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Low-Cost
Solar Array Project

DOE/JPL-1012-51
Distribution Category UC-63b

Progress Report 16

for the Period April to September 1980

and Proceedings of the 16th Project Integration Meeting

(NASA-CR-164073) PROCEEDINGS OF THE 16TH PROJECT INTEGRATION MEETING Progress Report, Apr. - Sep. 1980 (Jet Propulsion Lab.) 492 p HC A21/MF A01 CSCL 10A

N81-20545

Unclas
G3/44 41906

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

(JPL PUBLICATION 80-100)

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

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period April to September 1980. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held September 24 and 25, 1980.

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NOMENCLATURE

A	Angstrom(s)
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
BSF	Back-surface field
B-T	Bias/temperature
B-T-H	Bias/temperature/humidity
CFP	Continuous-flow pyrolyzer
CLF	Continuous liquid feed
CVD	Chemical vapor deposition
Cz	Czochralski (classical silicon crystal growth method)
DCF	Discounted cash flow
DLTS	Deep-level transient spectroscopy
DOE	Department of Energy
DS/RMS	Directionally solidified/refined metallurgical-grade silicon
EB	Electron beam
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EPR	Ethylene propylene rubber
EPSDU	Experimental Process System Development Unit
ESB	Electrostatic bonding
EVA	Ethylene vinyl acetate
FAST	Fixed abrasive slicing technique
FBR	Fluidized-bed reactor
FPUP	Federal Photovoltaics Utilization Program
GRC	Glass-reinforced concrete

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HCl	Hydrochloric acid
HEM	Heat exchanger method (silicon crystal ingot growth method)
HF	Hydrofluoric acid
HNO_3	Nitric acid
ID	Inner diameter
ILC	Intermediate Load Center
IPEG	Interim Price Estimation Guidelines
IPEG4	Improved Price Estimation Guidelines
I_{sc}	Short-circuit current
I-V	Current-voltage
LAPSS	Large-area pulsed solar simulator
LAR	Low-angle ribbon (silicon growth method)
LAS	Large-Area Silicon Sheet Task
LCP	Lifetime cost and performance
LeRC	Lewis Research Center
LSA	Low-Cost Solar Array
mgSi	Metallurgical-grade silicon
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratories
MBS	Multiblade sawing
MWS	Multiwire sawing
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NOCT	Nominal operating cell temperature
PMMA	Polymethyl methacrylate
P_{max}	Maximum power
PnBA	Poly-n-butyl acrylate
OTC	Optional test conditions

P	Individual module output power
PA&I	Project Analysis and Integration Area
P_{avg}	Module rated power at SOC, Vno
PDU	Process Development Unit
PEBA	Pulsed electron beam annealing
P/FR	Problem/failure report
PIM	Project Integration Meeting
$POCl_3$	Phosphorus oxychloride
PP&E	Production Process and Equipment Area
ppba	Parts per billion atomic
ppma	Parts per million atomic
PRDA	Program Research and Development Announcement
PV	Photovoltaic
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RNHT	Relative normal hemispherical transmittance
RTR	Ribbon-to-ribbon (silicon crystal growth method)
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SCIM	Silicon coating by inverted meniscus
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute
$SiCl_4$	Silicon tetrachloride
SiF_4	Silicon tetrafluoride

$SiHCl_3$	Trichlorosilane
SOC	Silicon on ceramic (crystal growth method)
SOC	Standard operating conditions (module performance)
SOLMET	Solar-meteorological
SPG	Silicon particle growth
SSMS	Spark-source mass spectrometry
STC	Standard test conditions (cell performance)
Ti	Titanium
UV	Ultraviolet radiation
V	Vanadium
V_{no}	Nominal operating voltage
V_{oc}	Open-circuit voltage
$ZnCl_2$	Zinc chloride

PROGRESS REPORT

Project Summary

The principal achievement of the Low-Cost Solar Array Project during the reporting period, April-September 1980, was reflected in the announcement at the 16th Project Integration Meeting that $2.80/$W_p$ Technical Readiness has been attained in 1980, and that processes and equipment now commercially available can make possible a deliverable product in 1982.

Other important achievements include: demonstration that many of the technical features required for attainment of the $0.70/$W_p$ goal are now at hand in the HEM, EFG and web sheet-silicon technologies; automated production process (Phase III) contracts under negotiation with Westinghouse and Solarex will demonstrate Technical Readiness by 1982; sophisticated automatic cell assembly machines are now cost-effective, and, although field results show that typical Blocks I to III module designs do not yet meet 1986 reliability and durability goals, analysis shows that the problems that have been encountered are corrigible or controllable by known techniques and that most have already been corrected.

Hemlock Semiconductor Corp. has demonstrated an increased rate of deposition of silicon, with decreased energy consumption, by using dichlorosilane (DCS) instead of trichlorosilane (TCS) in its production process. This is an important step toward achieving the Program's objective of a silicon product price less than $21/kg. The silicon deposition rate using DCS was more than twice that of the TCS process.

Union Carbide Corp. has completed preparation of its site for the Experimental Process System Development Unit (EPSDU) and construction of the plant has started. Its free-space reactor was operated successfully at its designed rate of 2.3 kg/h of Si for 12 h. The process design for the 1000 MT/yr plant has been completed.

Low-cost (2¢/W) junction formation has been found possible with either ion implantation or polymer dopants.

Recent demonstrations have shown copper to be emerging as a substitute for silver in cell metallization.

A prototype array for intermediate-load applications has been demonstrated using frameless modules. It was proof tested to 40 lb/ft^2 loading, and has been priced at $24/m^2, including array fabrication, module installation, shipping to the site and site installation for quantities of 20 MW, by Los Angeles area suppliers.

IPEG4, an interactive computer program with coefficients calculated from Solar Array Manufacturing Industry Simulation (SAMIS), has been released. Its coefficients can be tailored to a specific process or to a sequence of processes, or both; sensitivity cases can be run and plotted interactively.

PROJECT SUMMARY

SAMIS contains algorithms that will, when a data base of energy content of materials now being compiled is completed, enable each SAMIS run to calculate energy payback time.

Proceedings Summary

Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

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

An assessment of Technical Readiness for $2.80/W$_p$ photovoltaic module production was presented at the 16th Project Integration Meeting and is shown in the Proceedings of the PIM (p. 447 of this document). The analysis indicated that the \$2.80/W_p milestone in 1982 is technically achievable even with rather conservative assumptions. The assumptions included only equipment and processes used in production today or that could be ordered today and installed and in operation by 1982. The present price of polysilicon was assumed. Although the module price included a fair after-tax return on equity, the actual market price in 1982 will be determined by the forces at work in the energy marketplace at that time.

The latest addition to the SAMICS family of models, IPEG4, has been released for use. The program can be used in conjunction with SAMIS in a variety of ways, interactively from a computer terminal. IPEG coefficients, tailored for a specific process or sequence, can be generated. These can then be used to obtain quick and inexpensive parametric sensitivities and optimizations. The presentation given at the 16th PIM is shown in the Proceedings section of this document (p. 461).

In cooperation with the Large-Area Sheet Task, a major review of the required-price analysis for ingot technology presented at the 15th PIM in April 1980 has been conducted. The results are being compiled into a document to be published early in 1981. This document will summarize the best available projections for ingot technology in 1986.

The analysis of the trade-off between module efficiency and price goal was presented at the 16th PIM and is summarized in the Proceedings section of this document. The methodology, developed with the Engineering Area, will permit the comparison of the goals for array subsystems in the same application but with different efficiencies. Tax credits, marketing and distribution, insurance, property tax, discount rates and roofing credits (where applicable) are accounted for in the methodology. The selection of appropriate values for these parameters is presently the subject of a spirited discourse.

PROJECT ANALYSIS AND INTEGRATION AREA

Many requests have recently been received for information regarding the energy payback time for photovoltaic modules. There is an algorithm in SAMIS to calculate it, but the algorithm has not been exercised because the data on energy content of materials has not been sufficiently complete. The necessary data base is now being compiled. A description of this was presented at the 16th PIM and is shown in the Proceedings of the meeting (p. 459 of this document).

TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

INTRODUCTION

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

TECHNICAL GOALS, ORGANIZATION AND COORDINATION

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

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

Silicon Material Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SEMICONDUCTOR-GRADE SILICON PROCESSES	
Battelle Columbus Laboratories Columbus OH JPL Contract No. 954339	Reduction of $SiCl_4$ by Zn in fluidized-bed reactor
Energy Materials Corp. Harvard MA JPL Contract No. 955269 (near-term cost-reduction contract)	Gaseous melt replenishment system
Hemlock Semiconductor Corp. Hemlock MI JPL Contract No. 955533	Dichlorosilane CVD process for silicon production
Union Carbide Corp. Tonawanda NY JPL Contract No. 954334	Silane/Si process
SOLAR-CELL-GRADE SILICON PROCESSES	
Dow Corning Corp. Hemlock MI JPL Contract No. 954559	Electric-arc furnace process
SRI International Menlo Park CA JPL Contract No. 954771	Na reduction of SiF_4
Westinghouse Electric Corp. Trafford PA JPL Contract No. 954589	Reduction of $SiCl_4$ by Na in arc heater reactor
IMPURITY STUDIES	
Lawrence Livermore Labs Livermore CA NASA Defense Purchase Request No. WO-8626	Impurity concentration measurements by neutron activation analysis
Sah, C. T., Associates Urbana IL JPL Contract No. 954685	Effects of impurities on solar cell performance

Silicon Material Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
	IMPURITY STUDIES
Westinghouse R&D Center Pittsburgh PA JPL Contract NO. 954331	Definition of purity requirements
	SUPPORTING STUDIES
AeroChem Research Laboratories Princeton NJ JPL Contract No. 955491	Silicon halide/alkali metal flames
Lamar University Beaumont TX JPL Contract No. 954343	Technology and economic analyses
Massachusetts Institute of Technology Cambridge MA JPL Contract No. 955382	Hydrochlorination of metallurgical-grade silicon

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

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

Battelle Columbus Laboratories failed in numerous attempts to operate the Si process development unit (PDU) in runs of eight-hour duration. The difficulties had a variety of causes, prominent among them being condenser plugging and breakage of equipment interconnections. The closest approach to success was a mid-July 47-minute operation, which was terminated by a failure in an ancillary apparatus.

In support studies, Battelle defined and characterized two options for handling residual zinc impurity. One option, post-process heat treatment to drive off the zinc, was found not to be a viable option because of time, temperature, sintering and contamination difficulties. The second option is in-process control to avoid zinc misting. Battelle reports that, mainly by temperature control, the zinc content can be kept below a 100-ppm level.

According to Battelle, when Si containing zinc in this concentration is melted, the zinc is almost entirely evaporated, presenting no impurity problem for the solar cell and only a minor problem of contamination for a Czochralski crystal puller.

Energy Materials Corp. continued development of a silicon melt replenishment system for Czochralski crystal growth, under a near-term cost-reduction (NTCR) contract. Ten reactor tests were completed, six of which yielded Si deposits.

A silicon deposition rate of 6 μm/min and a production rate of 235 g/h at 20% conversion of trichlorosilane to Si were the best test results. A larger reactor, intended to attain the goals of 500 g/h Si production rate at 18% conversion efficiency, was designed and constructed, and the unit is about to undergo testing.

Hemlock Semiconductor Corp. is developing a process to make Si of a quality approaching semiconductor grade from dichlorosilane (SiH_2Cl_2) using a Siemens-type C-reactor. Correlations between reactor operating parameters and reponses (conversion efficiency, power consumption, and deposition rate) were established by making a series of tests with SiH_2Cl_2 in an experimental reactor in which the conditions of feed and rod temperature were systematicaly varied.

Experiments were performed in a laboratory-scale rearranger to provide information on the kinetics of trichlorosilane ($SiHCl_3$) redistribution to produce SiH_2Cl_2, and on catalyst behavior. Kinetic parameters were determined for liquid-phase redistribution at 77°C and were found to be more favorable than originally expected.

Construction of a process development unit (PDU) for investigating the scaled-up redistribution process was delayed pending the results of safety-related tests on SiH_2Cl_2 by Hazards Research Corp. These data indicate that the hazards of handling SiH_2Cl_2 are greater than had been expected (e.g., lower autoignition temperature than given in the literature, and capability of SiH_2Cl_2/air mixtures in a confined space to detonate). Changes were made in the PDU design to reduce the hazards of handling SiH_2Cl_2, and a new site for the PDU was selected, so that construction can now start.

A preliminary economic analysis for a 1000-MT/yr plant was performed, indicating an Si product cost of $15.47/kg (1980 dollars) and a price of $19.85 (20% ROI).

The Union Carbide Corp. process consists of the hydrochlorination of metallurgical-grade silicon (mgSi) to $SiHCl_3$ and rearrangement of the latter to silane (SiH_4), which is pyrolyzed to Si. Effort continued on the 100 MT/yr-capacity experimental process system development unit (EPSDU). The site preparation was completed and a company was selected to perform the civil installation work. Equipment for the EPSDU is undergoing detailed design and procurement has started.

The free-space reactor (FSR) PDU work entered a new phase to demonstrate operability and product pruity. The reactor-wall temperature profile was modified to eliminate or reduce the occurrence of Si wall deposits, and a quartz liner was installed. Five consecutive tests each of 2-h duration and one 12-h test were conducted at the design throughput of 2.3 kg Si/h. The latter milestone was achieved one month ahead of schedule. No wall deposits were observed, and the quartz liner remained intact.

Small-scale experiments for melting FSR Si powder and dropping shot were conducted. A prototype melter system, not including the powder feeder, was designed.

A review of the fluidized-bed reactor (FBR) R&D program was held. The design criteria for the FBR are well within the suggested operating range established by JPL testing. The UCC design for a 6-in.-dia FBR was approved. The contractor completed the detailed design of an FBR PDU that will incorporate this FBR.

Based on the EPSDU design, a process design for a 1000 MT/yr Si production plant was completed, including flow sheet, process description, mass balance, facility layout, and equipment functional specifications. This package will provide the basis for an economic assessment.

Development of Processes for Producing Solar-Cell-Grade Silicon

Three contracts are active in this area; all are in the final-report preparation stage. SRI International's final report on its process for producing Si by the sodium (Na) reduction of silicon tetrafluoride was reviewed by JPL and is soon to be issued by the contractor. Draft final reports from the Dow Corning Corp. on its electric-arc furnace process and from the Westinghouse Electric Corp. on the direct arc reactor process are being reviewed by JPL.

Impurity Studies

C. T. Sah Associates investigated the effects of cell thickness on the efficiency of back-surface-field solar cells with zinc impurity. The efficiency of a back-surface-field cell peaks as the cell thickness decreases due to two opposing dependences: I_{sc} decreases and V_{oc} increases with decreasing cell thickness. Computer calculations using zinc as a model recombination center in n+/p/p+ cells showed that there is a broad efficiency peak around 70 μm cell thickness in high-efficiency cells (base lifetime of 40 μs to 4 μs for zinc concentrations of 10^{12} to 10^{13} Zn/cm^3) with efficiencies in the range of 14% to 17%. Detailed computer results showed that high-injection-level conditions become important in these high-efficiency cell structures under one sun illumination at AM1. Thus, the analytical ideal low-level theory commonly used by previous workers can no longer give reliable prediction of cell performance. Improvements in cell performance by multiple optical passes with reflecting back surface and higher base doping are expected in thin cells.

Westinghouse R&D Center began its Phase IV effort, which includes five major topics of study: (1) evaluation of experimental silicon materials, (2) investigation of impurity effects in polycrystalline devices, (3) identification of impurity thresholds for high-efficiency cells, (4) assessment of process effects such as ion implanting on impurity-doped devices, and (5) an extension of studies to identify long-term impurity effects. The major activities so far have been in the areas of polycrystalline cells, impurity aging effects, and high-efficiency cell modeling.

It was found that the threshold for ingot structural breakdown is lower during polycrystalline silicon growth than when growing single crystals, at least for the impurities iron, titanium, vanadium, chromium, and molybdenum.

At impurity concentrations for which single crystals can be grown, polycrystalline ingots develop metal-rich inclusions. The effect of the inclusions is to shunt solar cells, producing very low efficiencies. When the melt impurity concentration is reduced by 30% to 50%, inclusion incorporation is generally eliminated. Polycrystalline cells doped with lower levels of titanium and vanadium ($\approx 10^{13}$ cm^{-3}) show little indication of impurity segregation to grain boundaries.

Further studies of accelerated aging effects under thermal stress indicated that while solar cells containing titanium and molybdenum would show essentially no performance reduction due to impurities after 20 years, cells doped with chromium and silver degrade much more rapidly, apparently in keeping with their expected high diffusion constants. Niobium-doped cells fall somewhat between these pairs.

The development of a model to depict the functional relationships between cell performance and impurity content for high-efficiency devices including back-surface-field cells was intiated. Qualitatively, the model predicts lower impurity thresholds for performance reduction in high-efficiency cells than in standard devices.

Supporting Studies

The AeroChem contract was extended and reoriented to constitute an effort supporting the silicon process developments in Task 1. The objective of the work is to characterize the kinetics and mechanism of the formation and growth of Si particles from the decomposition of SiH_4 at high temperatures. A high-temperature fast-flow reactor (HTFFR) was modified for this work. The unit consists of a 2.5-cm-dia alumina reactor tube electrically heated to give a zone of uniform temperature into which the SiH_4 wil be injected. A fluidized-bed feed system will be used to inject silicon seed particles. Gaseous species concentration and particle formation and growth will be measured.

Lamar University devoted its major effort in chemical engineering analysis to the Hemlock process. Two changes in the process flow sheet (relocation of the redistribution reactor and addition of a final distillation column) were introduced to increase the yield of SiH_2Cl_2 by 10% to 20%, to help insure product purity, and to reduce the amount of components in the polysilicon reactor feed material that might produce Si dust by fine-particle nucleation. Hemlock agrees on relocation of the redistribution reactor to increase yield. Also, Lamar identified potential chemical reactions involving boron halides and hydrides and remedies for eliminating boron compounds from the process stream.

The preliminary process design was completed for that portion of a plant that would produce SiH_2Cl_2, and a preliminary cost analysis was made indicating that, for a plant producing 1000-MT Si/yr, the cost of SiH_2Cl_2 (without profit) is $1.29/kg.

Analyses of process system properties were continued for important chemical materials involved in the processes under development for production of Si, centering on physical, thermochemical, and transport data for Si. Specific property data were reported for liquid and solid thermal conductivity, vapor presure, heat of vaporization, heat of sublimation, and heat of capacity as functions of temperature, as well as critical constants.

The Massachusetts Institute of Technology is conducting a program, supportive of the UCC SiH_4-to-Si process development, to study the hydrochlorination of mg-Ci to $SiHCl_3$, the feedstock for chlorosilane disproportionation to SiH_4. Experiments were conducted to study the use of cuprous chloride (CuCl) to catalyze this reaction. It was found that CuCl is an effective catalyst at a concentration as low as 2 wt% of the Si. Its advantage over copper as a catalyst is that with CuCl there is no induction period during which there is little or no catalytic activity.

Tests were made to study the effect of impurities in mgSi on the hydrochlorination reaction rate. A pure Si mass produced from semi-conductor-grade Si had a reaction rate about one order of magnitude slower than that of mgSi. The impurities in mgSi appear to act as a catalyst. Addition of CuCl to the high-purity Si greatly increased the reaction rate, to the same level as that of mgSi with CuCl catalyst added. Thus CuCl provides a convenient means for recycling off-specification Si.

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

Tests of the 2-in.-dia FBR were completed. Preliminary parametric results define the operating range to be used in future studies.

Data from the in-house program were presented at a meeting on FBR technology held by JPL's Oregon State University consultants and representatives of the Union Carbide Corp. and JPL. The results were encouraging for the UCC FBR program, the UCC design criteria (i.e., 700°C and 10 mole% SiH_4 in hydrogen) appear to be well within the suggested operating zone found by JPL. Low Si dust formation (<6%) was obtained for SiH_4 concentration up to 14%.

A 6-in.-dia FBR experimental system was designed and procurement was initiated. The system will be used to complement the UCC FBR program in the areas of heating, particle handling, seed production, process monitoring and fundamental understanding. It was designed for maximum versatility to study alternative processing schemes if needed during the UCC FBR development period.

In the program on conversion of SiH_4 to Si powder in the FSR, the reactor was modified to include a scraper to prevent Si accumulation in the reactor during long-term operation. In tests, the scraper provided a thin, soft uniform coating of fine Si powder in the reactor wall as intended but was unable to prevent accumulation of hard Si deposits.

The design, fabrication, and installation of the SiH_4-to-Si converter were completed. The newly constructed surface preparatory furnace for the reaction crucibles was successfully operated at 2200°F.

A method is being developed in the Silicon Material Research Laboratory to consolidate the sub-μm Si powder produced by the free-space reactor of the UCC process. The method consists of melting the powder on top of a pedestal, followed by unidirectional solidification. A test apparatus was constructed using the high-frequency generator of a Lepel float-zone apparatus as the source of heat that will be applied to produce a stable melt on top of the pedestal. In the area of analysis for impurities in Si by the TSCAP (Thermally Stimulated Capacitance) measurement apparatus, the facilities and equipment required to fabricate Schottky diodes for these measurements were completed, and diodes are being prepared from n-type Si obtained from the Westinghouse R&D Center program on impurity studies.

Large-Area Silicon Sheet Task

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

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

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

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

ORGANIZATION AND COORDINATION

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

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

Large-Area Silicon Sheet Contracts

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

Large-Area Silicon Sheet Task Contractors

CONTRACTOR	TECHNOLOGY AREA
SHAPED RIBBON TECHNOLOGY	
Arco Solar, Inc. Chatsworth CA JPL Contract No. 955325	Vacuum die casting
Mobil Tyco Solar Energy Corp. 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 Corp. Bloomington MN JPL Contract No. 954356	Silicon-on-ceramic substrate

Large-Area Silicon Sheet Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem MA JPL Contract No. 954373	Heat-exchanger method (HEM); cast ingot and multiwire fixed abrasive slicing (FAST)
Kayex Corp. Rochester NY JPL Contract No. 954888	Advanced Cz growth
P. R. Hoffman Co. Carlisle PA JPL Contract No. 955563	MBS wafering
Siltec Corp. Menlo Park CA JPL Contract No. 955282	ID wafering
Siltec Corp. Menlo Park CA JPL Contract No. 954886	Advanced Cz growth
Semix Corp. Gaithersburg MD 20670 DOE Contract No. DE-FL01-80ET 23197	Ingot casting
DIE AND CONTAINER MATERIALS STUDIES	
University of Missouri Rolla Columbia MO JPL Contract No. 955415	Partial pressures of reactant gases
MATERIAL EVALUATION	
Applied Solar Energy Corp. City of Industry CA JPL Contract No. 955089	Cell fabrication and evaluation
Cornell University Ithaca NY JPL Contract No. 954852	Characterization--Si properties

Large-Area Silicon Sheet Task Contractors (Continued)

CONTRACTOR	TECHNOLOGY AREA
MATERIAL EVALUATION	
Charles Evans & Associates San Mateo CA JPL Contract No. LK-694028	Technique for impurity and surface analysis
Spectrolab Sylmar CA JPL Contract No. 955055	Cell fabrication and evaluation
UCLA Los Angeles CA JPL Contract No. 954902	Material evaluation
Materials Research, Inc. Centerville UT JPL Contract No. 957977	Quantitative analysis of defects and impurity evaluation technique

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

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

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

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

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

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

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

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

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

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

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

A small ongoing effort is being supported at the University of California Los Angeles to provide evaluation of silicon sheet by device fabrication and electrical characterization.

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

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

SUMMARY OF PROGRESS

Ingot Technology--Crystal Systems (HEM): Three 45-kg ingots have been successfully cast (30 x 30 x 13 cm, 34 x 34 x 17 cm, and 33 x 33 x 20 cm, respectively). The highest average solidification rate observed was 1.25 kg/h. CSI has been having problems in scaling up for demonstration of 30- to 35-kg runs. Cracked crucibles have resulted in numerous molten silicon spills. The goals for the process were reviewed and have now been revised. Previous goals were for 63-kg ingots (30 x 30 x 30 cm), 65-h cycle time. The new goals call for 35-kg ingots (30 x 30 x 15 cm) and a 56-h cycle time. IPEG analysis of these new goals show that the HEM process together with an agressive FAST wafering program can meet its price allocations for \$0.70/W_p technology.

Crystal Systems (FAST): Three 10-cm ingots were sliced using a single blade electroplated on only one side. Yields were 91%, 70% and 44%. A new 750-blade head was delivered and installed on the saw. This head is intended to reduce vibration, increase capacity and cut faster (blade-head speeds of 500 ft/min were measured). Two runs were made using one electroplated nickel-flashed wire pack on the new 750-blade head. Cutting rates were 4 and 3.8 mils/min; yields were 96% and 48%, respectively. Both cuts were at 19 wafers/cm (goals: 4 mils/min, 95% yield, 5 cuts/wire pack, 25 wafers/cm).

Kayex (Advanced Cz): Three 150-kg (per crucible) growth runs were successful; the last two were controlled for part of the process by a microprocessor controller developed under the NTCR contract. A new conical heat shield also developed under the NTCR effort permitted growth rates up to 4.5 kg/h to be achieved. A cold-crucible recharging method bench test was successful. An experimental sheet-growth unit (ESGU) design package has been submitted to JPL for review. TR goals of 150 kg/crucible, 2.5 kg/throughput, 14% solar cell efficiency, and 15-cm ingot θ have been demonstrated.

Siltec (Advanced Cz): The continuous liquid-feed (CLF) crystal-growth system's pull mechanism was extended 60 cm to allow a 50-kg 15-cm-θ ingot to be pulled above the gate valve. A 65-kg 15-cm-θ, $\approx$2-m-long ingot was grown. For this run, 55 kg of silicon was transferred by the CLF mechanism. In another run, 100 kg of silicon comprising three 14-cm-θ ingots was grown at a throughput rate of 2.1 kg/h from a single crucible (goals: 150 kg, 2.5 kg/h). Siltec is lagging in its schedule of milestone demonstrations.

Siltec (ID Wafering): Blade deflection of only 5 to 8 μm has been achieved with the new blade-deflection controllers. In the blade development area, e-beam and laser welding of stainless steel and copper-beryllium cores to diamond inserts were abandoned after repeated failures. The 12-in. blade head was replaced with a 16.625-in. head to eliminate the high-frequency vibrations that had been responsible for excessive wafer breakage. Wafers of 8, 10, and 12 mil have been cut with 10- and 12-mil kerfs with yields up to 70%, and 2.5 cm/min plunge rates on the NTCR program (goal: rotation cutting of 10-cm-θ, one wafer/min, 25 wafers/cm.

P. R. Hoffman (MBS Wafering): Hoffman's initial efforts showed little difference in the quality of performance between Hoffman, Meyer-Burger, and Varian saws. A follow-on effort is being planned. The results show that state of the art in MBS cannot achieve the goal of 25 wafers/cm for 10-cm-dia ingots.

Semix (Semicrystalline Casting): The DOE/Semix cooperative agreement--semicrystalline casting process development and verification--was announced at the 16th PIM. JPL will provide the technical management support to DOE for this work. An appropriate non-disclosure agreement for DOE and JPL is being drafted for adoption before the initial plant visit. The goals of this agreement are to: (1) demonstrate commercial readiness for \$2.80/W_p technology; and (2) demonstrate technical readiness for \$0.70/W_p technology in three years.

Shaped Ribbon Technology--ARCO Solar (vacuum casting). ARCO Solar and JPL have agreed that the contract be terminated, based on the results of the work.

Mobil Tyco (EFG): 10-cm-wide ribbon 6 to 8 mils thick has been grown at speeds up to 3.8 cm/min in the multiple-ribbon-growth system and 4.2 cm/min in the single-ribbon system (goals 4.5 and 5 cm/min, respectively). Automatic width control was demonstrated for 200 min continuously on a single ribbon machine early in the reporting period and is now in place and operating regularly on the multiple machine. Excessive thermal interaction between the cartridges is indicated as the source of control problems experienced in the multiple runs. This is being investigated. The introduction of a partial pressure of oxygen (2000 ppm CO_2) to the single-ribbon system resulted in longer lifetimes in the grown ribbon. The effect of the partial pressure of oxygen on ribbon quality is now under intense study at Mobil Tyco.

Westinghouse (Web): An automatic melt-recharging melt-level sensor designed and built at Westinghouse has been demonstrated in the WEB growth system (melt level was maintained $\underline{+}0.1$ mm for 8 h during growth). An ESGU design review and the execution of a follow-on contract are planned for November.

Supported Film--Honeywell (SOC): Cells of 10.5% (AM1) efficiency have been obtained using an improved diffusion process on dip-coated films grown at 3.4 cm/min (TR82 goals: 0.25 cm/sec, 100 μm thickness, 11% at AM1). Hydrogen passivation of the cells has shown improved lifetimes measured at the grain boundaries. SCIM II profile modifications continue in an effort to avoid substrate warpage and breakage. Coating speeds of up to 30 cm/min, producing films of 1 to 2 μm thickness have been obtained on SCIM II (goals: 350 cm^2/min growth rate on 12-cm-wide substrates, demonstrated 11% cell efficiency).

Material Evaluation--Applied Solar Energy Corp.: Attempts to correlate structure of EFG ribbon as characterized with cell performance were unsuccessful. Contact resistance on EFG cells was improved by a 600°C bake after processing and AR coating. Average efficiencies of 12% AM1 and a maximum of 13.5% AM1 were obtained. Optimized processing of carefully selected 2 x 2 cm single-crystal HEM samples yielded cells with an average efficiency of 15% AM1 and a maximum of 15.7% vs 16% to 16.2% for control cells. Cells (2 x 2 cm) made from a vertical section of a HEM ingot cast from semiconductor-grade silicon showed a surprising spread of values (6.9% to 12.6% AM1 (control cells were 12.2%)). Cells from the bottom half of the ingot were generally the best, with low values seen in cells from the center of the ingot and from around the seed. There was no apparent dependence upon crystallinity. Additional measurements on this material will be made.

Cornell University: Cornell is presently operating under a no-cost extension of their original contract. Structural evaluation of EFG ribbon and SOC films continues. Spectrolab: A 2 x 2 cm SOC cell was produced with hand-painted contacts; it gave a V_{OC} of 400 V and I_{SC} of 140 mA. Efficiency of 3.5% AM1 has been achieved on this material. Work continues on a BSF for EFG ribbon and shallow-junction formation for web.

University of Missouri Rolla (UMR): Attempted melting of silicon on sialon resulted in the encapsulation of the silicon by calcia fron the sialon grain boundaries. This prevented the melting of silicon. UMR will measure oxygen partial pressures in the crystal-growth systems of three Task II contractors under the terms of the current contract.

Materials Research, Inc. (MRI): EFG and web samples have been supplied to MRI for characterization. HEM and SOC material are being prepared for evaluation. A hard-disc copy of a silicon defect characterizatrion computer program for use on a QTM-Quantimet has been delivered to JPL. This was a new-technology item developed under this contract.

JPL In-House Activities: A 1.3-m length of EFG ribbon was pulled from a CNTD:SiC coated hot-pressed SiC die at Mobil Tyco. This material looks promising and another test is planned. RF-grown EFG ribbon was analyzed and observed to be asymmetrical; i.e., one side of the ribbon contained more twins and grain boundaries than the other. Thick ribbons were observed to have a central through-the-thickness grain structure.

In support of the MBS wafering program, fatigue properties of -metal ribbons supplied by Allied Chemical were measured and found to be lower than those of 1095 steel. The hardness and ultimate strength of these materials were promising. One corrosion inhibitor solution has been identified as having great promise for use with a 1095-steel and water-based slurry MBS system. In-machine tests will be run to confirm this.

Directional solidification of both metallurgical and semiconductor grade Si has been accomplished in graphite, mullite, SiC, Si_3N_4 and SiO_2 crucibles.

Additional characterization of HEM material is being pursued. In addition to activities with the support contractors (Charles Evans, Cornell, MRI and ASEC), in-house measurements of other electrical properties of the HEM material (surface photovoltage, diffusion length, spreading resistance and solar cell performance measurements on as-received HEM material and material that has been thermally annealed at low temperatures) has begun.

Continuing activities in the area of crystal growth include more bicrystals grown; initiation of Cz ingot growth with polysilicon obtained from the Battelle process, and evaluation of polysilicon material of different quality by crystal growth and subsequent measurements. Facilities are being prepared for installation of two MBS wafering machines from Varian. These machines will be used in the continuing studies of blade and slurry materials for the MBS technique.

A program is being developed to examine the sensitivity of technical features of the individual technologies using IPEG2. An initial analysis of ID wafering was performed and it was confirmed that capital and labor costs are major cost drivers. This points to a multiple-ingot cutting technique as an attractive alternative. The input data for a Monte Carlo simulation model is being updated. The model has been run only with the non-ingot technologies. The necessary data for ingot technologies is being collected to include them in the analyses.

Encapsulation Task

INTRODUCTION

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

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

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

ENCAPSULATION TASK

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

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

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

SUMMARY OF PROGRESS

Materials and Process Development

A primer developed by Dr. Edwin P. Plueddemann of Dow Corning has been compounded successfully with ethylene vinyl acetate (EVA) pottant by Springborn Laboratories. EVA containing this primer needs no other coupling agent to promote adhesion of EVA to glass and silicon cells. Also, Springborn successfully incorporated a vinyl tinuvin UV screening agent prepared by Dr. Otto Vogl of the University of Massachusetts with a Dow Corning silicone-acrylic UV screening film and with EVA. The technology to mass-produce vinyl tinuvin has been transferred from the University of Massachusetts to Springborn Laboratories.

Small modules with cells electrostatically bonded (ESB) to Type 7070 borosilicate glass are being routinely produced by Spire Corp. Module size is approximately 6 x 8 in. with six rectangular cells producing a packing density of 94%. The module backs are encapsulated with white EVA pottant and an aluminum-Mylar back cover. Four of these small modules are installed in a frame to produce a standard 12 x 16-in. minimodule. Three of a scheduled 10 minimodules have been delivered to JPL; two have been installed at the JPL outdoor weathering site.

Similar six-cell modules using trapped silver-mesh front contacts have been made by the electrostatic-bonding process with I-V curve fill factors of 66%, compared with 72% for the regular-type EBS modules.

The Phase I analytical design studies by Spectrolab-Hughes on performance encapsulation systems (thermal, optical, electrical, and mechanical) were completed and will be reported at the 17th PIM.

ENCAPSULATION TASK

Experimental solar cells with ion-plated front-and-back metallizations are now routinely produced by the Illinois Tool Works. However, diffusion of the ion-plated metallization into the silicon wafer is apparently insufficient to achieve the required ohmic contact. Ion-plating techniques to achieve improved ohmic contact are being explored.

Twenty-four 12 x 16-in. minimodules with advanced encapsulation material systems and 92 two-cell submodules were installed at the JPL outdoor weathering site on July 1, 1980. Similar modules will be installed at sites at Goldstone and Point Vicente, California, in the next few months. The types of modules installed at the JPL site were:

Minimodules (12 x 16 in.):

Applied Solar Energy Corp.--three types of glass superstrate designs with EVA pottant.

Springborn Corp.-Solar Power Corp.--one glass superstrate design and two substrate designs, all with EVA pottant.

MBAssociates--a glass-fiber-reinforced concrete substrate design with EVA pottant.

General Electric Co.--glass superstrate design with low-cost RTV silicone-rubber pottant.

Spire Corp.--glass superstrate design with cells electrostatically bonded to Type 7070 glass.

Submodules (two cells each):

Springborn-Solar Power--one glass superstrate design and three substrate designs, all with EVA pottant.

Also installed at the JPL weathering site for monitoring the environment were five actinometers, two integrating solar energy detectors, an acid-rain pH meter and a moisture detector.

Life Prediction and Material Degradation

The test to validate the Battelle accelerated-test plan for predicting the service life of photovoltaic modules in an array at Mead, Nebraska, is under way in-house. Two weeks of exposure to cyclic temperature (-15°C to +95°C), 85% RH (at 30°C), and 1 ppm SO_2 are completed. The test is expected to continue for approximately five months.

Atmospheric corrosion monitors located at the Mead test site show that the RTV silicone pottant continues to provide full corrosion protection after nine months of outdoor exposure. A detailed program plan for broadening the corrosion models developed for the Mead site, to apply to new module designs, material combinations, and other atmospheric conditions, was presented to JPL by the Rockwell Science Center in July.

Three areas of work are being investigated in house in the thermomechanical modeling of solar cell modules, with primary emphasis on the solar-cell interfaces. Progress to date for these areas of work is cited below:

Compatability of materials: A finite element model has been coded and checked out, as reported earlier. The model is now being used for parametric studies varying the thickness and modulus of the adhesive-pottant layer.

Failure modes: this work will be divided into three tasks: failure of encapsulation materials, cell cracking, and localized hot spots. No work has yet been done in this area.

Thermoelastic Behavior of Solar Cells: the purpose of this analysis is twofold: to verify the results of the finite element model, and to aid in the simplification of the finite element model to reduce computer costs. This investigation is being conducted at JPL by Professor Harry Williams.

PRODUCTION PROCESS AND EQUIPMENT AREA

AREA OBJECTIVES

The current Phase II objective is to develop equipment and facilities to demonstrate, in 1982, technical readiness for fabricating finished, crated, solar modules of silicon sheet material within the Project Price Goal Allocation (see Figure 1).

A second objective has been to complete the near-term process development contracts and to begin evaluation of their effectiveness.

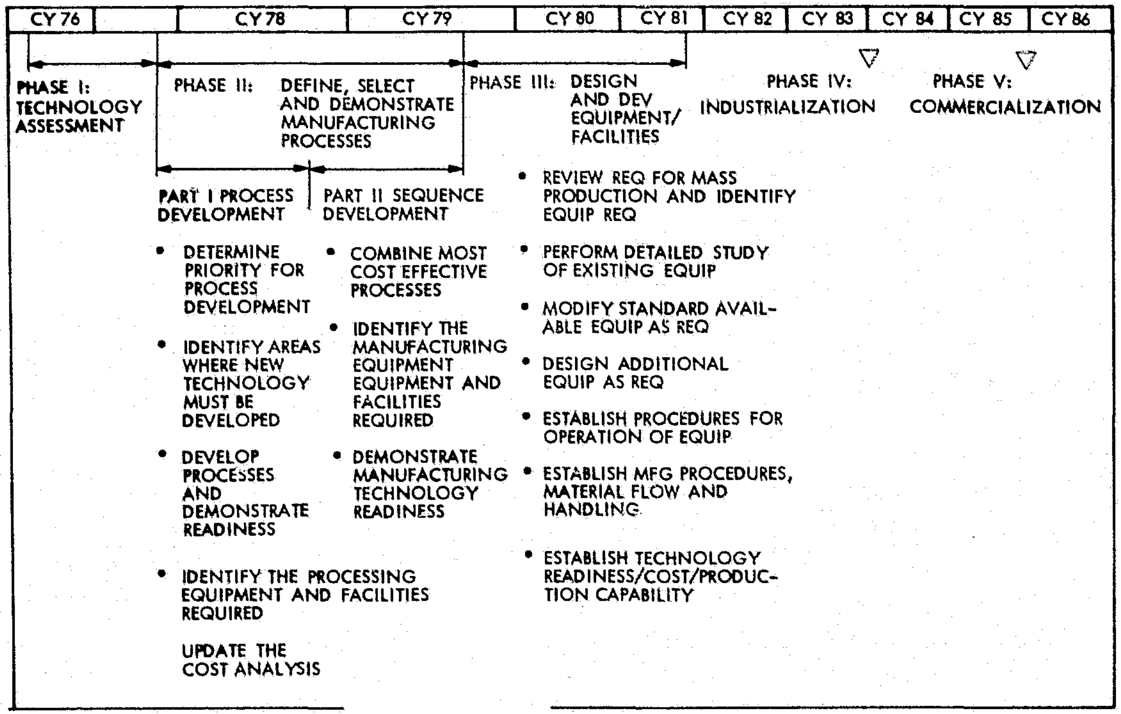
SUMMARY OF PROGRESS

Previous contracts, completed in Phase II, have developed data that allow more than one process sequence which is cost effective (see Figure 2). Costs analyses of these sequences shows metallization and assembly to be the cost drivers at this stage (see Figure 3).

Cost-effective manufacturing of solar modules by several process sequences was described during the last reporting period. Most of the process development contracts completed their development in this period. Work will continue in the following years to complete the ion implantation and annealing machine and to continue advances on the main cost drivers (metallization and assembly).

Near-term contract development work has been completed. Some contracts are lingering in order to complete reporting of developments. The evaluation of their cost effectiveness in the next few years in industry has started. The results of all the evaluations are scheduled to be presented in the next reporting period.

