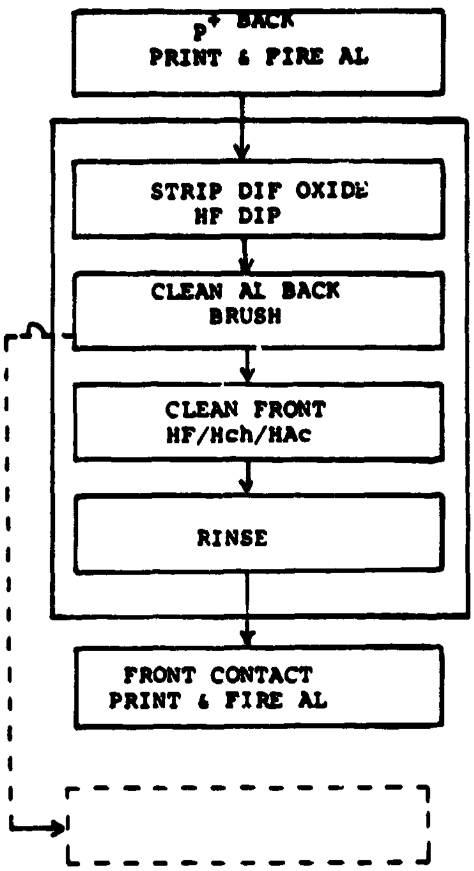
Comparison of Average AM-1 Parameters Before and After Spray AR Coating

	$\overline{J_{sc}}$ (mA/cm²)	$\overline{V_{oc}}$ (mV)	$\overline{FF}$ -	$\overline{\eta}$ (%)	$J_{sc\ max}$ (mA/cm²)	$V_{oc\ max}$ (mV)	FF_{max} -	η_{max} (%)
Before	21.1	593	0.754	9.37	21.6	599	0.771	9.56
After	28.7	601	0.752	12.65	29.3	610	0.761	13.2

I_{sc} Before and After Spray AR Process for Lot 910

Cell No.	$I_{sc\ No\ AR}$ (mA)	$I_{sc\ AR}$ (mA)	$\Gamma = \frac{I_{sc\ AR}}{I_{sc\ No\ AR}}$ -
910 - 1	875	1170	1.34
910 - 2	870	1150	1.32
910 - 3	890	1180	1.33
910 - 4	842	1090	1.29
910 - 5	848	1170	1.38
910 - 6	869	1150	1.32
910 - 7	906	1150	1.27
910 - 8	871	1140	1.31
910 - 9	849	1110	1.31
910 - 10	864	1200	1.39
910 - 11	870	1050	1.21
910 - 12	909	1150	1.27
910 - 13	875	1170	1.34
910 - 14	881	1130	1.29
			Ave. 1.31

BACK CLEAN--CHEMICAL



BACK CLEAN—PLASMA ETCH

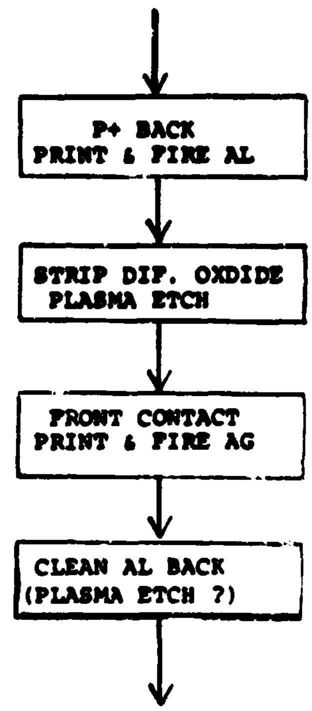
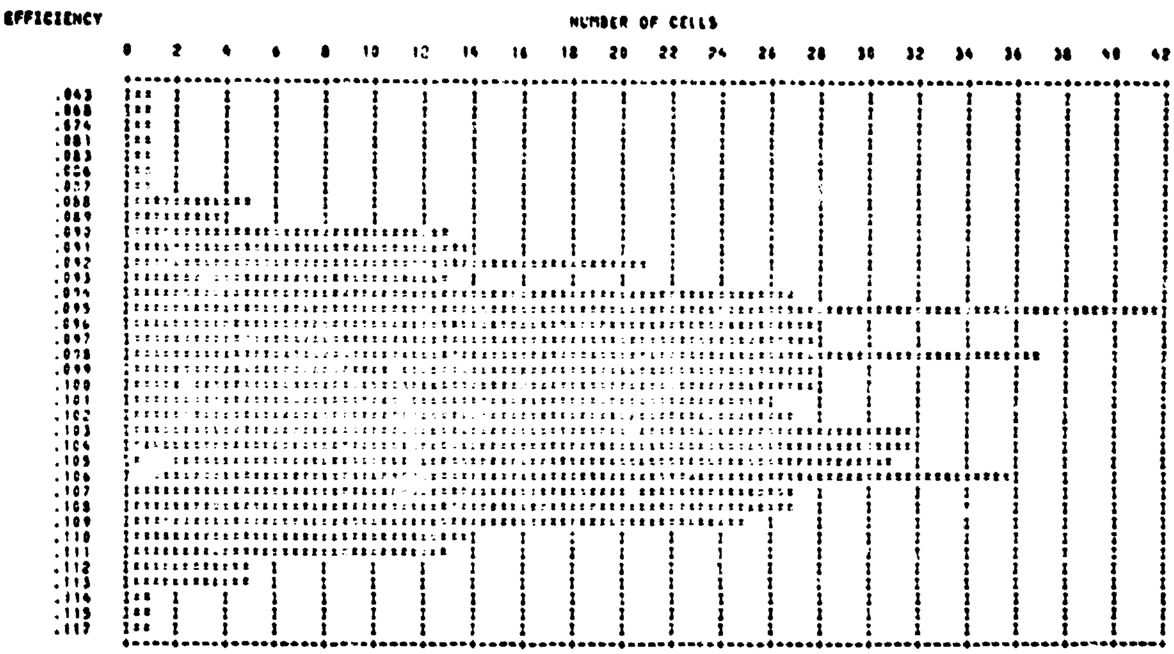
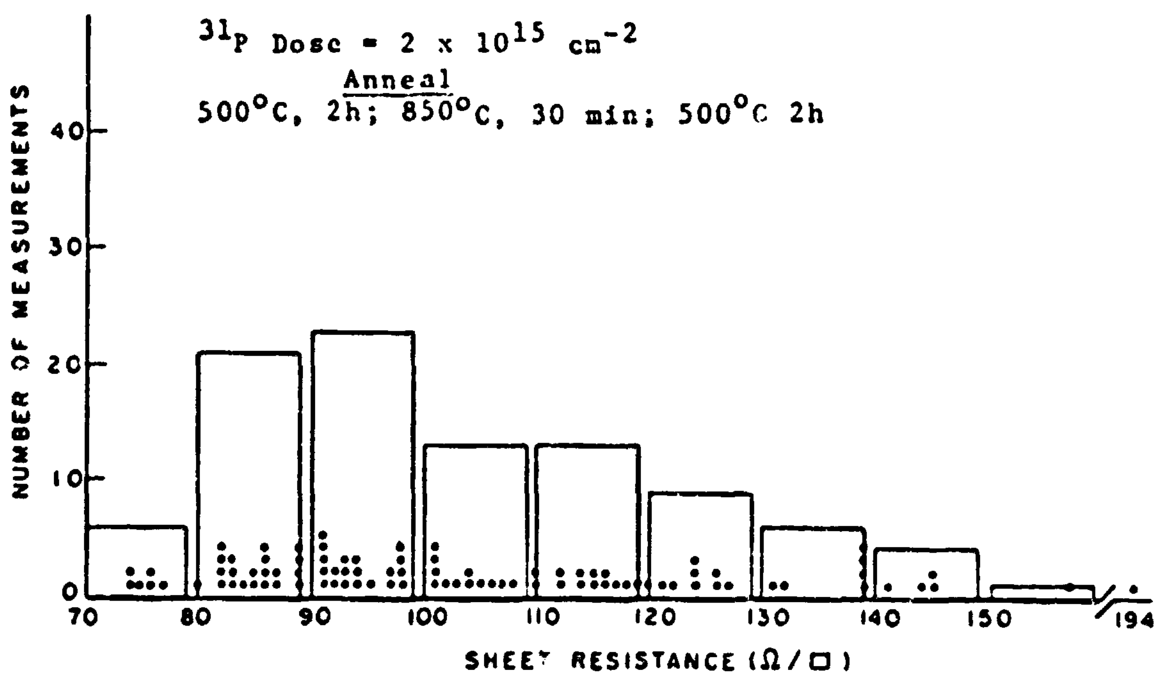


TABLE TO CHECK CALCULATOR INPUT PRIOR TO COATING FOR LOT NUMBER 983

CELL NUM	OPEN CIR VOLT	CELL CURRENT	MAX POWER	FILL FACT	SER RESIS	SHUNT RESIS	PMAX CURRENT	PMAX VOLT	EFF	BASE TEMP
D3H5983001	.576	968.	9.26	.699	.767	285.70	850.	.458	.093	25.7
D3H5983002	.576	962.	9.17	.697	.878	650.30	863.	.447	.092	25.7
D3H5983003	.566	935.	8.72	.695	.872	2,814.00	808.	.453	.087	25.6
D3H5983004	.591	1,042.	9.96	.682	1.885	29.01	888.	.471	.100	25.8
D3H5983005	.583	1,015.	9.62	.685	1.676	127.60	876.	.461	.097	25.9
D3H5983006	.592	1,035.	9.23	.635	1.724	25.35	867.	.447	.093	25.9
D3H5983007	.590	1,060.	10.06	.692	1.464	1,759.00	925.	.457	.101	26.1
D3H5983008	.592	1,055.	10.16	.686	1.593	167.20	919.	.466	.102	26.1
D3H5983009	.591	1,037.	10.06	.692	1.318	22.27	905.	.467	.101	26.1
D3H5983010	.592	1,056.	10.11	.684	1.257	1,550.00	906.	.469	.102	26.1
D3H5983011	.586	1,065.	9.77	.674	.694	174.90	897.	.458	.098	26.2
D3H5983012	.590	1,062.	10.22	.701	1.385	131.20	911.	.471	.103	26.2
D3H5983013	.591	1,062.	10.10	.692	.339	99.65	925.	.459	.101	26.3
D3H5983014	.586	1,066.	9.96	.689	1.079	26.67	905.	.462	.100	26.4
D3H5983015	.567	960.	8.61	.683	.744	813.70	810.	.447	.087	26.6
D3H5983016	.586	1,083.	10.73	.681	.534	1,802.00	918.	.468	.103	26.6
D3H5983017	.577	1,066.	9.76	.686	1.178	895.40	912.	.449	.098	26.5
D3H5983018	.590	1,067.	10.03	.686	.281	1,435.00	907.	.464	.101	26.9
D3H5983019	.586	1,041.	9.97	.690	1.929	607.90	906.	.463	.100	26.6
D3H5983020	.588	1,034.	9.98	.694	.137	176.00	903.	.466	.100	26.6
D3H5983021	.591	1,067.	10.06	.687	2.179	364.70	913.	.463	.101	26.6
D3H5983022	.592	1,060.	9.89	.672	2.322	3,618.00	894.	.465	.099	26.6
D3H5983023	.589	1,066.	10.16	.696	1.607	17.44	919.	.463	.102	26.4

HISTOGRAM OF EFFICIENCY AT P_{MAX} VS CELLS (500 CELLS)

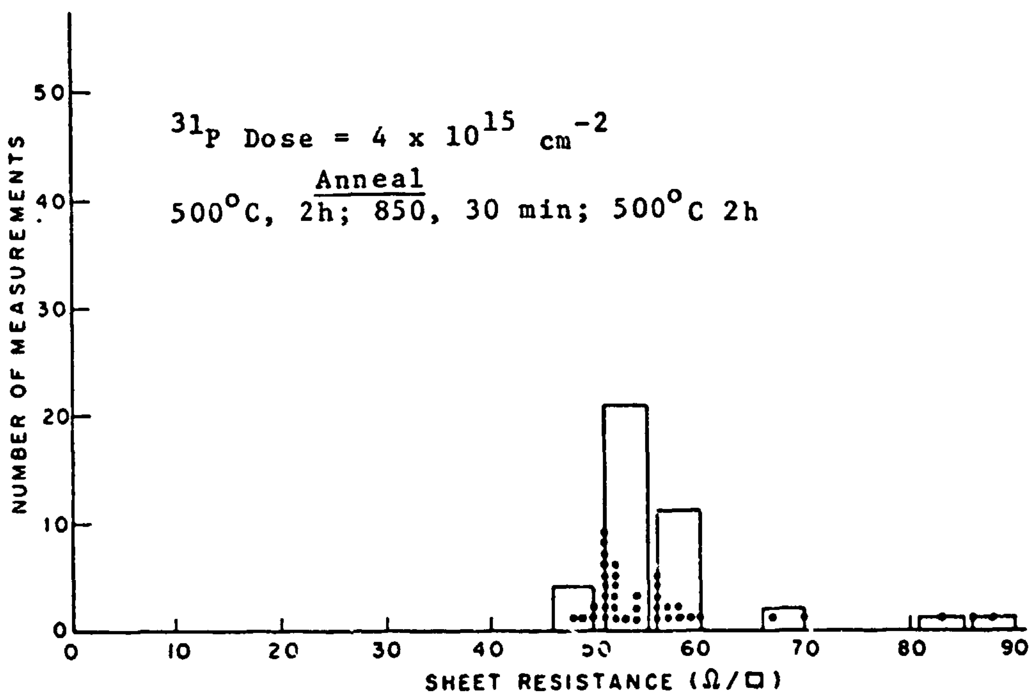




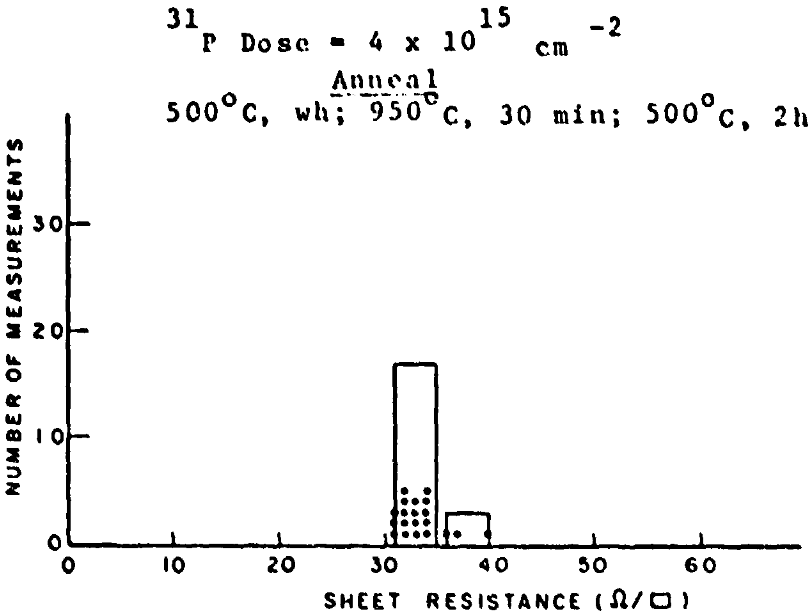
Distribution of sheet resistance for lots 950, 951, and 952

Lot No.	^{31}P Dose (A/cm^2)	Furnace Anneal	$\bar{R}_\square$ ($\Omega/\square$)
107P	$4x10^{15}$	L* 850°C L 30 min	58
106P	$4x10^{15}$	L 950°C L 30 min	34
910P	$2x10^{15}$	L 950°C L 30 min	52

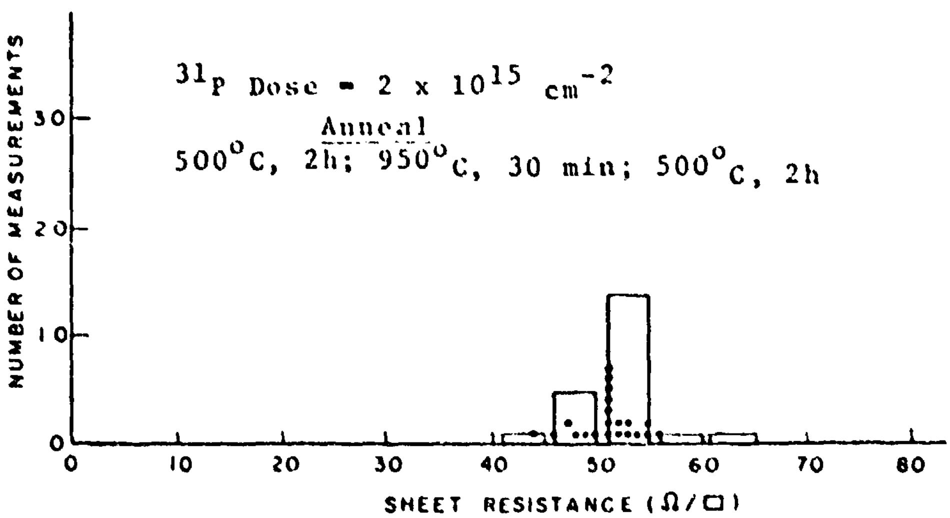
*L = 500°C, 2 h



Distribution of sheet resistance for wafers of lot 907P.



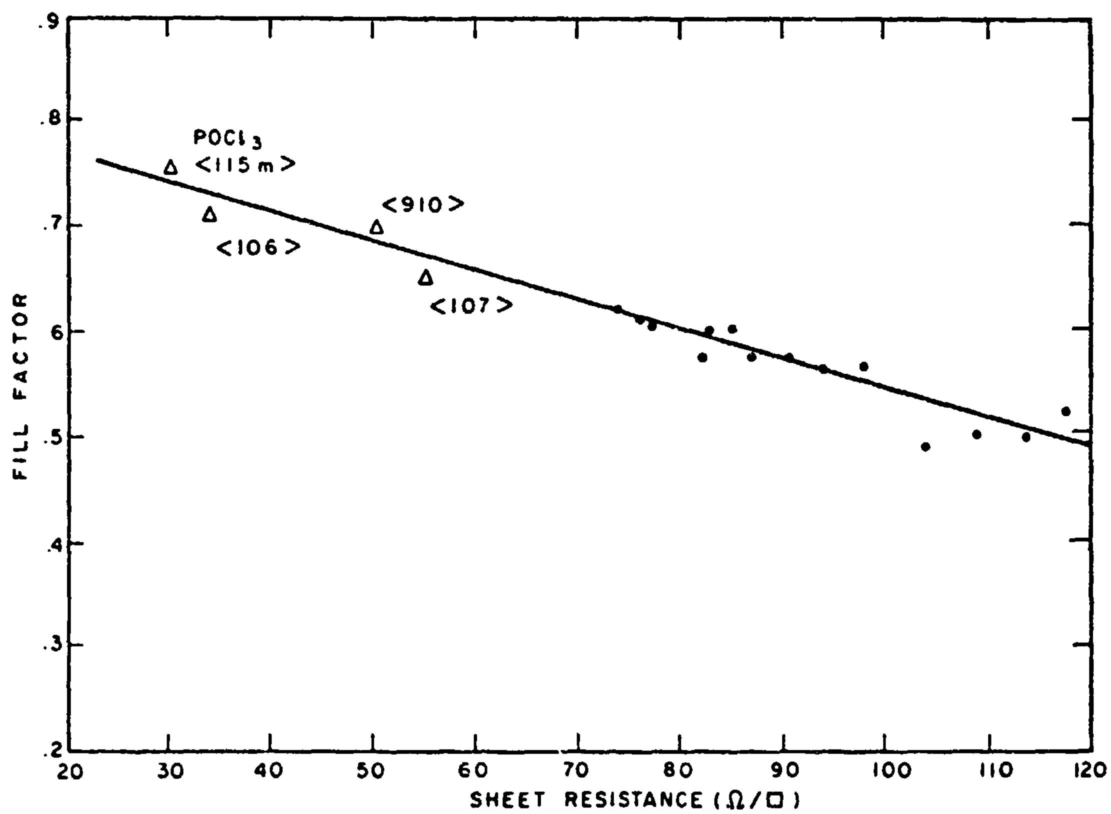
Distribution of sheet resistance for wafers of lot 106P.



Distribution of sheet resistance for wafers of lot 910P.

Lot No.	$\overline{J_{sc}}$ (mA/cm^2)	$\overline{V_{oc}}$ (mV)	$\overline{FF}$ -	$\overline{\eta}$* (%)	$\overline{R_{\square}}$ (Ω/□)
107P	21.7	552	0.659	7.9	58
106P	20.7	557	0.710	8.2	34
910P	20.5	560	0.700	8.0	52
950 - 952	19.5	499	0.518	5.1	75-150

*No AR Coating



Fill factor as a function of sheet resistance including average values for lots 106, 107, 910, and 115m.

TEST MATRIX CONDITIONS

Lot, Material	ρ Ω-cm	Implant Front	Implant Back		Furnace Anneal		Sheet Resistance RΩ	Comment
106, S. G.[a]	2	$^{31}P, 4x10^{15}$	None	L*	950°C 30 min	L	34	saw, etch
121, Wacker	1.5	$^{31}P, 4x10^{15}$	None	L	950°C 30 min	L	25	Polished front
122, Monsanto[b]	12	$^{31}P, 4x10^{15}$	$^{11}B, 4x10^{15}$	L	950°C 30 min	L	27	etched
123, Monsanto[b]	12	$^{31}P, 4x10^{15}$	None	L	950°C 30 min	L	'.7	etched
115m Monsanto	1.5	$POCl_3$ diffusion		-	850°C 60 min	-	30	etched

(a) S.G. = Solar Grade wafer from Monsanto, St. Louis, MO.
(b) Supplied by SPIRE
* L = 500°C, 2h

RESULTS OF TEST MATRIX

Lot	Mat'l	RΩ	Ink Front	Ink Back	$\bar{I}_{sc}$	$\bar{V}_{oc}$	$\overline{F.F}$	$\bar{\eta}$ [a]
106	S. G.	34	3347	422-F	869	557	0.710	8.2
121-A	Wacker	25	3347	422-F	810	553	0.743	7.92
121-B	Wacker	25	3347	Al-p$^+$ Ag pad	815	545	0.709	7.54
123-A	Monsanto†	27	3347	422-F	823	518	0.698	7.1
123-B	Monsanto†	27	3347	Al-p$^+$ Ag Pad	840	517	0.646	6.68
122	Monsanto†	27	3347	3347	876	526	0.696	7.64
115m	Monsanto[b]	30	3347	422-F	852	580	0.761	9.23

(a) No AR coating
(b) Included for reference - not part of the matrix-test
† Supplied by SPIRE

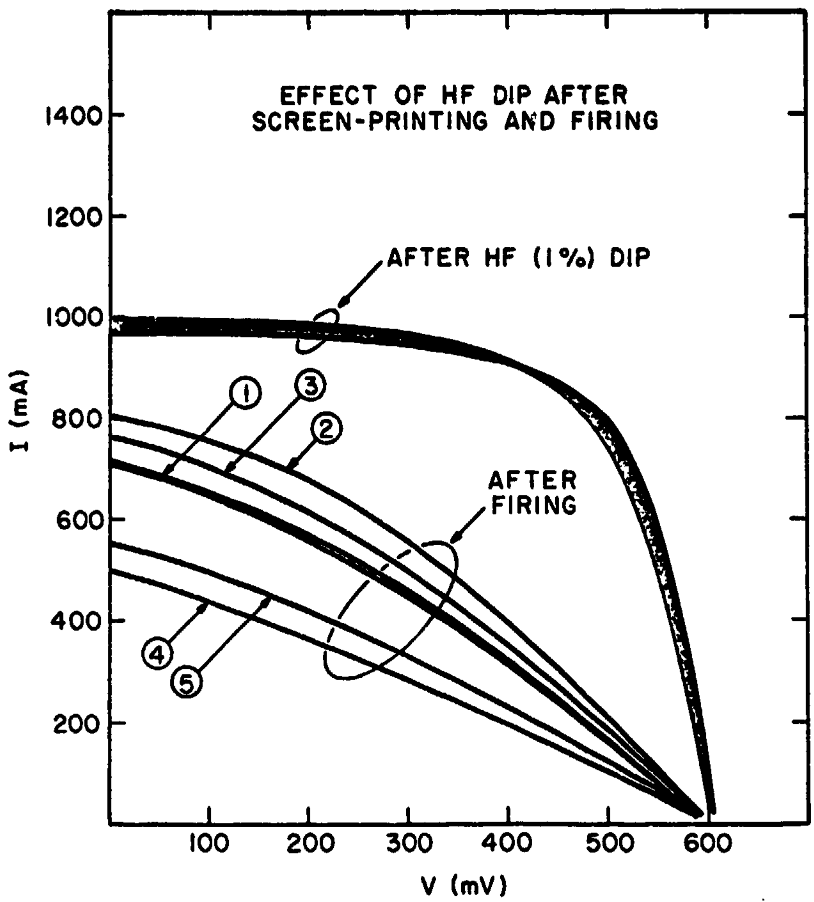


TABLE TO CHECK CALCULATOR INPUT AFTER COATING FOR LOT NUMBER 983

CELL NUM	OPEN CIR VOLT	CELL CURRENT	MAX POWER	FILL FACT	SER RESIS	SHUNT RESIS	PMAX CURRENT	PMAX VOLT	EFF	BASE TEMP
D3NS983001	.581	1,232.	10.80	.635	.607	748.40	1,020.	.445	.108	25.2
D3NS983002	.551	1,232.	10.56	.620	.480	35.94	1,019.	.436	.106	25.4
D3NS983003	.570	1,194.	10.42	.644	1.340	27.48	996.	.439	.104	25.7
D3NS983004	.597	1,358.	11.26	.555	.271	31.31	1,065.	.444	.113	25.9
D3NS983005	.589	1,319.	11.49	.624	.719	310.60	1,091.	.443	.115	26.1
D3NS983006	.600	1,315.	7.87	.421	.626	4.00	757.	.437	.079	26.1
D3NS983007	.597	1,368.	12.99	.670	.481	150.00	1,188.	.459	.130	26.3
D3NS983008	.639	1,344.	10.43	.513		127.40	1,006.	.436	.105	26.5
D3NS983009	.599	1,362.	12.48	.646	1.000	160.60	1,166.	.450	.125	26.3
D3NS983010	.598	1,359.	10.42	.541	.975	33.62	1,034.	.423	.105	26.4
D3NS983011	.592	1,344.	11.55	.613	1.271	18.33	1,088.	.446	.116	25.5
D3NS983012	.598	1,368.	12.94	.668	.954	125.00	1,165.	.466	.130	26.6
D3NS983013	.597	1,354.	12.14	.633	.623	83.91	1,141.	.447	.122	26.5
D3NS983014	.591	1,347.	12.23	.647	.451	1,000.00	1,144.	.448	.123	26.6
D3NS983015	.570	1,191.	9.67	.603	.956	1,318.00	972.	.418	.097	26.6
D3NS983016	.592	1,378.	12.72	.659	.607	2,685.60	1,176.	.454	.128	26.8
D3NS983017	.584	1,345.	11.95	.643	.496	25.00	1,106.	.454	.120	26.8
D3NS983018	.596	1,347.	12.07	.635	.542	8,489.00	1,113.	.456	.121	26.8
D3NS983019	.593	1,350.	12.67	.669	.198	31.82	1,165.	.457	.127	26.9
D3NS983020	.594	1,322.	10.12	.545	.874	48.01	1,015.	.419	.102	26.9
D3NS983021	.598	1,349.	12.48	.654	.729	51.96	1,123.	.466	.12'	27.0
D3NS983022	.599	1,350.	10.73	.562	1.312	39.75	1,011.	.446	.108	27.1
D3NS983023	.596	1,349.	12.38	.651	1.097	70.17	1,105.	.470	.125	27.1

PAGE 1

AVERAGE CALCULATOR INPUT VALUES AFTER COATING FOR LOT NUMBER 983

AVE OPEN CIR VOLT	AVE CELL CURRENT	AVE MAX POWER	AVE FILL FACTOR	AVE SER RESIS	AVE SHUNT RESIS	AVE PMAX CURRENT	AVE PMAX VOLTAGE	AVE EFF	AVE BASE TEMP
.594	1,325.	11.41	.612	.722	679.14	1,072.	.446	.115	26.4

NUMBER OF OBSERVATIONS= 23

AVERAGES OF CELL PARAMETERS FOR PROCESS 3 SOLAR CELLS BEFORE AR COATING

AVE OPEN CIR VOLT	AVE CELL CURRENT	AVE MAX POWER	AVE FILL FACTOR	AVE SER RESIS	AVE SHUNT RESIS	AVE PMAX CURRENT	AVE PMAX VOLTAGE	AVE EFF
.585	1,032.	9.40	.685	1.318	480.98	869.	.454	.095

TABLE TO CHECK CALCULATOR INPUT PRIOR TO COATING FOR LOT NUMBER 114

CELL NUM	OPEN CIR VOLT	CELL CURRENT	MAX POWER	FILL FACT	SER RESIS	SHUNT RESIS	PMAX CURRENT	PMAX VOLT	EFF	BASE TEMP
D3NS114001	.571	942.	8.37	.661	1.065	28.22	828.	.426	.085	27.2
D3NS114002	.569	920.	8.50	.688	.372	126.60	804.	.444	.086	27.1
D3NS114003	.570	929.	8.64	.693	.619	99.45	827.	.439	.087	27.2
D3NS114304	.575	939.	7.70	.606	.719	41.24	773.	.418	.078	27.3
D3NS114005	.575	947.	8.31	.648	.481	128.10	832.	.419	.084	27.3
D3NS114006	.572	953.	8.66	.674	.902	142.30	835.	.436	.088	27.4
D3NS114007	.569	936.	8.56	.683	.160	18.99	830.	.433	.086	27.4
D3NS114008	.570	946.	8.76	.689	.513	276.80	831.	.443	.089	27.4
D3NS114009	.576	944.	8.01	.627	.852	150.40	779.	.432	.081	27.6
D3NS114010	.575	938.	8.01	.632	.405	29.02	786.	.428	.081	27.3
D3NS114011	.572	944.	8.69	.684	.212	264.60	820.	.445	.088	27.5
D3NS114012	.570	940.	8.72	.692	.307	451.70	832.	.440	.088	27.6
D3NS114013	.569	927.	8.59	.686	.871	13.70	828.	.436	.087	27.7
D3NS114014	.573	928.	8.14	.645	.032	311.40	783.	.437	.082	27.8
D3NS114015	.572	919.	8.26	.647	.041	1,136.00	842.	.412	.084	27.7
D3NS114016	.568	925.	8.33	.678	1.204	13.60	819.	.430	.085	27.7
D3NS114017	.568	928.	8.47	.682	1.323	302.80	840.	.423	.086	27.8
D3NS114018	.569	940.	8.66	.659	1.756	170.40	819.	.444	.088	27.7
D3NS114019	.572	938.	8.33	.661	.038	58.75	804.	.435	.084	27.7
D3NS114020	.572	932.	8.12	.648	.953	164.30	794.	.429	.082	27.8
D3NS114021	.570	933.	8.64	.691	.281	119.30	831.	.437	.087	27.7
D3NS114022	.569	936.	8.65	.698	.259	695.70	816.	.445	.088	27.6
D3NS114023	.571	940.	8.24	.654	1.113	438.70	806.	.430	.084	27.8
D3NS114024	.572	938.	8.20	.650	.549	28.66	793.	.434	.083	27.8

PAGE 1

AVERAGE CALCULATOR INPUT VALUES PRIOR TO COATING FOR LOT NUMBER 114

AVE OPEN CIR VOLT	AVE CELL CURRENT	AVE MAX POWER	AVE FILL FACTOR	AVE SER RESIS	AVE SHUNT RESIS	AVE PMAX CURRENT	AVE PMAX VOLTAGE	AVE EFF	AVE BASE TEMP
.571	938.	8.40	.667	.626	217.11	815.	.433	.085	27.6

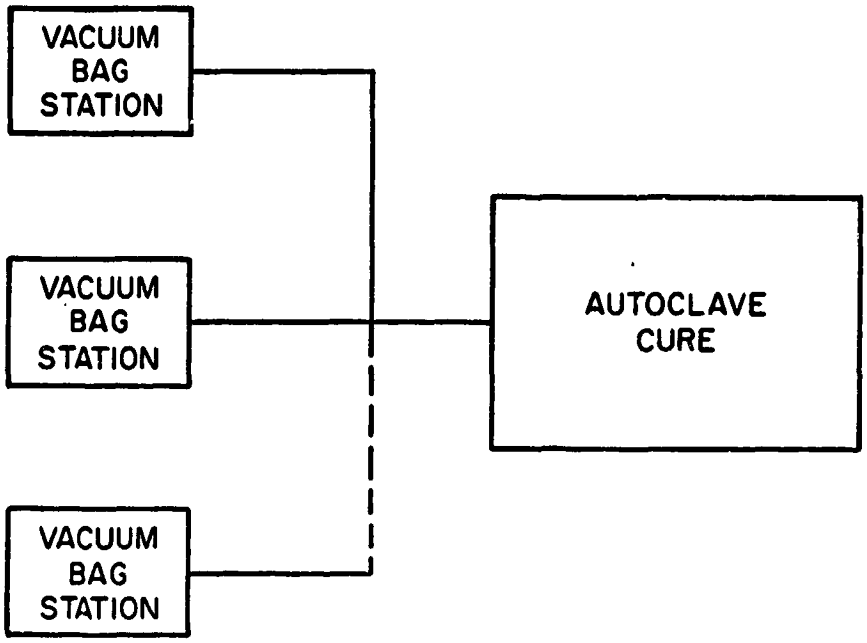
AUTOCLAVE

1 VACUUM BAG
HEAT, PRESSURE

2 CURING

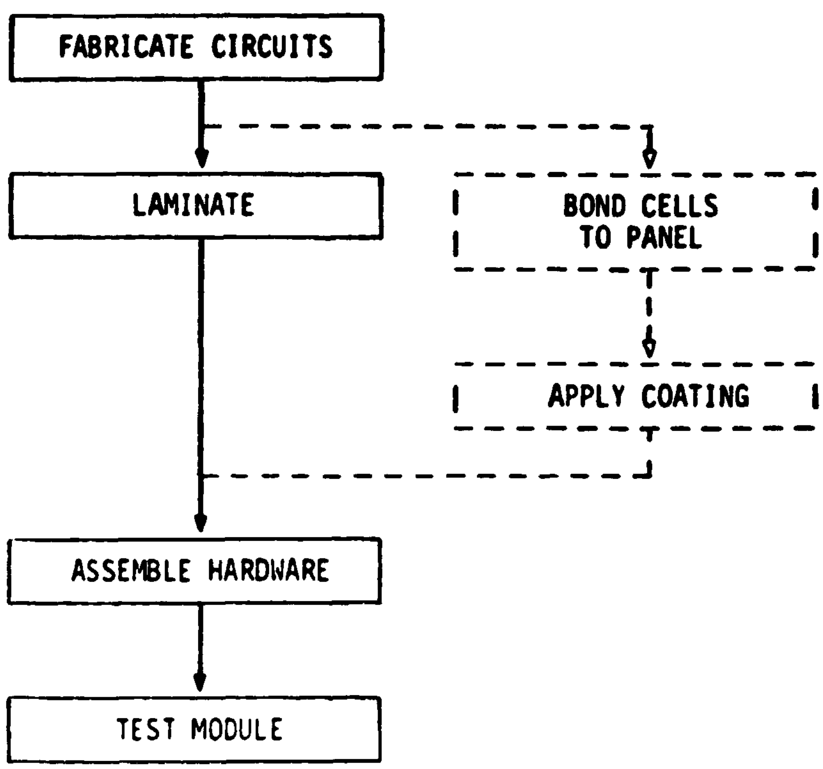
SINGLE STEP DOUBLE-GLASS LAMINATION

AUTOCLAVE USED FOR BOTH VACUUM BAG AND CURING OPERATION

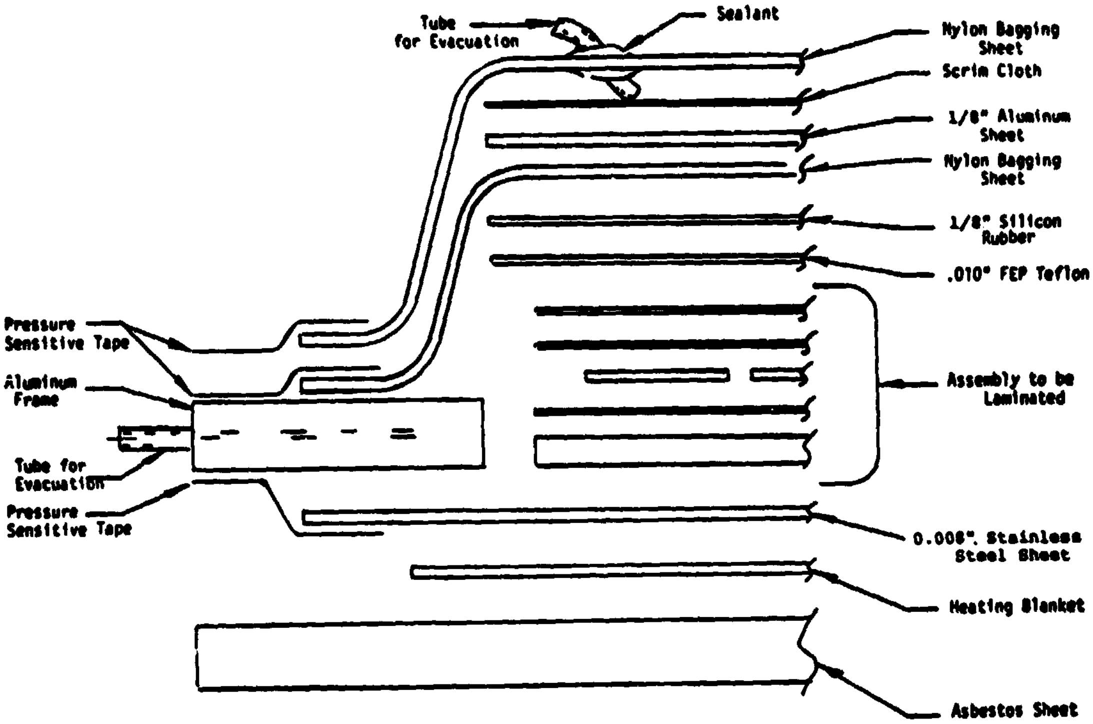


TWO-STEP DOUBLE-GLASS LAMINATION PROCESS

MODULE PROCESS SEQUENCE



LAMINATING FIXTURE



PLANS FOR NEXT REPORTING PERIOD

1. FURTHER RESEARCH RELATING TO ION IMPLANTATION, USE OF SOLAR-GRADE WAFERS AND THE SCREEN-PRINTING PROCESS.

2. CONTINUE SEQUENCE I-III PROCESSING AS SCHEDULED. EVALUATE SILICON DENDRITIC WEB SHEET IN CRITICAL PROCESSES.

3. EVALUATE THE OVERALL PROGRAM AND PREPARE A SUMMARY REPORT.

MEGASONIC CLEANING OF SILICON WAFERS

RCA CORPORATION

A. MAYER

PURPOSE: Scale up, automate and improve the existing RCA-invented Megasonic Cleaning System, increase its throughput from about 600 to about 2500 wafers per hour.

COST SAVING PROJECTED TO BE $0.16 per peak watt

MAJOR COST SAVINGS FACTORS

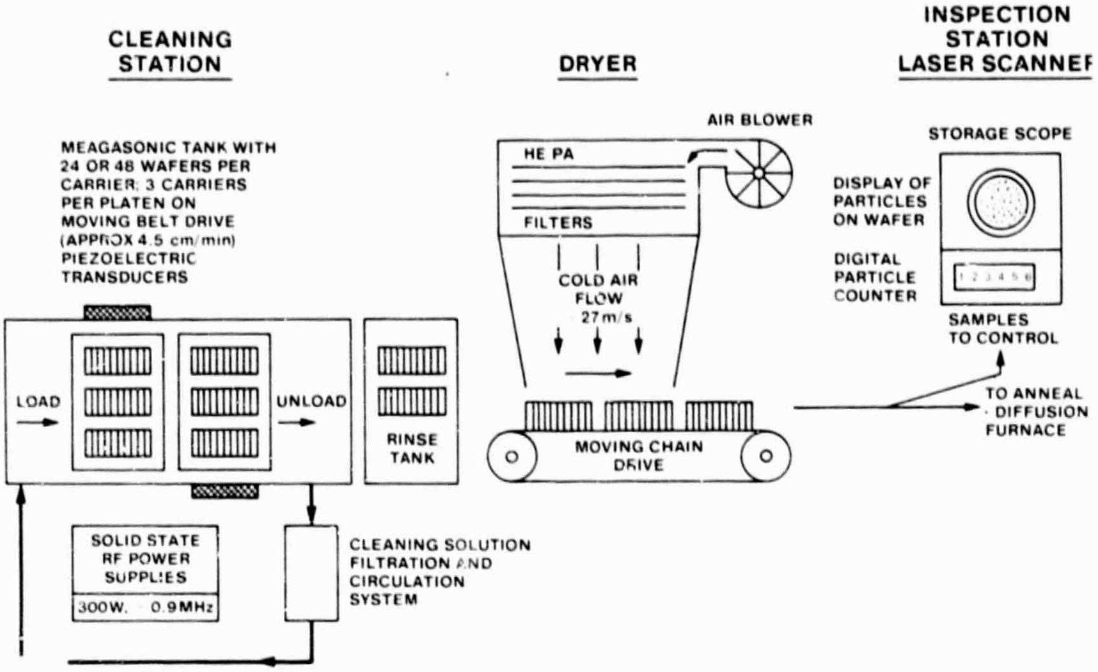
1. With megasonic energy the water-hydrogen peroxide-ammonia cleaning solution is not heated. Thus, it does not decompose rapidly, and is utilized to its maximum by continuous circulation and filtration.
   This also minimizes cost of waste disposal.

2. By cleaning wafers with megasonic energy in the quartz carriers in which they are to be diffused, impurities and particles are removed from both sides of the wafers and from the carriers. This is expected to improve the average energy conversion efficiency because the average carrier diffusion length is expected to be longer.

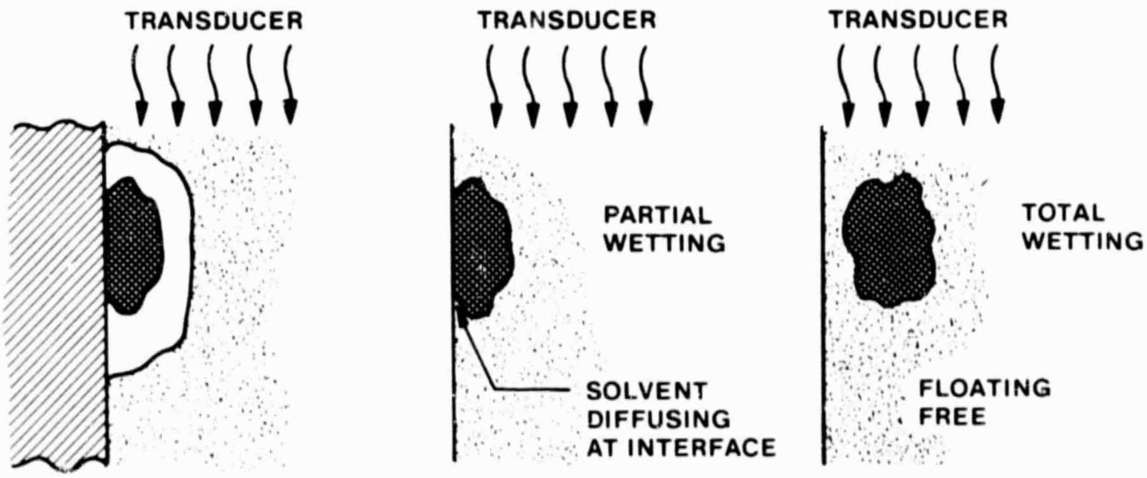
3. Less breakage is expected and less handling is needed because wafers need not be transferred to different carriers through cleaning, drying, and diffusion.

4. The operating cost is expected to be low because the entire megasonic system, i.e., the cleaning tank, air dryer and inspection station can be fully automated. System consumes only about 5 Kw, and maintenance and capital investment are expected to be low.

SCHEMATIC OF MEGASONIC SYSTEM

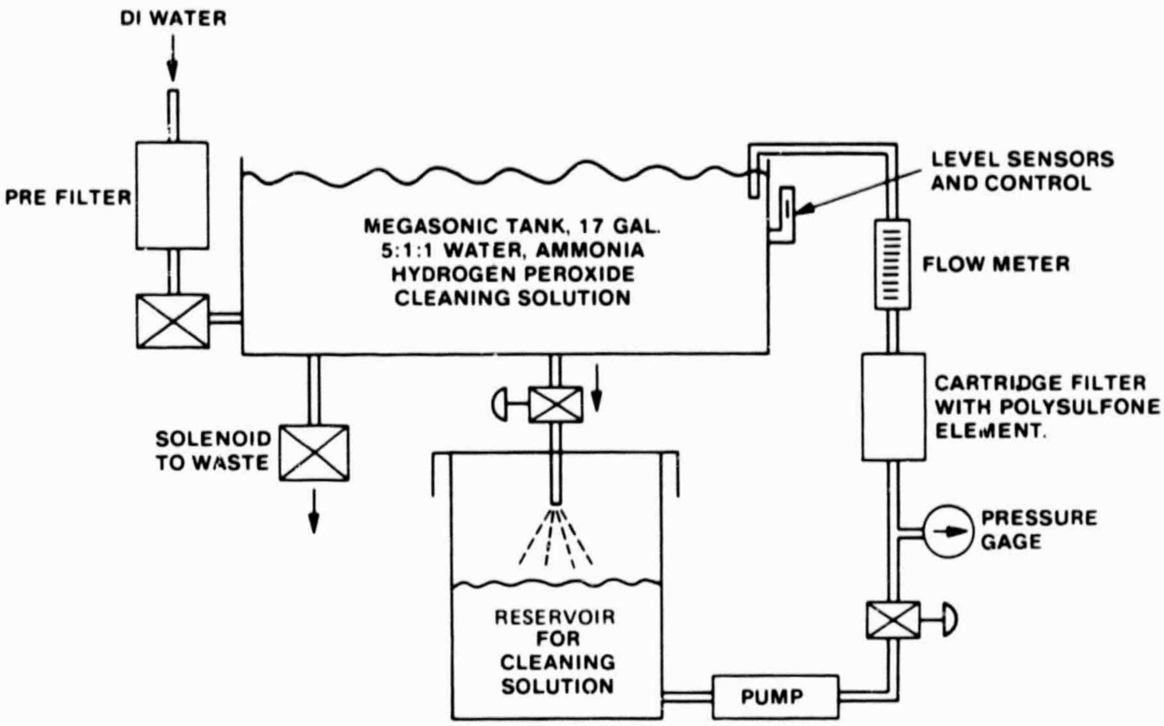


MODEL OF MEGASONIC ACTION ON A PARTICLE HELD ON A SILICON WAFER

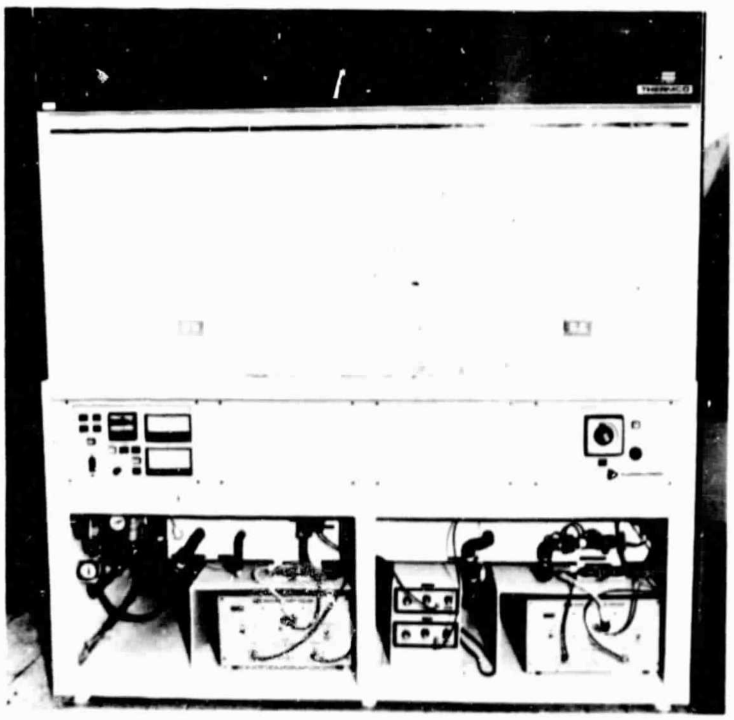


FREQUENCY 900 KHz
PRESSURE 9.1 x 10^5 N/m^2
VELOCITY ~ 0.3 m/s
WAVELENGTH ~ 1.3 mm
ACCELERATION ~ 10^5g
MOTION OF H_2O MOLECULE ~ 0.1 μm

CLEANING SOLUTION RECIRCULATION SYSTEM



MEGASONIC UNIT



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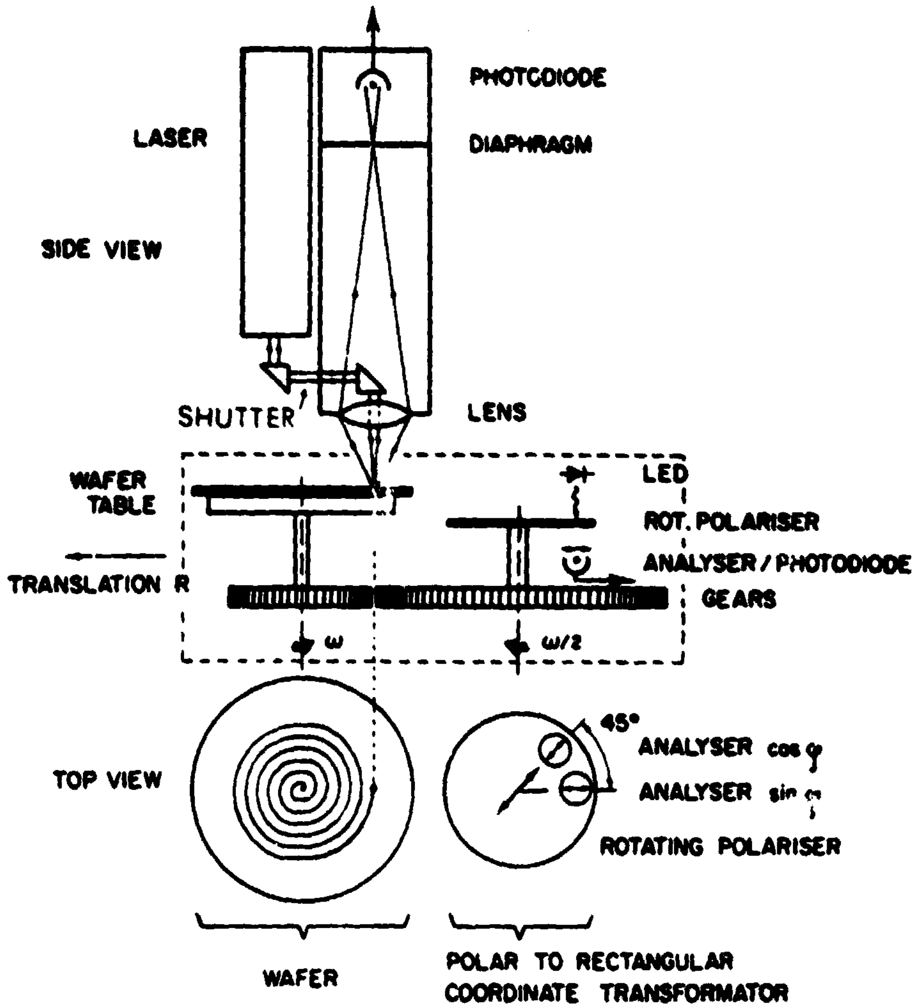
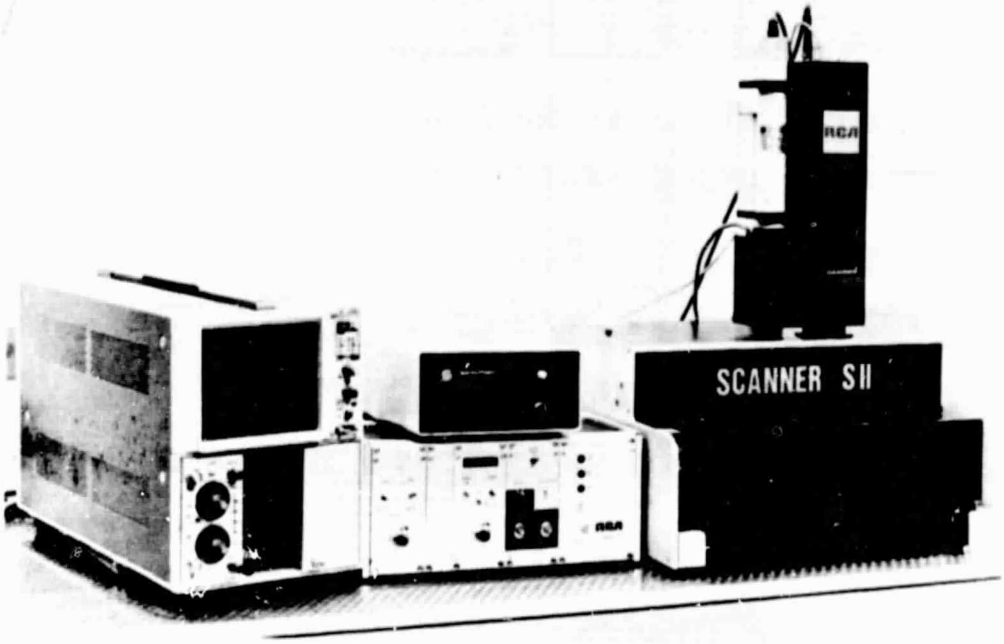
OF POOR QUALITY

MEASURING ARRANGEMENT

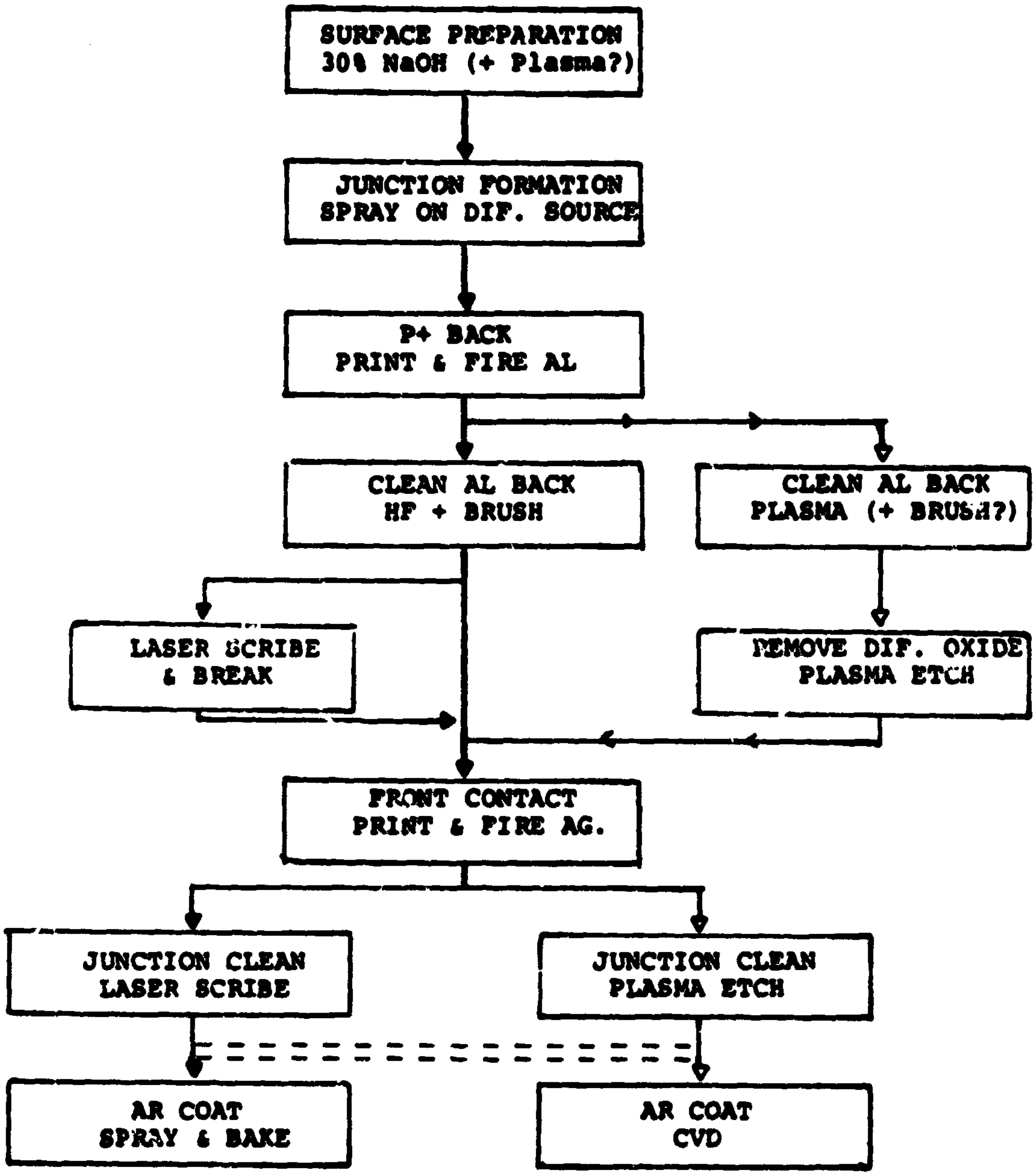


LASER SCANNER



PHASE II: PROCESS DEVELOPMENT

SPECTROLAB, INC.