PRODUCTION PROCESS AND EQUIPMENT AREA



- DETERMINE PRIORITY FOR PROCESS DEVELOPMENT
- IDENTIFY AREAS WHERE NEW TECHNOLOGY MUST BE DEVELOPED
- DEVELOP PROCESSES AND DEMONSTRATE READINESS

- COMBINE MOST COST EFFECTIVE PROCESSES
- IDENTIFY THE MANUFACTURING EQUIPMENT EQUIPMENT AND FACILITIES REQUIRED
- DEMONSTRATE MANUFACTURING TECHNOLOGY READINESS

- IDENTIFY THE PROCESSING EQUIPMENT AND FACILITIES REQUIRED

UPDATE THE COST ANALYSIS

- REVIEW REQ FOR MASS PRODUCTION AND IDENTIFY EQUIP REQ
- PERFORM DETAILED STUDY OF EXISTING EQUIP
- MODIFY STANDARD AVAILABLE EQUIP AS REQ
- DESIGN ADDITIONAL EQUIP AS REQ
- ESTABLISH PROCEDURES FOR OPERATION OF EQUIP
- ESTABLISH MFG PROCEDURES, MATERIAL FLOW AND HANDLING
- ESTABLISH TECHNOLOGY READINESS/COST/PRODUCTION CAPABILITY

Figure 1. Production Process and Equipment Area Phase Breakdown

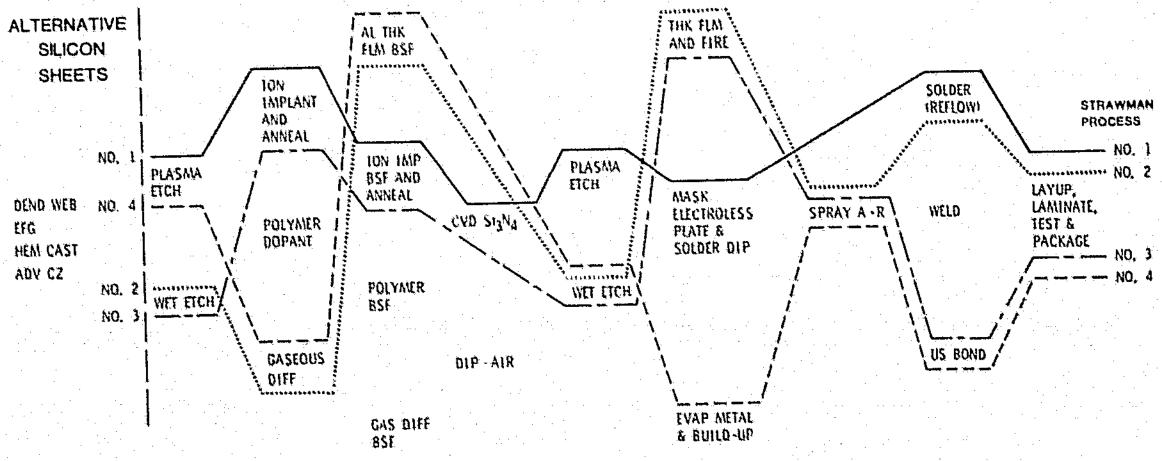


Figure 2. Alternative Production Processes

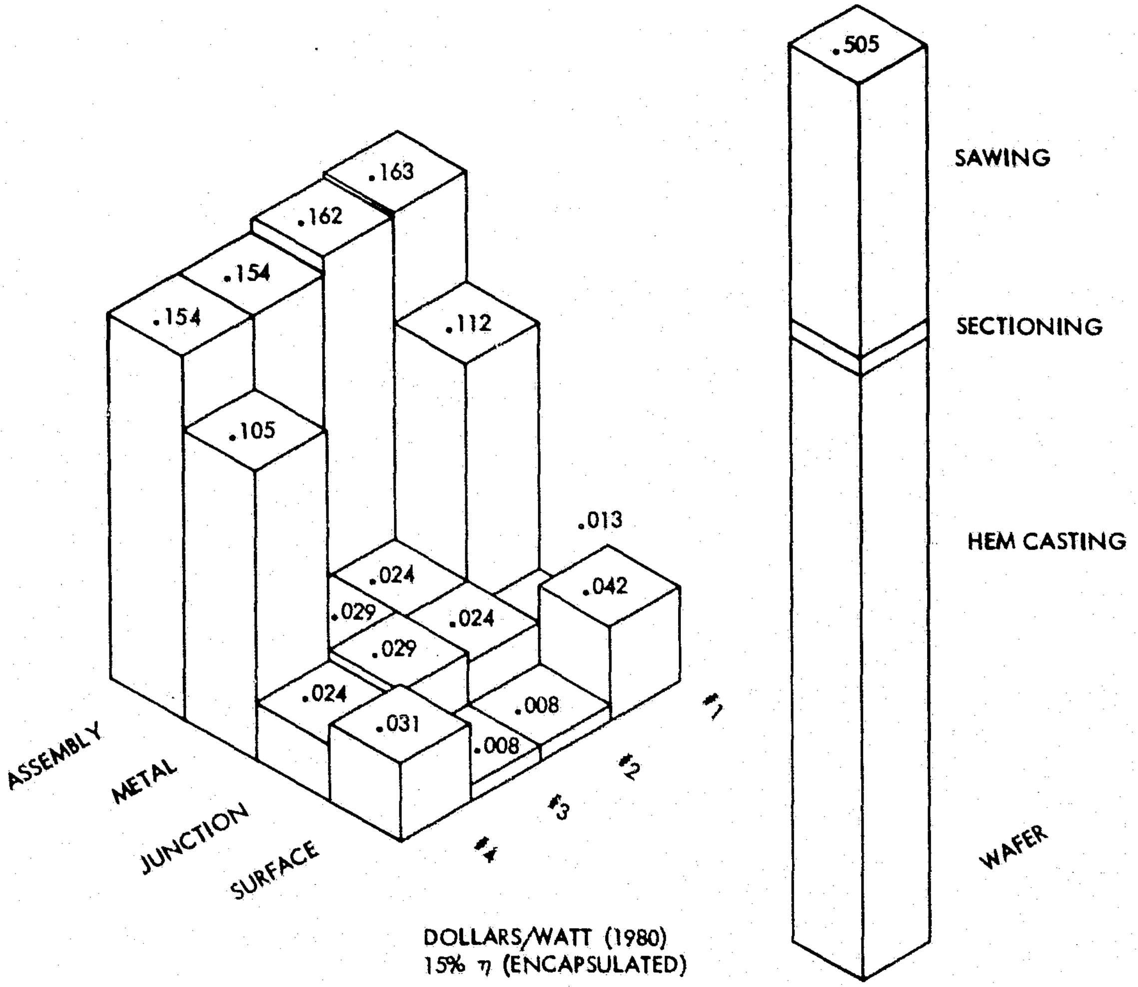


Figure 3. Alternative Process Sequences

Junction Formation

The pulsed electron beam annealing (PEBA) machine has advanced well into the fabrication phase. Experiments were done to determine the critical beam parameters. A design was completed and a design review conducted. The machine is being constructed.

Ion-implanted cells from a non-mass-analyzed source were found to have efficiencies comparable to those of conventionally ion implanted cells. This is a major development that increases throughput by orders of magnitude while reducing cost by several factors.

Metallization

The Midfilm metallization technique evaluation was completed. The system appears to be promising, possibly yielding a low-cost fine-grained grid pattern that uses a minimum of silver metal powder. The cell efficiency increases as the grid pattern fineness improves. An additional contract has been signed with Spectrolab to develop this process further. There is a possibility that the Midfilm process will accommodate some of the Bernd Ross Associates copper-based metallurgy as well.

Sample quantities of Bernd Ross Associates copper-based metal powder systems were ordered from AVX Corp., one of the large suppliers of thick-film inks. When delivered, these inks did not reproduce the desirable characteristics noted originally. The reason is being investigated and if excessive sensitivity to variables is found, the process will be altered to a more stable condition.

Direct nickel-plating-on-silicon efforts at Solarex have met the contract goals, but verification work in the PP&E laboratory has shown the process to be marginal. The nickel will short the cell junction if fired at a time and temperature that will guarantee adhesion. The system appears to have excellent humidity resistance.

Both ASEC and Motorola have been successful in plating copper for cell metallization buildup. The copper is cheaper than dipping in solder and is more tolerant of temperature cycling.

Assembly

Kulicke & Soffa has successfully completed its contract to develop and build an automated cell assembly machine. The machine was shipped to California for display at the 16th Project Integration Meeting.

ARCO Solar believes that its automatic cell assembly machine still needs improvement. The value of the current machine is yet to be determined. The verification run is currently scheduled for December 1980.

MBAssociates has designed, constructed and demonstrated an end effector (attachment) that allows the robot to pick up an entire array of cells and manipulate it with appropriate speed and directional versatility for automatic lamination. Conceptual designs have been completed and proof of concept models have been constructed and operated to complete the lamination process of cell laydown, PVB or EVA rollout, and glass placement.

PRODUCTION PROCESS AND EQUIPMENT AREA

Production Process and Equipment Area Contractors

Ongoing contracts:

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Spire	955640	Ion implantation equipment
Westinghouse	955624	Silicon dendritic web material process development
OCLI	955423	Laboratory services
University of Pennsylvania	954796	Analysis & evaluation of process & equipment
Bernd Ross	955688	Fritless metal inks
Lockheed	955696	Laser anneal
MBAssociates	955699	Automated module assembly
Science Applications	955787	Light-trapping analysis

Contracts involving completed work, awaiting completion of final reports:

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Sensor Technology	954685	Phase II add-on spray-on & microwave evaluations
Solarex	954854	Phase II add-on metallization; Ni plating
Spectrolab	954853	Phase II add-on process sequence development
OCLI	955217	Development of high-energy (14%) solar cell array module
ARCO Solar	955278	Automated solar panel assembly line

Production Process and Equipment Area Contractors (Continued)

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Kulicke & Soffa	955287	Automated solar module assembly line
Motorola	955324	Wax patterning
Motorola	955328	Thin silicon substrate for solar cells
RCA	955341	Megasonic cleaning
Sensor Technology	955265	Development of low-cost polysilicon solar cells
Kinetic Coating	955079	Phase II add-on hermetically sealed cells
Motorola	954847	Plasma pattern etching Si_3N_4
RCA	954868	Phase II add-on process sequence development

ENGINEERING AREA

During this reporting period the activities within the Engineering Area were reorganized for improved visibility and increased capability for technology transfer to the photovoltaic community. Emphasis has been placed on array requirements generation, array subsystem development, array component engineering, and performance criteria and standards development. Detailed status of the Engineering Area contracts (listed on p. 36) was reported in the 16th PIM handout.

ARRAY REQUIREMENTS

Activities in the array requirements task consisted principally of monitoring and coordination of the contracts investigating array fire resistance and electrical safety, ILC building codes, and array wind loading levels. Additionally, a second PV circuit design optimization workshop was conducted at JPL on May 19-20 for photovoltaic program participants who had missed the workshop held in conjunction with the 15th PIM.

Underwriters Laboratories, Inc., is under contract to develop array and module safety requirements. As part of this effort, testing of a limited number of modules by the procedures described in Underwriters Laboratories

(UL) Standard 790, "Tests for Fire Resistance of Roof Covering Materials," has been conducted. The results obtained are being factored into a proposed safety standard for photovoltaic modules and panels now in development. Details of these tests were presented at the 16th PIM. UL has also reviewed the 1978 National Electric Code (NEC) with regard to existing specifications that may be applied to photovoltaic arrays. Limited suggestions have been made concerning changes in the NEC that may be considered for photovoltaic arrays. Included in this work is a discussion of connections for proper functioning of ground-fault detection equipment. Sample modules supplied by JPL from Block III and IV have been examined with regard to conformance with UL proposals now under consideration, and the resulting assessment will be included in the contract final report.

Burt Hill Kosar Rittelman Associates continued work on the contract to study code-related design issues for commercial and industrial applications, usually referred to as Intermediate Load Center (ILC) Applications. The design process is analyzed in terms of the building sequence as well as the various agents providing input. Particular detail is provided for through studies of the three model building codes, the National Electric Code, selected city codes and a special look at the legal and moral burden on the design profession regarding approval for new products specified.

Specific standards and associated testing methods are required in many instances for the approval of building-code officials. Investigation to date suggests that standards required will be dependent upon the ultimate placement and utilization of the photovoltaic modules, including building construction type, designated code classification, array mounting configuration, proximity to fire zones, and multiple functions that the module may be expected to serve. The value placed on standards by code officials and design professionals receives special attention due to the length of time necessary to secure standards approval as well as the expense to nationally recognized testing agencies.

Once compliance with the fixed safety requirements of the abovementioned agencies is accomplished, selection of materials and assembly techniques are based primarily on economics. To quantify the dynamic relationship between the photovoltaic power system and the building interface, five building applications selected independently of this report are being analyzed empirically to learn more about cost drivers in system and subsystem design. By analyzing the entire photovoltaic power system and building interface, it will be possible to identify appropriate tradeoffs and predict life-cycle paybacks accurately. We will thereby assist the industry in market targeting.

The observations and conclusions of the report, scheduled for publication February 1981, will provide valuable insights into obstacles and delays peculiar to the building industry in the accelerated development of photovoltaics in commercial and industrial applications.

The Boeing contract to study wind loads on flat-plate photovoltaic array fields was in the wind-tunnel test phase during this reporting period. The loads due to wind on an array and on its support structure strongly influence the design and ultimately the cost of the photovoltaic panels, panel and array support structures, and foundations. This contract consists of an experimental boundary-layer wind-tunnel test, using 1/24-scale models, of the wind forces on 8-foot-chord flate-plate photovoltaic arrays. Local pressure coefficient distributions and normal force coefficients were obtained on the arrays for a range of various parameters, including tilt angle, array separation, ground clearance, and protective wind barriers. Test data were compared with theoretical results previously reported. The most significant result from the test is the large reduction in the aerodynamic forces on arrays interior to the array field. The array on the outer boundary of the array field protects the interior arrays from the wind. Fences, in turn, can be used to protect the arrays on the outer boundary. Other results showed that the smaller the ground clearance of the arrays, the lower the aerodynamic load. Array spacing had very little effect. Array tilt-angle variation showed larger loads on outer boundary arrays with increasing tilt angle. However, the larger array tilt angles produced smaller aerodynamic loads on the arrays interior to the field. A brief movie of these tests was shown during the contract status presentation at the 16th PIM.

The tests show that aerodynamic loads on the array side edges due to oblique wind are higher by several orders of magnitude than the aerodynamic loads at locations interior from the edges. Attempts to reduce these edge loads by modifying the fence and array edges are being made.

ARRAY SUBSYSTEM DEVELOPMENT

Work on optimum ground-mounted arrays continued with present emphasis on detailed design features including module-edge treatment and gasketing, ground-handling provisions, and aesthetics. A status update together with a new full-scale prototype current-technology ground-mounted array 8 feet high by 20 feet long was presented at the PIM. The new array demonstrated the use of the JPL-optimized low-cost structure concept in the context of present intermediate-load-center applications and present-day Block IV modules. Present-day costs are being generated for quantities as small as one or two units and as large as several thousand units. Bids are being obtained for fabricating one of the structural-beam sections using actual high-speed mass-production rolling-mill tooling. The particular section is difficult to fabricate using manual techniques and offers the opportunity of obtaining real mass-production costs for a one-mile-long minimum order.

In the area of residential array designs, LSA Engineering Area personnel completed evaluation of proposals for the integrated residential photovoltaic-array development effort. Contract award is expected in September 1980.

Burt Hill Kosar Rittelmann Assdociates completed the contract to investigate the costs associated with operation and maintenance practices for residential photovoltaic modules, panels and arrays.

Six basic topics related to operation and maintenance of residential photovoltaic arrays were investigated: general (normal) maintenance, cleaning, panel replacement, gasket repair and replacement, wiring repair and replacement, and termination repair and replacement. The effects of the mounting types (rack mount, stand-off mount, direct mount, and integral mount) and the installation and replacement type (sequential, partial erection, and independent) have been identified and described. Recommendations on methods of reducing maintenance costs have also been identified.

ENGINEERING AREA

Several major conclusions were drawn as a result of this study. The most important conclusion one can draw from the investigation of residential operation and maintenance procedures is the unlikelihood of the residential owner's involvement in any maintenance procedures, preventive or corrective. As a result, the photovoltaic industry must, in its design, ensure a maintenance-free, long-lived photovoltaic device. This includes such simple maintenance procedures as cleaning; the life-cycle-costing analysis indicates that cleaning once a year is not cost-effective. Also, in the event that corrective maintenance procedures are required, the module, panel and array should be designed to facilitate such procedures. For example, the replacement of a module should be a quick and inexpensive process in order to minimize the potentially high materials and labor costs associated with such a process.

It will also be necessary for the photovoltaics industry to develop comprehensive operation and maintenance manuals for those residential owners are are "do-it-yourselfers" and those trained personnel who will be performing the typical day-to-day maintenance procedures on photovoltaic power systems.

The final report was distributed to the photovoltaic community through NTIS as Report No. DOE/JPL 955614-80/1, "Operation and Maintenance Cost Data for Residential Photovoltaic Modules/Panels," July 1980.

ARRAY COMPONENT ENGINEERING

Array component engineering continued in a number of areas including module electrical insulation, hot-spot testing, array circuit design, cell environmental testing, cell fracture strength testing, encapsulant soiling, module environmental testing, and PV/Thermal module development.

In the area of module electrical insulation, an extensive series of breakdown tests on .48-mil Mylar have been completed; tests have begun on 1.42-mil Mylar. A computer code is being created to compute flaw density vs voltage stress, intrinsic breakdown probability, and module breakdown probability.

Other activities include continued measurement of Block II and III minimodules in an attempt to define a procedure suitable for assessing the voltage breakdown probability statistics for the Block IV modules to be delivered this fall. Past hi-pot testing only provided a go--no go binary measurement.

The series-parallel effort is now focused on developing tests for determining the reverse-bias characteristics of individual cells that are shadowed or cracked in a module that is operating in the short-circuit mode. Selected cells in each module are being subjected to the 100-hour hot-spot endurance test. Preliminary results were described in a 16th PIM presentation. The series-parallel final report is also in preparation.

Work continued at Clemson University on environmental testing of various solar cell types. An important byproduct of the workshop held at Clemson last May is added interest shown by several of the cell manufacturers. One cell manufacturer has now considered engaging Clemson in a special cell-test program on development cells, whereby some costs may be shared by the cell manufacturer. A document that will contain the proceedings of the Cell Reliability Workshop is presently in preparation at JPL for distribution to LSA and the photvoltaic communities. The current status of the Clemson contract was presented at the 16th PIM.

Design of a proof-test version of the four-point cell-fracture strength test fixture proceeded. When fabricated the fixture will be used to evaluate the feasibility of in-line proof testing of wafers to decrease later yield losses due to poor cell strength.

In the module-soiling task, deployment of material samples at the California exposure sites for the second year of the module-soiling investigations was completed. Samples will be retrieved on 90-day centers. Borosilicate glass (#7809) samples are being added to all sites.

In the area of PV/T module development, several performance test mthods have been identified and iterated with members of the PV/T standards subgroup. A general-purpose test collector has been completed and the PV/T test site at JPL is in operation. Verification testing of the proposed test methods was initiated in August.

DSET Laboratories, Inc., Phoenix, Arizona, continued work during this reporting period on its contract to perform sunlight-aging tests of solar cell modules.

The accelerated aging of minimodules was continued using DSET's Super-Maq Fresnel-concentrating accelerated weathering machine. Through August 24, 1980, the two Block II modules were subjected to 2,770,780 langleys of radiation, and the six Block III modules were subjected 1,352,920 langleys of radiation. The Block II and Block III modules have been exposed to an equivalent of 14.5 and 7 years, respectively, of outdoor weathering in an "average" southwestern environment.

Weekly visual inspections, monthly 35mm slide photos, and monthly I-V measurements are used by DSET in monitoring the physical and electrical characteristics of the modules. Failure modes such as cell cracking, delamination, carbonation, and contact corrosion, as well as P_{max} losses, non-ohmic contact, and series resistance changes have been observed during the Super-Maq exposure program. In several cases, early detection of such failures has accurately predicted similar field failures in block series modules deployed in DOE demonstration programs.

A total of 27 new minimodules and subminimodules were shipped to DSET sunlight-aging tests. All of the new modules have been visually inspected and photographed, and initial I-V measurements have been made. Accelerated and real-time exposure testing of these modules will start in October.

Performance Criteria and Standards

Comments on the draft version of the Interim Performance Criteria document have been forwarded to SERI. Initial industry comments ranged the full spectrum from "acceptable as is," to constructive critique, to "unacceptable at this time" because it would adversely affect the photovoltaic industry's ability to reduce cost. This principal issue for the array subsystem is the standard reporting conditions, specifically 800 W/m^2 standard irradiance condition.

The electrical performance subgroup of the Array Subsystem Task Group met at Sandia on July 15-16, 1980. Draft test methods for the I-V and thermal characteristics of actively and passively cooled concentrator modules were reviewed. Several of these proposed methods were reviewed by the task group during the annual meeting of the Performance Criteria and Test Standards Project in Colorado in August.

Engineering Area Contractors

CONTRACTOR	CONTRACT NUMBER	DESCRIPTION
Boeing Co. Seattle WA	954833	Wind-loading study on module and array structures
Burt Hill Kosar Rittelman Associates Butler PA	955614	Residential module O&M requirements study
Clemson University Clemson SC	954929	Solar cell reliability test
DSET Laboratories, Inc. Phoenix AZ	713137	Spectral radiometric measurements and standards
IIT Research Institute Chicago IL	955720	Reliability engineering of modules and arrays
Underwriters Laboratories Melville NY	955392	Solar array and module safety requirements

OPERATIONS AREA

LARGE-SCALE PRODUCTION TASK

Block IV Design and Qualification

Six of eight manufacturers have now delivered prototypes to JPL for test. Photowatt has postponed module fabrication while working on improvements in cell efficiency and yield; ARCO Solar is incorporating a number of design changes mainly directed toward improving voltage isolation. Qualification test results are given in the table below.

Block IV Qualification Test Results

Vendor Code	Construction (from top down)	Principal Problems	Recommended Action
GR	Glass, cells bonded with clear silicone, white silicone, weatherproofed cardboard. Flex portion: reinforced white Hypalon with foam-rubber core.	Dummy shingles of built-up roof section warped.	
MS	Glass, PVB, cells, PVB, Tedlar. Mesh interconnects make contact at cell top center.	Set 1 (4 mdls): extensive cell cracking, frame seal delam., electrical degradation (1 mdl). Set 2 (3 mdls) with improved processing: 2 cells cracked in 1 mdl, electrical degradation (10%) in another with later recovery.	Test needed with larger sample size
RS	Glass, PVB, cells, PVB, Tedlar/Al/Tedlar rear cover. Butyl rubber seal to stainless sheet frame.	Sealant extruded, 3 cells cracked, one frame corner broken (1 mdl), hi-pot failures.	Design improvements and retest needed
SS	Glass, EVA, cells, EVA, ripstop, Mylar/Al backing, backspray.	J-box threads stripped, small blisters on back side (1 mdl).	
YR	Glass, EVA, cells, EVA, Tedlar, no frame.	Back side Tedlar delam (4 mdls), one cracked cell, marginal electrical degradation.	Retest needed after process improvements
YS	Same as YR, with Al frame.	Tedlar delam. (2 mdls), air bubbles.	Retest needed after process improvements
ZS	Polyester top cover, EVA, cell, EVA, scrim, acrylic, EVA, porcelainized steel pan, steel back structure.	Encapsulant lifting off pan, cracked cells, edge delamination, marginal electrical degradation (1 mdl). Failed hail tests.	Redesign and retest needed

Block IV Production

Purchase orders have been issued for small quantities of modules from five manufacturers. Most of these modules are to be deployed to the 16 JPL field-test sites.

Block V

The procurement plan has been drafted.

MODULE TEST AND EVALUATION

Environmental Testing

Five more types of Block IV modules have completed qualification testing in addition to the two reported in April. Three other types have not yet been received at JPL. Of the seven designs tested to date, none passed without some problems. Modules from the production contracts will be retested to confirm that design changes and process improvements will be effective. A short summary of the principal problems are given in the table below.

Several other modules were tested to the qualification sequence with results as described at the Project Integration Meeting.

Two problems have appeared recently with modules deployed in field applications: hot cells, with cell cracking, and broken interconnects. These problems indicate deficiencies in the qualification tests as now performed. A reverse voltage bias test has been added to the exploratory testing of Block IV modules, and the Block V qualification tests will add this requirement. Several possibilities are under review for the interconnect problem, including greatly extended temperature cycling tests.

A series of controlled laboratory tests for Nominal Operating Cell Temperature (NOCT) have been performed. A simulated wind was supplied by blower and duct to modules situated in the artificial sun of the 25-foot Space Simulator. One interesting finding was that NOCT is more sensitive to winds above 1 m/s than realized. A revised wind-correction factor will be applied to the outdoor data in an effort to reduce data scatter.

Performance Measurements

Round-robin electrical measurements have been completed by JPL and Solarex in an effort to resolve observed differences on Block IV modules. One finding was that the spectral response of current Solarex semicrystalline cells did not match that of the reference cells in use. New reference cells have been fabricated, calibrated, and distributed to Solarex, MIT/LL, Sandia, and the JPL Test Group.

Analysis of the JPL field test data is continuing. In the previous progress report, sky shadowing was hypothesized as the cause of observed anomalies in module power output. Data taken through the summer confirm this.

Field Tests

The primary focus of the field testing activity during this past period was on the collection of electrical performance and physical degradation data from the 12 continental remote sites. All of the sites were visited from May to August for this purpose. Electrical performance data were obtained with the new portable I-V Data Logger. I-V field data were collected and recorded on solid-state IPROM units for later offloading into the field test computer at JPL for printout, plotting, analysis, and archiving. Typically, six I-V curves were acquired on each module over a two-day period. These data were then normalized and compared with the pre-installation data. Modules whose fill factors differed by more than 5% from the pre-installation values were put on the "suspicious" list and their I-V curves carefully scrutinized. From this examination a definitive cataloging of electrical degradation was made. A summary of the electrical performance data was given at the Project Integration Meeting by Peter Jaffe.

All of the modules at Mines Peak were stolen sometime in April and May. Unfortunately, such thievery has been widespread. Twenty-five other modules have been stolen from four sites (nine were subsequently recovered). One of the sites is on a closed NASA facility and another is on a remote Navy island. Innovative devices for ensuring module security are now being considered.

The most difficult and subjective part of endurance testing is the evaluation of the physical condition of modules. Using composite observations from all sites, a list of common or prevalent defects for each design was prepared and then used as a check-list for observations at each site. The prevalent defect list alone is valuable as an index of problems for each module type. Comparisons between sites show how the different environments affect the common problems. Data from the latest surveys are contained in the Project Integration Meeting Proceedings.

Failure Analysis

Laboratory reverse voltage bias (hot-spot) testing of the 30-watt Mount Laguna modules has been completed, confirming that pressure from substrate outgassing is the cause of the progressive cell cracking on these modules. Similar tests on 30-watt glass superstrate modules from the same manufacturer (to be used in PRDA-38 applications) show no problems of this type.

Modules returned from the village power systems at Upper Volta, Africa, and Schuchuli, Arizona, have been analyzed to determine the cause of open circuits. These 20-watt Block II type modules have a glass-fiber-reinforced polyester substrate with a high coefficient of thermal expansion, which induced plastic yielding and fatigue failures in the cell interconnects as a result of diurnal temperature cycling.

Eleven Block III modules with glass superstrates and stainless-steel backs were returned from Natural Bridges National Monument for failure analysis. Three underlying causes were found: electrical shorts between the cell interconnect foil and the case, on eight modules; poor solder joint between the interconnect foil and the terminal, causing local heating, on two modules, and terminal feedthrough insulator damage due to heavy impact, on one module.

Inspection of a second type of glass-superstrate module returned from Natural Bridges National Monument has been made as part of the preliminary investigation of cracked cover glasses, reported to have affected as many as 50 modules in this array. The cracks originate at edge flaws in the annealed glass. Engineering Area personnel are carrying out tests to determine the source of the breaking stress.

A field survey has been completed at the Mt. Laguna 60 kW application to determine present electrical performance of the array. Analysis of the results shows increased degradation of both the 30-watt and 20-watt silicone-encapsulated modules. The 20-watt modules showed a 3.1% increase in failed modules and the 30-watt module showed a 5.75% increase in failures over a five-month period. Analysis of 12 failed modules of the 20-watt design showed 10 open circuits from fractured interconnects and two failures from cracked cells and heating. Analysis of a module returned from the John F. Long residential experiment in Phoenix has been completed. The module, which had an EVA-laminate encapsulation system on a steel substrate, exhibited cell cracking of the type associated with encapsulant outgassing and resultant pressure buildup beneath the affected cells. A similar failure was generated in the laboratory by applying reverse voltage bias to a cell, which produced the heat needed to initiate the failure mechanism.

A summary of the work described above was presented at the 16th Project Integration Meeting.

PROCEEDINGS

Highlights of the 16th Project Integration Meeting, held September 24 and 25, 1980, at the Pasadena Center, Pasadena, California:

The first day of the meeting was devoted to summaries of silicon-sheet technology, a module durability workshop, and to a series of panel discussions on residences with photovoltaic electric supply, on cadmium sulfide cell and module technology, on the commercial market prospects for photovoltaics, and on industry's perspective of and role in meeting the Department of Energy's goals in photovoltaic energy development.

The photovoltaic homes panel discussions included presentations on a partially PV-powered house in Phoenix, Arizona, built by John Long Homes, and on another at the Florida Solar Energy Center at Cape Canaveral. The panel was moderated by John L. Hesse of JPL.

Krishna Koliwad of JPL moderated the panel discussion of the progress of, and prognosis for, cadmium sulfide as a solar cell and PV module material.

Paul Maycock of the Department of Energy was moderator of the panel on photovoltaic market problems and observations, with university and industry representatives participating.

The fourth panel on industry perspectives of PV goals, and industry's role in meeting them, produces a consensus that the goals can be met, but dissenting viewpoints were offered.

Underwriters Laboratories fire-test data indicate that present PV modules meet Class A (the highest) fire rating when directly mounted on a roof structure, but they degrade roof structures' ratings when standoff or rack mounts without fire stops are used. The first draft of the UL flat-plate module and array safety requirements are to be delivered to JPL about the first of October 1980.

Semix Inc. reported on the initiation of its cooperative agreement with the Department of Energy on the development and verification of a semi-crystalline coating process.

A life-cycle cost method for array component reliability allocation has been developed, and strawman allocations were presented at a reliability and durability workshop on September 23.

Latest analysis and test procedures for designing around hot-spot, interconnect-fatigue, electrical-breakdown and glass-breakage module failure modes was presented.

Plenary Session

SILICON RIBBON AND HEM CRITICAL REVIEW

J. Liu, Chairman

- SUMMARY OF TECHNICAL AND PROGRAMMATIC REVIEW OF SHAPED SHEET AND NON-CZOCHRALSKI INGOT CONTRACTS
  - CRITICAL ASSESSMENT OF THE CURRENT STATE OF TECHNOLOGY DEVELOPMENT
  - EVALUATION OF TODAY'S DEMONSTRATED TECHNOLOGY AS REFLECTED IN PROJECTED SHEET PRICES.

<u>TECHNOLOGIES REVIEWED</u>

- HEAT EXCHANGER METHOD (HEM) – CRYSTAL SYSTEMS
- EDGE DEFINED FILM-FED GROWTH (EFG) – MOBIL TYCO
- WEB DENDRITIC GROWTH (WEB) – WESTINGHOUSE
- SILICON ON CERAMIC (SOC) – HONEYWELL

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HEM Technology Status

	TECHNICAL FEATURE		GOAL	INDIVIDUAL DEMONSTRATION	SIMULTANEOUS DEMONSTRATION
	YIELDED INGOT MASS	(kg)	63	45	45
	INGOT DIMENSIONS	(cm)	30x30x30	33x33x17.7	33x33x17.7
	CYCLE TIME	(hr)	48	VARIES	66
	SILICON GROWTH RATE	(kg/hr)	2.5	3.1	1.25
	YIELD	(%)	86	85	75
	CELL EFFICIENCY	(%AM1)	15	15.7	N.A.
	MACHINES/OPERATOR		10	(5)	(5)
	MACHINE COST	($)	35,000	(60,000)	(60,000)
	MAT'LS & UTIL/CYCLE	($)	159	(300)	(300)
IPEG	GROWTH ADD-ON	($/kg)	8.50	–	31.50
	SHEET ADD-ON	($/m^2)	21.63*	–	66.87**
	SHEET ADD-ON	($/W$_p$)***	0.15	–	0.47

* ASSUMES 1 m^2/kg, \$13.13/m^2 WAFERING ADD-ON

** ASSUMES 0.85 m^2/kg, \$29.81/m^2 WAFERING ADD-ON

***MODULE EFFICIENCY AT 14.25% AM1

( ) – ESTIMATED

HEM Add-On Sheet Price Sensitivity

TECHNICAL FEATURE	ORIGINAL GOAL	CHANGED TO:	$\Delta\$/W_p$
YIELDED INGOT MASS (kg)	63	45	0.024
CYCLE TIME (hr)	48	96	0.029
EXPENDABLES/RUN ($)	159	300	0.019
MACHINES/OPERATOR	10	5	0.013
MATERIAL UTILIZATION (m^2/kg)	1.0	0.85	0.011
MACHINE COST ($)	35,000	60,000	0.007

EFG Technology Status

TECHNICAL FEATURE	GOAL	INDIVIDUAL DEMONSTRATION	SIMULTANEOUS DEMONSTRATION
RIBBON WIDTH (cm)	10	10	10
GROWTH RATE (cm/min)	4	4.2	2.8
RIBBON THICKNESS (μm)	150	150	300
RIBBONS/FURNACE	4	5 (5 cm width) 3 (10 cm width)	3
FURNACES/OPERATOR	3	1	1
CELL EFFICIENCY (%AM1)	12	13.2 (5 cm width) 10.5 (10 cm width)	8.5
EQUIPMENT COST ($)	49,000	N.A.	(60,000)
GROWTH PERIOD (hr)	160	15	7
DUTY CYCLE (%)	90	90	60
MELT REPL. & AUTO CONTROL	YES	YES	YES
YIELD (%)	90	90	55
IPEG SHEET ADD-ON ($/m^2)	14.41	–	92.61*
IPEG SHEET ADD-ON ($/$W_p$)	0.13**	–	1.15***

* ASSUMES GROWTH PERIOD OF 116 HRS

** MODULE EFFICIENCY OF 11.4% AM1

***MODULE EFFICIENCY OF 8.05% AM1

( ) – ESTIMATED

EFG Add-On Sheet Price Sensitivity

TECHNICAL FEATURE	ORIGINAL GOAL	CHANGED TO:	$\Delta\$/W_p$
FURNACES/OPERATOR	3	1	0.068
GROWTH RATE (cm/min)	4	2.8	0.054
EXPENDABLES/RUN ($)	287	574	0.008
EQUIPMENT COST ($)	49,000	60,000	0.005
GROWTH PERIOD (hr)	160	80	0.005

Web Technology Status

TECHNICAL FEATURE		GOAL	INDIVIDUAL DEMONSTRATION	SIMULTANEOUS DEMONSTRATION
RIBBON WIDTH	(cm)	5	4	3
GROWTH RATE	(cm^2/min)	25	27	15
RIBBON THICKNESS	(μm)	150	150	150
FURNACES/OPERATOR		18	1	(2)
CELL EFFICIENCY	(%/AM1)	15	15	15
EQUIPMENT COST	($)	15,400	N.A.	(25,000)
GROWTH PERIOD	(hr)	72	24	8
DUTY CYCLE	(%)	90	71	71
MELT REPL & AUTO CONTROL		YES	YES (8 hr)	NO
YIELD	(%)	90	70	70
IPEG SHEET ADD-ON	($\$/m^2$)	18.39	–	116.60*
IPEG SHEET ADD-ON	($\$/W_p$)**	0.13	–	0.82

( ) - ESTIMATED

* ASSUMES GROWTH PERIOD OF 72 HR, MELT. REPL. & AUTO CONTROLS.

**MODULE EFFICIENCY OF 14.25%AM1

Web Add-On Sheet Price Sensitivity

TECHNICAL FEATURE	ORIGINAL GOAL	CHANGED TO:	$\Delta\$/W_p$
GROWTH RATE (cm^2/min)	25	15	0.086
FURNACES/OPERATOR	18	9	0.038
EQUIPMENT COST ($)	15,400	25,000	0.033
GROWTH PERIOD (hr)	72	36	0.012

SOC Technology Status

TECHNICAL FEATURE	GOAL	INDIVIDUAL DEMONSTRATION	SIMULTANEOUS DEMONSTRATION
SUBSTRATE WIDTH (cm)	12.5	10	10
GROWTH RATE (cm/min)	14	30	30
SUBSTRATES/COATER	2	1	1
FILM THICKNESS (μm)	100	<100	<100
COATERS/OPERATOR	12	1	1
CELL EFFICIENCY (%AM1)	11	10.5*	N.A.
EQUIPMENT COST ($)	50,800	N.A.	N.A.
SUBSTRATE COST ($/m^2)	5.68	N.A.	N.A.
DUTY CYCLE (%)	85	N.A.	N.A.
MELT REPL. & AUTO CONTROL	YES	NO	NO
YIELD (%)	92	N.A.	N.A.
IPEG SHEET ADD-ON ($/m^2)	12.97	–	INSUFFICIENT DATA
IPEG SHEET ADD-ON ($/W$_p$)	0.13	–	

*DIP COATING, NO SCIM DATA YET AVAILABLE

( ) - ESTIMATED

ORIGINAL SHEET ADD-ON PRICE –$0.128/W$_p$

TECHNICAL FEATURE	ORIGINAL GOAL	CHANGED TO:	Δ\$/W$_p$
SUBSTRATE COST ($/m^2)	5.68	11.36	0.103
GROWTH RATE (cm/min)	14	10	0.054
COATERS/OPERATOR	12	6	0.024

Add-On Price Status Summary ($/$W_p$)

TECHNOLOGY	LSA PROJECT ALLOCATION	PROJECTED GOAL ACHIEVEMENT	CURRENT SIMUL. ACHIEVEMENTS
HEM	0.256	0.15*	0.47**
EFG	0.205	0.13	1.15
WEB	0.292	0.13	0.82
SOC	0.190	0.13	N.A.

*INCLUDES \$0.09/W_p FOR WAFERING
**INCLUDES \$0.21/W_p FOR WAFERING

Status of Technology Commercialization

- CSI IS CURRENTLY OFFERING HEM INGOTS AND WAFERS FOR SALE.
- MTSEC IS INSTALLING A REVERSE OSMOSIS WATER DESALINATION PLANT POWERED BY 8 kW OF EFG MODULES IN SAUDI ARABIA.
- WESTINGHOUSE IS CONSTRUCTING A 50 kW/yr WEB MODULE-PRODUCTION FACILITY. A PORTION OF THE OUTPUT IS SLATED FOR A JOINT WESTINGHOUSE/ ELECTRIC UTILITIES PROJECT.

Conclusions

- TECHNICAL FEATURES REQUIRED FOR ACHIEVEMENT OF $0.70/$W_p$ GOAL HAVE BEEN DEMONSTRATED BY THE EFG AND WEB TECHNOLOGIES.
- ADDITIONAL DEVELOPMENT IS REQUIRED FOR THE HEM AND SOC TECHNOLOGIES TO DEMONSTRATE ALL TECHNICAL FEATURES.
- VERIFICATION OF PRODUCTION TECHNICAL FEATURES (i.e., YIELD, GROWTH CYCLE, DUTY CYCLE, MACHINES/OPERATOR) REQUIRES EXPERIMENTAL SHEET GROWTH UNITS (ESGU) AND WILL BE ACCOMPLISHED IN THE UPCOMING ESGU DEVELOPMENT PHASE.
- ENCOURAGING PROGRESS IS OBSERVED IN INDUSTRY'S COMMERCIALIZATION EFFORTS FOR THESE TECHNOLOGIES.

REPORTS

Crystal Systems, Inc.: Heat Exchanger Method (HEM) -- The size of silicon ingot cast by HEM has been increased to 34 x 34 x 20 cm weighing 45 kg, the largest silicon ingot to be cast. The first ingot, of 34 x 34 cm cross section, was 10 cm high and weighed 20 kg. Solidification rates of 3 kg/h were achieved; there was no problem with crucible attachment or ingot cracking. This achievement was followed by the casting of a 26-kg ingot and, later, two 45 kg ingots.

One of the problems encountered in ingot casting has been cracking of the crucible. Cracking occurred during heat treatment, done to develop a graded structure, or while loading. Reducing the gradients eliminated cracking during heat treatment and minimized cracking under load. The crucible needs to be annealed to minimize stresses before loading, and to be supported to provide uniform loading conditions.

Mobil Tyco Solar Energy Corp.: Edge-Defined Film Growth (EFG) -- Achievability of solar cell efficiencies greater than 13% was demonstrated, using resistance machine-produced EFG material at small (6 cm^2) areas. Additionally, in non-continuous growth of single 10-cm-wide ribbons, growth speeds of up to 4.5 cm/min were attained with this ribbon.

Ribbons 10 cm wide were grown over 8 to 9 h at speeds of about 3.5 cm/min under fully automatic control, using single continuously melt-replenished cartidges. All automatic control systems for the multiple-ribbon equipment were built, assembled and tested well before the planned completion date.

Although in all four full-scale multiple runs significant lengths of ribbon were grown from some of the cartridges, the duration of stable full-width ribbon growth from all cartridges was much too short. It must be concluded that a 4-in. multiple furnace needs significant further engineering development and some redesign before conclusions can be drawn on the detailed design features of a future full-scale production unit.

Westinghouse: Web Dendrite Growth (Web) -- The melt-level control system developed for this program consists of a three-component control loop comprising: a) a melt-replenishment system, b) a melt-level sensing system, and c) a circuit that closes the loop with components a) and b). During the previous reporting period, long-term manually controlled melt replenishment was demonstrated for 17 h which constitutes the growth period for a 24-h growth cycle. In the same period a melt-level sensing system was installed and operated successfully. Closing of the loop provided fully automatic control of melt replenishment and, in so doing, provided semi-automatic control of web growth. The semi-automatic growth mode is cost-effective because operator action is greatly reduced and the permissible duration of growth run is extended to the desired order of three days or greater.

Evaluation of the economics of dendrite recycling was completed. The economic significance of three options for dendrite recycling was reported. The assumed high quality of web grown from melts containing recycled dendrites has now been verified, thus confirming the economic projection that recycling of dendrites provides a small but significant cost saving.

Honeywell: Silicon-on-Ceramic (SOC) -- SCIM coating of wide substrates (10 x 100 cm) has been investigated over a range of substrate speeds (4 to 30 cm/min). At high speeds the coating process works very well, but the layers have been too thin (<50 μm). At the speeds required for adequate thickness (3 to 5 cm/min) there have been problems with substrate buckling and breakage due to thermal strees developed on cooling. Attainment of the desired linear longitudinal temperature profile in the cooling zone has been slow due to difficulties in measuring the temperature of moving substrates. Thermal modeling has been helpful in quantitative design and in qualitative understanding of the various temperature readings.

Cell efficiencies have been significantly increased by using a slow cooldown after the phosphorus diffusion. The best SOC cell had a total area conversion efficiency of 10.5%, (AM1, AR) for a cell area of 5 cm^2. For 29 recent cells, the average efficiency was 9.9% with a standard deviation of 0.3%.

Cornell University: Characterization of Silicon Sheet.

Web material

Observations on the web material agree with previous published findings, which report that:

(1) The major structural defect in the web material is a single or

multiple twin in the central plane of the ribbon.

(2) The dislocation density varies over the cross section but is generally relatively low ($\approx 10^5$ cm^{-2}).

(3) The dislocations have Buerger vectors $\langle 110 \rangle$ and line directions $[\bar{2}\bar{1}1]$ and $\langle 110 \rangle$.

New features, not previously reported, are:

(1) The central twinning region may be a microtwin or twins.

(2) Dislocations with Buerger vectors of the $\langle 211 \rangle$ type accommodate small tilt components between the twin planes.

(3) Hexagonal partial dislocations arrays accommodate small twist components between the twin planes.

EFG material

The new findings are:

(1) The electrical activity of twin boundaries exhibiting dotted EBIC contact is associated with the presence of partial dislocations in the boundary.