SURFACE PREPARATION

ASSUMPTIONS:
4" SQUARE SHEET GROWN WAFERS
APPROX. 110 ORIENTATION (W/BOUNDARIES)

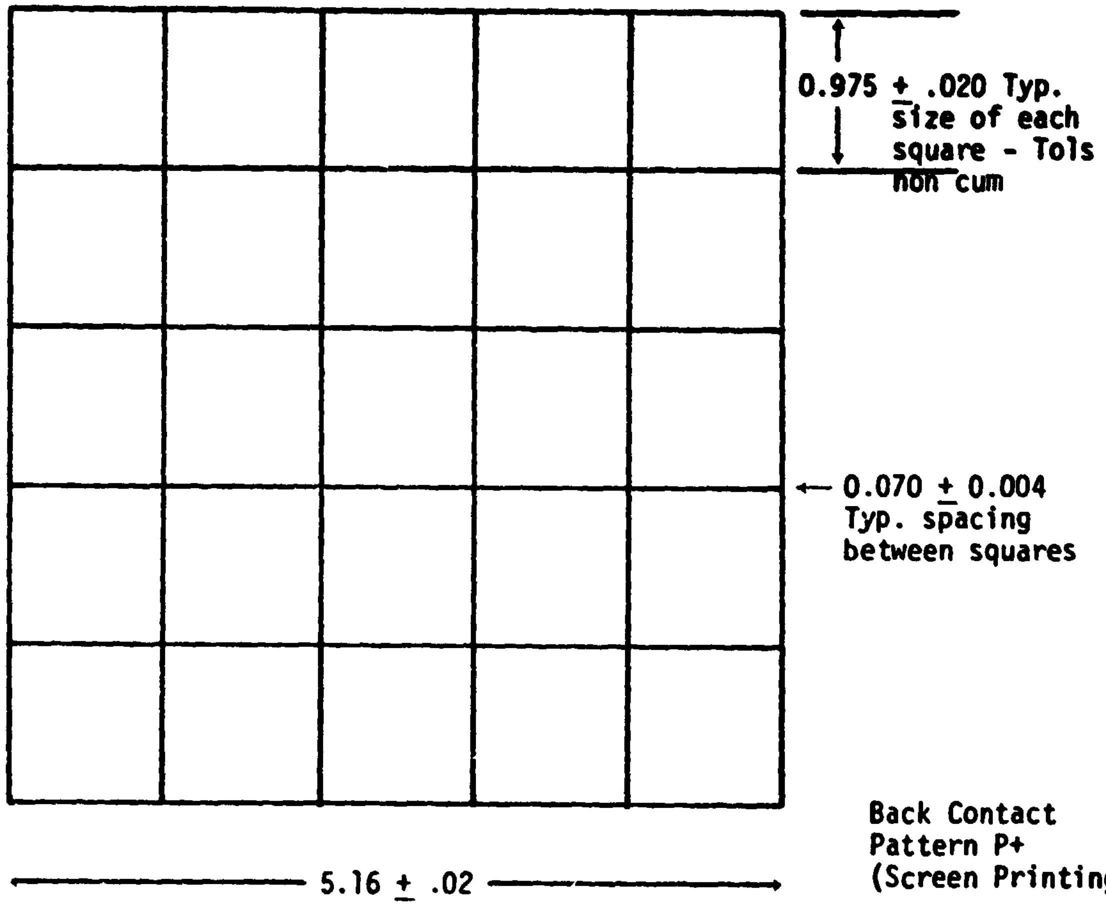
EQUIP.	84,000	\$1975 (117,600 1980)
OUTPUT	25	PARTS/MIN
SPACE	75	SQ. FT
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	.25	PRSN/SHIFT
MATERIALS	0.10	\$1975/MIN (\$0.14 1980)
POWER	0.10	KW HR/MIN
QUAN.	15.3	MWP/YR
P(IPEG)/WP	0.0127	\$1975 (\$0.0178 1980)

DIFFUSION

ASSUMPTIONS:-
SPRAY ON PX 10
15 MIN AT 900 °C

EQUIP	230,000	\$1975 (\$322,000 1980)
OUTPUT	75	PARTS/MIN
SPACE	1,120	SQ. FT.
ASSEMBLERS	3	PRSN/SHIFT
MAINT. PERS.	0.5	PRSN/SHIFT
MATERIALS	0.008	\$1975/MIN (0.012 1980)
POWER	3.75	KW HR/MIN
QUAN.	45.9	MWP/YR
P (IPEG)/WP	0.0114	\$1975 (\$0.0160 1980)

PATTERNED P+ BACK



Back Contact Pattern P+ (Screen Printing)

BACK CONTACT

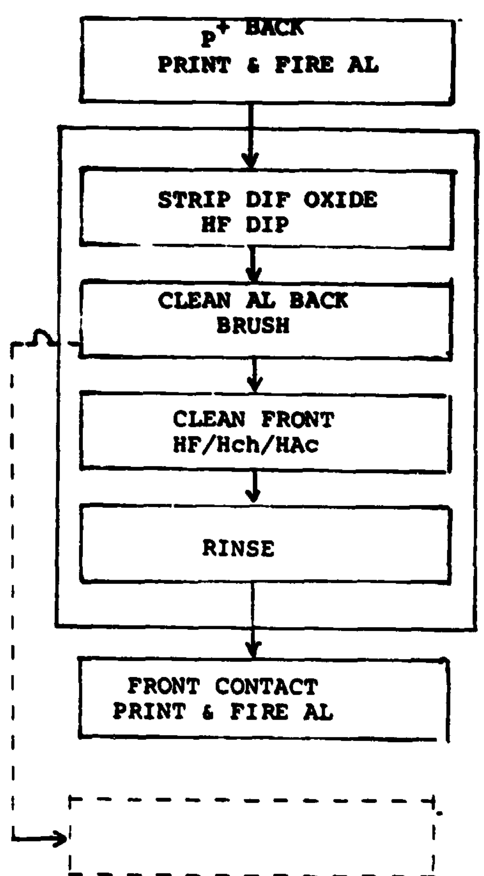
ASSUMPTIONS:
PRINTED ALUMINUM

EQUIP.	132,000	$1975 ($184,800 1980)
OUTPUT	25	PARTS/MIN
SPACE	750	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.25	PRSN/SHIFT
MATERIALS	0.055	$1975 / MIN ($0.077 1980)
POWER	1.5	kW HR/MIN
QUAN.	15.3	MWP/YR.
P(IPEG)/WP	0.0183	$1975 ($0.0256 1980)

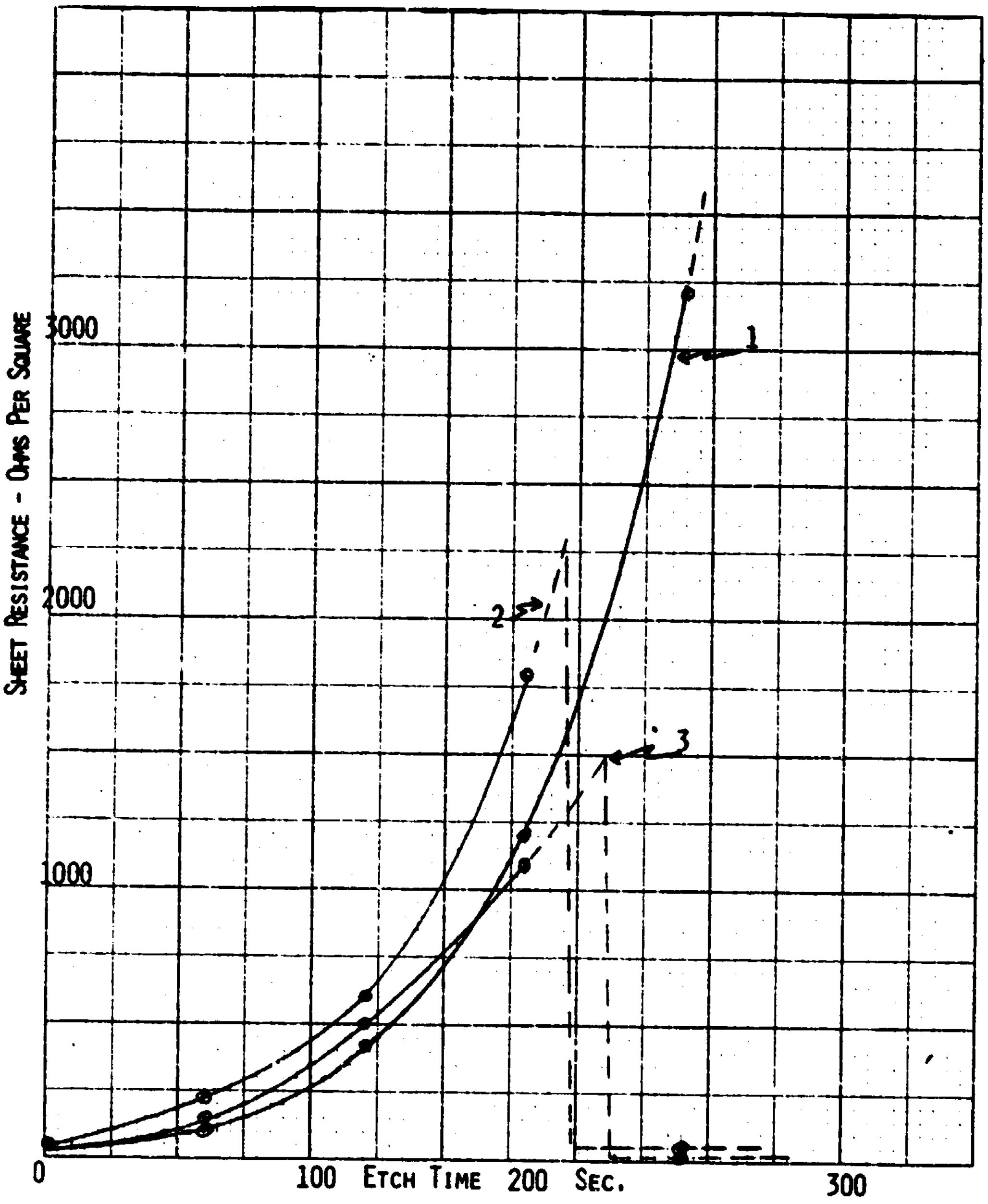
CLEAN ALUMINUM BACK

ASSUMPTIONS:
ACID DIP + MECHANICAL BRUSHING

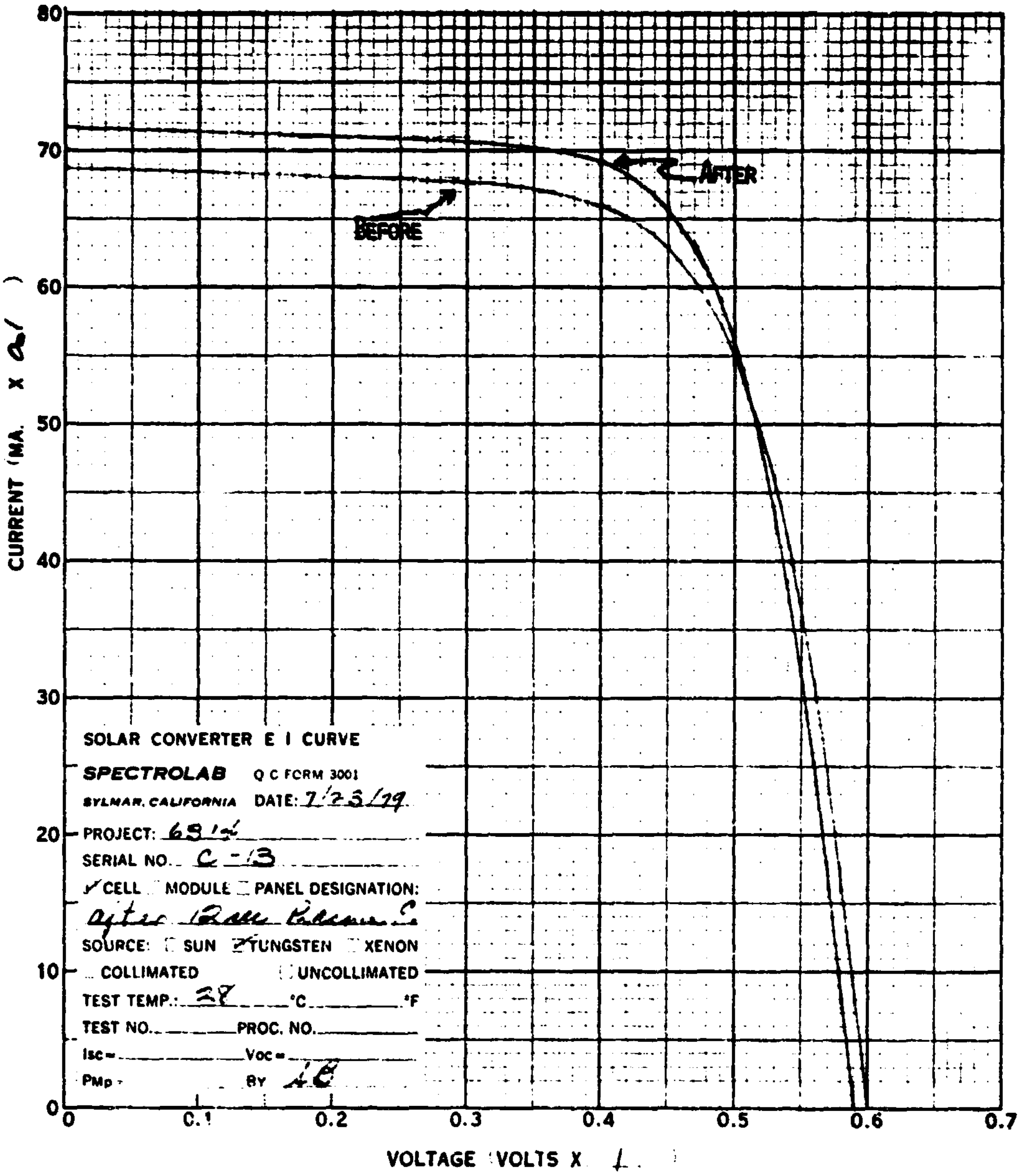
EQUIP.	19,500	$1975 (112,000 1980)
OUTPUT	6	PARTS/MIN
SPACE	60	SQ. FT.
ASSEMBLERS	0.25	PRSN/SHIFT
MAINT. PERS.	0.05	PRSN/SHIFT
MATERIALS	0.014	$1975/MIN ($0.0196 1980)
POWER	0.10	KW HR/MIN
QUAN.	3.67	MWP/YR
P(IPEG)/WP	0.0124	$1975 ($0.0174 1980)



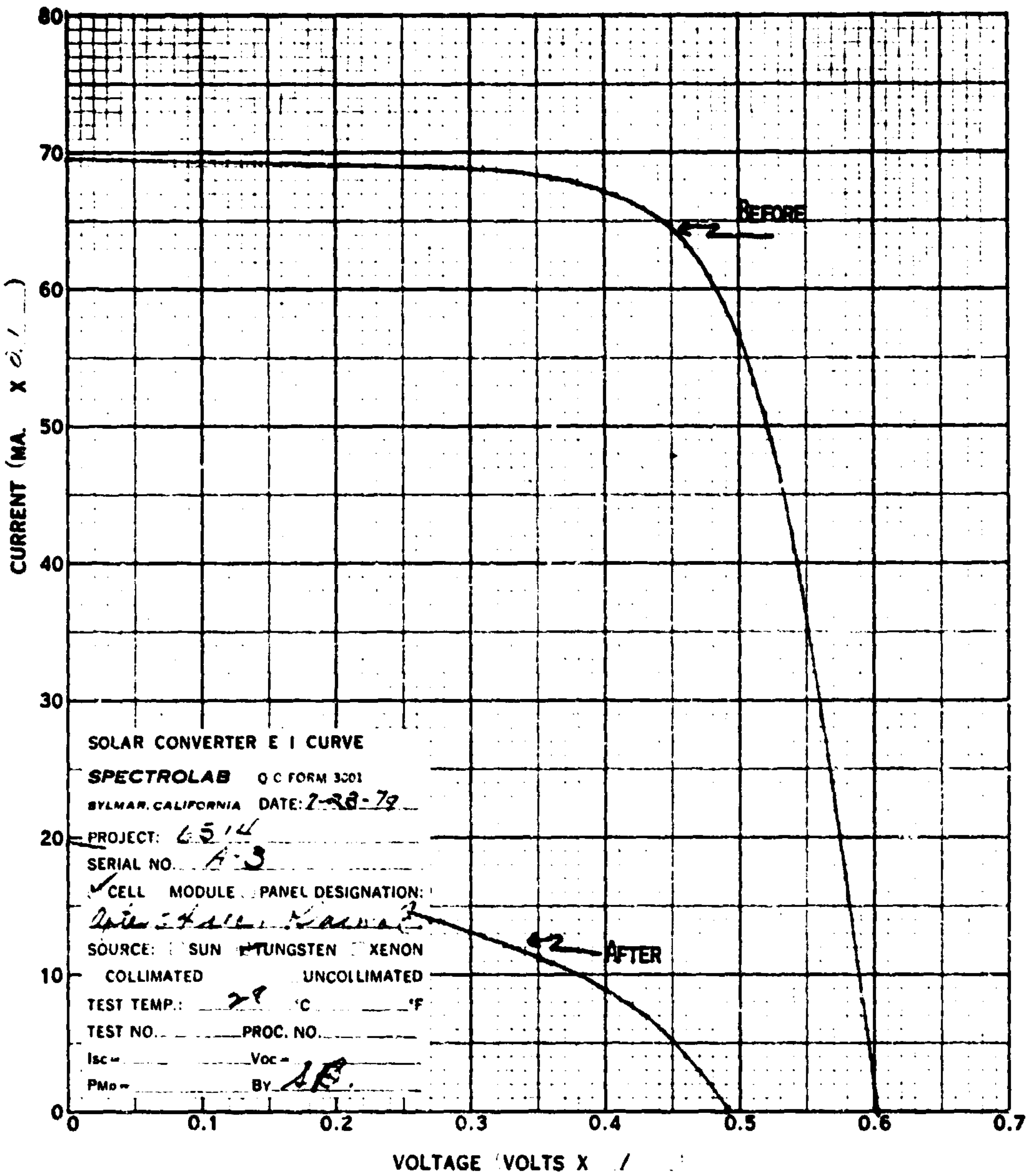
JUNCTION REMOVAL BY PLASMA ETCHING



AFTER 12 SEC PLASMA ETCH



AFTER 24 SEC PLASMA ETCH



POSSIBLE EXPLANATIONS FOR INCREASE OF I_{SC}

1. REDUCTION OF RECOMBINATION LOSSES BECAUSE OF DEAD LAYER REMOVAL
2. REDUCTION IN JUNCTION DEPTH
3. AR COATING EFFECTS
4. MICROTEXTURING

FRONT CONTACT

ASSUMPTIONS:
SCREEN PRINTED SILVER 8% COVERAGE

EQUIP.	132,000	\$1975 (\$184,800 1980)
OUTPUT	25	PARTS/MIN
SPACE	750	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.25	PRSN/SHIFT
MATERIALS	0.442	\$1975 /MIN (\$0.6188 1980)
POWER	1.5	KW HR/MIN
QUAN.	15.3	MWP/YR
P(IPEG)/WP	0.0332	\$1975 (\$0.0465 1980)

JUNCTION CLEAN

ASSUMPTIONS:
FRONT SURFACE LASER SCRIBE

EQUIP.	80,000	$1975 ($112,000 1980)
OUTPUT	15	PARTS/MIN
SPACE	60	SQ. FT.
ASSEMBLERS	1	PRSN/SHIFT
MAINT. PERS.	0.10	PRSN/SHIFT
MATERIALS	0	$1975/MIN (-0- 1980)
POWER	0.4	KW HR/MIN
QUAN.	9.18	MWP/YR.
P(IPEG)	0.0128	$1975 ($0.0179 1980)

ANTI-REFLECTION COATING

ASSUMPTIONS:
SPRAY ON

EQUIP.	50,000	$1975 ($70,000 1980)
OUTPUT	12.5	PARTS/MIN
SPACE	120	SQ. FT.
ASSEMBLERS	0.5	PRSN/SHIFT
MAINT. PERS.	0.1	PRSN/SHIFT
MATERIALS	0.021	$1975/MIN ($0.029 1980)
POWER	0.4	KW HR/MIN
QUAN.	7.15	MWP/YR.
P(IPEG)	0.0135	$1975 ($0.0189 1980)

IPEG COST SUMMARY (I)

	SURFACE PREPARATION	DIFFUSION	BACK CONTACT	CLEAN BACK
EQUIP	0.0027	0.0025	0.0042	0.0026
SPACE	0.0005	0.0024	0.0048	0.0016
LABOR	0.0056	0.0051	0.0056	0.0055
MATERIALS	0.0038	0.0001	0.0021	0.0022
POWER	0.0001	0.0013	0.0016	0.0004
TOTAL (1975)	0.0127	0.0114	0.0183	0.0124
(1980)	0.0178	0.0160	0.0256	0.0174

IPEG COST SUMMARY (II)

	CONTACT	CLEAN	COAT	($1975)
EQUIP	0.0043	0.0043	0.0034	0.0240
SPACE	0.0048	0.0006	0.0016	0.0163
LABOR	0.0056	0.0072	0.0056	0.0402
MATERIALS	0.0170	-0-	0.0017	0.0269
POWER	0.0016	0.0007	0.0010	0.0067
TOTAL (1975)	0.0332	0.0128	0.0135	0.1143
(1980)	0.0465	0.0179	0.0189	0.1600

SOLAR PANELS
FROM DENDRITIC WEB SILICON

WESTINGHOUSE R&D CENTER

PROCESS SEQUENCE

1. $POCL_3$ DIFFUSION
   - MOST DEVELOPED OF AVAILABLE TECHNOLOGIES
2. AL BSF
   - SPUTTERING SHOWN COST EFFECTIVE; SILK SCREENING REQUIRES SPECIAL EQUIPMENT.
     USE AL METAL ON BACK FOR CONTACT.
3. AR/PR DIP AND GRID DELINEATION
   - PARTICULARLY SUITED TO WEB; FINE LINE GRID → HIGHER PERFORMANCE
4. METALLIZATION
   - BARRIER METAL REQUIRED; TOTAL PLATED NOT COMPATIBLE
5. LASER SCRIBING AND TESTING
   - WELL DEVELOPED TECHNOLOGY
6. INTERCONNECTION AND ENCAPSULATION
   - ULTRASONIC BONDING - NO EXPENSIVE MATERIALS; USE LESS ADHESIVE DUE TO NO SOLDER BUILD UP -- GLASS SIZE OPEN

1. $POCl_3$ DIFFUSION

PURPOSE: TO FORM N^+P JUNCTION ON WEB

PROCESS:
- INCOMING MATERIAL CLEANED USING PLASMA ETCHING
- N_2 CARRIER GAS
- $850°C \, {}^{+\,5°C}_{-\,10°C}$; 35 MIN. ± 10 MIN.

PROCESS CONTROL: SHEET RESISTIVITY TO BE $50 \pm 10 \; \Omega/\square$

METHODS OF Al DEPOSITION FOR BACK-SURFACE FIELDS

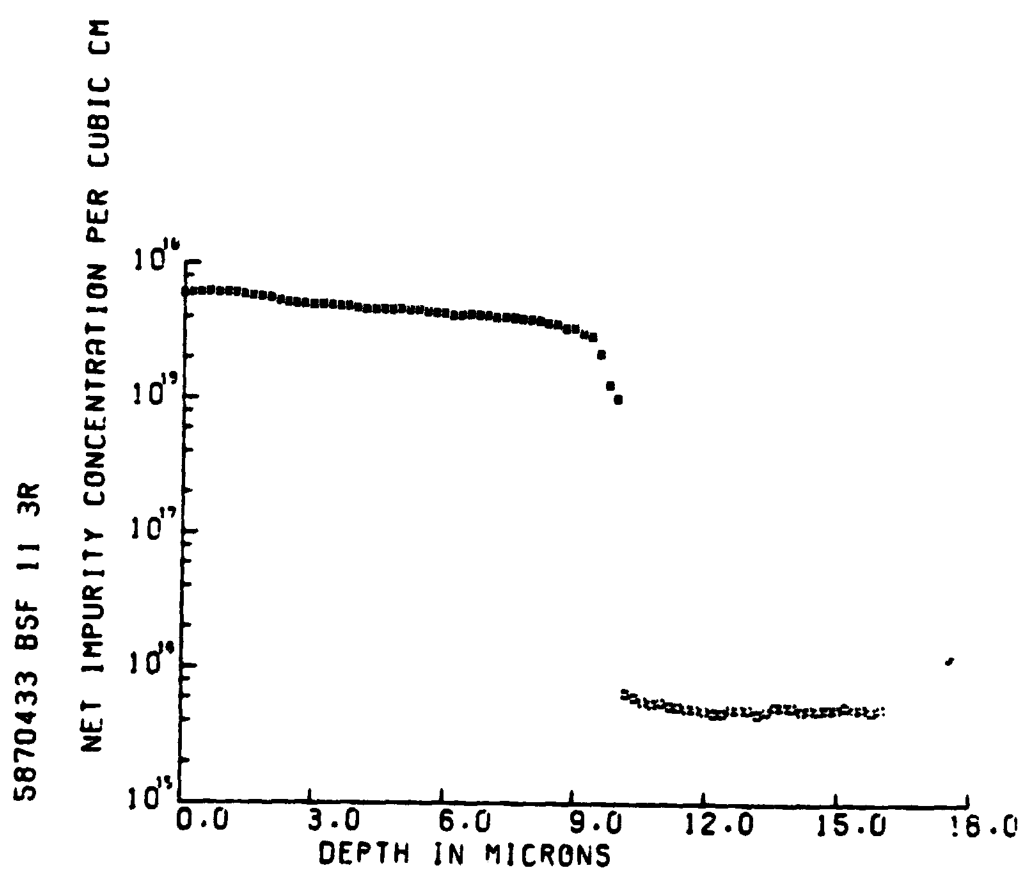
EVAPORATION
SPUTTERING
SILK SCREENING

2. ALUMINUM BACK-SURFACE FIELD

PURPOSE: TO FORM BACK SURFACE FIELD

PROCESS:
- SPUTTER ALUMINUM - 10 ± 3 μM
- AL DRIVE 850°C ± 10°C; 1 MIN. ± 0.25 MIN
- ATMOSPHERE - N_2 - ATMOSPHERIC PRESSURE

PROCESS CONTROL: DEPTH OF P+ LAYER TO BE 10 μM ± 3 μM



3. AR/PR DIP—GRID DELINEATION

PURPOSE: DEPOSIT ANTIREFLECTIVE COATING AND DEFINE GRID

PROCESS:
- AR COATING OF MIXED OXIDES APPLIED BY DIPPING. THICKNESS CONTROLLED BY VISCOSITY AND RATE OF WITHDRAWAL. BAKE AT 400°C ± 25°C.
- PR APPLIED BY DIPPING. THICKNESS OF ≈ 1 μM CONTROLLED BY VISCOSITY AND RATE OF WITHDRAWAL. BAKE AT 90 ± 3°C FOR 25 MIN. ± 3 MIN.
- MASK - EXPOSE - DEVELOP
- OPEN GRID WITH PR DEVELOPER AND AR ETCH

PROCESS CONTROL: COLOR OF AR COATING
WIDTH OF GRID LINES (25 μM $^{+5}_{-0}$ μM)

4. METALLIZATION

PURPOSE: FORMATION OF CONDUCTIVE PATH ON GRID DESIGN

PROCESS:
- EVAPORATE 250 Å ± 50 Å TI
  250 Å ± 50 Å PD
- REJECT EXCESS TI-PD USING PR DEVELOPER
- ELECTROPLATE CONDUCTIVE LAYER OF CU (AG)

PROCESS CONTROL: CU(AG) LAYER TO BE 8 μM ± 2 μM

5. LASER SCRIBING AND TESTING

PURPOSE: TO SEPARATE CELL FROM DENDRITIC WEB MATRIX

PROCESS:
- LASER SCRIBE CELL FROM BACK
- FRACTURE FROM MATRIX
- TEST CELL

PROCESS CONTROL:
- CELL AREA = $A_0 \pm 0.5\%$
- NO CRACKS OR CHIPS ON CELL
- LASER PENETRATION NO GREATER THAN 60 μm
- CELL PARAMETERS MEET SPECIFICATIONS

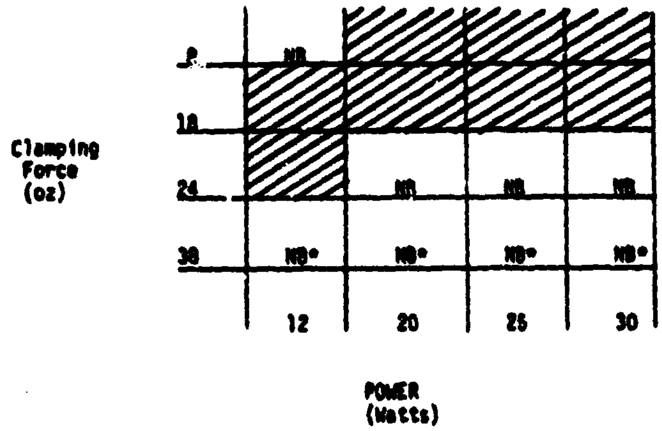
6. INTERCONNECTION AND ENCAPSULATION

PURPOSE: INTERCONNECT AND ENCAPSULATE CELLS

PROCESS:
- ULTRASONIC BONDING OF Cu(AL) STRAPS TO CONTACT METAL
- CELLS MOUNTED SUN SIDE DOWN ON GLASS WITH ADHESIVE
- MINIMAL SUBSTRATE ATTACHED WITH ADHESIVE

PROCESS CONTROL:
- PULL STRENGTH OF INTERCONNECT BOND > 50 GMF
- RESISTANCE OF BOND < $10^{-5}\ \Omega$
- MINIMUM AMOUNT OF BUBBLES IN GLASS/CELL INTERFACE
- PANEL PACKING FACTOR > 96%

Ni TO PLATED Ag (T = 1.2 sec) PPE



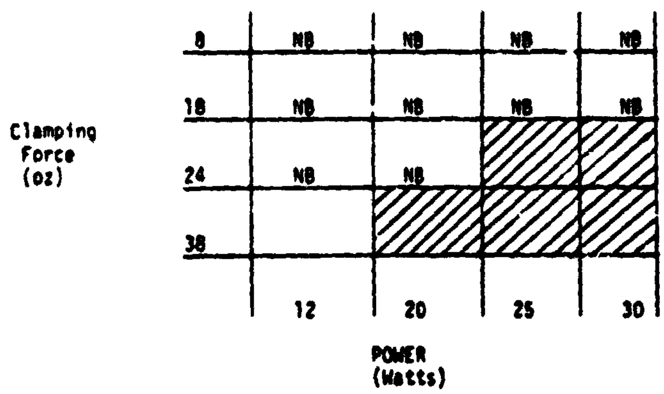
Shaded area - bonds made

NB - no bonding

NB* - Ni bonded to weld tip

4 x 4 clamping force - power matrix for nickel ribbon ultrasonically welded to plated silver (1.2 second weld time)

Cu TO PLATED Ag (T += 1.2 sec)



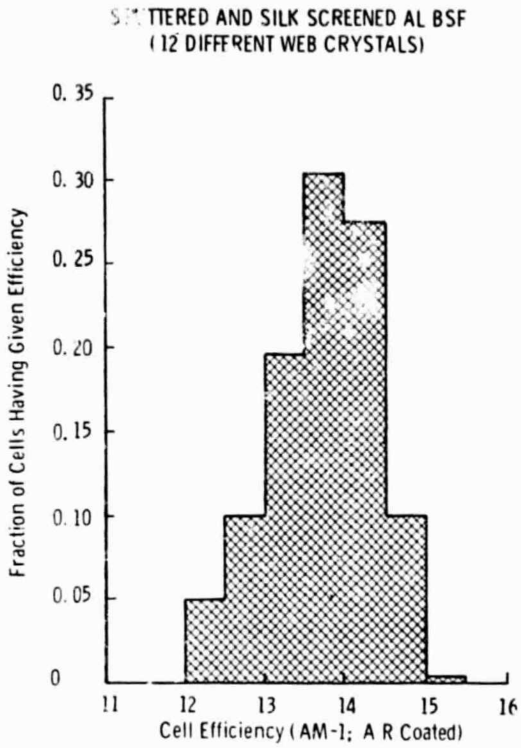
Shaded area - bonds made

NB - no bonding

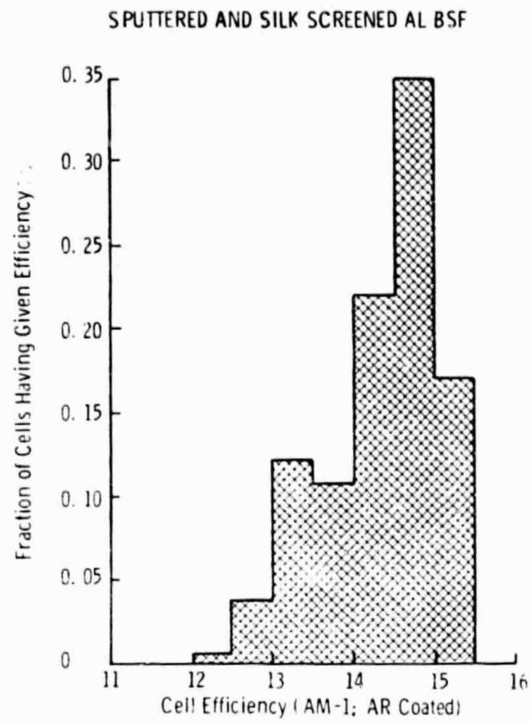
4 x 4 clamping force - power matrix for copper ribbon ultrasonically welded to plated silver (1.2 second weld time)

EFFICIENCY DISTRIBUTION

DENDRITIC WEB CELLS



FLOAT ZONE CELLS



ASSUMPTIONS USED FOR CONCEPTUAL MANUFACTURING LINE

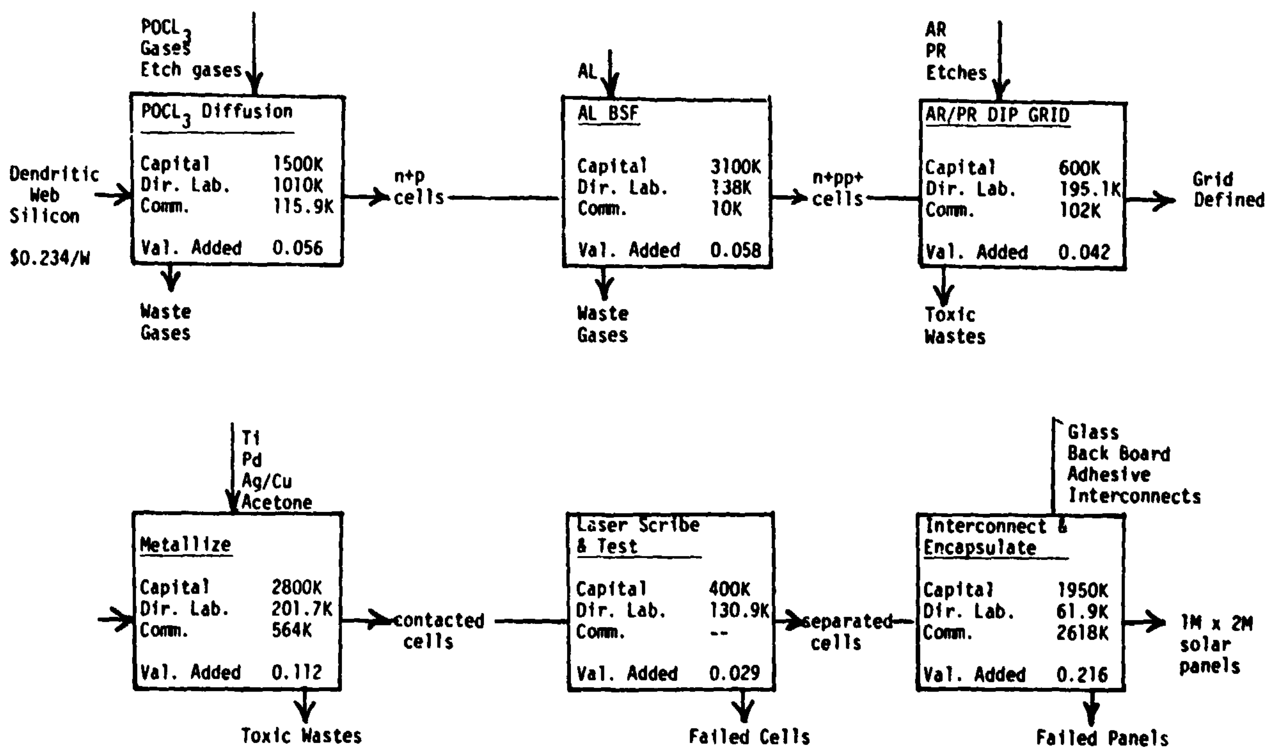
- 25 MW/YR
- 5000 CM^2/MIN THROUGHPUT OF WEB
- 5 CM WIDE WEB
- 345 DAYS/YEAR OPERATION
- 3 SHIFT OPERATION
- BALANCED LINE

WESTINGHOUSE PROCESS SEQUENCE TOTAL COSTS—1980 $

ASSUMPTIONS: 25 MW/YR PRODUCTION
12% PANEL
5 CM WIDE WEB
85% YIELD OF CELLS
95% YIELD OF PANELS
SILICON INPUT COST - $0.234/WATT PEAK

CAPITAL	$10,350,000
DIRECT LABOR	$ 1,920,000
FLOOR SPACE	4800 FT^2
COMMODITIES	$ 3,410,000

SELLING PRICE PER WATT-PEAK - $0.75



SAMICS COSTING (1980 $)

PLASMA ETCH

PRE DIFFUSION CLEANING BY A PLASMA ETCHING PROCESS HAS A VALUE ADDED COST OF $0.018 $/WATT PEAK

BACK SURFACE FIELD FORMATION

VALUE ADDED FOR GIVEN BSF PROCESS

BORON DIFFUSED	0.079 $/WATT PEAK
SPUTTERED AL	0.058 $/WATT PEAK
SILK SCREENED AL	0.039 $/WATT PEAK

SAMICS COSTING SENSITIVITY ANALYSIS (1980 $)

CAPITAL EXPENDITURES

FOR $10 x 10^6 ± 10% CAPITAL EXPENDITURE, EACH $10^6 OF CAPITAL ADDS $0.03/WATT PEAK TO THE SELLING PRICE

YIELD

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

WEB WIDTH

WHEN WEB WIDTH IS DECREASED FROM 5.0 CM TO 2.5 CM, THE SELLING PRICE IS INCREASED BY $0.07/WATT PEAK.
(ASSUME EQUAL YIELD AND EQUAL CELL EFFICIENCY)

PANEL EFFICIENCY

IN THE RANGE OF 10 - 15% PANEL EFFICIENCY; FOR EACH 1% INCREASE IN EFFICIENCY THE SELLING PRICE IS DECREASED BY $0.06/WATT PEAK.
(ASSUME EQUAL YIELD)

IN-DEPTH STUDY OF SILICON WAFER SURFACE TEXTURIZING

PHOTOWATT INTERNATIONAL, INC.

(FORMERLY SENSOR TECHNOLOGY, INC.)

SUMMARY OF WAFER SURFACE PREPARATION COSTS FOR 1968 IN 1975 ¢/Wp

COST ELEMENTS	WAFER* CLEANING	TWO STAGE TEXTURIZING	HOT AIR DRYING	SUBTOTAL	RECYCLE* GETTERING	TOTAL
EQUIPMENT	0.023	0.079	0.035	0.137	0.316	0.453
FLOOR SPACE	0.017	0.013	0.020	0.050	0.098	0.148
LABOR	0.563	0.164	0.117	0.844	0.477	1.321
MATERIAL	0.057	0.004	0.114	0.175	0	0.175
UTILITIES	0.024	0.022	0.006	0.052	0.077	0.129
TOTAL	0.684	0.282	0.292	1.258	0.968	2.223

*USED CURRENTLY AVAILABLE MACHINES.

OBJECTIVES

IN-DEPTH STUDY ON WAFER SURFACE PREPARATION TO REDUCE COSTS IN THE FOLLOWING STEPS:

1. WAFER CLEANING
2. TWO STAGE WAFER SURFACE TEXTURIZING
3. GETTERING PROCESS (RECYCLE DIFFUSION GAS)
4. WAFER DRYING

WAFER CLEANING

EQUIPMENT: DELTA SONIC MODEL DS-10R-3 ULTRASONIC VAPOR DEGREASER

CHEMICALS: TRICHLOROETHYLENE OR FREON TMS

RESULTS: COST IS ONLY 0.68 ¢ / WATT IN 1975 CENTS

TWO STAGE WAFER SURFACE TEXTURIZING AND GETTERING

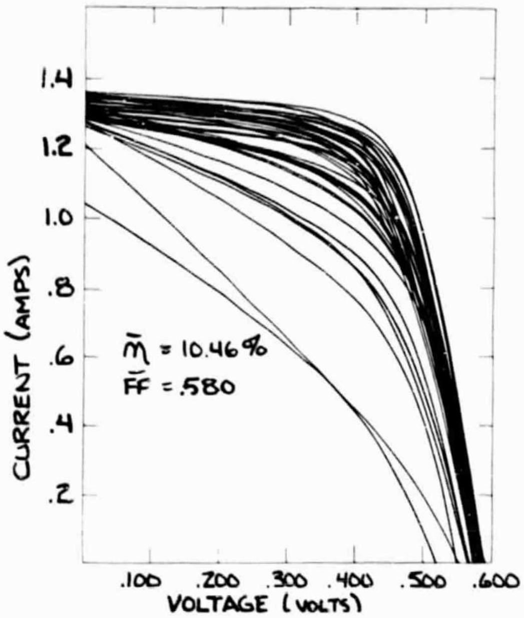
KEY PROCESS PARAMETERS

1. PROCESS SEQUENCE
2. GETTERING TEMPERATURE AND TIME
3. TEXTURIZING CONCENTRATION AND TIME
4. CELL SIZE

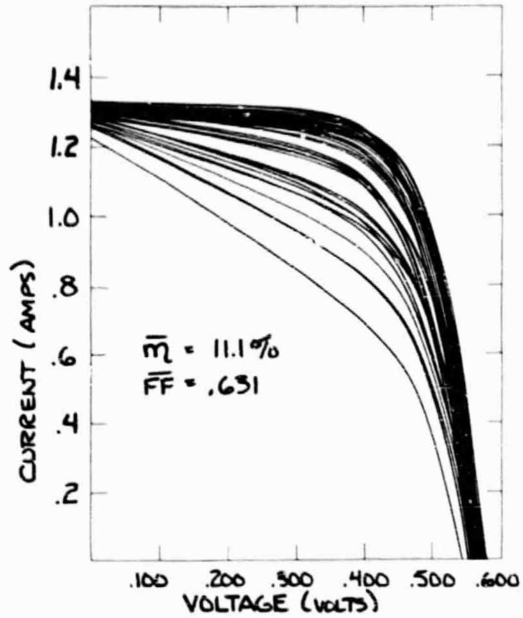
RESULTS (3" DIAMETER CELLS)

1. INTERMEDIATE GETTERING IS BEST
   HIGH $\overline{\eta}$ AND HIGH $\overline{FF}$
2. OPTIMUM GETTERING TEMPERATURE
   875° C, 35 MIN

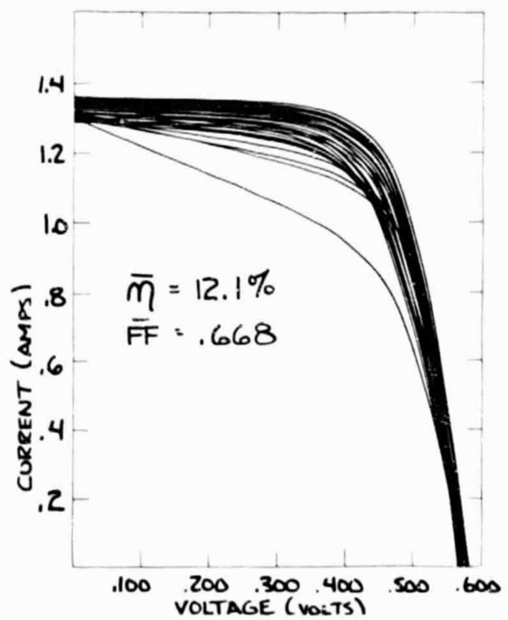
GETTERING TEMPERATURE



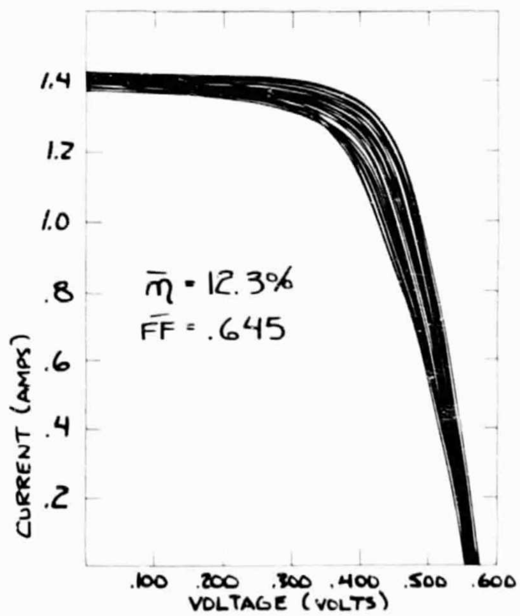
TEMP. = 1050°C



TEMP. = 975°C

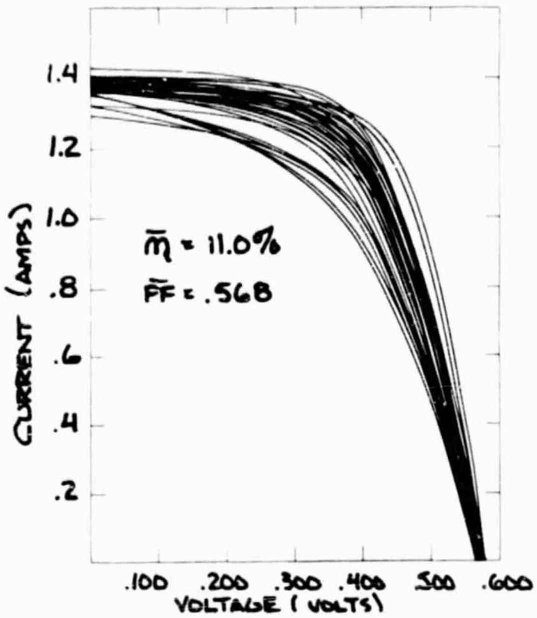


TEMP. = 900°C

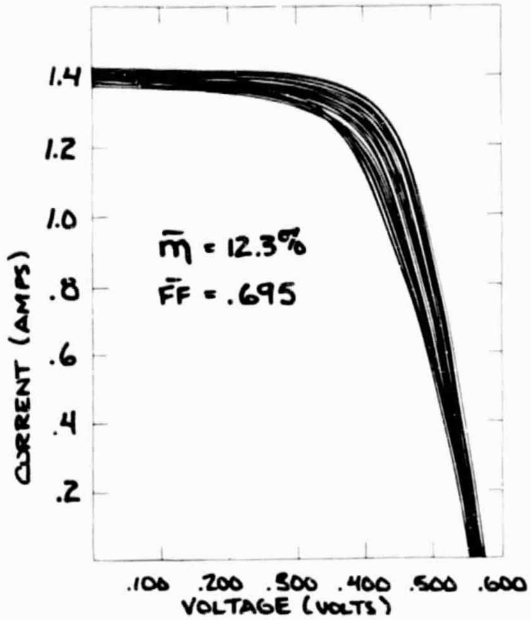


TEMP. = 875°C

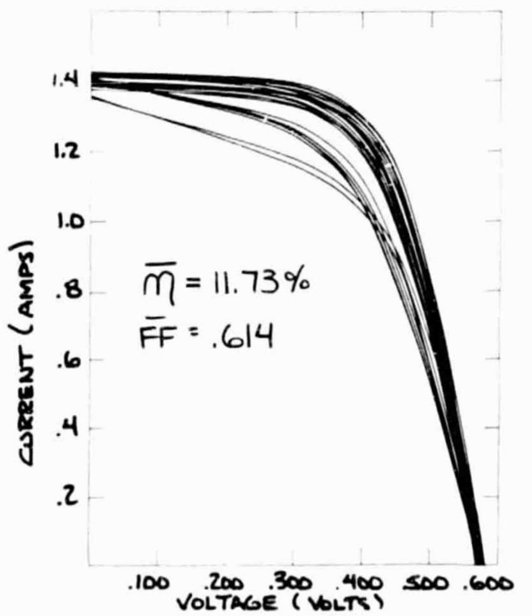
PROCESS SEQUENCE



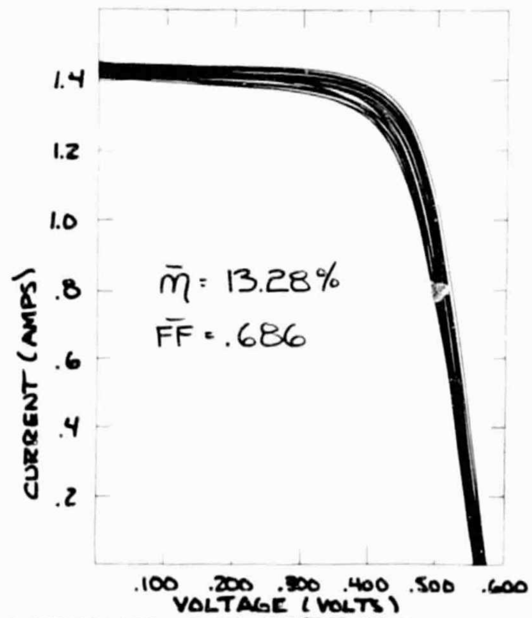
TWO STAGE TEXTURING
(10% NaOH / 1% NaOH)



INTERMEDIATE GETTERING



PRE GETTERING



INTERMEDIATE GETTERING
WITH SiO

INTERTASK SESSION: PP&E AND TASK 2

REPEAT QUESTION FROM 7TH PIM: AUG 1977 -
"ARE THERE ANY OPTIMUM OR PREFERRED SIZE AND SHAPE CONSIDERATIONS FOR SILICON SHEET THAT ARE APPARENT AT THIS TIME?"

- ALL PREFERRED SHEET GROWTH SIZES ARE 150 MM OR LESS IN WIDTH
- PROCESSING AND CELL DESIGN NOT CRITICAL UP TO 150 MM DIMENSION
- PRIMARY PROCESSING CONCERN WITH HANDLING DELICATE MATERIALS

3. Engineering Area

TECHNOLOGY SESSION

L. N. Dumas, Chairman

Engineering Area personnel and contractors made presentations during the 13th Project Integration Meeting summarizing recent progress in both analytical and empirical testing activities related to a variety of module design and performance-requirements investigations. Current emphasis on development plans for residential module and array requirements was described by Ronald G. Ross (JPL) at the Wednesday morning primary session. The current status of the Clemson cell-reliability study was presented, showing particularly the results of recent measurements of reverse-bias characteristics of all cell types currently undergoing stress tests. Bechtel provided a presentation covering analysis of array costs when a curved glass superstrate is used and describing high voltage stress design requirements for module encapsulation systems.

Modifications of the sunlight-accelerated aging equipment at DSET laboratories for temperature control and recent natural-sunlight spectral measurements in support of performance standards were described. The results of wind-tunnel testing of flat solar panels conducted by Sandia Labs at Colorado State University indicated that screening can effectively lower maximum wind pressures on modules and hence reduce array structure costs. Investigation of the effect of lifetime wind loading on cell interconnects has shown that cyclic wind loading will not result in fatigue failure of a variety of interconnect designs. The latest results of the ongoing series/parallel studies, which relate life-cycle energy cost to module size and circuit design for various failure replacement structures, were described.