(2) A significant fraction of the straight twin boundaries present are secondary twins of the (111)-(115) type. These secondary twins contain a high density of dislocations and are strongly active electrically.

The latter finding is particularly interesting, since it was previously assumed by all investigators of EFG material that the straight twin boundaries are all of the same type, i.e., coherent twins.

Applied Solar Energy Corp.: Cell Fabrication and Analysis -- Solar cells were fabricated using a baseline process. Performance of other process variations, such as formation of shallow junction, fine grid lines, BSF, better AR coating and application of gettering, etc., was evaluated under both AMO and and AM1 illumination conditions. Comparison was made with conventional Cz silicon slices processed with the sheets. In addition, back-up measurements were made of minority carrier diffusion length, spectral response, dark diode I-V characteristics and small light-spot scanning. Good agreement was found between these back-up measurements and the cell performance. In particular, minority carrier diffusion length was still seen to be a dominant factor in determining cell efficiency.

Directional Solidification by HEM

TECHNOLOGY

INGOT CASTING

APPROACH

DIRECTIONAL SOLIDIFICATION BY THE HEAT EXCHANGER METHOD (HEM)

CONTRACTOR

CRYSTAL SYSTEMS, INC.

GOALS

- 30 CM CUBE INGOTS (63 KG)
- ⩾ 15% CELL EFFICIENCY
- > 90% SINGLE CRYSTAL
- ⩽ 65 HOURS CYCLE TIME
- TECHNICAL FEATURES DEMONSTRATION 12/15/80
- TECHNOLOGY READINESS 10/01/82

REPORT DATE

- 08/25/80

STATUS

- 34 CM X 34 CM X 20 CM INGOT (45 KG)*
- 15% CELL EFFICIENCY DEMONSTRATED
- 90% SINGLE CRYSTAL
- 12.3 % CELL EFFICIENCY DEMONSTRATED WITH UMG SILICON
- FLAT PLATE CRUCIBLES DEMONSTRATED
- 3.1 KG/HR GROWTH RATE DEMONSTRATED*

* NEW ACHIEVEMENT

HEM

	AVERAGE CELL PARAMETERS (AM1)					
	Voc, mV	Jsc mA/cm^2	CFF,%	η , %	PROCESS USED	η_o,%
1	564	25.9	73	10 .8	BL (I,S)	11.5
2	560	26.0	74	10.8	BL (I,P)	11.5
3	580	25.3	73	10.8	BL (II,S)	12.1
4	580	23.7	63	8.7	BL (II,P)	10.7
5	591	27.7	71	11.7	GET+BL (II,S)	13.5
6	583	26.3	72	11.2	GET+BL (II,P)	12.8
7	550	23.9	74	9.8	BL (III,SP)	12.6
8	557	24.9	73	10.2	GET+BL(III,SP)	12.1
9	597	32.5	78	15.0	GET+SJ+BSF+MLAR	15.7
10	550	23.5	75	9.8	BL (III,SP)	12.8
CONT	588	28.1	76	12.6	BL	13.8

NOTE: 1. #7, 8, and 9 from a cube (4"x 4"x4", Crystal System #41-07)

2. #10 from a vertically cut wafer (a whole ingot, Crystal system #41-24)

Multiple-Ribbon EFG Growth

TECHNOLOGY

RIBBON GROWTH

APPROACH

MULTIPLE RIBBON EDGE-DEFINED FILM-FED GROWTH

CONTRACTOR

MOBIL TYCO SOLAR ENERGY CORPORATION

GOALS

LONG RANGE:
- 10 CM WIDE RIBBON AT 4.5 CM/MIN.
- MULTIPLE GROWTH, 12 RIBBONS/OPERATOR.
- CELL EFFICIENCY (50 CM^2 AREA) ≥ 12%.

SHORT RANGE: (7/1/80)
- CONVERSION EFFICIENCY ON A SMALL CELL (MIN. 4 CM^2): ≥ 12.75%
- TECHNICAL FEATURES DEMSTRATION.

REPORT DATE

8/25/80

STATUS

- TECHNICAL FEATURES DEMON. - 4 ATTEMPTS.
  THREE RIBBONS 10 CM WIDE AT 2.8 - 3.5 CM/MIN;
  MAXIMUM LENGTH OF A SINGLE RIBBON (NOT REPRODUCIBLE):
  16 M WITH TOTALLY AUTOMATIC CONTROL FOR 9 HOURS;
  10 MIL THICKNESS, CONVERSION EFFICIENCIES UP TO 9%.
- SINGLE CARTRIDGE GROWTH;
  10 CM WIDE RIBBON AT 4.2 CM/MIN WITH CELL EFFICIENCIES ON 50 CM^2 CELLS OF 10.5%; 8 MILS THICK.
  5 CM WIDE RIBBON WITH SOLAR CELL EFFICIENCIES BETWEEN 11% AND 12.5% WHEN CO_2 IS ADDED TO THE CARTRIDGE INERT GAS. PEAK EFFICIENCIES ON SMALL CELLS (6 CM^2) OVER 13%.

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS:
- GROWTH OF 12 RIBBONS, 10 CM WIDE AT 4 CM/MIN, USING ONE OPERATOR AT $6/HOUR.
- TOTAL EQUIPMENT CAPITAL COST: $147,000.
- DUTY RATE OF EQUIPMENT: 90% FOR 20 SHIFTS/WEEK, 48 WEEKS/YEAR.
- 6 MIL THICK RIBBONS.

PROJECTION
- $14.41/$M^2$ ADDED VALUE.
- $22.31/$M^2$ TOTAL SHEET COST (SILICON 30% BURDENED).
- AT AN ASSUMED 11.4% PANEL EFFICIENCY AND YIELDED BY 0.95 x 0.995 FOR CELL AND PANEL YIELDS:
  $.13/WATT ADDED VALUE.
  $.21/WATT TOTAL SHEET COST.

Technical Features Demonstration, July 1980: Goals

Ribbon Width:	10 cm
Run length:	8 hours
Growth rate:	4.5 cm/minute
Machine duty rate:	≥ 85%
Solar cell efficiency:	10.2% (mean of a 10% random sample)
Automatic controls:	operational
Number of ribbons growing:	3

Run 16-215

Run duration (minutes): 572
Time percentage of simultaneous three-ribbon growth: 12.7

	Cartridge No. 1	Cartridge No. 2	Cartridge No. 3	Total
Length of ribbon growth (m)	6.64	4.08*	10.75	21.47
Length ≥ 10 cm wide ribbon (m)	3.89	1.14	7.01	12.04
Percentage ≥ 10 cm wide ribbon	58.6	27.9	65.2	56.1
Growth time total (minutes)	221	201	419	
Longest growth time (minutes)	92	128	273	
Number of freezes	11	5	6	
Average growth rate (cm/minute)	3.00	2.03*	2.56	
Percentage of run time operating	38.6	35.1	73.3	

*It appears that the very low ribbon output from this cartridge is in error, due to not recording, some broken segments.

Theoretical possible length of ribbon (572 minutes x 2.8 cm/minute x 3) = 48.05 m

$$\text{Duty rate based on total length actually grown} = \frac{21.47\ \text{m}}{48.05\ \text{m}} = .447$$

$$\text{Duty rate based on total length of 10 cm wide ribbon} = \frac{12.04\ \text{m}}{48.05\ \text{m}} = .251$$

5-cm-Wide Ribbons

Multiple-Ribbon Throughput Data for 15.5-Hour Growth Demonstration Run 16-187, May 21, 1979

Cartridge No.	1	2	3	4	5
Total quantity (meters)	30.4	29.6	29.9	31.1	27.7
Total duration of growth (minutes)	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 (minutes)	692	331	505	490	508
Average growth rate (cm/minute)	3.34	3.33	3.62	3.38	3.34
Overall duty rate (%)			94.7		

Earlier EFG (RH)

	AVERAGE CELL PARAMETERS				PROCESS USED	η_a (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1),%		
1	500	18.5	73	6.7	BL	7.2
2	509	19.5	66	6.6	SE + BL	7.2
3	514	18.4	70	6.6	ST + BL	7.1
4	532	21.8	73	8.5	GBP + BL	9.3
5	523	22.9	68	8.1	GET + BL	8.4
6	527	22.0	71	8.2	BL + BSF	9.0
7	533	22.5	75	9.0	SJ + MLAR	10.2
CONT.	588	28.1	76	12.6	BL	13.8

New EFG (RH)

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1), %		
8	524	21.4	71	8.1	BL	8.7
9	568	24.3	75	10.3	BL	11.1
10	565	28.4	76	12.1	SJ + BSR + MLAR	13.6

Silicon Web Process

Technology

Single crystal ribbon growth

Approach

Silicon dendritic web growth

Contractor

Westinghouse Electric Corp.
Research & Development Center

Goals

- Area rate of growth 25 cm^2/minute
- Continuous melt replenishment
- Cell efficiency $\geq$ 15% AM1
- Semi-automatic growth
- Thickness 100-200 μm
- Dislocation density $< 10^4/cm^2$

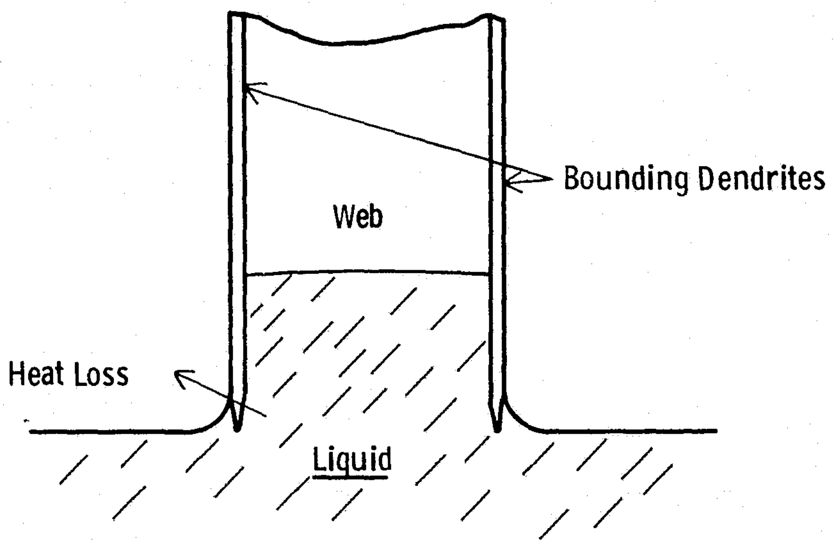
Report Date

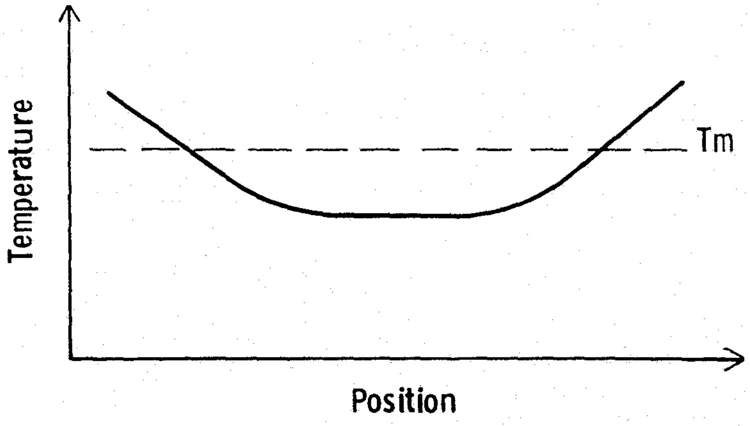
09/23/80

Status

- 27 Square centimeters per minute growth demonstrated
- One-day manually-controlled melt replenished growth cycle demonstrated
- Solar cell efficiency of 15.5% AM1 demonstrated. Average efficiency = 13.5% AM1
- Semi-automated growth demonstrated - 8 hours
- Thickness routinely 100-200 μm
- Dislocation density routinely $< 10^4/cm^2$

Web Growth vs Temperature Profile at Melt Surface





Progress Highlights

	April 1977	April 1978	April 1979	July 1980
Maximum Demonstrated Area Growth Rate, cm^2/mm	2.3	8	23	27
Maximum Demonstrated Width, cm	2.4	3.5	4.0	4.7
Maximum Demonstrated Cell Efficiency, AM1%	~13	~14	~15	~15.5
Continuous Melt Replenishment	-	Concept Only	Demonstrated	Long Term
Semi-Automatic Growth	-	-	Concept	Demonstrated

Dendritic Web

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF,%	η (AM1) %		
1	543	27.7	76	11.5	BL	12.1
2	582	32.8	75	14.3	SJ+BSF+BSR+MLAR	15.5
CONT	583	27.9	77	12.5	BL	12.7

1986 Cost Projections (1980 $) SAMICS-IPEG

Assumptions:

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

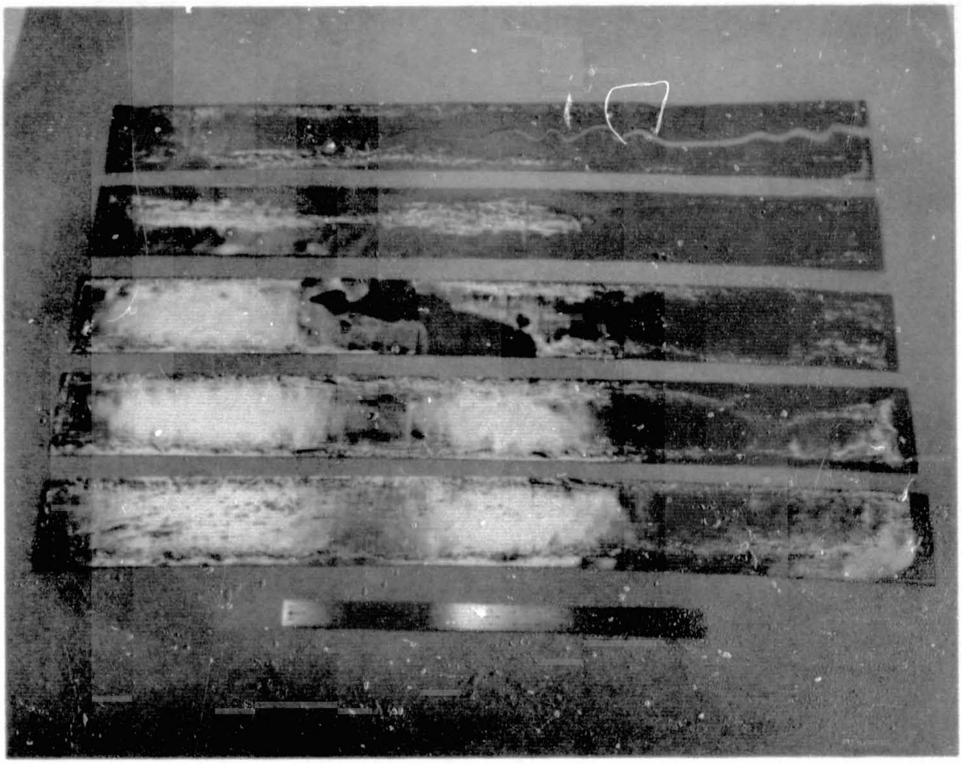
	Projected Cost, $/$W_{pk}$
Value-Added Wafer Cost	.134
Polysilicon Cost	.039
Total Wafer Cost	.173
DOE/JPL 1986 Goal	.224

Overview of Approach

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

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

Silicon on Ceramic



Top down: 6 cm/min, 9 cm/min, 12 cm/min, 20 cm/min, 30 cm/min

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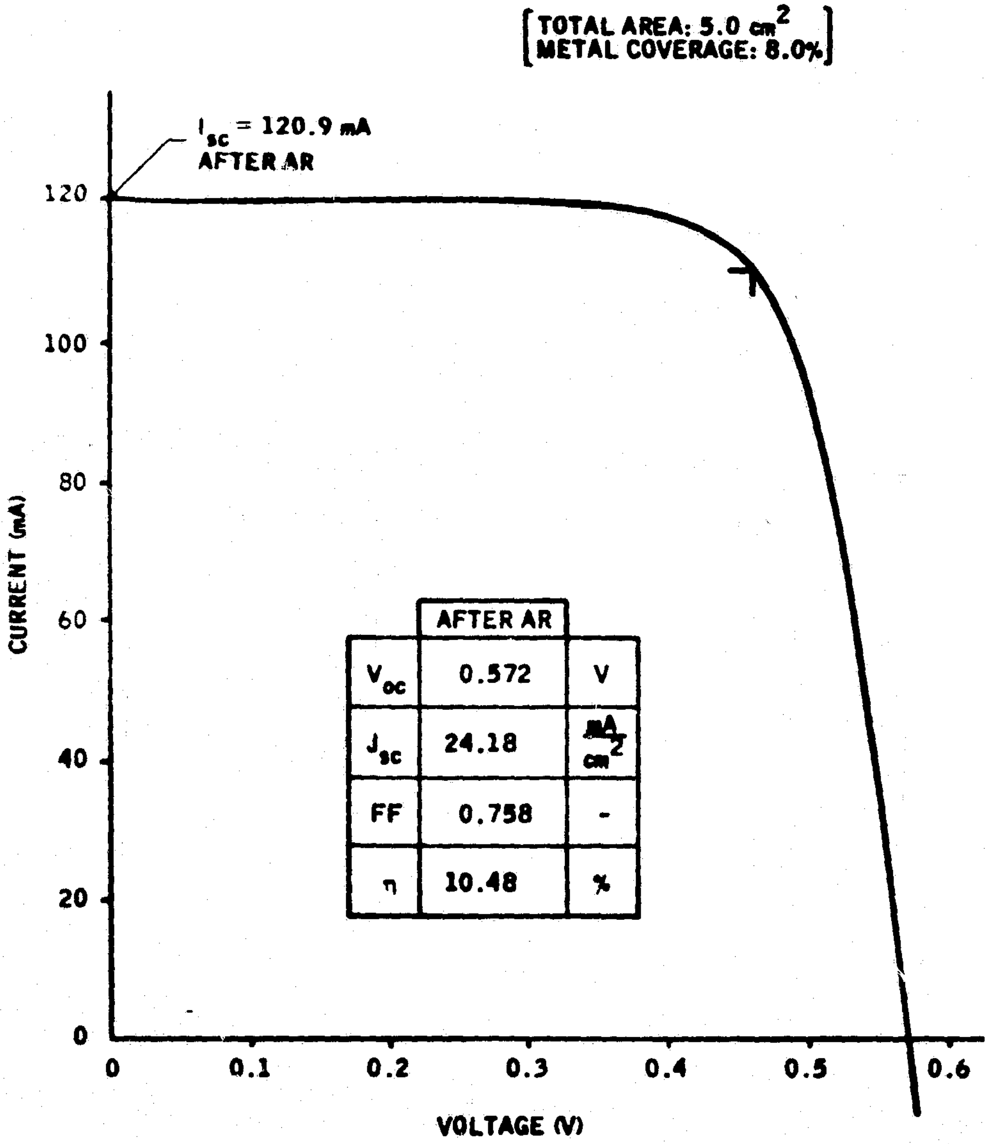


	AFTER AR	
V_{oc}	0.572	V
J_{sc}	24.18	$\frac{mA}{cm^2}$
FF	0.758	-
η	10.48	%

SOC

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1)%
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1),%		
0	532	19.3	66	6.9	PHASE I	7.9
1	524	22.6	65	7.6	STD	8.3
2	523	23.5	64	7.8	SJ+STD	8.2
3	529	23.7	67	8.4	SJ+MLAR	8.9
4	555	24.1	69	9.3	SJ+MLAR	9.6
5	564 (574)	23.0 (23.5)	73 (74)	9.5 (9.9)	HONEYWELL	9.8 (10.2)

STD Process

1. EVAPORATION OF Al ON THE BACK.
2. STD DIFFUSION
3. BACK CONTACT EVAPORATION (Ti-Pd-Ag) AND SINTER
4. FRONT CONTACT (Ti-Pd-Ag) BY PHOTORESIST TECHNIQUES.
5. MESA FORMATION
6. AR COATING BY EVAPORATION (SiO)
7. INDIUM-TIN SOLDER FILL IN THE BACK SLOTS.

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS:

- $\$5.78/\text{M}^2$ CERAMIC COST
- \$50,800 PER SCIM-COATER
- 2 PANELS/SCIM-COATER
- 0.25 CM/SEC PULL SPEED
- 1 OPERATOR/12 COATERS
- 6 MACHINES/STACK
- 85% DUTY CYCLE
- 92% SHEET YIELD
- 95% CELL YIELD
- 99.5% MODULE YIELD
- 11% ENCAPSULATED CELL EFFICIENCY

PROJECTIONS:

- $\$12.97/\text{M}^2$ ADDED VALUE
- $\$17.23/\text{M}^2$ TOTAL SHEET VALUE
- $\$13.1¢/W_p$ ADDED VALUE
- $\$17.4¢/W_p$ TOTAL SHEET VALUE

MODULE DURABILITY AND LIFE TESTING WORKSHOP

C.D. Coulbert, Chairman

AGENDA

TIME	SPEAKER	SUBJECT
8:00	C. Coulbert	INTRODUCTION Objective, scope of workshop, definitions
8:30	R. Ross	MODULE DURABILITY GOALS Quantification of durability Allowable failure levels
9:15	L. Dumas	MODULES DURABILITY EXPERIENCE Field exposure/application sites Failure experience versus goals Key failure mechanisms
	MODULE DURABILITY DESIGN TECHNIQUES	
10:15	C. Coulbert	INTRODUCTION
10:30	J. Arnett	Soiling Cell cracking/hot spots
11:45	D. Moore	Interconnect fatigue
	LUNCH	
12:45	D. Moore	Structural failure and glass breakage
1:10	G. Mon	Electrical termination failure Electrical insulation breakdown
1:40	A. Gupta	Encapsulant thermal degradation Encapsulant photodegradation Delamination
2:40	D. Kaelble	Corrosion
3:15	APPROACHES TO IMPROVED RELIABILITY AND LIFE: INDUSTRY PANEL R. Ross, Moderator	

SUMMARY

A one-day workshop was conducted at JPL on Tuesday, September 23, to present and review with the photovoltaic community the status of field-test experience and module-design technology available for the achievement and assessment of module reliability and durability.

The economic impact of specific failure and degradation rates was defined quantitatively, along with tentative limits required if the LSA Project overall cost, performance, and life goals are to be met. Field-test experience was reviewed in terms of the kinds of module failure and failure rates encountered expressed in terms comparable to the tentative goals. The status of understanding the causes, consequences and possible cures for 10 specific module failure modes was reviewed in detail with application to present and future module designs,

A two-hour panel discussion with six industrial representatives considered the problems and approaches to commercial implementation of appropriate measures to achieve module reliability and durability.

Key problems defined during the discussion included the following:

(1) Present module acceptance and qualification tests do not assure reliability or long life.

(2) Module life-predictive test methods and design analysis'tools are not yet available for most potential failure modes.

(3) Current high-visibility field application experiments may lead to a wrong public perception of the reliability of solar power unless such experiments are properly planned, monitored, and publicized.

Key conclusions and recommendations included the following:

(1) There is no substitute for well-planned and analyzed real-time field application experience to assess module reliability and durability.

(2) There is a need for an objective independent organization to provide test standards, conduct tests and make the results available to the user community.

(3) There is a need to make available in the most useful and concise format the results of photovoltaic field testing, analytical design studies and the results of failure analyses. (Design manual?)

(4) Automation holds promise for impoved reliability if appropriate quality-assurance programs are established by industry to achieve process control, reproducibility, and feedback.

It was agreed by all that the present user community is more concerned with module reliability than with price and efficiency, The emphasis within the photovoltaic industry may shift more toward the achievement of reliability now that the price and efficiency goals are in sight.

A summary of these workshop presentations and panel discussion was presented at the 16th PIM plenary session on Wednesday morning. A brief discussion of the workshop presentations is presented below with selected figures that convey the scope of the technical material presented. It may be noted that more detailed presentations of various ongoing failure investigations were presented at of PIM sessions and specific technical reports will be availiable for such subjects as module circuit design, soiling, interconnect failures, and glass-design criteria.

Module Durability Goals

An approach to the quantification of the LSA module life goals was presented, in terms of equivalent life cycle energy costs, by Ron Ross. If life-cycle energy cost is calculated for 70¢/watt modules with 10% efficiency and a 20-year service life, then a series of module preformance values and degradation characteristics can be defined that will give equivalent life-cycle energy costs.

Four general module performance-loss characteristics that result from the typical degradation mechanisms observed in the field were defined:

(1) Array efficiency fixed loss (constant average power loss).

(2) Array efficiency loss increasing with time (without module replacement).

(3) Constant module replacement rate due to inoperative or unsafe conditions.

(4) Rapid module wearout at end of life.

Accompanying figures presented the economic impact of various failure mechanisms in terms of failure levels causing a 10% increase in life-cycle energy cost. Based on the observation that various combined degradation modes will occur and affect array performance over the life to the modules, a strawman degradation allocation was presented for which the life-cycle energy cost would be equivalent to the original LSA goals. This allocation allowed for reasonable values of soiling, yellowing, cell failure, hail damage, electrical insulation bereakdown, interconnect fatigue and corrosion.

Module Durability Experience

A summary of module durability experience with Block I, II, III, IV, and other developmental and commercial modules was presented by Larry Dumas. The deployment sites, times of exposure, and the types and frequency of failures were described. One chart was presented on which the strawman degradation allocations could be compared with the observed ranges of degradation experience in the various field and application test sites. A great diversity of failure experience is noted for a relatively short exposure time. It is believed that most of the failures observed can be corrected by design changes of quality-control measures and are not inherently life-limiting.

Module Durability Design Techniques

In this session, 10 module failure and degradation mechanisms were presented in terms of their causes, effects, and possible cures. The general approach in the investigation of failure mechanisms indentified during field and laboratory testing was described. In most instances, failure mechanisms were simulated in controlled tests to link the failures with specific environmental exposure stresses. Where possible, a quantitative relationship was established between the failure probability, failure rate or performance degradation rate and the environmental parameters. The three basic approaches to possible cures were:

(1) Minimizing the effect by fault tolerant design.

(2) Eliminating by design and material selection.

(3) Assuring quality of hardware with appropriate standards, inspections, and tests.

The following brief comments on failure or degradation mechanisms express some of the highlights of ongoing investigations, which are covered in greater detail elsewhere.

Soiling

Module surface-soil accumulation is one of the most significant causes of performance degradation. Power losses greater than 40% may be incurred in a few weeks in industrial locations. Soil retention in the presence of rain washing varies greatly between glass and polymeric encapsulant surfaces. Glass is best, but current studies are developing criteria for reduced soil retention on both glass and polymeric-film module covers.

Cell Cracking and Hot Spots

Cell cracking due to pre-existing cell-edge flaws and various loads during manufacture, handling and environmental exposure is an obtrusive fact of life. It is currently coped with by a fault-tolerant design approach, e.g., multiple-cell contacts and appropriate circuit design with series-parallel and diode optimization.

Interconnect Fatigue

Fatigue failure of copper-ribbon interconnects between cells in modules with glass fiber-polyester substrates has been observed as a field-test wearout failure mode. Analysis of the stress on the copper ribbon due to thermal expansion differences between the cells and substrate reveals that plastic strain occurs and that fatigue failures can be predicted for the design in question. Design criteria for interconnect materials and stress-relief configurations to eliminate this failure mode can be derived.

Structural Failure and Glass Breakage

The glass used for module covers and superstrates must withstand at least three common loading conditions: hail impact, wind, and thermal-stress gradients. Field failures have been attributed to both hail and thermal stress; wind stresses are generally much lower than design-allowable. Quality criteria and recommendations are available for glass type, thickness, heat treatment and edge finish.

Electrical Termination Failure

Visible deterioration of electrical termination hardware in the field has occurred, but this has not been a serious cause of module power loss. An LSA contractor report by Motorola Inc./ITT Cannon (DOE/JPL 955367-80/1) sets forth termination design and selection criteria and ranks various avilable hardware approaches. This area is the subject of ongoing studies.

Electrical Insulation Breakdown

Electrical insulation breakdown of modules has been attributed primary to manufacturing flaws rather than to exceeding the intrinsic dielectric strength of the layers of encapsulant materials. Flaws have included voids, sharp edges, contaminants and projections. The most promising design approach appears to be the use of multiple-layer insulation films and elimination of flaws by design and process control.

Encapsulant Thermal Degradation and Photodegradation

These two polymer degradation modes may occur separately or as a combined effect. They are identified separately because they have been identified with different field failure modes. Thermal degradation associated with high cell temperatures during back-bias cell heating has caused polymer decomposition and gas-bubble formation with cell bulging and encapsulant scorching. The possible cures are the selection of the most thermally stable polymers and the adoption of a circuit design that limits the power dissipation in a back-bias situation. The thermal stability of all candidate encapsulants is being assessed along with solar ultraviolet stability. Materials being characterized include silicones, EVA, PVB, acrylics, Tedlar, PnBA, polyurethane, and candidate UV screening films.

Delamination

Delamination of the encapsulant layers from module substrates of metal and plastic has been a common visible field degradation mode. Usually this has not been the proximate cause of a module failure. Delaminations at terminals and module edges is attributed mainly to inadequate surface preparation and priming. Delamination of silicone from substrates can also be caused by UV degradation of the plastic substrate; hydroxyl formation in silicones at the interface between silicone and a substrate also leads to spontaneous delamination. Delamination over a cell results directly in an optical transmission loss. Delaminations also allow the accumulation of condensed water and would be expected to lead to cell corrosion. In general, surfaces with well-bonded organic coatings will not allow condensed water accumulation and corrosion would not occur at their interfaces.

Corrosion

Corrosion of exposed module and array structure hardware is a visible degradation mode. Its long-term effect on module power has not yet been quantified. One corrosion mechanism that is being investigated experimentally as having long-term degrading implications is the corrosion current generated across the thickness of cracked cells due to the cells' front-to-back potential and the opportunity for moisture condensation in cell cracks. The seriousness of the problem and possible cures have yet to be determined.

Workshop Objective

PRESENT AND REVIEW AVAILABLE CRITERIA AND APPROACHES FOR THE IMPROVEMENT OF MODULE RELIABILITY AND SERVICE LIFE

Workshop Scope

1. QUANTIFYING MODULE DURABILITY GOALS
    - BASED ON LIFE-CYCLE ENERGY COST
    - EFFECT OF FAILURE AND DEGRADATION RATES ON COST
    - ALLOWABLE FAILURE LEVELS
2. MODULE DURABILITY EXPERIENCE
    - SCOPE OF TESTING EXPERIENCE
    - FAILURE EXPERIENCE AT VARIOUS SITES
    - KEY FAILURE AND DEGRADATION MODES
3. STATUS OF DETECTION, ANALYSIS, AND PREVENTION OF TEN POTENTIAL LIFE-LIMITING FAILURE MECHANISMS
4. INDUSTRY PANEL DISCUSSION OF PRACTICAL APPROACHES TO IMPROVED RELIABILITY AND SERVICE LIFE

LSA Activities Related to Durability But Not Detailed in Workshop

CONTRACTS:

SPECTROLAB – MODULE DESIGN, ANALYSIS, AND TEST VERIFICATION

IIT RESEARCH INSTITUTE – RELIABILITY ENGINEERING AND TECHNICAL SUPPORT

CLEMSON UNIVERSITY – SOLAR CELL RELIABILITY TESTING

JPL IN-HOUSE: (WITH CONTRACTOR SUPPORT)

QUALITY ASSURANCE

CODES AND STANDARDS DEVELOPMENT

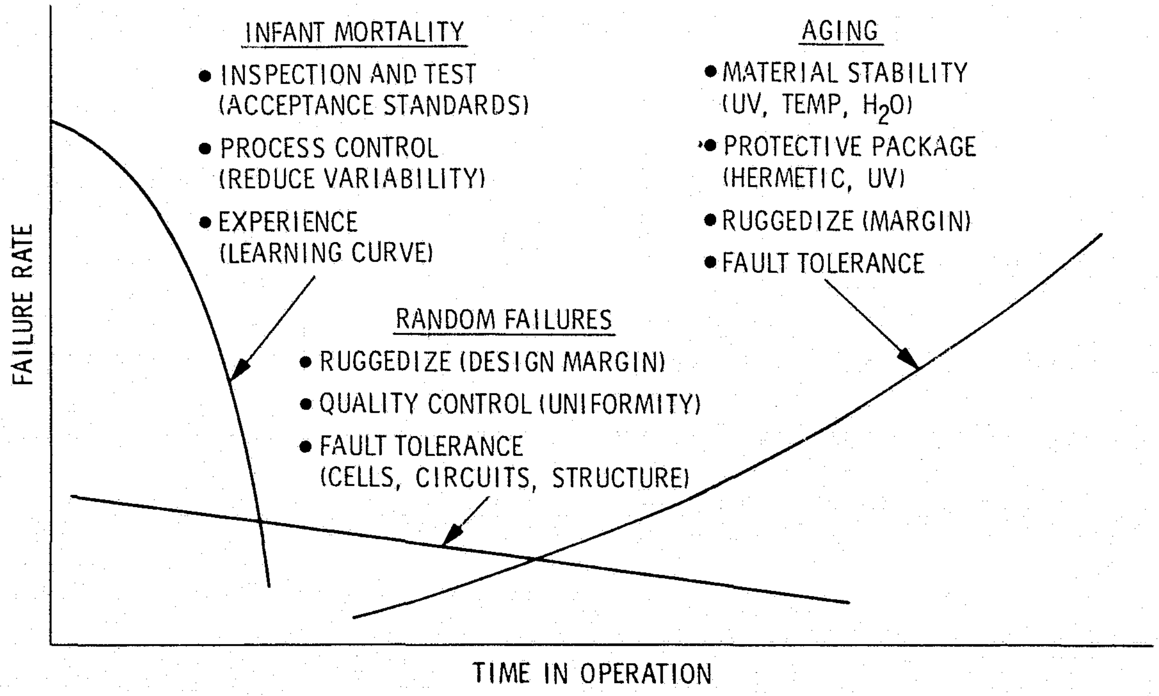
ACCELERATED OUTDOOR EXPOSURE, DSET

OUTDOOR EXPOSURE OF ADVANCED ENCAPSULANT SYSTEMS

DIAGNOSTIC AND MONITORING TECHNOLOGY FOR MODULE TESTING

QUALIFICATION TEST DEVELOPMENT

Approaches to Module Reliability Reduce Each Failure Rate Curve



INFANT MORTALITY

- INSPECTION AND TEST (ACCEPTANCE STANDARDS)
- PROCESS CONTROL (REDUCE VARIABILITY)
- EXPERIENCE (LEARNING CURVE)

AGING

- MATERIAL STABILITY (UV, TEMP, H_2O)
- PROTECTIVE PACKAGE (HERMETIC, UV)
- RUGGEDIZE (MARGIN)
- FAULT TOLERANCE

RANDOM FAILURES

- RUGGEDIZE (DESIGN MARGIN)
- QUALITY CONTROL (UNIFORMITY)
- FAULT TOLERANCE (CELLS, CIRCUITS, STRUCTURE)

Failure Classification

INFANT MORTALITY

FAILURES AT NORMAL EXPOSURE AND USE CONDITIONS DUE TO FLAWS INTRODUCED INTO THE HARDWARE DURING MANUFACTURE AND NOT DETECTED BY APPLICABLE INSPECTIONS AND ACCEPTANCE TESTS

RANDOM FLAW/STRESS FAILURES

FAILURES DUE TO THE STATISTICAL INTERACTION OF EXCESSIVE RANDOM LOADS WITH INHERENT MATERIAL FLAWS OR LOCALIZED DESIGN WEAKNESSES

WEAROUT FAILURES

FAILURES DUE TO MATERIAL AGING, WEAR, CORROSION, FATIGUE AND DAMAGE ACCUMULATION. WEAROUT FAILURE ASSUMES SOME NONREVERSIBLE PREFAILURE CHANGE IN THE CHEMICAL OR PHYSICAL CHARACTERISTICS OF THE MODULE OR MODULE MATERIALS

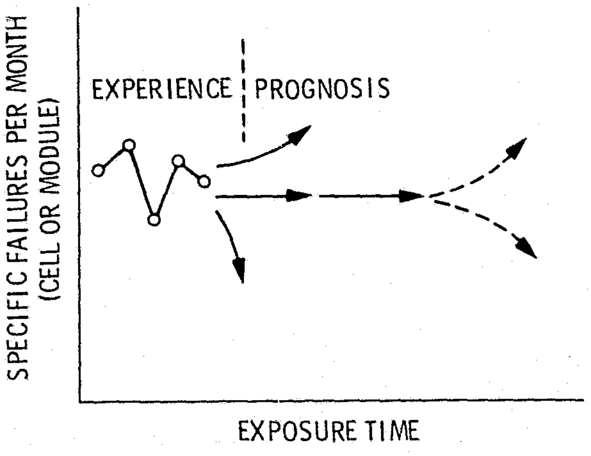
Reliability Definition

THE PROBABILITY OF PERFORMING ACCEPTABLY DURING A SPECIFIC DURATION, WITHIN A SPECIFIC ENVIRONMENT, UNDER SPECIFIC OPERATING CONDITIONS

APPLICATION NOTES

- TARGET VALUES VARY AMONG SOLAR ARRAY ELEMENTS (e.g., CELLS, MODULES, BRANCH CIRCUITS)
- NEED TO DEFINE: ACCEPTABLE PERFORMANCE (ALLOWABLE DEGRADATION)
  SPECIFIC DURATION (SERVICE LIFE)
  SPECIFIC ENVIRONMENT (GEOGRAPHIC AND APPLICATION)
  SPECIFIC CONDITIONS (APPLICATION)

Failure Analysis



FAILURE ANALYSIS

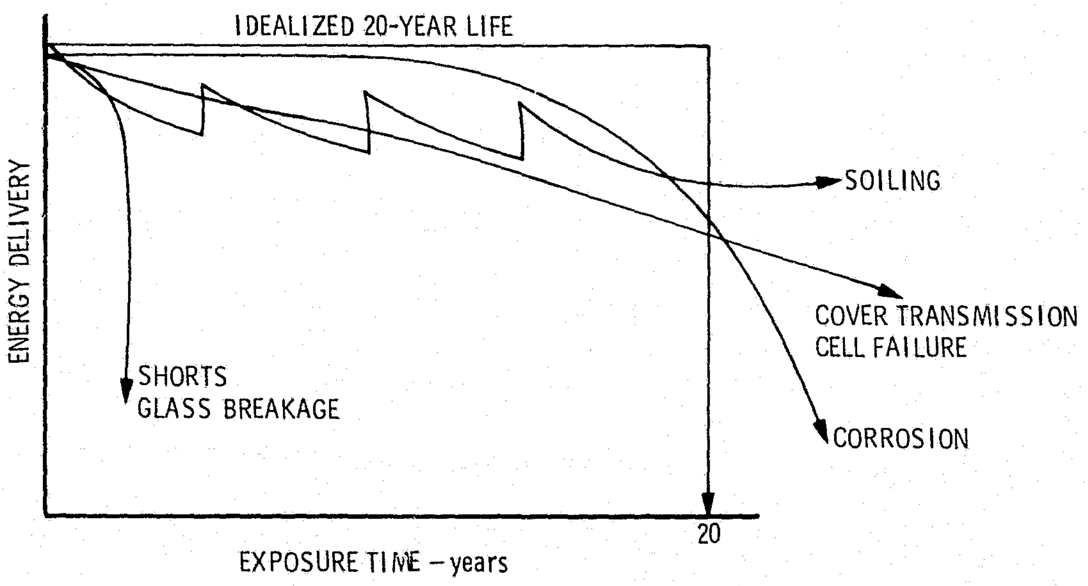
WHAT FAILED?
- WHICH COMPONENT
- CONSEQUENCES

WHY/MECHANISM?
- DESIGN WEAKNESS
- RANDOM FLAW
- WORKMANSHIP
- RANDOM OVERSTRESS

PROGNOSIS?
- WILL IT CONTINUE?
- WILL IT DECREASE?
- WILL IT INCREASE?

CURE?
- DESIGN
- MATERIALS
- FABRICATION CONTROLS
- QC STANDARDS

Effect of Failures on Array Performance (Basis of Life-Cycle Energy Cost)



MODULE DURABILITY GOALS

R. G. Ross Jr.

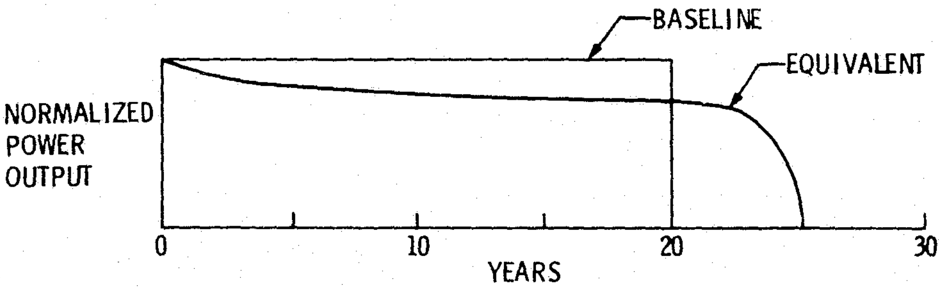
Array Reliability & Durability Goals

BASELINE PROJECT GOALS:

PRICE: 70¢/WATT (1980$)
EFFICIENCY: ≥ 10 PERCENT
LIFETIME: 20 YEARS

GENERALIZED RELIABILITY/DURABILITY GOAL:

- LIFE-CYCLE ECONOMIC PERFORMANCE SHALL BE EQUIVALENT TO 70 ¢/WATT, 10 PERCENT EFFICIENCY, NO DEGRADATION FOR 20 YEARS.