MAJOR UNREPORTED ENGINEERING ACTIVITIES

- ELECTRICAL TERMINATION STUDY (MOTOROLA)
- ELECTRICAL SAFETY REQUIREMENTS (UL)
- ENVIRONMENTAL TEST DEVELOPMENT (JPL)
  - SOILING
  - INSULATION DURABILITY
- IR CAMERA HOT-SPOT TEST RESULTS (JPL)
- CENTRAL STATION WIND LOADS (BOEING)
- RESIDENTIAL MODULE REQUIREMENTS (JPL/BURT HILL)
- CELL RELIABILITY TESTING (CLEMSON)
- ARRAY STRUCTURAL ANALYSIS AND ELECTRICAL INSULATION REQ (BECHTEL)
- MODULE ACCELERATED TESTING (DSET)
- ARRAY WIND TESTING (SANDIA)
- MODULE CYCLIC FATIGUE TESTING (JPL)
- SERIES-PARALLEL ANALYSIS UPDATE (JPL)

RESIDENTIAL PHOTOVOLTAIC MODULE AND ARRAY ENGINEERING

RON ROSS (JPL)

OBJECTIVES

- DEFINE DETAILED RESIDENTIAL ARRAY DESIGN REQUIREMENTS UTILIZING:
  - PV-SYSTEM PERFORMANCE CONSIDERATIONS
  - RESIDENTIAL BUILDING PRACTICES AND STANDARDS
  - MAINTENANCE PRACTICES AND COSTS
  - MARKETING CONSIDERATIONS (AESTHETICS, ETC)
- DEVELOP RESIDENTIAL ARRAY CONCEPTUAL DESIGNS AND PROTOTYPE HARDWARE
- DEVELOP EVALUATION CRITERIA AND TEST METHODS FOR RESIDENTIAL ARRAYS
- GENERATE DESIGN COMPARISON TRADE-OFF DATA LEADING TO IMPROVED DESIGNS AND COMPONENT TECHNOLOGY DEVELOPMENT.

STATUS HIGHLIGHTS

PV-SYSTEM PERFORMANCE IMPLICATIONS (SANDIA, ET. AL.)

- ARRAY SIZE: 8 TO 15 kW PER RESIDENCE
- COST/LIFE: 70¢/WATT @ 20 YEAR LIFE
- ARRAY VOLTAGE: 110 TO 300 VDC
- ARRAY EFFICIENCY: HIGH ($\geq$13%) TO MAXIMIZE ROOF AREA UTILIZATION

BUILDING PRACTICE AND STANDARDS IMPLICATIONS (BURT HILL)

- DEVELOP INTEGRATED MODULE/ARRAYS TO MINIMIZE SITE-SPECIFIC ENGINEERING, CONSTRUCTION, AND INSTALLATION LABOR.

- BUILDING CODES AND NEC AMBIGUOUS WITH RESPECT TO PHOTOVOLTAICS (SHOULD DEVELOP CODE RECOMMENDATIONS FOR 1984 REVISIONS).

- ATTEMPT TO HAVE INTEGRATED ARRAYS CLASSIFIED AS "PREMANUFACTURED ITEM WITH INTERNAL WIRING" TO ALLOW TYPE-APPROVAL AND AVOID SITE-SPECIFIC CODE INTERPRETATIONS.

- ARRAY CONSTRUCTION CONSTRAINTS:
    - WIRING: J-BOXES WITH #14 AWG CONDUCTORS UNTIL QUICK-CONNECT IS CODE APPROVED.
    - SAFETY: GROUNDED, FIRE RESISTANT
    - STRUCTURAL: 50 psf LOADING PLUS 250 lb POINT LOAD IN 4 in^2 AREA (HIGHER IN SNOW BELT)
    - ENVIRONMENTAL: MOISTURE, UV, THERMAL, FUNGUS RESISTANT
    - DIMENSIONS/TOLERANCES (FOR GLASS): + 1/8, -1/16 in FOR DIMENSIONS 4 ft, OTHERWISE +3/16, -1/16 in
    - WEIGHT: 50 TO 120 lbs. PER MODULE

MAINTENANCE PRACTICES AND COSTS

- DESIGN FOR MAINTENANCE-FREE OPERATION
- DESIGN FOR EASY, LOW-COST REPAIR

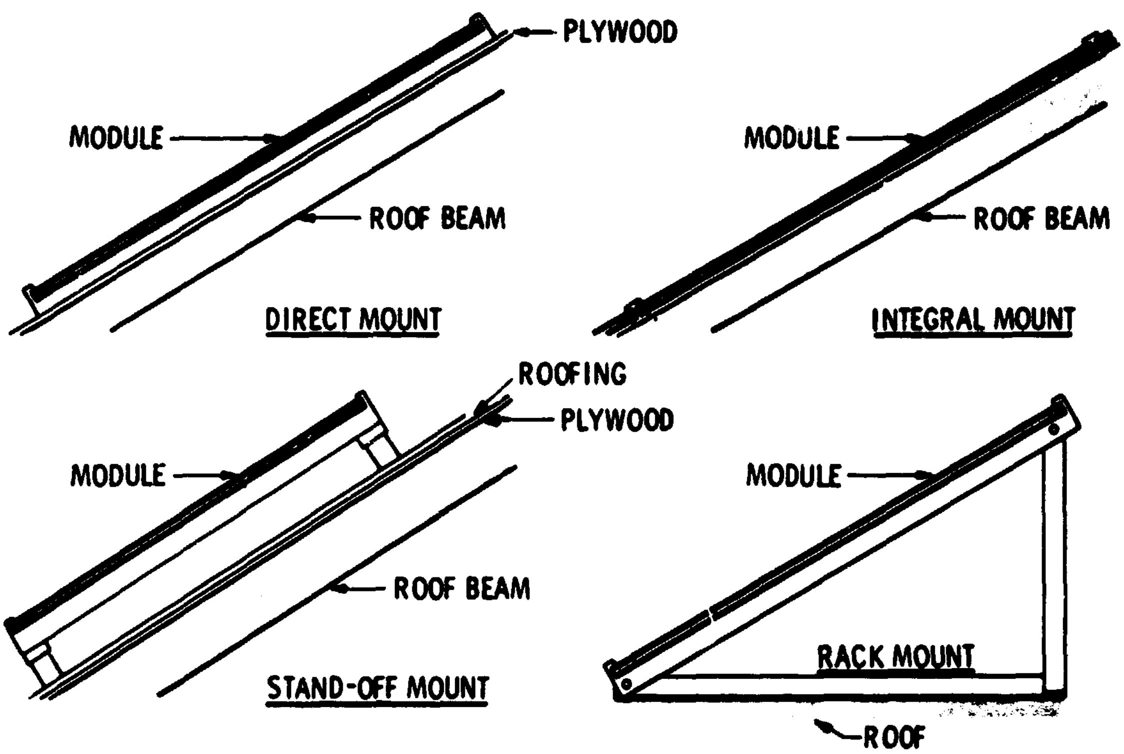
MARKETING AND AESTHETIC CONSIDERATIONS

- RECTANGULAR ASPECT RATIO MODULES (32 x 96 in)
- DARK EARTHTONE, MATTE-LIKE SURFACE
- LIE IN AND BE CONTINUATION OF ROOF PLANE (DIRECT OR INTEGRAL MOUNT)
- ARRAY AREA LESS THAN 74 m^2 (800 ft^2)

RESIDENTIAL ARRAY CONCEPTUAL DESIGNS

- PANEL-TYPE (DIRECT, INTEGRAL, STAND-OFF, RACK)
- SHINGLE

MODULE MOUNTING TYPES



STATUS HIGHLIGHTS

DESIGN COMPARISON TRADE-OFF DATA:

ROOF MOUNTING TRADEOFFS: BURT HILL (IN PUBLICATION)
ARRAY WIRING TRADEOFFS: BURT HILL (IN PUBLICATION)
THERMAL PERFORMANCE: JPL 5101-31, 5101-76
SERIES/PARALLEL: JPL (IN WORK)
HAIL PERFORMANCE: JPL 5101-62
STRUCTURAL SIZING: JPL (IN PUBLICATION)

PLANS

CONTINUED REQUIREMENT IDENTIFICATION:

- ELECTRICAL SAFETY (UL)
- PV-THERMAL SYSTEM INTERFACE
  (SANDIA, MIT/LL)

CONTINUED ARRAY CONCEPTUAL DESIGN:

- INTEGRATED MODULE/ARRAY DESIGNS
- PV-THERMAL DESIGNS

CONTINUED EVALUATION CRITERIA AND TEST METHOD DEVELOPMENT

- SERI INTERFACE

CONTINUED TRADE-OFF DATA GENERATION

- SERIES/PARALLEL
- STRUCTURAL LOADING
- PV-THERMAL PERFORMANCE
- ARRAY MAINTENANCE COSTS

RESIDENTIAL PHOTOVOLTAIC SYSTEMS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

M. C. RUSSELL

SUMMARY OF PERFORMANCE OF RESIDENTIAL PHOTOVOLTAIC SYSTEMS

	University of Texas At Arlington		M.I.T. Lincoln Laboratory System Test Facility
	June 79	Nov. 78-June 79	July 12-26 79
Average Electrical Energy Consumed (kWh/day)	74.9	93.7	21.2
Average PV Energy Produced (kWh/day)	23.3	20.1	28.2
(kWh/day-kWp)	3.11	2.68	3.86
Average PV Energy 'Sell-Back' (kWh/day)	4.00	4.8	---
Average Purchased Electrical Energy (kWh/day)	60.3	82.8	6.8
• Array Size	7.5 kWp		7.3 kWp

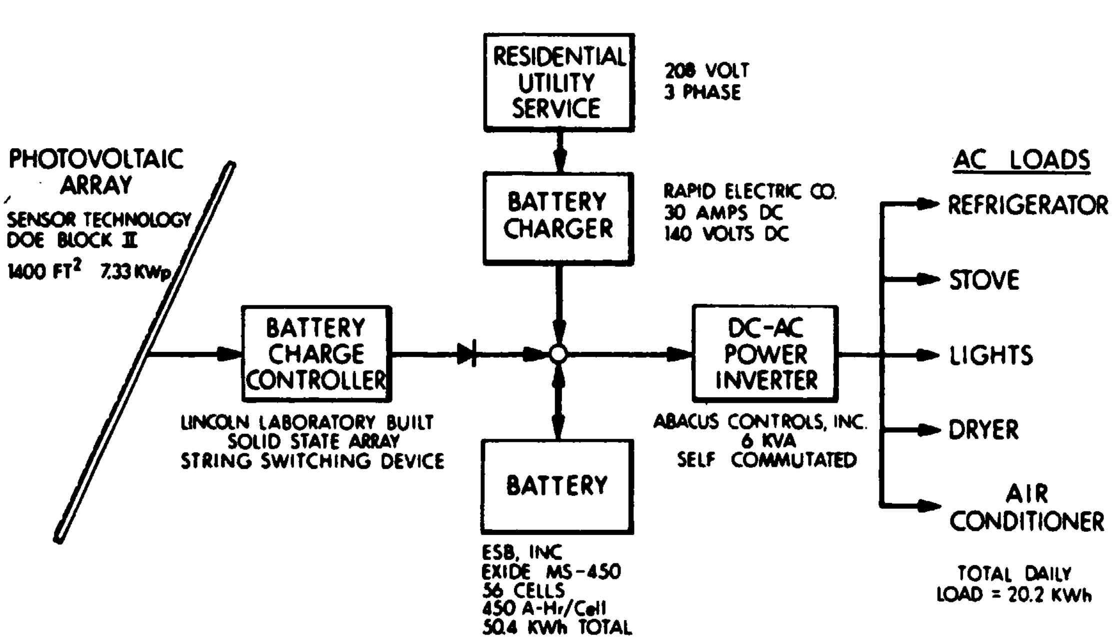
FY80 PLANS

UNIVERSITY OF TEXAS AT ARLINGTON

- ADD AIR-TO-AIR (PARALLEL) HEAT PUMP SYSTEM
- COMPARE PERFORMANCE OF PARALLEL HEAT PUMP TO EXISTING SYSTEM

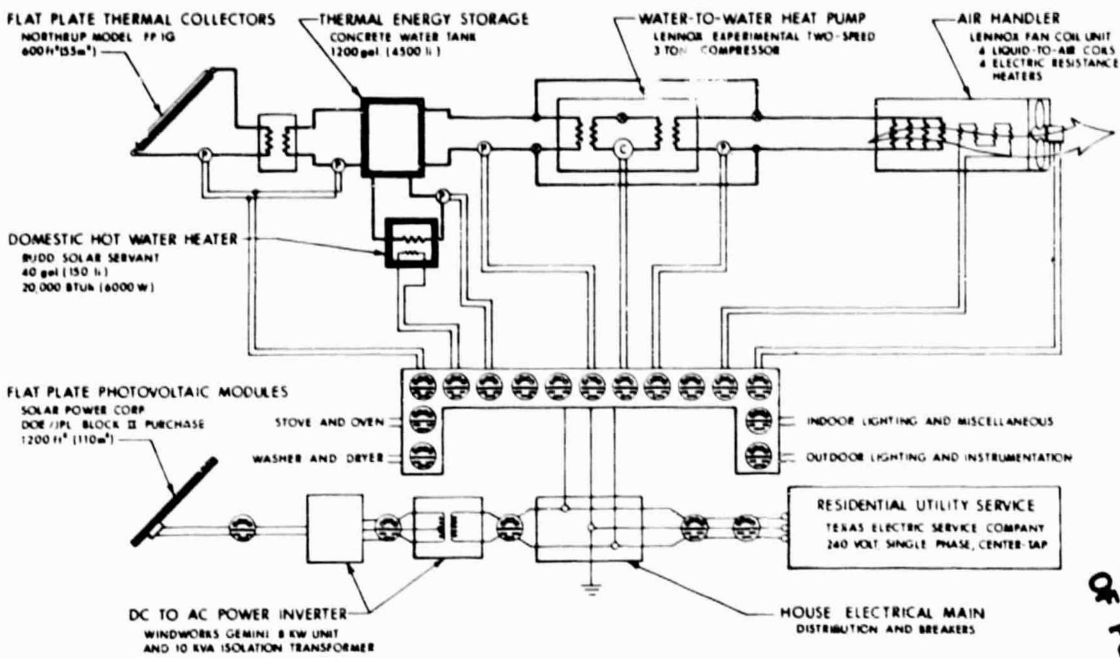
M.I.T./LL SYSTEMS TEST FACILITY

- CONTINUE SYSTEM PERFORMANCE MEASUREMENT FOR 12 MONTHS
- CHARACTERIZE PERFORMANCE OF COMPONENTS, IMPROVE SYSTEM COMPUTER SIMULATIONS

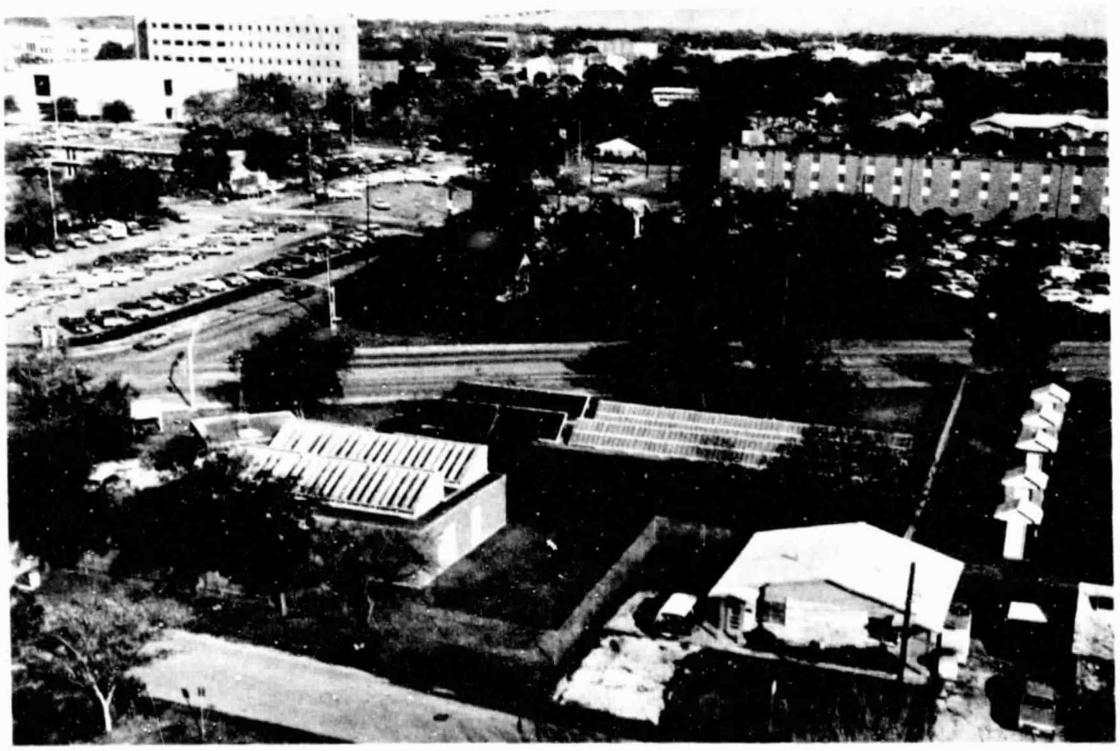


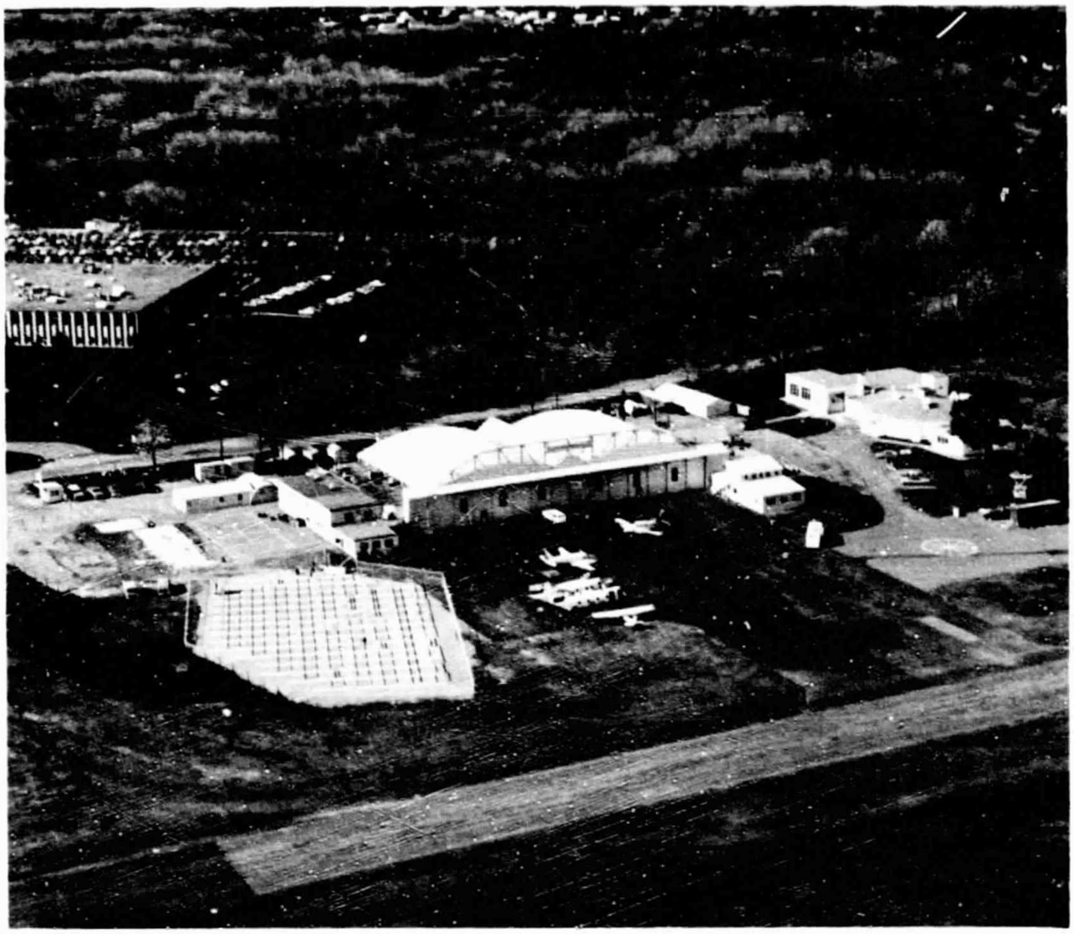
NORTHEAST RESIDENTIAL EXPERIMENT STATION
RESIDENTIAL SYSTEM DEVELOPMENT EXPERIMENT
JULY 1979

UNIVERSITY OF TEXAS AT ARLINGTON
RESIDENTIAL HEATING SYSTEM



ORIGINAL PAGE IS
OF POOR QUALITY





PV RESIDENTIAL PROJECT

- Latest (July) Draft of Residential Plan:
  - Distributed 3 July.
  - SLA Comments received 27 July.
  - Further MIT/LL activity pending JPL/LC guidance.

- Northeast Residential Experiment Station
  - Long-Term Lease obtained.
  - FAA approval for additional land area pending.
  - Subcontract A & E support on board.
  - Boston Edison and Concord Municipal Light Plant Utility Briefings: Boston Edison - Strong Interest, Concord Municipal - Lukewarm.

- Residential Activity in MIT/LL FY 80 AOP
  - Northeast Activity: Consistent with Residential Plan.
  - ISEE Grants: Consistent with Augmented Funding.
  - Southwest Activity: Consistent with Augmented Funding.
  - Southeast Activity: Consistent with Residential Plan.

RADIO STATION WBNO 15kW PV POWER SYSTEM

STATUS:

- System successfully operated at MIT/LL STF with 60% array in July.
- System now installed at Bryan, Ohio.
- System testing at Bryan, Ohio presently underway.
- Successful operation of AM Radio Transmitter on 17 August 1979.

PROJECTIONS:

- System Turn-On and Dedication 29 August 1979.

NATURAL BRIDGES 100 kW PV POWER SYSTEM

STATUS:

- Array Area Cleared and Graded
- Building Foundations Poured
- PV Power System Design/Fab - On Schedule
- Request for TRO Denied
- No further action taken by Plaintiff (8/17/79)

PROJECTIONS:

- PV Array Inst. - October 1979
- Elect Equipment Inst. - November 1979
- System Integration Tests - December 1979
- Acceptance Tests - January 1980
- Available for Dedication - January 1980

RESIDENTIAL APPLICATIONS PLAN

M. D. POPE

OVERVIEW OF RESIDENTIAL PLAN

THREE REGIONS:	NORTHEAST, SOUTHWEST, SOUTHEAST
THREE HOUSING CATEGORIES:	SINGLE-FAMILY, LOW-DENSITY, MOBILE-HOME
THREE EXPERIMENT CLASSES:	PROTOTYPE, ISEE, SRE
THREE PROGRAM ENTRY POINTS:	BASELINE, ALTERNATE, GRANT PROGRAM

HOUSING CATEGORIES AND PROJECTED YEAR 2000 INVENTORY

SINGLE-FAMILY	ONE UNIT DETACHED STRUCTURES	63%
LOW-DENSITY	ONE UNIT ATTACHED AND 2-4 UNIT STRUCTURES	15%
MOBILE-HOME	TRANSPORTABLE STRUCTURES	8%
		86%

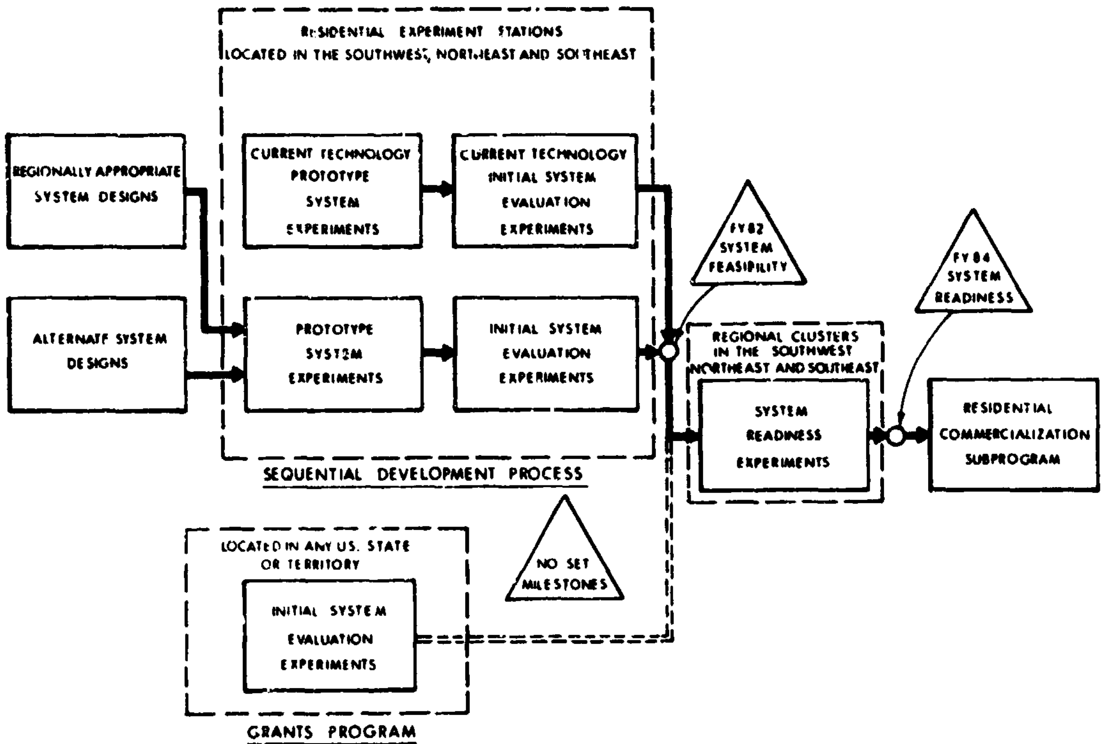
EXPERIMENT CLASSES

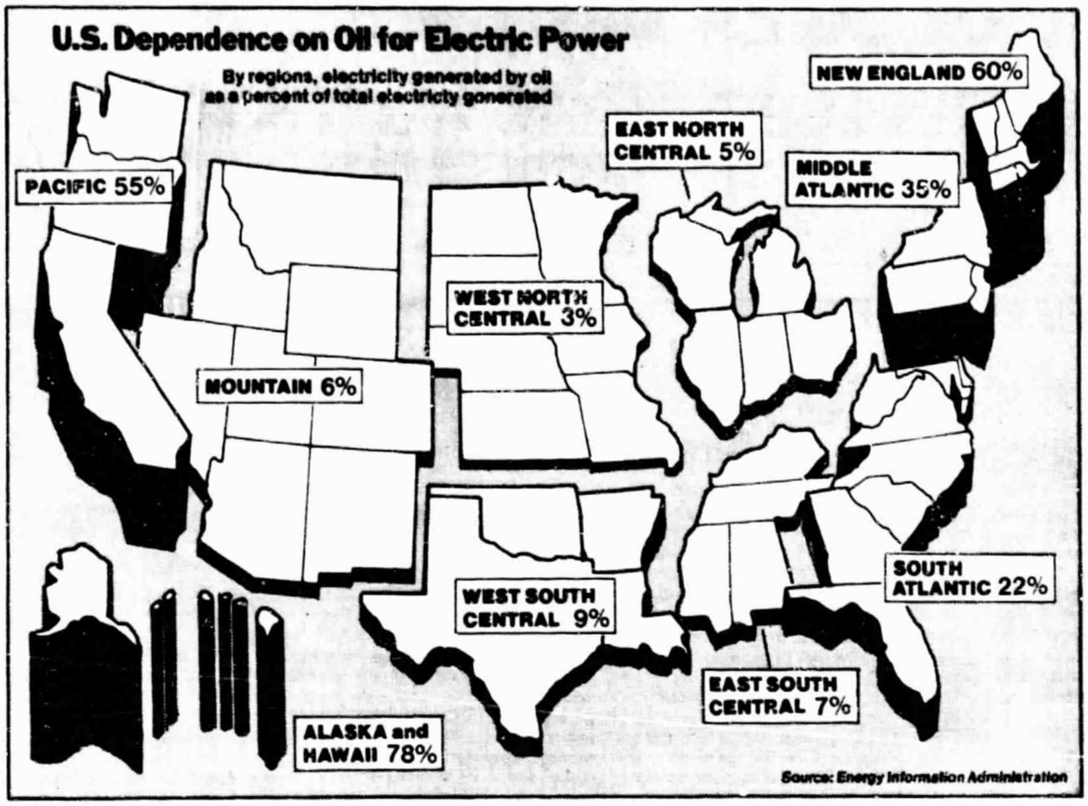
PROTOTYPES: UNOCCUPIED RESIDENCES SITED AT RESIDENTIAL EXPERIMENT STATIONS - PHYSICAL PERFORMANCE MONITORED.

ISEEs: OCCUPIED RESIDENCES IN COMMUNITY NEAR RESIDENTIAL EXPERIMENT STATIONS - PHYSICAL AND INSTITUTIONAL PERFORMANCE MONITORED.

GRANTS PROGRAM: OCCUPIED RESIDENCES IN ANY LOCALE - DIVERSITY OF PROGRAM.

SREs: CLUSTER OF OCCUPIED RESIDENCES - PHYSICAL, INSTITUTIONAL AND MARKET PERFORMANCE MONITORED, UTILITY IMPACT ASSESSED.





RESIDENTIAL APPLICATION SCHEDULE

(Operational Dates)

	FY-80	FY-81	FY-82	FY-83	FY-84	FY-85	FY-86
Northeast Region	RES PRO/C	PRO/B ISEE/C	ISEE/B PRO/A	ISEE/A	SRE/1	SRE/100	--
Southwest Region	RES	PRO/C ISEE/C PRO/B	ISEE/B PRO/A	ISEE/A	SRE/1	SRE/100	--
Southeast Region	--	RES	PRO/B PRO/A	ISEE/B ISEE/A	--	SRE/1	SRE/100
National Grants Program	ISEE/G	ISEE/G	ISEE/G	ISEE/G	ISEE/G	--	--

LEGEND

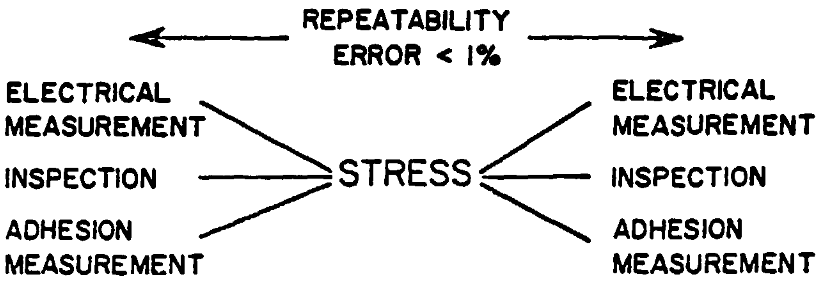
RES	Residential Experiment Station
PRO	Prototype System
ISEE	Initial System Evaluation Experiment
SRE	System Readiness Experiment
/C	Current Technology
/B	Baseline Technology
/A	Alternate Technology
/G	Grants Program
/1	First System Operation
/100	One Hundredth System Operational

INVESTIGATION OF RELIABILITY ATTRIBUTES AND ACCELERATED STRESS FACTORS ON TERRESTRIAL SOLAR CELLS

CLEMSON UNIVERSITY

J. W. LATHROP

J. L. PRINCE



ELECTRICAL PARAMETERS

V_{oc} I_{sc} R_s V_m I_m P_m

INSPECTION

LOW POWER MAGNIFICATION

PHOTOGRAPHY

ADHESION

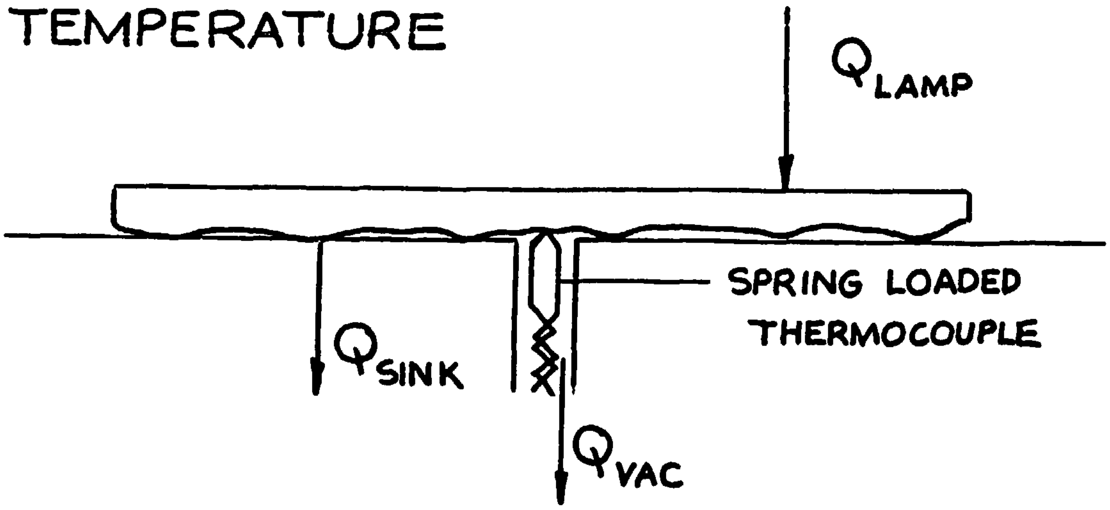
PULL STRENGTH DETERMINATION

PHYSICAL CHARACTERISTICS OF CELL TYPES SUBJECTED TO ACCELERATED STRESS TESTING

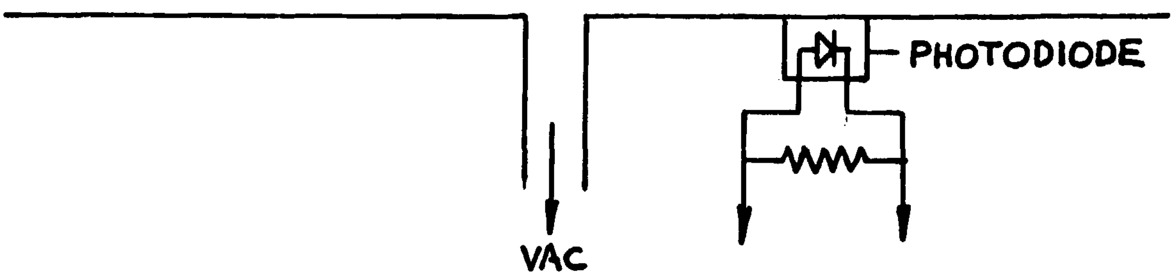
Cell Type	Cell Size (inch)	Nominal Cell Thickness (mils)	Antireflective Coating	Primary Metalization	Cell Technology
A	4 DIA	24	No	Solder	P/N
B	3 DIA	19	Yes	Ti/Pd/Ag	N/P
C	2 DIA	20	Yes	Solder	N/P
E	3 DIA	15	No	Thick-Film Ag	N/P
F	3.9 x .8	13	Yes	Cr/Ti/Ag + Solder	N/P
G	3 DIA	12	Yes	Pd/Ni + Solder	N/P
H	2 x 2	12	Yes	Ti/Pd/Ag	N/P

MEASUREMENT VARIABLES

TEMPERATURE

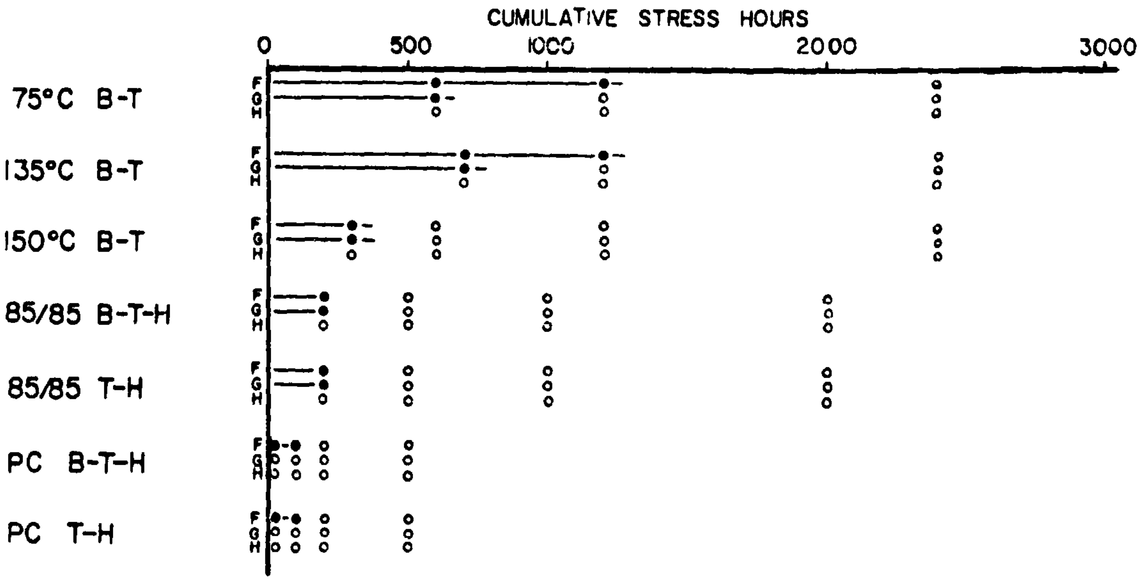


ILLUMINATION

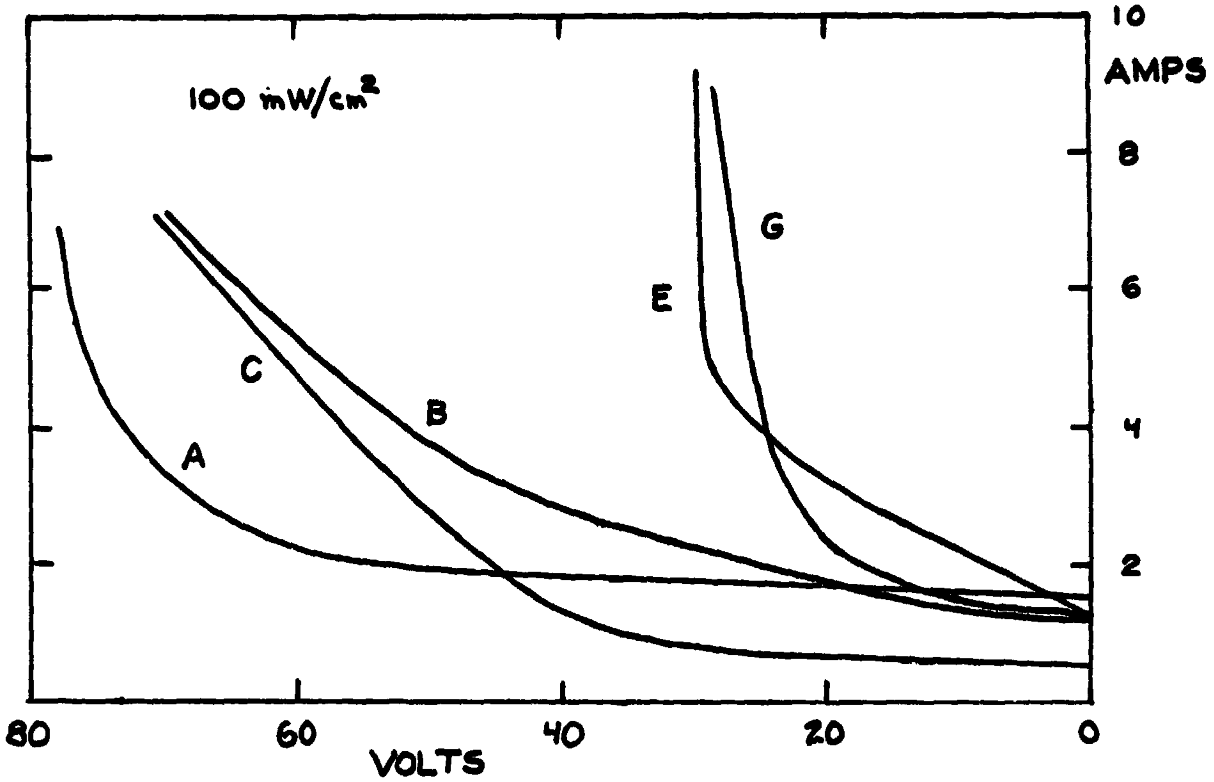


DEGRADATION MECHANISMS AND ACCELERATING STRESSES

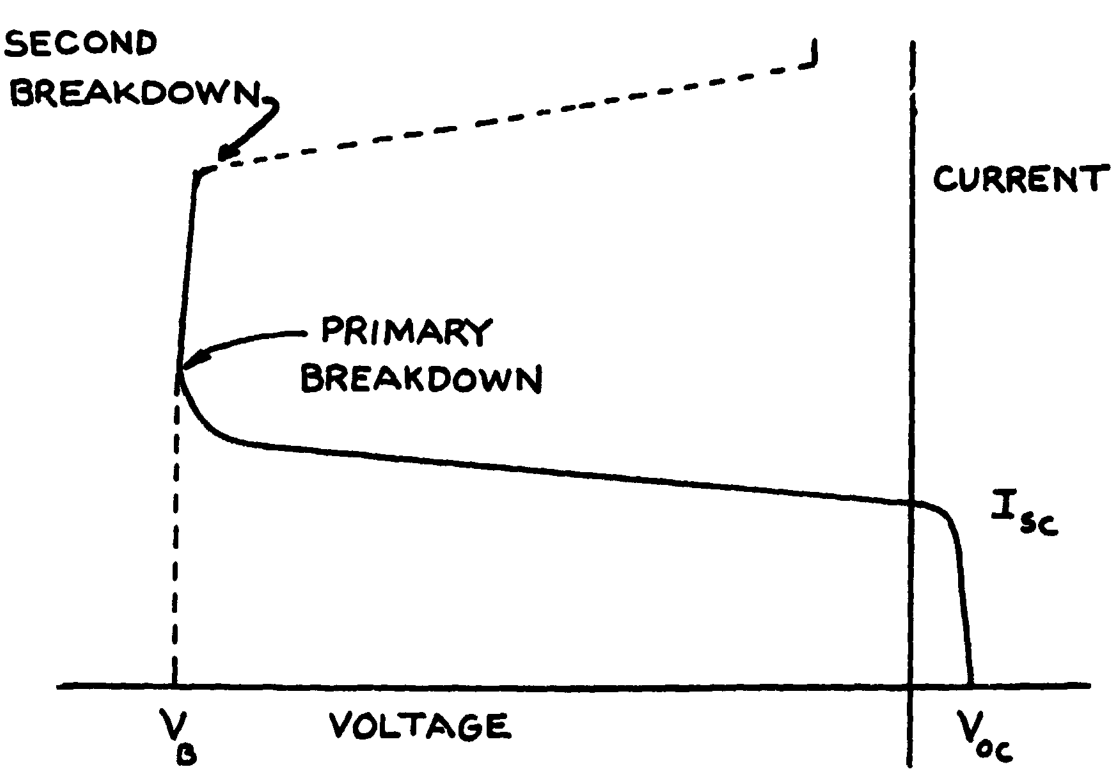
	B	T	H	I	dT/dt
CORROSION	✓	✓	✓		
KIRKENDALL VOIDING		✓			
ELECTROMIGRATION		✓		✓	
CONTACT SPIKING		✓		✓	
METAL SEGREGATION		✓			✓
ELECTROPLATING	✓	✓	✓		
METAL DELAMINATION	✓	✓	✓		✓
CELL FRACTURE					✓
AR COAT FRACTURE/DELAM.					✓
AR COAT DECOMPOSITION		✓	✓		



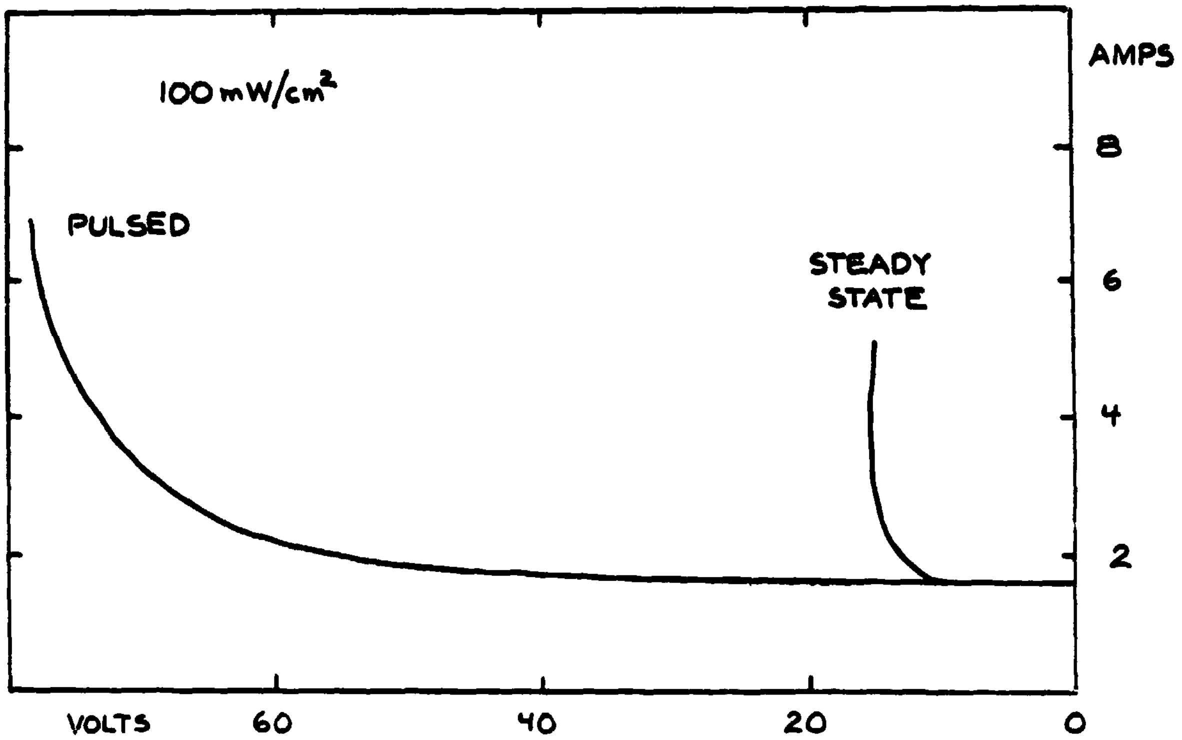
TYPICAL SECOND-QUADRANT CHARACTERISTICS



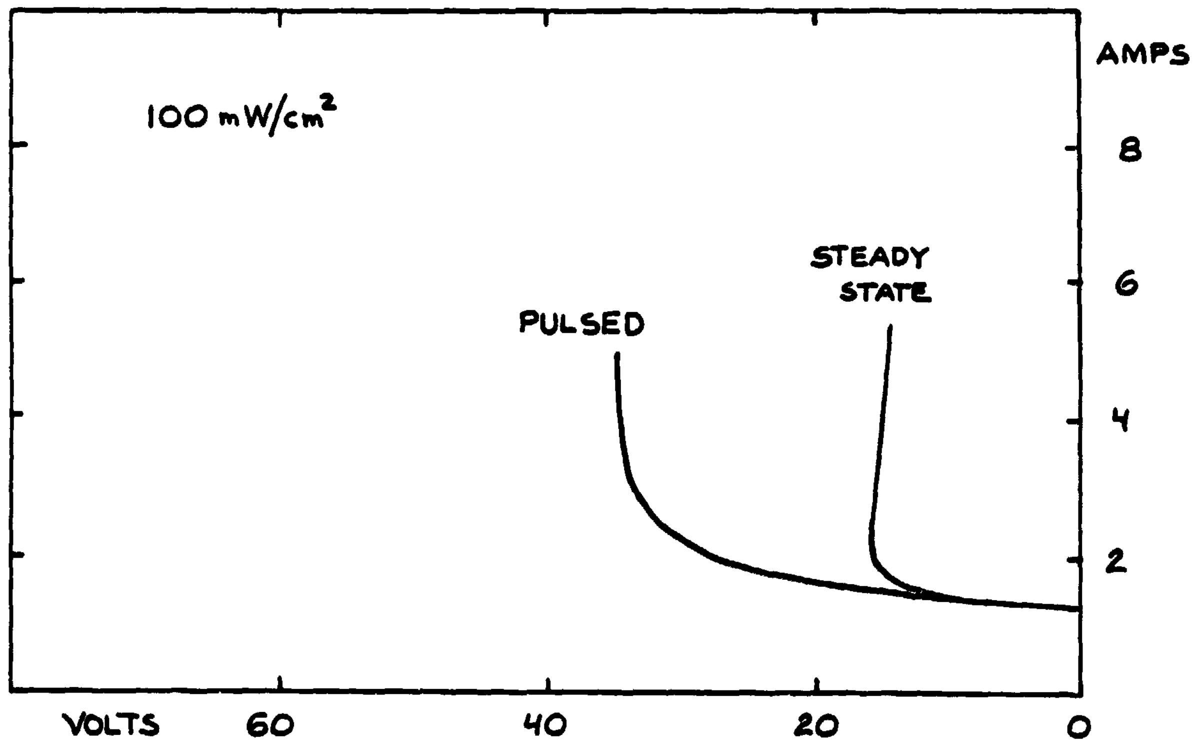
SCHEMATIC I-V CHARACTERISTIC



INTRINSIC AND FREE-AIR SECOND-QUADRANT CHARACTERISTICS FOR A-CELL



INTRINSIC AI⁾⁾ FREE-AIR SECOND-QUADRANT CHARACTERISTICS FOR G-CELL



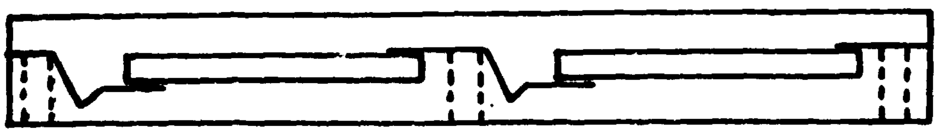
SECOND-QUADRANT VOLTAGES

	$V@2I_{sc}$	$V@3I_{sc}$
A	62 ± 28	69 ± 32
B	37 ± 21	46 ± 19
C	39 ± 14	50 ± 15
E	12 ± 2	21 ± 3
G	25 ± 6	29 ± 5

INTRINSIC

A	14 ± 3	13 ± 3
B	8 ± 1	8 ± 1
C	13 ± 2	13 ± 2
E	7 ± 2	7 ± 2
G	13 ± 3	13 ± 2

STEADY STATE



Considerations involved in the stress testing of individual encapsulated and interconnected cells

- Sample preparation
- Contacting
- Measurement
- Stress test schedule

ENGINEERING STUDY OF THE MODULE/ARRAY INTERFACE FOR LARGE TERRESTRIAL PHOTOVOLTAIC ARRAYS

BECHTEL NATIONAL, INC.

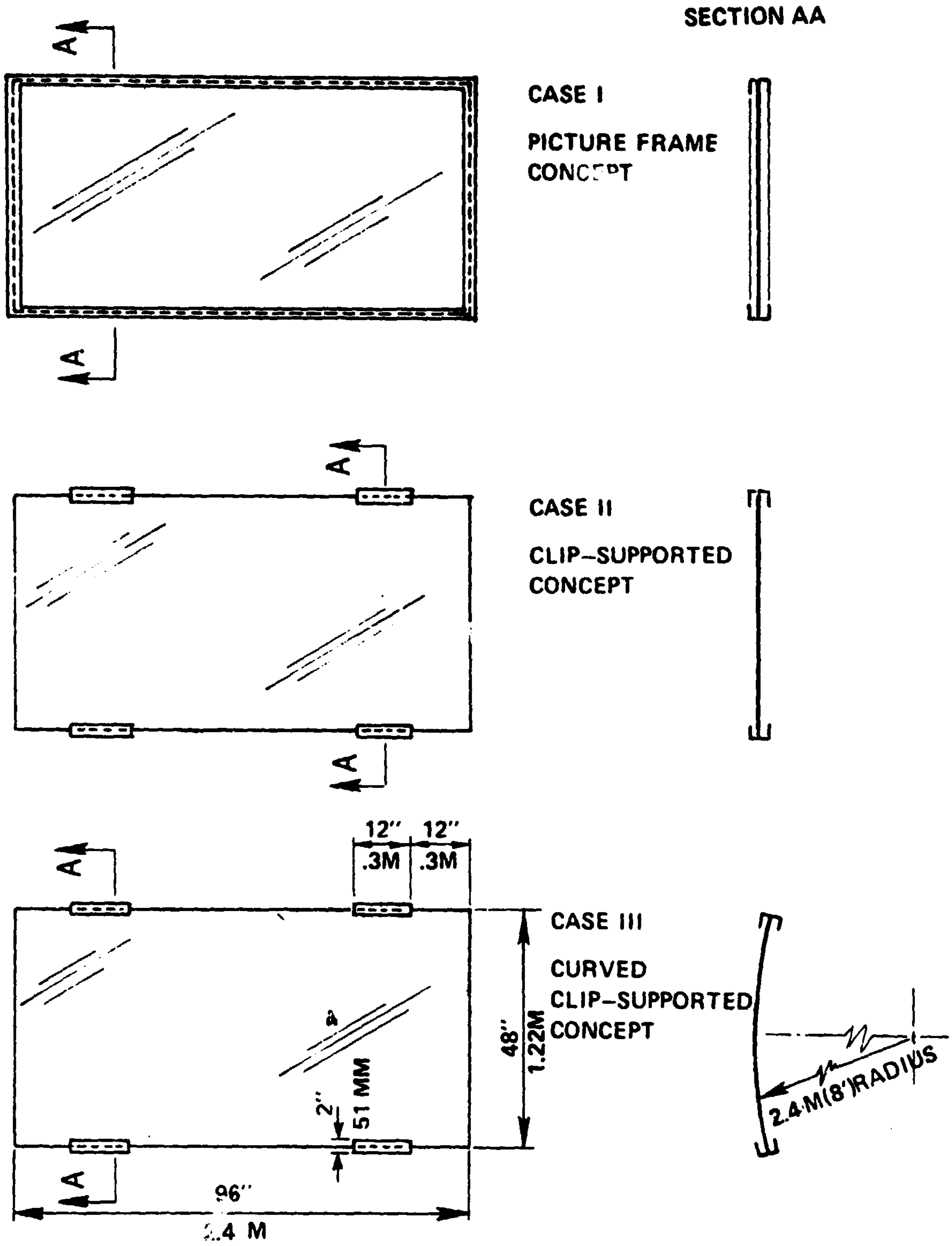
TASK 7: CURVED-GLASS MODULE EVALUATION

- SURVEY GLASS MANUFACTURERS
- DESIGN AND ESTIMATE INSTALLED COSTS FOR CURVED GLASS MODULES AND SUPPORT STRUCTURES
- PERFORM COMPUTER AIDED STRESS ANALYSIS OF CURVED GLASS SHEET
- DEVELOP TEST PLAN

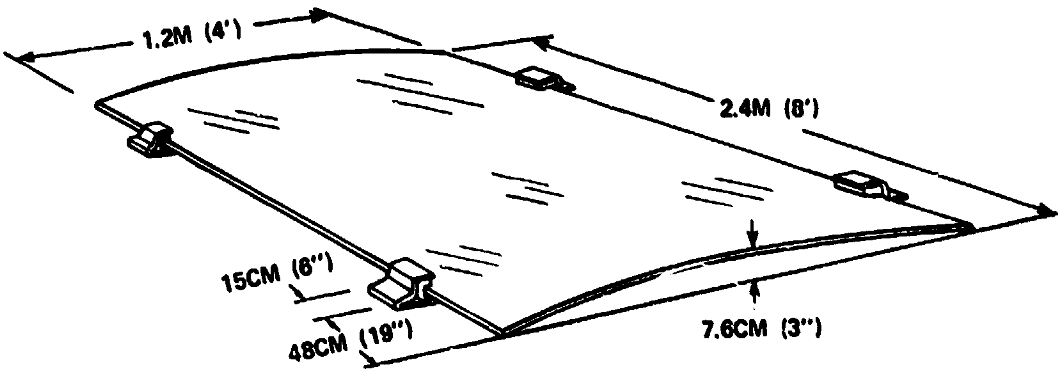
TASK 8: VOLTAGE ISOLATION DESIGN REQUIREMENTS

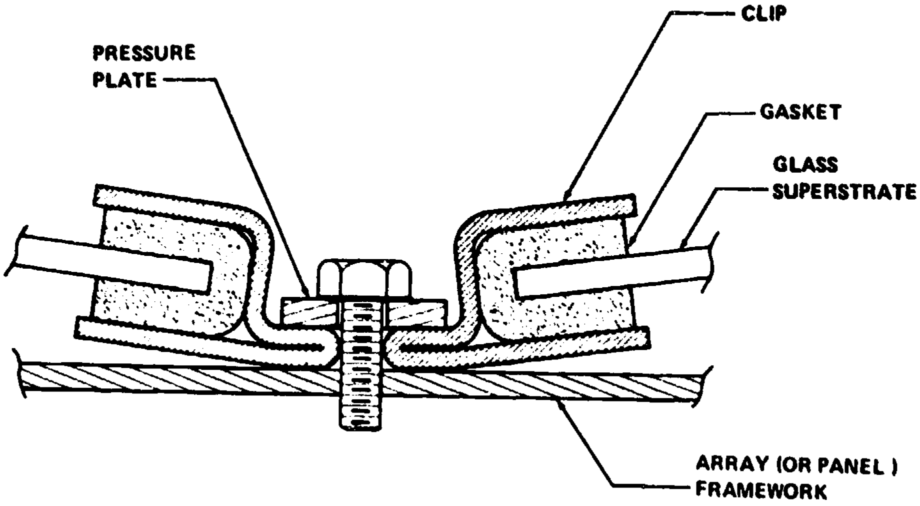
- REVIEW EXISTING INDUSTRY PRACTICE
- CORRELATE SHORT-TERM TESTS AND FIELD EXPERIENCE
- CATALOG IMPORTANT MATERIAL PROPERTIES
- ESTABLISH DESIGN GUIDELINES
- IDENTIFY AREAS REQUIRING FURTHER STUDY

GLASS SUPERSTRATE MODULE CONCEPTS



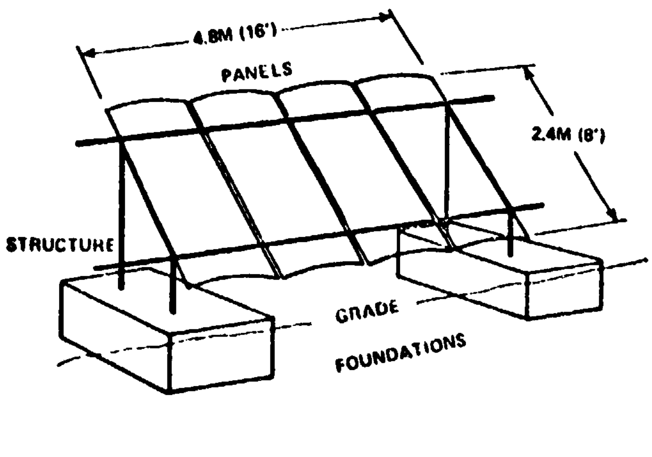
CURVED-GLASS MODULE

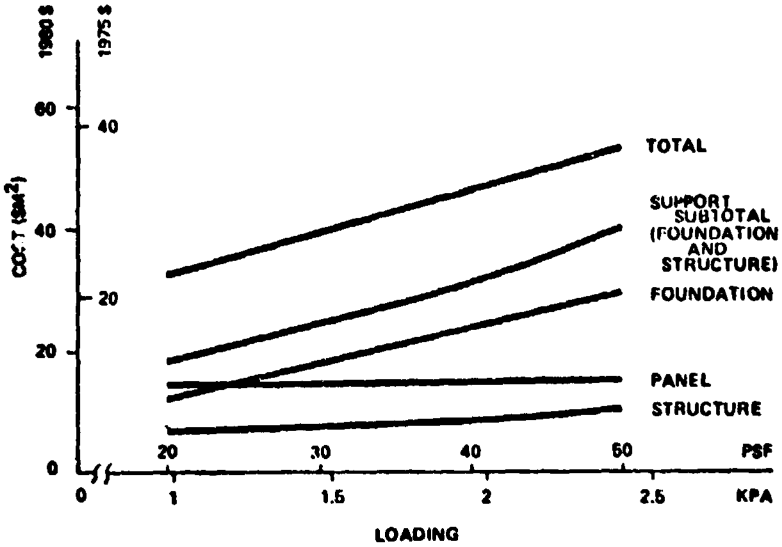




MODULE SUPPORT CLIP

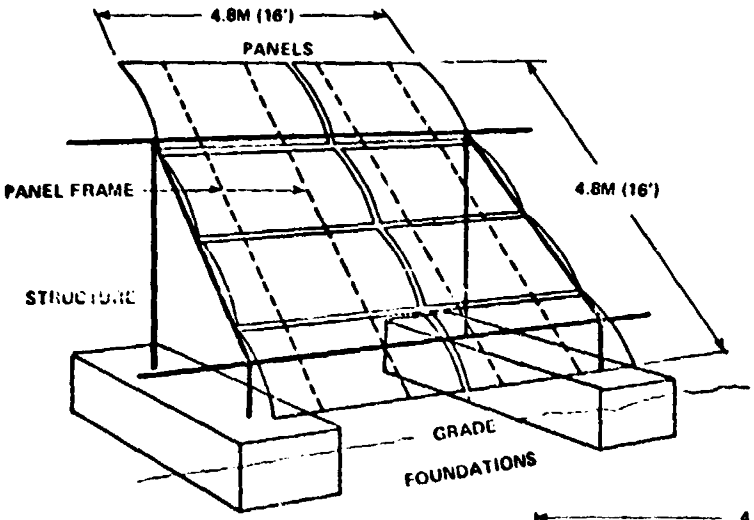
CASE 10 ARRAY

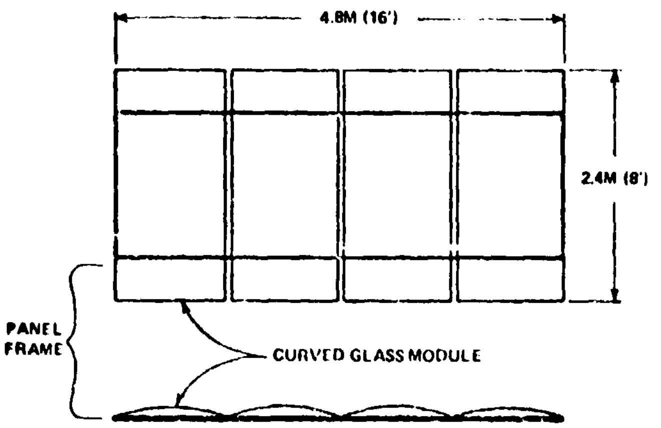




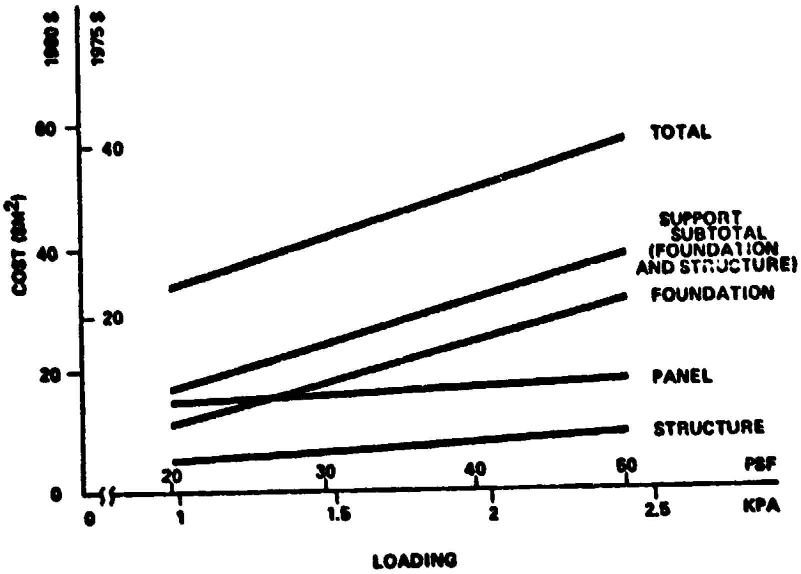
CASE 10 ARRAY COSTS

CASE 11 ARRAY



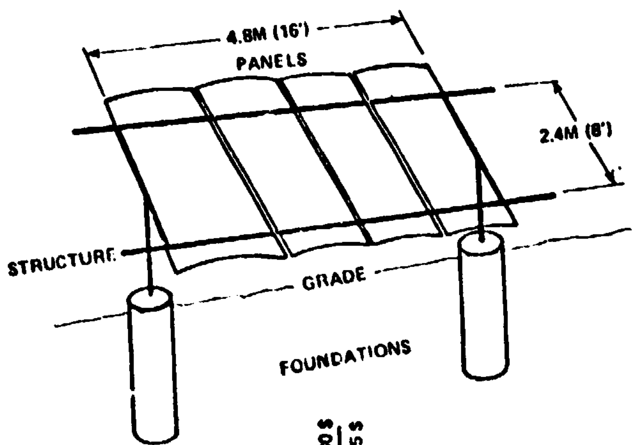


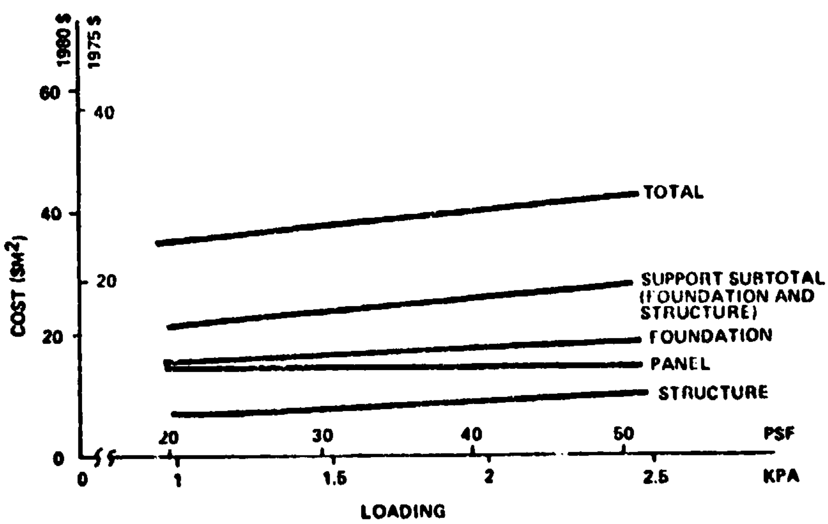
CASE11 PANEL CONFIGURATION



CASE 11 ARRAY COSTS

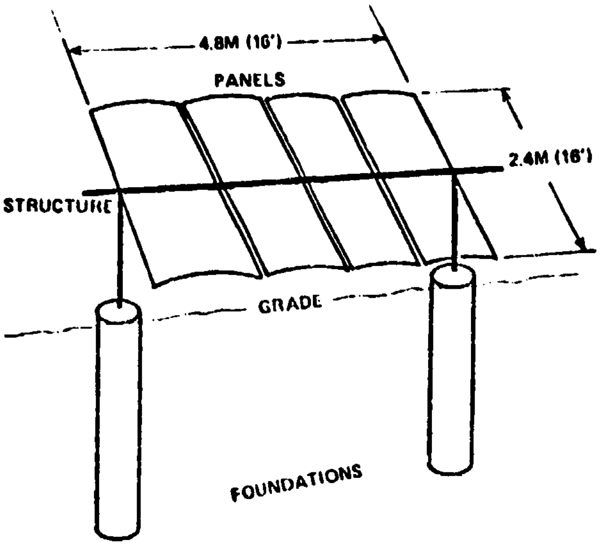
CASE 12 ARRAY

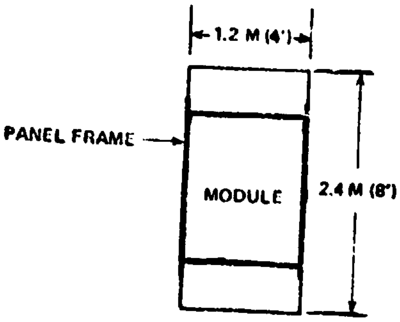


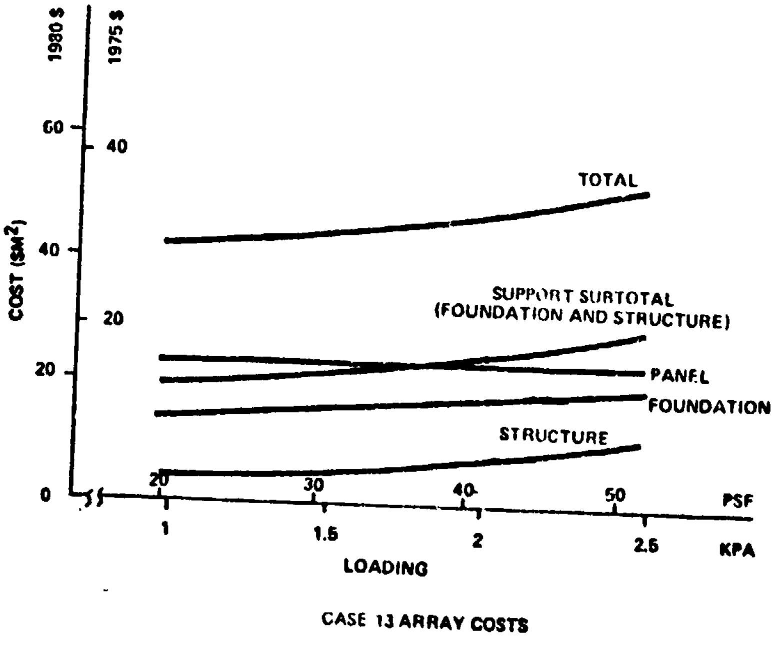


CASE 12 ARRAY COSTS

CASE 13 ARRAY

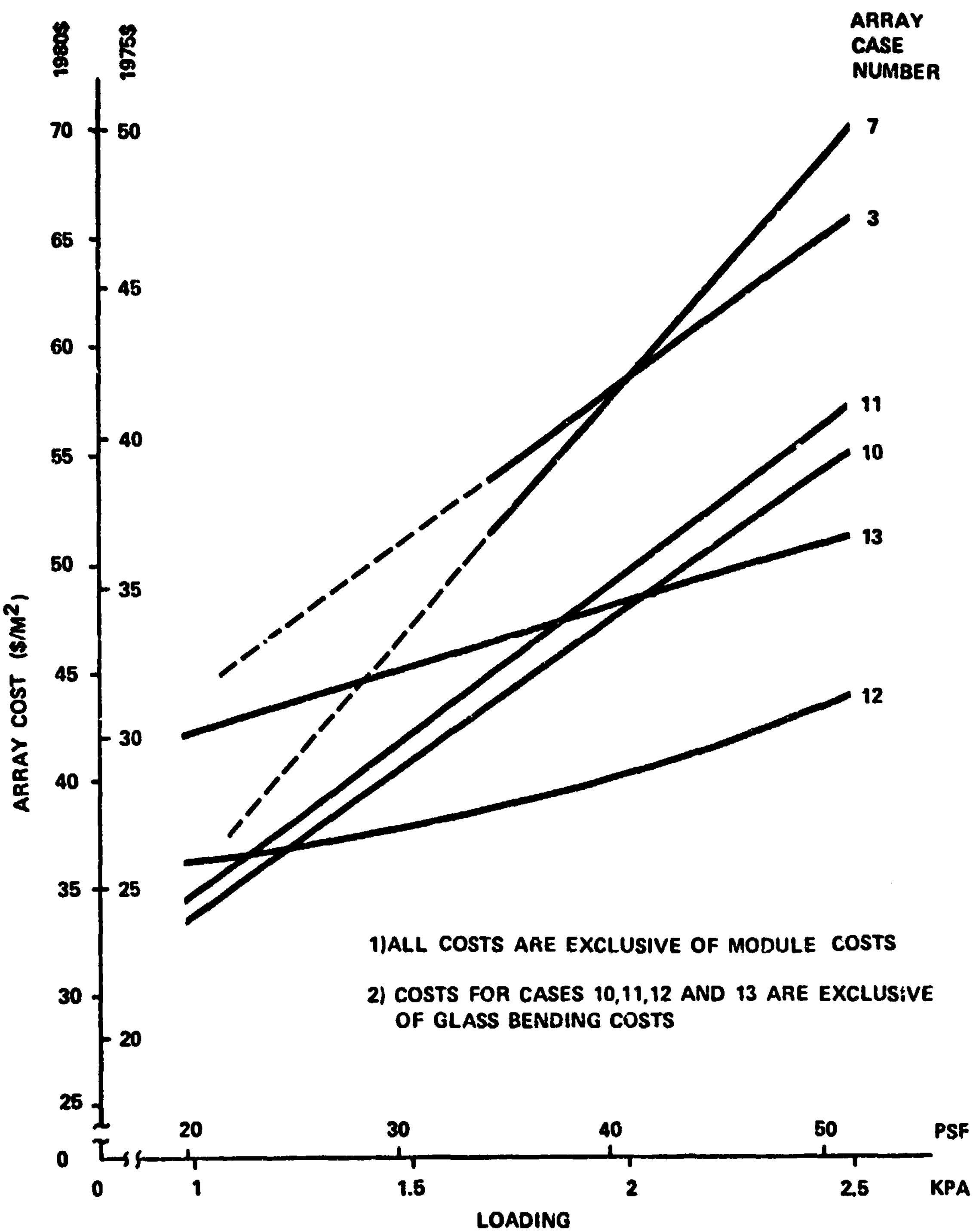




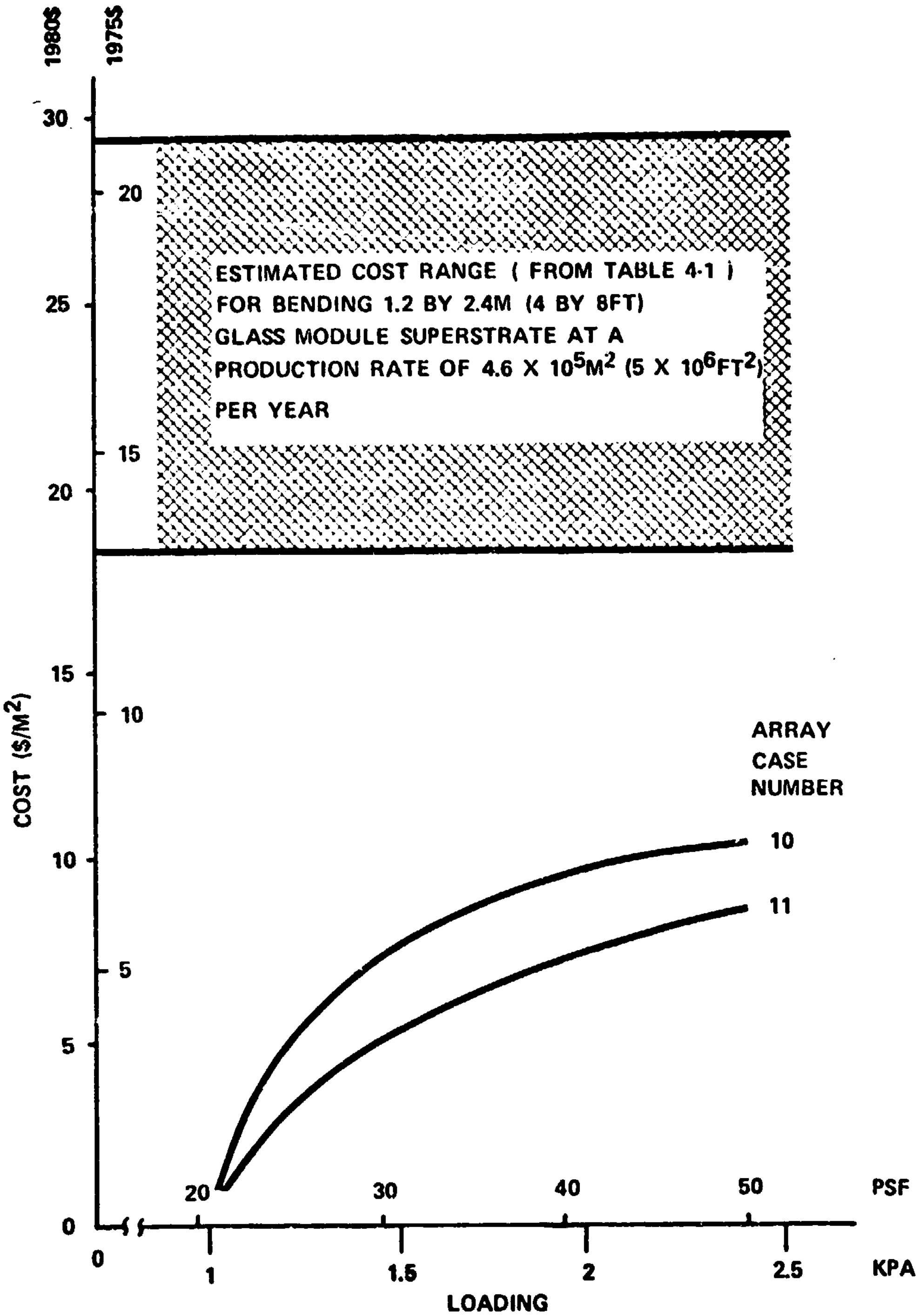


CASE 13 ARRAY COSTS

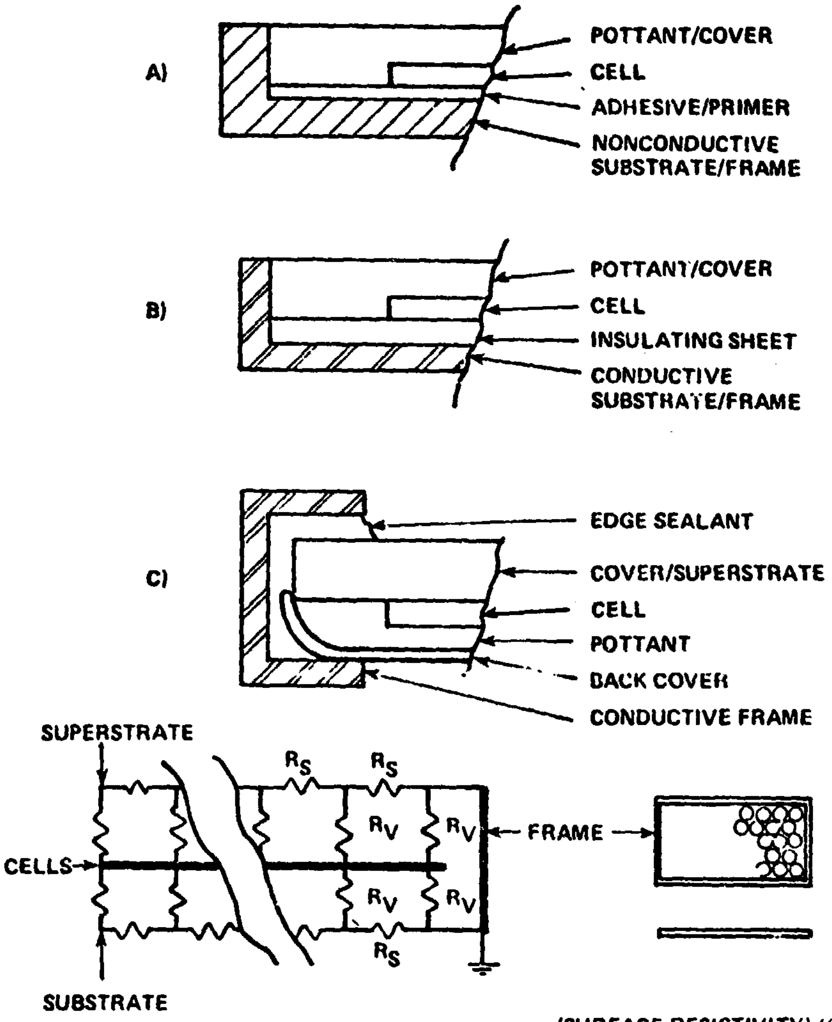
ARRAY COST COMPARISON



ALLOWABLE GLASS BENDING COSTS



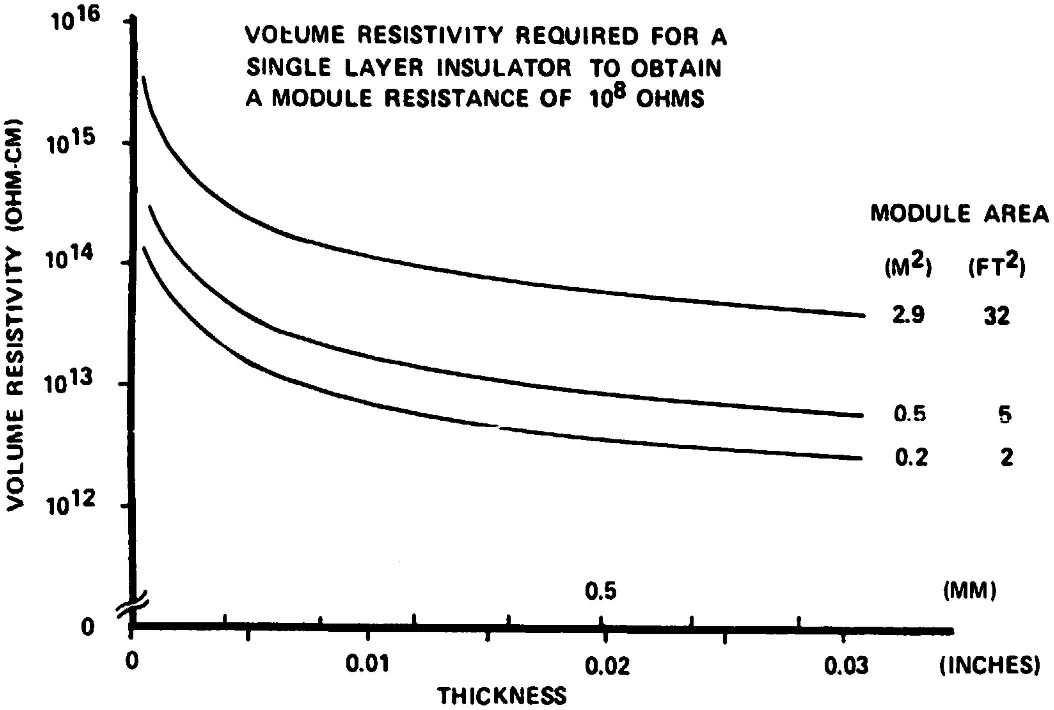
MODULE INSULATION CONFIGURATIONS



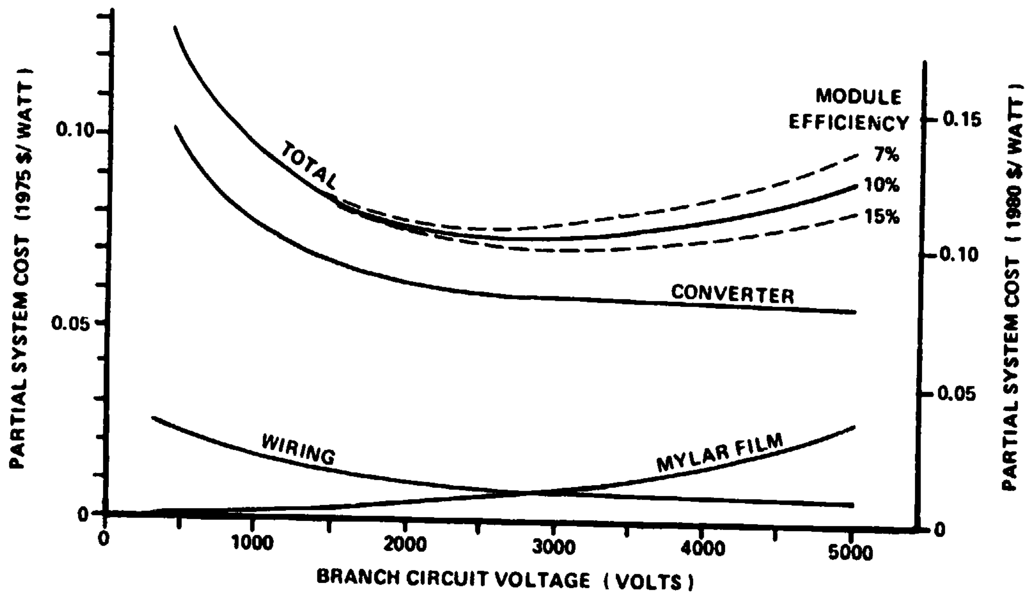
R_S – ELEMENT OF SURFACE RESISTANCE $= \frac{\text{(SURFACE RESISTIVITY) (GAP LENGTH)}}{\text{(ELEMENT PERIMETER)}}$

R_V – ELEMENT OF VOLUME RESISTANCE $= \frac{\text{(VOLUME RESISTIVITY)(THICKNESS)}}{\text{(ELEMENT AREA)}}$

ELECTRICAL ISOLATION REQUIREMENTS



VOLUME RESISTIVITY REQUIREMENTS



COST SENSITIVITY TO VOLTAGE

ELECTRICAL ISOLATION DESIGN CONCLUSIONS

- EXISTING INFORMATION RELATES PRIMARILY TO INSULATION IN AC FIELDS.
- MAXIMUM STRESS LEVELS MUST BE KEPT WELL BELOW MEASURED SHORT-TIME BREAKDOWN VALUES.
- DESIGN EVALUATION MUST CONSIDER:
  - SHORT TERM MATERIAL CHARACTERISTICS
  - EFFECTS OF AGEING ON MATERIAL CHARACTERISTICS
  - EFFECTS OF CONFIGURATION AND CONSTRUCTION ON THE STRESS DISTRIBUTION WITHIN THE ENCAPSULATING MATERIALS
- SHORT-TIME TESTS DO NOT SUBJECT THE MODULE TO THE EFFECTS OF AGEING ENCOUNTERED IN SERVICE AND ARE OF LIMITED USE IN PREDICTING LONG TIME PERFORMANCE
- REAL TIME TESTING UNDER ACTUAL OPERATING CONDITIONS IS NECESSARY TO VERIFY INSULATION DESIGN INTEGRITY

ACCELERATED SUNLIGHT AGING OF SILICON SOLAR CELL MODULES

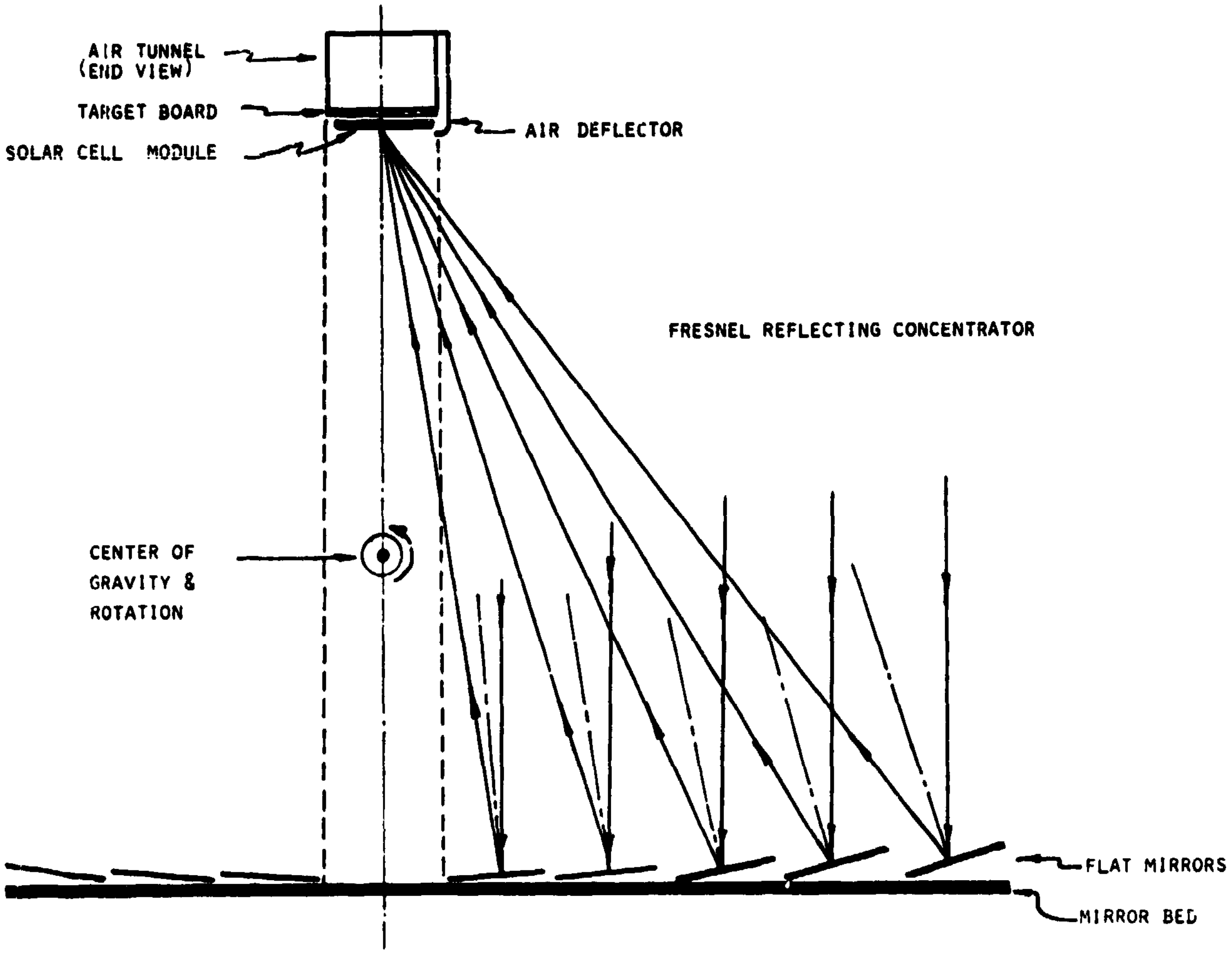
DSET LABORATORIES, INC.

EMMAQUA TESTING

- EMMAQUA® IS SERVICE MARK OF DSET LABORATORIES, INC.
- EMMAQUA® TEST MACHINE = EQUATORIAL MOUNT WITH MIRRORS FOR ACCELERATION
  = FRESNEL REFLECTING CONCENTRATOR
  = ACCELERATED WEATHERING DEVICE
- 3 MONTHS EMMAQUA® TESTING ≈ 2 1/2 YEARS FLORIDA FOR MOST MATERIALS

- 220 EMMA(QUA)® TEST MACHINES IN OPERATION AT NEW RIVER, ARIZONA
- 1800 UNIT-YEARS EXPERIENCE WITH EMMA(QUA)® TEST MACHINES AT DSET

OPTICAL SYSTEM



CONTROL OF MODULE TEMPERATURE ON SUPER-MAQ

GOAL: TESTING AT CELL TEMPERATURES OF NOCT + 10°C OR LESS

TEMPERATURE HISTORICALLY CONTROLLED (REDUCED) BY:

- BAFFLING
- VENTING TARGET BOARD DIRECTLY UNDER SPECIFIC MODULES
- DEFLECTOR ADJUSTMENT
- MODULE MODIFICATION (AT DSET)

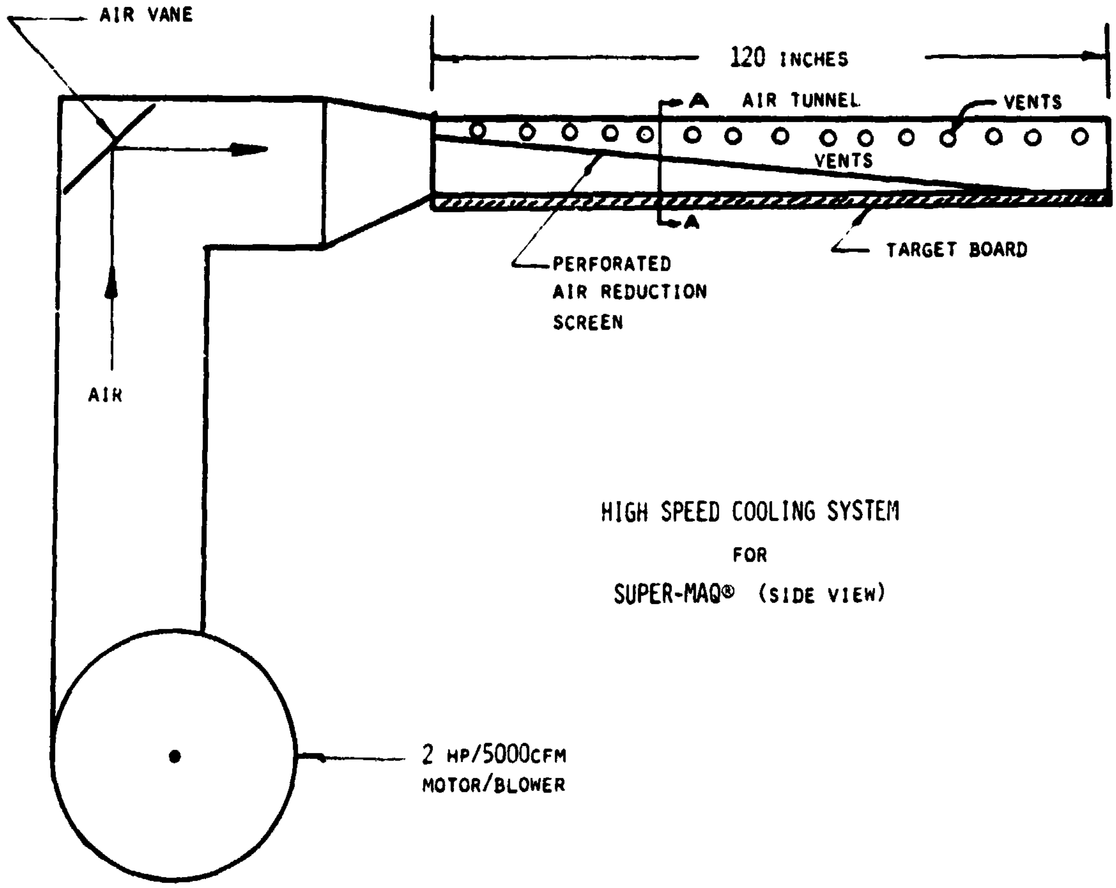
NEW MODULES (BLOCK III) REQUIRED:

- ADDITION OF LARGE BLOWER/PLENUM ~ 5000 CFM

FUTURE OPTIONS (ADDITIONAL TECHNIQUES IF REQUIRED):

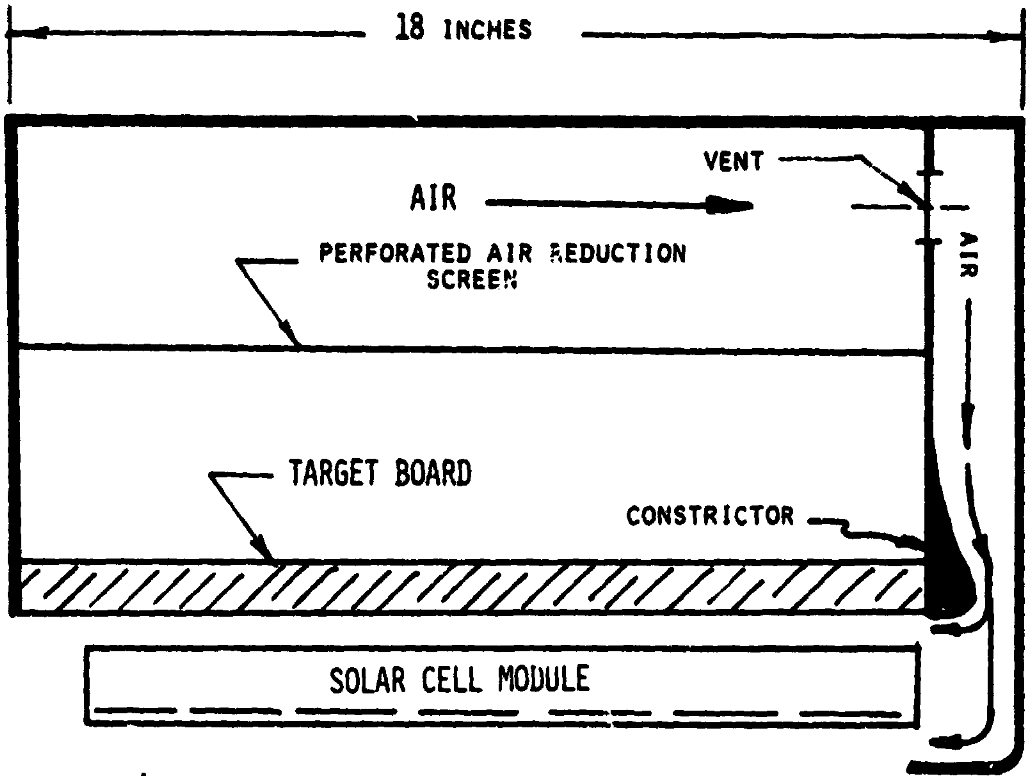
- REFRIGERATION COOLING AIR IN PLENUM
- EVAPORATIVE COOLING OF AIR IN PLENUM
  (NOT EFFECTIVE IN AUGUST BUT MOST NECESSARY IN JUNE/JULY)

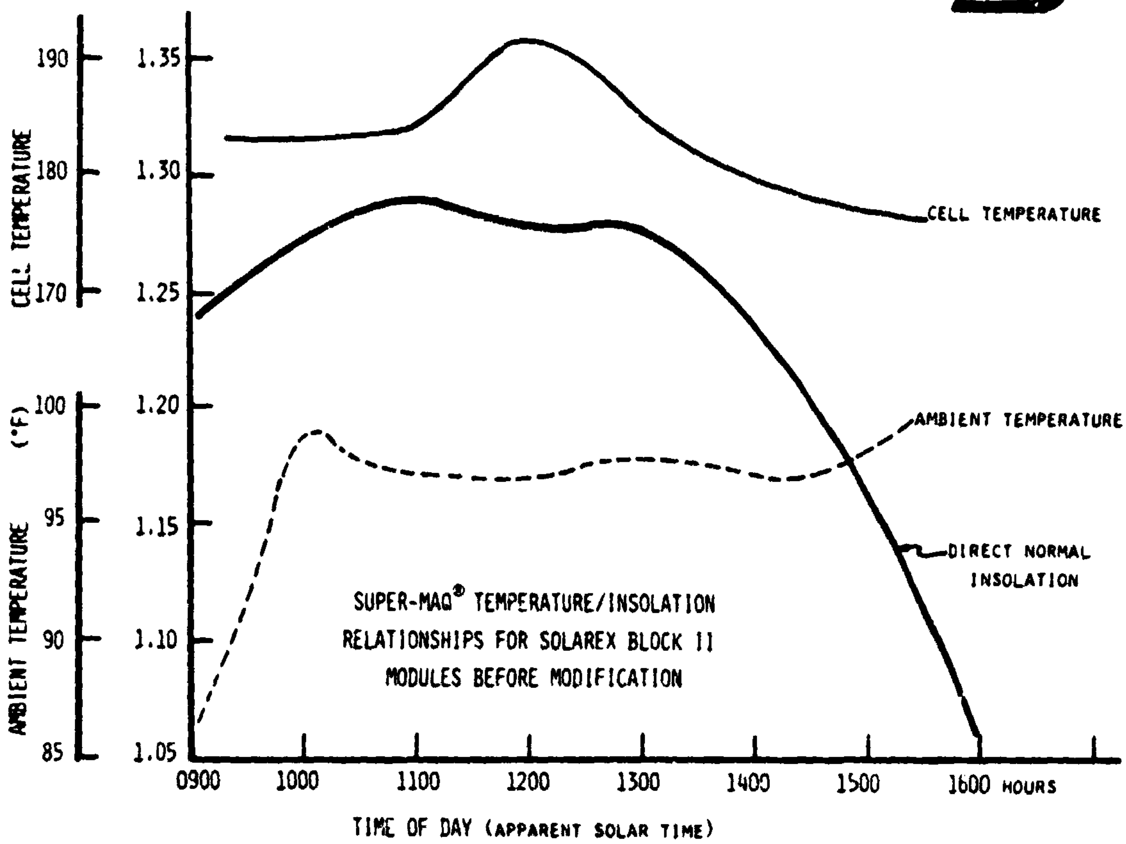
HIGH-SPEED COOLING SYSTEM (SIDE VIEW)



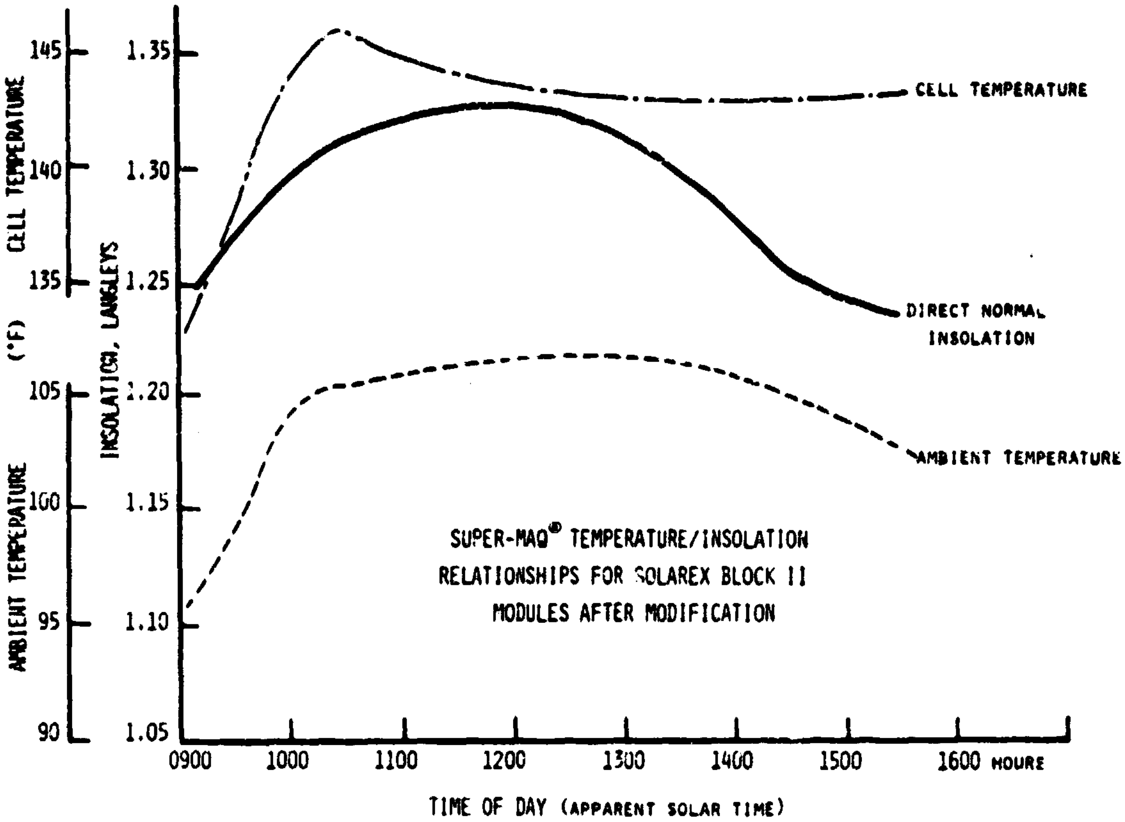
HIGH SPEED COOLING SYSTEM
FOR
SUPER-MAQ® (SIDE VIEW)

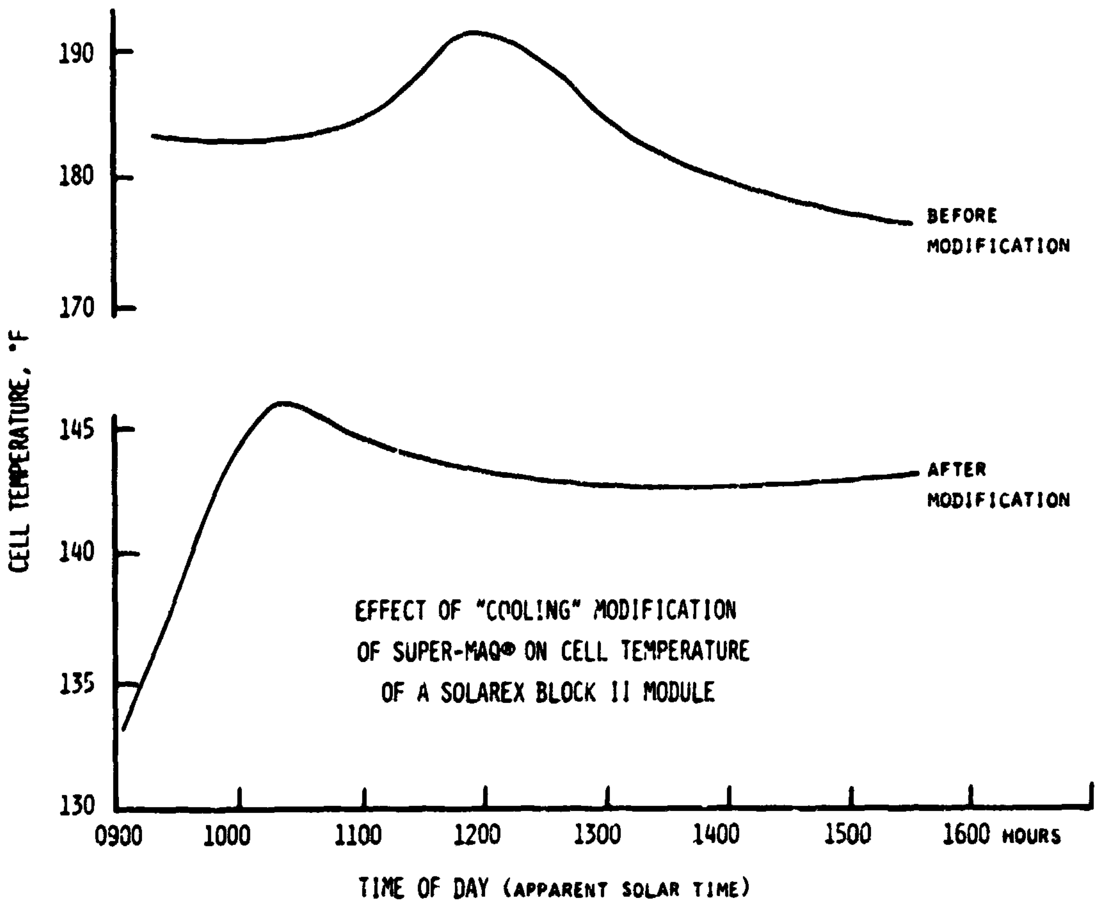
CROSS-SECTION A-A OF WIND TUNNEL

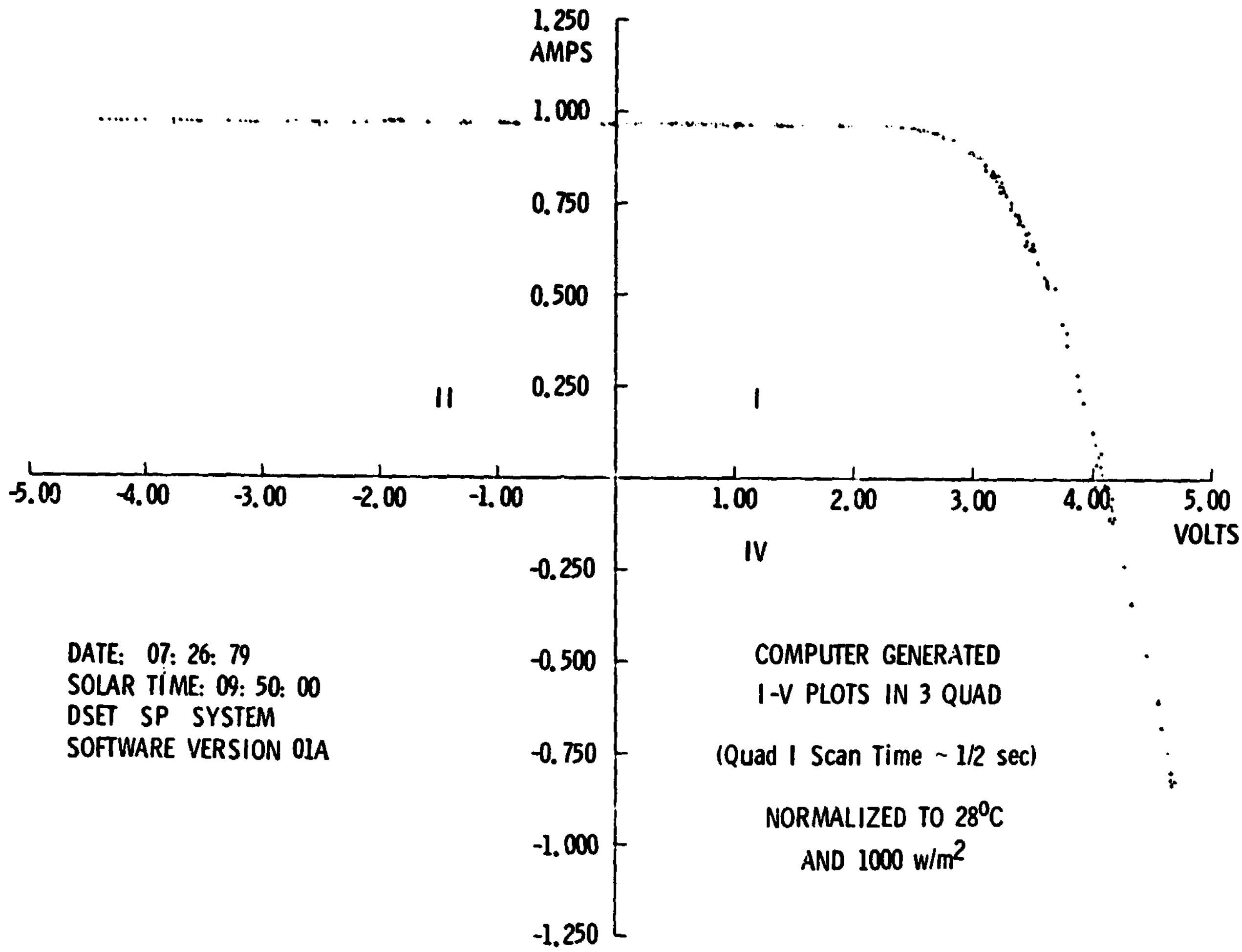




SUPER-MAQ® TEMPERATURE/INSOLATION RELATIONSHIPS FOR SOLAREX BLOCK II MODULES BEFORE MODIFICATION


CELL TEMPERATURE
INSOLATION, LANGLEYS
AMBIENT TEMPERATURE (°F)
CELL TEMPERATURE
DIRECT NORMAL INSOLATION
AMBIENT TEMPERATURE
SUPER-MAQ® TEMPERATURE/INSOLATION RELATIONSHIPS FOR SOLAREX BLOCK II MODULES AFTER MODIFICATION
TIME OF DAY (APPARENT SOLAR TIME)
0900 1000 1100 1200 1300 1400 1500 1600 HOURS