Life-Cycle Energy Cost Expression

- NOTING THAT:

$$E_0 = \begin{pmatrix}\text{INITIAL}\\ \text{ANNUAL}\\ \text{ENERGY}\end{pmatrix} = \begin{pmatrix}\text{ANNUAL}\\ \text{INSOLATION}\end{pmatrix}\begin{pmatrix}\text{INITIAL}\\ \text{PLANT}\\ \text{EFFICIENCY}\end{pmatrix}\begin{pmatrix}\text{ARRAY}\\ \text{AREA}\end{pmatrix}$$

- AND DEFINING

$$\sum_{n=1}^{L} \epsilon_n (1 + k)^{-n} = \sum_{n=1}^{L} \left(\frac{\text{POWER IN YEAR } n}{\text{INITIAL POWER}}\right)(1 + k)^{-n} \equiv \begin{pmatrix}\text{LIFE-CYCLE}\\ \text{ENERGY}\\ \text{FRACTION}\\ \epsilon_{LC}\end{pmatrix}$$

- GIVES

$$\boxed{\begin{pmatrix}\text{ENERGY}\\ \text{COST}\\ \text{\$/kWh}\end{pmatrix} = \frac{\begin{pmatrix}\text{BALANCE}\\ \text{OF PLANT}\\ \text{COST, \$/kW}\end{pmatrix} + \begin{pmatrix}\text{INITIAL}\\ \text{ARRAY}\\ \text{COST/m}^2\end{pmatrix} + \begin{pmatrix}\text{ARRAY}\\ \text{L-C O\&M}\\ \text{COST/m}^2\end{pmatrix} \Big/ \begin{pmatrix}\text{PLANT EFFICIENCY}\\ 100 \text{ mW/cm}^2\text{, NOCT}\end{pmatrix}}{\begin{pmatrix}\text{ANNUAL}\\ \text{INSOLATION}\\ \text{kWh/m}^2\text{/yr}\end{pmatrix} \times \begin{pmatrix}\text{L-C ENERGY}\\ \text{FRACTION}\end{pmatrix}}}$$

Economic Impact of Degradation Types

TYPE OF DEGRADATION	UNITS	LEVEL CAUSING 10%* COST INCREASE	
		k = 0	k = 10
FIXED DROP IN POWER	FRACTION	0.10	0.10
LINEAR DROP IN POWER	FRACTION PER YEAR	0.010	0.014
FIXED CELL FAILURE RATE**	FRACTION PER YEAR	0.0006	0.0008
FIXED MODULE FAILURE RATE	FRACTION PER YEAR	0.007	0.016
DROP IN MODULE WEAROUT LIFE	YEARS	2.0	4.75

*10% INCREASE IN LIFECYCLE ENERGY COST, k = DISCOUNT RATE

**BRANCH CIRCUIT = 12 PARALLEL x 100 SERIES BLOCKS WITH DIODES

Strawman Degradation Allocations
(Equivalent to 20-Year Life)

TYPE OF DEGRADATION	INCLUDED MECHANISMS	UNITS	DEGRADATION ALLOCATION
FIXED DROP IN POWER	SOILING	FRACTION	0.05
LINEAR DROP IN POWER	YELLOWING, AR COATING, CELL DEGR.	FRACTION PER YEAR	0.01
FIXED CELL FAILURE RATE	CELL CRACKING	FRACTION PER YEAR	0.0001
FIXED MODULE FAILURE RATE	STRUCT. FAILURE, INSUL. BREAK	FRACTION PER YEAR	0.005
MODULE WEAROUT LIFE	FATIGUE, CORROSION	YEARS	25

MODULE DURABILITY EXPERIENCE

Larry Dumas

Scope of Field Surveillance

	kW	ARRAY FAILURE	MODULE FAILURE	MOD. ELECT DEGR. (25%)	PHYSICAL INSPECTION
APPLICATIONS EXPERIMENTS					
• NASA LeRC					
SCHUCHULI INDIAN VILLAGE	3.5	✓	✓		
UPPER VOLTA VILLAGE (GSA BUY)	1.8	✓	✓		
REMOTE STAND-ALONE	2.5	✓			
• MIT/LL					
NATURAL BRIDGES, UTAH	100	✓	✓		
MEAD, NEBRASKA	28	✓	✓		✓
BRYAN, OHIO	15	✓	✓		✓
RESIDENTIAL	22	✓	✓		✓
CHICAGO MUSEUM	2	✓	✓		✓
• DOD					
MOUNT LAGUNA, CALIFORNIA	60	✓	✓	✓	✓
MILITARY APPLICATIONS	12	✓			
FIELD TEST SITES					
• NASA LeRC	33	✓	✓	✓	✓
• MIT LL	9	✓	✓	✓	
• JPL	9	✓	✓	✓	✓
• SANDIA	4	✓	✓		

Field Test & Applications P/FR Summary

BLOCK	INTERCONNECT FRACTURES	UNSOLDERED INTERCONNECTS	CRACKED CELLS	WIRE AND TERMINAL CORROSION	GROUNDED CELL STRING	EXPOSED INTERCONNECTS	ENCAPSULANT DELAMINATION
I	24	11	22	9	2	4	27
II	26	15	71	7	18	4	29
III	14	4	24	5	11	0	21
TOTAL	64	30	117	21	31	8	77

Application Experiments Module Failures

FIELD CENTER	INSTALLATION	# OF MODULES	# OF FAILURES	% MODULES FAILED	OPERATING TIME
NASA LeRC	SCHUCHULI	192	34	17.7	1 1/2 YEARS
	UPPER VOLTA	100	20	20.0	14 MONTHS
	ALL OTHERS	289	33	11.4	1 1/2 - 3 1/2 YEARS
MIT/LL	NATURAL BRIDGES	5216	54	1.0	3 MONTHS
	MEAD	2080	48	2.3	2 1/2 YEARS
	UTA	240	63	26.5	14 MONTHS
	ALL OTHERS	2050	33	1.6	1 - 2 1/2 YEARS
JPL	MT. LAGUNA	2366	179	7.6	14 MONTHS
TOTAL		12,536	464	3.7	

A Sampling of Current Experience

TYPE OF DEGRADATION	INCLUDED MECHANISMS	UNITS	DEGRADATION ALLOCATION	RANGE OF OBSERVED DEGRADATION	SOURCE
FIXED DROP IN POWER	SOILING	FRACTION	0.05	0 - 0.13	GLASS; VARIOUS SITES
LINEAR DROP IN POWER	YELLOWING, AR COATING, CELL DEGR.	FRACTION PER YEAR	0.01	NOT AVAILABLE	———
FIXED CELL FAILURE RATE	CELL CRACKING	FRACTION PER YEAR	0.0001	0.0002 - 0.001	MEAD; MT. LAGUNA
FIXED MODULE FAILURE RATE	STRUCT. FAILURE INSUL. BREAK	FRACTION PER YEAR	0.005	0.005 - 0.02	BLOCK I-II
MODULE WEAROUT LIFE	FATIGUE CORROSION	YEARS	25	2 - ?	UPPER VOLTA; OTHER SITES

MODULE DURABILITY DESIGN TECHNIQUES

C. D. Coulbert

Key Elements in Achieving Life Goals

1. IDENTIFY LIFE-LIMITING FAILURE AND DEGRADATION MODES
2. RELATE FAILURE RATES AND DEGRADATION RATES TO LIFE-CYCLE COSTS
3. SIMULATE FAILURES TO LINK MECHANISMS TO EXPOSURE STRESSES
4. MEASURE CHANGE IN PERFORMANCE AND PROPERTIES VERSUS STRESS
    - FIELD TESTS AND APPLICATION EXPERIMENTS
    - LABORATORY ACCELERATED AND NORMAL STRESSES
5. FORMULATE QUANTITATIVE (EMPIRICAL OR THEORETICAL) MODELS
    - DIRECT: PERFORMANCE LOSS VERSUS STRESS
    - INTERMEDIATE: PERFORMANCE VERSUS PROPERTY VERSUS STRESS
6. INTEGRATION EFFORT:
    - VARIOUS FAILURE MODES
    - VARIOUS SITE AND APPLICATION STRESSES
    - VARIOUS DESIGNS AND CONFIGURATIONS
    - VARIOUS LIFE-CYCLE AND ENERGY COST PARAMETERS
7. MINIMIZE EFFECTS BY FAULT TOLERANT DESIGN
8. ELIMINATE DEGRADATION BY DESIGN AND MATERIAL SELECTIONS
9. ASSURE QUALITY BY APPROPRIATE STANDARDS, INSPECTIONS AND TESTS

Failure and Degradation Mechanisms Studied

- SOILING
- CELL CRACKING/HOT SPOTS
- INTERCONNECT FATIGUE
- STRUCTURAL FAILURE/GLASS BREAKAGE
- ELECTRICAL TERMINAL FAILURE
- ELECTRICAL INSULATION BREAKDOWN
- ENCAPSULANT THERMAL DEGRADATION
- ENCAPSULANT PHOTODEGRADATION
- DELAMINATION
- CORROSION

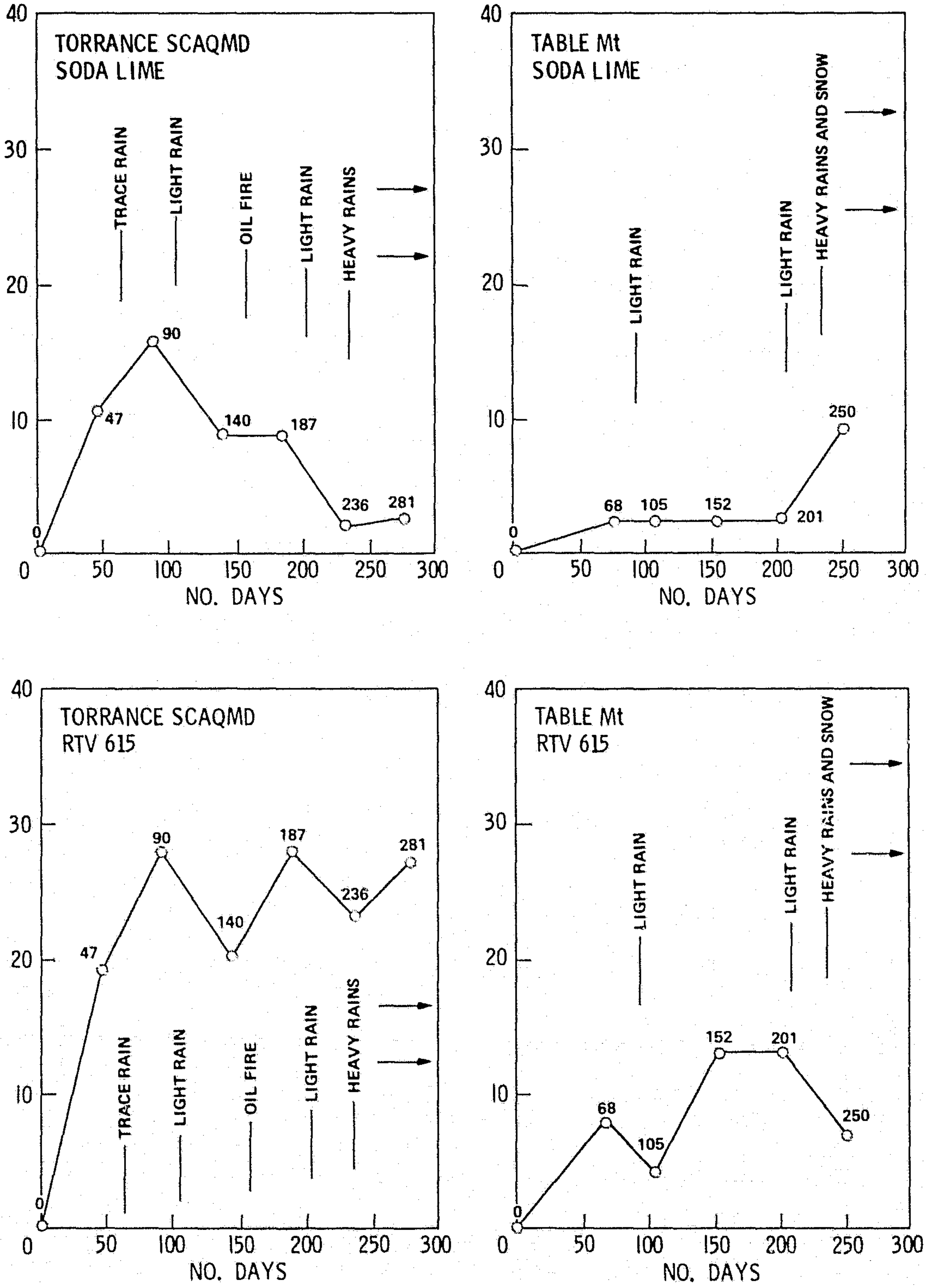
MODULE SOILING

J. C. Arnett

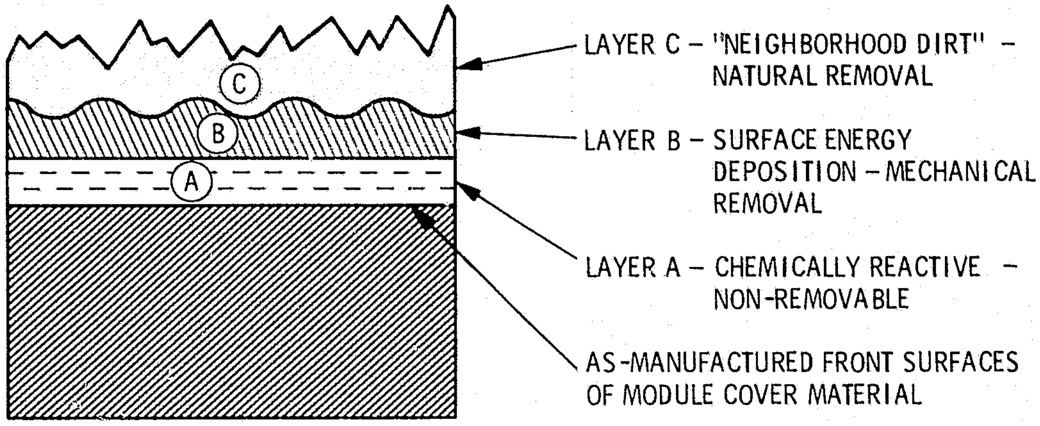
Example of Module Soiling Data

MODULE DESCRIPTION AND LOCATION	TILT ANGLE	EXPOSURE DURATION	CHANGE IN I_{SC} (%)	
			BEFORE CLEANING	AFTER CLEANING
OUTER COVER: RTV615				
- CLEVELAND, OHIO	40^0	83d	-14	-7
- NYC, NEW YORK	45^0	6mo	-47	-8
OUTER COVER: GLASS				
- CLEVELAND, OHIO	40^0	83d	-3	+3
- NYC, NEW YORK	45^0	6mo	-11	+3
OUTER COVER: SYLGARD 184				
- CLEVELAND, OHIO	40^0	90d	-26	-5
- NYC, NEW YORK	45^0	6mo	-69	-15

Percentage Loss in RNHT for Materials Exposed at Two Locations



Three-Layer Soiling Mechanism



Summary and Observations

- A THREE-LAYER SOILING MECHANISM THAT HAS SIGNIFICANT EFFECT ON TOTAL DEGRADATION AND CLEANABILITY HAS BEEN POSTULATED

- PROPER DESIGN OF MATERIAL SURFACE FINISHES MAY CONTROL FORMATION OF NON-REMOVABLE BASE CONTAMINANTS TO IMPROVE NATURAL REMOVAL PROCESSES

- UNTIL THEN, GLASS IS BEST!

CELL CRACKING, HOT SPOTS

J. C. Arnett

Cracked Cells in Modules at Final Inspection

MODULE TYPE	TOTAL CELLS IN BUY	FRACTION CRACKED
BLOCK II	252,070	0.0004 - 0.02
BLOCK III	158,048	0.0009 - 0.02

Cracked and Failed Cells Due to Field Exposure

SITE	TOTAL NUMBER OF CELLS IN FIELD	FRACTION* CRACKED PER YEAR	FRACTION FAILED PER YEAR
MEAD NEBRASKA	90,168	0.010	0.00021
MT. LAGUNA CALIF.	96,236	0.025	0.0010

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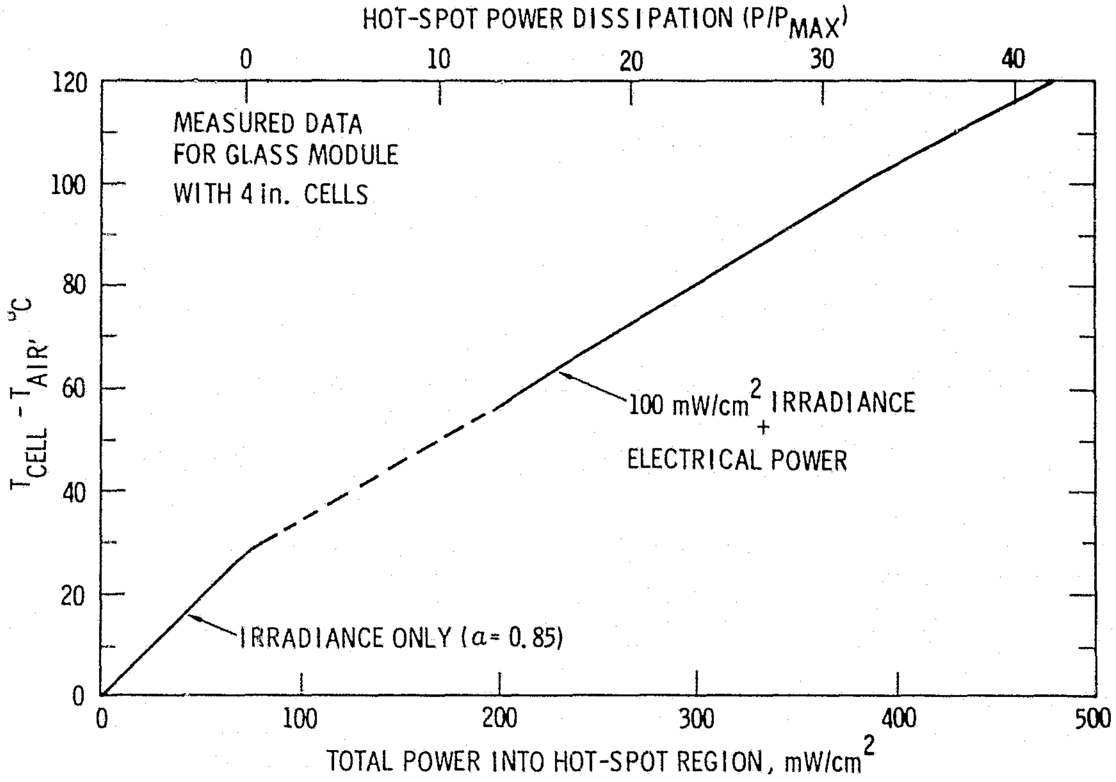
*30 TO 50% DUE TO HAIL IMPACT

Typical Hot-Spot Heating Level for Flat-Plate Module



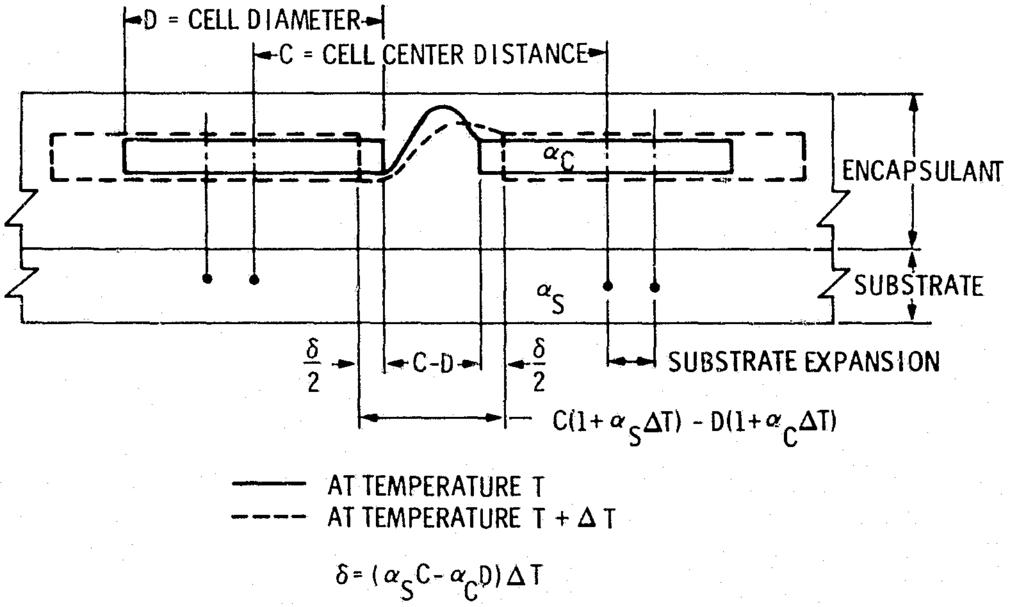
Recommendations and Conclusions

- MULTIPLE CELL CONTACTS CONSIDERABLY REDUCE RISK OF FAILURE DUE TO CELL CRACKING
- USE OF BYPASS DIODES BEST CIRCUIT DESIGN TOOL TO REDUCE POWER LOSS AND HOT SPOT PROBLEMS
- PARALLELING OF CELL STRINGS WITHIN MODULES EFFECTIVE FOR REDUCING CELL MISMATCH AND MODULE YIELD LOSS
- USE OF INCREASED NUMBER OF SERIES BLOCKS CAN EXACERBATE HOT SPOT PROBLEM - SHOULD BE ACCOMPANIED BY USE OF BYPASS DIODES
- DETERMINATION OF POTENTIAL HOT SPOT PROBLEMS - SHOULD BE ACCOMPLISHED BY TESTING MODULES HAVING ARTIFICIALLY INDUCED HOT SPOTS
- NUMBER OF PARALLEL CELLS PER MODULE CAN BE CHOSEN TO GIVE PROPER POWER PER BRANCH CIRCUIT

INTERCONNECT FATIGUE

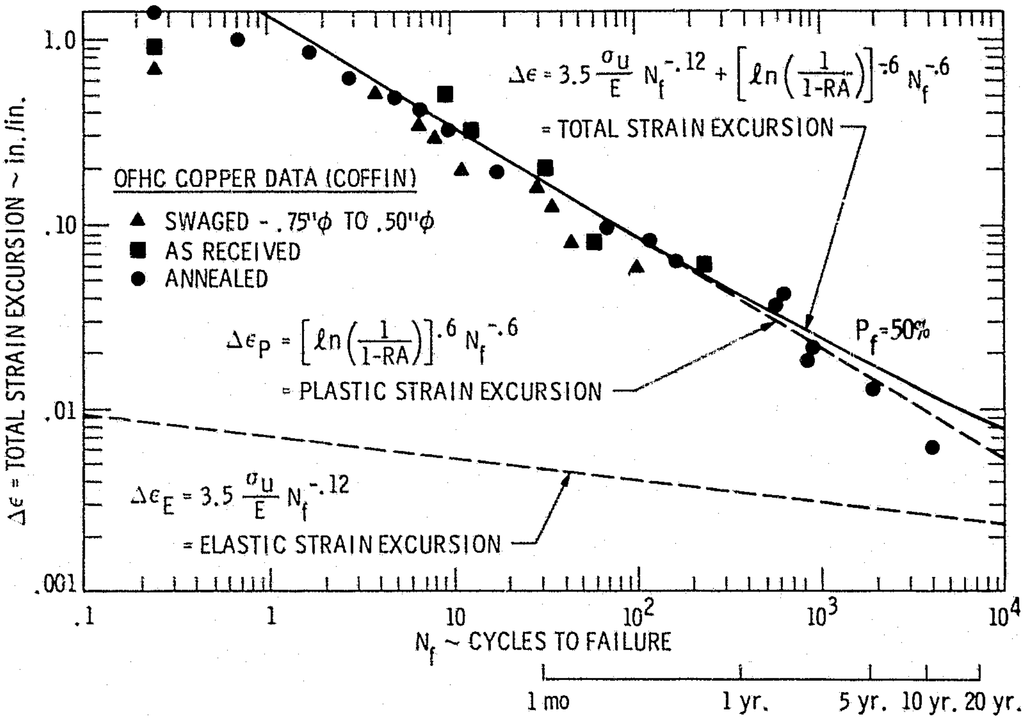
D. M. Moore

Relative Cell Motion Due to Differential Thermal Expansion



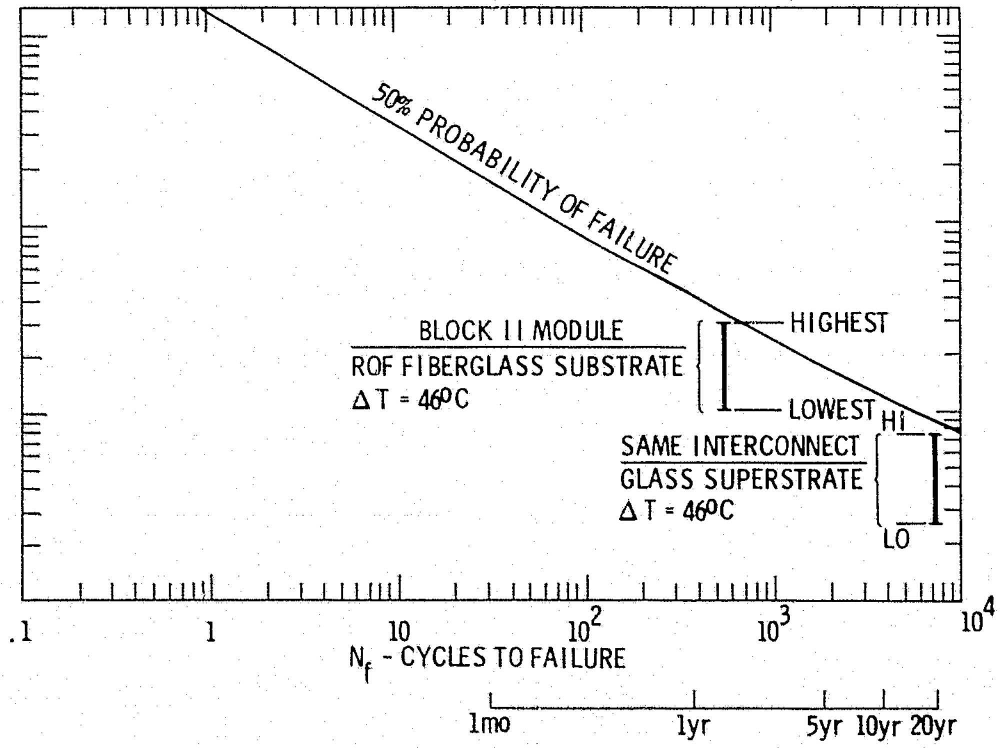
Construct Fatigue Curve

(Annealed Copper: $\sigma_u = 34{,}000$ psi, RA = .80)



Failure Prediction

(Annealed Copper: $\sigma_u = 34{,}000$ psi, RA = .80)

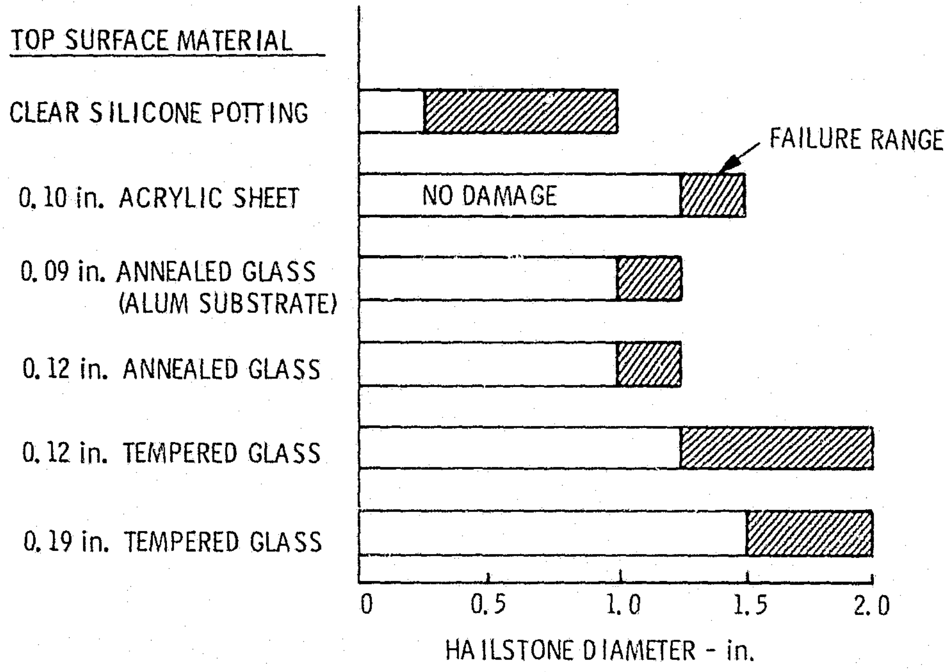


STRUCTURAL FAILURE AND GLASS BREAKAGE

D. M. Moore

Hail Impact Resistance

REF: PHOTOVOLTAIC SOLAR PANEL RESISTANCE TO HAIL
LSA TASK REPORT 5101-62, DOE/JPL-1012-78/6



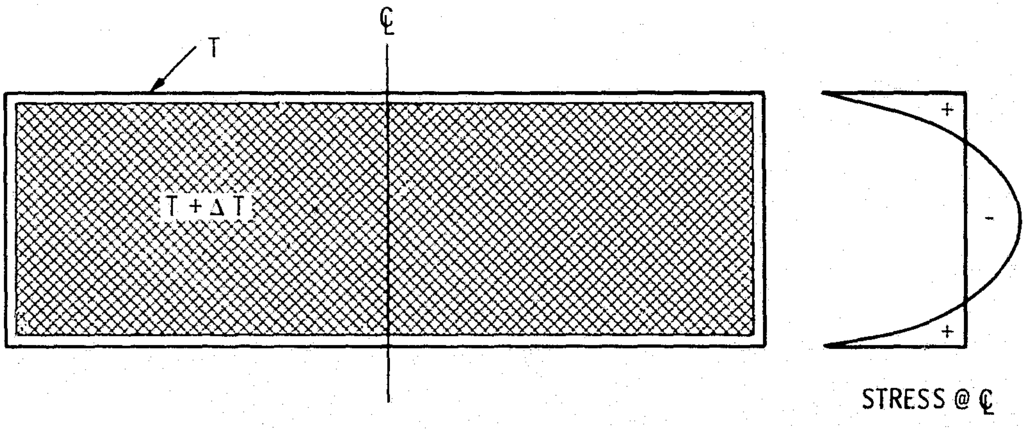
Glass Thickness Recommendations (in Inches)

MODULE SIZE (ft) GLASS TYPE	2 X 2	2 X 4	4 X 4	4 X 8
ANNEALED	0.12	0.21	0.27	0.48
SEMI-TEMPERED	0.12 (0.035)	0.12 (0.062)	0.12 (0.092)	0.15
TEMPERED	0.12	0.12	0.12 (0.046)	0.12 (0.078)

NOTES:

1. DESIGNS ABOVE HEAVY LINE ARE PRESSURE LOAD CRITICAL (50 lb/ft^2, 1000 min. DURATION, $P_f = 0.01$)
2. FIGURES IN PARENTHESES ARE GLASS THICKNESS REQUIRED FOR PRESSURE LOADING
3. DESIGNS BELOW HEAVY LINE ARE DICTATED BY
    - HAIL WITHSTAND REQUIREMENT OR
    - MINIMUM THICKNESS FOR TEMPERING
4. ANNEALED GLASS (SHADED AREA) NOT CURRENTLY RECOMMENDED CRACKING DUE TO THERMAL EDGE STRESSES NOT YET RESOLVED

Stress Due to Cold Edges



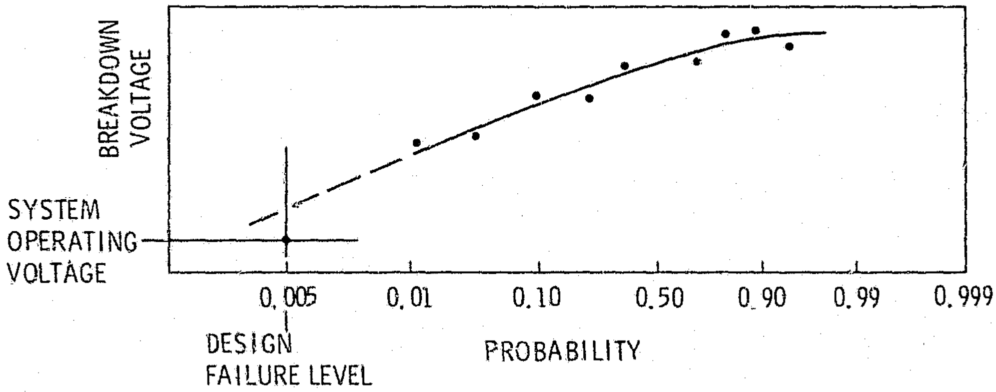
ELECTRICAL DEGRADATION

G. R. Mon

Electrical Insulation Design Approach

PROBLEM

- MODULE BREAKDOWN IS A STATISTICAL PHENOMENON REQUIRING QUANTIFICATION FOR ADEQUATE MODULE DESIGN



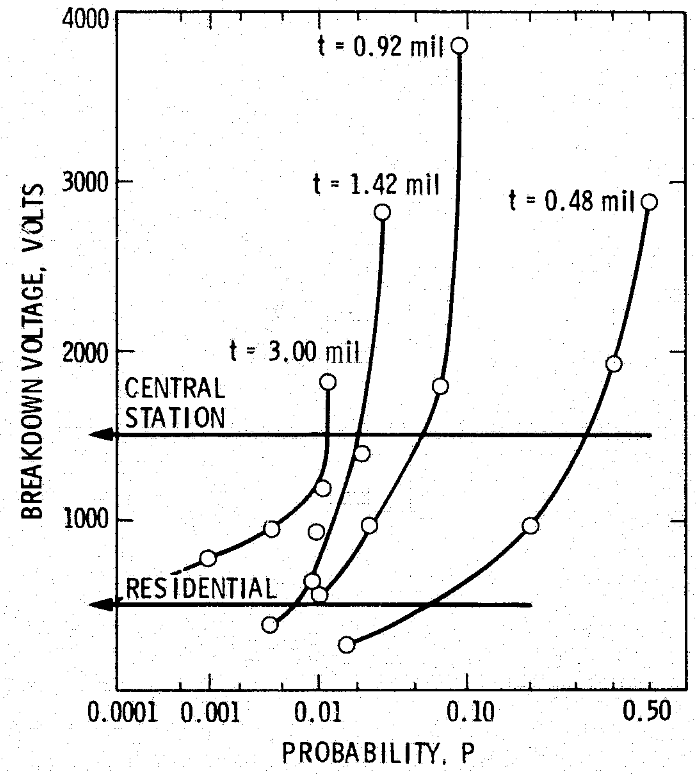
APPROACH

- GATHER QUANTITATIVE DATA CHARACTERIZING INSULATION BREAKDOWN VOLTAGE STATISTICS
- COMPARE PROJECTED BREAKDOWN VOLTAGE AT DESIGN FAILURE LEVEL WITH SYSTEM OPERATING VOLTAGE

Typical Module Electrical Flaws

- DEFECTS PRODUCING STRESS INTENSIFICATION
  1. SHARP EDGES/CORNERS ON ELECTRIFIED PARTS
  2. PROJECTIONS
     - a. METALLIZATION ON CELLS
     - b. SOLDER JUNCTIONS
  3. CONTAMINANT PARTICLES IN ENCAPSULANT
- VOIDS IN ENCAPSULANT
- DEFECTIVE THROUGH-PORTS (TERMINATIONS)

Voltage Breakdown Probability of Mylar — Experimental



4 FT x 8 FT MODULE – LAYERS OF MYLAR REQUIRED

t (mils)	NO. LAYERS	
	CENTRAL STATION	RESIDENTIAL
3.00	4	2
1.42	4	3
0.92	5	3
0.48	>>5	5

C-2

Conclusions

- DEFECT DESIGN APPROACH TO ELECTRICAL ISOLATION PROBLEM REQUIRES MULTI-LAYER THIN POLYMER INSULATION FILMS

- BASED UPON DEFECT DESIGN CONSIDERATIONS TEDLAR PERFORMS BETTER THAN MYLAR; BASED UPON INTRINSIC STRENGTH, MYLAR IS THE PREFERRED MATERIAL

- COST CONSIDERATIONS WILL DICTATE ULTIMATE CHOICES OF MATERIALS AND THICKNESSES

- DESIGN TO MINIMIZE LOCAL VOLTAGE STRESS ENHANCEMENT SITES

- OF THE MATERIALS CONSIDERED, THE FOLLOWING OFFER THE BETTER HOPE FOR LOW COST DESIGN:

  EVA
  TEDLAR
  MYLAR

ENCAPSULANT DEGRADATION

A. Gupta

Photothermal Ranking Studies

- MATERIALS
    - EVA, PVB, PU, POTTANT, RTV
    - 3M PMMA, TEDLAR, KORAD, PMMA - TINUVIN COPOLYMER
- STRESSES
    - UV (30 SUN LEVEL AT 295 - 360 NM)
    - TEMP ^{0} C(30^0, 70^0, 85^0, 105^0)
    - O_2 LEVEL (FULL ACCESS, 2 IN SQ. SAMPLES IN BETWEEN TWO SHEETS OF GLASS, NO EDGE SEAL)

UV Testing Technology

COMBINED ENVIRONMENTAL REACTOR

- UV FLUX: 6 SUNS (295-370 nm)
- UV ACCELERATION: 30 SUNS (")
- TEMPERATURE 30° - 90° C
- O_2 / H_2O (V) / POLLUTANTS / N_2

Monitoring of Environment

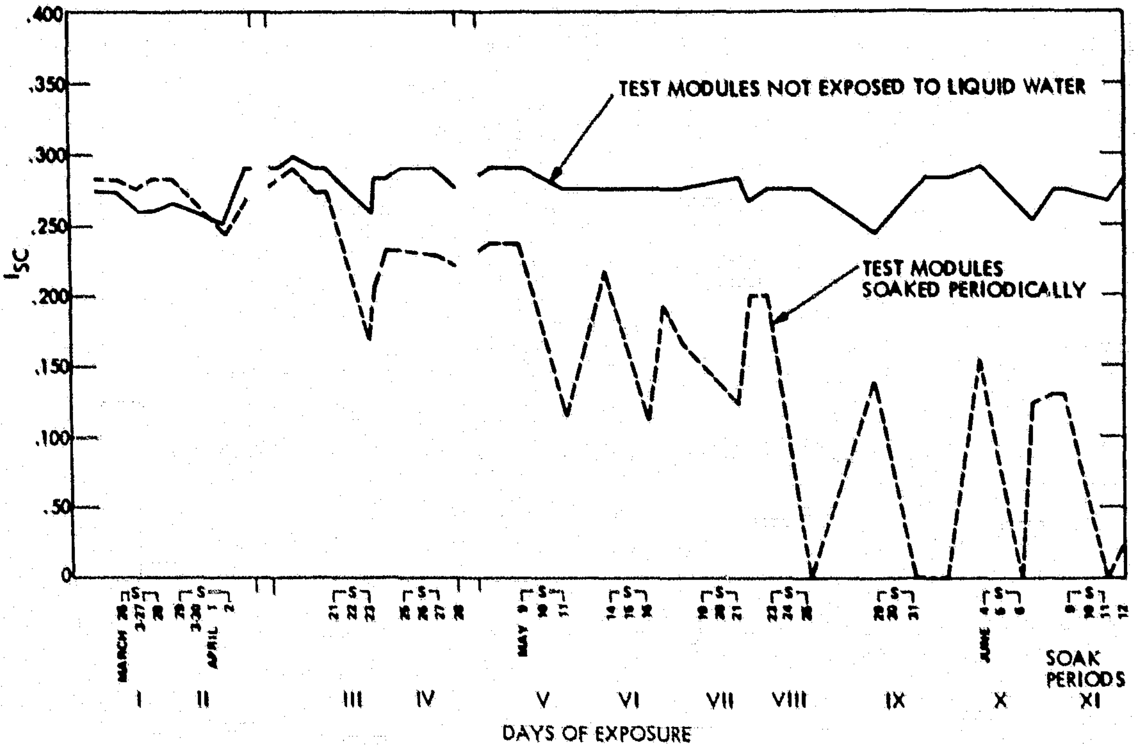
- ACTINOMETERS (UNIV. TORONTO AND IN HOUSE)
- CORROSION MONITORS (ROCKWELL SCIENCE CENTER)
- SUN SENSORS
- pH OF CONDENSED MOISTURE
- CONDUCTIVITY OF CONDENSED MOISTURE
- CONDENSED MOISTURE ON TEST SURFACE

Indoor Life Testing at Springborn Laboratories

MATERIAL	TIME-TO-DEGRADE	ACCUMULATED TIME W/O DEGRADATION
• POLYPROPYLENE CONTROL(1)	100 HOURS	
• PROTECTED POLYPROPYLENE (UV SCREEN)	-	18,000 HOURS
• KORAD 212 (2)	500 HOURS	-
• POLY VINYL DUTY RAL (PVB)	350 HOURS	-
• ELVAX 150 EVA	1000 HOURS	-
• CURED, COMPOUNDED ELVAX 150 EVA(3)		12,600 HOURS
• ETHYLENE METHACRYLATE CONTROL		2,000 HOURS
• CURED, COMPOUNDED EMA		2,000 HOURS
• TEDLAR		3,000 HOURS

(1) OUTDOOR DEGRADATION OCCURS IN ABOUT 6 MONTHS
(2) OUTDOOR DEGRADATION OBSERVED BETWEEN 9 MONTHS TO 1 YEAR
(3) SPRINGBORN FORMULATION, A-9918

Plot of I_{SC} vs Period of Aging



Mechanical Property Changes of Candidate Pottant Materials on Photothermal Aging

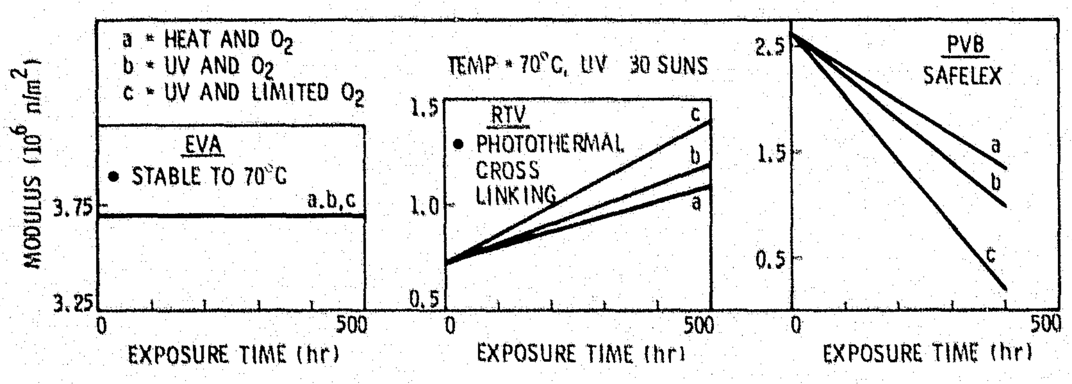
OBJECTIVE:

DETERMINE PHOTOTHERMAL AND OXYGEN EFFECTS ON MECHANICAL PROPERTIES OF POTTANT MATERIALS

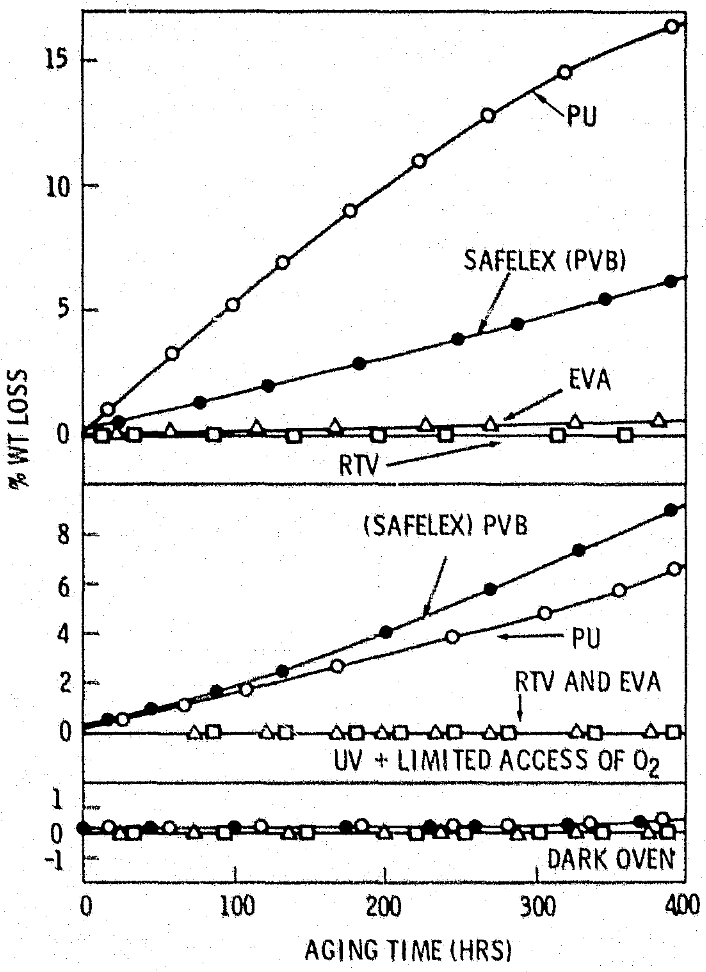
APPROACH:

MEASURE MECHANICAL PROPERTIES OF FILMS EXPOSED TO

- UV (450 WATT MEDIUM PRESSURE Hg LAMP)
- OXYGEN CONCENTRATION
- TEMPERATURE (30-105°)



Weight Loss in Photothermal Aging of Pottants at 70°C



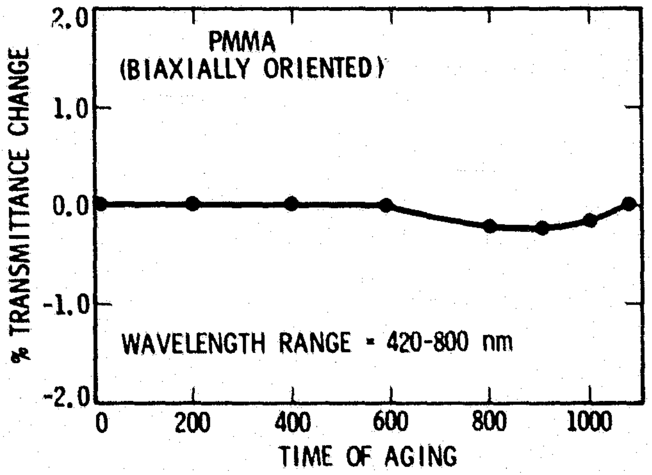
Outer Cover Development and Testing

LONG-TERM OPTICAL CLARITY AND DIMENSIONAL STABILITY OF BIAXIALLY-ORIENTED POLYMETHYLMETHACRYLATE FILMS

OBJECTIVE:

DETERMINE LONG-TERM OPTICAL CLARITY AND DIMENSIONAL STABILITY OF THE BIAXIALLY-ORIENTED PMMA USED AS TOP COVER

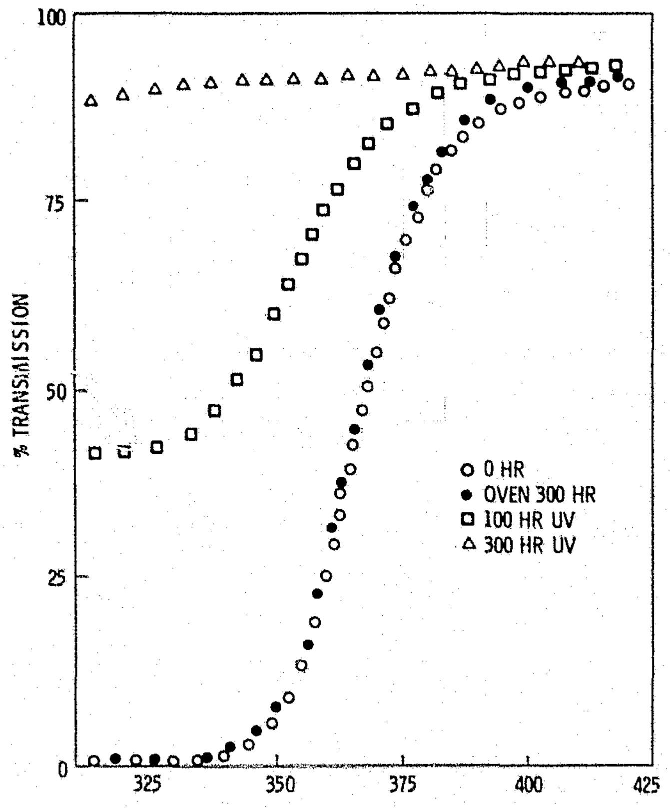
TRANSMITTANCE AND DIMENSIONAL CHANGES OF FILMS UP TO 1100 hrs AT 50, 60, 70 AND 85°C



RESULT
- GOOD LONG-TERM OPTICAL CLARITY (EXCLUDE SOILING EFFECT)
- NO MEASURABLE DIMENSIONAL CHANGE (EXCLUDE MOISTURE EFFECT)

POINTS OF CONCERN
- SURFACE CRAZING

Photothermal Degradation of UV Screening Capability of Korad at 80°C



Panel Discussion Members

• DICK ADDIS	SOLAR POWER CORP.
• STEVE FORMAN	MIT/LINCOLN LAB
• RICHARD PETERSON	AMP, INC.
• GENE RALPH	SPECTROLAB
• ELMER STREED	NBS
• TOM WINGERT	ARCO SOLAR

Questions and Issues

1. HOW SHOULD FIELD TEST DATA BE VIEWED AND USED TO ACHIEVE MODULE RELIABILITY AND LIFE?
2. WHAT INCENTIVES AND METHODS ARE NEEDED TO ENCOURAGE AND FACILITATE INDUSTRIAL ADOPTION OF ADEQUATE QUALITY ASSURANCE MEASURES?
3. WHAT IS THE PRIMARY CONCERN OF POTENTIAL PV MODULE CUSTOMERS IN SELECTING MODULE HARDWARE FOR DEMONSTRATION SYSTEM OR COMMERCIAL APPLICATIONS?
4. WHAT SHOULD THE ROLES OF GOVERNMENT & INDUSTRY BE IN ACHIEVING RELIABILITY & LIFE GOALS (I.E., R&D, STANDARDS, TESTING, CERTIFICATION, WARRANTIES, ETC.)?

Problems Defined

1. PREDICTING FAILURES AND DEGRADATION RATES APPLICABLE TO 20-YEAR LIFE
2. CURRENT QUALIFICATION AND ACCEPTANCE TESTS DO NOT ASSURE RELIABLE MODULE PERFORMANCE
3. HIGH VISIBILITY APPLICATION EXPERIMENTS USING DEVELOPMENT HARDWARE MAY LEAD TO MISINTERPRETATION OF DURABILITY PROBLEMS ENCOUNTERED
4. MAKING SUFFICIENT FIELD TEST MEASUREMENTS IN TERMS OF KINDS OF DATA ON LARGE NUMBERS AND VARIETIES OF DEPLOYED MODULES IS EXPENSIVE

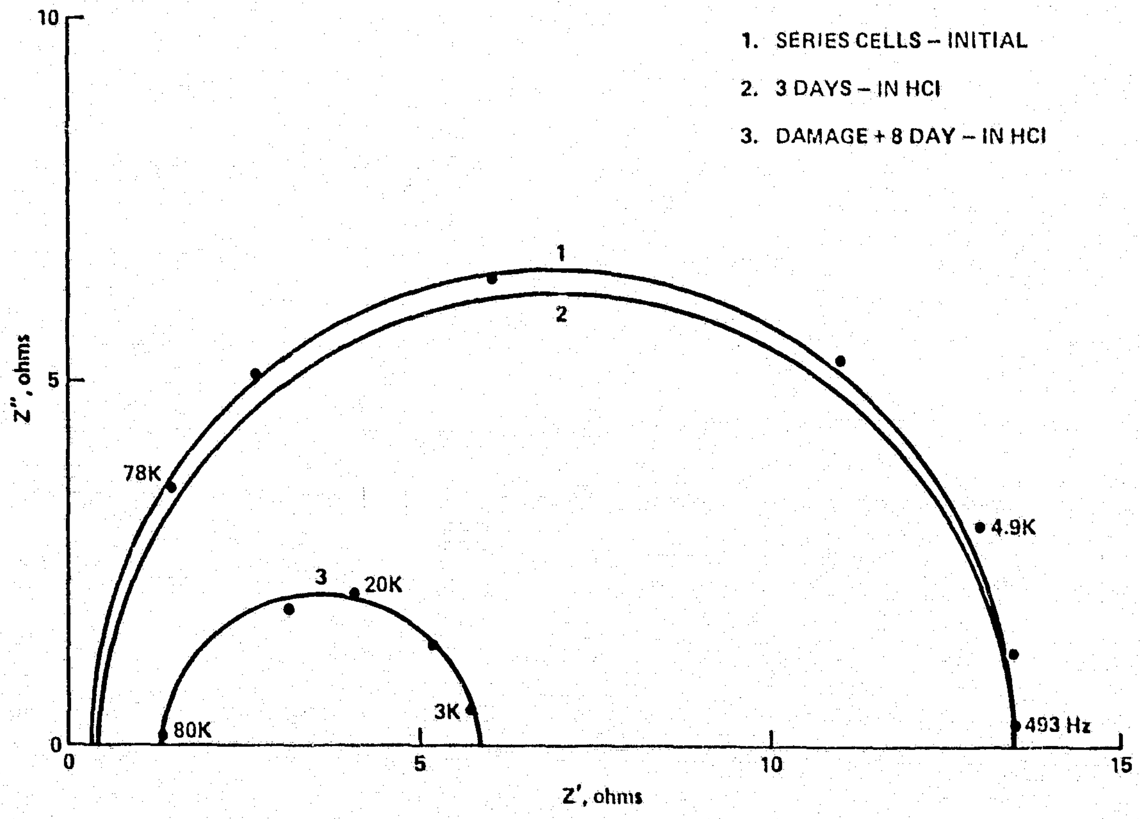
Conclusions and Recommendations

1. NO SUBSTITUTE FOR REAL-TIME FIELD-APPLICATION EXPERIENCE TO ASSESS RELIABILITY & DURABILITY IF EXPERIMENTS ARE PROPERLY PLANNED, MONITORED, AND INTERPRETED
2. NEED FOR OBJECTIVE INDEPENDENT ORGANIZATIONS TO PROVIDE TEST STANDARDS, CONDUCT TESTS, MONITOR DEPLOYED HARDWARE AND PROVIDE DATA TO USER COMMUNITY
3. DATA FROM CURRENT FIELD & APPLICATION TESTING, RESULTS OF ANALYTICAL STUDIES, AND FAILURE-MECHANISM STUDIES SHOULD BE AVAILABLE IN MOST USEFUL & CONCISE FORM (REPORTS?)
4. AUTOMATION HOLDS PROMISE FOR IMPROVED RELIABILITY THROUGH PROCESS CONTROL, REPRODUCIBILITY, AND FEEDBACK

CORROSION

ROCKWELL INTERNATIONAL SCIENCE CENTER

M. Kendig



Single-Cell AC Impedance Relations When $I_L = I_D = 0$

$$Z^* = Z^1 + iZ^{11}$$

$$|Z^*| = \left[(Z^1)^2 + (Z^{11})^2 \right]^{1/2}$$

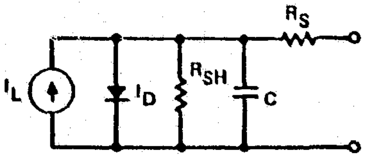
$$\tau = CR_{SH}$$

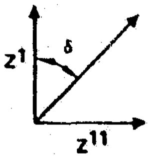
$$Z^1 = R_S + \frac{R_{SH}}{1 + (W\tau)^2}$$

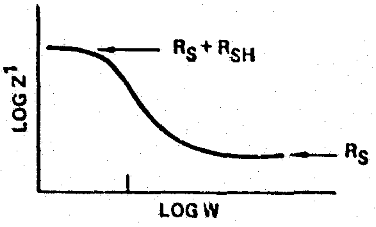
$$Z^{11} = \frac{W\tau R_{SH}}{1 + (W\tau)^2}$$

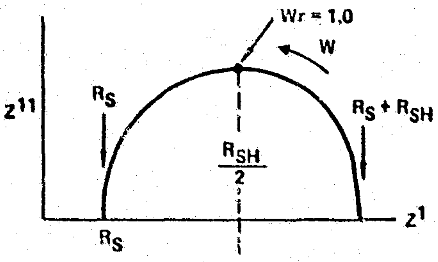
$$\text{TAN}\,\delta = \frac{Z^{11}}{Z^1} = \frac{W\tau R_{SH}}{R_{SH} + R_S \left[1 + (W\tau)^2 \right]}$$

SYMBOL	MEANING
Z^*	COMPLEX IMPEDANCE
Z^1	STORAGE COMPONENT
Z^{11}	LOSS COMPONENT
i	$\sqrt{-1}$
τ	RELAXATION TIME
W	RADIAL FREQUENCY (RADIAN/SEC)
R_{SH}	SHUNT RESISTANCE
R_S	SERIES RESISTANCE
C	CAPACITANCE
I_L	LIGHT GENERATED CURRENT
I_D	DIODE LOSS CURRENT









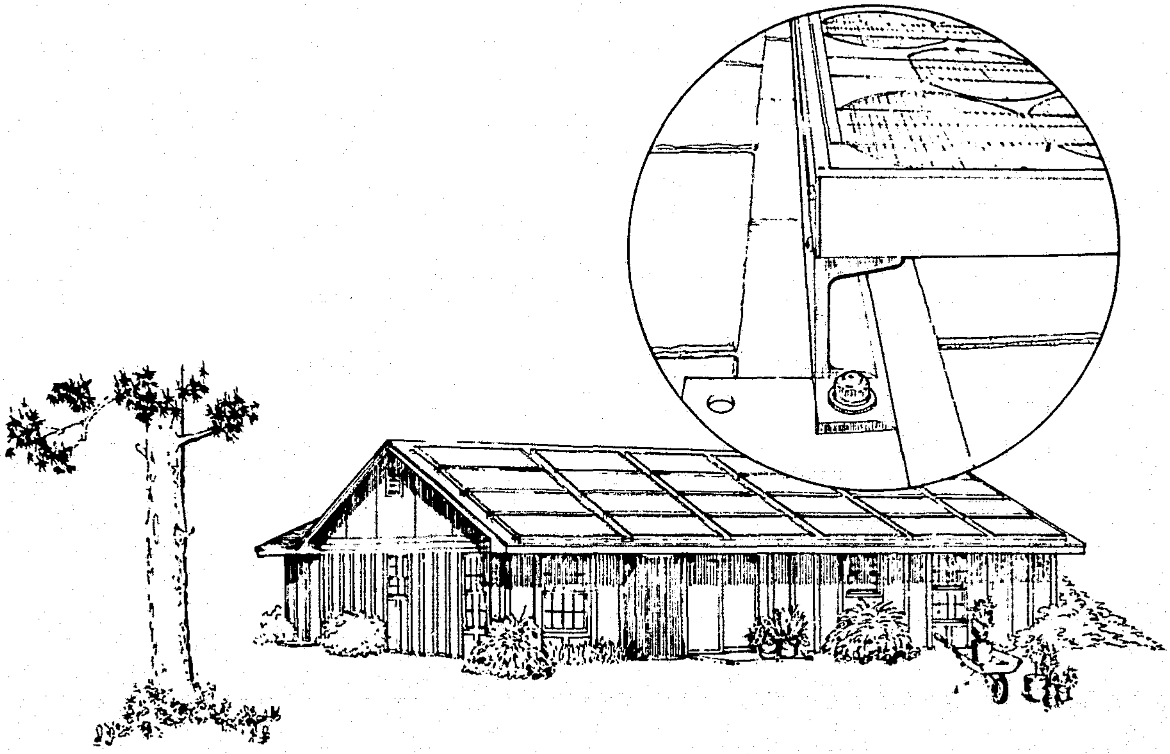
Panel Discussions

PHOTOVOLTAIC HOUSES

John Hesse, Moderator

EXPERIMENTAL PHOTOVOLTAIC RESIDENCE

FLORIDA SOLAR ENERGY CENTER
Arthur H. Litka



PV Residence Specifications

- o 5,000 WP (NOCT)
- o 62.5 M^2 OF STAND-OFF MOUNTED ARRAYS (ARCO 16 - 2000 MODULES)
- o GRID CONNECTED INVERTERS (2 - 4 KW GEMINI UNITS)
- o 8,000 TO 10,000 KWH ANNUAL OUTPUT EXPECTED
- o 1,300 FT^2 ENERGY EFFICIENT "PANELIZED" WOOD FRAME RESIDENCE (3 BR/2 BATH)
- o SPACE CONDITIONING: HEAT PUMP (EER = 7.7, COP = 2.6)
- o WATER HEATING: DEDICATED HEAT PUMP (COP = 2.5)

Objectives of Experimental PV Residence

TECHNICAL/ECONOMIC:

- PERFORMANCE MONITORING/PERFORMANCE MODEL VERIFICATION
- SYSTEM DYNAMICS/PROJECTED ECONOMIC BENEFIT UNDER VARIOUS UTILITY PRICING AND CREDIT STRATEGIES
- DEVELOPMENT OF SIMPLIFIED DESIGN TECHNIQUES
- POWER QUALITY STUDIES/UTILITY INTERFACE
- INTEGRATION WITH A FULL SIZE RESIDENTIAL STRUCTURE
- DETECTION/CORRECTION OF OPERATIONAL PROBLEMS
- PRODUCT DEVELOPMENT SUPPORT
- DEVELOPMENT OF LOW ENERGY BUILDING DESIGN TECHNIQUES COMPATIBLE WITH PV IN A SOUTHEAST CLIMATE

LEGAL/INSTITUTIONAL:

- SUNRIGHTS ISSUES
- UTILITY FEEDBACK
- CODES, ORDINANCES, TRADE JURISDICTION AND SKILLS STUDIES
- FINANCING ISSUES
- INSURANCE REQUIREMENTS STUDIES
- HIGH PUBLIC VISIBILITY/FEEDBACK

Florida Power & Light (FPL) Involvement

PROVIDING 1 KW OF PHOTOVOLTAIC MODULES

PROVIDING A DC TO AC INVERTER

PROVIDING INSTRUMENTATION

PROVIDING TECHNICAL CONSULTATION

PROVIDING RESIDENTIAL LOAD PROFILE DATA

Experimental Results Useful to FPL

SYSTEM PERFORMANCE FOR SEVERAL YEARS

INSTALLATION, OPERATIONAL, AND MAINTENANCE TIME AND COST

UTILITY INTERFACE INFORMATION

SYSTEM COSTS

Potential Benefits From PV Residents

FUEL SAVING

DEFERRAL OF NEW T&D CONSTRUCTION

REDUCTION IN TRANSMISSION LOSSES

Three-Day Preliminary Performance Record

DATE	TIME INTERVAL	SYSTEM OUTPUT KWH	TOTAL INTEGRATED INSOLATION KWH/M^2	NET SYSTEM* EFFICIENCY
9/16	12-5	11.20	3.35	.064
9/17	8-5	19.70	6.03	.063
9/18	8-5	22.50	6.50	.066
9/19	8-12	7.20	2.43	.058

η_{OVERALL} = .063

Overall Output (12 p.m. 9/16 to 12 p.m. 9/19): 61.9 KWH

Average Daily Output: 20.6 KWH

Predicted Average Daily Output for September**: 19.3 KWH

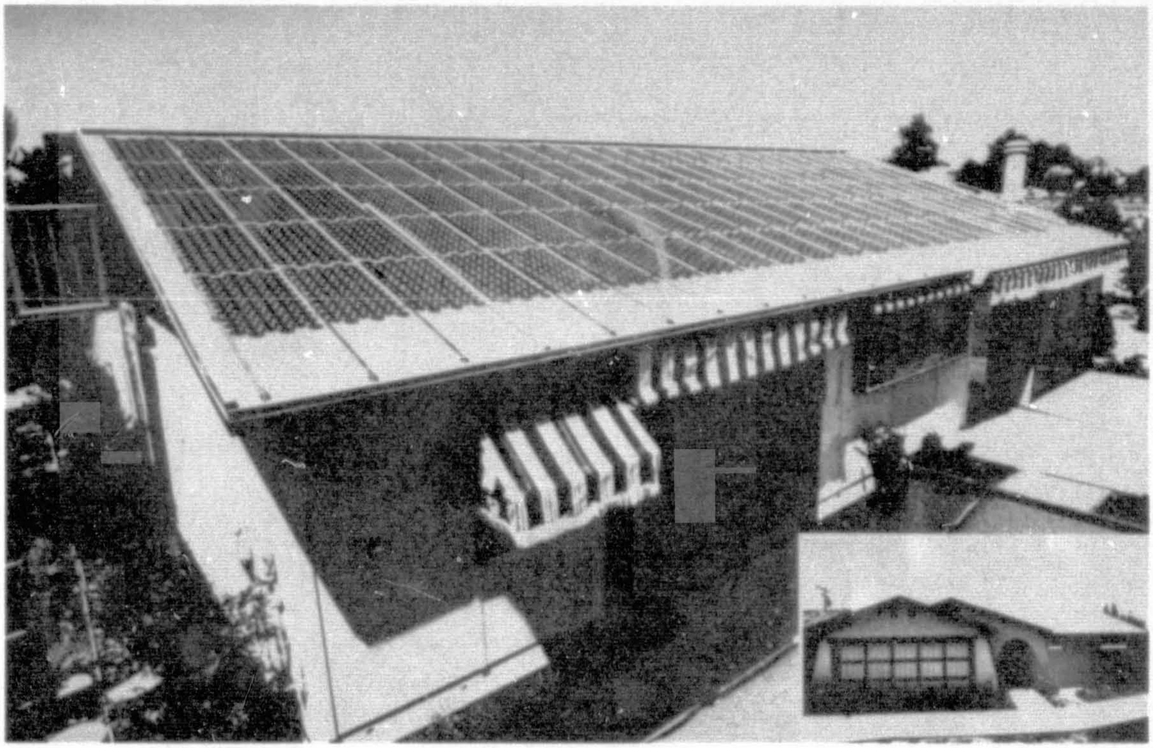
*52.1 M^2 Array Area

**(From Historical Insolation Data and a Simple Performance Calculation Methodology)

PHOENIX PHOTOVOLTAIC SYSTEM

ARCO SOLAR, INC.

Jack Kelly

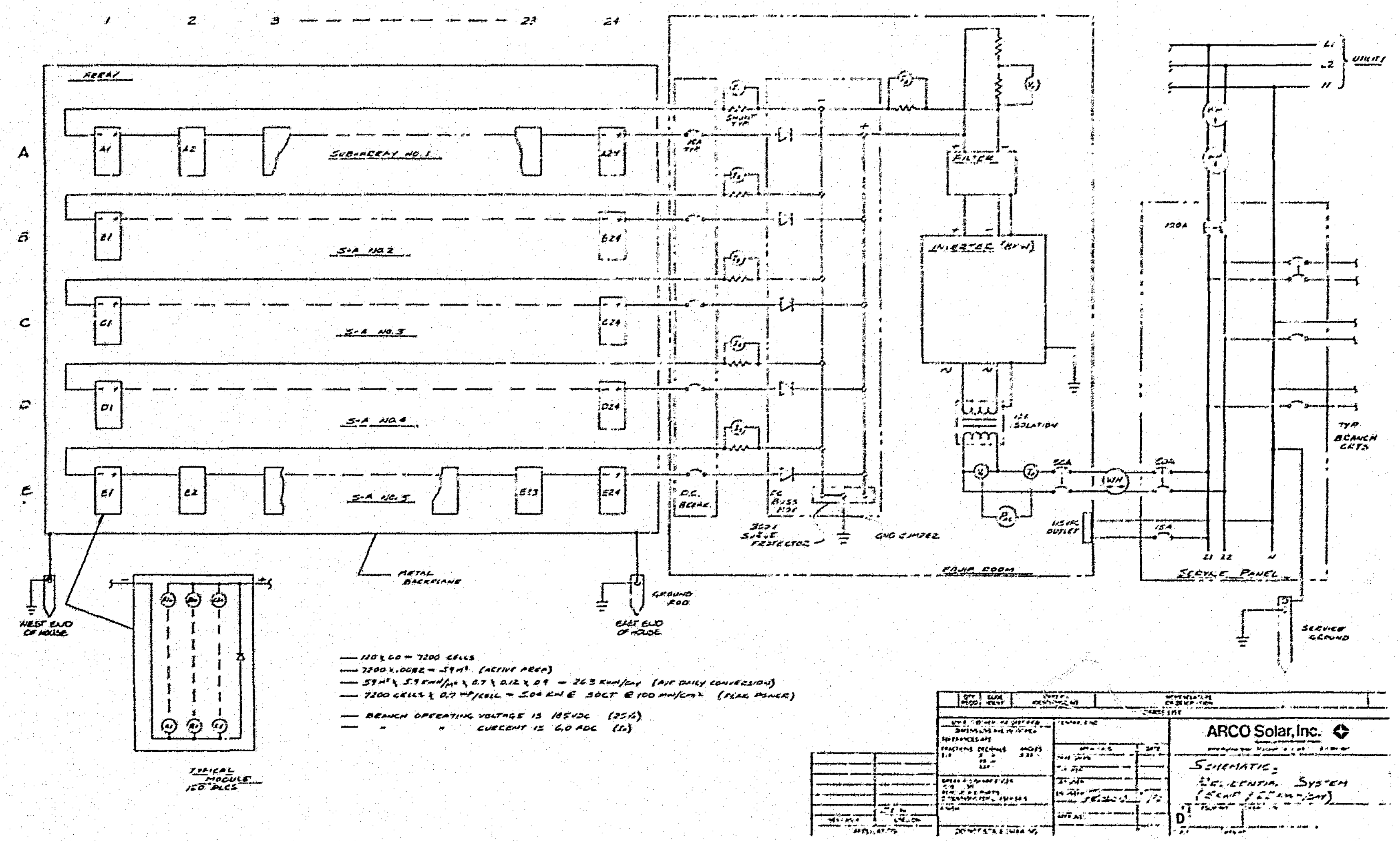


PHOENIX, ARIZONA: Site of the first demonstration of an architecturally integrated solar electric roof. Manufactured by ARCO Solar, Inc., the solar system incorporates photovoltaic cells onto standard batten and seam roofing material. It produces approximately 6 kilowatts per peak hour or 11,000 to 13,000 kilowatt hours per year. The demonstration is located on a model home built by John H. Long Homes, Inc.

The PV power system for the Phoenix house was developed, designed and supplied by ARCO Solar under a contract with John F. Long Homes, Inc., owner of the house. It consists of a rooftop array of 120 experimental modules, power conditioning including a Gemini 30-amp inverter, and a metered two-way link to the utility, Salt River Project.

Following a two-week test of the first 24-module subarray, the rest of the array was installed using standard batten-seam roofing techniques by roofers and electricians in two days during the last week of May 1980. Operation and demonstration began in the first week of June. The module used

Schematic, Residential System



in this system is mechanically compatible with sheet-steel batten seam roofing: it is a 24-guage galvanized steel sheet with upturned long edges, about 21" x 48", overlapping in shingle fashion and joined at the upturned sides by steel battens and clips. Each module contains sixty 4-inch cells in three parallel strings of 20, with EVA pottant and Korad encapsulation layers both on the steel and on the top. Module interconnects and all wiring are in the channel space between vertical rows of modules, covered by the standard inverted-V battens and clips. The steel pans and battens are grounded.

Two types of short-circuit failure were exhibited. During installation, in some cases, battens or clips overran the intended positions, broke through the encapsulation and contacted cells within the module. This required procedural correction.

A more serious failure occurred at the module interconnects. Insulation failure due to damage during connector clip installation permitted shorting between bus ribbon and the steel module substrate. This was corrected by a design change using "pigtail" wires and wire nuts for interconnects as shown in Figure 1. Minor difficulties also occurred with the inverter, and these continue to be studied.

The Phoenix rooftop-array shorts were identified by JPL using an infrared scanner. This permitted rapid identification and correction of local problems.

During four weeks in August, service meters indicated that the photovoltaic system delivered 650 kWh; 460 kWh were taken from the utility, and 480 kWh went back to the utility.

Discussion of a cogenerating system or QF (Qualifying Facility) first requires basic understanding of a utility distribution system.

Figure 2 is a single-line schematic of a representative system served by a utility substation. A single-phase lateral may serve over 600 customers. Distribution transformers serve an average of seven customers each.

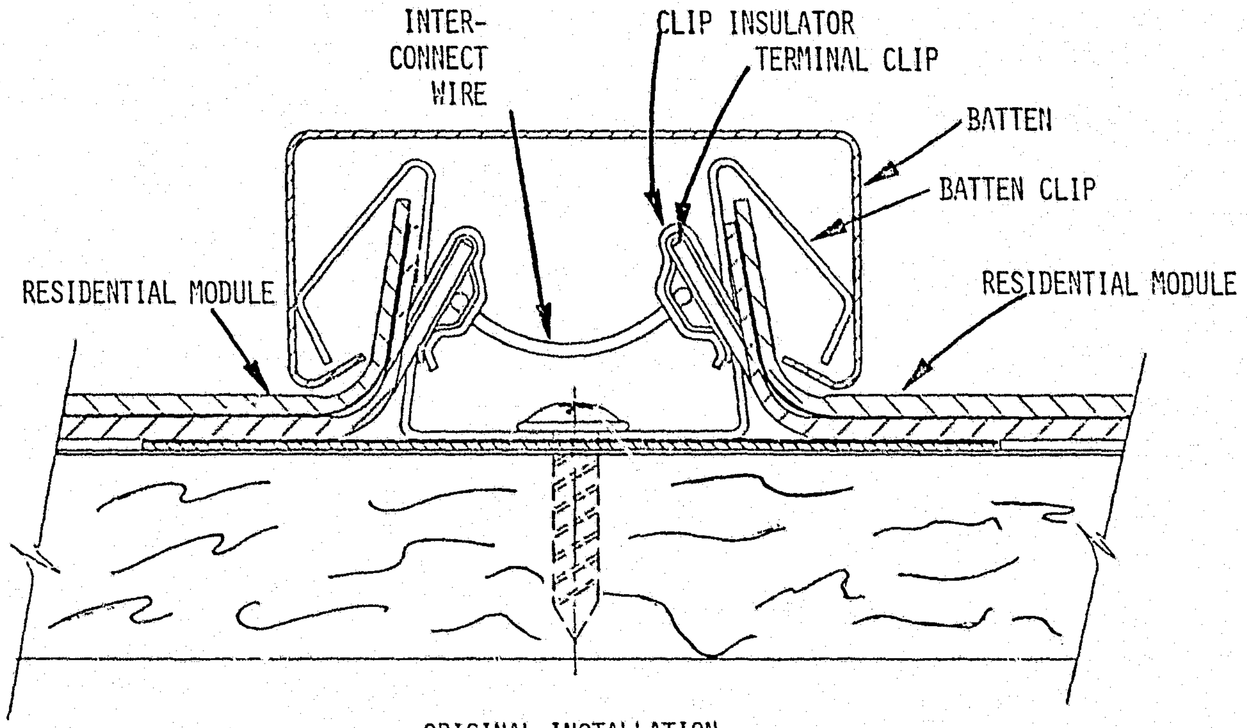
The three-phase system is provided with overcurrent protection at the substation. Either a fault or an excessive imbalance in the load will disconnect all three phases. The utility's vulnerability to a large number of cogenerating customers on a common single-phase lateral can therefore be cause for concern. On the other hand, a few isolated and scattered residential cogenerating customers should not create problems in this respect.

The John F. Long connection is illustrated. This consists of two model homes served by a 37.5 kVa distribution transformer. One of the homes is equipped with a photovoltaic system.

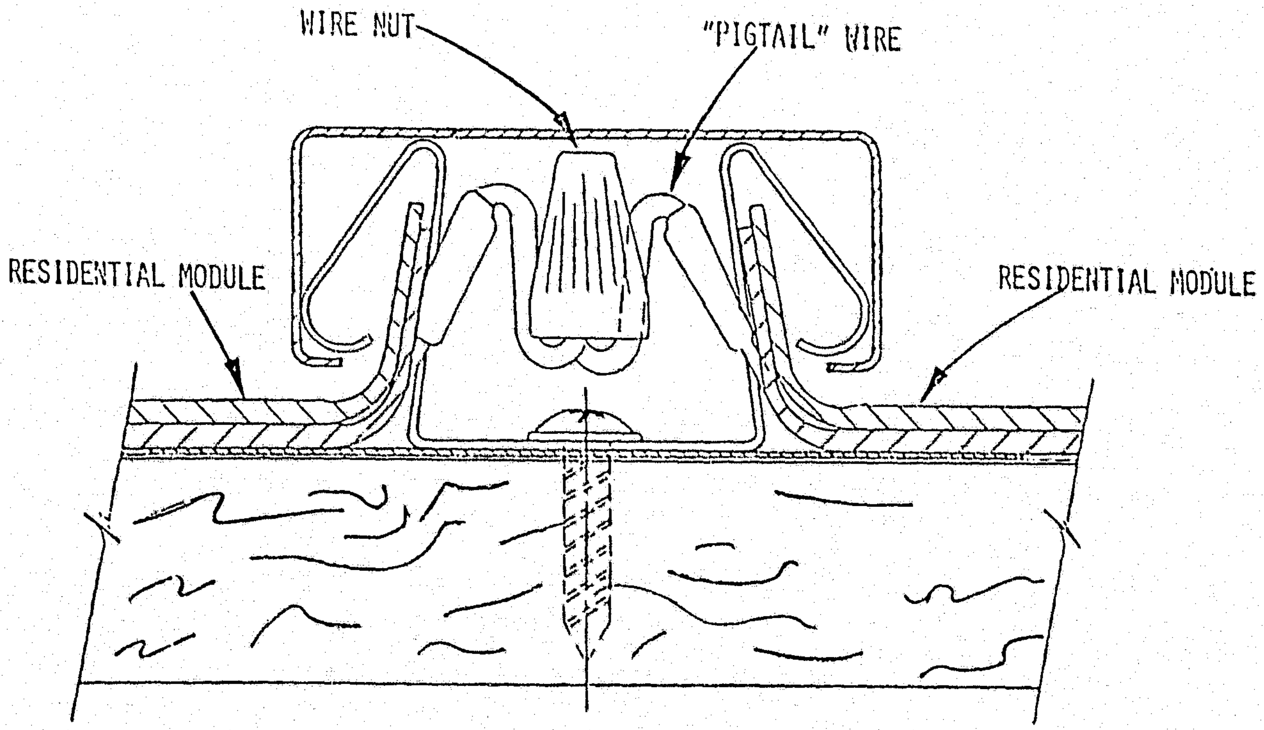
Figure 3 illustrates a typical residential service equipped with a single watt-hour meter.

When a qualifying cogenerating facility is connected to the utility system it may be represented as illustrated in Figure 4. Note the disconnect switch, which must be under utility control and capable of being locked in the

Figure I



ORIGINAL INSTALLATION



IMPROVED INTERCONNECT DETAIL

Figure 2

UTILITY DISTRIBUTION SYSTEM
EXAMPLE
TOTAL 309,700 RESIDENTIAL CUSTOMERS

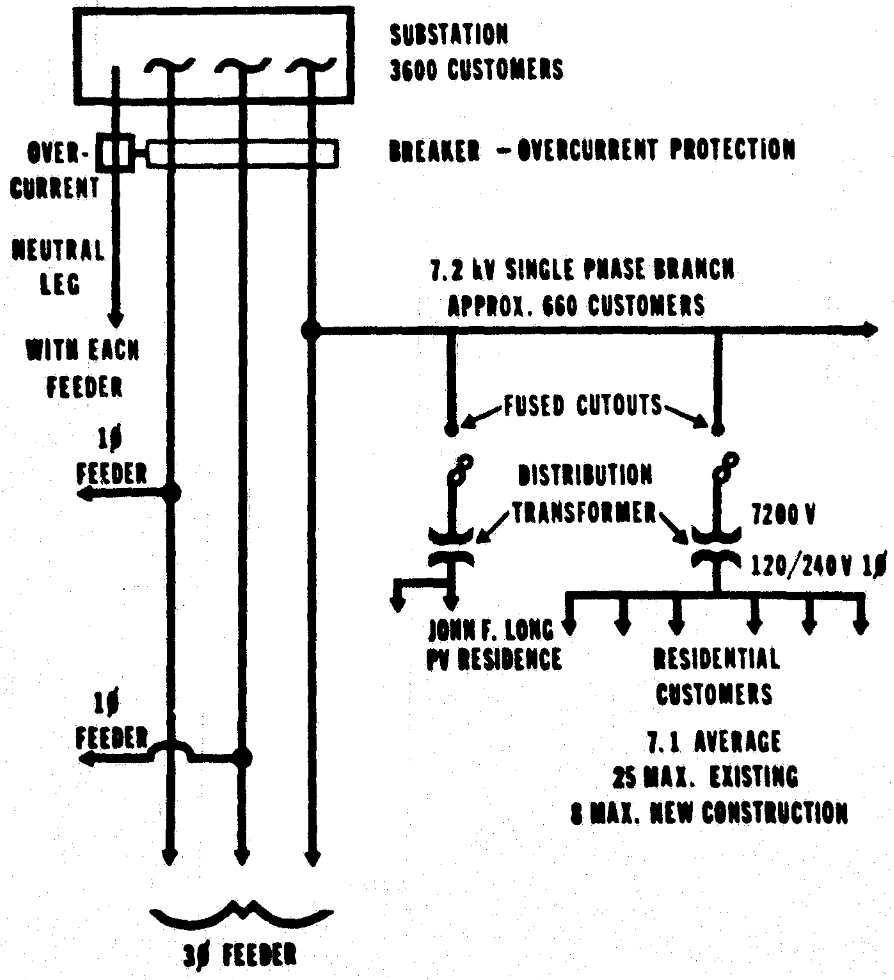


Figure 3

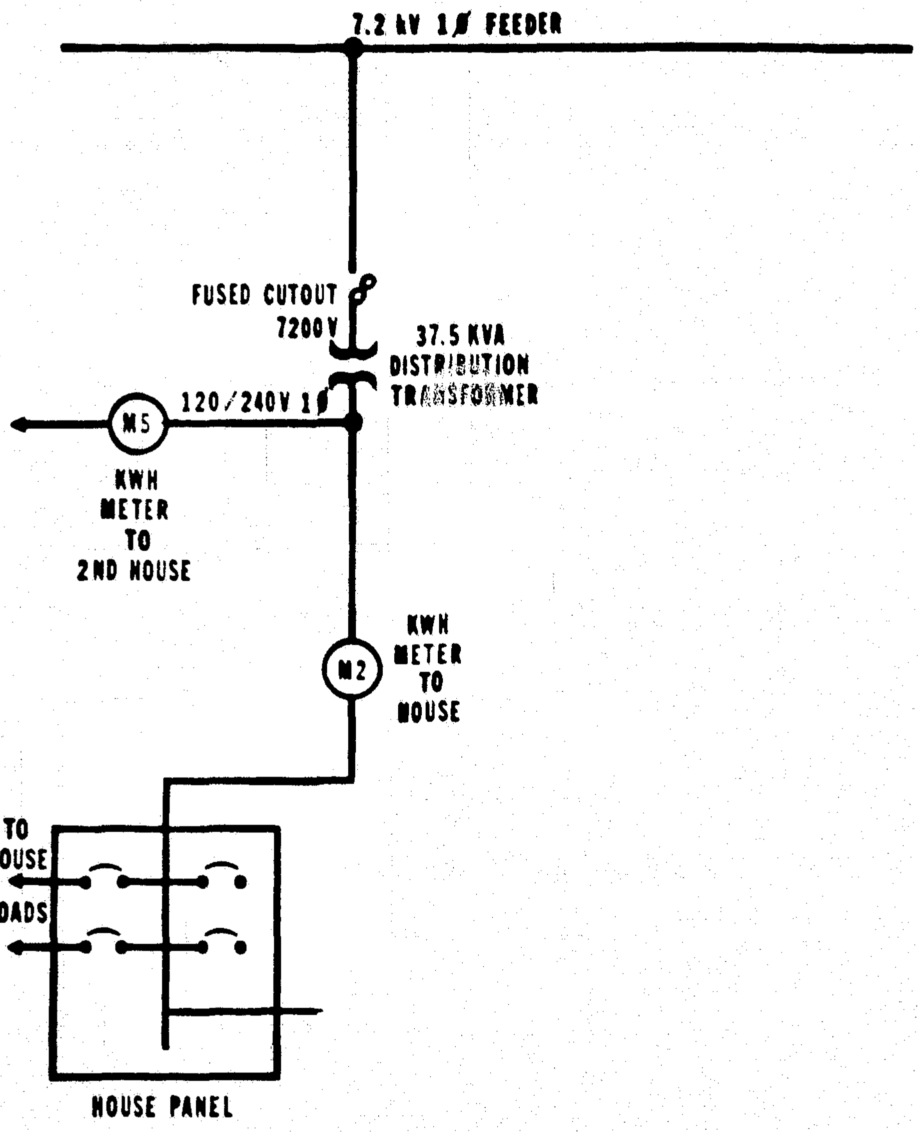
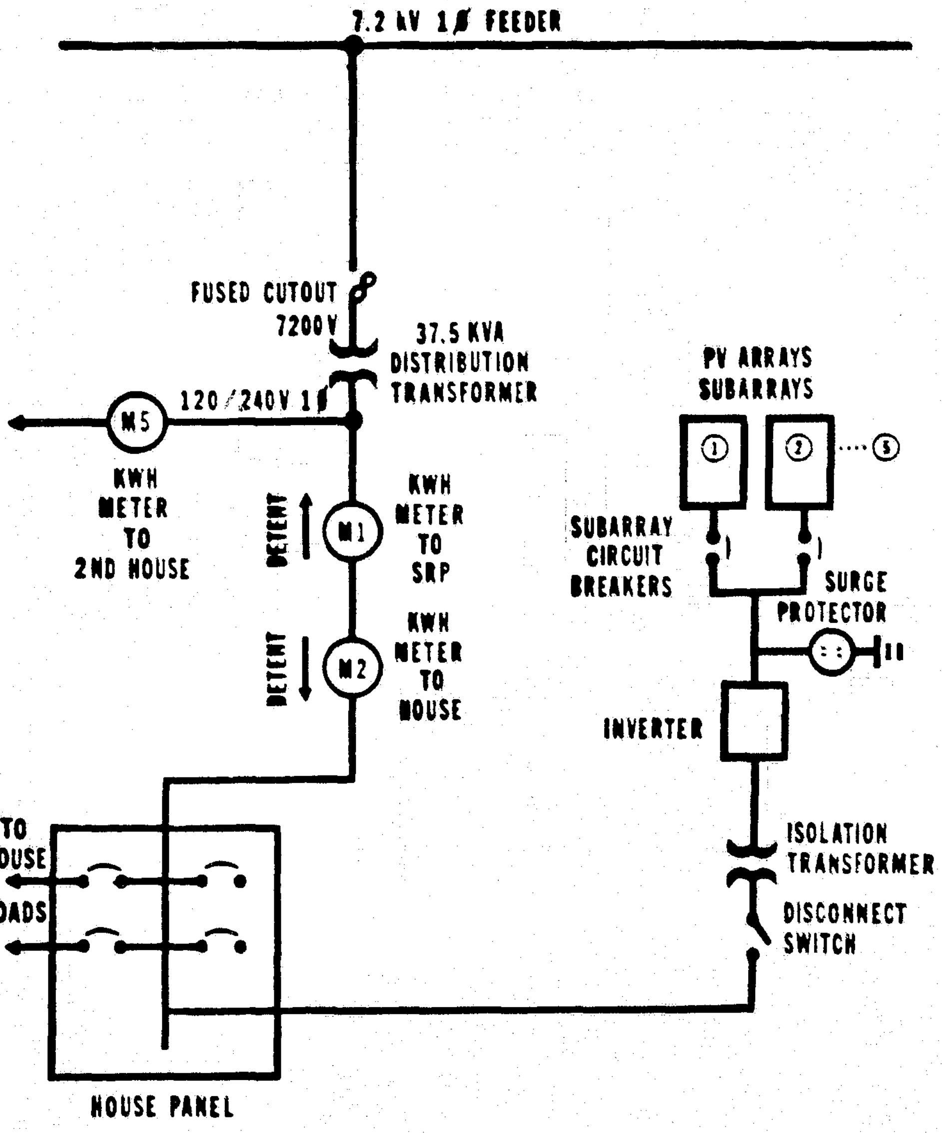

7.2 kV 1∅ FEEDER
FUSED CUTOUT 7200V
37.5 KVA DISTRIBUTION TRANSFORMER
120/240V 1∅
M5
KWH METER TO 2ND HOUSE
M2
KWH METER TO HOUSE
TO HOUSE LOADS
HOUSE PANEL

Figure 4



open position. This provides the means to prevent backfeeding when maintenance is required on the utility side of the system. It also makes it possible to provide maintenance on the photovoltaic side of the system without interrupting power to the residence.