CELL TEMPERATURE, °F
BEFORE MODIFICATION
AFTER MODIFICATION
EFFECT OF "COOLING" MODIFICATION OF SUPER-MAQ® ON CELL TEMPERATURE OF A SOLAREX BLOCK II MODULE
TIME OF DAY (APPARENT SOLAR TIME)
0900 1000 1100 1200 1300 1400 1500 1600 HOURS



NORMALIZED DATA

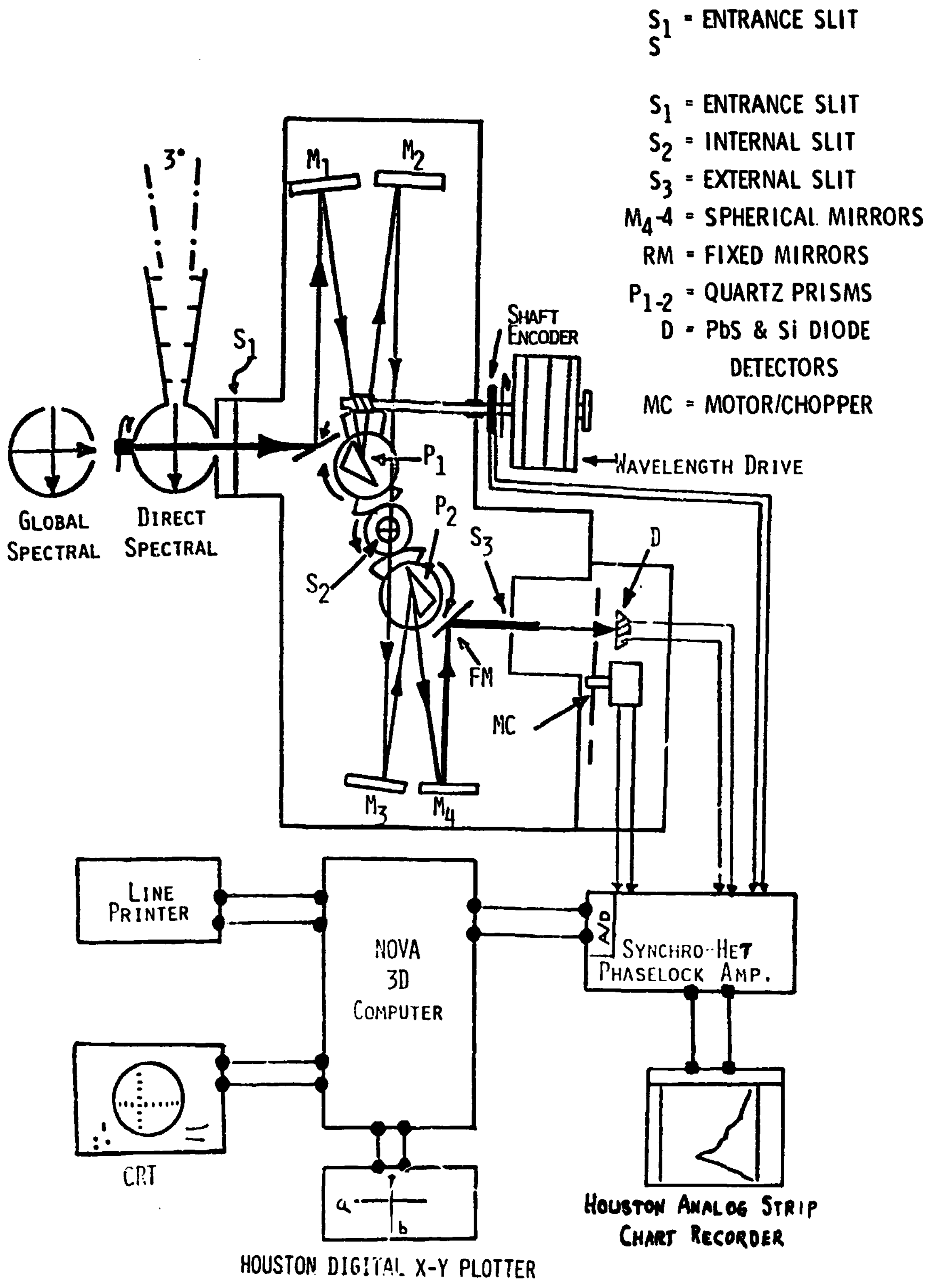
DSET *:	ARNET		IT (PSP)	924.0	W/M**2
COMPANY:	QUALITY CONTROL, INC.		VOC:	4090.3	MV
MODULE:	MODULE, LG		ISC:	965.4	MA
SERIAL *:	SERIAL -- QC		V (P MAX):	3074.0	MV
T CELL:	94.00	OF	I (P MAX):	875.3	MA
T AMB:	100.00	OF	P MAX:	2690.9	MW

EXPOSURE RESPONSE HISTORY OF BLOCK II MODULES

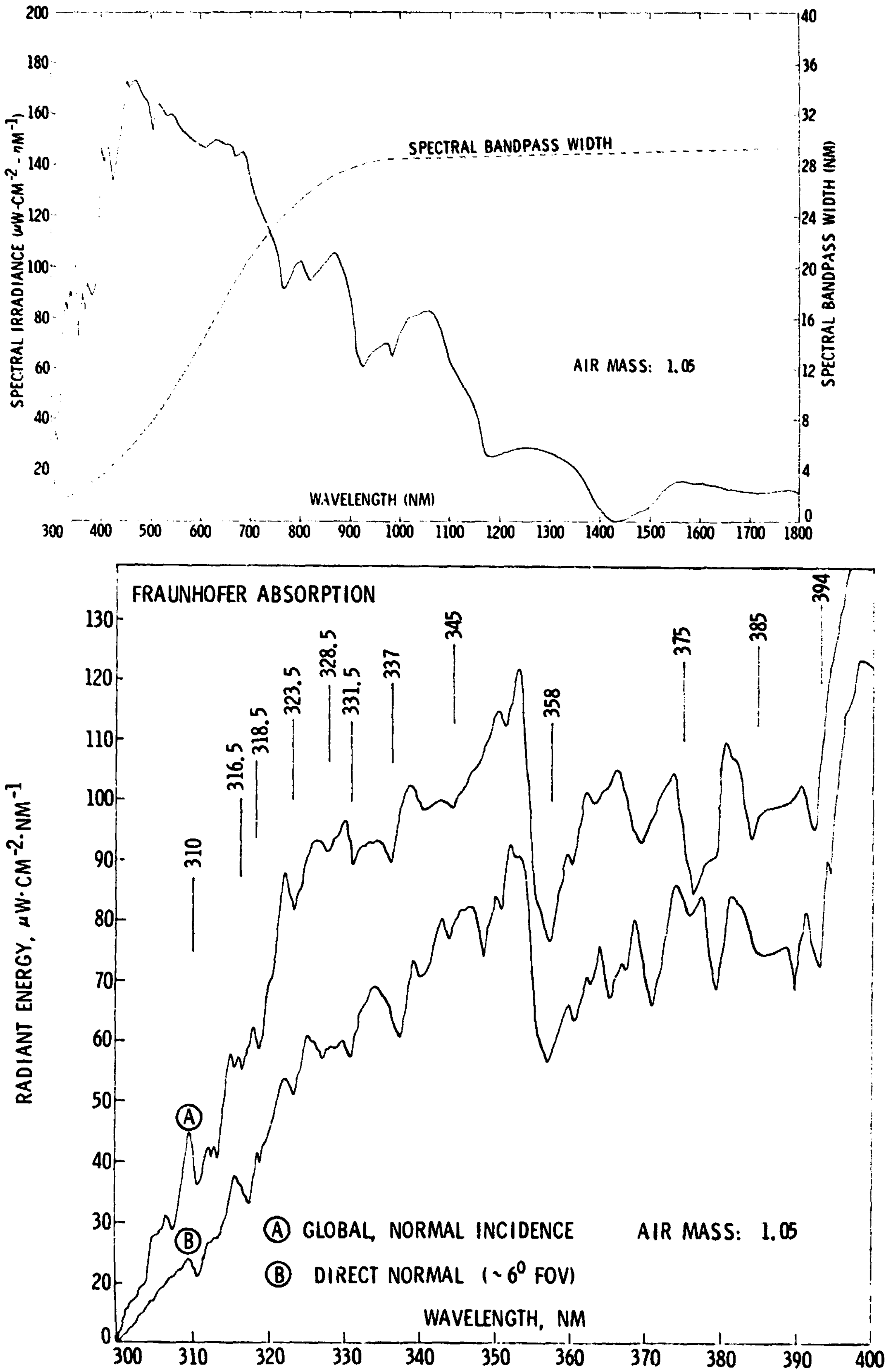
MODULE	SN		INITIAL	EXPOSURE, KLYS 955	1,245	1,418	REMARKS
SILICONE	021	I_{sc}	1.43	1.34	1.28	1.27	YELLOWING OF INTERCONNECTS &
RUBBER		V_{oc}	6.71	6.93	6.59	6.53	SUBSTRATE. MODERATE WATER SPOTTING
ENCAP., POLYESTER	024	I_{sc}	1.48	1.37	1.31	1.31	SLIGHT DIRT RETENTION.
SUBSTRATE		V_{oc}	6.77	6.96	6.66	6.60	
SILICONE	002	I_{sc}	0.52	0.50	0.47	0.34	MODERATE DIRT RETENTION & WATER
RUBBER		V_{oc}	13.43	13.77	13.16	13.19	SPOTTING. SLIGHT HAZE OF ENCAPSULANT.
ENCAP., ALUMINUM	058	I_{sc}	0.58	0.54	0.51	0.49	TERMINAL DISCOLORATION.
SUBSTRATE		V_{oc}	13.44	13.42	13.25	13.33	
SILICONE	826	I_{sc}	2.19	(TERMINATED 8/7/78)			EXTENSIVE DELAMINATION (SWELLING);
RUBBER		V_{oc}	4.71	("	")		CRACKED CELLS
ENCAP., MOLDED	828	I_{sc}	2.21	0.39	0.41	0.23	DELAMINATION OF ENCAPSULANTS; YELLOWING
POLYESTER SUBSTRATE		V_{oc}	4.76	5.15	4.65	5.54	CRACKED CELL. WATER SPOTTING.
GLASS	028	I_{sc}	2.02	0.62	(TERMINATED 8/7/78)		SEVERE CARBONATION; CRACKED GLAZING,
SUPERSTRATE,		V_{oc}	5.04	4.80	("	")	WHITE & YELLOW HAZE EXTENSIVE
PVB/ MYLAR	042	I_{sc}	2.03	1.81	1.71	1.65	CARBONATION; SLIGHT WATER SPOTTING;
LAMINATE		V_{oc}	4.96	5.12	4.55	4.54	YELLOWING OF INTERCONNECTS.
			EXP.	807	1,098	1,271	KLYS
			EQUIVALENT YEARS =	5	6-1/2	7-1/2	YEARS
			EXCEPT V =	4-1/4	5-3/4	6-3/4	YEARS

FY80 PLANS

- CONTINUE SUPER-MAQ® EXPOSURE OF BLOCK III MODULES
- CONTINUE TEMPERATURE CONTROL STUDIES (BELOW NOCT NOT DESIRABLE)
- PERFORM DETAILED SPECTRAL MEASUREMENTS AT DSET AND ELSEWHERE
- INITIATE REAL TIME EXPOSURE OF BLOCK III MODULES
- IMPLEMENT MULTIPLE STANDARD CELL REFERENCES



S1 = ENTRANCE SLIT
S
S1 = ENTRANCE SLIT
S2 = INTERNAL SLIT
S3 = EXTERNAL SLIT
M4-4 = SPHERICAL MIRRORS
RM = FIXED MIRRORS
P1-2 = QUARTZ PRISMS
D = PbS & Si DIODE DETECTORS
MC = MOTOR/CHOPPER
3°
M1
M2
S1
SHAFT ENCODER
P1
WAVELENGTH DRIVE
GLOBAL SPECTRAL
DIRECT SPECTRAL
P2
S3
D
S2
FM
MC
M3
M4
LINE PRINTER
NOVA 3D COMPUTER
A/D
SYNCHRO-HET PHASELOCK AMP.
CRT
HOUSTON DIGITAL X-Y PLOTTER
HOUSTON ANALOG STRIP CHART RECORDER


SPECTRAL IRRADIANCE (μW-CM-2-nM-1)
SPECTRAL BANDPASS WIDTH
SPECTRAL BANDPASS WIDTH (NM)
AIR MASS: 1.05
WAVELENGTH (NM)
FRAUNHOFER ABSORPTION
310
316.5
318.5
323.5
328.5
331.5
337
345
358
375
385
394
RADIANT ENERGY, μW·CM-2·NM-1
Ⓐ GLOBAL, NORMAL INCIDENCE
AIR MASS: 1.05
Ⓑ DIRECT NORMAL (~6° FOV)
WAVELENGTH, NM

WIND TUNNEL TESTING OF COLLECTOR ARRAYS

SANDIA LABORATORIES

HAL POST

- Low-Cost Structures Studies
  - Loading Criteria
  - Wind Loading Cost Sensitivity
- Wind Tunnel Tests
  - Flat Panel Collectors
  - Parabolic Trough Collectors
- Wind Loading Standards
  - Loading Comparison

LOW-COST STRUCTURES STUDIES

- Contractors : Bechtel National and Motorola
- Status : Studies completed
- Study emphasis : Ground mounted, flat panel collectors for large intermediate and central station applications
- Design criteria : Detailed loading and acceptance criteria; designs based on present design standards
- Wind loading : Bechtel--24 psf net
  Motorola--50 psf combined
- Detailed structure/foundation designs : 22

- COSTING : COSTS INCLUDE SITE PREPARATION, FOUNDATION EARTHWORK, MATERIALS, SUPPORT STRUCTURE INSTALLATION, AND FIELD CONSTRUCTION; COSTS EXCLUDE PV MODULES AND PANEL FRAMEWORK

- COST RANGE : MAJORITY OF DESIGNS IN \$ 20-35/M^2 (1975\$) RANGE

- COST SENSITIVITY TO WIND LOADING

SUPPORT SYSTEM	WIND LOADING VARIATION	COST INCREASE
CAISSON FOUNDATION/ FULL FRAME	24-53 PSF	\$0.52/M^2/PSF
CONTINUOUS FOOTING/ FULL FRAME	24-53 PSF	\$0.54/M^2/PSF

- MAJOR CONCERN : WIND LOADING UNCERTAINTIES

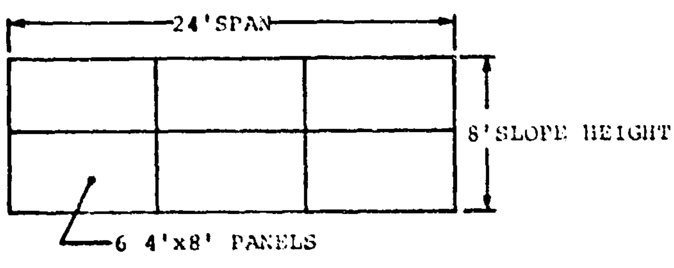
FLAT-PANEL WIND TUNNEL TESTS

- SANDIA CONTRACTOR - BECHTEL NATIONAL

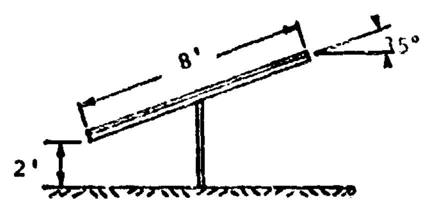
- TEST FACILITY - METEOROLOGICAL WIND TUNNEL
  COLORADO STATE UNIVERSITY
  FORT COLLINS, CO

- STATUS - TESTING COMPLETED 8/14/79; DATA REPORT DUE EARLY SEPTEMBER

- COLLECTOR ARRAY CONFIGURATION (FULL SCALE)



PLAN VIEW



END VIEW

TEST MATRIX

SINGLE ARRAY

- BOUNDARY LAYER : $(z/z_0)^{.14}$, $(z/z_0)^{.26}$, AUG TURB
- MODEL SCALE SIZE : 1:12, 1:24, 1:48
- SLOPE ANGLE : 25°, 35°, 45°, 90°
- GROUND CLEARANCE : 0, 1, 2, 3, 4, 5 FT
- PANEL POROSITY : 0, 2.5, 5, 10 %
- ASPECT RATIO : 2, 3, 4
- SLOPE HEIGHT : 4, 8, 16 FT
- WIND YAW ANGLE : 0 - 180°, 15° INCREMENTS
- FENCE STUDY : HEIGHT - 2,4,5,6,8 FT
  DISTANCE - 15,20,30, 40 FT
  POROSITY - 0,30,50 %

ARRAY FIELD

- FIELD SIZE : 3 ARRAYS PER ROW, 9 ROWS
- ROW SPACING : 14.6 FT, CENTER TO CENTER
- WIND DIRECTION : TOWARD ARRAY FRONT, BACK, YAW VARIATIONS
- FENCE : WITH AND WITHOUT
- FENCE CORNER EFFECTS : WITH AND WITHOUT MODIFICATION
- DATA ARRAYS : INTERNAL FIELD - ROWS 1,2,4,7
  EDGE FIELD - ROWS 1,2,4,7
  ROW SPACES - ROW 7 (ROWS 6,8,9 REMOVED)

PRELIMINARY RESULTS

- MODEL SCALES 1:12 AND 1:24 SHOW STABLE RESULTS, EXCELLENT AGREEMENT; MODEL SCALE 1:48 TOO SMALL
- TEST DATA SHOW NO EFFECT OF REYNOLDS NUMBER VARIATIONS
- MAXIMUM NORMAL FORCE ON 35° ARRAY OCCURS AT A WIND YAW ANGLE OF 45°; NORMAL FORCE APPROXIMATELY 15 % HIGHER THAN AT YAW ANGLE OF 0°

- As panel porosity increases from 0 to 10 %, normal force decreases by approximately 5 to 10 %
- As array height above ground increases from 2 to 5 ft, normal force increases approximately 10 to 15 %
- Aspect ratio variations show no significant effect on the data
- For a 5-ft fence of 30 % porosity located 20 ft from array :

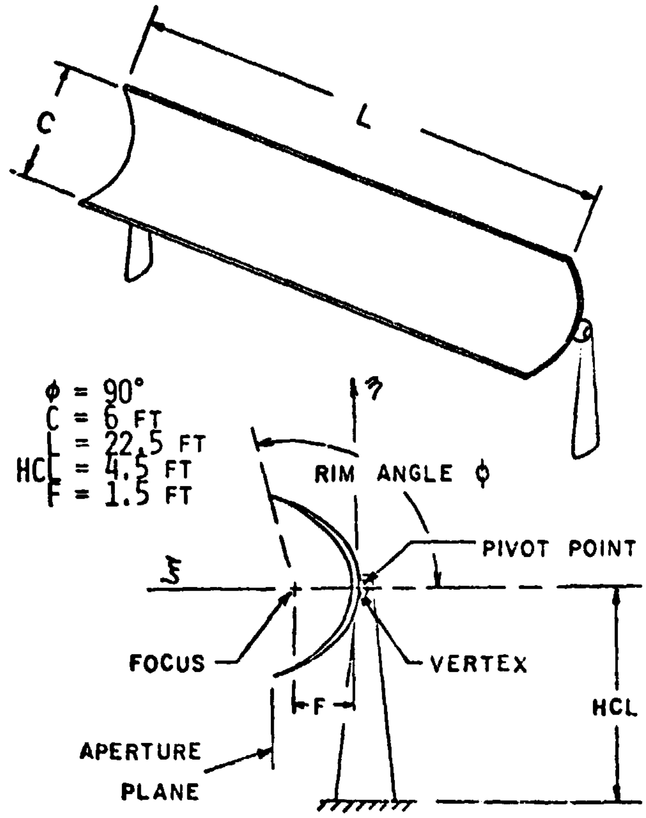
Wind Direction	Results
Normal, yaw = 0°	75 % decrease in array forces
Yaw = 45°	40 % decrease in array forces

- Qualitatively, array field tests show pronounced sheltering effects due to adjacent arrays; data reduction in progress

PARABOLIC-TROUGH WIND TUNNEL TESTS

- Sponsor - Sandia Laboratories
- Test Facility - Meteorological Wind Tunnel
  Colorado State University
  Fort Collins, CO
- Status - Testing completed July 1979; final report in preparation

• Collector Array Configuration (Full Scale)



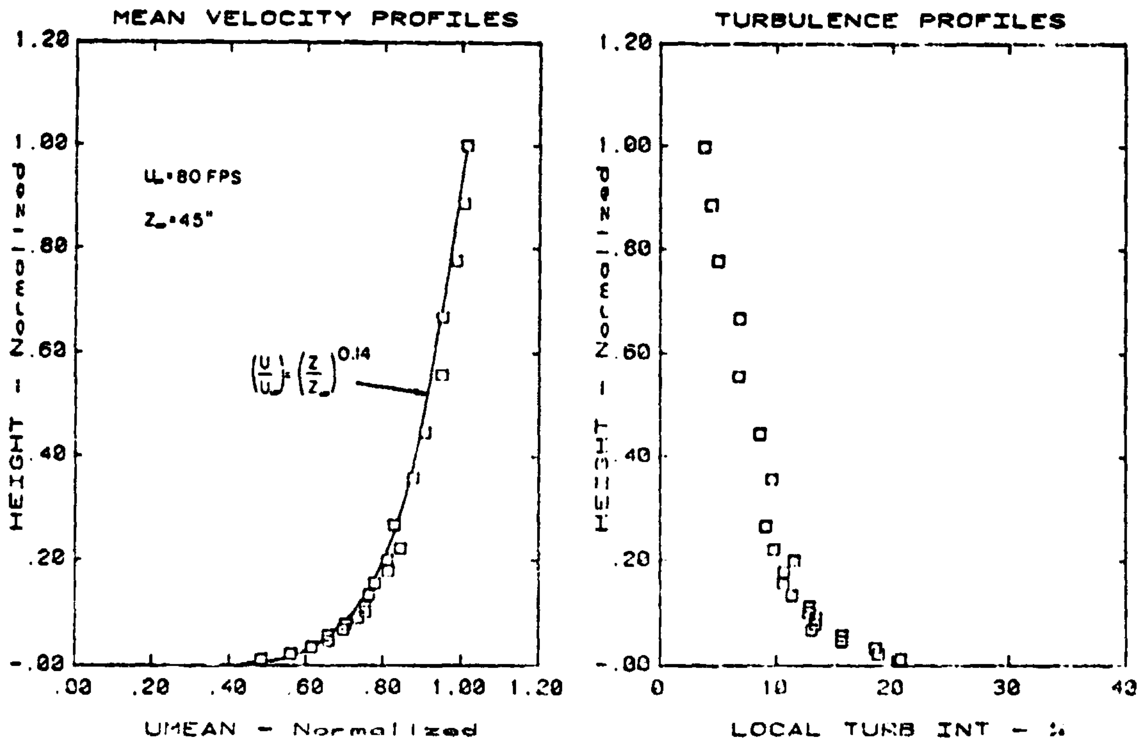
TEST MATRIX

Single Array

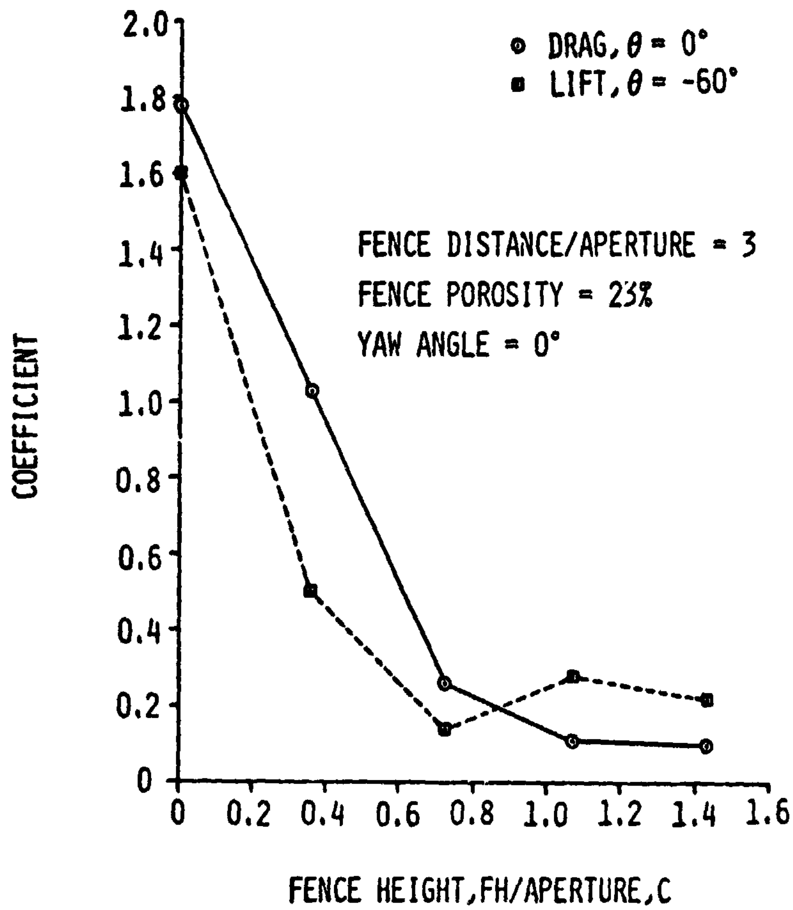
- Boundary layer : $(z/z_0)^{.14}$
- Model scale size : 1:25
- Rim angles : 40°, 65°, 90°, 120°
- Collector height : HCL/C = 0.6 - 2.0, 0.75
- Wind yaw angle : -15° to 60°
- Collector pitch angle : -135° to 180°

ARRAY FIELD

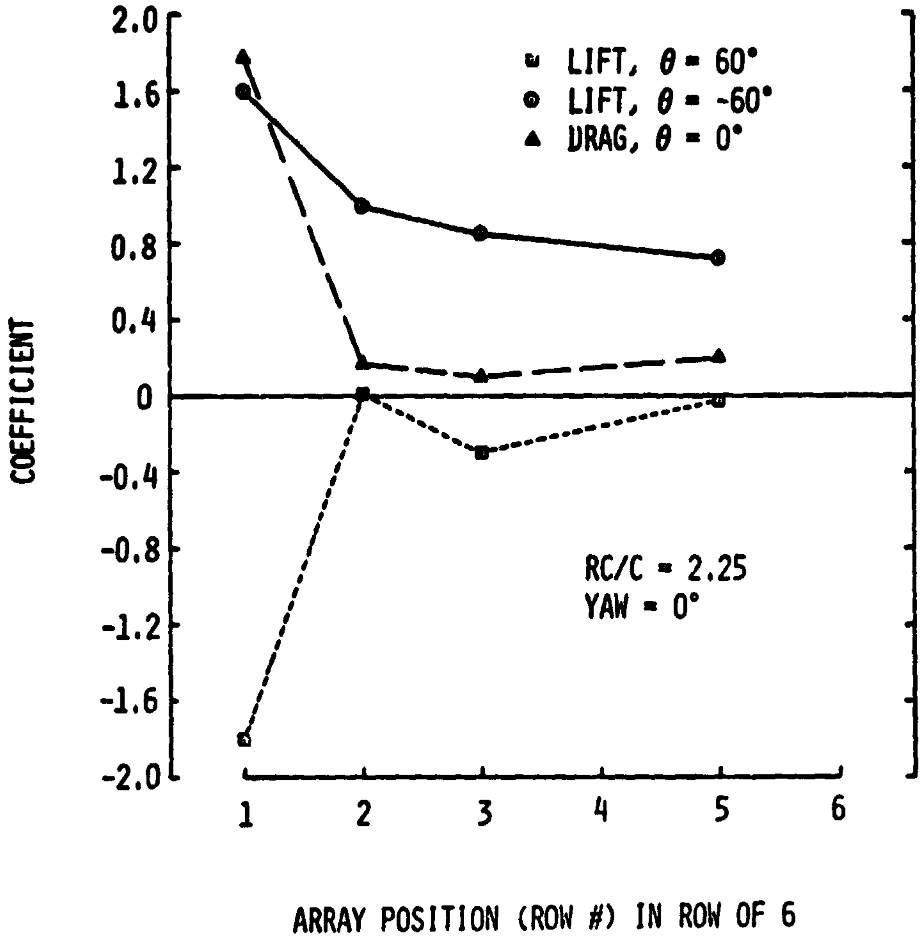
- FIELD SIZE : 3 ARRAYS PER ROW, 6 ROWS
- ROW SPACING : R/C = 2.0, 2.25, 2.5, 3.0
- GAP SPACING : G/C = 0.06 - 3.6, 0.54
- FENCE STUDY : HEIGHT, FH/C = .36,.71,1.07,1.43
POROSITY - 23%
DISTANCE, FS/C = 2,3,5
- BERM STUDY : HEIGHT, FH/C = .36,.71,1.07
DISTANCE, FS/C = 3
- COLLECTOR TORQUE TUBE : WITH AND WITHOUT
- DATA ARRAYS : INTERNAL FIELD - ROWS 1,2,3,5
- COLLECTOR PITCH ANGLES : 0°,120°,180°,-60° (YAW = 0°)



FENCE SHIELDING EFFECTS



ARRAY SHIELDING EFFECTS

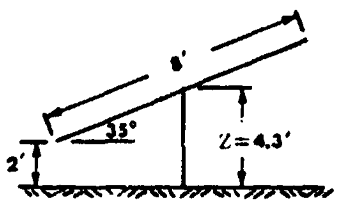


DESIGN STANDARDS FOR WIND LOADING

- ANSI A58.1-1972; "BUILDING CODE REQUIREMENTS FOR MINIMUM DESIGN LOADS IN BUILDINGS AND OTHER STRUCTURES"
  - SIGNS AND OUTDOOR DISPLAY STRUCTURES
  - MINIMUM HEIGHT 30 FT
  - LOAD REDUCTIONS DUE TO AERODYNAMIC SHIELDING SPECIFICALLY PROHIBITED

- PROPOSED REVISION TO WIND LOADING PROVISIONS OF ANSI A58
  - MUCH EASIER TO UNDERSTAND AND USE
  - MINIMUM DESIGN PRESSURE OF 15 PSF SPECIFIED
  - SPECIFICALLY ALLOWS PROPERLY CONDUCTED WIND TUNNEL TESTS FOR DETERMINATION OF DESIGN WIND LOADS
  - MINIMUM HEIGHT 15 FT
  - INCLUDES COMPREHENSIVE LISTING OF ANNUAL EXTREME FASTEST-MILE WIND SPEEDS FOR 129 U S WEATHER STATIONS

COMPARISON OF WIND-LOADING CALCULATIONS



- ALBUQUERQUE LOCATION
  - V = 83 MPH (100 YR FASTEST-MILE WIND SPEED)
  - WIND REFERENCE HEIGHT, Z_0 = 30 FT
  - SMOOTH TERRAIN

WIND LOADING USING PROPOSED REVISION TO ANSI A58.1-1972

$Q_Z = 0.00256\, K_Z V^2$

$K_Z = 0.80$ ($z < 15'$)

$Q_Z = 14.1$ PSF

$F/A = GC_N Q_Z$

GUST FACTOR, $G = 1.39$ ($z < 15'$, COMPONENTS&CLADDING)

$GQ_Z = 19.6$ PSF

$C_N = 1.10$ (INCLINED FLAT PLATE ROOFS OVER OPEN BUILDINGS)

$F/A = 21.6$ PSF

ALTERNATE CALCULATION

$V_{4.3} = V_{30}(z/z_0)^{.14} = 62.9$ MPH

$Q_{4.3} = 10.2$ PSF

$F/A = GC_N Q_{4.3}$

$G = 1.52$ ($z = 4.3'$)

$GQ_{4.3} = 15.5$ PSF

$C_N = 1.10$, $F/A = 17.0$ PSF

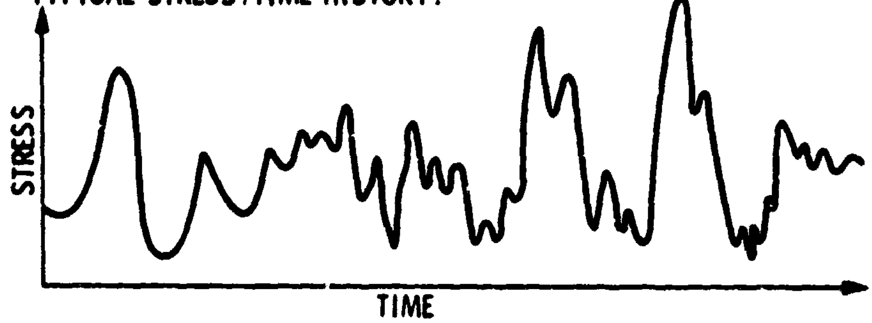
40% SHIELDING	75% SHIELDING
$F/A = 10.2$ PSF	$F/A = 4.3$ PSF

THERMAL/WIND CYCLIC LOADING ANALYSIS

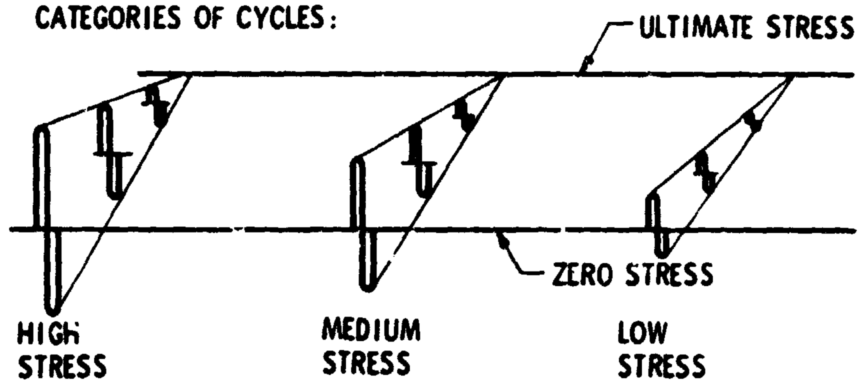
- OBJECTIVE:
  - CHARACTERIZE FATIGUE LOADING LEVEL ASSOCIATED WITH TERRESTRIAL THERMAL AND WIND ENVIRONMENTS AND DERIVE EQUIVALENT TEST ENVIRONMENTS
- APPROACH:
  - DEVELOP METHOD FOR COUNTING CYCLES
  - CHARACTERIZE ENVIRONMENTS AT VARIOUS GEOGRAPHICAL LOCATIONS
  - DETERMINE STRESS - CYCLE (FATIGUE) BEHAVIOR OF MODULES
  - DEFINE LOW-CYCLE TEST ENVIRONMENT WHICH CREATES EQUIVALENT FATIGUE LOADING ON MODULES

FATIGUE CYCLE COUNTING

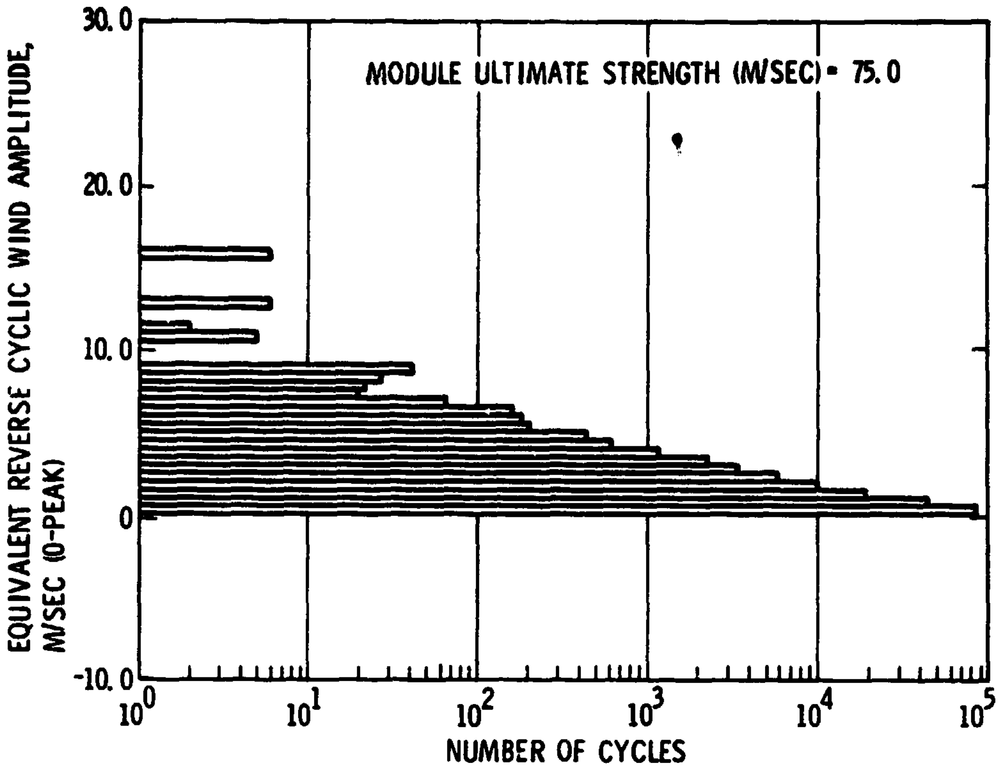
TYPICAL STRESS/TIME HISTORY:



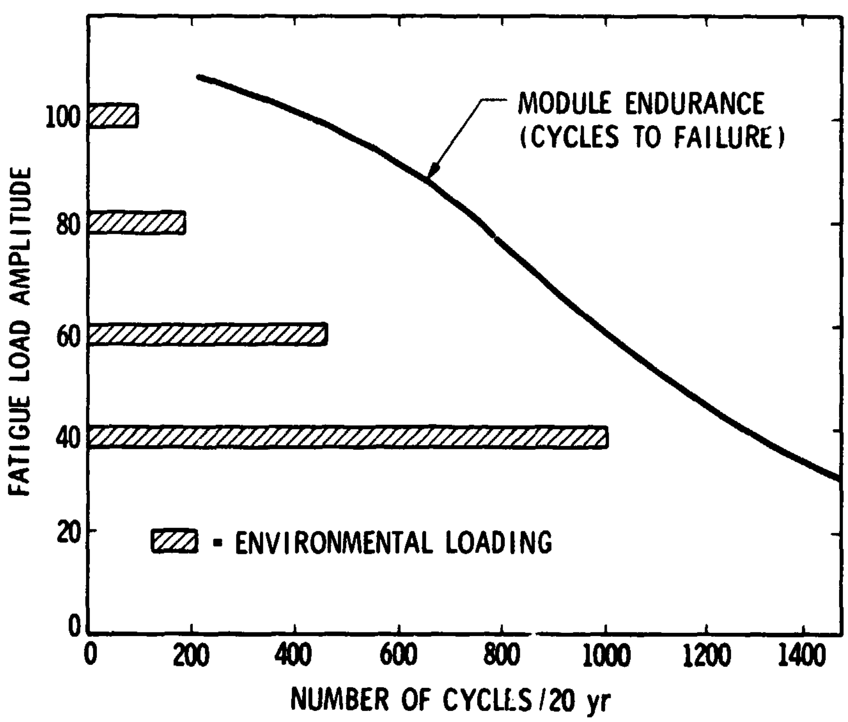
CATEGORIES OF CYCLES:



DENVER WIND SPEED DATA CYCLES



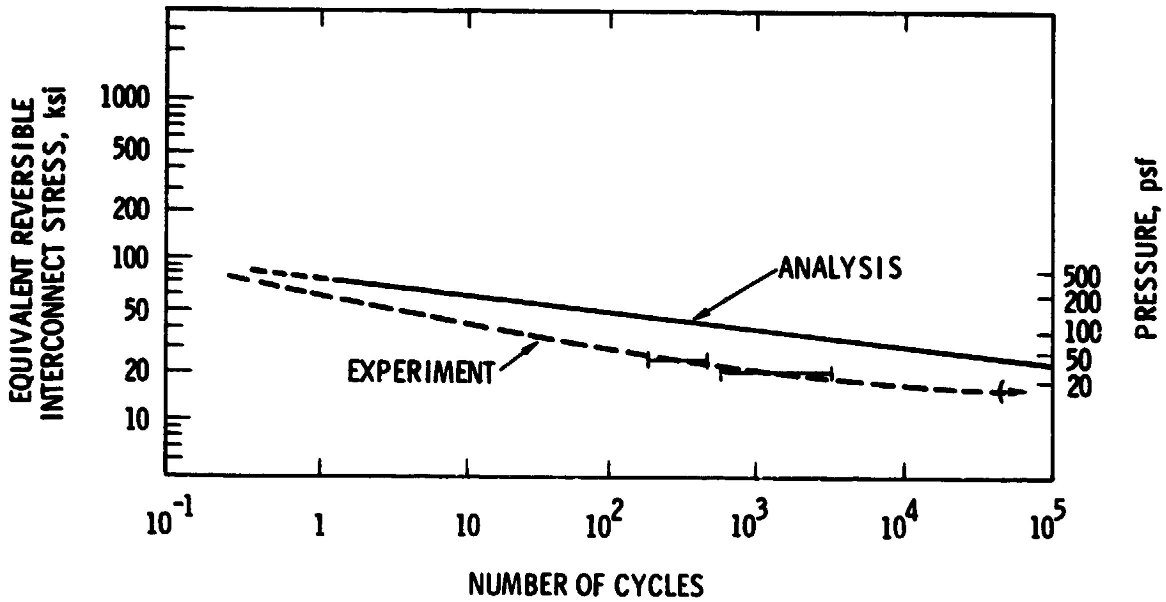
ENVIRONMENTAL LOADING vs MODULE ENDURANCE



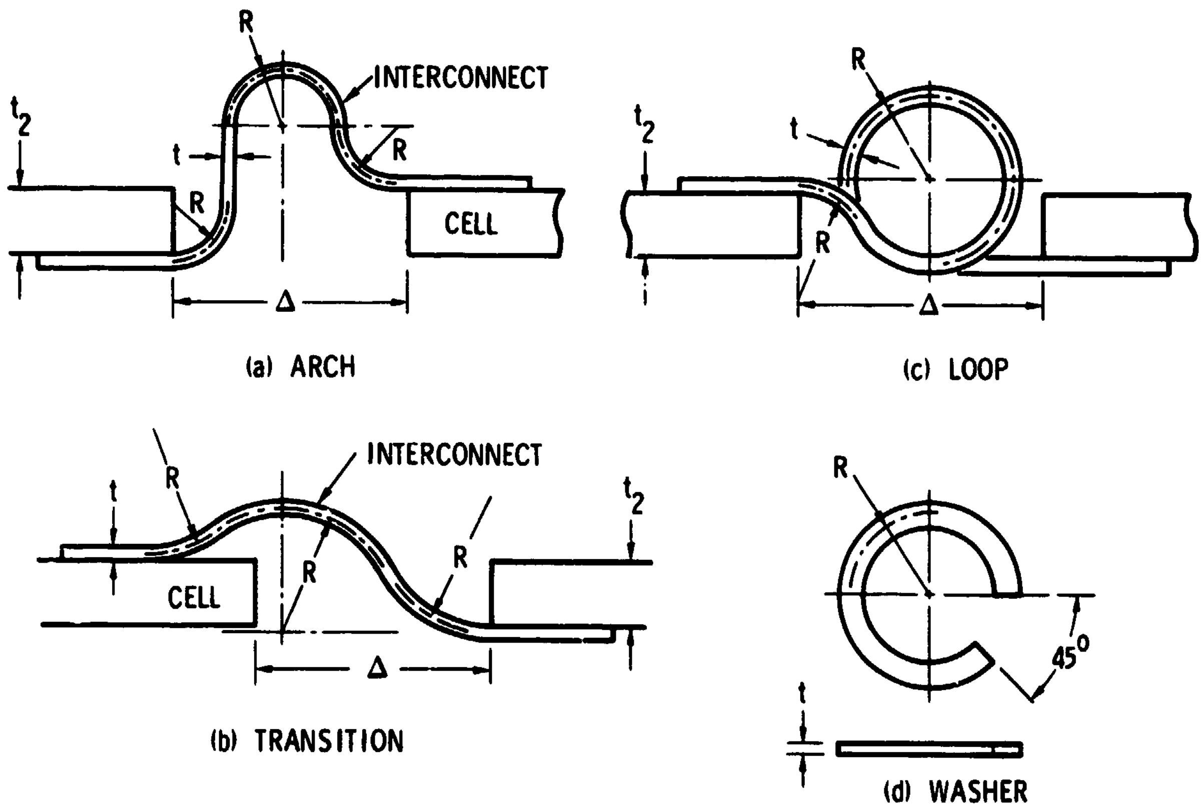
C-5

INTERCONNECT STRESS vs NUMBER OF CYCLES TO FAILURE

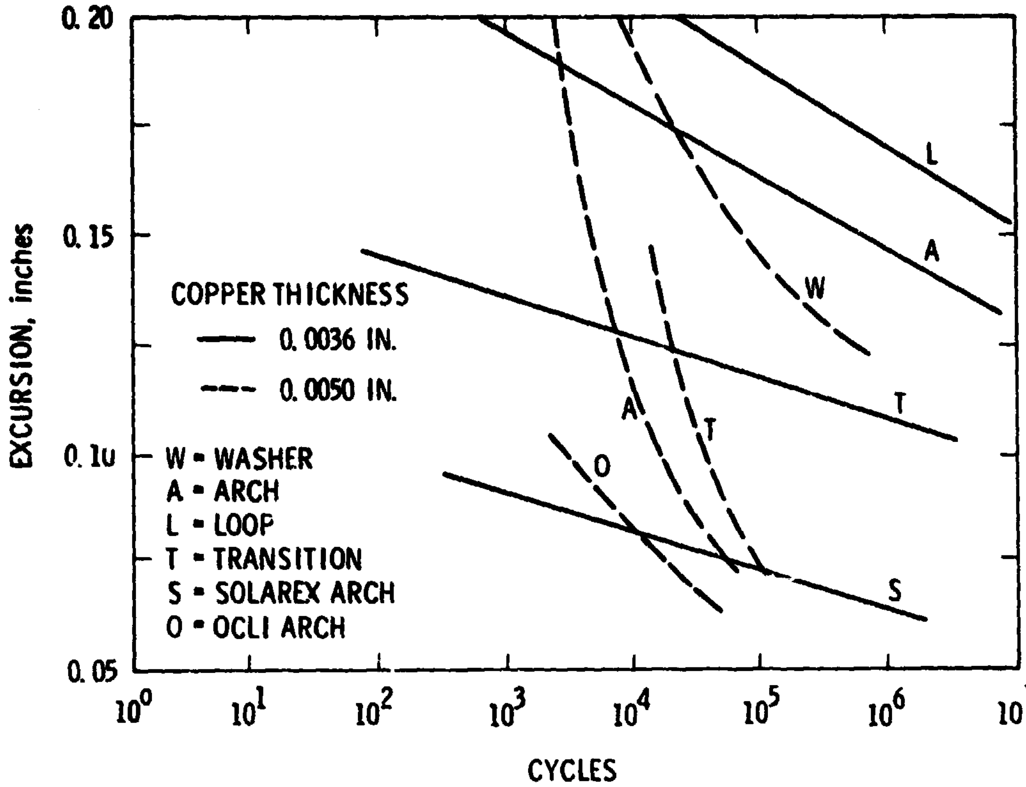
(SOLAREX, BLOCK I)



TRIAL INTERCONNECT DESIGNS

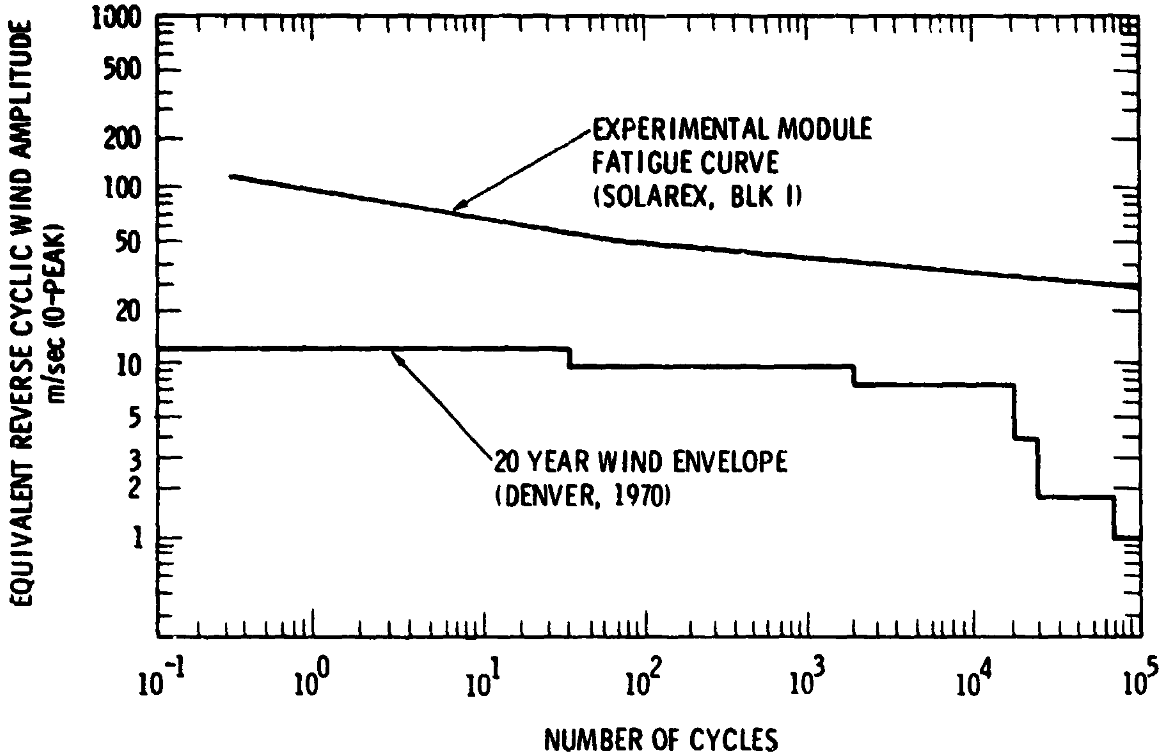


FATIGUE CURVES FOR TYPICAL CELL INTERCONNECTS

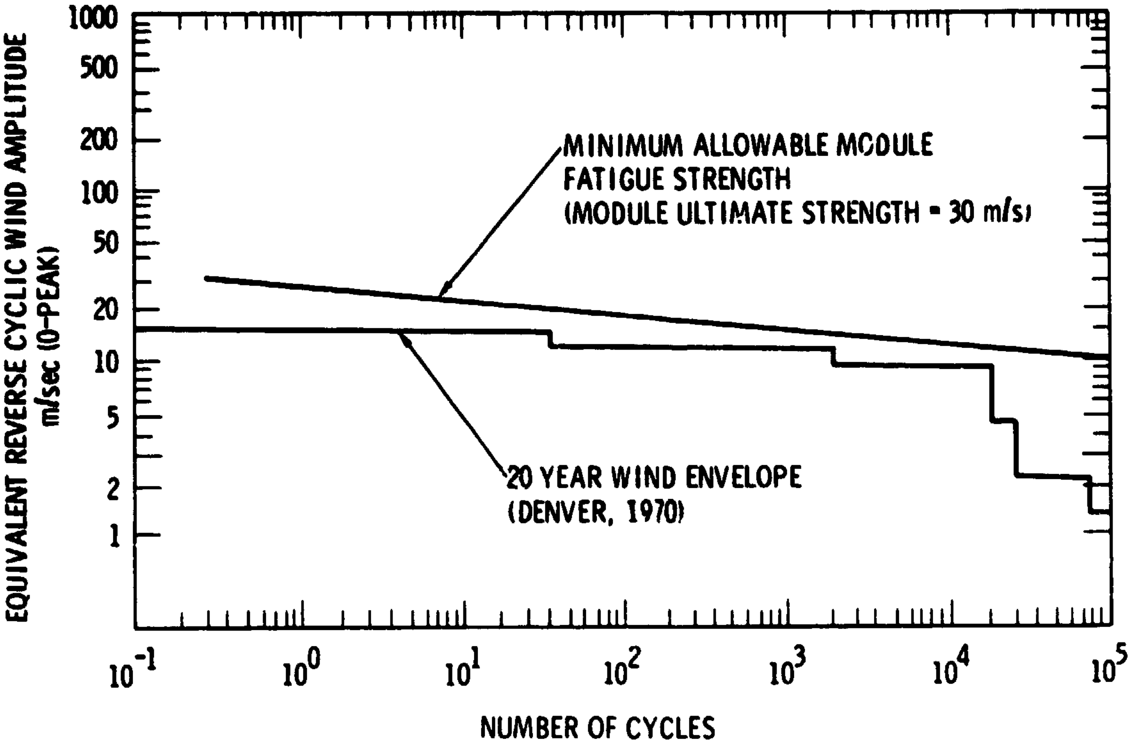


MODULE/WIND FATIGUE ENDURANCE COMPARISON

(MODULE ULTIMATE STRENGTH = 120 m/sec)



MINIMUM MODULE FATIGUE STRENGTH REQUIREMENT



MODULE SERIES/PARALLEL STUDIES UPDATE

OBJECTIVE

- DEVELOP CRITERIA FOR OPTIMUM:
  - MODULE SIZE
  - MODULE SERIES/PARALLEL
  - MODULE VOLTAGE/CURRENT LEVEL
  - ELECTRICAL TERMINALS
  - FAILURE PROTECTION DEVICES (DIODES)
  - FAILURE DETECTION DEVICES
  - MISMATCH ACCEPTANCE
  - MODULE REPLACEMENT STRATEGY

BASED ON MINIMUM LIFE-CYCLE ENERGY COST FOR ALTERNATE SERIES/PARALLEL SYSTEM CONFIGURATIONS

SERIES/PARALLEL STATUS

(AUGUST 1978)

ACCOMPLISHMENTS

- DEVELOPED FIRST GENERATION SERIES/PARALLEL PROGRAM
- EVALUATED ARRAY POWER DEGRADATION FOR LOW CELL FAILURE DENSITIES
- DETERMINED PRELIMINARY LIFE-CYCLE ECONOMICS

PRELIMINARY CONCLUSIONS:

- MODULE YIELD COST FOR LARGE SINGLE STRING MODULES UNACCEPTABLY HIGH
- OPTIMUM ARRAY HAS HIGH DEGREE OF SERIES/PÅRALLELING AND NO MODULE REPLACEMENT