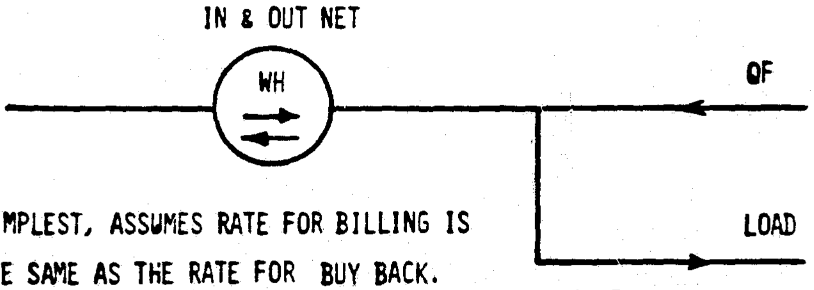
There is variety of metering options; this illustrates one of them. In this case a second meter is added; both meters are provided with detents to prevent reverse metering. This example may be used when the power factor is acceptable but the rates for power supplied and power returned are different. A few other metering options are illustrated by Figures 5 and 6.

The John F. Long system is equipped with an additional watt-hour meter M3, a VAR-hour meter M6 and a magnetic tape recorder for test purposes. A current transformer and a power transformer are also provided on the 7200-volt

Figure 5

METERING OPTIONS

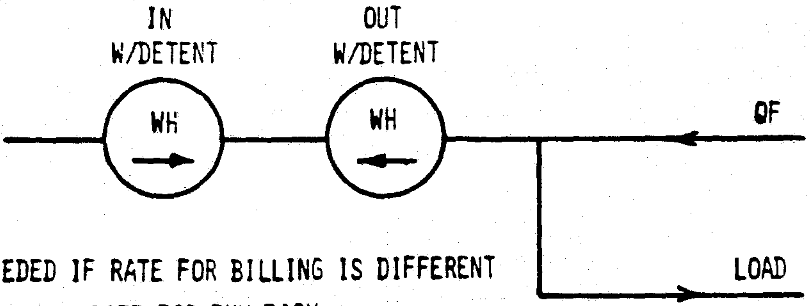
OPTION 1



SIMPLEST, ASSUMES RATE FOR BILLING IS THE SAME AS THE RATE FOR BUY BACK.

COSTS:	METER	$ 25
	LABOR	58
	TOTAL	$ 83

OPTION 2

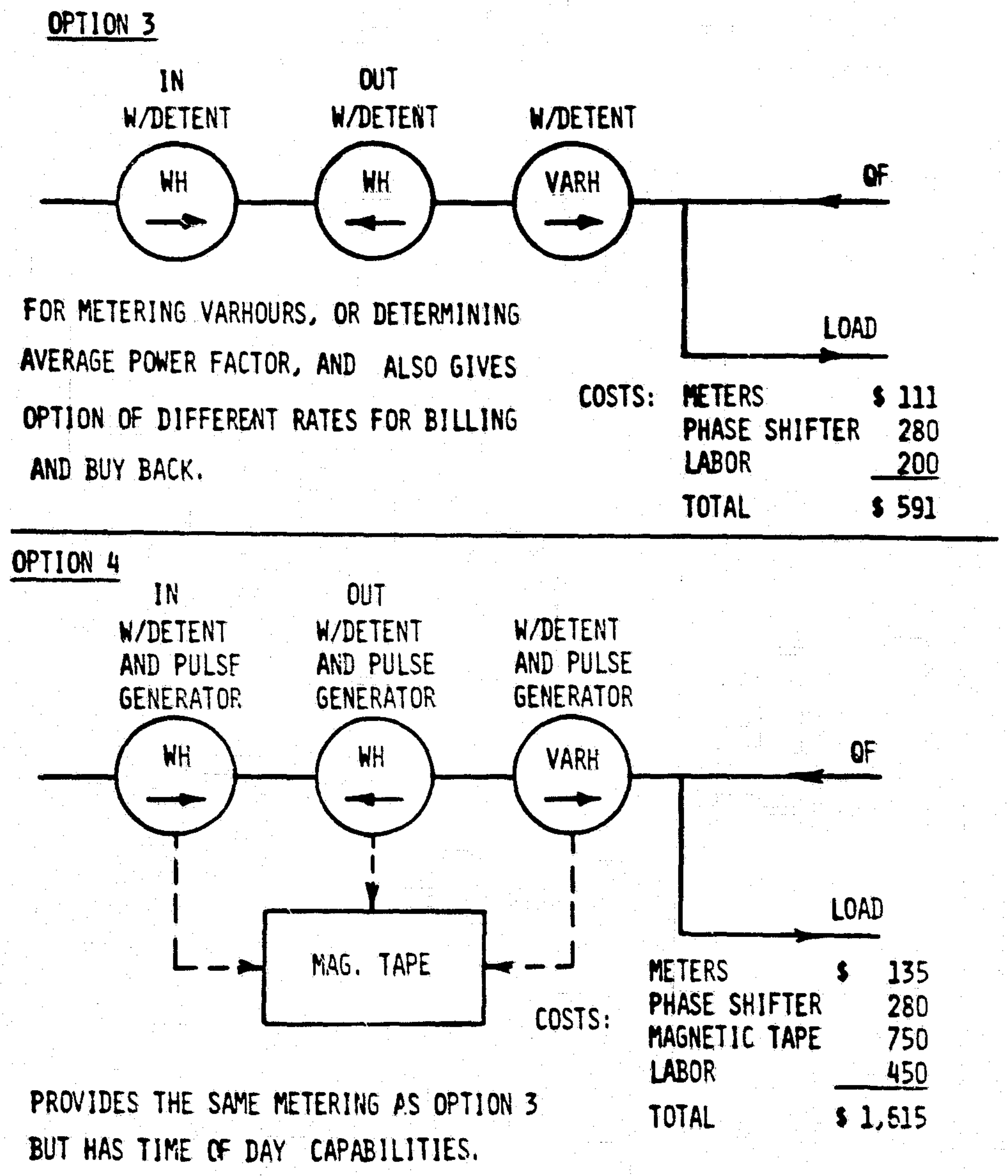


NEEDED IF RATE FOR BILLING IS DIFFERENT THAN THE RATE FOR BUY BACK.

COSTS:	METER	$ 72
	LABOR	77
	TOTAL	$ 149

Figure 6

METERING OPTIONS



OPTION 3

FOR METERING VARHOURS, OR DETERMINING AVERAGE POWER FACTOR, AND ALSO GIVES OPTION OF DIFFERENT RATES FOR BILLING AND BUY BACK.

COSTS:

METERS	$ 111
PHASE SHIFTER	280
LABOR	200
TOTAL	$ 591

OPTION 4

PROVIDES THE SAME METERING AS OPTION 3 BUT HAS TIME OF DAY CAPABILITIES.

COSTS:

METERS	$ 135
PHASE SHIFTER	280
MAGNETIC TAPE	750
LABOR	450
TOTAL	$ 1,615

side of the distribution transformer to facilitate the measurement of harmonics.

Instruments used included a spectrum analyzer and plotter, oscilloscope and camera, phase angle meter, ammeter and voltmeter. (See Figure 7.)

Table 1 is a tabulation of the watt-hour and VAR-hour meter readings. The VAR-hour meter M6 was installed on July 16 and both it and the watt-hour meter M3 were zeroed at that time. Note that the average daily power readings and the average daily house loads have not varied significantly for the three periods of time indicated in the date column. The calculated power factor is running less than 40%.

Figure 7

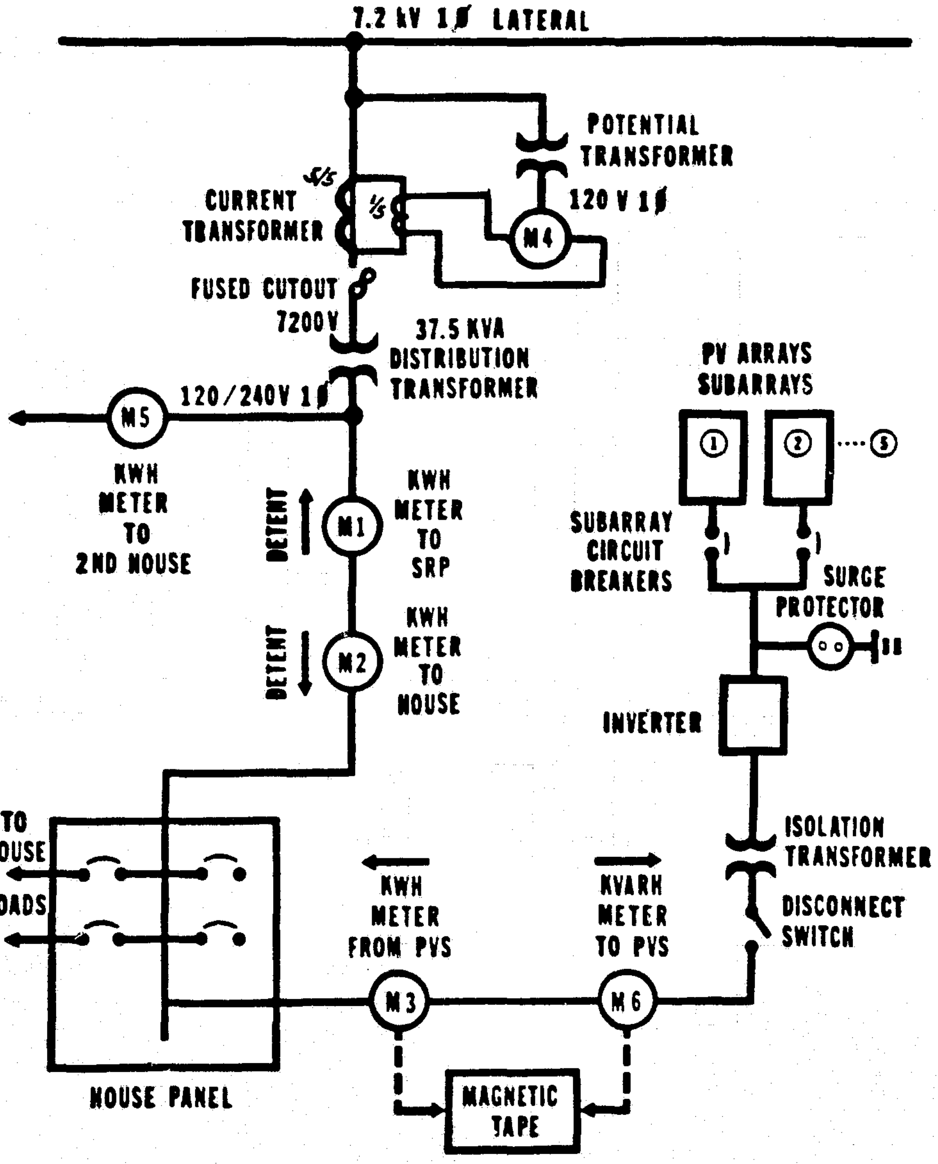

7.2 kV 1Ø LATERAL
POTENTIAL TRANSFORMER
120 V 1Ø
5/5
CURRENT TRANSFORMER
1/5
M4
FUSED CUTOUT 7200V
37.5 KVA DISTRIBUTION TRANSFORMER
120/240V 1Ø
M5
KWH METER TO 2ND HOUSE
DETENT
M1
KWH METER TO SRP
DETENT
M2
KWH METER TO HOUSE
PV ARRAYS SUBARRAYS
①
②
⑤
SUBARRAY CIRCUIT BREAKERS
SURGE PROTECTOR
INVERTER
ISOLATION TRANSFORMER
DISCONNECT SWITCH
TO HOUSE LOADS
KWH METER FROM PVS
KVARH METER TO PVS
M3
M6
HOUSE PANEL
MAGNETIC TAPE

Table 1

JOHN F. LONG PHOTOVOLTAIC PROJECT
WATT-HOUR & VAR-HOUR METERING

MAY 23, 1980 TO SEPTEMBER 17, 1980 (117 DAYS)

DATE		METER				DAILY AVERAGE KWH	CALC LOAD		CALC AV PF
FROM	TO	NO.	FUNCTION	UNITS	TOTAL		TOTAL KWH	AV KWH/DAY	
5/23	9/17	3	FROM PVS	KWH	2377	20.3			
TOTAL		1	TO SRP	KWH	1659	14.2			
117 DAYS		2	FROM SRP	KWH	1738	14.9			
							2456	21.0	
7/16	9/17	3	FROM PVS	KWH	1217	19.3			
LAST		1	TO SRP	KWH	879	14.0			
63 DAYS		2	FROM SRP	KWH	958	15.2			
		6	TO PVS	KVARH	3086	49.0			
							1296	20.6	0.37
9/4	9/17	3	FROM PVS	KWH	286	22.0			
LAST		1	TO SRP	KWH	224	17.2			
13 DAYS		2	FROM SRP	KWH	186	14.3			
		6	TO PVS	KVARH	704	54.2			
							248	19.1	0.38

It should be pointed out that periodic service and refinements of the photovoltaic system and changes in the cooling system have caused several interruptions in the system operation.

The loads are not representative of an occupied residence and the water heater and range are not connected. In-depth testing, planned for October, will include the imposition of more representative loads. Also, the tapes of 15-minute-interval readings of the inverter kWh and VARH meters will provide hourly profile of these readings.

Initial tests for wave form, harmonics and power factor have underlined the need for more in-depth investigation of these variables. They also point up the need for more precise reference measurements on existing residential distribution systems.

The preliminary tests made at the John Long photovoltaic system interconnection revealed power factors in the range of 0.2 to 0.6 on the 7.2 kV side against 0.92 with the photovoltaic system disconnected.

Total harmonics were measured up to 36% on the 7.2 kV side against approximately 5% with the photovoltaic system disconnected. The effect of harmonics on appliances, telephone systems and adjacent customers is not clearly understood and bears further investigation. It is also uncertain how far back into the distribution system these harmonics can be seen.

In summary, some of the utility concerns include:

(1) Power factor, metering and buy-back rate structure.

(2) Effect of harmonics and adjacent customers, touch-tone telephone systems, TV and radio interference, etc.

(3) Imbalance of the three-phase load with multiple cogenerating system on a single-phase lateral.

(4) Voltage regulation and frequency matching.

(5) Voltage flicker.

(6) Dynamic response (clouds, etc.)

(7) Safety, system protection and utility operation and maintenance procedures.

(8) Delineation of responsibility and liability.

We welcome the opportunity to seek these answers in the interest of moving toward the successful integration of cogenerating customers into our system. By March of 1981 we and other utilities will have developed technical requirements and rates to accommodate such systems. But we believe that there are many unanswered questions that may be answered by research installations such as John Long's and the Florida residence. It is too soon to place these systems on the commercial market and into the hands of customers in any number unti the critical questions have been answered and safety for the customer and utility personnel can be assured.

PANEL DISCUSSIONS: PHOTOVOLTAIC HOUSES

JOHN F. LONG HOMES

John F. Long Homes has built over 33,000 homes in the Phoenix area since 1947. R. (Casey) Kayes has been with John F. Long Homes for 23 years and has found the construction of homes has become even more exciting with the advent of photovoltaics.

Kayes did not believe that his company encountered many problems during the building of these unique photovoltaic homes. He believes this is partly because of their experience in home construction; by using their knowledge, they were able to resolve potential problems before they could cause work stoppages.

Since this was the first group of homes ever built using photovoltaics, John F. Long Homes went to the Phoenix Building and Safety Department to discuss any potential problems. If they had had to go to a variance board with code problems during construction it would have caused at least a 90-day work stoppage. After they met with the Building and Safety Department at the onset of construction, the City Director and other city officials became interested in the project and pledged their cooperation to keep the job moving in case code problems should surface. Because of the good reputation of John F. Long Homes, the city was willing to expedite it regulatory functions.

Some problems could have arisen with the labor unions. Since the panels were married to roofing materials, the roofers' union might have claimed the right to install them; since these panels are electrical, the electricians could have claimed jurisdiction. Again, because of the vast experience of the company and the reputation within the city, they were able to resolve these issues early.

Kayes urged potential photovoltaic manufacturers to contact reputable construction companies before any installation is begun, to anticipate potential problems.

CdS CELL AND MODULE PROGRESS AND PROGNOSIS

K.M. Koliwad, Moderator

SPRAYED CdS BACKWALL CELLS AND PANELS

PHOTON POWER, INC.
G.A. Roderick

Summary

This paper summarizes Photon Power's current status in the research, development and manufacture of CdS/Cu_x cells, panels and modules. It also discusses briefly the company's proposed activities for the immediate future.

Introduction

Photon Power has some 70 employees at present, of whom 13 are in the research division, with most of the remainder in the development and manufacturing activity and a small administration and marketing section (12).

Apart from research into our CdS/Cu_xS sprayed cell and its configuration we are in the process of installing the equipment for our 5 MW factory. This factory is designed to process between 1 million and 2 million ft^2 of glass per year on a continuous basis (8000 h/yr) by coating 2 x 2-ft sheets of glass at up to 24 in./min line speed.

Research

In our research department we have divided our work into three areas:

1. Materials selection and evaluation.

2. Device development.

3. Process development.

Our results to date include 1 cm^2 cells with efficiencies greater than 7% made by a new junction forming process.

Cells of almost 7% made with dipped films, and pilot line cells of almost 6% (all laboratory cells are of 1 cm^2 area).

In addition to this we have achieved currents of 26.3 mA/cm^2, voltages of 0.535 and fill factors of 75%, all of which, we believe, will lead to an 8% cell this year.

We are also looking at Cd/Zn sulfides and have open circuit voltage of 750 mV with such films (although with poor currents so far).

We are actively looking at both different chemicals and different techniques for crystal growth.

Development

We have two development lines, one a railway-based line that processes glass sheets 20 x 24 in. at some 2 in./min. This is the line which has produced 1-cm^2 cells of almost 6%, and panels with an active area of 2300 cm^2 at almost 3%. Smaller areas (1150 cm^2) have achieved higher efficiencies (3.1%) and single cells (39 cm^2) are at 3.5%, roughly.

The second line, which utilizes a belt conveyor, can handle 24 x 24 in. glass and has run at 6 in./min for filming the glass.

In addition to the hot line process development we have two areas of work on the panels -- (1) Subdivision of the sprayed panels into 60 series connected cells. This is done on a machine tool -- we are currently developing the fourth generation model! (2) The framing of our panels (once made) into what we call a module. This is a treated wooden frame containing eight panels, wired in any reasonable manner, suitable for direct field installations.

Manufacture

We have now moved into our new factory building (62,000 ft^2) and are in the process of installing and commissioning the equipment. As of this date 80% of the equipment is installed and we have tested the glass washer, the tin oxide line and all our services. This line, which is designed to run from 12 to 24 in./min with 24 x 24-in. glass, should be fully commissioned by Christmas.

The basis for the design is the achievement of a 70% yield of 3% panels in 1981 and a maximum of 75% yield of 5% panels by 1983/4.

The factory will employ about 120 people by next April.

Life

We are in the midst of a major test program to evaluate:

(1) Device stability.

(2) Product behavior in the environment.

As far as we can tell the device is stable. Degradation is temperature related and output reaches a constant level for any given operating temperature. In our tests we have tried both constant illumination and dark oxygen has no measurable effect. In particular we experience no current loss at all, only a decline in fill factor when degradation does occur.

As regards the product we are working on both the series connection (which does in some cases degrade) and the encapsulant.

We began to install modules outside 2 years ago. Our first module (8 panels) was only 1% efficient and in 2 years has degraded 18% due to one panel dropping from 2 Watts to 0.4 Watts; the remainder of the panels being within 10% of the original output.

Other modules have been exposed for 18 months and our first sales modules have been installed this year.

Outlook

We hope to achieve 8% research cells (1 cm^2) this year and will continue to aim for a 10% goal in 1981.

In the factory we hope to run the line for some 6,000 hours next year and will be aiming at sales of about 1 MW ± 250 kW during 1981. We shall be looking for some larger applications (50 kW and above) among what we hope will be a large number of 1 kW-10 kW sales. A few smaller (50 W) sales are also anticipated.

One incidental note: we shall also be selling tin oxide-coated glass for various uses with maximum sheet size of 24" x 24" and $\Omega/\square$ ranging from 5 to 200. Glass thickness of 1/8" (3 mm), 1/16 and possibly thinner will be available.

Taking all this into account, we hope for a break-even in 1981 with sales and costs in the \$5 million to \$7 million range.

SOLAR ENERGY SYSTEMS, INC.
Steve DiZio

U.S. Government Participation

ASSUMING OBJECTIVE IS TO MAKE CdS/Cu_2S TECHNOLOGY A VIABLE ALTERNATIVE TO SILICON:

- SUPPORT SYSTEMATIC DETERMINATION OF FUNDAMENTALS (MATERIALS AND DEVICE PARAMETERS) WHICH IMPACT EFFICIENCY AND LIFETIME, BOTH INDIVIDUALLY AND INTERACTIVELY.
- FORM "PARTNERSHIP(S)" WITH COMPANIES TO CARRY OUT INTEGRATED PRODUCT AND PRODUCTION DEVELOPMENT. PROPRIETARY POSITION (AND PATENT RIGHTS) OF COMPANIES IS KEY ISSUE.

- RESEARCH FUNDED FOR "PROOF OF TECHNOLOGY" WITH RESPECT TO EFFICIENCY

MAJOR PROBLEMS

- FEW LABORATORIES AVAILABLE WITH TECHNICAL EXPERTISE AND EQUIPMENT WILLING TO FOCUS ON FUNDAMENTAL RESEARCH WORK.
- TECHNOLOGY DOES NOT LEND ITSELF TO BREAKDOWN OF PROCESSES INTO INDIVIDUAL PROBLEM AREAS.
- FEW, IF ANY, COMPANIES CAPABLE OF DOING PROCESS AND EQUIPMENT DEVELOPMENT.
- COMPANIES PAYING HIGH "ENTRY FEE" UNLIKELY TO GIVE UP PROPRIETARY ADVANTAGE.

CONCLUSION

- PRESENT GOVERNMENT POLICIES AS USED IN SILICON DEVELOPMENT EFFORT ARE NOT LIKELY TO BE SUCCESSFUL WITH CdS/Cu_2S.

Industrial Participation

- ONE COMPANY IN "MARKET ENTRY PHASE"
- ONE COMPANY IN "PRODUCTION STARTUP/PRODUCT DEFINITION PHASE"
- ONE COMPANY IN "FORMATION PHASE"
- SEVERAL COMPANIES IN "CONCEPTUAL TECHNOLOGY PHASE"

MAJOR PROBLEMS

- PROOF OF TECHNOLOGY UNAVAILABLE AND EXPENSIVE TO DEVELOP.
- PROCESS AND EQUIPMENT DEVELOPMENT COSTS (AND TIME) FAR EXCEED TECHNOLOGY DEVELOPMENT COST.
- REQUIRED TECHNOLOGICAL "TEAMS" DO NOT EXIST.
- PHOTOVOLTAICS POOR MATCH FOR EXISTING COMPANIES "BUSINESS REQUIREMENTS."

Summary, CdS-Cu_2S Technology

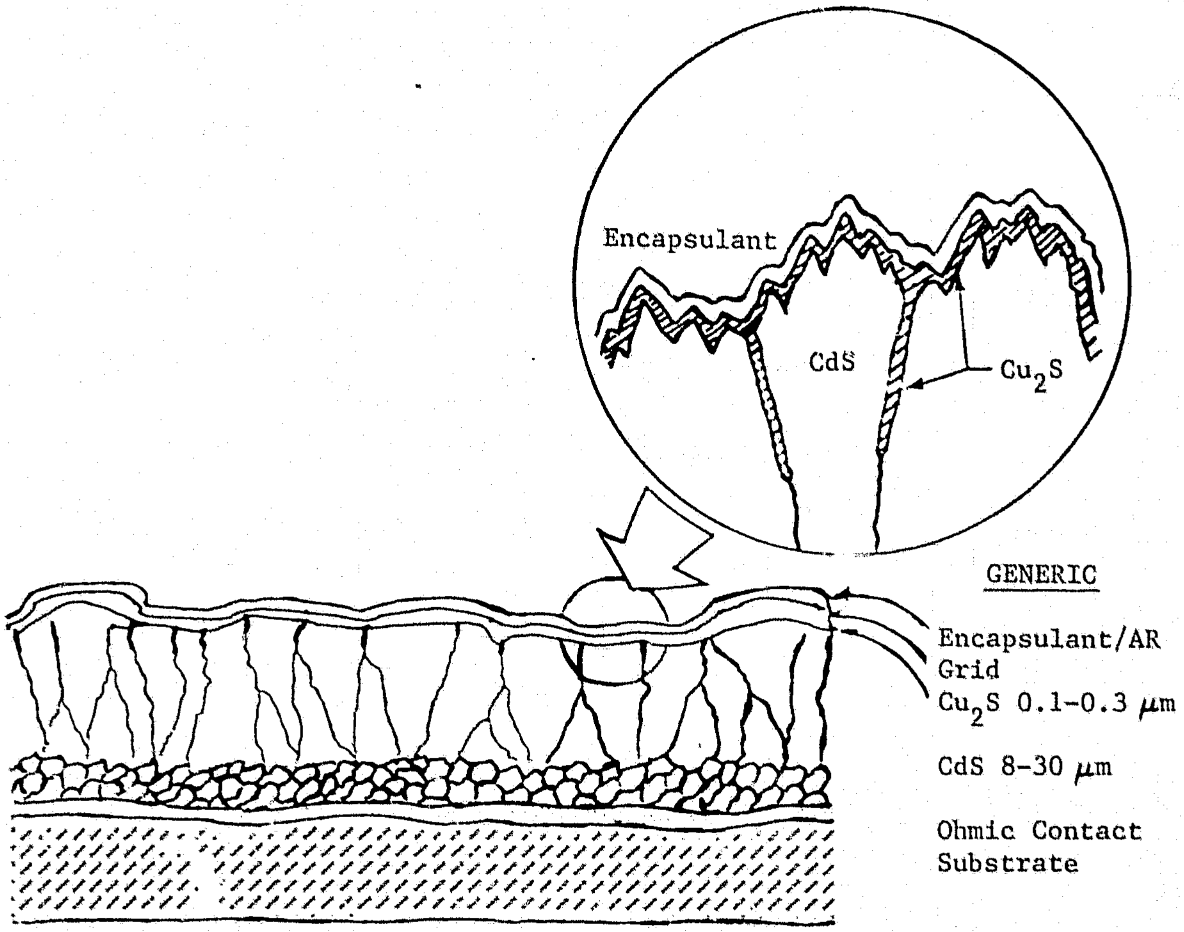
- EFFICIENCY
  - 7% TO 10% PROVED
  - 10% TO 12% PROBABLE
  - 12% to 15% POSSIBLE
- LIFE EXPECTANCY (MEAN TIME TO 80% OF START VALUE)
  - 5 TO 10 YEARS PROVED
  - 10 TO 20 YEARS PROBABLE
  - GREATER THAN 20 YEARS POSSIBLE
- ECONOMICS (BURDENED MANUFACTURING COSTS - 1980 $)
  - 50¢ TO $1/WATT PROVED
  - 25¢ TO 50¢/WATT PROBABLE
  - LESS THAN 25¢/WATT POSSIBLE

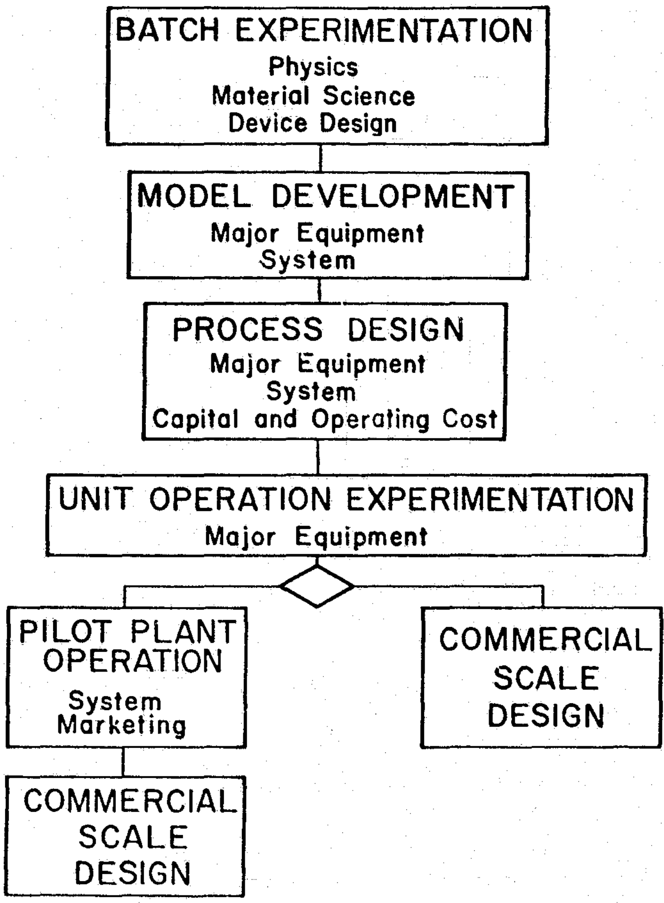
INFORMATION IN "PUBLIC DOMAIN"

INFORMATION "PROPRIETARY"

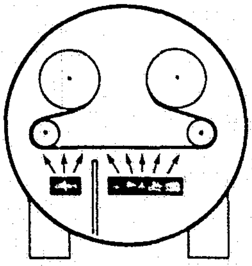
UNIVERSITY OF DELAWARE

Fraser Russell

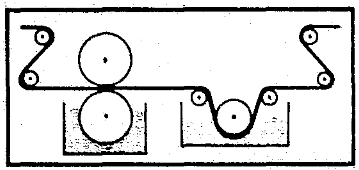




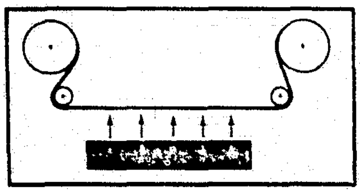
Key Unit Operations



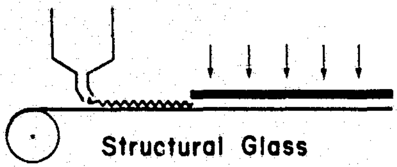
Continuous Deposition of Active Semiconductor Layers



Deposition of Transparent Front Contact



Integral Glass Encapsulant



Structural Glass Encapsulant

RAW MATERIAL	QUANTITY (lb/yr)	COST ($/watt)
Plate Glass Encapsulant	1.25×10^7 m^2/yr	.039 - .075
Gold Grid (<1000Å, 10% Area)	5.3×10^3	0 - .034
One Mil Brass Substrate	6×10^6	.029
(Five Mil Brass Substrate)	30×10^6	.064
Cadmium Sulfide (10 Micron, 60% Util)	1.8×10^6	.020
Integral Glass Encapsulant	370×10^3	.004
PVB Binder	5.5×10^6	.003
Buss Insulator (TPA-85)	22×10^3	.001
Cu (Grid Lines, Buss)	172×10^3	.0005
CuCl	24×10^3	.0002
Miscellaneous		.001

	BATCH		CONTINUOUS	
UNIT OPERATION	COST*	LABOR†	COST*	LABOR†
Substrate Preparation	805 - 1,130	11	455 - 620	5
CdS Evaporation	47,000 - 70,500	40	19,000 - 25,000	10
CuCl Evaporation/Rxn	47,605 - 59,490	45	19,580 - 25,730	13
Grid Print/Plate	1,090 - 1,390	8	890 - 1,140	4
Integral Encapsulant Evap.	47,000 - 58,750	40	19,000 - 25,000	10
Plate Glass Installation	110 - 140	7	190 - 240	7
Misc. Scrubbers & Precipitators	80 - 100	1	80 - 100	1
TOTALS	143,690 - 191,500	150	59,195 - 77,830	50

		100 MEGAWATT		1000 MEGAWATT	
		B	C	B	C
I.	TOTAL MANUFACTURING COSTS	.45 - .68	.26 - .39	.37 - .57	.22 - .34
	A. COST OF CAPITAL	.10 - .14	.04 - .06	.08 - .11	.03 - .05
	B. RAW MATERIAL	.10 - .20	.10 - .17	.10 - .20	.10 - .17
	C. UTILITIES	.06 - .10	.03 - .06	.06 - .10	.03 - .05
	D. PRODUCTION LABOR	.10 - .12	.05	.07 - .08	.03
	E. OVERHEAD & MISC.	.09 - .12	.04 - .05	.06 - .08	.03 - .04
II.	TOTAL NON-PRODUCTION COSTS	.10 - .25	.06 - .14	.07 - .20	.04 - .12
	TOTAL PRODUCT COST	.55 - .93	.32 - .53	.44 - .77	.26 - .46

Capital Requirements

	MILLIONS $ (1979)	
PLANT SIZE	BATCH	CONTINUOUS
10^5 M^2/YR. (10 MW)	12 - 18	10 - 15
10^6 M^2/YR. (100 MW)	80 - 107	34 - 46
10^7 M^2/YR. (1000 MW)	636 - 854	263 - 347

Labor Requirements

	PERSON-YEARS	
PLANT SIZE	BATCH	CONTINUOUS
10^5 M^2/YR. (10 MW)	68	56
10^6 M^2/YR. (100 MW)	168	80
10^7 M^2/YR. (1000 MW)	600	200

PHOTOVOLTAIC MARKETS

STRATEGIES UNLIMITED
B. Murray

The Photovoltaic Market

Year	Shipments (kWp)	ASP ($/Wp)	Dollars ($M)
1976	240	28.50	6.8
1977	450	19.00	8.6
1978	950	14.70	14.0
1979	1,450	13.50	19.6
1980*	3,250	12.00	39.0

(* Estimated)

Demand Trends:

1. U.S. Government: Variable, 25% - 40%.
2. Foreign Commercial: Growing, 50% (1979).

Photovoltaic Applications, 1979

CLASS	TYPE	% MARKET
Developed Commercial	Communications Cathodic Protection Navaids Railroads Consumer Other	63%
Developing Commercial	Water Pumping Village Power Other	16%
Government	Miscellaneous	21%

Still to come: Residential Facility
Industrial Facility
Utility

Photovoltaic Competition

Total: Active Organizations - 385

Subtotals: System Integrators - 10%
Module Manufacturers - 7%
Module Researchers - 26%
Material Researchers - 12%
BOS Suppliers - 3%
Universities - 25%
Utilities - 6%
Other - 11%

Photovoltaic Technology

Generation	Type	Lifetime *
1st	Single Crystal Cz	1971 --- ?
2nd	Advanced Cz Polycrystalline Cz	1983 --- ?
3rd	Thick Film	1985 --- ?
4th	Thin Film	1990(?) --- ?

(*For Major Market Impact)

MARKET DARKHORSE - CdS

Photovoltaic Economics

Competitive Technology	PV Breakeven ($/Wp)
Primary Batteries	$35-25/Wp
Thermoelectric Generators	$20-15/Wp
Small Diesel Engine Generators[1]	$12-7/Wp
Large Diesel Engine Generators[2]	$ 7-4/Wp .
Grid Extensions	$10-3/Wp
Primary Grid	$ 3-1/Wp

(1 - Less than 10 kW; 2 - Less than 100 kW)

Photovoltaic Marketing

CHARACTERISTIC	REQUIREMENT
Infant Technology	User Basic Education Direct Sales or "Advanced" Distributor Proven Quality and Reliability
System Business	Optimized Systems Designs Flexible Component Capabilities In-Depth Applications Support Developed BOS Capabilities Full Service Follow-up
Worldwide Market Base	Extensive Geographic Coverage Export/Import Expertise Socioeconomic Knowledge Local Trained Follow-up
Variable Economics	Selected Applications Emphasis Market Sector Selection Finance and Trade Expertise Competitive Technology Expertise Financing Flexibility
Long Term Market	Patience and Perseverance

Photovoltaic Market

- Barriers to Penetration -

"Unproven" Technology

Lagging Systems Development

Short Term "Hands On" Experience

Limited Market Knowledge

Limited Market Infrastructure

Localized Economics

Varying Government Energy Plans

Changing Basic Technology

Stiff Foreign Competition

Political Instability

Institutional Issues Unsettled

Limited Available Financing

- The Positive Side -

Competent Personnel

Demonstrable Technical Progress

Demonstrable Economics

Developing Market Relationships

Significant Industry Investment

Continuing Energy Demand

Escalating Energy Costs

Increasing User Support

Worldwide Government Recognition

"Photovoltaics" is Pronouncable

INTERNATIONAL PV VILLAGE POWER MARKET ASSESSMENT

MOTOROLA SEMICONDUCTOR PRODUCTS, INC.

Clyde Ragsdale

A "GRASS ROOTS" EVALUATION OF THE MARKET POTENTIAL FOR PHOTOVOLTAIC APPLICATIONS IN REMOTE VILLAGES IN THE U.S. AND ITS TERRITORIES PROVIDES AN ESTIMATE OF ALMOST 14 MW AVAILABLE FOR CONVERSION FROM A POTENTIAL TO A REAL MARKET.

THIS TOTAL POWER POTENTIAL IS BASED ON THE ENERGY NEEDS OF ALMOST 400 SITES REPORTED BY FEDERAL AGENCIES AND INPUTS FROM OVER 100 INDIAN TRIBES. THIS POTENTIAL CONSISTS OF THE FOLLOWING:

U.S. GOVERNMENT AGENCIES	3,000 KWp
INDIAN VILLAGES	10,000 KWp
ALASKAN VILLAGES	370 KWp
TERRITORIES	500 KWp
U.S. COMMERCIAL	NEGLIGIBLE
TOTAL	13,870 KWp

The Developing Country Dilemma

THE SITUATION

ENERGY, ESPECIALLY ELECTRICITY, IS THE KEY TO INCREASING ECONOMIC DEVELOPMENT.

LESS THAN 30 PERCENT OF THE PEOPLE IN DEVELOPING COUNTRIES HAVE ACCESS TO ELECTRICITY.

MUCH OF THE NEED FOR ELECTRICITY IS FOR SMALL, REMOTE, DECENTRALIZED LOADS.

OIL FIRED GENERATING PLANTS ARE NO LONGER A SUITABLE OPTION FOR SMALL DECENTRALIZED LOADS DUE TO:

- UNCERTAIN AVAILABILITY OF OIL.
- ESCALATING COST OF OIL.
- DIFFICULTY OF DELIVERY AND STORAGE OF OIL.

MAINTENANCE AND REPAIR CAPABILITY AND SPARE PARTS AVAILABILITY ARE A PROBLEM IN DEVELOPING COUNTRIES AND ARE PRACTICALLY NONEXISTENT IN REMOTE VILLAGES.

EVEN OIL-RICH DEVELOPING COUNTRIES WANT TO CONSERVE OIL FOR FUTURE NEEDS AND AS A SOURCE OF FOREIGN EXCHANGE.

MOST DEVELOPING COUNTRIES HAVE LIMITED SOURCES FOR FOREIGN EXCHANGE.