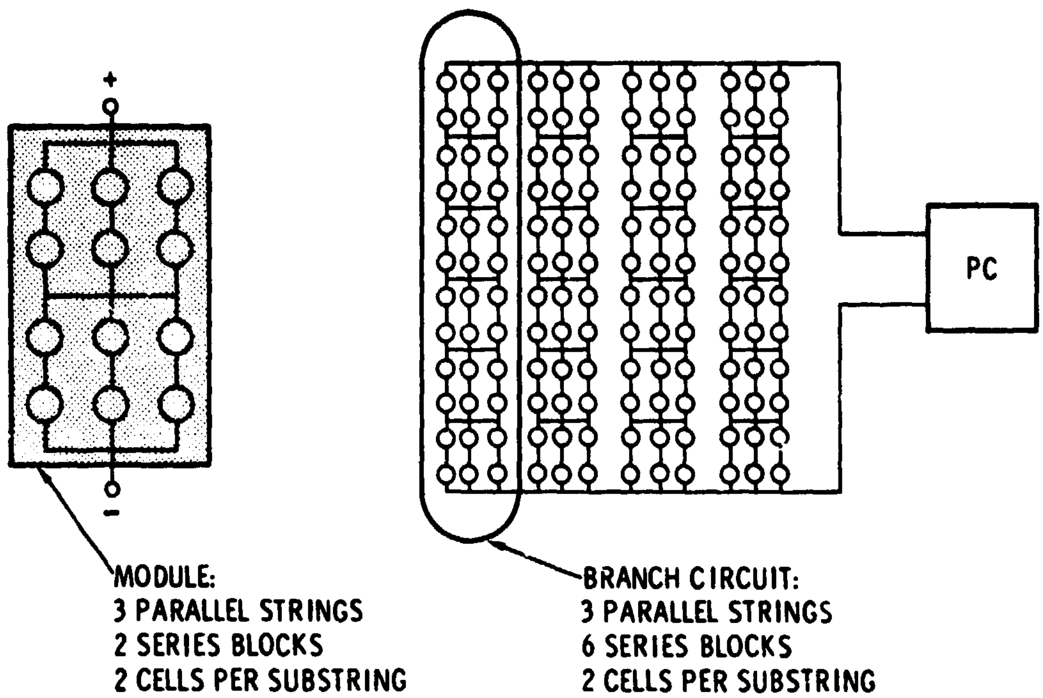
ANALYSIS DEFFICIENCIES:

- POWER DEGRADATION MODEL NOT VALID FOR HIGH CELL FAILURE DENSITIES
- INFLUENCE OF SERIES/PARALLELING ON MODULE YIELD NOT INCLUDED

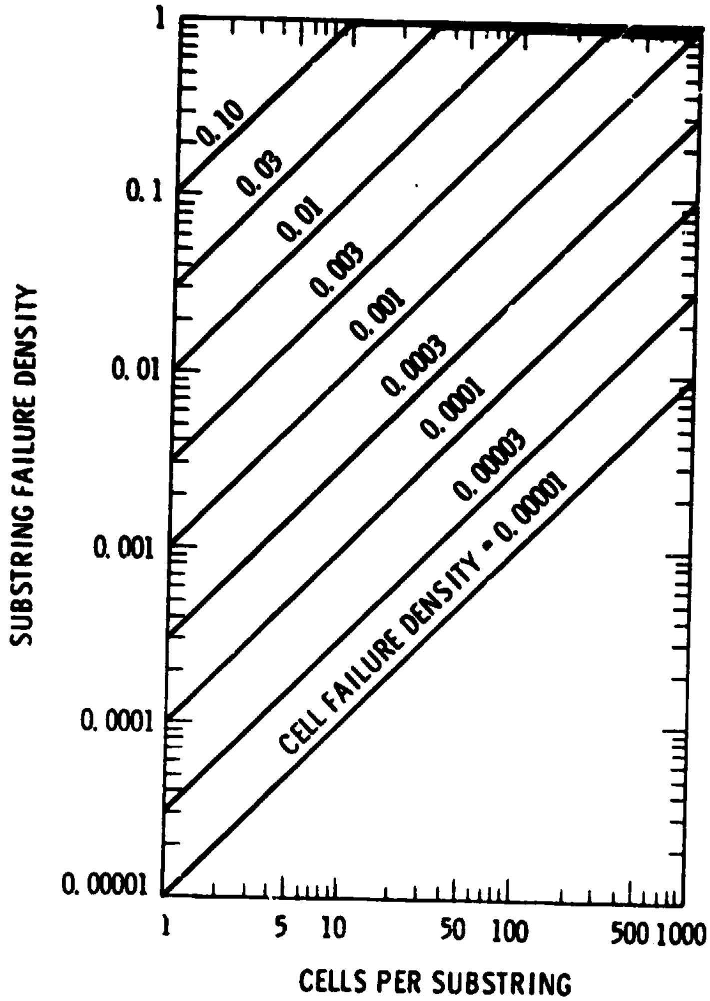
(AUGUST 1979)

- COMPLETED HIGH-ACCURACY SERIES-PARALLEL COMPUTER PROGRAM
- ANALYZED INFLUENCE OF SERIES/PARALLELING ON MODULE YIELD
- ANALYZED INFLUENCE OF SERIES/PARALLELING ON CELL MISMATCH WITHIN MODULE
- ANALYZED INFLUENCE OF CELL MISMATCH ON CELL HOT-SPOT HEATING
- COMPLETED COMPLEX ANALYSIS OF ARRAY DEGRADATION WITH HIGH CELL FAILURE DENSITIES
- UPDATED LIFE-CYCLE COST TRADE-OFFS OF ALTERNATIVE ARRAY CIRCUIT CONFIGURATIONS

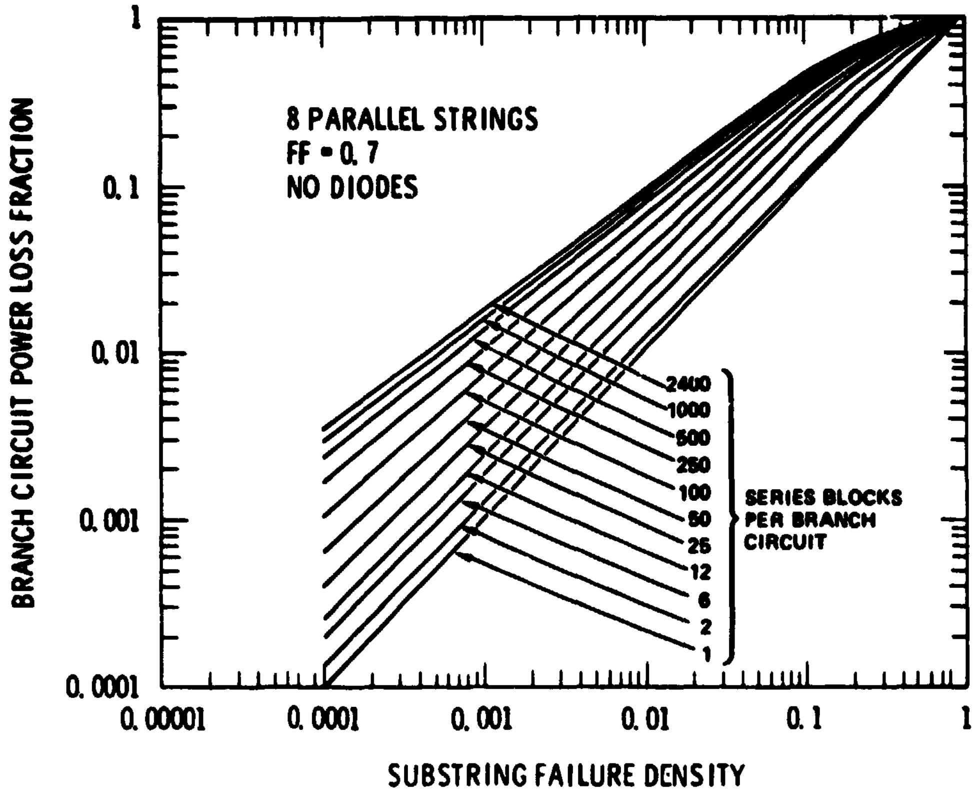
SERIES/PARALLEL NOMENCLATURE



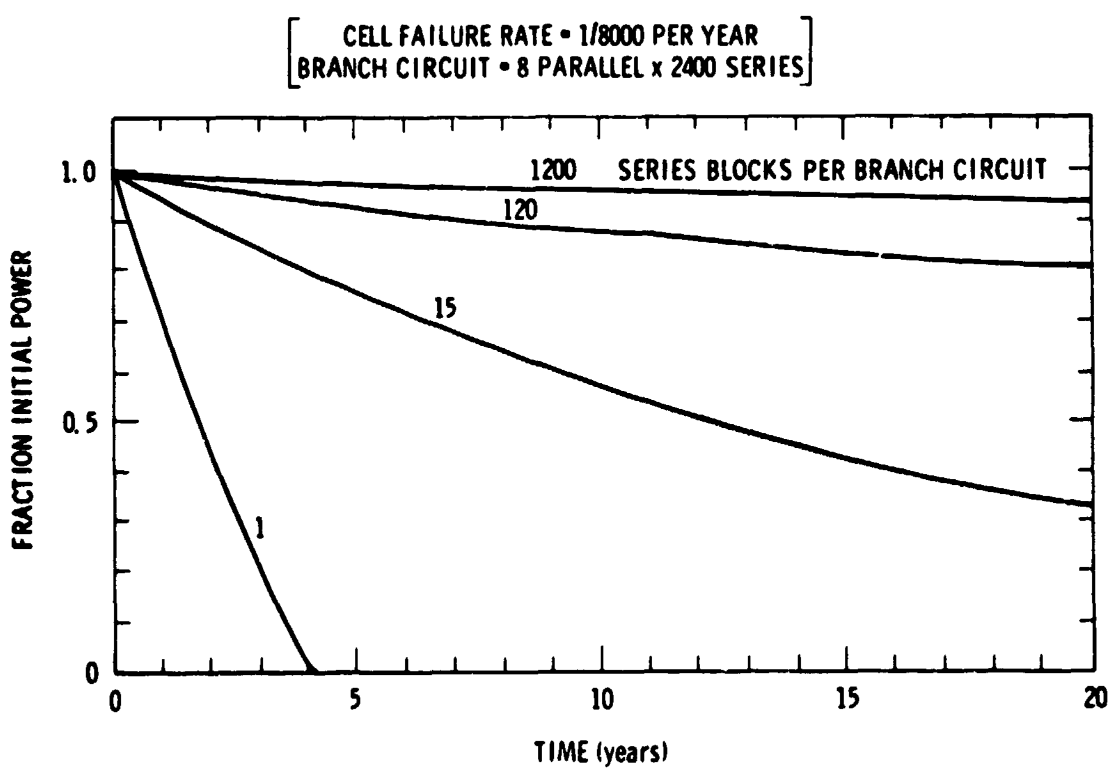
SUBSTRING FAILURE DENSITY vs CELL FAILURE DENSITY



ARRAY POWER LOSS FRACTION vs SUBSTRING FAILURE DENSITY



ARRAY POWER DEGRADATION vs TIME



NOMINAL ARRAY COSTS

ELEMENT	UNITS	COST		
		2 x 4	4 x 4	4 x 8
INITIAL:				
MODULE DIRECT COST	$/m2	60	60	60
MODULE YIELD COST	$/m2	0-5	0-8	0-23
• MODULE SUBTOTAL	$/m2	60-65	60-68	60-83
PANEL FRAME	$/m2	24	18	15
PANEL WIRING	$/m2	2-4	2-3	1-2
• PANEL SUBTOTAL	$/m2	26-28	20-21	16-17
PANEL INSTALLATION	$/m2	1	1	1
INSTALLED ARRAY STRUCT	$/m2	22	22	22
• ARRAY TOTAL	$/m2	109-116	103-112	99-123
PER REPLACEMENT ACTION:				
FAULT IDENTIFICATION	$/PANEL	4	4	4
PANEL SUBSTITUTION LABOR	$/PANEL	21	21	21
MODULE REPLACEMENT LABOR	$/MOD	12	12	12
REPLACEMENT MODULE PARTS (INC 1% INVENTORY COST)	$/m2	61-66	61-69	61-84

ADDITIONAL PERFORMANCE PARAMETERS

MODULE FAILURE RATE

ENCAPSULATION	1 CELL PER 1000
FIELD EXPOSURE	1 CELL PER 8000 PER YEAR

MODULE EFFICIENCY

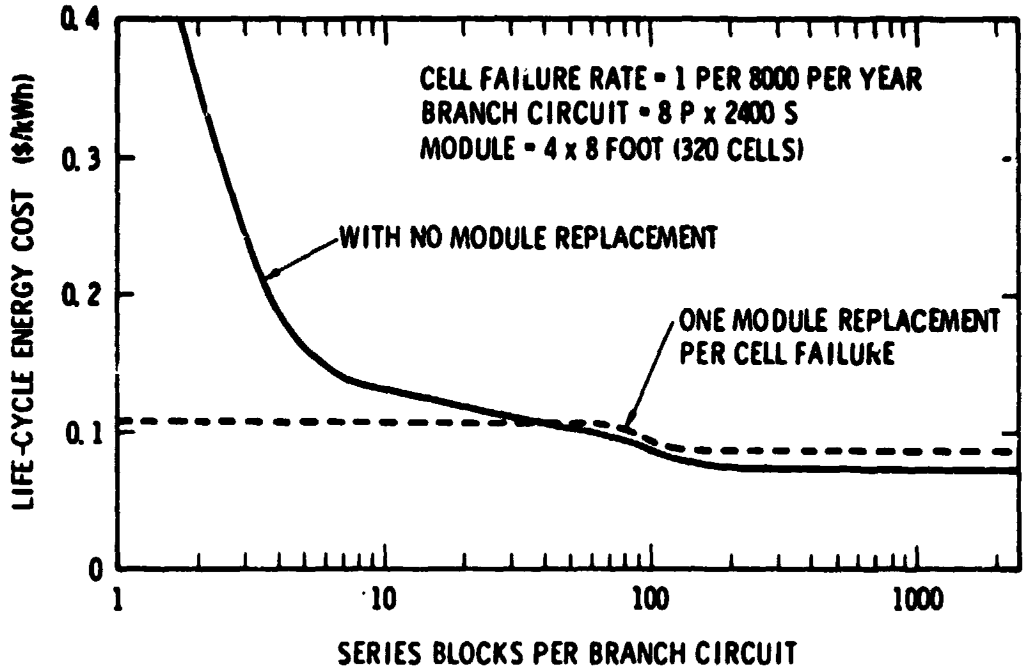
ENCAP. CELL EFFICIENCY	0.15
NOCT EFFICIENCY	0.92
PACKING EFFICIENCY	0.92
MODULE EFFICIENCY SUBTOTAL	0.127

BALANCE-OF-PLANT EFFICIENCY

ELECTRICAL EFFICIENCY	0.92
MODULE SOILING EFFICIENCY	0.92
BALANCE-OF-PLANT SUBTOTAL	0.85

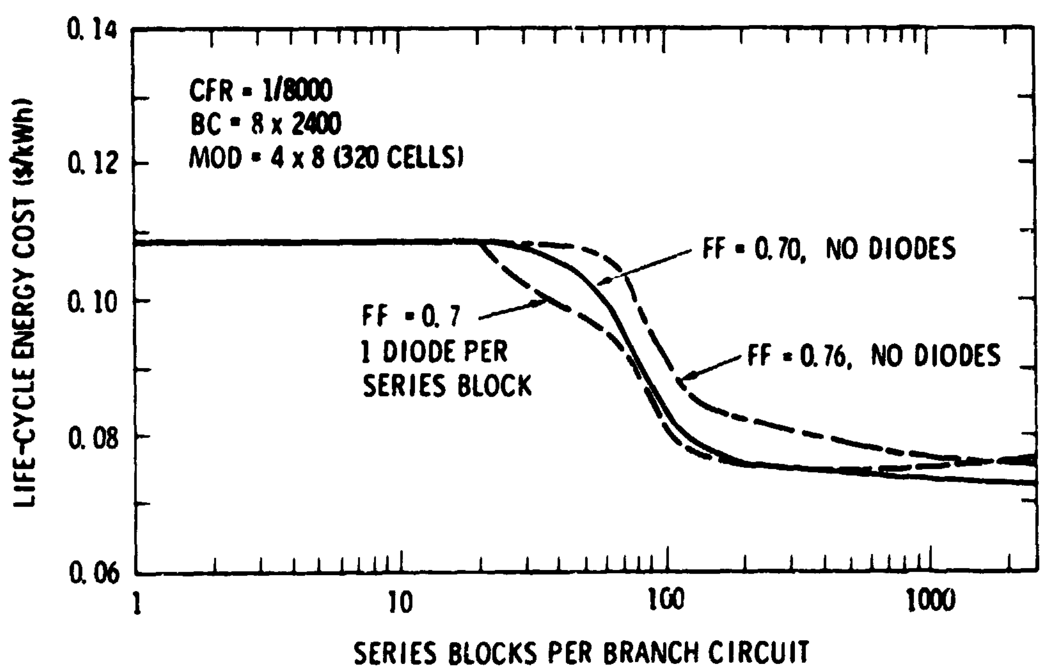
BALANCE-OF-PLANT COST	150 $/kW
DISCOUNT RATE (OVER INFLATION)	10%
PEAK HOUR OF INSOLATION	1825 hrs/yr

LIFE-CYCLE ENERGY COST vs CIRCUIT CONFIGURATION

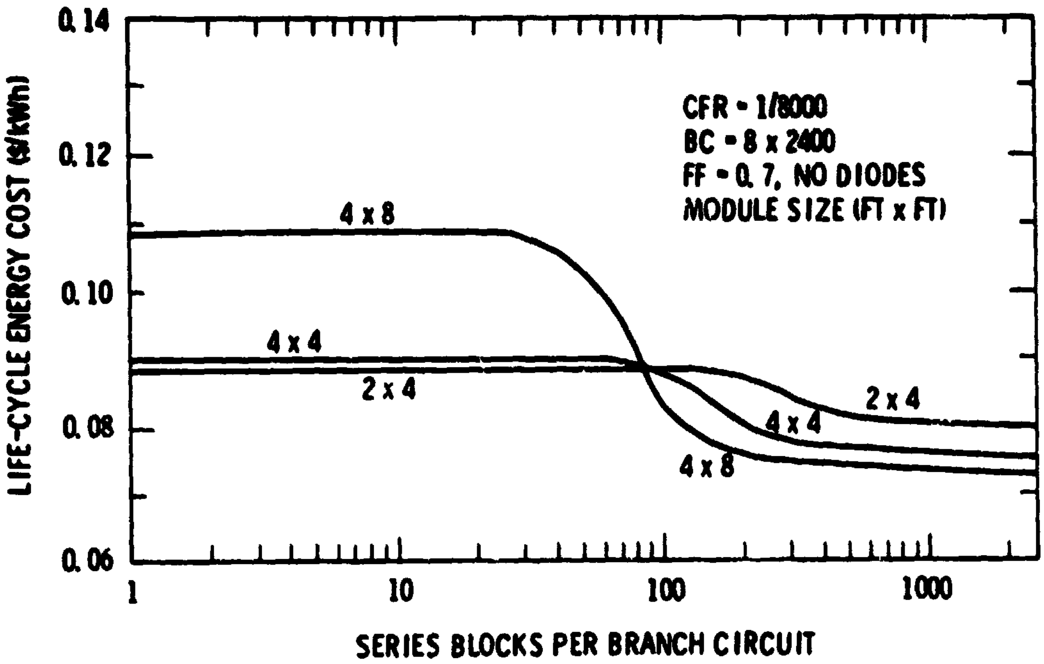


LIFE-CYCLE ENERGY COST vs CIRCUIT DESIGN

(OPTIMUM MAINTENANCE)



LIFE-CYCLE ENERGY COST vs MODULE SIZE



SERIES/PARALLEL CONCLUSIONS

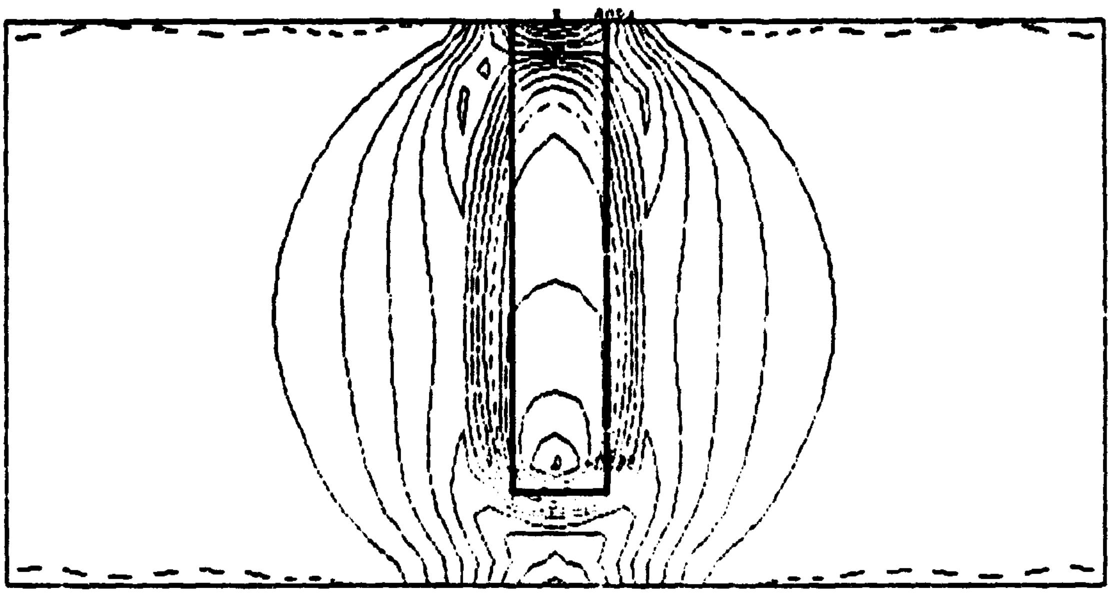
- OPTIMUM ARRAY HAS HIGH DEGREE OF SERIES/PARALLELING AND NO MODULE REPLACEMENT FOR ROUTINE CELL FAILURES
- OPTIMUM STRATEGY FOR LOW-SERIES/PARALLEL ARRAYS IS MODULE REPLACEMENT FOR EACH CELL FAILURE
- HIGH MODULE FILL FACTOR INCREASES POWER LOSS AND HOT-SPOT PROBLEMS
- USE OF DIODES DOES NOT REDUCE ARRAY LIFE-CYCLE COSTS, BUT MAY BE NECESSARY TO AMELIORATE HOT-SPOT PROBLEMS
- SEMI-OPTIMUM ARRAY: 4 x 8 FOOT MODULES
320 CELLS (8P x 40S)
1 TO 5 CELLS PER SUBSTRING
60 MODULES PER BRANCH CIRCUIT

FUTURE SERIES/PARALLEL ACTIVITIES

- COMPLETE RESULTS FOR 4 AND 16 CELLS IN PARALLEL AND ADDITIONAL DIODE CASES
- DOCUMENT RESULTS IN DESIGN HANDBOOK
- CONDUCT SERIES/PARALLEL WORKSHOP AROUND NEXT FEBRUARY.

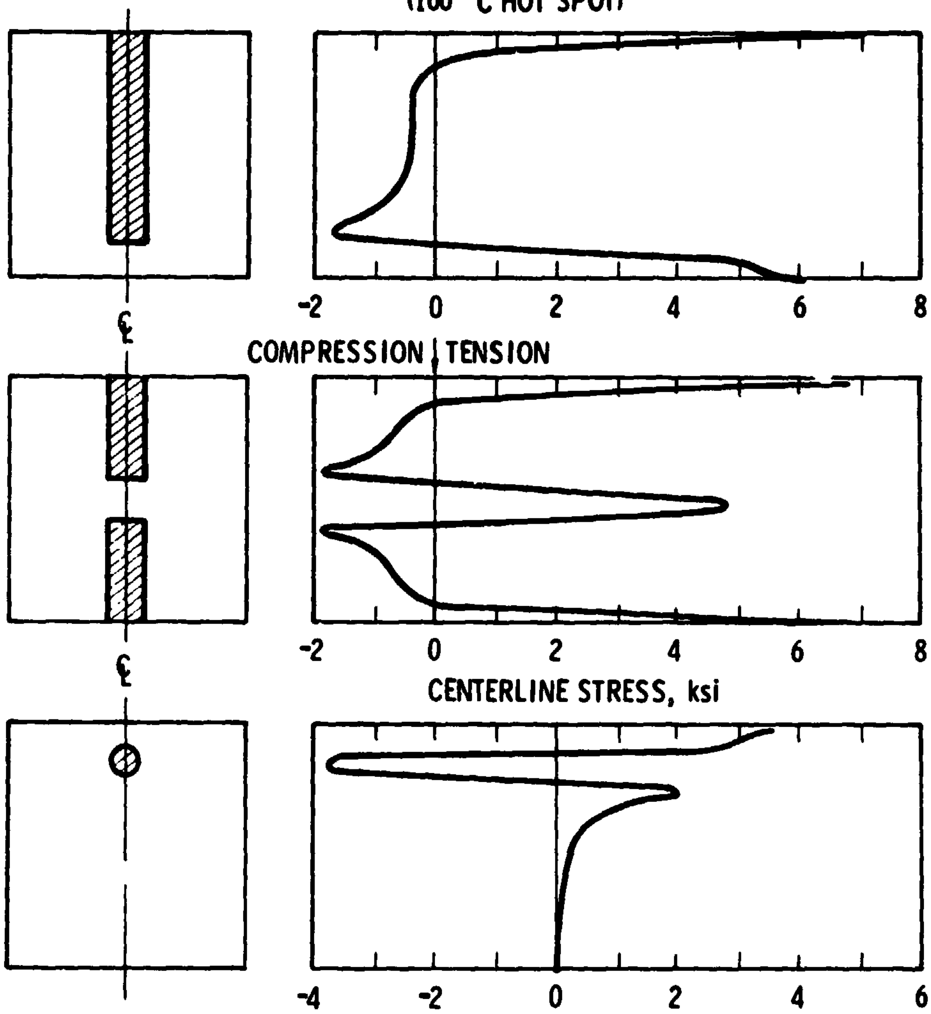
TYPICAL COMPUTER STRESS CONTOUR PLOT

(2 x 4-FOOT MODULE)
(500 psi/100°C PER INTERVAL)



GLASS STRESS IN MODULES DUE TO HOT-SPOT CELL HEATING

(4 x 4 FOOT MODULES)
(100^0 C HOT SPOT)



4. Operations Area

TECHNOLOGY SESSION

Larry N. Dumas, Chairman

The major JPL in-house activity in the area of module environmental test and performance analysis over the past several months has been the Flat-Panel Experiments (PRDA-38) module qualification test program. The results of this effort were described in a presentation by Jim Fortenberry, JPL Applications Representative. The tight delivery schedule for the qualification test modules led to a number of design and workmanship deficiencies that were manifested by test problems. JPL problem/failure analysis indicates that these problems are all correctable by straightforward improvements in design, in workmanship, and in quality assurance.

A status report on the survey of the LeRC-installed endurance test sites was presented by Larry Dumas on behalf of Pete Jaffe, JPL Field Test Director. To date, 132 Block II modules have been inspected at nine sites. Six modules have failed or shown significant electrical degradation. Embedded dirt in silicone rubber encapsulant is a common problem, but the modules are in generally good condition after 1 1/2 years in the field. The marine environment of Key West is producing the worst physical degradation, while the alpine environment of Mines Peak appears to be the least harmful.

Steve Forman of MIT/LL gave a comprehensive overview of module performance at their test sites. The cumulative failures at all sites to date stand at 1.5%; the largest installation--Mead, Nebraska--has shown 1.6% failures after two years of operation. The physical condition of the modules is less encouraging, with cracked cells and encapsulant degradation increasingly prevalent. The degree to which present physical degradation portends future functional degradation remains to be established. An apparently progressive type of cell cracking failure has been observed at the University of Texas test site; a simple single crack led to massive cracking and "bulging" of that cell over a six month period, presumably as a result of reverse bias overheating. JPL engineers reported that a similar phenomenon at the Mount Laguna site has been observed and is being analyzed. Forman also reported on the effects of snow on module output: some power is delivered even with a 2-in snow coverage.

The DOD Mount Laguna PV installation was dedicated August 15. The half-acre array field of Block II and III Solarex and Solar Power modules delivers 64kW, making this system the world's largest. MERADCOM managed the program for DOE.

Dan Runkle and Jim Arnett of JPL reviewed the scope and status of the Block IV module contracts, and the design features and functional performance expected for this block were compared with past block procurement modules. Particularly striking is the almost universal use of glass as a superstrate, shaped (closely packed) cells, and laminated encapsulation systems. The high cell-packing factors for the Block IV module designs will result in marked improvements in module efficiency as compared to previous designs. Module efficiencies of 9 to 14% are being projected by the manufacturers.

AN OVERVIEW OF MODULE TEST RESULTS: PHOTOVOLTAIC FLAT-PANEL APPLICATIONS EXPERIMENTS (PRDA 38)

JIM FORTENBERRY (JPL)

WHAT IS PRDA 38?

- PROGRAM RESEARCH AND DEVELOPMENT ANNOUNCEMENT
- SYSTEM SIZE ≈ 20-500 kW
- FLAT-PANEL PV MODULES
- DOE — ALBUQUERQUE / SANDIA LABORATORIES
- THREE PHASES
  - (1) SYSTEM DESIGN — COMPLETE (6 MONTHS)
  - (2) BUILD, CHECK OUT — JUST STARTING (1 YEAR)
  - (3) OPERATE, EVALUATE — 1-2 YEARS

PRDA 38—PROPOSED APPLICATIONS

(1) UTILITY GRID

(2) TELEPHONE SWITCHING

(3) MACHINE SHOP

(4) WASTE TREATMENT

(5) AMUSEMENT PARK

(6) BATTERY MANUFACTURE

(7) SHOPPING CENTER

(8) COMMUNITY CENTER

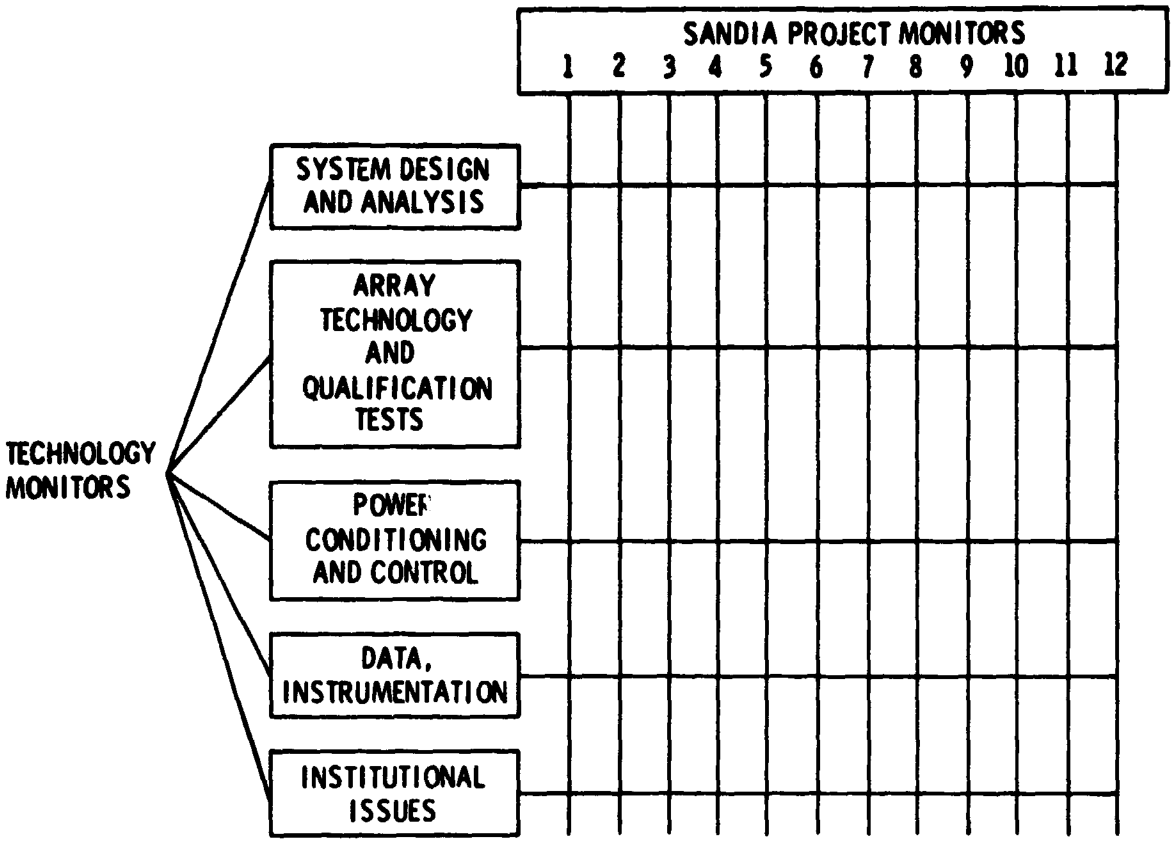
(9) WATER DESALINATION

(10) UTILITY PLANT CONTROL

(11) SCIENCE / ART CENTER

(12) HIGH SCHOOL

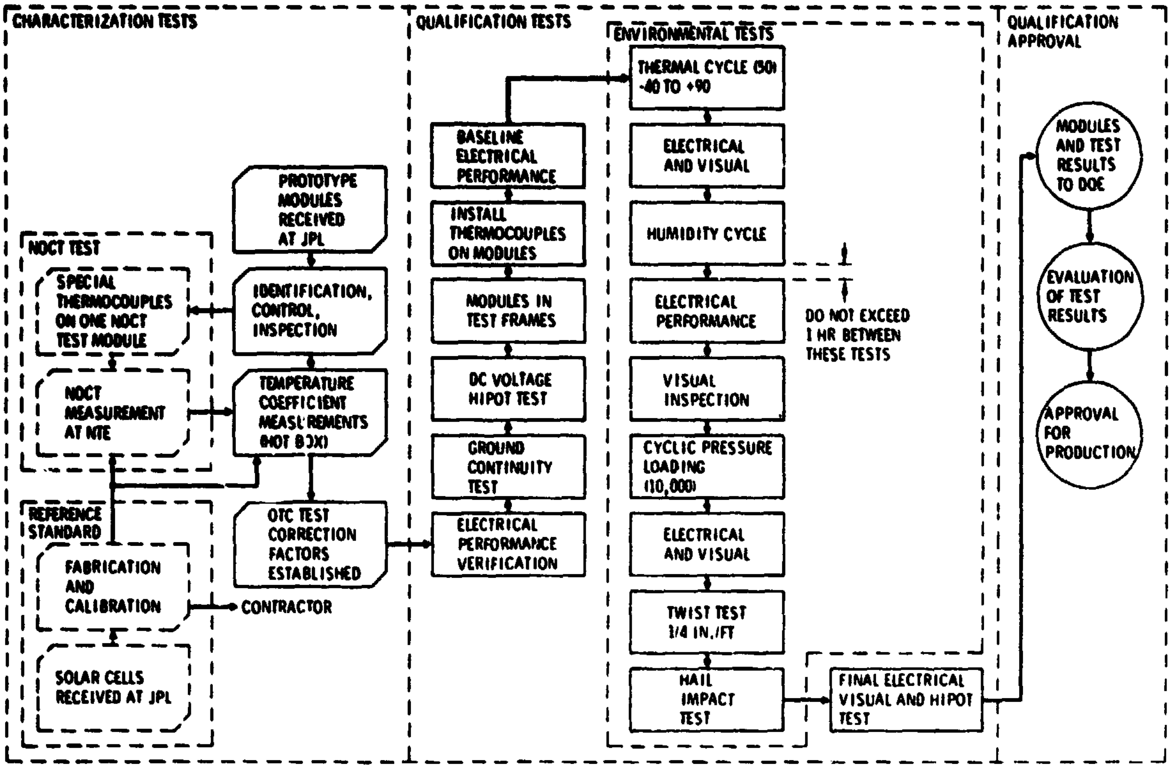
WHERE DOES LSA FIT IN?



SUPPORT PROVIDED BY LSA

- PROPOSAL EVALUATION
- DESIGN REVIEWS
- DESIGN, TEST SPECIFICATIONS
- PERFORMANCE MEASUREMENT STDS
- PROBLEM / FAILURE REPORTING
- PROTOTYPE MODULE TESTING

PROTOTYPE MODULES TEST FLOW AT JPL



PRDA 38 MODULE QUALIFICATION TEST MATRIX

	THERMAL CYCLING	HUMIDITY CYCLING	MECHANICAL CYCLING	HAIL IMPACT
GROUND CONTINUITY ($R < 0.050\ \Omega$)				
ELECTRICAL ISOLATION ($I < 50\ \mu A$)				
POWER DEGRADATION < 5%				
PHYSICAL DEGRADATION				

o ° o EACH MODULE IS SUBJECTED TO 16 MODULE TESTS.

BOX SCORE OF PRDA 38 MODULE TEST RESULTS

TEST	NUMBER OF MODULE TESTS	NUMBER OF PROBLEMS	% PROBLEMS
THERMAL	178	49	28
HUMIDITY	178	42	24
MECHANICAL	170	17	10
HAIL	162	5	3
	688	113	16%

BOX SCORE OF PRDA 38 MODULE TEST CRITERIA

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

GROUND CONTINUITY AND ELECTRICAL ISOLATION PROBLEMS

- GROUND CONTINUITY : 5%
  - JUMPERS AND/OR CONNECTIONS USED TO MAKE ALL PARTS OF MODULE FRAME COMMON TO GROUND POORLY CONNECTED (LOOSE ATTACHMENTS, RIVETS, ETC)

- ELECTRICAL ISOLATION : 22%
  - MOISTURE PENETRATION INTO DIELECTRIC
  - CELL STRING BUS-TO-CABLE CONNECTION CLOSE TO FRAME
  - SHARP CORNERS OF J-BOX ABRAIDED CABLE INSULATION
  - CONDUCTIVE SEALING COMPOUND

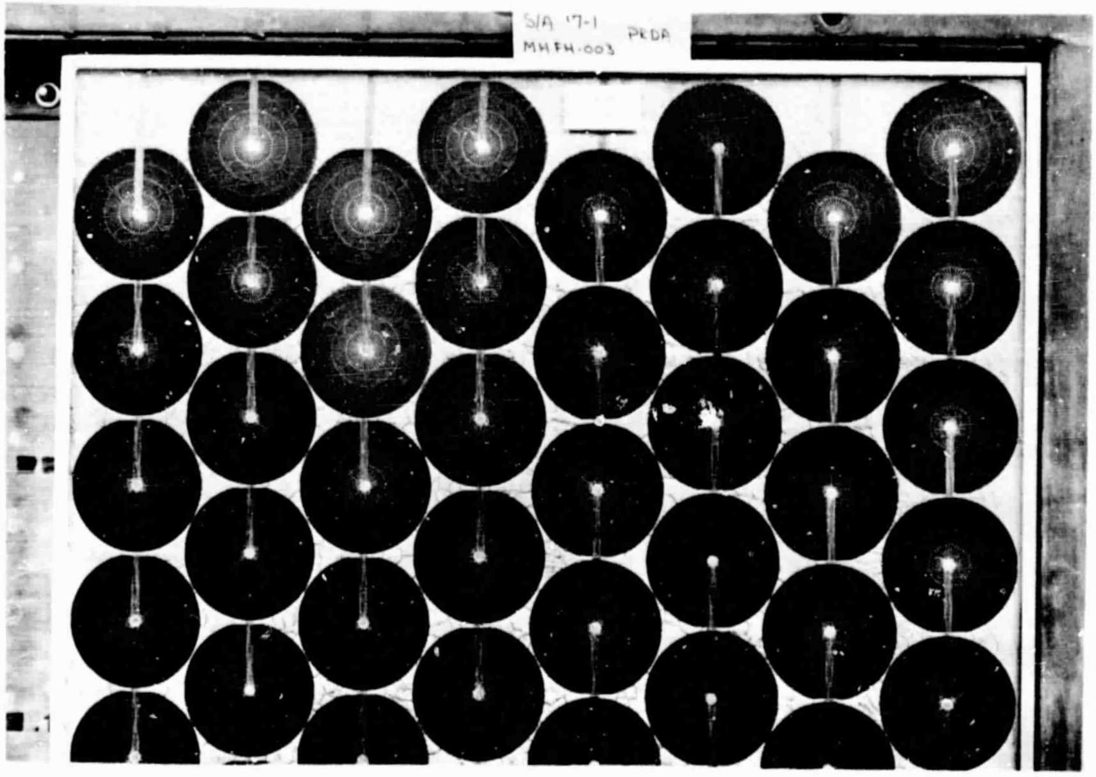
POWER DEGRADATION PROBLEMS (19%)

- CRACKED CELLS
  - CELLS SHORTED OUT
    - BURIED HEAT SINK PLATE, DIODE
    - EDGES TOUCHING
- UNVERIFIED, TBD

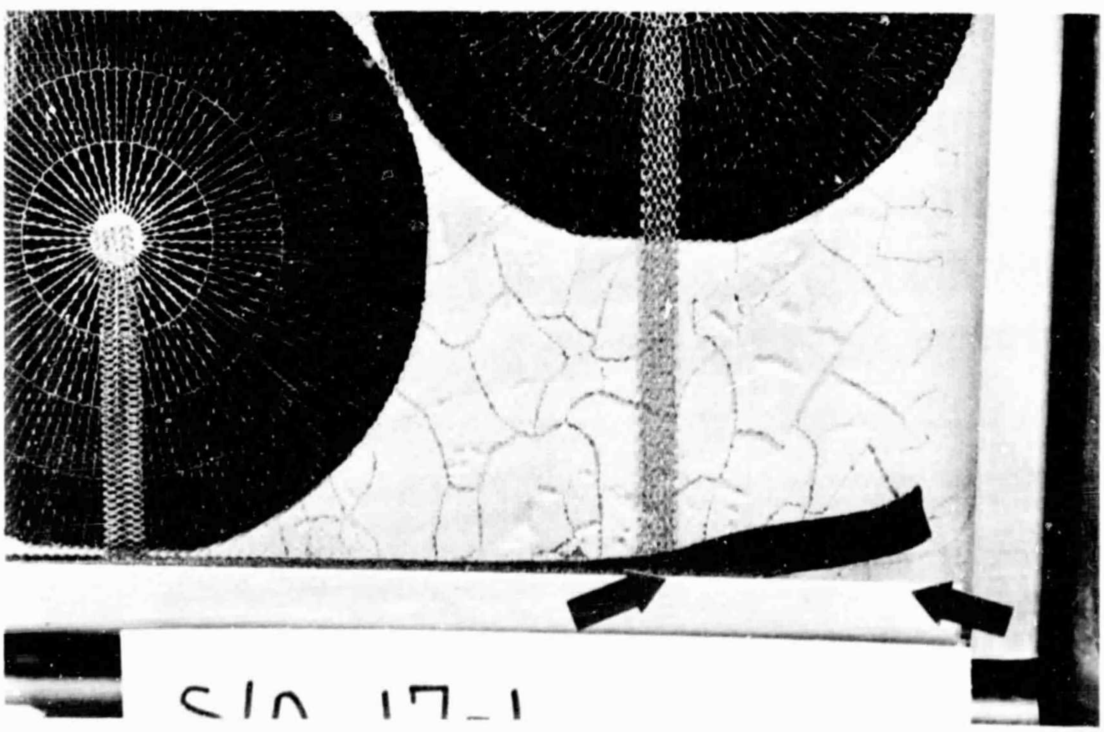
PHYSICAL DEGRADATION (54%)

- DELAMINATION, GAS BUBBLES, SURFACE SPLITS
- SUBSTRATE BREAKDOWN
- GASKET EXTRUSION
- STRUCTURAL FAILURE
- MELTED JUNCTION BOXES
- HAIL IMPACT

THERMAL CYCLING DAMAGE TO SUBSTRATE

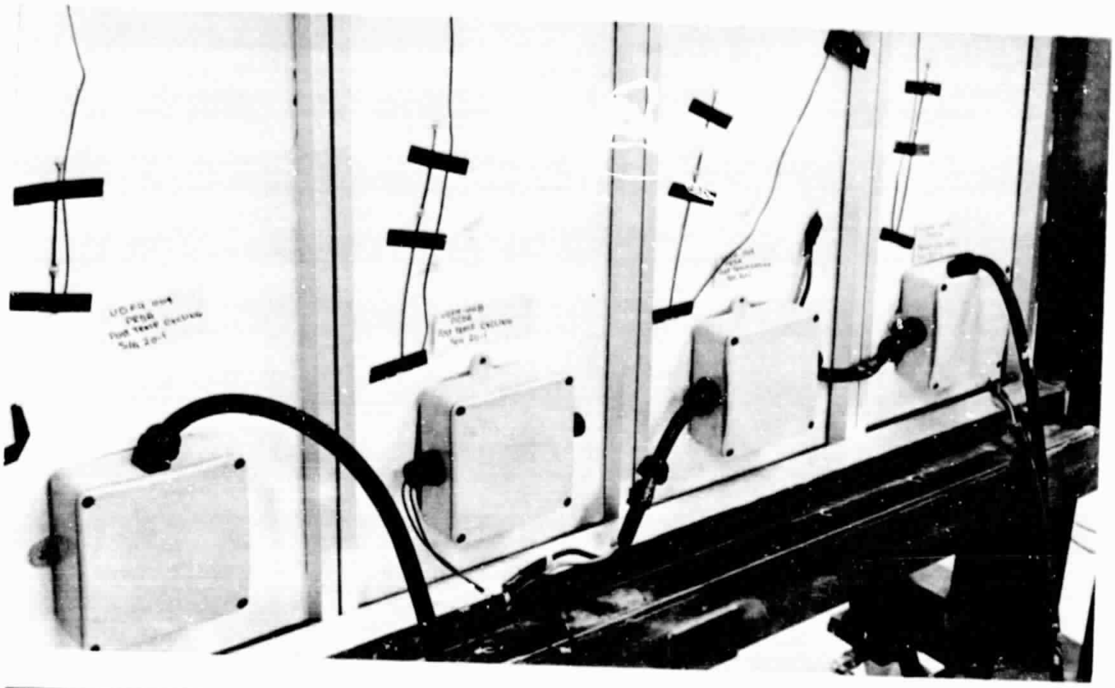


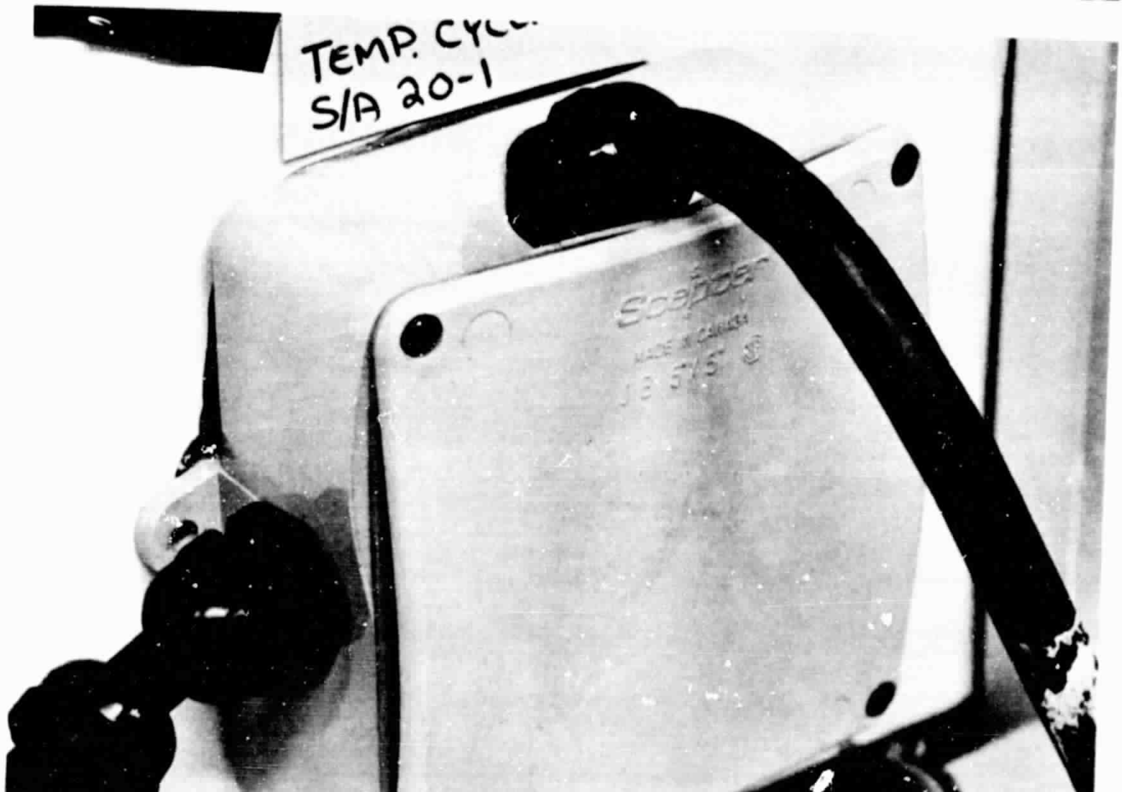
THERMAL CYCLING DAMAGE TO MODULE FRAME/GLASS GASKET



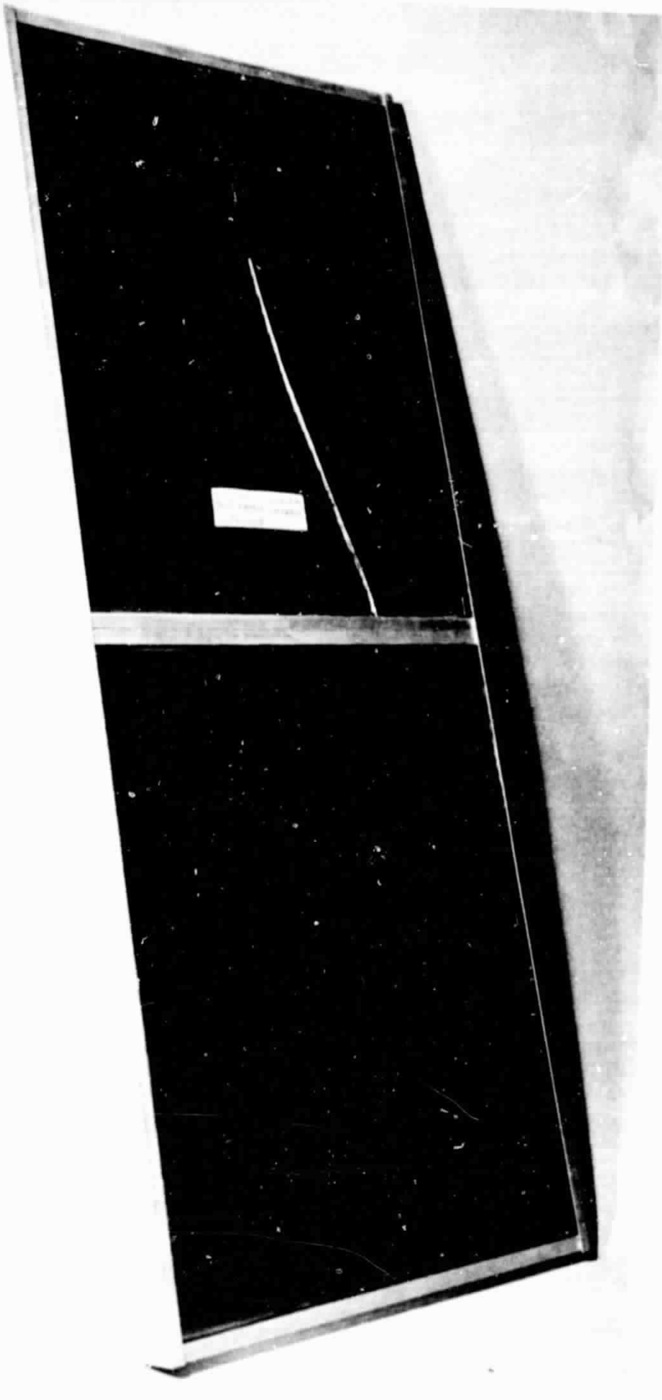
ORIGINAL PAGE IS
OF POOR QUALITY

THERMAL CYCLING DAMAGE TO JUNCTION BOXES

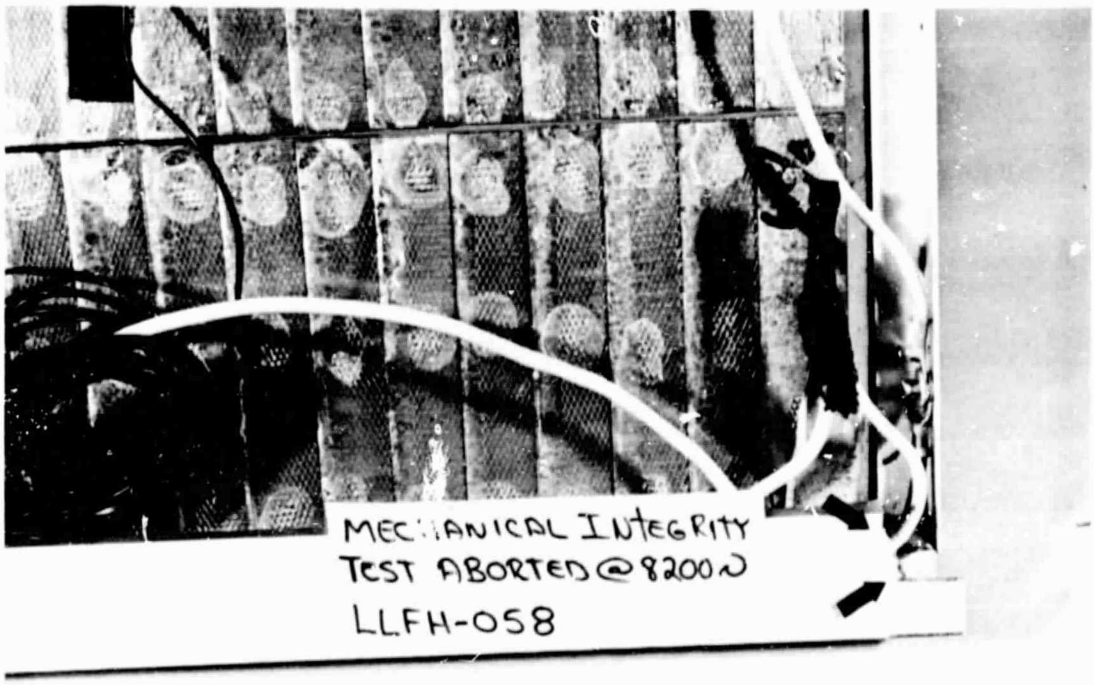




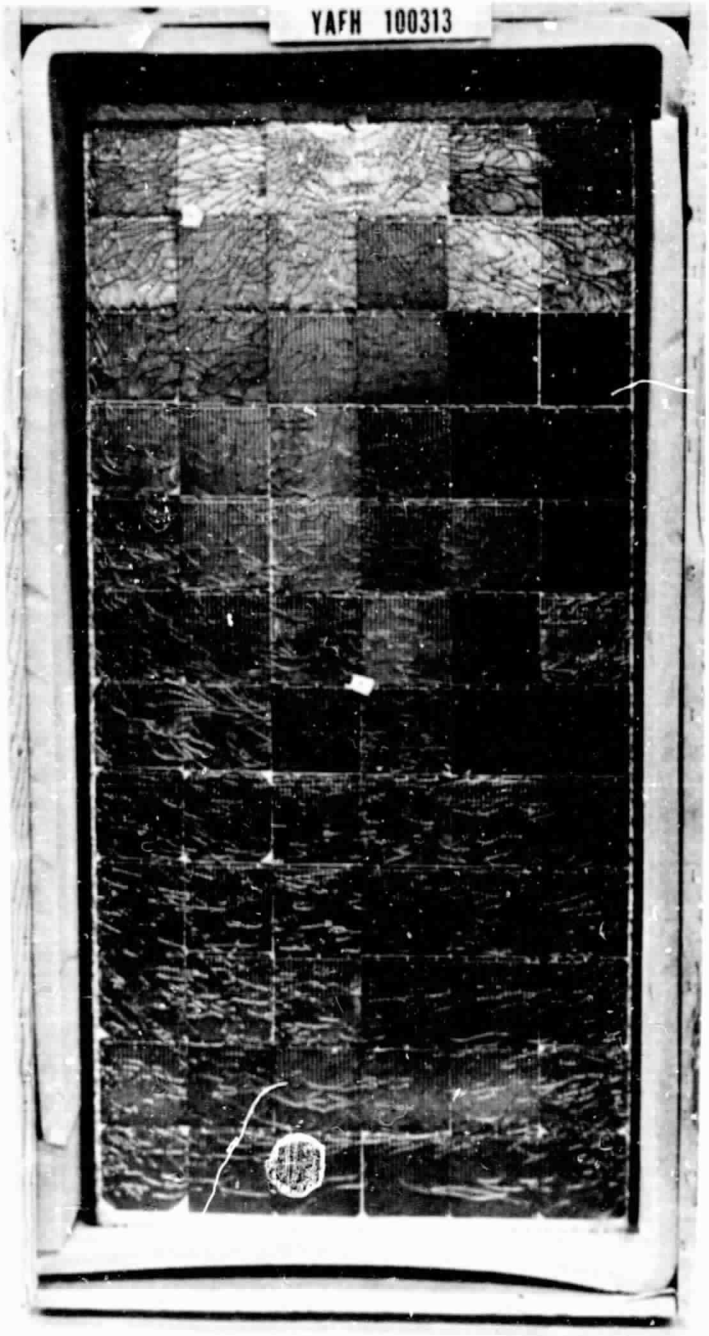
MECHANICAL CYCLING DAMAGE



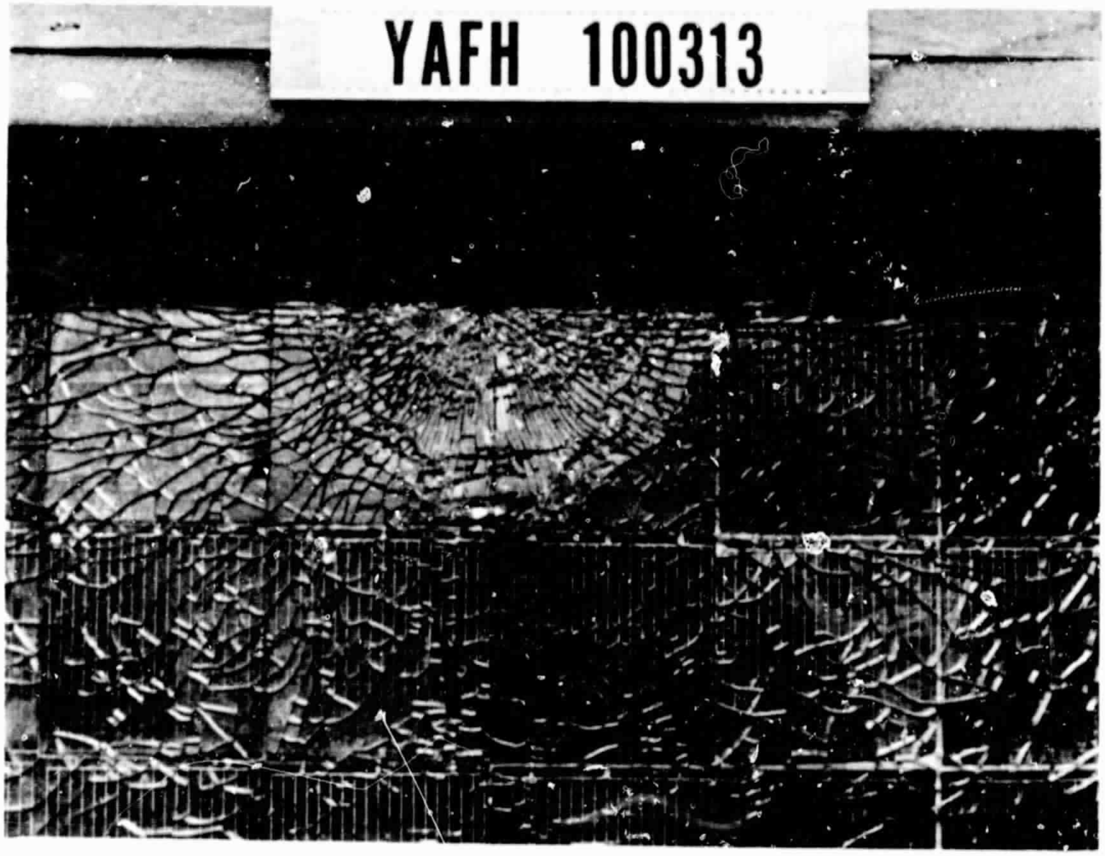
MECHANICAL CYCLING DAMAGE



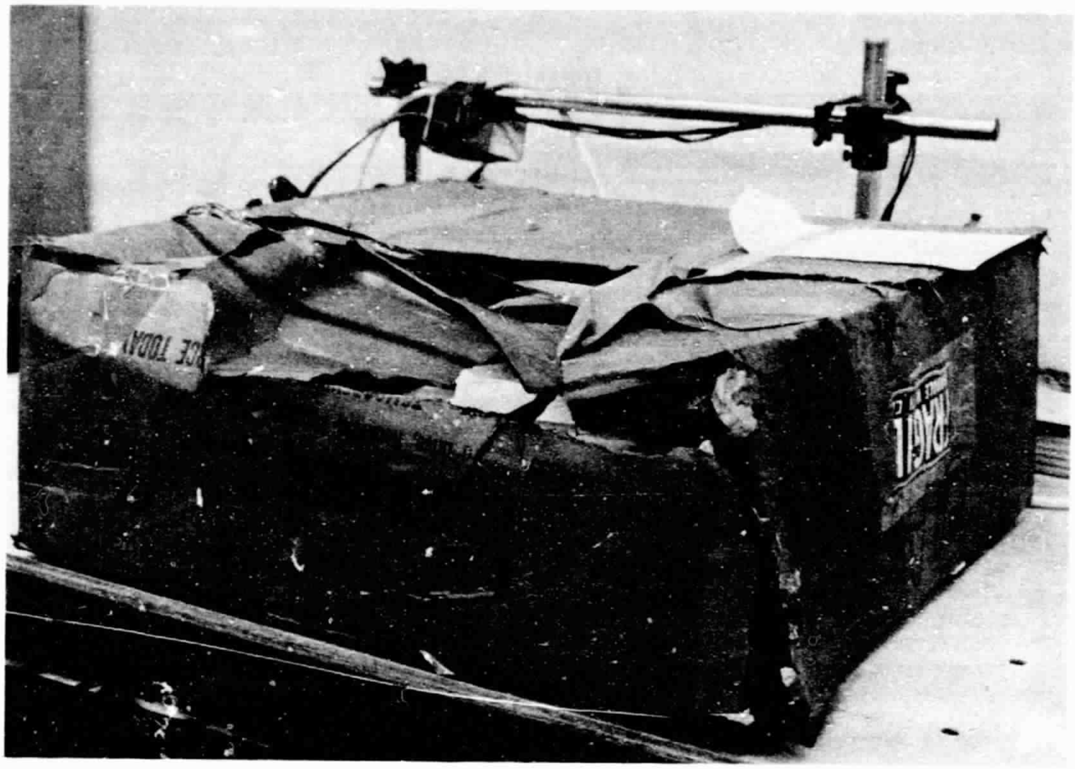
HAIL IMPACT DAMAGE

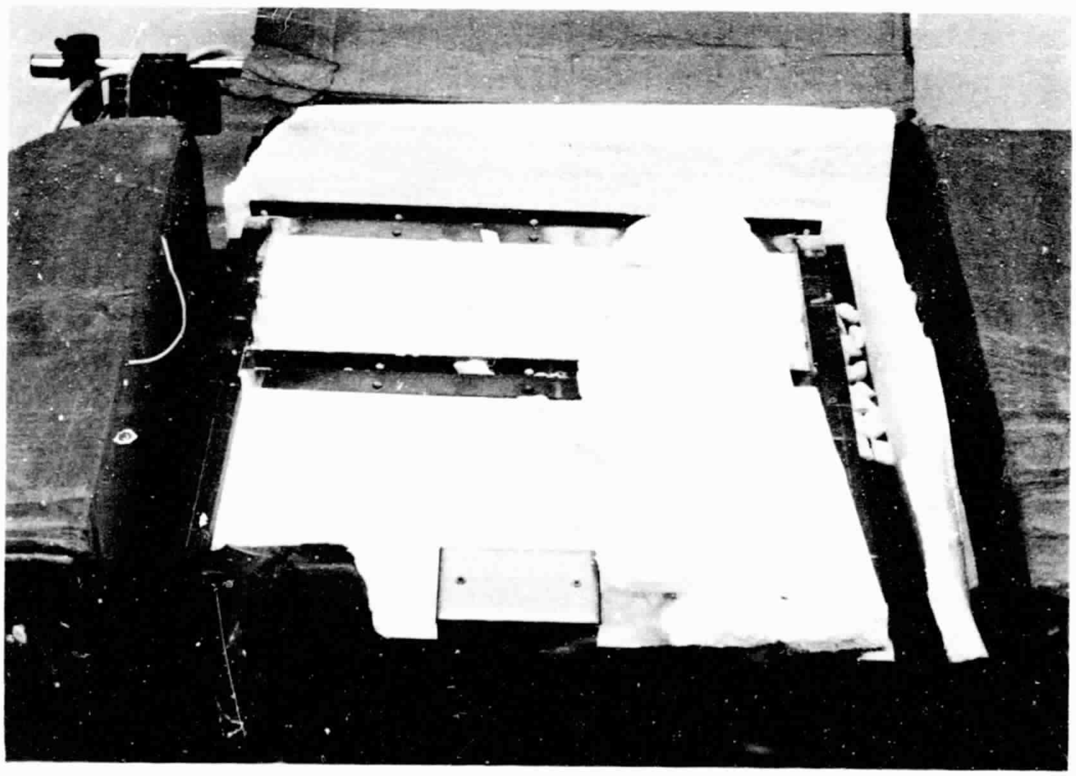


HAIL IMPACT DAMAGE



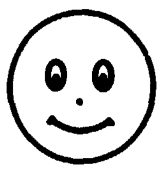
FORKLIFT TEST

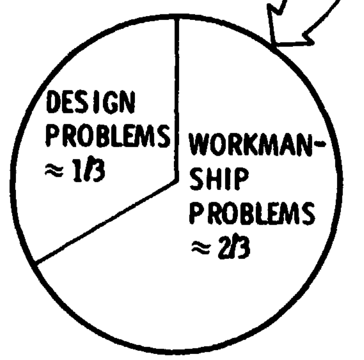




LESSONS LEARNED

- MODULES, IN GENERAL, NOT UP TO EXPECTATIONS
- TIGHT SCHEDULE → IMMATURE DESIGNS, HASTY FABRICATION, MINIMUM QA
- ALL FIXABLE





STATUS OF JPL/LEWIS ENDURANCE TEST SITES

SITE SURVEY

- ACQUIRE BASELINE DATA ON THE ELECTRICAL AND PHYSICAL STATUS OF EACH MODULE
- OBTAIN FIRST-HAND PERSPECTIVE OF THE SITES IN ORDER TO DEVELOP AN OVERALL TEST PLAN

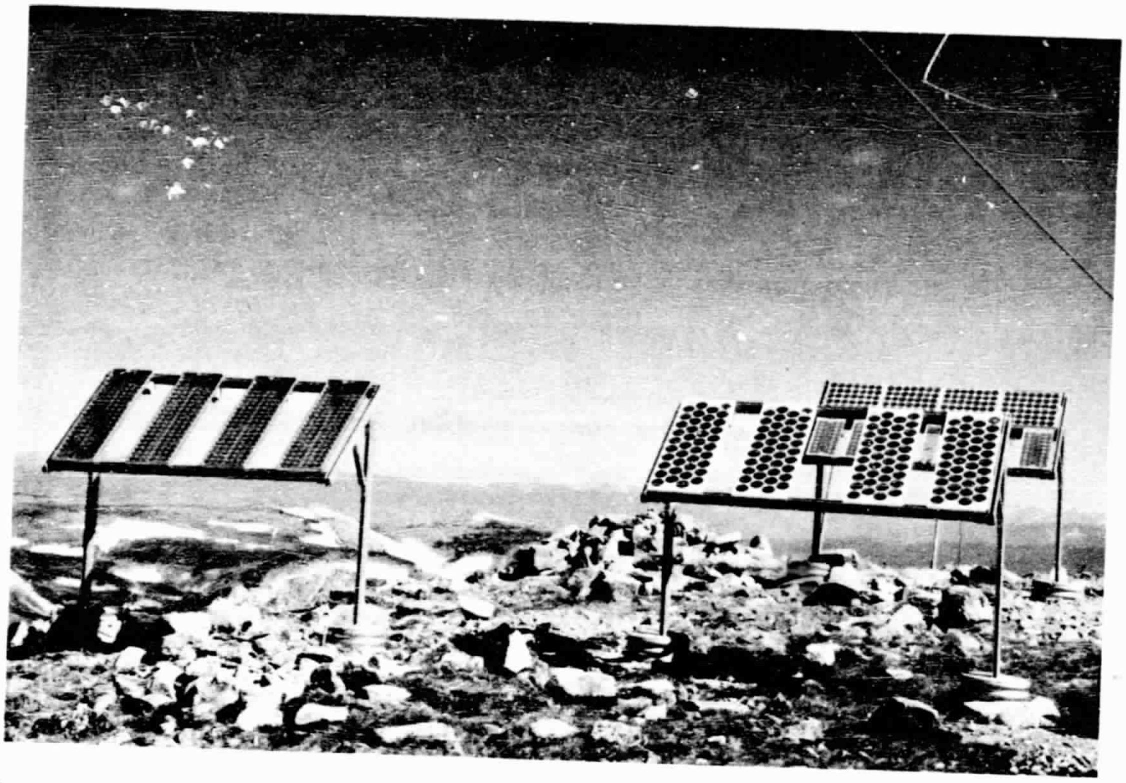
SITE CONDITIONS

- ALL SITES HAVE THE SAME INVENTORY OF MODULES: 4 EACH OF BLOCK II SENSOR TECH, SPECTROLAB, SOLAREX AND SOLAR POWER
- MODULES ARE TILTED TO THE LOCAL LATITUDE
- ALL MODULES ARE INDIVIDUALLY LOADED NEAR THE PEAK-POWER POINT
- MODULES HAVE TYPICALLY BEEN IN THE FIELD 1 1/2 years

SITE INSPECTION

- ALL MODULES WASHED PRIOR TO ACQUISITION OF DATA
- I_{SC}, V_{OC} AND PEAK-POWER OBTAINED ON EACH MODULE WITH PORTABLE INSTRUMENT
- RESULTS COMPARED WITH PRE-INSTALLATION DATA TO DETERMINE ELECTRICAL CHANGE
- EFFECTS OF EMBEDDED DIRT ELIMINATED BY USE OF FILL-FACTOR AS CHANGE CRITERIA
- A PHYSICAL INSPECTION OF EACH MODULE AND SUPPORTING EQUIPMENT PERFORMED

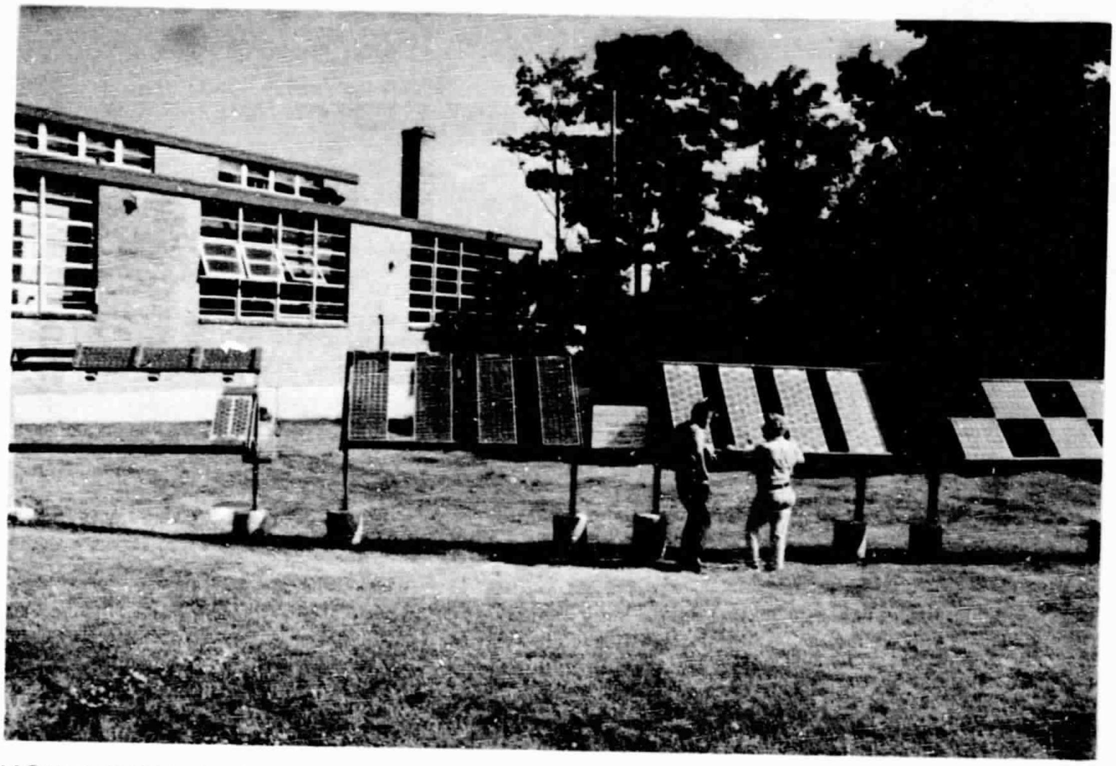
MOUNTAIN ENVIRONMENT



MINES PEAK, COLORADO LATITUDE: 40° ALTITUDE: 13,000 FT

UPPER GREAT LAKES SITE

WINTER OF 1978-79

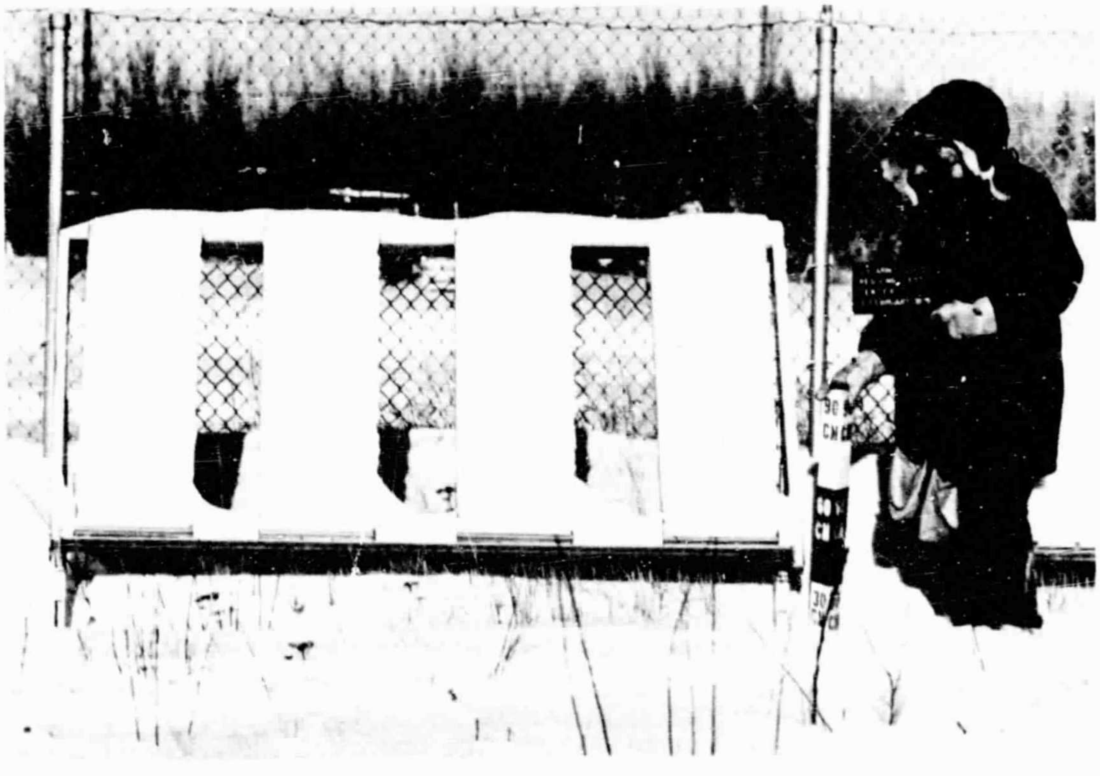


HOUGHTON, MICHIGAN LATITUDE: 47° ALTITUDE: 750 FT

EXTREME WEATHER SITES

CANAL ZONE   LATITUDE: 9° NORTH   ALTITUDE: ALMOST SEA LEVEL

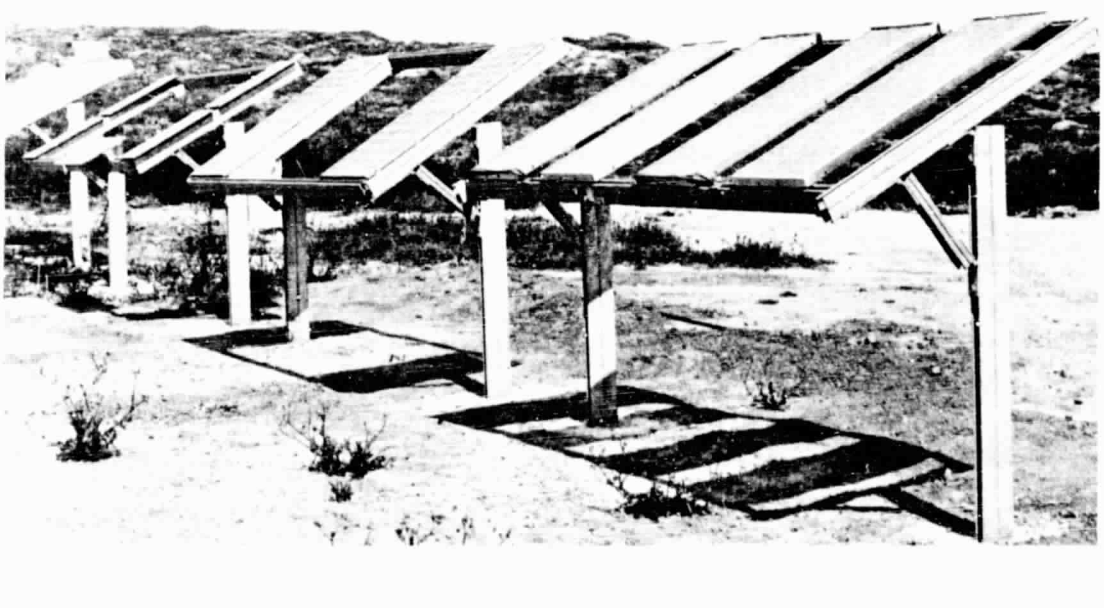
FORT GREELY, ALASKA   LATITUDE: 64°   ALTITUDE: 1,270 FT



MARINE ENVIRONMENTS

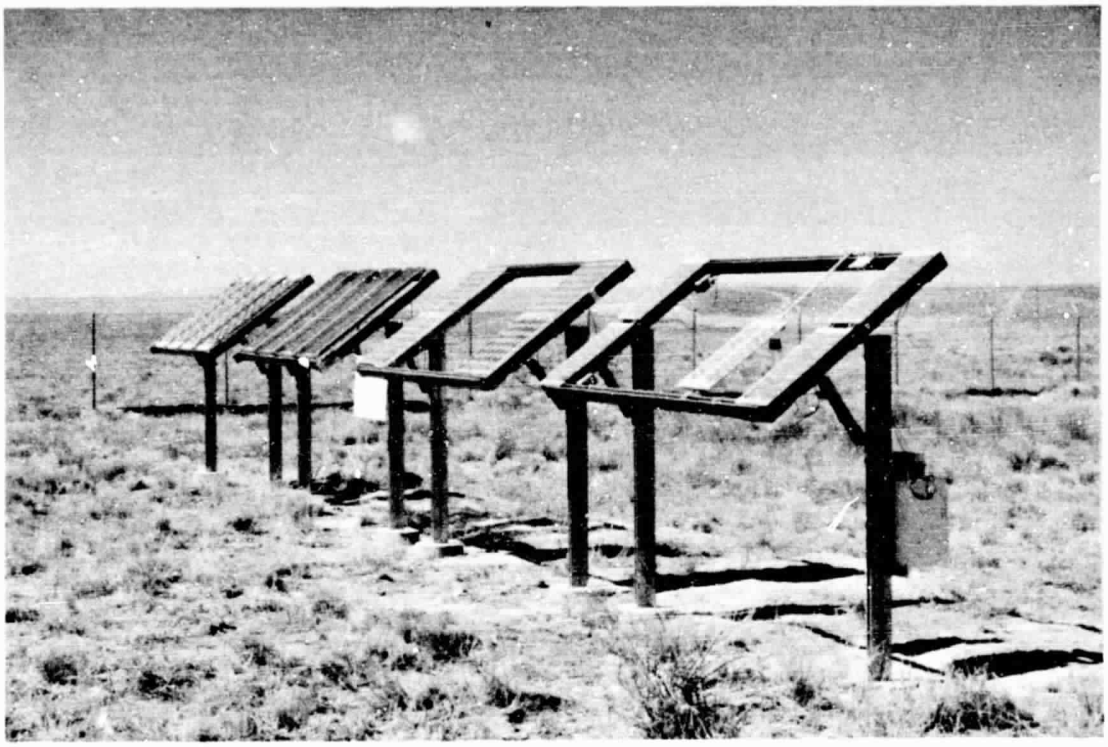
KEY WEST, FLORIDA LATITUDE: 25°

SAN NICOLAS ISLAND, CALIFORNIA LATITUDE: 34°

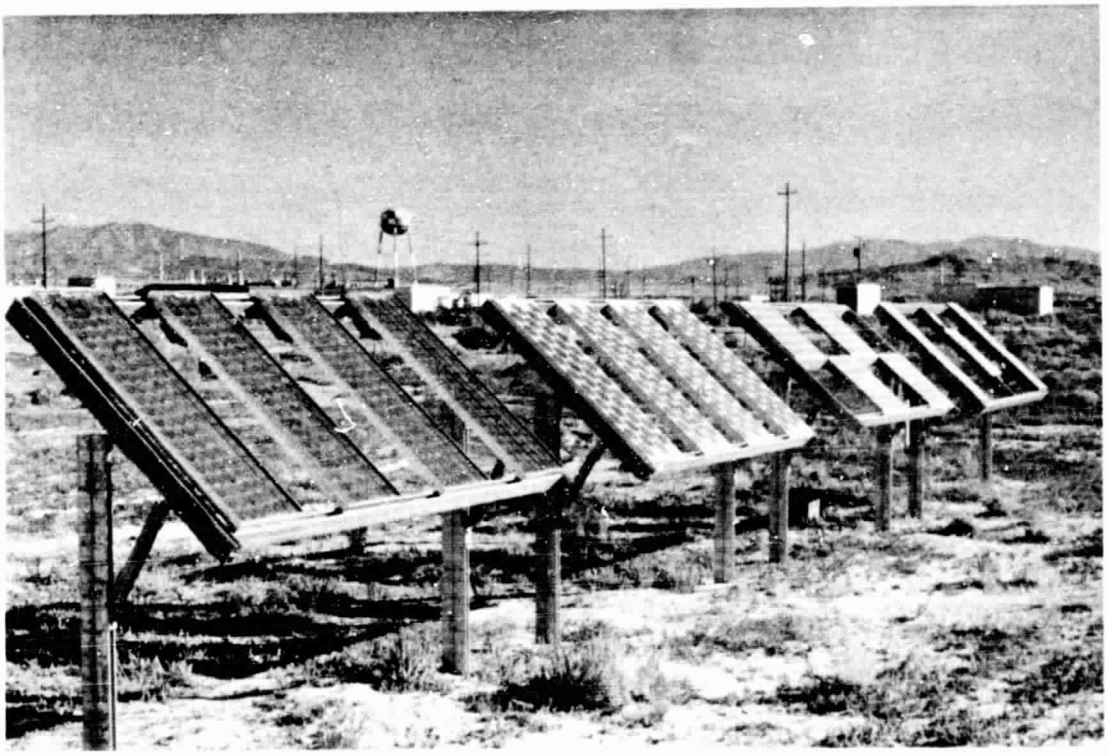


HIGH DESERT SITES

ALBUQUERQUE, NM LATITUDE: 35° ALTITUDE: 5,200 FT

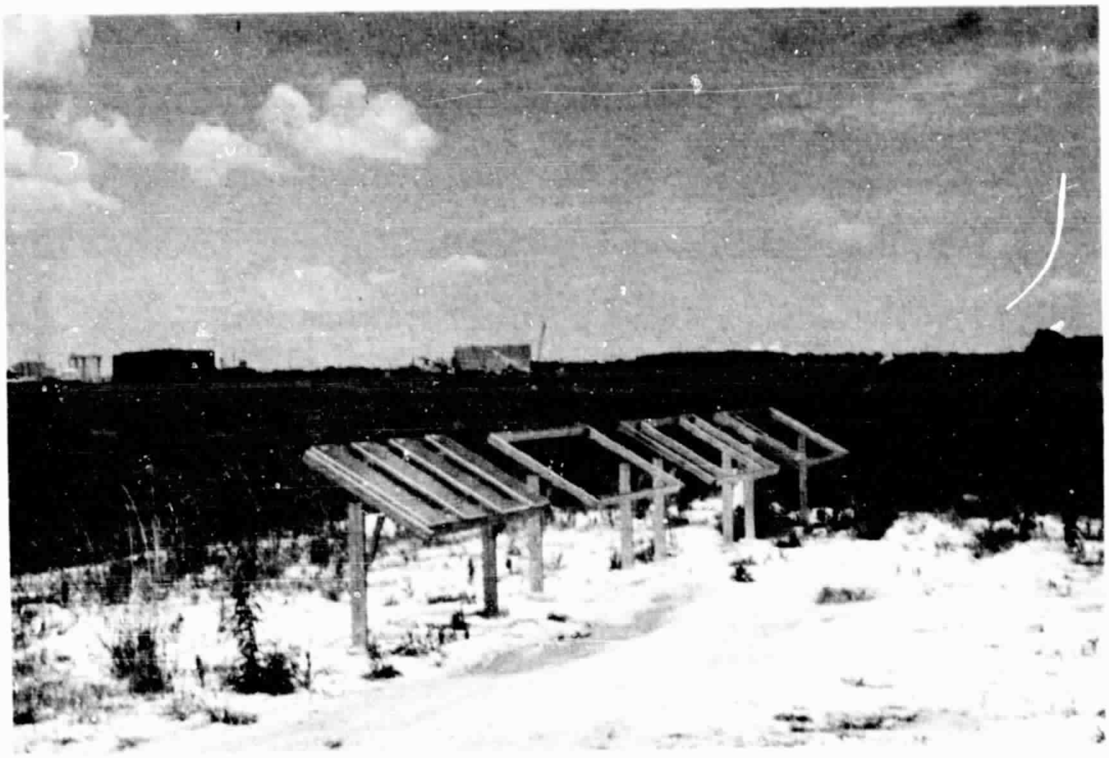


DUGWAY, UTAH LATITUDE: 40° ALTITUDE: 4,300 FT

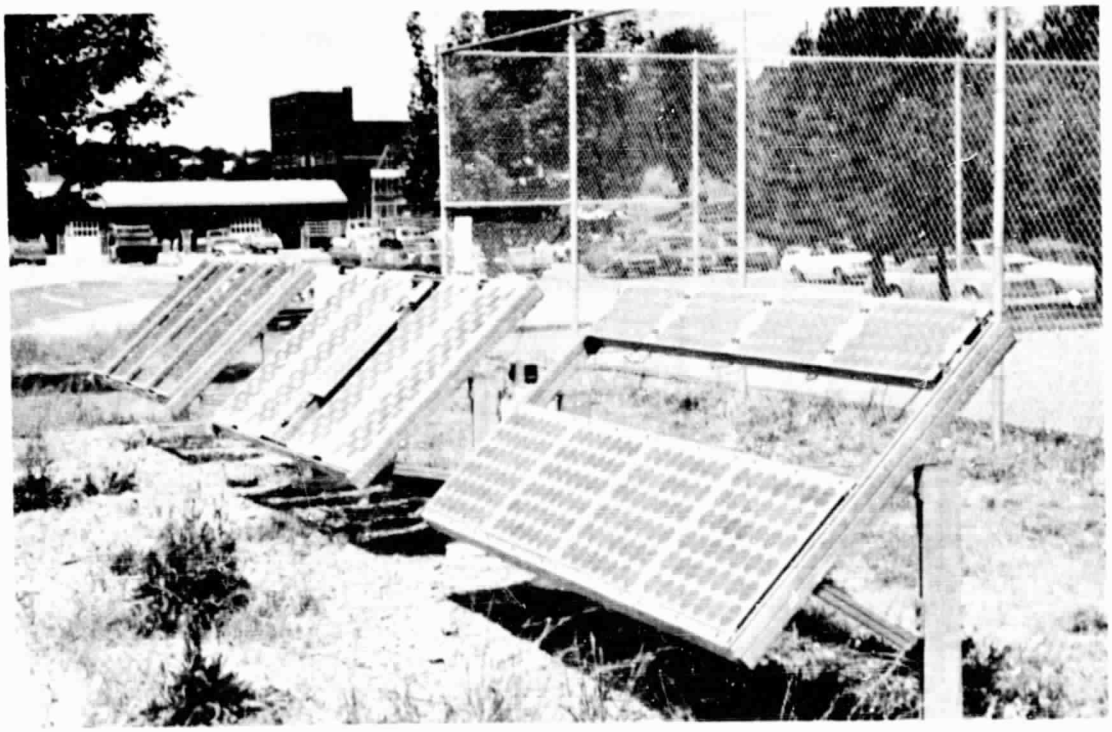


URBAN COASTAL SITES

NEW ORLEANS LATITUDE: 30°

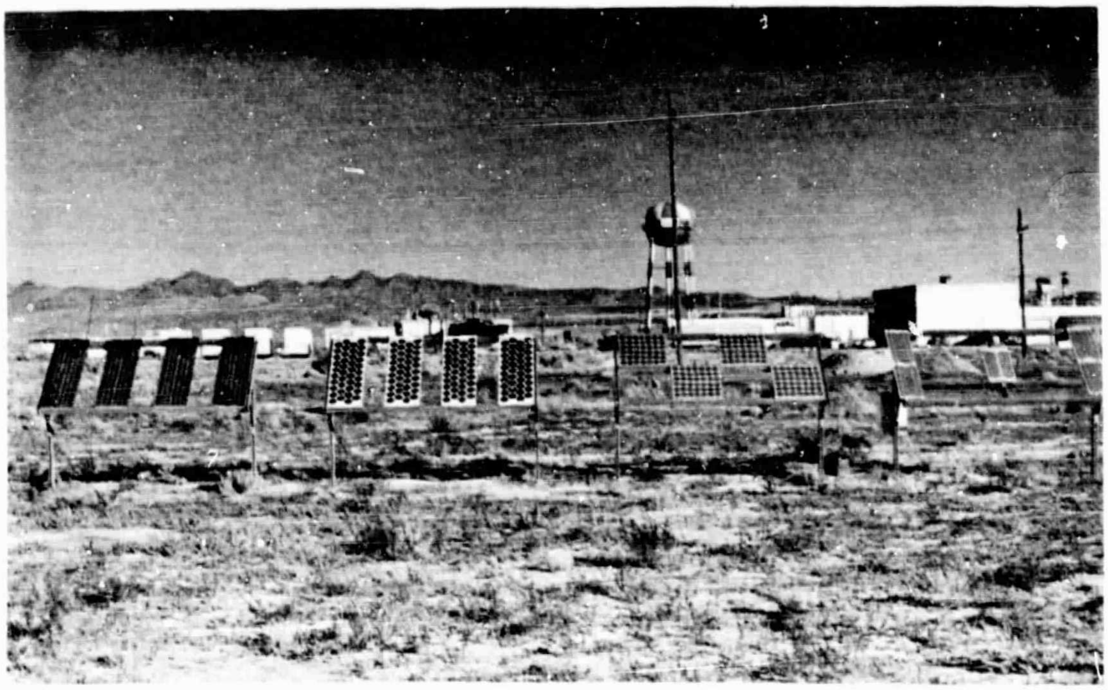


NEW LONDON, CONNECTICUT LATITUDE: 41°



MIDWEST SITE

CRANE, INDIANA LATITUDE: 39° ALTITUDE: CLOSE TO SEA LEVEL



SUMMARY OF FIELD DATA

MODULES INSPECTED: 132	CANAL ZONE	KEY WEST	NEW ORLEANS	CRANE	HOUGHTON	NEW LONDON	MINES PEAK	ALBUQUERQUE	DUGWAY	
ELECTRICAL DEGRADATION										
FAILED MODULES	[1]*							[1]		
DEGRADED MODULES	[2]	[1]			[1]					
PHYSICAL DEGRADATION										
CRACKED CELLS										
METALLIZATION DISCOLORED/CORRODED		•				•		•		
DELAMINATION										
FRAME/HARDWARE CORROSION		•	•						•	
CONNECTOR DETERIORATION		•						•	•	
WIRING DETERIORATION										
EMBEDDED DIRT		•	•	•	•	•		•	•	
STAND CORROSION	•	●	•	•		•			●	

• MODERATE AMOUNT ● SUBSTANTIAL AMOUNT

*ENCAPSULANT DAMAGED BEFORE INSTALLATION

SUMMARY AND OBSERVATIONS

- IN GENERAL THE MODULES ARE ENDURING WELL BOTH PHYSICALLY AND ELECTRICALLY IN ALL ENVIRONMENTS
- COMBINED ELECTRICAL DEGRADATION AND FAILURES TOTAL 4.5%
- NO SIGNIFICANT QUANTITIES OF CRACKED CELLS OR DELAMINATION OBSERVED
- THE MINES PEAK HIGH ALTITUDE ENVIRONMENT, OSTENSIBLY ONE OF THE MOST SEVERE, WAS THE MOST BENIGN
- ALL SILICONE ENCAPSULATED MODULES AT ALL SITES EXPERIENCED A POWER DEGRADATION DUE TO EMBEDDED DIRT. IT IS ESTIMATED THAT IN SOME CASES IT WAS AS MUCH AS 30 percent
- THE GALVANIZED SUPPORT STRUCTURES ARE NOT FAIRING AS WELL AS THE MODULES, PARTICULARLY NEAR THE OCEAN

PV MODULE PERFORMANCE AT VARIOUS MIT/LL TEST SITES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY--LINCOLN LABORATORY

STEVE FORMAN

I. SYSTEM TEST FACILITIES

MEAD, NEBRASKA: 25kW
RESIDENTIAL TEST BED, MASS.: 25 kW
ROOFTOP TEST BED, MASS.: 10 kW
UNIVERSITY OF TEXAS: 7.5 kW
CHICAGO MUSEUM: 1.5 kW

II. ENVIRONMENTAL TEST SITES

NEW YORK UNIVERSITY (23 MODULES)
COLUMBIA UNIVERSITY (10 MODULES)
MASSACHUSETTS INSTITUTE OF TECHNOLOGY (18 MODULES)
MT. WASHINGTON, N.H., WEATHER STATION (5 MODULES)

MIT LINCOLN LABORATORY PHOTOVOLTAIC PROJECT
MATERIALS, PROCESSES AND TESTING LAB

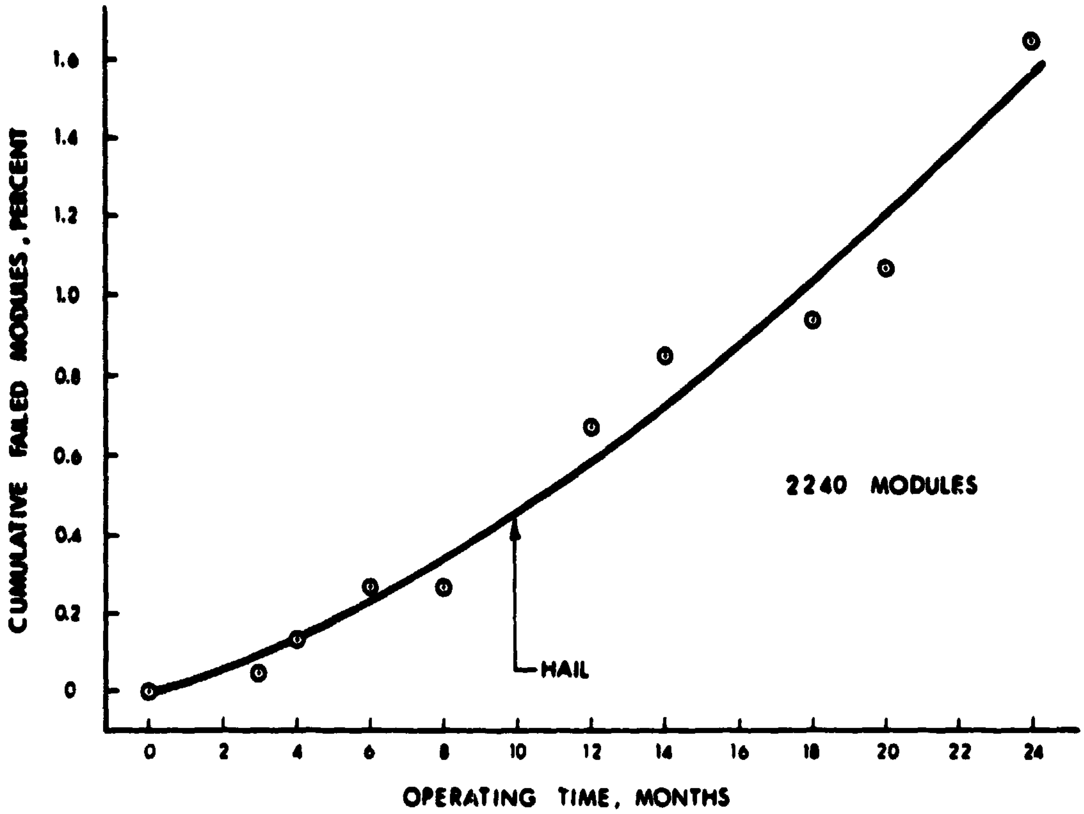
1. EVALUATE INITIAL QUALITY OF AS-RECEIVED PV MODULES.
2. FIND MODULE FAILURES AND DETERMINE CAUSES AT VARIOUS TEST SITES.
3. PERFORM VISUAL & ELECTRICAL DEGRADATION ANALYSIS ON FIELD EXPOSED MODULES.
4. DEVELOP TOOLS AND TECHNIQUES TO PERFORM ABOVE FUNCTIONS.

MODULE FAILURES AT MIT/LL TEST SITES

DATA UP TO 8/79

MANUFACTURER STARTING DATE	NEB (7/77)	RTB (11/78)	RTTB (5/77)	UTA (8/78)	CHICAGO (7/77)	TOTALS	%
A (I)	–	–	9/945	–	0/288	9/1233	0.7
B (II)	–	–	5/64	6/240	–	11/304	3.6
C (II)	18/1512	13/720	0/36	–	–	31/2268	1.4
D (II)	19/728	–	–	–	–	19/728	2.6
						70/4533	1.5%

IN-SERVICE PERFORMANCE: NEBRASKA PV MODULES



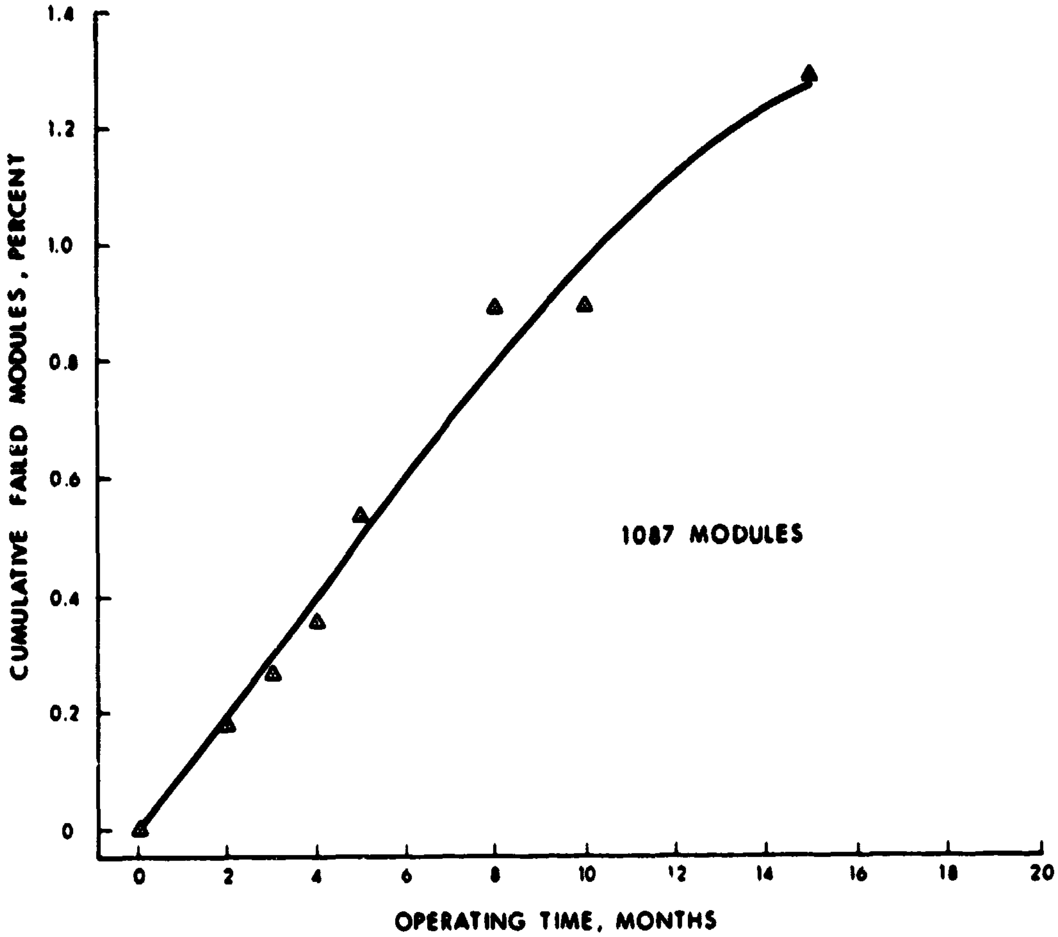
MODULE FAILURES AT MEAD TEST SITE

FRONT ROW = 728 MODULES
BACK ROW = 1512 MODULES

FAILURE = ZERO SHORT-CIRCUIT CURRENT
STARTING DATE = JULY 1977

DATE OF SEARCH	NUMBER OF FAILURES FOUND FRONT ROW	BACK ROW
OCTOBER 1977	0	1
NOVEMBER 1977	1	1
FEBRUARY 1978	0	3
MARCH 1978	0	0
JULY 1978	6	3
SEPTEMBER 1978	3	1
FEBRUARY 1979	2	0
MARCH 1979	1	2
JULY 1979	6	7
TOTALS	19	18

IN-SERVICE PERFORMANCE: ROOFTOP PV MODULES



PHYSICAL DEGRADATION AT MEAD TEST SITE

MODULES INSPECTED	2084 MODULES
EDGE-SEAL DELAMINATION	1037
NEWLY-CRACKED CELLS	821
DELAMINATION OVER CELLS	386
DELAMINATION OVER OR AROUND IC	65
SPLIT ENCAPSULANT OVER IC OR CELL	54
PROTRUDING IC OR CELL	35
TERMINAL POST AREA DELAMINATION*	1097
ENCAPSULANT TORN AROUND MOUNTING BOSS*	384
PROTRUDING GROUND SCREW*	5

*BACK ROW ONLY (OF 1400 MODULES)

FIELD INSPECTION RESULTS: UT ARLINGTON

MODULES INSPECTED	120 OF 240 BLOCK II MODULES
TYPE OF DEGRADATION	NUMBER OF MODULES
1. DELAMINATION	
TERMINAL AREA	29
EDGE SEAL	115
AROUND CELLS	45
UNDER INTERCONNECTS	33
2. DISCOLORATION	
AROUND TERMINALS (RUST-COLORED)	40
ON CELLS (WHITE RESIDUE)	31
3. CORROSION	
INTERCONNECTS (GREEN)	48 (294 PLACES)
(RUST)	9 (17 PLACES)
TERMINAL BUSS BAR (GREEN)	76
4. SPLITS IN ENCAPSULANT/HARDCOAT	10
5. CRACKED CELLS	9
6. PROTRUDING INTERCONNECTS	4
7. CRACKED INTERCONNECTS	1
8. CRACKED BUSS BARS	3

BLOCK II ELECTRICAL DEGRADATION

MFG	ENCAPSULANT	LENGTH OF EXPOSURE	AVERAGE POWER LOSS
		NEBRASKA	
B	RTV 615	16-18 MOS.	3-6%
C	SYLGARD 184	16-18 MOS.	1.5-2.5%
		ROOFTOP TEST BED	
D	RTV/HARDCOAT	11 MOS.	3%

SOIL ACCUMULATION STUDIES

MEAD, NEBRASKA TEST FACILITY

LENGTH OF EXPOSURE	AVERAGE % POWER LOSS	
	MODEL B	MODEL C
2 MONTHS	--	4.2 (11)
5 MONTHS	7.7 (8)	7.5 (5)
7 MONTHS	9.9 (22)	7.2 (12)
9 MONTHS	6.3 (28)	5.5 (12)
12 MONTHS	9.2 (28)	8.7 (12)
14 MONTHS	12.4 (28)	12.5 (11)

THE NINE-MONTH MEASUREMENT CORRESPONDS TO MARCH 1978 WHICH WAS CLOSE TO BEING THE WETTEST IN NEBRASKA'S HISTORY.

FIELD AND LAB CLEANING TECHNIQUE FOR RTV COVERED MODULES

1. WASH WITH ALCONOX AND HOT WATER.
2. RINSE WITH COLD/HOT WATER.
3. WASH WITH PUMICE AND HOT WATER.
4. RINSE WITH COLD/HOT WATER.
5. DRY USING RUBBER SQUEEGEE/SOFT CLOTH.

RECENT SOIL ACCUMULATION DATA

(12/78 - 6/79)

PERCENT POWER LOSS

MODULE TYPE	NYU	COLUMBIA	MIT	LEX	UTA
I-GLASS (PLAIN)	13.9%	--	7.2%	--	--
II-RTV -615	43.3	42.4%		8.5%	--
II-SYLGARD -184	52.9	48.1	29.9	--	--
II-RTV + 4D CT	40.5	--	13.5	5.7	4.5%
III-RTV-615	41.1	43.1	18.5	12.0	--
III-SYLGARD-184	47.3	42.7	20.3	9.9	--
III-GLASS (PLAIN)	9.3	18.1	22.5	5.3	--
III-GLASS (MATTE)	2.7	4.3	4.2	1.1	--

EFFECTS OF SNOW DEPTH ON MODULE OUTPUT POWER

PERCENT LOSS IN OUTPUT POWER

SNOW DEPTH	RTV COVERED	GLASS COVERED
1/4 IN.	50%	25-40%
1/2 IN.	60%	45-60%
1 IN.	80%	70%
1-1/2 IN.	90%	80%
2 IN.	95%	90%

SNOW DENSITY .5-.6 GMS/CC.

COLORIMETRY IN SOLAR CELL DISCOLORATION

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

EDWARD B. MURPHY

1. INSPECTION REPORTS ON FIELD EXPOSED PV SOLAR MODULES.

   - "ORIGINAL DARK STAINS RANGE FROM LIGHT GREY TO VARIOUS SHADES OF RUST"
   - "ORIGINAL PALE BLUE TENDS TO RANGE FROM PALE GOLD TO A RUSTY HUE"
   - "ORIGINAL DARK BLUE/BLACK TENDS TOWARD BROWN SHADE"

   30 MODULES FROM NEBRASKA (1/30/79)

   MODULE DEGRADATION ANALYSIS REPORT # 15

2. PRINCE AND LATHROP FROM CLEMSON UNIVERSITY REPORTED SIX PERCENT P_M LOSS ON SINGLE CELL EXPERIMENT DUE TO DISCOLORED AR COATING (5/79).

COLORIMETRY

THE COLOR-MATCHING PROPERTIES OF THE CIE 1931 STANDARD COLORIMETRIC OBSERVER ARE DEFINED BY SPECTRAL TRISTIMULUS VALUES (COLOR MATCHING FUNCTIONS) $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, WHOSE VALUES AT 5-NM X INTERVALS ARE TABULATED IN THE FOLLOWING VUEGRAPH. THESE FUNCTIONS ARE TO BE USED WHENEVER A CORRELATION IS DESIRED WITH VISUAL COLOR MATCHING OF FIELDS OF ANGULAR SUBTENSE BETWEEN 1 AND 4^o AT THE EYE OF THE OBSERVER.

HANDBOOK OF OPTICS
McGRAW-HILL PUB.