THE NEED

WHAT THE DEVELOPING COUNTRIES NEED THEN IS A SOURCE OF GENERATION OF ELECTRICITY WHICH HAS THE FOLLOWING CHARACTERISTICS:

- **ADEQUATE AVAILABILITY OF FUEL.**
- **REASONABLE COST OF FUEL.**
- **FUEL EASY TO DELIVER AND STORE.**
- **MODULAR AND SCALEABLE IN SIZE.**
- **EQUIPMENT RELIABLE AND RELATIVELY MAINTENANCE-FREE.**
- **MAXIMUM LOCAL CONTENT.**
- **MINIMUM CAPITAL INVESTMENT.**

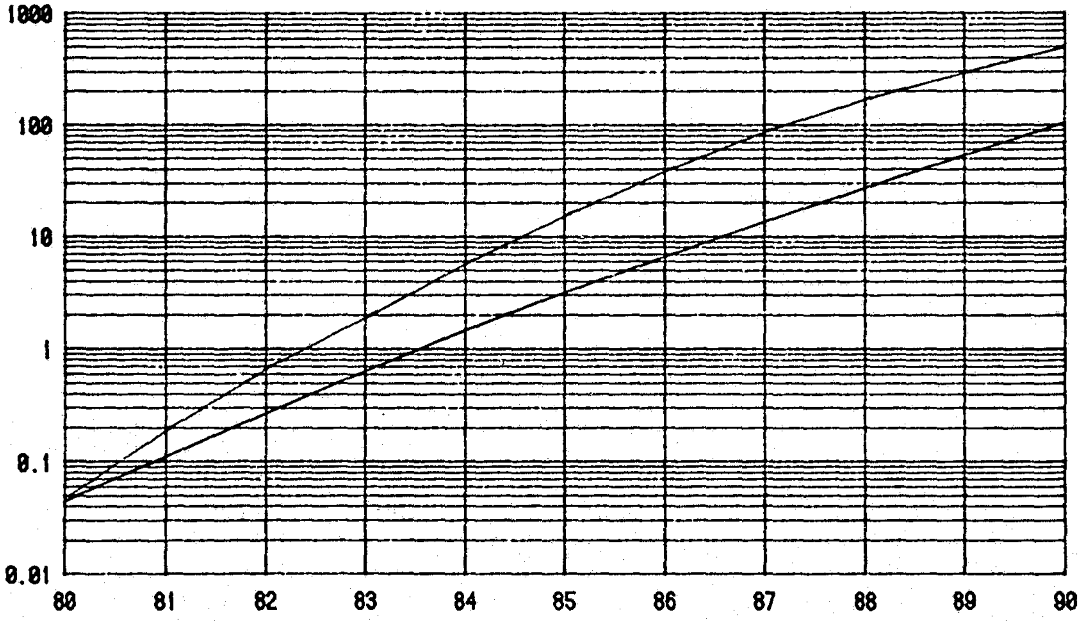
Market Potential

REMOTE VILLAGES HAVING NO ELECTRICITY	3.2 MILLION
AVERAGE VILLAGE SIZE	500 PEOPLE
ELECTRICITY REQUIRED FOR BASIC NEEDS PER VILLAGE	10 KWP
TOTAL POTENTIAL	32,000 MWP
NEAR-TERM (10 YEAR) PENETRATION RATE	3 PERCENT
NEAR-TERM MARKET	1000 MWP

Impediments to Market Development

- LIMITED FINANCIAL RESOURCES OF MOST DEVELOPING COUNTRIES
- HIGHER PRIORITY PROGRAMS THAN VILLAGE ELECTRIFICATION
- LACK OF AWARENESS OF AND CONFIDENCE IN PV
- HIGH INITIAL COST OF PV
- POLITICAL INSTABILITY OF MANY DEVELOPING COUNTRIES

Village Power Market, MW_p



Recommendations

I. INITIATE EDUCATIONAL/PROMOTIONAL PROGRAM

- A. U.S. OVERSEAS PERSONNEL
  1. COMMERCIAL ATTACHES
  2. AID PERSONNEL
- B. LOCAL GOVERNMENT OFFICIALS
  1. ENERGY
  2. RURAL DEVELOPMENT
  3. EDUCATION
  4. AGRICULTURE
  5. UTILITY
  6. COMMUNICATIONS
- C. METHOD
  1. IN-COUNTRY SEMINARS
  2. REGULAR MAILINGS
  3. INVITATION TO U.S. CONFERENCES/EXHIBITIONS

II. CONTINUE DEMONSTRATION PROGRAM

- A. MAJOR DEMONSTRATIONS IN EACH REGION (AFRICA, LATIN AMERICA, S.E. ASIA)
- B. DEMONSTRATIONS IN ALL KEY COUNTRIES
- C. U.S. GOVERNMENT COST SHARE WITH HOST GOVERNMENT
- D. MAKE MAXIMUM USE OF INTEGRATION INTO EXISTING PROGRAMS (AID, ETC.)

III. COMMERCIALIZATION

A. ESTABLISH MECHANISM WHEREBY IN THE EARLY STAGES OF MARKET DEVELOPMENT INDUSTRY CAN BRING POTENTIAL U.S./ FOREIGN COUNTRY PROGRAMS TO U.S. GOVERNMENT FOR ASSISTANCE (FINANCIAL OR OTHERWISE)

B. PROVIDE MECHANISM BY WHICH FOREIGN COUNTRY INTEREST AND/ OR LEADS CAN BE FUNNELED BACK TO INDUSTRY; ALSO COMPETING COUNTRY ACTIVITIES IN PV

C. PUBLICIZE SUCCESSES THROUGH EMBASSIES AND OTHER INTER-GOVERNMENTAL CHANNELS

D. ESTABLISH ACCELERATED WEATHER DATA GATHERING AND DISSEMINATION PROGRAM

Summary

SALE OF PHOTOVOLTAIC SYSTEMS AND COMPONENTS TO DEVELOPING COUNTRIES REPRESENTS AN UNUSUAL OPPORTUNITY WITH POTENTIAL BENEFITS TO ALL PARTIES CONCERNED:

INDUSTRY: INCREASES EXPORT SALES
INCREASES VOLUME PRODUCTION

HOST COUNTRY: IMPROVES ECONOMIC DEVELOPMENT
IMPROVES STANDARD OF LIVING
TAKES ANOTHER STEP TO ENERGY INDEPENDENCE

U.S. GOVERNMENT: IMPROVES BALANCE OF TRADE
IMPROVES 3D WORLD RELATIONS
ACCELERATES PV HAVING AN ENERGY IMPACT IN THE U.S.

ASSISTANCE IN THE DEVELOPMENT OF FOREIGN MARKETS FOR PHOTOVOLTAICS

SOLAR POWER CORP.
Gerald F. Hein

Government Support of Photovoltaic Technology

- PHOTOVOLTAIC TECHNOLOGY DEVELOPMENT GREATLY ASSISTED BY BLOCK PURCHASES AND RESEARCH PROGRAMS
- PRDA'S AND FPUP CONTINUED TECHNICAL ASSISTANCE
- COMMUNICATION PROGRAMS HAVE BEEN EXCELLENT
- INDUSTRY PARTICIPATION IS SUPPORTED BY GOVERNMENT
- INDUSTRY ATTENTION IS HIGHLY FOCUSED ON SEVERAL ORGANIZATIONS

BOTTOM LINE: GOVERNMENT HAS ASSISTED TECHNOLOGY DEVELOPMENT PROGRAM FOR PHOTOVOLTAICS

Government Support of Photovoltaic Marketing

- THERE IS NO DIRECT SUPPORT OF THE INDUSTRY IN MARKETING
- MARKET STUDIES ARE TYPICALLY NOT DONE BY THE INDUSTRY AND STUDY TIME LAGS ARE ON THE ORDER OF TWO YEARS
- COMMUNICATION PROGRAMS ARE NOT TIMELY IF EXISTENT AT ALL
- GOVERNMENT SOMETIMES IMPEDES FOREIGN MARKETS THROUGH ITS MISSIONARY WORK
- INDUSTRY ATTENTION IS VERY DIFFUSE
- GOVERNMENT PROGRAMS ARE SOMETIMES CUMBERSOME AND INEFFICIENT WHEN COMPARED TO FOREIGN GOVERNMENT PROGRAMS

BOTTOM LINE: THERE IS LITTLE FINANCIAL OR TECHNICAL ASSISTANCE FOR A DIFFICULT AND EXPENSIVE TASK, ESPECIALLY FOR THE SMALLER COMPANIES

PANEL DISCUSSION: PHOTOVOLTAIC MARKETS

Possible Government Support for Photovoltaic Marketing

- INDUSTRY NEEDS AN ADVOCATE IN THE WORLD MARKETPLACE
- INDUSTRY COULD USE BLOCK GRANT ASSISTANCE IN MARKETING
- INDUSTRY NEEDS AN EFFECTIVE PROGRAM OF COMMUNICATION WITH THE GOVERNMENT
- INDUSTRY NEEDS ADVANCE NOTICE OF FOREIGN MISSIONS AND THE OPPORTUNITY TO PARTICIPATE
- INDUSTRY NEEDS BETTER COORDINATION AMONG DOE, STATE, EXPORT-IMPORT BANK, COMMERCE
- INDUSTRY DOES NOT NEED A DISCUSSION OF PRICES WHEN THEY ARE CONSTRUED AS COSTS
- INDUSTRY DOES NOT NEED A TRANSFER OF MANUFACTURING TECHNOLOGY

RESIDENTIAL MARKET ANALYSIS FOR PHOTOVOLTAICS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY ENERGY LABORATORY
Gary L. Lilien

- CONCEPTS
- APPROACH
- PRELIMINARY FIELD RESULTS

What Do Demonstration Programs Do?

THEY EXPOSE LARGE NUMBERS OF PEOPLE TO <u>PRODUCTS</u> AND <u>CONCEPTS</u>.

<u>PRODUCT</u>: SPECIFIC HARDWARE

<u>CONCEPT</u>: SOLAR ENERGY, IN GENERAL
SOLAR ELECTRICITY IN PARTICULAR

DEMONSTRATION PROGRAMS IMPACT:

> RATE OF PENETRATION IN THE AREA AND (PERHAPS) THE RATE OF PENETRATION OF SIMILAR TECHNOLOGIES.

TO MAKE FULLEST USE OF THE INFORMATION EXCHANGE OCCURRING AT DEMONSTRATION SITES, THAT INFORMATION MUST BE CAPTURED SYSTEMATICALLY, AND ANALYZED SCIENTIFICALLY.

Objectives of PV Market Monitoring Program:

(A) TO MEASURE CHANGES IN THE LEVEL OF PV AWARENESS AND ATTITUDES TOWARD PV SPECIFICALLY, AND SOLAR AWARENESS AND CONSIDERATION MORE GENERALLY IN THE GEOGRAPHIC AREA.

(B) TO DETERMINE EXPECTED SALES ACCELERATION, USING INTENT-TO-PURCHASE MEASURES, IN THE AREA, AS LEADING INDICATORS FOR (1) LONG-TERM PV SALES AND (2) SHORTER-TERM SALES OF OTHER SOLAR SYSTEMS.

(C) TO ACT AS AN EXPERIMENTAL UNIT TO DETERMINE THE SPHERE-OF-INFLUENCE OF THE DEMONSTRATION PROGRAM. (HOW FAR FROM THE UNIT IS AWARENESS STILL RISING?)

(D) TO PROVIDE DATA FOR THE DESIGN OF FURTHER GOVERNMENT SUPPORT PROGRAMS (WHAT WOULD PRICE AND OTHER INCENTIVES HAVE TO BE TO ALLOW THE SYSTEM TO BE BOUGHT?), AND FOR INPUT INTO TECHNOLOGY DIFFUSION ANALYSES.

(E) TO ACT AS AN IDENTIFIER OF EARLY POTENTIAL ADOPTERS OF PV.

(F) TO PROVIDE DESIGN FEEDBACK FROM FUTURE POTENTIAL BUYERS SO THAT SYSTEM READINESS EXPERIMENTS CAN PROCEED MORE RAPIDLY.

PV Field Data Collection

- PRE-TEST OF MEASUREMENT INSTRUMENTS
- ANALYSIS OVERVIEW
- SOME SUGGESTIVE HYPOTHESES

Procedure

A TELEPHONE SCREENER

- HOME OWNER
- NOT ELECTRIC HEAT USER
- IN WESTERN BOSTON OR SOUTHERN BOSTON SUBURB

COLLECT:

- GENERAL SOLAR AWARENESS, ATTITUDES, INTENT TO PURCHASE ACTIVE SOLAR
- PV AWARENESS, ATTITUDES
- DEMOGRAPHICS AND LIFE-STYLE VARIABLES

Mail Questionnaire:

- TECHNICAL DESCRIPTION OF PV
- FINANCIAL DISCUSSION OF PV (FUTURE SCENARIO)
- LIKELIHOOD OF PV INSTALLATION AT BASE PRICE AND VARIED PRICES/SAVINGS
- GENERAL QUESTIONS ABOUT PV
- PERSONAL INNOVATIVENESS AND ATTITUDES TOWARD INFLATION

Pilot Study Data

254 VALID CASES RETURNED

RESPONSE RATE = 59%

Sample Description

50% Western Boston Suburbs

50% Southern Boston Suburbs

1.2% USES A SOLAR ENERGY SYSTEM NOW
(HALF FOR WATER HEATING,
HALF FOR SPACE HEATING)

72% HAVE SEEN A HOME WITH SOLAR COLLECTORS.

28% KNOW SOMEONE WITH SOLAR COLLECTORS.

20% HAVE ACTIVELY SOUGHT SOLAR INFORMATION.

PV Perceptions

34% HAVE HEARD OF PV POWER SYSTEMS TO GENERATE ELECTRICITY IN THE HOME.

15% BELIEVE THEY CAN BUY IT IN THEIR AREA.
(NATIONAL SURVEY GIVES 26% BELIEVING AVAILABILITY)

37% KNOW OF FEDERAL INCENTIVES FOR PV INSTALLERS.

	% WHO STRONGLY OR MODERATELY AGREE WITH THE FOLLOWING STATEMENTS	
	PRE	POST
• I UNDERSTAND HOW PV POWER SYSTEMS WORK.	63.5%	81.7%
• I UNDERSTAND THE FINANCIAL MERITS OF PV.	35.7%	73.5%
• PV POWER SYSTEMS FOR HOME USE CAN PROVIDE RELIABLE AND DEPENDABLE POWER.	28.2%	27.8%
• I CURRENTLY CAN OBTAIN A PV POWER SYSTEM THAT MAKES ECONOMIC SENSE FOR HOME USE.	16.5%	27.0%
• PV POWER SYSTEMS WILL BE WIDELY USED IN FIVE YEARS.	21.2%	16.3%

Likelihood of PV Purchase in Next Year

ASSUMING 5-½ YEAR PAYBACK --

I.E., 1986 COST PROJECTION IS:

2.8% HAVE GREATER THAN 80% LIKELIHOOD

13.7% HAVE GREATER THAN 50% LIKELIHOOD

Stated Likelihood of PV Installation in Next 5 Years:

16.7% ARE VERY OR SOMEWHAT LIKELY TO INSTALL

COMPARES TO 35% FOR ACTIVE SOLAR SPACE AND WATER HEATING SYSTEMS.

(ASSUMES 1986 COST GOALS MET.)

Pilot Results in Explaining Intent to Purchase PV

MOST IMPORTANT VARIABLES

- PV ECONOMIC IMPORTANCE
- SAVINGS/PRICE
- SOLAR INFORMATION SEARCH
- INTENT-TO-PURCHASE ACTIVE SOLAR
- PV INSTALLATION LIKELY SIZE

NEXT MOST IMPORTANT VARIABLES

- BELIEF IN PV RELIABILITY/DEPENDABILITY
- PRICE

OF LESSER IMPORTANCE

- PV RISK
- ECONOMIC INVESTMENT CRITERIA
- ECONOMIC UNDERSTANDING
- PV BELIEVABILITY/AESTHETICS

* 1/3 VARIANCE IN STATED INTENT-TO-PURCHASE EXPLAINED BY EQUATIONS.

** ALL VARIABLES SIGNIFICANT AT .05 LEVEL.

Some Variables That Were Not Important

- EDUCATION
- SEX
- AGE
- FAMILY SIZE
- WORKING STATUS
- PV TECHNICAL COMPREHENSION

Some Preliminary Hypotheses & Conclusions

- MEASUREMENT EFFORT IS CAPTURING A SIGNIFICANT AMOUNT OF INFORMATION ABOUT CONSUMER'S PURCHASE INTENTIONS.
- RE-WORKING OF FINANCIAL PRICE/SAVINGS SEEMS NECESSARY.
- GENERAL OVER-STATEMENT ABOUT PV KNOWLEDGE -- SHOULD BE TRACKED. CONFUSION WITH OTHER SOLAR TECHNOLOGIES.
- FOLLOW-UP REQUIRED FOR ACTIVE SOLAR INTENTIONS.
- UNLIKELY TO FIND EARLY PV ADOPTERS BY DEMOGRAPHICS.
  - THE EARLY PV ADOPTER
    - HAS PV SAVINGS/ELECTRIC COSTS IMPORTANT TO HIM.
    - HAS SOUGHT OTHER SOLAR INFORMATION AND INTENDS TO PURCHASE ACTIVE SOLAR.
    - HAS LARGE ELECTRICITY NEEDS.
    - FINDS SAVINGS/PRICE KEY.
    - BELIEVES PV IS RELIABLE.
  - THE MOST SIGNIFICANT INCREASE IN PV ACCEPTABILITY WOULD COME IF IT COULD PROVIDE HEATING AND COOLING.

Field Study Status Report

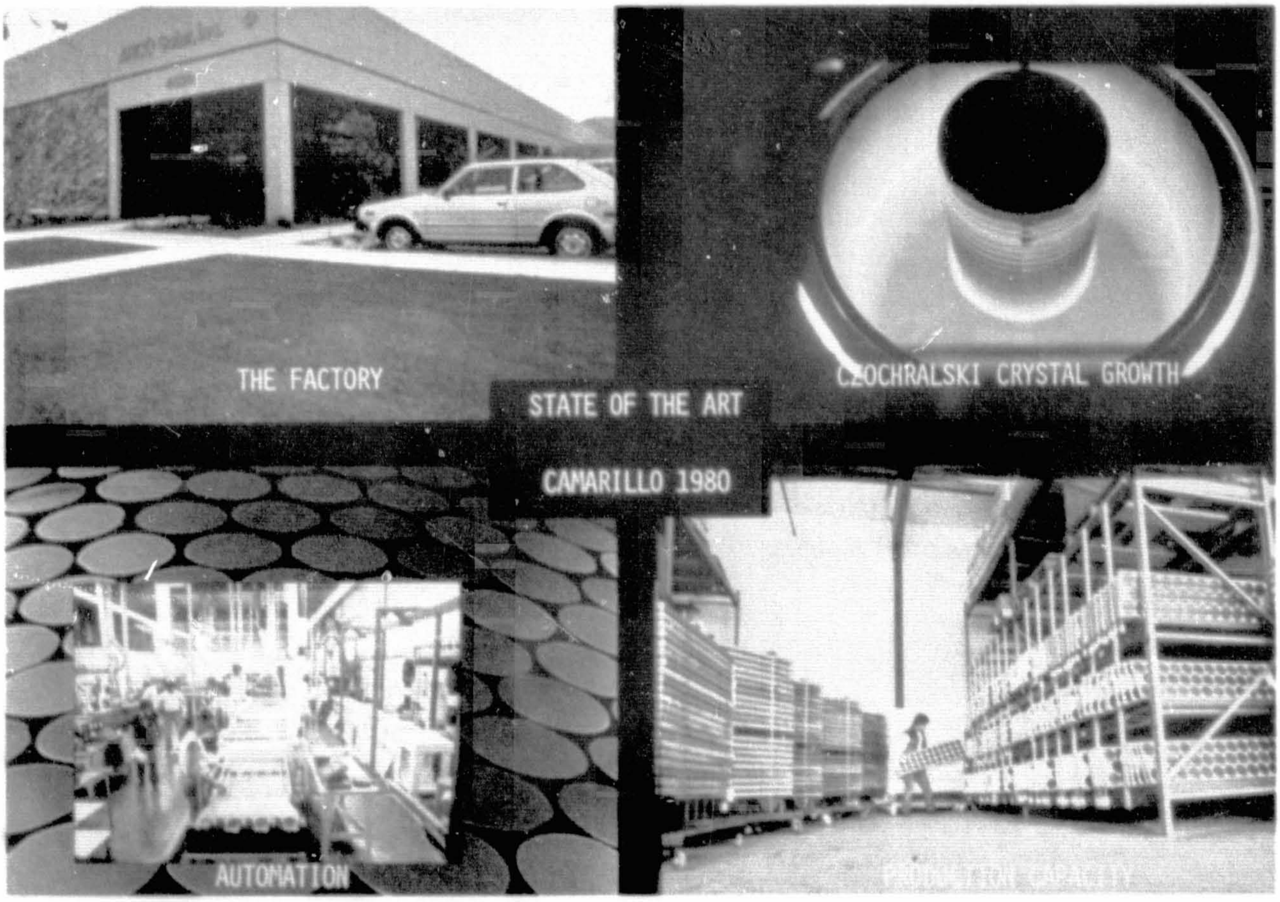
	COMPLETION DATE
1. DESIGN OF PROTOTYPE MEASUREMENT INSTRUMENTS.	15 JUNE 1980
2. FOCUS GROUP INTERVIEW -- CONCEPT TEST.	1 JULY 1980
3. PRE-TEST OF MEASUREMENT INSTRUMENTS/ PILOT ANALYSIS.	10 AUGUST 1980
4. MEASUREMENT INSTRUMENT REDESIGN.	15 SEPTEMBER 1980
5. PROPOSAL/PACKAGE TO OMB/BUREAU OF CENSUS.	15 OCTOBER 1980
6. FIRST WAVE -- FIELD IMPLEMENTATION/ SHAKE DOWN.	SPRING 1981

INDUSTRY'S PERSPECTIVE OF AND ROLE IN MEETING THE DOE PV GOALS

ARCO SOLAR, INC.

C. F. Gay

The DOE knows it is making progress toward its goal of cost reduction and market penetration when private industry begins to spend its own money. ARCO Solar, Inc. (ASI) has started to do so in Camarillo, CA.



The factory, shown above left in the photo, will manufacture more than 1 million watts of photovoltaic modules in 1980. Czochralski silicon technology was selected for use here because of its reliability and ability to readily allow cost reductions in a direct, evolutionary fashion. Many of the automated processes and materials used by ARCO Solar have evolved from JPL inititatives.

The last element of the photo -- the warehouse -- demonstrates three things:

1. The factory is designed so that production capacity can always exceed demand.

2. The photovoltaics industry is rapidly becoming involved in the materials handling aspects of business. Parts movement in being aided by automation but product transport needs simplification.

3. The major portion of the business has evolved only to the stage of module manufacture.

We are just beginning to address the issues of customer acceptance, institutional interactions, and education. Although low-cost materials and automation are important, people are the key ingredient in the manufacturing of our product and certainly in accepting this thing called a photovoltaic electric generator.

TECHNOLOGY DEVELOPMENT AREA
Silicon Material Task

TECHNOLOGY SESSION

Ralph Lutwack, Chairman

Progress in developing silicon (Si) production processes, in impurity studies and support activities was reported by eight contractors and by JPL.

Union Carbide Corp. reported on progress in designing and building a 100-MT/yr Experimental Process System Development Unit for producing Si and in conducting supporting R&D. Site preparation for the EPSDU was completed and purchase orders were issued for most of the equipment. MIT described its work in converting metallurgical-grade Si to trichlorosilane, which is used in the UCC process (it is rearranged to form silane, from which Si is made by pyrolysis).

Energy Materials Corp. operated its experimental system for making Si from $SiHCl_3$, obtaining 20% conversion efficiency (exceeding their goal). Battelle Columbus Laboratories reported on their tests of a process development unit (PDU) consisting of the four full-sized items needed for a 50-MT/yr EPSDU using their Si production process (zinc reduction of silicon tetrachloride). Difficulties prevented accomplishment of the planned eight-hour-duration runs, but operation for 30 minutes and 47 minutes was achieved in tests made at half the design flow rate before problems caused test terminations.

Hemlock Semiconductor Corp. continued development of its process based on chemical vapor deposition of Si from dichlorosilane (SiH_2Cl_2). Reactor problems that might have been expected because of the increased reactivity of SiH_2Cl_2, such as Si deposition on inside surfaces of the bell jar or production of Si fines, were not encountered. Construction of a PDU for SiH_2Cl_2 production was delayed because safety-related tests of SiH_2Cl_2 indicated a lower autoignition temperature than that cited in the literature, and the SiH_2Cl_2-air reaction was more violent than expected. Design was changed to reduce the danger.

In the area of impurity studies, Westinghouse R&D Center reported on the effects of impurities on Si ingot structural breakdown, lowered solar cell performance, and age-related performance decreases. A presentation by C.T. Sah Associates covered their development of a computer model based on the fundamental parameters of solar cells for determining the effects of impurities and defects on the performance of Si solar cells.

In the area of supporting studies, Lamar University presented results of its analysis of that portion of the Hemlock process involved in making SiH_2Cl_2, and JPL reviewed work that is being done in the Silicon Materials Research Laboratory.

POLYCRYSTALLINE SILICON

UNION CARBIDE CORP.

TECHNOLOGY

POLYCRYSTALLINE SILICON

REPORT DATE

09/25/80

APPROACH

HIGH-PURITY SILANE PRODUCTION FROM METALLURGICAL-GRADE SILICON; AND SILANE PYROLYSIS AND CONSOLIDATION TO FORM SEMICONDUCTOR-GRADE POLYCRYSTALLINE SILICON

CONTRACTOR

UNION CARBIDE CORPORATION

GOALS

- DEMONSTRATE PROCESS FEASIBILITY AND ENGINEERING PRACTICALITY.
- ESTABLISH TECHNOLOGY READINESS USING "EPSDU" SIZED TO 100 MT/YR.
- SILICON PRICE OF LESS THAN $14/KG FOR HIGH VOLUME PROCESS.
- DEFINE PROCESS ECONOMICS.

STATUS

DESIGN & ENGINEERING WORK ON THE EPSDU

- PURCHASE ORDERS ISSUED FOR MAJORITY OF EQUIPMENT
- SITE PREPARATION WORK COMPLETED
- CIVIL INSTALLATION WORK JUST UNDERWAY
- MECHANICAL & ELECTRICAL INSTALLATION DESIGN IN PROGRESS.

SILANE PYROLYSIS R & D

- SUCCESSFUL LONG-DURATION RUN DEMONSTRATED WITH THE FREE-SPACE PDU.
- NO UNDESIRABLE HARD DEPOSIT OBSERVED IN THE LINER OF THE PDU.
- FABRICATION OF Si POWDER MELTING/SHOTTING SYSTEM STARTED BY KAYEX.
- FABRICATION OF FLUID-BED PYROLYSIS SYSTEM 50% COMPLETE.
- SLIM-ROD AND EPITAXY REACTORS FOR EPSDU Q.C. OPERATIONAL.

Problems and Concerns

EPSDU ENGINEERING & CONSTRUCTION

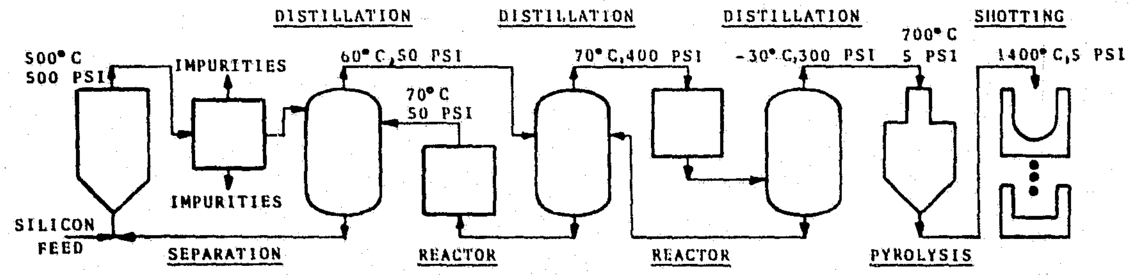
- COMPLETION OF P & I DIAGRAMS, MECHANICAL DESIGN, AND ELECTRICAL DESIGN MAY BE DELAYED. THE EPSDU START-UP DATE SHOULD NOT BE AFFECTED.
- MECHANICAL DESIGN HAS NOT BEEN THOROUGHLY EXAMINED FROM THE STANDPOINT OF PERSONNEL SAFETY AND OPERABILITY.

SILANE PYROLYSIS R & D

- RELIABLE Si POWDER REMOVAL FROM THE FREE-SPACE REACTOR HAS NOT BEEN DEMONSTRATED.
- Si POWDER PURITY HAS NOT BEEN ADEQUATELY MEASURED.
- LONG-DURATION OPERABILITY OF SILICON MELTING/SHOTTING SYSTEM NEEDS TO BE DEMONSTRATED.

Silane-Silicon Process

- ●METALLURGICAL SILICON IS PURIFIED BY CONVERTING IT TO VOLATILE CHLOROSILANE INTERMEDIATES
- ●CATALITIC REDISTRIBUTION YIELDS SILANE, WHICH IS PYROLIZED TO HIGH PURITY SILICON
- ●THE SILICON IS CONVERTED TO POLYCRYSTALLINE SHOT, READY FOR PROSESSING TO SHEET FORM, FOR SOLAR CELLS



REACTION

$Si+3SiCl_4+2H_2O \rightarrow 4HSiCl_3$ $2HSiCl_3 \rightarrow H_2SiCl_2+SiCl_4$ $3H_2SiCl_2 \rightarrow 2HSiCl_3+SiH_4$ $SiH_4 \rightarrow 2H_2+Si$

EPSDU Design and Engineering

1. ESDU - DESIGN/PROCUREMENT

PROCESS DESIGN:

- THE WASTE TREATMENT SYSTEM DESIGN WAS COMPLETED.
- THE PYROLYSIS PROCESS DESIGN HAS STARTED.

FACILITY DESIGN:

- THE FACILITY DESIGN WAS COMPLETED.
- THE GANTRY SCALE MODEL IS 70% COMPLETE.
- WORK ON PERSONNEL SAFETY AND PLANT OPERABILITY IS BEING ADDRESSED.

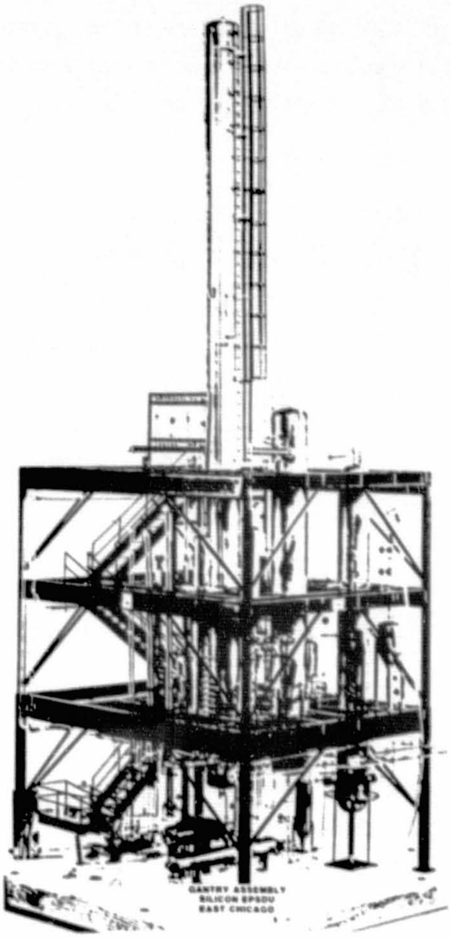
EQUIPMENT DESIGN & SPECIFICATION:

- WORK WAS COMPLETED ON ALL PROCESS EQUIPMENT.
- WORK ON INSTRUMENTATION COMPONENTS IS IN PROGRESS BUT IS BEHIND SCHEDULE.
- WORK ON ALL MISCELLANEOUS OR SPECIALTY ITEMS IS ALMOST COMPLETE.

INSTALLATION DESIGN SPECIFICATION, SUBCONTRACT:

- EQUIPMENT LAYOUT PROBLEMS HAVE BEEN IDENTIFIED AND ARE BEING RECTIFIED.
- MECHANICAL AND ELECTRICAL INSTALLATION DESIGN WORK IS ON SCHEDULE NOW, BUT IS EXPECTED TO SLIP BY AS MUCH AS TWO TO THREE MONTHS DUE TO A HIGHER THAN ANTICIPATED WORK LOAD IN THE COMING MONTHS.

Gantry Assembly, Silicon EPSDU, East Chicago



EPSDU Design and Engineering (Cont.)

II. EQUIPMENT FABRICATION/DELIVERY

- PURCHASE ORDERS WERE ISSUED FOR MOST OF THE EPSDU EQUIPMENT.
- MANY VENDOR DRAWINGS HAVE BEEN RECEIVED AND REVIEWED.
- ALL PIECES OF EQUIPMENT SHOULD BE FABRICATED AND DELIVERED ON SCHEDULE.

III. INSTALLATION & CHECKOUT

- SITE PREPARATION WAS COMPLETED.
- CIVIL INSTALLATION SUBCONTRACT WAS AWARDED AND WORK HAS BEGUN.

EPSDU Quality Control Laboratory

I. SLIM ROD REACTOR

PROGRAM PLAN:

- ESTABLISH INITIAL GROWTH PARAMETERS OF
    - SILANE FEED RATE
    - ROD TEMPERATURE
- GROW UNDOPED RODS TO ESTABLISH BASELINE PURITY LEVEL
- GROW PHOPHOROUS (PH_3) DOPED RODS OF SEVERAL CONTROLLED CONCENTRATIONS
- GROW BORON (B_2H_6) DOPED RODS OF SEVERAL CONTROLLED CONCENTRATIONS
- GROW RODS OF MIXED COMPOSITION
- ZONE REFINE ALL RODS (1 PASS ARGON, 6 PASSES IN VACUUM)
- MEASURE RESISTIVITY PROFILE

STATUS:

- WE ARE ABOUT TO START GROWING UNDOPED RODS TO ESTABLISH BASELINE PURITY LEVEL.

II. EPITAXY REACTOR

PROGRAM PLAN:

- ESTABLISH BASELINE GROWTH PARAMETERS
- DETERMINE BASELINE PURITY (RESISTIVITY) OF SILANE STANDARD
- GROW CONTROLLED DOPANT (B_2H_6 AND PH_3) FILMS INDIVIDUALLY AND MIXED
- DETERMINE IMPURITY CAPTURE EFFICIENCY AND SYSTEM MEMORY

STATUS:

- EPITAXIAL FILMS ARE BEING GROWN ON SILICON WAFERS FOR BASELINE PURITY DETERMINATION.

Silane Pyrolysis R&D

I. FREE-SPACE REACTOR

PURPOSE:

- TO MAKE A LONG-DURATION RUN AT A HIGH THROUGHPUT (5 LB/HR) WITHOUT HARD WALL-DEPOSIT FORMATION.
- TO DESIGN A DURABLE POWDER SCRAPER SYSTEM.
- TO DESIGN A RELIABLE POWDER WITHDRAWAL SYSTEM.
- TO DEMONSTRATE ADEQUATE POWDER PURITY.
- TO DESIGN A FSR FOR EPSDU.

STATUS:

- A LONG-DURATION RUN OF 12 HOURS WAS SUCCESSFUL. NO HARD WALL-DEPOSITS WERE OBSERVED.
- AN IMPROVED QUARTZ LINER HOLDER AND POWDER WITHDRAWAL SYSTEM ARE BEING INSTALLED.

PROBLEMS/CONCERNS:

- UP TO NOW, POWDER CANNOT BE WITHDRAWN WITHOUT BEING EXPOSED TO THE ATMOSPHERE.
- ACCEPTABLE POWDER PURITY HAS NOT BEEN PROVEN.

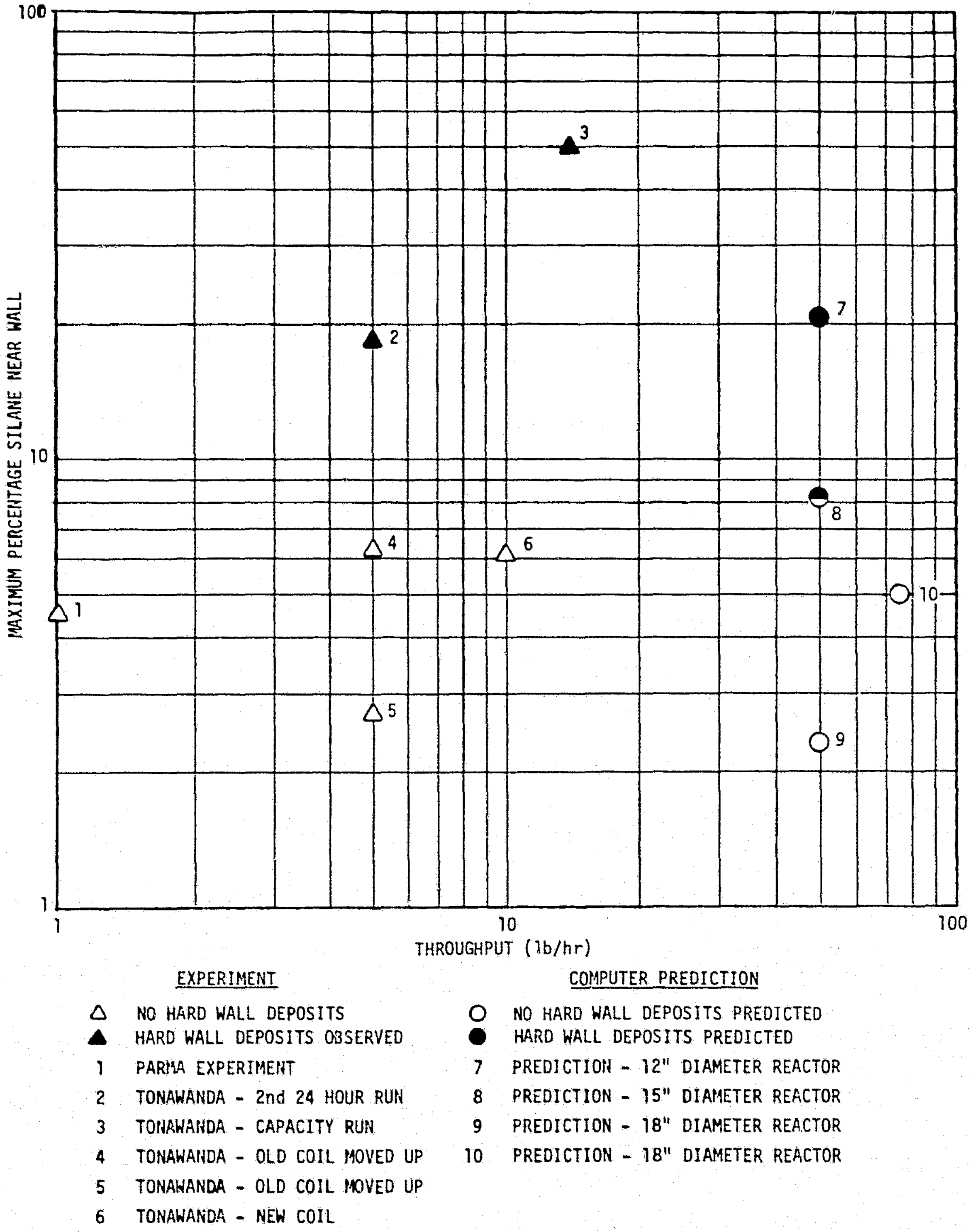
FSR Run Summaries

RUN NO.	DATE	DURATION	SILANE FLOW	MAX WALL TEMPERATURE	PRESSURE	HARD DEPOSITS	BULK DENSITY
8	7/ 9/80	2.0 hrs	2.3 kg/hr	870°C	138 Kpa	No	0.137 g/cm^3
9	7/22/80	2.0 hrs	2.3 kg/hr	940°C	138 Kpa	No	0.077 g/cm^3
10	7/25/80	2.25 hrs	2.4 kg/hr	915°C	276 Kpa	No	0.113 g/cm^3
11	8/14/80	2.0 hrs	3.1 kg/hr (6.8 lb/hr)	950°C(1)		No	0.085 gm/cm^3
12	8/18/80	3.1 hrs	2.8 kg/hr (6.1 lb/hr)	960°C		No	0.078 gm/cm^3
13	8/26/80	12.0 hrs	2.2 kg/hr (4.8 lb/hr)	950°C		No	0.036 gm/cm^3(2)

NOTES: (1) Run terminated when lower reactor wall temperature exceeded 1030°C

(2) Skimmed from top of powder bed in hopper. Average density was approximately 50% higher, or 0.054 gm/cm^3 (3.4 lb/ft^3). Average wall temperatures higher in run 13 than in run 12, although the maximum wall temperature was slightly lower.

Silane Concentration vs Hard Wall Deposit Formation



Silane Pyrolysis R&D (Cont.)

II. MELTING/SHOTTING SYSTEM

PURPOSE:

- TO DESIGN, FABRICATE, AND TEST A POWDER MELTING/ SHOTTING SYSTEM.
- TO DEMONSTRATE LONG-DURATION OPERABILITY.
- TO DEMONSTRATE PRODUCT PURITY.