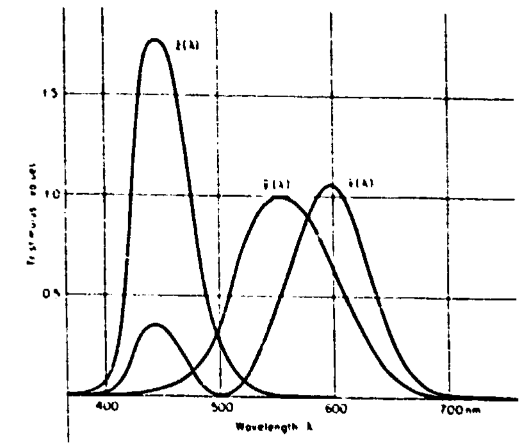
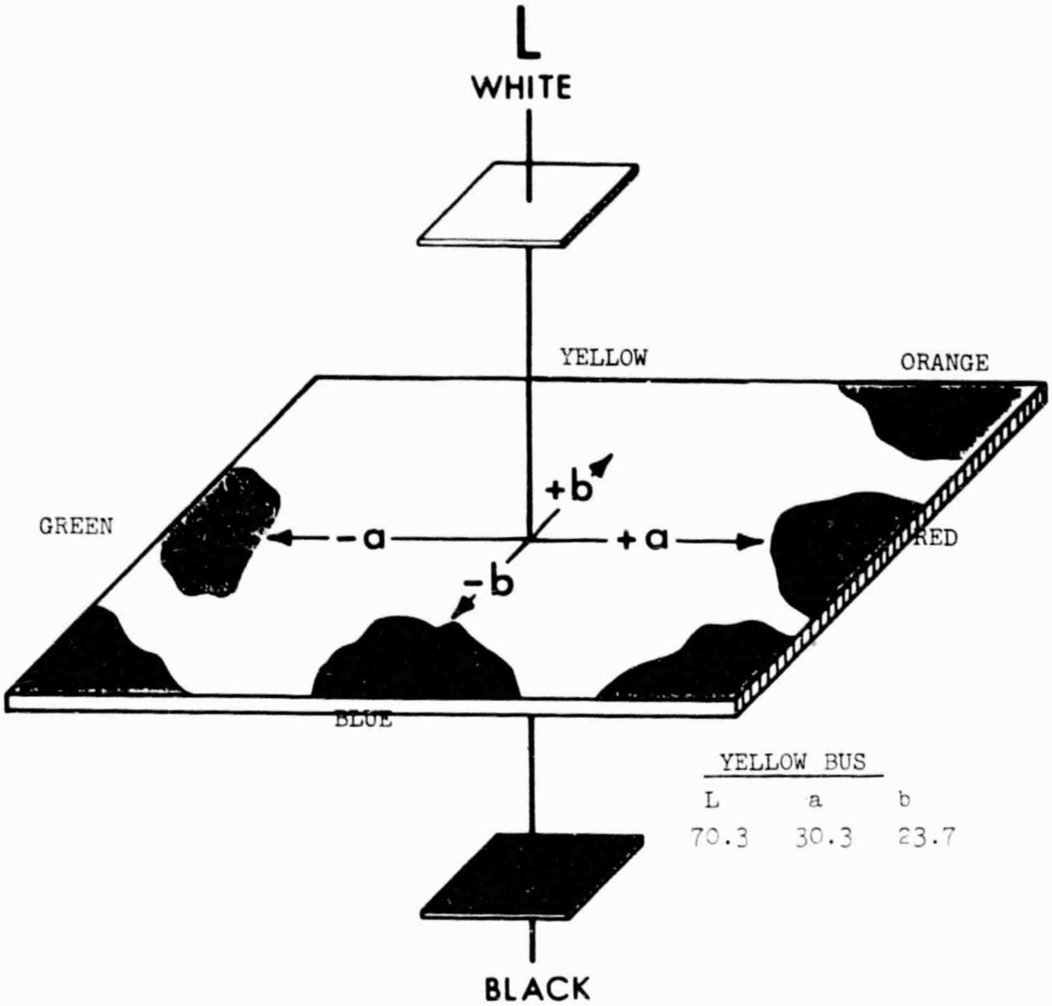


Fig. 1 Spectral tristimulus values (color-matching functions) $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ of CIE 1931 standard colorimetric observer.

L, a_L, b_L COLOR SPACE



YELLOW BUS		
L	a	b
70.3	30.3	23.7

TRISTIMULUS VALUES FROM COLOR PHOTOGRAPH

DARK BLUE CIRCUMFERENCE

L	A	B
44.6	-11.7	-10.9
45.4	-11.7	- 5.6
44.6	-11.4	- 5.6
46.3	-10.9	- 4.3
40.4	- 9.0	-12.5

L	A	B
100 = WHITE	+ RED	+ YELLOW
0 = BLACK	- GREEN	- BLUE

YELLOW CENTER ZONE

L	A	B
45.2	-9.6	-3.3
42.4	-9.8	-5.0
41.6	-8.7	-3.5

L	A	B
100 = WHITE	+ RED	+ YELLOW
0 = BLACK	- GREEN	- BLUE

CORRODED GRIDS

L	A	B
62.7	-2.9	10.2
54.4	-2.6	11.6
38.6	-4.8	3.6

L	A	B
100 = WHITE	+ RED	+ YELLOW
0 = BLACK	- GREEN	- BLUE

MISCELLANEOUS COLORIMETRIC MEASUREMENTS

	L	A	B
ST 3988 NEBRASKA	28.8	-1.2	-1.2
SL 10852	26.2	-0.2	-1.0
SX 3409	17.1	1.0	-6.2

CODE

L	A	B
100 = WHITE	+ RED	+ YELLOW
0 = BLACK	- GREEN	- BLUE

IN SITU MEASUREMENTS

	L	A	B
MODULE ST 4776 CELL #36 (UNEXPOSED)	27.3	-1.3	-1.8
CELL #1	26.9	-0.3	-2.8
	DIFFERENCE CELL # 36 FROM #1 = ▲ 4.5		
5 CENTER CELLS	27.8	-1.5	-2.4
	±2.8	±0.3	±0.8

CODE

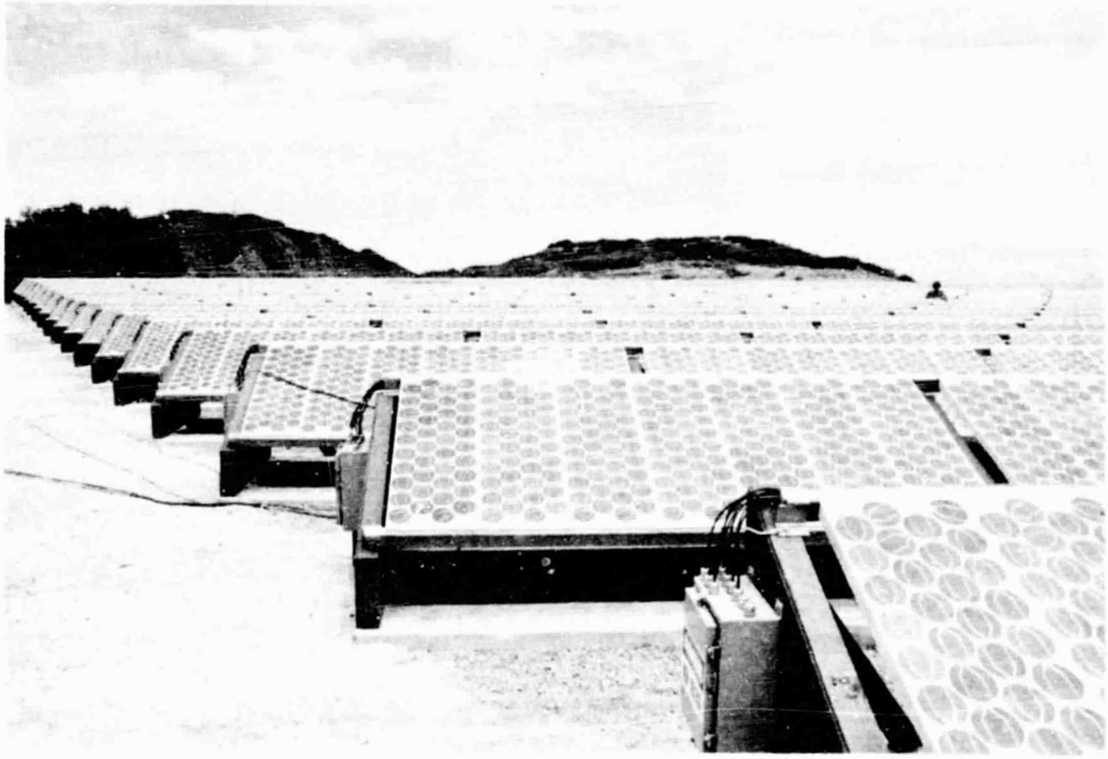
L	A	B
100 = WHITE	+ RED	+ YELLOW
0 = BLACK	- GREEN	- BLUE

CONCLUSIONS

1. COLOR CHANGES ON THE SILICON SOLAR CELL SURFACE CAN BE QUANTIFIED BY COLORIMETRIC MEASUREMENTS.
2. STUDIES INTO THE MECHANISM OF THIS COLOR CHANGE MAY BE CLARIFIED BY SPECTROPHOTOMETRIC MEASUREMENTS.
3. SINGLE CELL EXPERIMENTS RELATING THIS COLOR CHANGE TO PP CHANGES SHOULD BE PERFORMED.

DOD FIELD APPLICATIONS

MT. LAGUNA AIR FORCE STATION



ARRAY CHARACTERISTICS

- ARRAY POWER - 64 kW PEAK (60 kW SYSTEM AC OUTPUT)
- ARRAY BUS VOLTAGE - 230 V
- PERSONNEL PROTECTION BY AUTOMATIC GROUND FAULT DETECTION
- ELECTRICAL CONFIGURATION:

  169 PARALLEL STRINGS
  - 115 SOLAR POWER MODULES (BLOCK III)
  - 54 SOLAREX (BLOCK II AND III)
  - SERIES DIODE EACH STRING

14 MODULES PER STRING
SERIES CONNECTED
BYPASS DIODE EACH MODULE

2366 TOTAL MODULES
1610 SOLAR POWER (50 kW PEAK)
756 SOLAREX (14 kW PEAK)

STATUS

- SYSTEM DEDICATION - AUGUST 15, 1979
- OPERATION - WILL BE TRANSFERRED TO AIR FORCE
- MAINTENANCE BY CONTRACTOR - OCTOBER 1, 1979

APPLICATION

- 60 kW SYSTEM
- PROVIDES POWER AUGMENTATION FOR EXISTING DIESEL POWER PLANT
- NO STORAGE CAPABILITY
- POWER - CONDITIONING AND CONTROL - DECC
- DATA SYSTEM - SANDIA (HP-9845)

LARGE-SCALE PRODUCTION TASK

OBJECTIVES OF BLOCK PROCUREMENTS

- PROVIDES A MEASURE OF PROJECT SUCCESS
- PROVIDES AN INCENTIVE FOR INTRODUCING IMPROVEMENTS INTO MODULE DESIGN AND FABRICATION

- MAKES AVAILABLE UP-TO-DATE MODULE DESIGNS
- PROVIDES MODULES FOR FIELD TESTS
- PROVIDES MODULES FOR TEST AND APPLICATIONS EXPERIMENTS

BLOCK IV

PHASE ONE (UNDERWAY)

- COMPLETE DESIGN
- DEVELOP COMPLETE PRODUCTION AND INSPECTION DOCUMENTATION
- FABRICATE APPROXIMATELY ONE kW OF MODULES
- TEST MODULES TO BLOCK IV ENVIRONMENTAL SPEC
- PRICE ANALYSIS BY SAMICS/SAMIS

PHASE TWO (PLANNED)

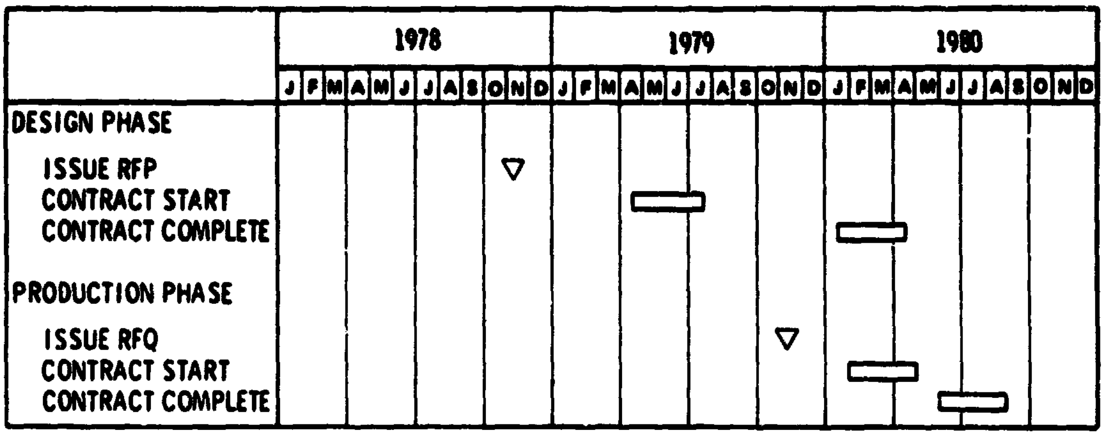
- PRODUCE 5 - 10 kW OF MODULE TYPES QUALIFIED IN PHASE ONE

CONTRACTORS	MODULE SPECIFICATION	
	INTERMEDIATE LOAD	RESIDENTIAL
ARCO SOLAR	X	X
GENERAL ELECTRIC		X
MOTOROLA	X	
APPLIED SOLAR ENERGY (OCLI)	X	
SENSOR TECH	X	
SOLAR POWER	X	
SOLAREX	X	X
SPIRE	X	

A SAMPLING OF BLOCK IV MODULE FEATURES

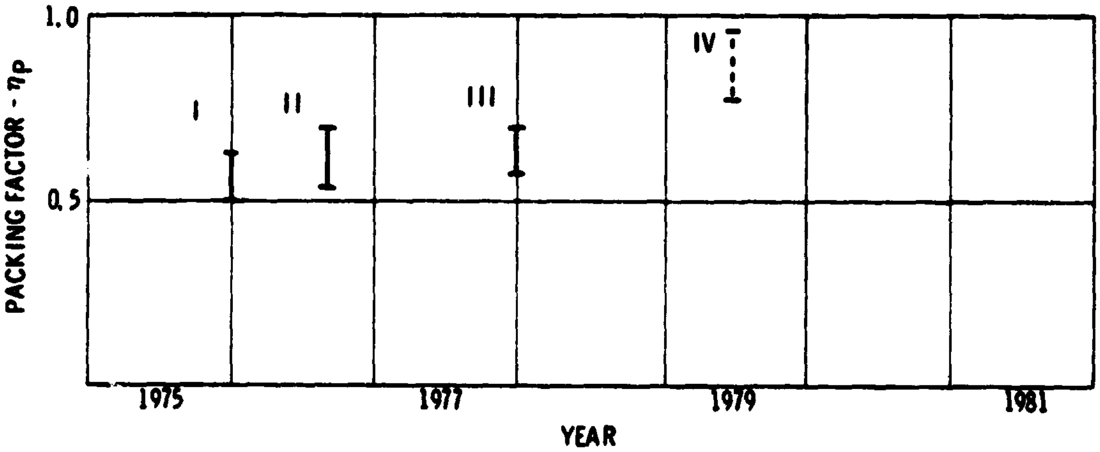
- LAMINATED ENCAPSULATION SYSTEM
- SHAPED CELLS
- BACK SURFACE FIELDS
- LOW IRON GLASS
- 15 VOLTS
- LARGER DIMENSIONS AND POWER
- ION IMPLANTED CELLS
- SEMICRYSTALLINE CELLS
- PORCELAINIZED STEEL SUBSTRATE
- FLAT INTEGRAL DIODES
- EVA ENCAPSULANT

BLOCK IV SCHEDULE

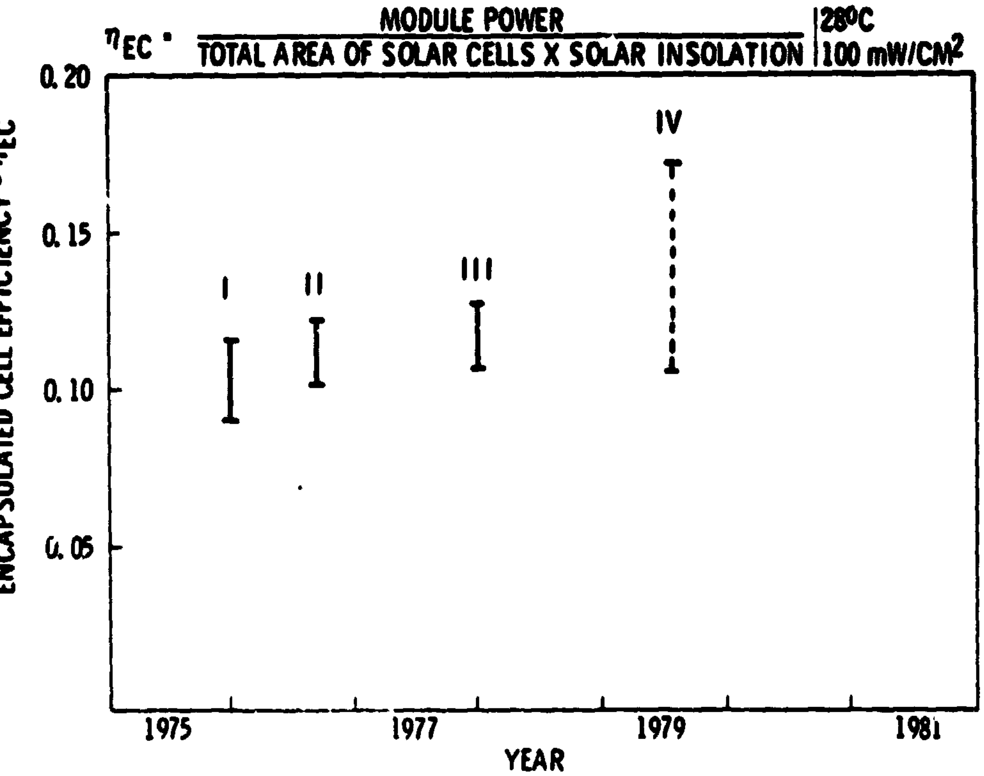


PACKING FACTOR FOR BLOCK PROCUREMENTS

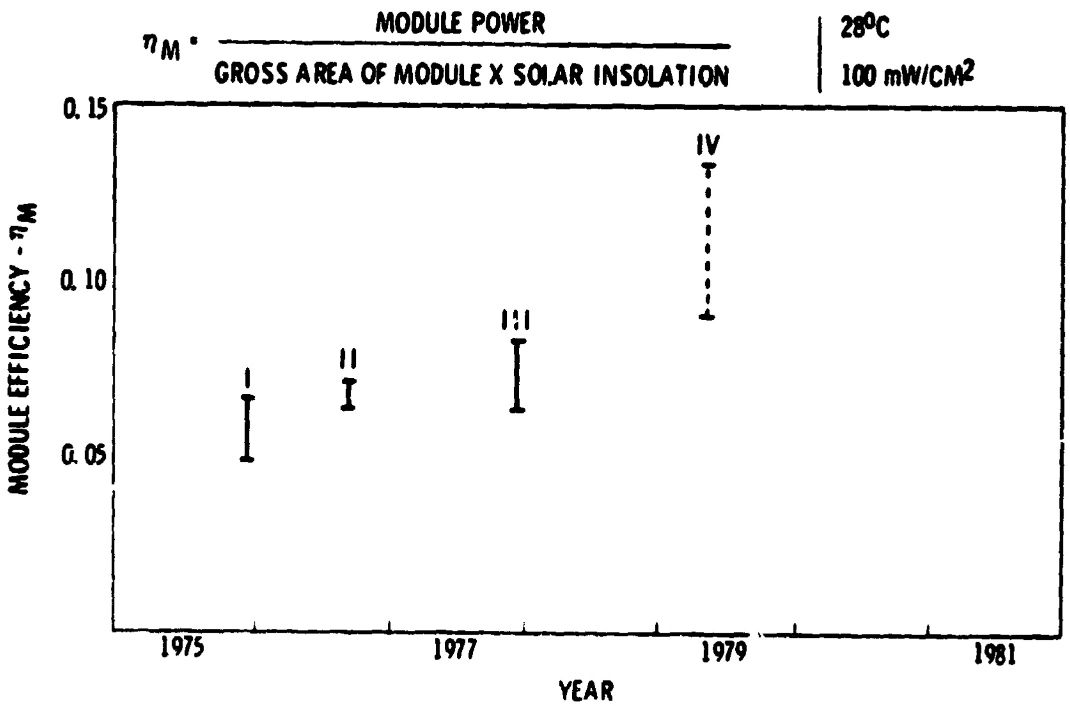
$$\eta_P = \frac{\text{TOTAL AREA OF SOLAR CELLS}}{\text{GROSS AREA OF MODULE}}$$



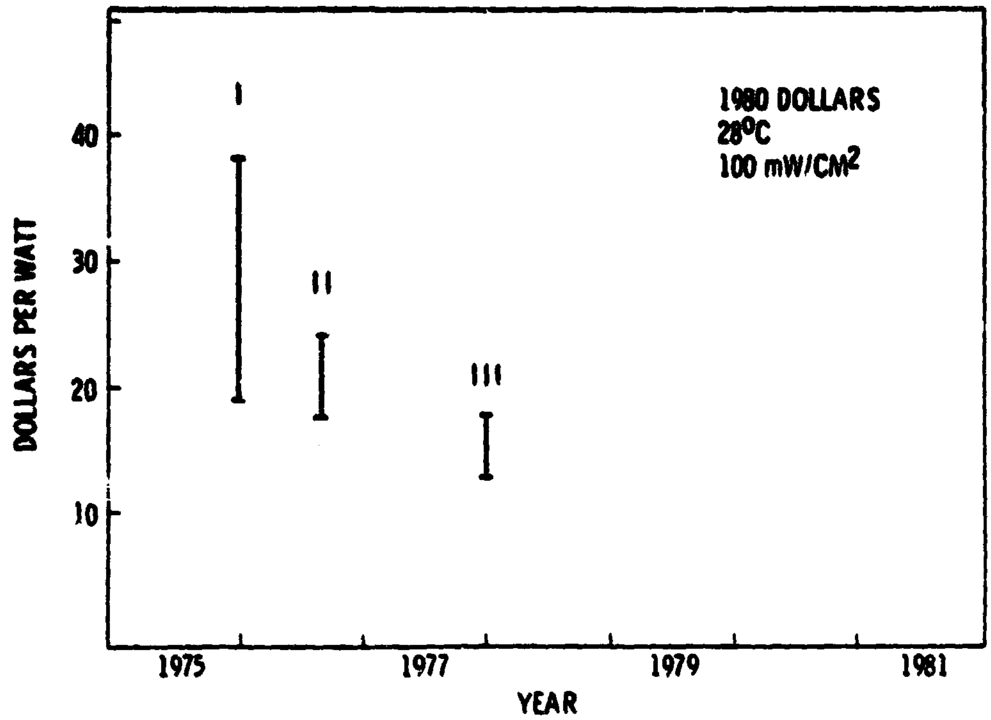
ENCAPSULATED CELL EFFICIENCY FOR BLOCK PROCUREMENTS



MODULE EFFICIENCY FOR BLOCK PROCUREMENTS



DOLLARS PER WATT FOR BLOCK PROCUREMENTS



BLOCK IV MODULE PROCUREMENT

DAN RUNKLE (JPL)

CONTRACT SCOPE AND STATUS

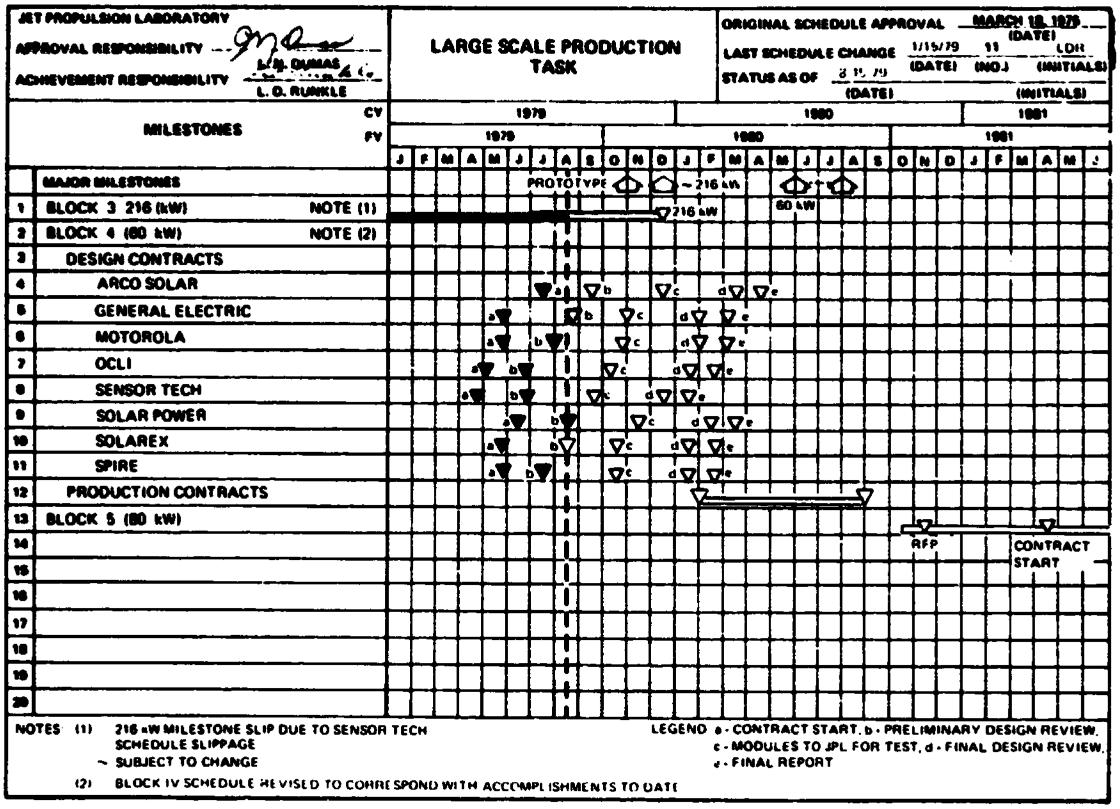
- CONTRACTOR REQUIREMENTS
- JPL REQUIREMENTS
- STATUS

BLOCK IV MODULES

- CONTRACTOR REQUIREMENTS
  - MODULE DESIGN, FABRICATION, TEST AND DELIVERY
  - STANDARDIZED PRICE ESTIMATE
  - REFERENCE CELLS
  - DOCUMENTATION
- MODULE DESIGN, FABRICATION, TEST AND DELIVERY
  - MODULE DESIGN COMPLETION TO SPEC 5101-16 OR 5101-83
  - COMPLETION OF INSPECTION SYSTEM PLAN
  - PRESENTATION OF PRELIMINARY DESIGN REVIEW
  - FABRICATION, INSPECTION, TEST AND DELIVERY OF MODULES
  - PRESENTATION OF FINAL DESIGN REVIEW
- STANDARDIZED PRICE ESTIMATE
  - USE SAMICS IN THE SAMIS COMPUTER PROGRAM
  - PRICE ESTIMATE FOR 10, 100 AND 1000 kW DELIVERED OVER THE CALENDAR YEAR 1980
- REFERENCE CELLS
  - PROVIDE 2 cm x 2 cm UNCALIBRATED REFERENCE CELLS
  - USE THE REFERENCE CELLS AS CALIBRATED BY JPL
- DOCUMENTATION
  - PROGRAM PLAN
  - TECHNICAL PROGRESS REPORT
  - DESIGN REVIEW DATE PACKAGES
    - PRELIMINARY
    - FINAL

- DOCUMENTATION (CONTINUED)
  - ENGINEERING AND MANUFACTURING DOCUMENTATION
    - PRELIMINARY
    - PRE PRODUCTION
    - PRODUCTION (PROPOSED)
  - INSPECTION SYSTEM PLAN
    - PRELIMINARY
    - PRE PRODUCTION
    - PRODUCTION (PROPOSED)
  - FINAL DESIGN REPORT
  - PRICE ESTIMATE
  - DELIVERY DATA PACKAGE
- JPL REQUIREMENTS
  - PROVIDE CALIBRATED REFERENCE CELLS
  - AUDIT INSPECTION PERFORMED BY CONTRACTOR
  - PROVIDE SAMICS/SAMIS TUTORIAL
  - CONFIRM VALIDITY OF CONTRACTOR MODULE PERFORMANCE MEASUREMENT TECHNIQUE AND PROCEDURES
  - PERFORM CHARACTERIZATION AND QUALIFICATION TESTS OF MODULES

LARGE-SCALE PRODUCTION TASK SCHEDULE



BLOCK IV DESIGN REQUIREMENTS

- PERFORMANCE
  - P_{avg} @ V_{no}, STANDARD OPERATING CONDITIONS
- ELECTRICAL
  - V_{no} = 15 VDC, OR FRACTION/MULTIPLE ≤ 60 VDC
  - SAFETY (2000 VDC/ILC - 1500 VDC/RESI.)
  - SERIES/PARALLEL FEATURES
  - REDUNDANT OUTPUT TERMINATIONS
- MECHANICAL
  - ILC PANELS 1.2 m X WIDTH UP TO 1.2 m
  - RESIDENTIAL INSTALLATION DESIGN DEPENDENT (PANELS/SHINGLES)
  - SELF CLEANING OPTICAL SURFACES
  - INTERCHANGEABILITY
- ENVIRONMENTAL
  - APPLICATION DEPENDENT TEST LEVELS SPECIFIED FOR TEMPERATURE, HUMIDITY, WIND LOADING, MOUNTING, AND HAIL

PERFORMANCE REQUIREMENTS

- MEASUREMENTS REFERENCED TO STANDARD OPERATING CONDITIONS (SOC):
  - IRRADIANCE = 100 mW/cm^2
  - CELL TEMPERATURE = NOCT
- NOMINAL OPERATING CELL TEMPERATURE (NOCT) DETERMINED FOR STANDARD THERMAL ENVIRONMENT
- TEMPERATURE CORRECTION COEFFICIENTS ESTABLISHED
- PROTOTYPE MODULE TESTS ESTABLISH INITIAL P_{avg}
- INDIVIDUAL MODULE POWER $\geq$90% P_{avg}

NOCT SPECIFICATION

- OBJECTIVE:
  - TO ALLOW THE ELECTRICAL PERFORMANCE OF MODULES OF VARIOUS THERMAL DESIGNS TO BE SPECIFIED AND COMPARED AT AN OPERATING POINT REPRESENTATIVE OF TYPICAL FIELD AMBIENT CONDITIONS
- APPROACH:
  - SPECIFY ELECTRICAL PERFORMANCE AT A CELL TEMPERATURE (NOCT) WHICH REFLECTS THE MEASURED CELL TEMPERATURE IN THE STANDARD THERMAL ENVIRONMENT:

AIR TEMPERATURE	= 20°C
WIND AVERAGE VELOCITY	= 1 m/s
INSOLATION	= 100 mW/cm^2
MOUNTING	= NORMAL TO SOLAR NOON, TYPICAL THERMAL BOUNDARY CONDITIONS
ELECTRICAL LOAD	= OPEN CIRCUIT

CORRECTION OF OTC POWER TO SOC

- MEASUREMENTS AT OPTIONAL TEST CONDITIONS
  - 100 mW/cm^2 INSOLATION
  - CELL TEMPERATURE AT LAB AMBIENT
  - TEMPERATURE COEFFICIENTS KNOWN

- $P = V_{no} (I_{OTC} + \Delta I)$

WHERE

I_{OTC} = I AT V_{OTC}

$\Delta I = C_I (T_{NOCT} - T_{OTC})$

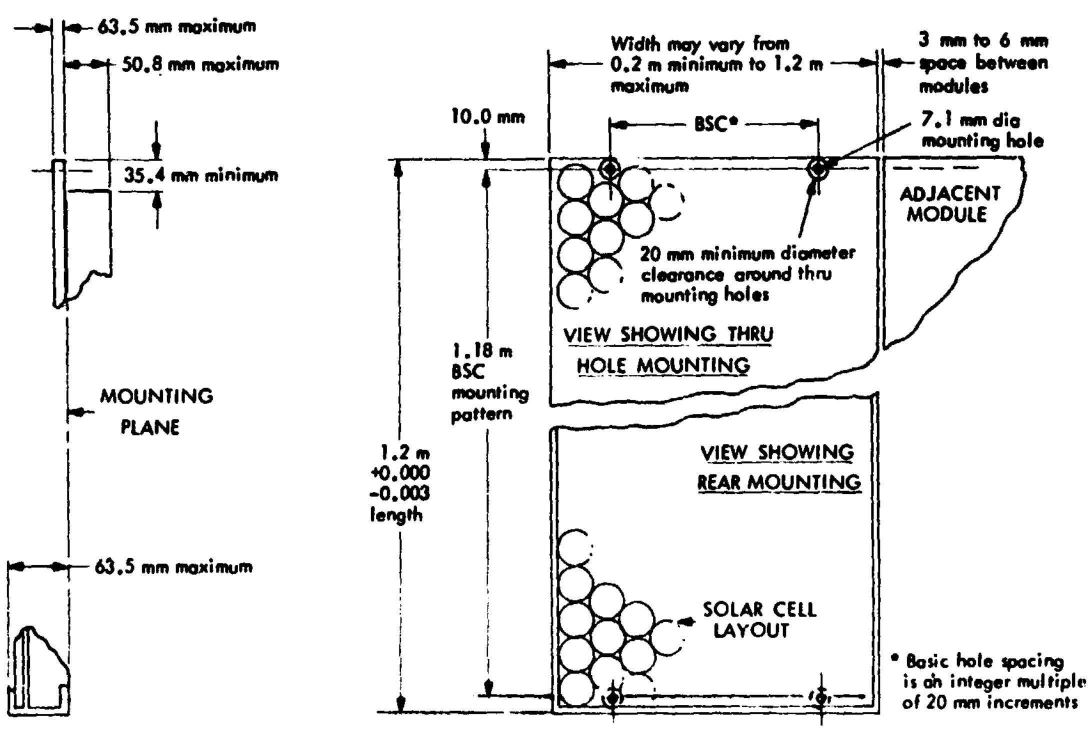
$V_{OTC} = V_{no} - \Delta V$

$\Delta V = C_V (T_{NOCT} - T_{OTC})$

C_I, C_V = TEMPERATURE COEFFICIENTS

INTERMEDIATE LOAD CENTER MODULE CONFIGURATION

(5101-16A)



ENVIRONMENTAL QUALIFICATION TESTS
FLAT-PLATE MODULES

TESTS	MODULES					TEST LEVELS
	BLK I	BLK II	BLK III	PRDA-38	BLK IV	
THERMAL CYCLE	X	X	X	X	X	-40°C, +90°C/hr 50 CYCLES (BLK I - 100 CYC)
HUMIDITY CYCLE	X	X	X	X	X	5 CYCLES, 95%, +40°, +28°C (BLK I 90%, 70°C)
MECHANICAL LOADING		X	X	X	X	±2.4 kPa, 10000 CYCLES (±1.7 kPa FOR RESIDENTIAL) (BLK II, III - 100 CYCLES)
TWIST		X	X	X	X	±2 cm/m
HAIL IMPACT				X	X	3 HITS, 3 PLACES W/20 mm ICE BALL
ELECTRICAL ISOLATION		X	X	X	X	2 X SYSTEM VOLTAGE PLUS 1000 VDC
WIND RESISTANCE					X SHINGLES ONLY	UL 997

CONFIGURATION/DESIGN FEATURES—BLOCK IV MODULES

- ICL MODULES
  - ALL DESIGNS MEET 5101 - 16A MOUNTING REQUIREMENTS
  - WIDTHS VARY FROM 340 mm TO 640 mm
  - CELLS ARE 100 cm OR SHAPED FROM LARGE CELLS
  - REDUNDANT OUTPUT TERMINATIONS
  - ENCAPSULATION SYSTEMS
    - GLASS SUPERSTRATE MOST COMMON
    - EVA AND PVB LAMINATIONS
    - LOWCOST (GALVANIZED, PORCELAINIZED) SUBSTRATES
  - FRAMING METHODS ADDRESS SIMPLIFIED ASSEMBLY

- RESIDENTIAL
  - LARGE CELLS ARRANGED WITH HIGH PACKING DENSITY
  - 3 APPROACHES TO INSTALLATION
  - 2 GLASS SUPERSTRATE, 1 METAL SUPERSTRATE
  - MODULE SIZES INFLUENCED BY INSTALLATION

ELECTRICAL PERFORMANCE OF BLOCK IV MODULES

ILC (7 mfgs).

V_{NO}:	15 Vdc
NOCT:	46^0C TO 57^0C
P@SOC:	36 WATTS TO 100 WATTS

RESIDENTIAL (3 mfgs).

V_{NO}:	5, 7.5, AND 15 Vdc
NOCT:	51^0C TO 64^0C
P@SOC:	17.3 WATTS TO 65 WATTS

ELECTRICAL DESIGN FEATURES—BLOCK IV ILC

MFG	CELLS	S/P	SEB	DIODE	TOP CONTACT REDUNDANCY	TERMINATION
A	33	33S	1	NO	MULTIPLE	STUD IN J-BOX
B	288	36S/8P	36	NO	MESH	STUD
C	152	38S/4P	38	YES	TRIPLE	CONNECTOR
D	136	34S/4P	6	YES	MESH	PIGTAIL
E	72	36S/2P	36	YES	MULTIPLE	PIGTAIL
F	120	40S/3P	5	NO	DUAL	TERMINAL BLOCK
G	35	35S	1	NO	MULTIPLE	STUD IN J-BOX

ELECTRICAL DESIGN FEATURES—BLOCK IV RESIDENTIAL

MFG	CELLS	S/P	SEB	DIODE	CONTACT REDUNDANCY	TERMINATION
A	19	19S	1	NO	DUAL	SCREW CONTACT
B	32	32S	1	NO	MULTIPLE	STUD IN CHANNEL
C	72	12S/6P	12	NO	SIX	PIGTAIL

MECHANICAL DESIGN—BLOCK IV ILC

MFG	GROSS AREA (CM^2)	CELL AREA (CM^2)	$P\eta$	DEEP (CM)	FRONT SURFACE
A	7200	6768	.96	4.6	ACRYLIC FILM
B	3600	3300	.92	4.7	GLASS
C	6720	5984	.89	4.0	GLASS
D	4800	4195	.87	6.1	GLASS
E	7680	6498	.85	3.8	GLASS
F	4785	3823	.79	6.3	GLASS
G	3600	2730	.76	3.8	GLASS

MECHANICAL DESIGN FEATURES—BLOCK IV RESIDENTIAL

MFG	GROSS AREA (CM^2)	CELL AREA (CM^2)	$P\eta$	DEEP (CM)	WEIGHT (kg)	W/kg	FRONT SURFACE
A	7620	6498	.85	5.0	10.7*	6.1	GLASS
B	743	568	.76	.5	3.8	4.5	GLASS
C	4270	2513	.59	2.5	3.8	8.6	TEDLAR

* DOES NOT INCLUDE MOUNTING HARDWARE.

BLOCK IV ENCAPSULATION SYSTEMS

• LAMINATED CONSTRUCTION	- ALL DESIGNS
• GLASS SUPERSTRATE	- 8 OF 10
• POTTANTS	- EVA (5)
	- PVB (4)
	- SILICONE (1)
• SUBSTRATE (OR BARRIER)	- PLASTIC FILM (7)
	- ALUM. FOIL LAMINATE (1)
	- STEEL (2)
• SEALANTS	- BUTYL RUBBER
	- PROGLAZE
	- SILICONE RUBBER
• FRAMES	- ALUMINUM
	- STAINLESS
	- REINFORCED PLASTIC

'THIRD GENERATION' DESIGNS

- IMPROVED SPECIFICATION OF POWER OUT
  - ACCOUNT FOR OPERATING TEMPERATURE DIFFERENCES
  - BETTER MODULE-TO-MODULE UNIFORMITY
  - CONSISTENCY WITH ACCEPTED INSOLATION LEVELS/PROCEDURES
- SERIES/PARALLEL CELLS FOR INCREASED RELIABILITY (IMPROVED YIELD)
- MECHANICAL/ELECTRICAL CONFIGURATION ADDRESSED TO GENERALLY LARGER APPLICATIONS
  - INCREASED MODULE SIZE FOR LOWER INITIAL AND INSTALLATION COSTS ENCOURAGED
  - OPERATING VOLTAGES CONSISTENT WITH APPLICATIONS
- IMPROVED ARRAY EFFICIENCY ENCOURAGED
  - INCREASED CELL EFFICIENCY
  - HIGHER CELL PACKING FACTORS
  - IMPROVED THERMAL DESIGN (LOWER NOCT)
- ENVIRONMENTAL QUALIFICATION PROCEDURES/LEVELS CONSISTENT WITH/RESPONSIVE TO APPLICATION FACTORS
- PROCESS CONTROL RELATED QA PROGRAMS EMPHASIZED
- INNOVATIVE DESIGN APPROACHES DEMONSTRATING TECHNOLOGY READINESS (CELLS, MATERIALS, PROCESSES)

5. Project Analysis and Integration Area

INTER-TECHNOLOGY SESSION

Paul K. Henry, Chairman

Four topics were addressed in this session. First, the release of an improved version of SAMIS III was described. This release occured on July 9. A technical correction of the one-time-cost submodel (startup costs and interest during construction) should reduce SAMIS prices by a small amount. Inflation rates have also been updated to match the recent changes in the economy. Indirect requirements have also been reviewed by a number of people. Numerous adjustments were made in this area so that the indirect costs calculated within SAMIS will more closely describe the actual costs of a photovoltaic manufacturing plant.

The second topic was the price allocation guidelines that have been proposed for elements of the LSA Project. The viewgraphs below describe current project thinking on this subject and a document that contains a definitive version of these guidelines will be available in the next few months.

The third topic was the seven candidate factories. PP&E provided four alternative cell processing sequences and four alternative sheet materials were obtained from Task 2. Early versions of these factories were used to supply numbers for the posters used in the PP&E poster session. A more developed version of these factories was available in time for the presentation on Thursday afternoon. Candidate process development will continue as an ongoing activity.

The final topic was an analysis of best case/worst case scenarios for alternative sheet technologies. These scenarios are based on upper and lower bounds on advanced technology that may reach a state of technical readiness by the end of 1982. The range of possible outcomes is large in all cases, with each technical approach providing a lower bound on price that is below the candidate factory prices and below the Project's price goal.

PV MODULE COST ANALYSIS

R. W. ASTER (JPL)

1. SAMIS III, RELEASE 2
2. PROPOSED PRICE ALLOCATION GUIDELINES
3. CANDIDATE FACTORIES

SAMIS MODIFICATIONS

1. RELEASE 2 IS AVAILABLE.
2. INFLATION AND DEFLATION RATES HAVE BEEN CHANGED.
3. SAMIS INDIRECT REQUIREMENTS.

SAMICS PRICE DEFLATORS

	OLD GNP INFLATION	CUMULATIVE DEFLATOR	NEW GNP INFLATION	CUMULATIVE DEFLATOR
1975	7.1		7.5	
1976	4.7	1.071	4.7	1.075
1977	6.0*	1.121	6.1	1.126
1978	6.0	1.189	8.3	1.194
1979	6.0	1.260	8.3**	1.294
1980	6.0	1.336	7.0	1.401
1981	6.0	1.416	7.0	1.499
1982	6.0	1.501	7.0	1.604
1983	6.0	1.591	7.0	1.716
1984	6.0	1.686	7.0	1.836
1985	6.0	1.787	7.0	1.965
1986	6.0	1.894	7.0	2.102

*ORIGINAL PROJECTION **DRI PROJECTION - MAY, 1979

SAMIS INDIRECT REQUIREMENTS

MODIFICATIONS HAVE BEEN PROPOSED BY:

- PP&E ENGINEERS (ESPECIALLY C. OLSEN, D. BICKLER, P. ALEXANDER);
- TB&A (BASED UPON COMPARISONS WITH CONVENTIONAL A&E DESIGNS.);
- PA&I INTERNAL REVIEW;
- LSA CONTRACTORS.

OBJECTIVES:

1. WHERE POSSIBLE, INDIRECT REQUIREMENTS SHOULD HAVE A CAUSAL RELATIONSHIP WITH DIRECT REQUIREMENTS;
2. WHERE NECESSARY, INDIRECT REQUIREMENTS THAT ARE NOT CAUSALLY RELATED TO DIRECT REQUIREMENTS MUST BE REASONABLE. THIS MEANS THAT THEY MUST BE AS CLOSELY CORRELATED AS POSSIBLE TO THE DIRECT REQUIREMENTS. (FOR EXAMPLE, LEGAL COSTS SHOULD CORRELATE WITH THE SIZE OF THE FIRM AND THE NUMBER OF PEOPLE EMPLOYED.)

EXAMPLES:

- WAREHOUSE USED TO BE PROPORTIONAL TO EQUIPMENT FLOOR SPACE. IT IS NOW PROPORTIONAL TO THE QUANTITY OF BULK MATERIAL (e.g., GLASS, PACKING CRATES) BEING USED.
- OFFICE SPACE WAS ADJUSTED TO REFLECT THE FACT THAT MANY "STAFF" PERSONNEL DO NOT USE INDIVIDUAL OFFICES (e.g., JANITORS, GROUNDKEEPERS).
- ITEMS HAVE BEEN ADDED, SUCH AS FORKLIFT TRUCKS FOR THE WAREHOUSE, A COMPUTER FOR THE COMPUTER ROOM, SUPERVISION FOR ENGINEERING AIDES.
- ITEMS HAVE BEEN REDUCED, SUCH AS OFFICE SUPPLIES, LAND USED FOR LANDSCAPING, CAFETERIA COSTS, ETC.

APPROXIMATELY 50 CHANGES WERE MADE.

PRICE ALLOCATION GUIDELINES
(A PRELIMINARY REVISION)

MAJOR CHANGES:

- GOALS ARE TIMED FOR TECHNOLOGY READINESS IN 1982.
- GOALS ARE BASED ON SPECIFIC SHEET TECHNOLOGIES.
- INGOT TECHNOLOGY EFFICIENCY GOALS ARE REDUCED.
- KNOWLEDGE GAINED IN THE LAST YEAR IS INCORPORATED.

PRELIMINARY 1982 TECHNICAL READINESS PRICE ALLOCATION GUIDELINES (1980 $)

	GOALS		
SILICON (POLYCRYSTALLINE)	14	$/Kg	0.035-0.117 * $/Wp
SHEET ALTERNATIVES:			
-Cz INGOT & SLICING	28.9	$/m^2 OF WAFER	0.204 "
-HEM INGOT & SLICING	35	$/m^2 WAFER	0.246 "
-EFG	24.2	$/m^2 WAFER	0.214 "
-WEB DENDRITIC	39.3	$/m^2 WAFER	0.297 "
-SOC	20.3	$/m^2 WAFER	0.196 "
CELL FABRICATION	21	$/m^2 OF CELLS	0.141-0.192 * "
ENCAPSULATION MATERIALS	14	$/m^2 OF MODULE	0.098-0.139 * "
MODULE ASSEMBLY	14	$/m^2	0.098-0.139 * "
MODULE TOTALS			0.70 $/Wp

* THIS RANGE IS CAUSED BY THE USE OF DIFFERENT SHEET TECHNOLOGIES.

BASIS FOR LSA PROJECT GOALS

	SHEET ALTERNATIVE				
	C_Z	HEM	EFG	WEB	SOC
CELL EFFICIENCY *	15	15	12	14	11
PACKING EFFICIENCY	78	95	95	95	95
MODULE EFFICIENCY	11.7	14.25	11.4	13.3	10.1
SHEET THICKNESS (MILS)	10	10	8	6	4
SHEET PROCESSING	0.50	0.50	0.90	0.90	0.92
CELL YIELD	0.95	0.95	0.95	0.95	0.95
MODULE YIELD	0.995	0.995	0.995	0.995	0.995
SI YIELD / Wpk (GRAMS/Wpk)	8.35	8.35	4.6	3.0	2.5

* ENCAPSULATED CELL EFFICIENCY; BARE-CELL η MUST BE > [illegible] BY 10%.

13TH PIM PRESENTATION ON CANDIDATE FACTORIES

- ASSUMPTIONS & CAVEATS
- SELECTION OF CANDIDATE PROCESSES
- EFFECT OF ALTERNATIVE SHEET MATERIALS

CANDIDATE FACTORIES

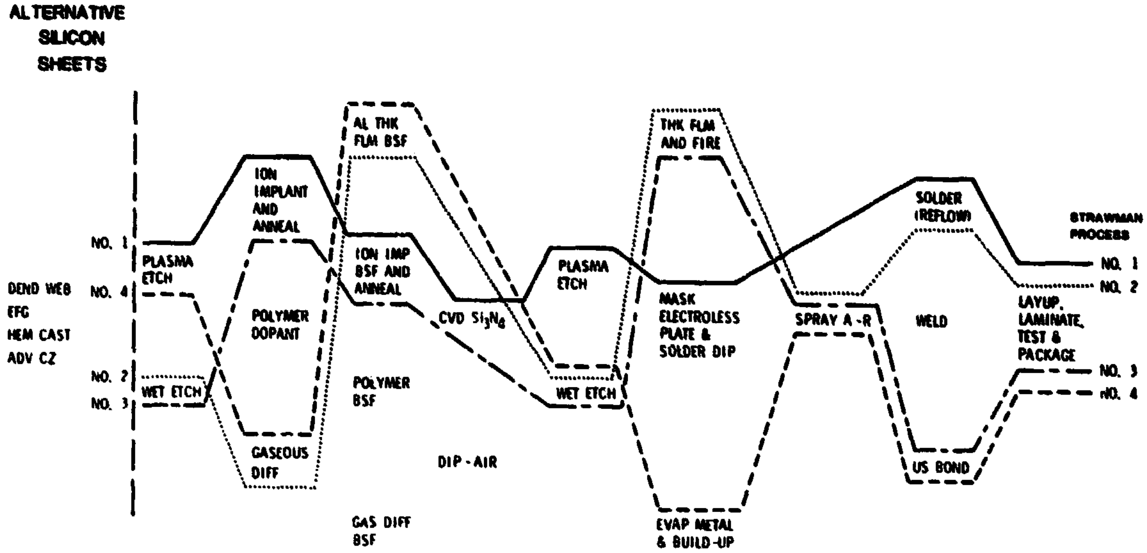
ASSUMPTIONS & CAVEATS

- FOB FACTORY PRICE
  - NO DISTRIBUTION COSTS
  - NO INSTALLATION COSTS
  - NO WARRANTY COSTS
- VERTICALLY INTEGRATED & BALANCED COMPANY
  - ASSUMES LARGE, ESTABLISHED INDUSTRY
  - ASSUMES EFFICIENT MANAGEMENT OF ALL FUNCTIONS SIMULTANEOUSLY
- 250 MW/YEAR ANNUAL PRODUCTION
- NO VERIFICATION AT ASSUMED OPERATION LEVEL
  - SPARE PARTS
  - MAINTENANCE
  - YIELDS

SELECTION OF CANDIDATE PROCESSES

- FORMATION OF PROCESS STEP MATRIX
- DETERMINATION OF PROCESS STEP COST
- SELECTION OF PROCESS SEQUENCE
  - HIGH TECHNOLOGY
  - LOW COST CONVENTIONAL TECHNOLOGY
  - AUTOMATION CAPABILITY
  - MODIFIED CONVENTIONAL TECHNOLOGY
- SELECTION OF BASELINE MATERIAL - HEM

ALTERNATIVE PRODUCTION PROCESSES



EFFECT OF ALTERNATIVE SHEET MATERIALS

- SHAPE CHANGES
  - NO ADDITIONAL HANDLING COSTS
  - NO ADDITIONAL YIELD LOSSES
- SIZE CHANGES
  - MATERIAL CHANGE/UNIT
  - AREA RELATED THRUPUT CHANGE
  - INTERCONNECT IDEAL RATIO CHANGE
- FORM CHANGES
  - DENDRITES
  - THIN WAFER

CANDIDATE STRAWMAN FACTORIES

CANDIDATE	PRICE (1980 $)
EFG #1	$0.562
WEB #1	$0.580
HEM #1	$0.670
HEM #2	$0.587
HEM #3	$0.565
HEM #4	$0.632
ADV. Cz #2	$0.683

CANDIDATE COMPARISONS SHEET (1980 $/$M^2$)

	PROPOSED GUIDELINE	CANDIDATE RESULT
EFG	24.2	17
DENDRITIC WEB	39.3	21
HEM	35.0	32
C_Z	28.9	44

ADVANCED CZ: BEST CASE/WORST CASE

	EXPERIMENTAL RANGE			
	1980 \$/KG OR \$/M^2		1980 \$/W_p	
	BEST	WORST	BEST	WORST
SILICON	10	21	0.08	0.45
SHEET	21	56	0.15	0.54
CELLS	8	21	0.06	0.16
ENCAPSULATION MATERIALS	8	20	0.06	0.21
MODULE	10	18	0.07	0.19
TOTAL			0.42	1.55

CASES	PARAMETERS					
	η_E	η_P	T_{WAFER}	γ_{SI}	γ_{CELL}	γ_{MOD}
BEST	0.15	0.92	10	0.50	0.95	0.995
WORST	0.13	0.75	15	0.40	0.80	0.990

DENDRITIC WEB: BEST CASE/WORST CASE

	EXPERIMENTAL RANGE			
	1980 \$/KG OR \$/M^2		1980 \$/W_p	
	BEST	WORST	BEST	WORST
SILICON	10	21	0.02	0.09
SHEET	21	100	0.15	1.02
CELLS	8	21	0.06	0.17
ENCAPSULATION MATERIALS	8	20	0.06	0.15
MODULE	10	18	0.07	0.17
TOTAL			0.36	1.60

CASES	PARAMETERS				
	η_E	η_P	T_{WAFER}	γ_{CELL}	γ_{MOD}
BEST	0.15	0.97	4	0.95	0.995
WORST	0.12	0.90	6	0.80	0.990

EFG SHEET: BEST CASE/WORST CASE

	EXPERIMENTAL RANGE			
	1980 \$/KG OR \$/M^2		1980 \$/W_P	
	BEST	WORST	BEST	WORST
SILICON	10	21	0.04	0.25
SHEET	20	34	0.17	0.44
CELLS	8	21	0.06	0.22
ENCAPSULATION MATERIALS	8	20	0.06	0.26
MODULE	10	18	0.08	0.24
TOTAL			0.41	1.41

CASES	PARAMETERS				
	η_E	η_P	T_{WAFER}	γ_{CELL}	γ_{MOD}
BEST	0.14	0.95	8	0.95	0.995
WORST	0.10	0.76	15	0.80	0.990

HEM CAST INGOT: BEST CASE/WORST CASE

	EXPERIMENTAL RANGE			
	1980 \$/KG OR \$/M^2		1980 \$/W_p	
	BEST	WORST	BEST	WORST
SILICON	10	21	0.08	0.45
SHEET	14	70	0.10	0.68
CELLS	8	21	0.06	0.16
ENCAPSULATION MATERIALS	8	20	0.06	0.21
MODULE	10	18	0.07	0.19
TOTAL			0.37	1.69

CASES	PARAMETERS					
	η_E	η_P	T_{WAFER}	γ_{SI}	γ_{CELL}	γ_{MOD}
BEST	0.15	0.95	10	0.50	0.95	0.995
WORST	0.13	0.80	15	0.40	0.80	0.990