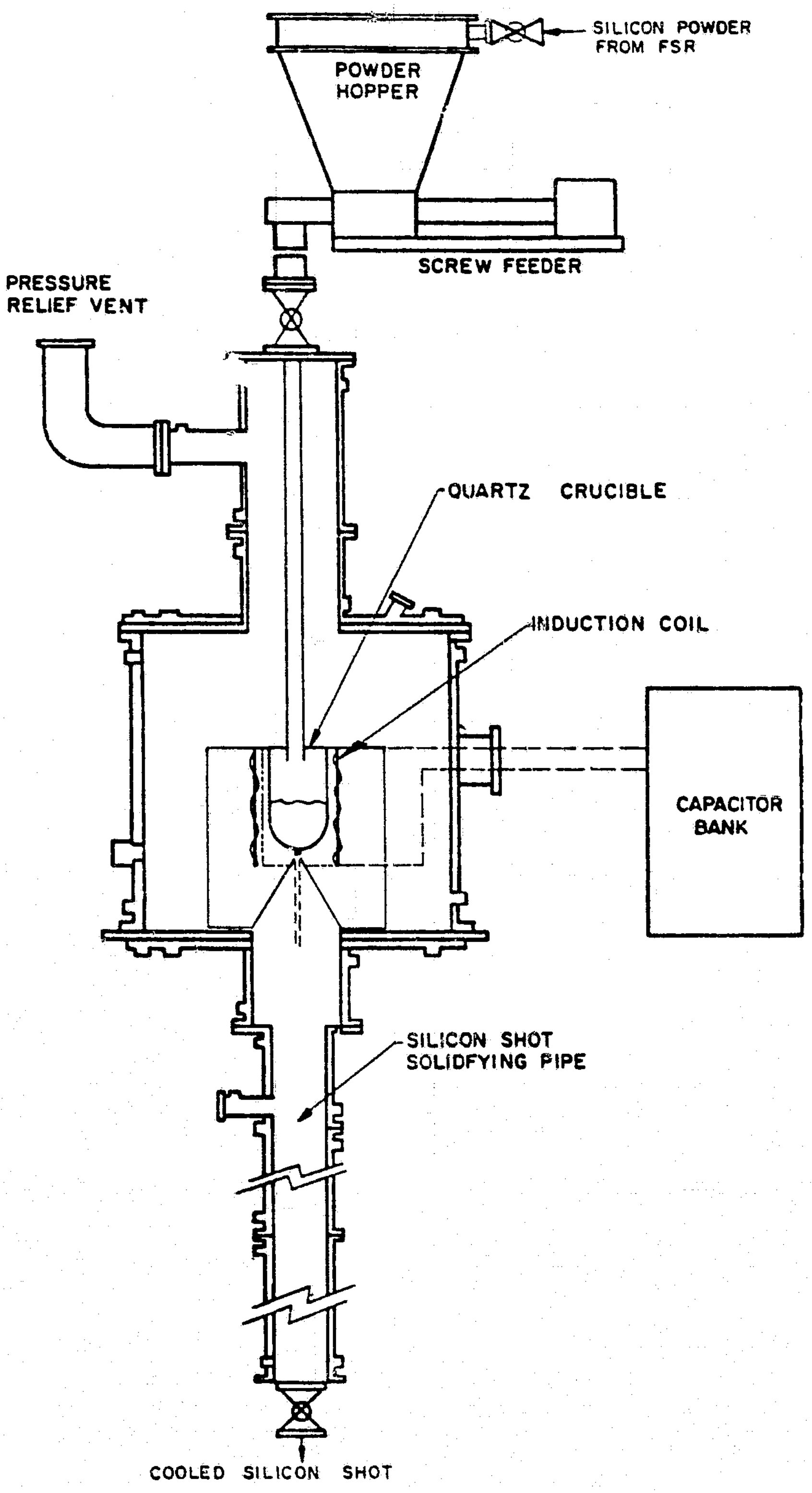
STATUS:

- BENCH-SCALE TESTS WERE COMPLETED AND WERE VALUABLE DURING DESIGN.
- THE DESIGN WAS COMPLETED AND FABRICATION HAS JUST BEGUN.

PROBLEMS/CONCERNS:

- LONG-DURATION OPERABILITY IS A CONCERN, PARTICULARLY IN THE AREAS OF POWDER FEEDING AND OF SHOTTING APERTURE STABILITY.

Silicon Powder Melting and Shotting System



Silane Pyrolysis R&D (Cont.)

III. FLUIDIZED-BED PYROLYSIS

PURPOSE:

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

STATUS:

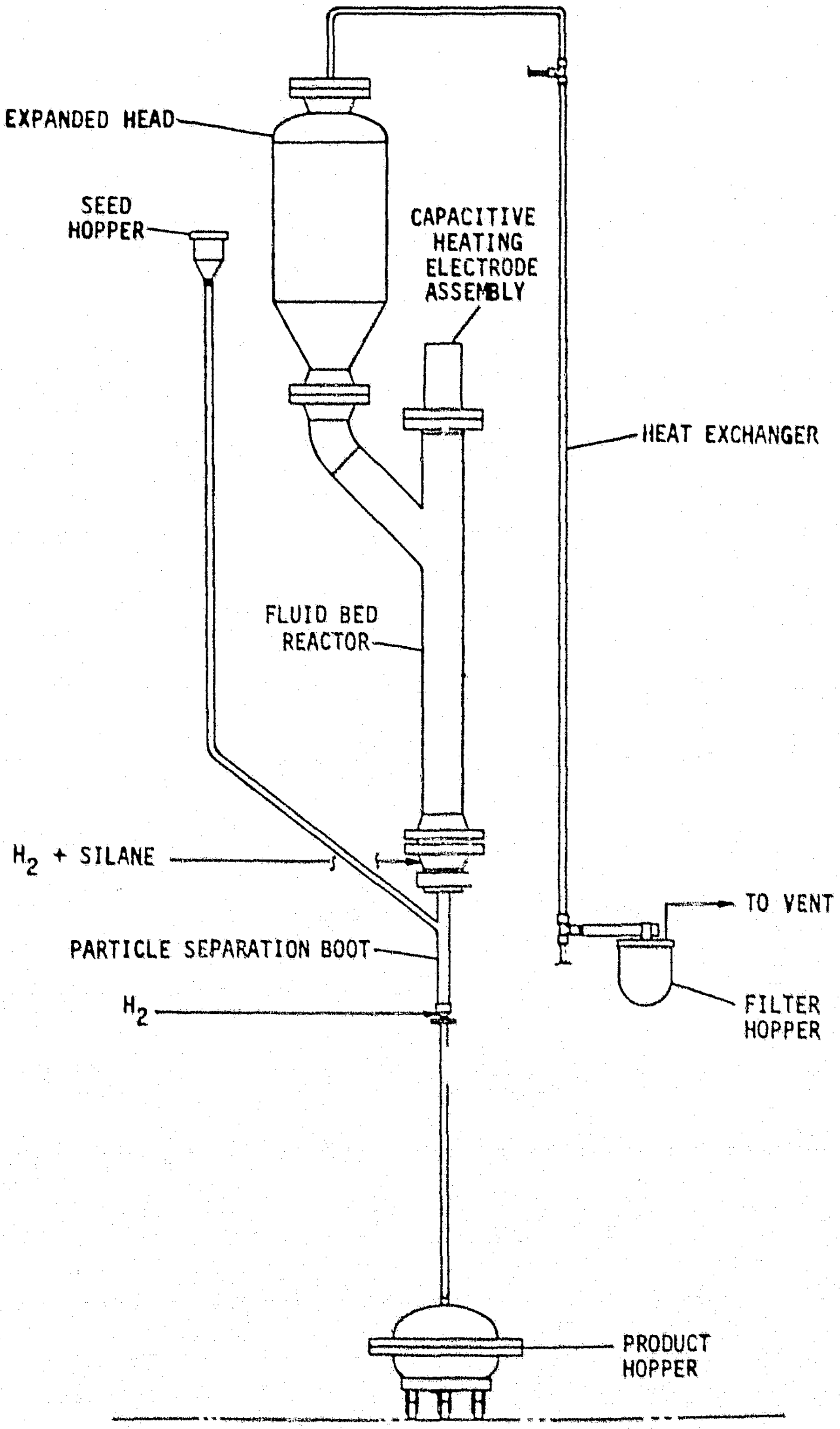
- FIXED-BED TESTS AND COLD FLUIDIZED-BED TESTS WERE COMPLETED FOR ESTABLISHING DESIGN BASIS.

- THE REACTOR SYSTEM DESIGN WAS COMPLETED AND FABRICATION IS UNDERWAY.

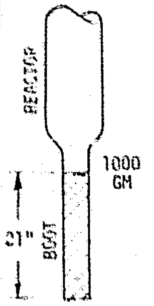
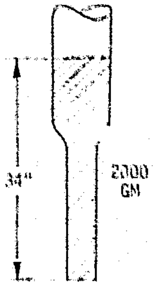
PROBLEMS/CONCERNS:

- SINTERING OF BED PARTICLES MAY PREVENT FLUIDIZATION.
- MORPHOLOGY OF DEPOSITS MAY BE POOR AND THE BED MIGHT PRODUCE EXCESSIVE FINES.

Fluid Bed Reactor Assembly



Summary of Particle Separation Tests in 1.5-in.-Dia Boot Bench Tester With Narrow Size Distribution

	BOOT U/U_{mf}	$\frac{X\ SAMPLE}{X\ BED}$ CONCENTRATION RATIO					
		323.5μ	273.5μ	213.5μ	163μ	127μ	96.5μ
	2	1.10	1.10	0.88	0.55	0.04	0.03
	3	1.10	1.12	0.88	0.50	0.03	0.02
	4	1.13	1.11	0.82	0.50	0.04	0.02
	2.9	1.12	1.15	0.77	0.80	0.11	0.02
	3.4	1.04	1.12	0.86	1.35	0.33	0.05
	5.5	1.07	1.11	0.81	1.35	0.39	0.08

258μ
BED MEAN
SIZE

Conclusion

EPSDU ENGINEERING

- THE PROCESS DESIGN AND FACILITY DESIGN HAVE BEEN COMPLETED.
- PURCHASE ORDERS FOR THE BULK OF THE EQUIPMENT HAVE BEEN PLACED.
- THE P & I, MECHANICAL INSTALLATION DESIGN, AND ELECTRICAL INSTALLATION DESIGN ARE BEHIND SCHEDULE.
- THE SITE PREPARATION WORK WAS COMPLETED AS SCHEDULED.
- THE CIVIL INSTALLATION WORK HAS BEGUN ON SCHEDULE.
- START-UP IN THE FOURTH QUARTER OF 1981 IS STILL VALID.

SILANE PYROLYSIS R & D

- A LONG-DURATION RUN WITH A FREE-SPACE REACTOR PDU WAS SUCCESSFUL.
- THE PDU IS BEING MODIFIED BY INSTALLING A NEW QUARTZ LINER HOLDER AND A NEW POWDER WITHDRAWAL SYSTEM.
- THE POWDER MELTER/SHOTTER SYSTEM WAS DESIGNED AND IS BEING FABRICATED. THIS WORK IS BEING PERFORMED BY KAYEX.

POLYCRYSTALLINE SILICON

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TECHNOLOGY

POLYCRYSTALLINE SILICON

APPROACH

HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE FOR PRODUCING SILICON

CONTRACTOR

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

GOALS

TO SUPPORT THE UNION CARBIDE SILANE-TO-SILICON PROCESS BY CONDUCTING EXPERIMENTAL AND THEORETICAL STUDIES,

- ESTABLISH FUNDAMENTAL UNDERSTANDING OF HYDROCHLORINATION OF METALLURGICAL GRADE SILICON IN TERMS OF REACTION KINETICS AND ROLE OF CATALYST
- OPTIMIZE THE REACTION CONDITION FOR THE HYDROCHLORINATION STEP

REPORT DATE

SEPTEMBER 25, 1980 16TH PIM

STATUS

I REACTION KINETICS MEASUREMENT
- TEMPERATURE
- PRESSURE
- $H_2/SiCl_4$ FEED RATIO
- COPPER CATALYST CONCENTRATION
  Cu SIGNIFICANTLY INCREASES REACTION RATE

II PARTICLE SIZE DISTRIBUTION
- REACTION RATE INDEPENDENT OF SILICON METAL PARTICLE SIZES

III IMPURITIES STUDY
- VERY SLOW REACTION RATE WITH HIGH PURITY, ELECTRONIC GRADE Si
- IMPURITIES IN M.G. SILICON METAL ACT LIKE A CATALYST

IV MASS LIFE STUDIES
- IN PROGRESS

Hydrochlorination of $SiCl_4$ and mg-Si to $SiHCl_3$

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

REACTION TEMPERATURE	400°-550° C
REACTOR PRESSURE	300 AND 500 PSIG
$H_2/SiCl_4$ FEED RATIO	1.0, 2.0 AND 2.8
Si PARTICLE SIZE	32 x 65, 65 x 150, 150 x 400 MESH
COPPER CATALYST	2% AND 5%

Hydrogenation of $SiCl_4$ at 500 psig, 450°C and $H_2/SiCl_4$ Ratio of 2.8

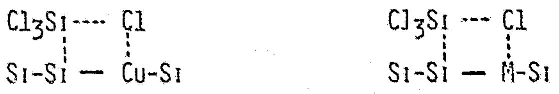
Experiment No.	Hydrogren Feedrate SCCM(1)	Residence Time Second	Reaction SiH_2Cl_2	Product Composition Mole% $SiHCl_3$	$SiCl_4$
1	2920	20.7	< 0.05	12.54	87.48
2	2045	29.6	0.064	15.87	84.06
3	1675	36.1	0.140	17.60	82.29
4	1530	42.1	0.232	18.99	80.89
5	1215	53.0	0.393	21.15	78.46
6	1020	63.1	0.651	22.75	76.60
7	477	135	0.969	29.83	69.20
8	235	257	1.224	33.38	65.40

(1) SCCM Standard C.C. per minute

Metallic Impurities in mg-Si

Fe - 0.5-0.9%
Al - 0.3-0.6%
Mn - 0.06%
Ca - 0.05%
Cu - 0.01%
Ni - 0.01%
Cr - 0.01%
Ti - 0.01%

Plausible Reaction Mechanism



- IN COMMON: BOTH Cu AND IMPURITIES M CAUSE CRYSTAL DEFECTS
- DIFFERENCE: Fe AND Al ACCOUNTS FOR THE BULK OF IMPURITIES IN M.G. SILICON
  Fe AND Al ARE CONVERTED TO $FeCl_3$ AND $AlCl_3$
  THE CONSUMPTION OF Cl MAY CAUSE THE EQUILIBRIUM TO SHIFT FAVORABLY TOWARD SiH

Summary of Progress

I COPPER CATALYST STUDIES (COMPLETED)

- 2% CuCl IS AS EFFECTIVE AS 5% CuCl OR 5% CEMENT COPPER
- COPPER CATALYST PROVIDES A MEANS TO RECYCLE OFF-SPEC. SOLAR Si TO HYDROGENATION REACTOR

II PARTICLE SIZE DISTRIBUTION (COMPLETED)

- REACTION RATE IS INDEPENDENT OF Si PARTICLE SIZE
- OUTPUT OF A GIVEN REACTOR SIZE CAN BE CONVENIENTLY INCREASED BY INCREASING Si PARTICLE SIZE TO COMPENSATE FOR INCREASE OF LINEAR GAS VELOCITY

III IMPURITIES STUDIES (COMPLETED)

- IMPURITIES ACT LIKE CATALYST

IV MASS LIFE STUDIES (IN PROGRESS)

- NO SIGNIFICANT CHANGE IN REACTION RATE AFTER 80 HOURS

GASEOUS MELT REPLENISHMENT

ENERGY MATERIALS CORP.

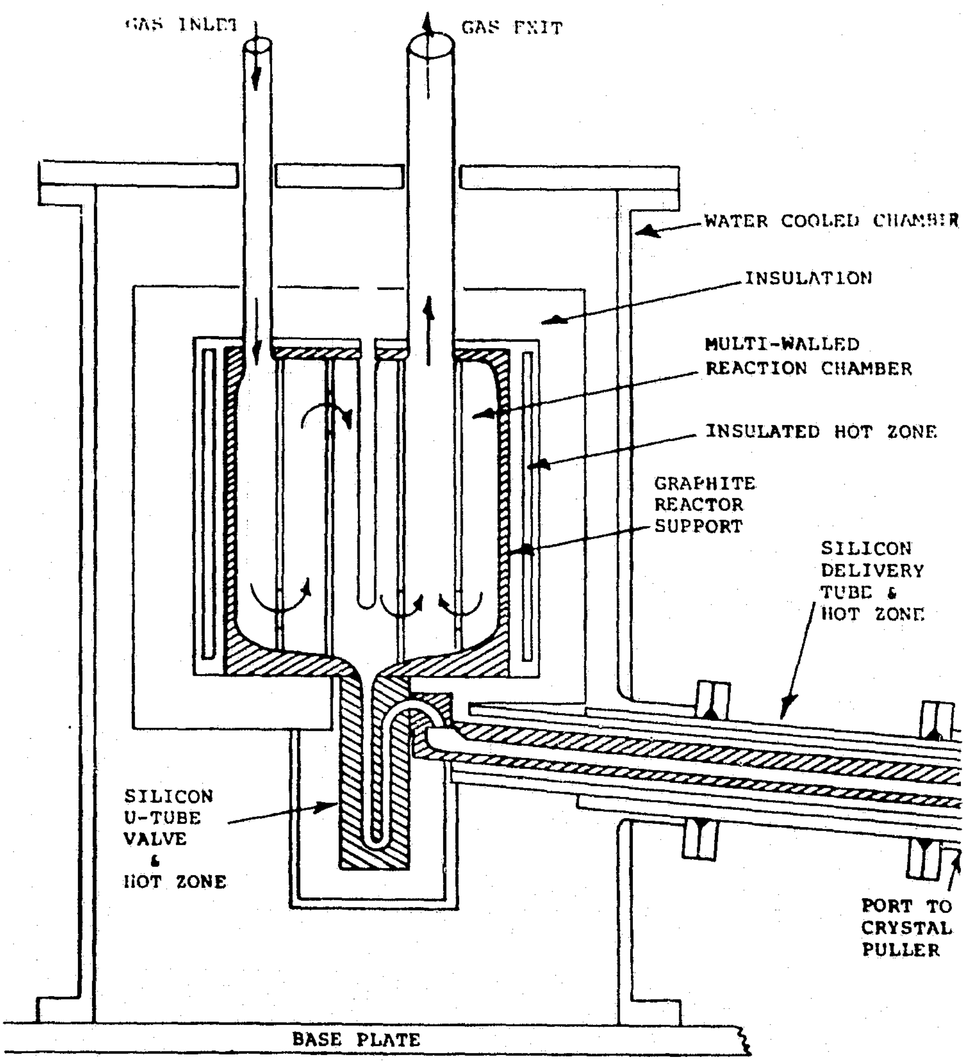
Goals

- 18% CONVERSION EFFICIENCY (TCS)
- 500 GM/HR PRODUCTION RATE
- 24 AND 96 HOUR OPERATION
- MOLTEN SILICON TRANSFER TUBE DEMONSTRATION

Demonstrated Results

- OPERATION OF CLOSED QUARTZ REACTION VESSEL WITH CYCLING OF U-TUBE VALVE.
- 20% CONVERSION EFFICIENCY (SINGLE PASS)
- 310 GM/HR PRODUCTION RATE
- 300 MICRON/HR DEPOSITION RATE
- 35 KWHR/KG ELECTRICAL ENERGY CONSUMPTION

Poly Reaction Chamber



GMR Reactor Test Data

RUN	TOTAL SURFACE AREA (IN.)^2	TOTAL VOLUME (IN.)	EFFECTIVE TEMPERATURE (^{o}K)	TOTAL GAS FLOW (SCFH)	MOLE % TCS	Cl/H ATOMIC RATIO
5	355	280	1100	225	1.5	0.02
6	355	280	900	170	5.0	0.08
7	355	280	975	255	6.25	0.10
8	428	280	1073	170,216 270	17.5	0.32
9	500	280	1000	125,115	19.8,25	0.37,0.50
10	500	280	1050	100	25	0.4
11	1560	1000	1200	500	10	0.17

GMR Run Data

RUN	TOTAL RESIDENCE TIME (SEC)	DEPOSITION RESIDENCE TIME (SEC)	HOURS OF DEPOSITION	% OF SURFACE AREA USED
5	0.55	0.19	5	33
6	1.04	0.63	8.75	62
7	0.64	0.61	8.5	96
8	0.88 0.69,0.55	0.88 0.69,0.55	4.49	100
9	1.27,1.38	0.75,0.83	9.1	30
10	1.52	0.95	9.5	69
11	0.95	0.95	3.5	100

GMR Reactor Performance Data

RUN	GRAMS SILICON PRODUCED	AVERAGE PRODUCTION RATE (GM/HR)	DEPOSITION RATE $GM/CM^2/HR$	DEPOSITION RATE (μ/HR)	AVERAGE CONVERSION %	POWER KW-HR KG
5	150	70.0	.039	170	20	410
6	293	33.5	.024	100	13	352
7	467	85.0	.039	166	18	145
8	1050	234	.085	354	20	56,45,35
9	1030	100,106	.040	166,176	11	115,108
10	1100	115	.051	223	15.3	98
11	1100	312	.031	133	17	43

GMR Reactor Conversion Efficiency

RUN	Cl/H	TEMP., °K	THEORETICAL CONVERSION %	ACTUAL CONVERSION %	ACT./THEOR.
5	.02	1100	38	20	.53
6	.08	900	17	13	.76
7	.1	975	19	18	.95
8	.32	1075	21	20	.95
9	.43	1000	19	11	.58
10	.4	1050	20	15.3	.76
11	.17	1200	27	17	.63

Prototype System Problem Areas

- OUTLET TUBE PLUGGING
- HCl IN RECYCLED H_2
- ~1250°C LIMIT BY QUARTZ ETCHING

Areas for Further Study

- REACTOR OPTIMIZATION
- REACTOR LIFETIME
- FEED SYSTEM OPTIMIZATION
- OUTLET DESIGN

POLYCRYSTALLINE SILICON

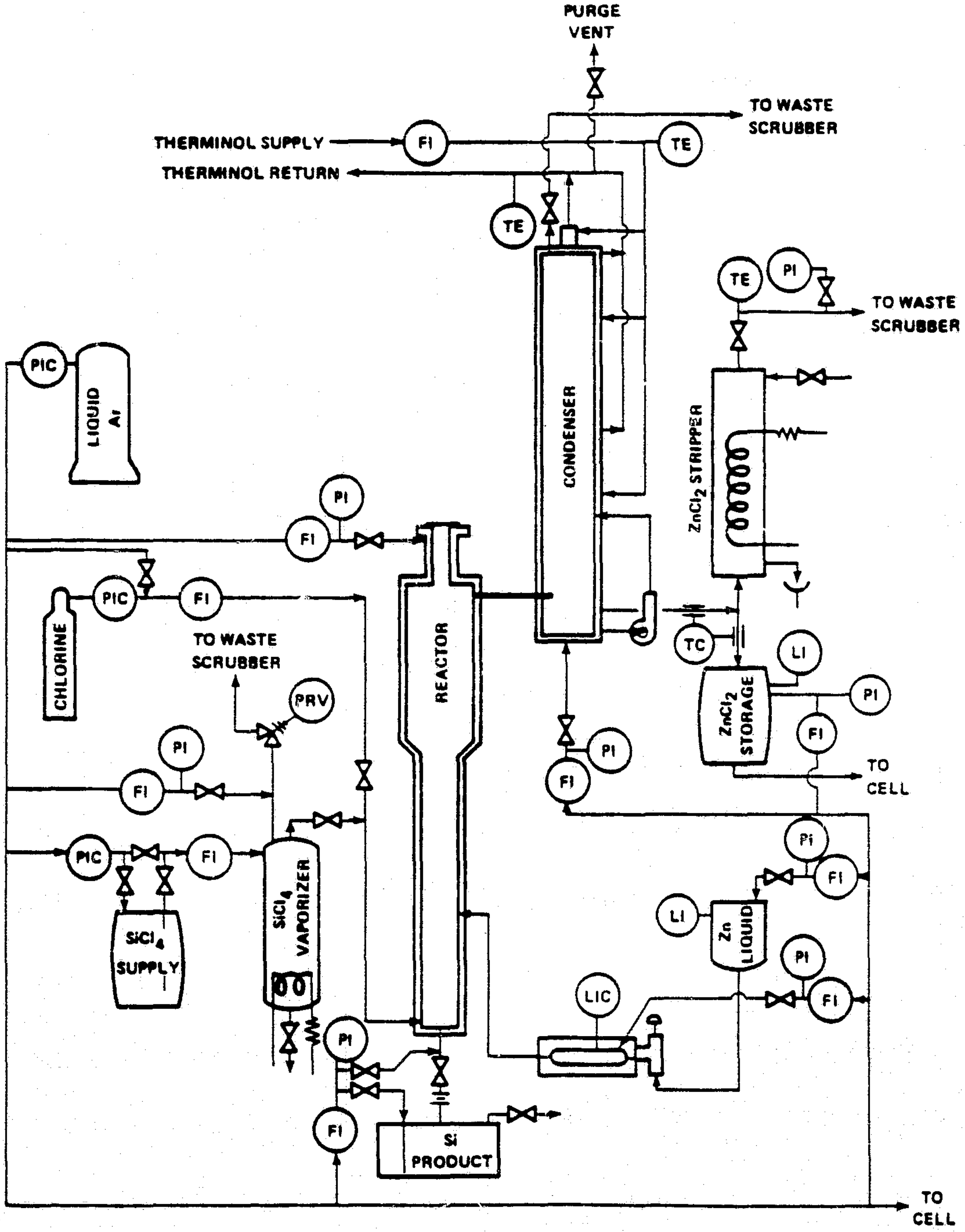
BATTELLE COLUMBUS LABORATORIES

TECHNOLOGY TASK 1: POLYCRYSTALLINE SILICON	**REPORT DATE** SEPTEMBER 23, 1980
APPROACH PREPARATION OF SILICON BY ZINC REDUCTION OF SILICON TETRACHLORIDE **CONTRACTOR** BATTELLE COLUMBUS LABORATORIES	**STATUS** • ECONOMIC ANALYSES INDICATE COST WITHIN \$14/kg GOAL. • PROCESS FEASIBILITY DEMONSTRATED ON LABORATORY SCALE. • WEB DENDRITE GROWN FROM FREE-FLOWING GRANULAR PRODUCT YIELDED 12.8% AMI CELLS. • PROCESS DEVELOPMENT UNIT (25MT/YEAR, BATCH-WISE OPERATION) BEING OPERATED TO OBTAIN ENGINEERING INFORMATION. • OPTIONS DEFINED FOR HANDLING RESIDUAL ZINC IMPURITY.
GOALS • DEMONSTRATE PROCESS FEASIBILITY • ESTABLISH TECHNICAL READINESS BY OPERATION OF EPSDU SIZED TO 50MT/YR • SILICON PRICE OF LESS THAN \$14/kg FOR HIGH-VOLUME PROCESS • DEFINE PROCESS ECONOMICS	

Summary of Program Since 15th PIM

- PDU
  - SPECIFIC OBJECTIVE OF CURRENT PHASE
  - STATUS
    TWO <1-HOUR RUNS
    DIFFICULTIES—MECHANICAL OR MATERIALS
    NO TECHNICAL DIFFICULTIES IDENTIFIED
    VALUABLE OPERATION AND DESIGN INFORMATION GAINED
- SUPPORT STUDIES
  TWO AREAS
- FUTURE PLANS

PDU Flow Diagram, Reaction Section



Problems and Solutions

ZINC FEED SYSTEM OPERATION

- LACK OF COUPLING, PLASMA FORMATION IN VAPORIZER
  + SUBSTITUTED ALTERNATE DESIGN VAPORIZER AND FEEDER
- FRAGILITY OF QUARTZ SYSTEM
  + INCREASED MECHANICAL SUPPORT
- LIQUID ZINC LEAKAGE AT MOVING, DISSIMILAR MATERIAL JOINTS
  + MODIFIED PACKING CONSTRUCTION
  + IMPROVED MANIPULATION OF VALVE PACKING

REACTOR OPERATION

- ZN VAPOR LEAKAGE AT REACTOR INLET
  + REVISED SEAL GLAND DESIGN
- GRAPHITE NOZZLE LINER BREAKAGE
  + REPLACED STIFF EXPANSION BELLOWS
  + INSTALLED FLANGE MOTION CONTROL APPARATUS
- INTERNAL CORROSION OF REACTOR SHELL BY $ZnCl_2$
  + REVISED PDU START-UP PROCEDURE
  + INCREASED SHELL PURGE FLOW CAPACITY
  + REPLACED PORTIONS OF SHELL
- DISTORTION OF STAINLESS STEEL SHELL
  + MODIFIED EXTERNAL SUPPORTS

Problems and Solutions (Cont.)

CONDENSER OPERATION

- PLUGGING FROM DUST FORMED IN CONDENSER, STRIPPER
  - \+ HEAT TRACED EXHAUST GAS PIPING
  - \+ MINIMIZED PRE-RUN PURGE GAS FLOWS
- MARGINAL PRE-HEATING OF UPPER CONDENSER
  - \+ ADDED HEATING CAPACITY TO CONDENSER TOP
  - \+ DECREASED HEAT LOSS FROM CONDENSER TOP
  - \+ INCREASED INSTRUMENTATION OF CONDENSER TOP
- ZINC CHLORIDE RECIRCULATION
  - \+ OPERATE WITHOUT RECIRCULATION
  - \+ INSTALLED THROTTLING VALVE TO REDUCE $ZnCl_2$ FLOW RATE
- PLUGGING OF CONDENSER TUBES
  - \+ BACK-CHLORINATE CONDENSER
  - \+ ZINC CHLORIDE FLUSH

Design Changes Indicated

FLUIDIZED BED REACTOR

- RELOCATE TET INLET PORT
- ENLARGE AND RELOCATE ZINC INLET PORT
- STRENGTHEN-GRAPHITE NOZZLE, FLANGE CONNECTIONS
- IMPROVE SEALS AT REACTOR SHELL PENETRATIONS

CONDENSER

- INCREASE SUMP TANK CAPACITY
- ENLARGE SUMP TANK INLET NOZZLE
- INCREASE TEMPERATURE MONITORING CAPABILITY
- PROVIDE INCREASED START-UP HEATING CAPABILITY
- ADD CAPABILITY TO DRAIN CONDENSER RESERVOIR
- INCREASE PASS PLATE DEPTH IN CONDENSER BOTTOM RESERVOIR
- PROVIDE LIQUID LEVEL MONITORING IN SUMP TANK

Support Activities

- RESIDUAL ZINC IN SILICON
- DIRECT COUPLED ZINC FEED SYSTEM

Options for Dealing With Residual Zinc

- Vacuum- or inert-atmosphere heat treatment
  - Probably days at 1100 C (~maximum to avoid sintering)
- Melting
  - Zn evolution almost instantaneous
  - Vapor pressure of Zn - 33 atm at 2420 C melting point of silicon
- Treat as part of the SiO evolution problem in sheet-forming process
  - For molten silicon in contact 4 hours with SiO_2 crucible 18-cm dia by 18-cm Si depth:

ppmw Zinc in Si	Ratio of volume of evolved zinc to volume of evolved SiO
100	0.048
200	0.096
500	0.24
1000	0.48

  - Evaporation of zinc dust falling back into melt should preclude detrimental effect on crystal growth

Residual Zinc in Silicon Granules

CONDITION: Highly segregated, up to 2.5 w/o in $1 \mu m^3$ volume.
(2-phase, solubility = 0.5 ppmw at 1100 C)

RANGE: 100 to 3000 ppmw in deposited silicon depending upon reactor geometry and run conditions. Should be ≤100 ppmw in well-run plant.

ORIGIN: Apparently result of occlusion of mist droplets from zinc vaporizer.

CORRECTION: In-Process: eliminate Zn mist (or raise fluidized bed temperature at cost of decreased efficiency?)

Post-Process: Vacuum or atmosphere heat treatment

POLYCRYSTALLINE SILICON

HEMLOCK SEMICONDUCTOR CORP.

TECHNOLOGY

POLYCRYSTALLINE SILICON

REPORT DATE

APPROACH

CHEMICAL VAPOR DEPOSITION OF SILICON FROM DICHLOROSILANE (DCS)

CONTRACTOR

HEMLOCK SEMICONDUCTOR CORPORATION

GOALS

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

STATUS

- SILICON GROWN FROM DCS IN EXPERIMENTAL REACTOR WITH
  - 2X TCS DEPOSITION RATE
  - SUBSTANTIALLY LOWER POWER CONSUMPTION
  - DIAMETER UP TO 53 MM
  - GOOD SURFACE QUALITY
  - FEW OPERATIONAL PROBLEMS
- REACTOR OPTIMIZATION PROGRAM COMPLETE
- TCS REDISTRIBUTION KINETICS ANALYZED
- PDU CONSTRUCTION SUSPENDED PENDING SAFETY-RELATED DATA
- PRELIMINARY ECONOMIC ANALYSIS COMPLETED

Dichlorosilane Process

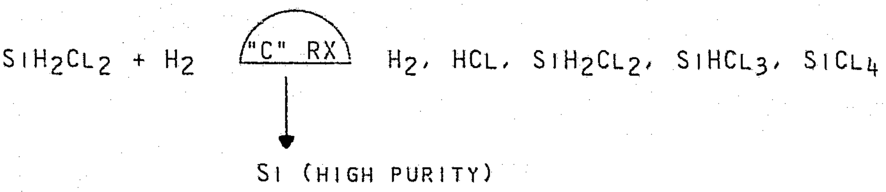
TRICHLOROSILANE REGENERATION

$$SiCl_4 + H_2 + Si\ (M.G.) \xrightarrow{FBR} SiHCl_3\ (+H_2,\ SiCl_4)$$

DICHLOROSILANE FORMATION

$$2\ SiHCl_3 \xrightleftharpoons{\text{BASIC CATALYST}} SiH_2Cl_2 + SiCl_4$$

SILICON GENERATION



$$SiH_2Cl_2 + H_2 \quad \text{"C" RX} \quad H_2,\ HCl,\ SiH_2Cl_2,\ SiHCl_3,\ SiCl_4$$

SI (HIGH PURITY)

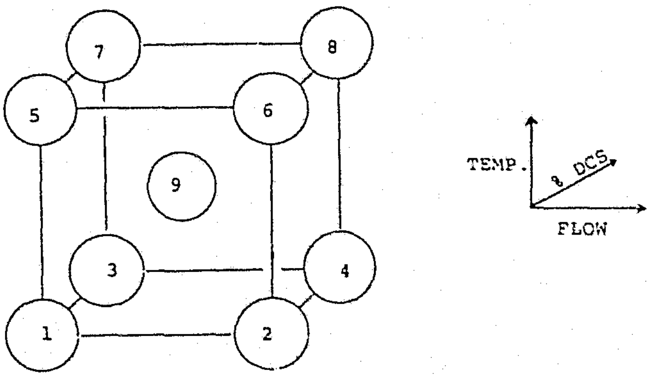
Dichlorosilane Experimental Reactor Milestones

DEPOSITION RATE	1.67 G/HR/CM	
CONVERSION	54.1 MOLE %	
POWER CONSUMPTION	89.1 KWH/KG	
PRODUCT DIAMETER	53 MM	(RECORD FOR REACTOR)

Dichlorosilane Experimental Design

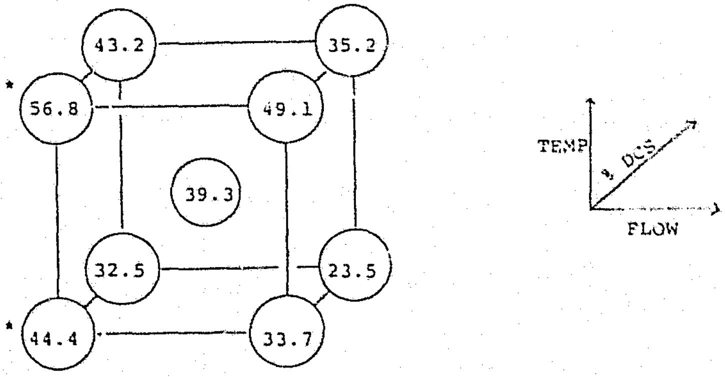
A. CONDITIONS AND RUN NUMBERS
B. CONVERSION VALUES (MOLE %)

A.



	LOW VALUE	HIGH VALUE
FLOW	90 SCFH	180 SCFH
TEMP.	1020°C	1120°C
% DCS	6	12

B.



* Extrapolated

Correlation of System Response With Variables in Experimental Design

POWER CONSUMPTION (KWH/KG) $= -98.15 + 0.1237A + 33.31B + 0.3402C + 0.0097D - 0.0006E - 0.0376F$

CONVERSION EFFICIENCY (MOLE %) $= -76.45 - 0.3513A + 2.854B + 0.1428C + 0.0027D + 0.0002E - 0.0050F$

SILICON DEPOSITION $(\mathrm{GHR}^{-1}\mathrm{CM}^{-1})$ $= 3.815 - 0.0300A - 0.2870B - 0.0032C + 0.0004D + 0.00003E + 0.0003F$

WHERE

A = FLOW (SCFH)

B = % DCS (MOLE)

C = TEMPERAURE (^{0}C)

D = FLOW x % DCS

E = FLOW x TEMPERATURE

F = % DCS x TEMPERATURE

EXAMPLE:

AT FLOW = 100 SCFH
MOLE DCS % = 8
TEMP. = 1100 ^{0}C

CONVERSION = 48.1%

Solar Cell Evaluation

POLYCRYSTALLINE SILICON RODS GROWN TO 37 MM DIAMETER EXCLUSIVELY WITH DCS (RUN 394-057)

SINGLE CRYSTAL CZ INGOT PULLED FROM MELT

650 G. SAMPLE SENT TO WESTINGHOUSE FOR SOLAR CELL EVALUATION

PRELIMINARY RESULTS:

12-14% EFFICIENCY (AM1)

Liquid-Phase Rearranger Data Summary

RUNS CONDUCTED WITH VARIABLE LENGTH BEDS AT 78°C
VOID VOLUME OF .5 ASSUMED

- DIFFUSION EFFECTS ARE IMPORTANT AT FLOW VELOCITIES <25-30 FT/HR
- THE LIMITING SECOND RATE CONSTANT AT HIGH VELOCITIES IS .20 MIN^{-1}
- YIELDS OF >6% DCS WERE OBSERVED WITH RESIDENCE TIMES OF 30 SECONDS

Experimental Results With Dowex Resin Redistribution Catalyst

CATALYST TRANSPORT EVALUATION

A PARTIALLY EQUILIBRATED (8% DCS, 9% STC) SAMPLE WAS STORED FOR 162 HRS AT ROOM TEMPERATURE, THEN FOR 26 HRS AT 62 °C. NO CHANGE IN COMPOSITION WAS OBSERVED.

MIXED TCS/STC REARRANGER FEED

MOLE % FEED	MCS	DCS	MCS/DCS
100% TCS	0.37	10.8	0.033
80% TCS/20% STC	0.10	5.0	0.021

CATALYST LIFETIME DATA

NO LOSS IN ACTIVITY WAS OBSERVED AFTER 4000 G TCS WAS PASSED THROUGH CA. 50 G DOWEX RESIN

PDU Status

- DESIGN, LOCATION SELECTED
- CONSTRUCTION SUSPENDED PENDING RECEIPT OF SAFETY-RELATED DATA FROM HAZARDS RESEARCH

Hazards Research Corp. Data for Dichlorosilane

PROPERTY	EXPT'L VALUE	LITERATURE VALUE
AUTOIGNITION TEMP. (10 L. SPHERE)	55-60°C	100°C
EXPLOSION SEVERITY (10 L. SPHERE) DCS/AIR	$(PSI/SEC)_{MAX}$ OF 120,000 @ 20% IN AIR	NONE (H_2/AIR) 33,000
HYDROLYSIS	COPIUS EVOLUTION OF HCL; NO IGNITION	IGNITION MAY BE POSSIBLE
EXPLOSIVE OUTPUT (5 FT. CUBE, WITH PLASTIC SHEET FACES)	(1) UNEXPECTED IGNITION ON FLOW TERMINATION (2) SEVERITY > PROPYLENE/AIR; NO DETONATION OBSERVED	NONE
EXPL. SEVERITY (10% DCS/90% H_2)/AIR	55,000 $(PSI/SEC)_{MAX}$	NONE

Summary of Hazards Research Corp. Dichlorosilane Experiments

1. VERY LOW IGNITION REQUIREMENTS
2. VERY BROAD FLAMMABILITY RANGE
3. DETONATION CAN OCCUR WITH CONFINEMENT

   FEASIBLE IN UNCONFINED VAPOR
4. HYDROLYTIC BEHAVIOR PROBABLY NOT OF SPECIAL CONCERN
5. COMBUSTION BEHAVIOR UNPREDICTABLE
6. DILUTION WITH H_2 ATTRACTIVE

PDU Revised Design Features

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

EPSDU Objectives

- PRODUCE DICHLOROSILANE FROM REDISTRIBUTION OF TRICHLOROSILANE
- PURIFY DICHLOROSILANE
- PRODUCE HIGH PURITY POLYCRYSTALLINE SILICON FROM DICHLOROSILANE
- RECOVER REACTOR VENT PRODUCTS
- OPERATE ON SCALE OF 100-200 TONNE SILICON/YR.

EPSDU Status

- MATERIAL, ENERGY BALANCES COMPLETED
- PLANT AND REACTOR LOCATION SELECTION UNDERWAY
- REQUIREMENTS FOR INTEGRATION WITH EXISTING RECOVERY SYSTEM BEING DEVELOPED

Problems and Concerns

- SAFETY-RELATED DESIGN AND LOCATION CONSIDERATION FOR PDU
- REACTOR VENT DEPOSITION IN RUN 394-067

CHEMICAL ENGINEERING AND ECONOMIC ANALYSES OF POLYSILICON PROCESSES

LAMAR UNIVERSITY

TECHNOLOGY

CHEMICAL ENGINEERING AND ECONOMIC ANALYSES OF POLYSILICON PROCESSES

APPROACH

PERFORM ANALYSES IN AREAS OF PROCESS SYSTEM PROPERTIES, CHEMICAL ENGINEERING, AND ECONOMICS FOR PROCESSES BEING DEVELOPED FOR THE HIGH VOLUME, LOW COST PRODUCTION OF POLYSILICON.

CONTRACTOR

LAMAR UNIVERSITY

GOALS

1. PERFORM ANALYSIS OF HEMLOCK SEMICONDUCTOR PROCESS
    - -DCS PRODUCTION AS SILICON SOURCE MATERIAL (1980)
    - -POLYSILICON PRODUCTION FROM DICHLOROSILANE (1981)
2. PREPARE FINAL REPORT
    - -PROPERTIES ANALYSIS (1980)
    - -CHEM ENG ANALYSIS (1980)
    - -ECONOMIC ANALYSIS (1980)
3. PERFORM ADDITIONAL ANALYSES (1980-85)
    - -UNION CARBIDE PROCESS UPDATE
    - -BATTELLE PROCESS UPDATE
    - -OTHERS

REPORT DATE

SEPTEMBER, 1980

STATUS

1. COMPLETED INITIAL ANALYSIS OF SIEMENS PROCESS -1977
2. COMPLETED INITIAL ANALYSIS OF UNION CARBIDE PROCESS -1978
3. COMPLETED ANALYSIS OF BATTELLE PROCESS -1979
4. ANALYSIS OF HEMLOCK SEMICONDUCTOR PROCESS BEING PERFORMED -1980
    - -DCS PRODUCTION (COMPLETED)
    - -POLYSILICON PRODUCTION (PLANNED)
5. RESULTS FOR DICHLOROSILANE PRODUCTION (DCS PROCESS - CASE A)

RATE OF RETURN	SALES PRICE (1980 DOLLARS)
0% DCF	1.29$/kg of DCS
10% DCF	1.41$/kg of DCS
20% DCF	1.54$/kg of DCS

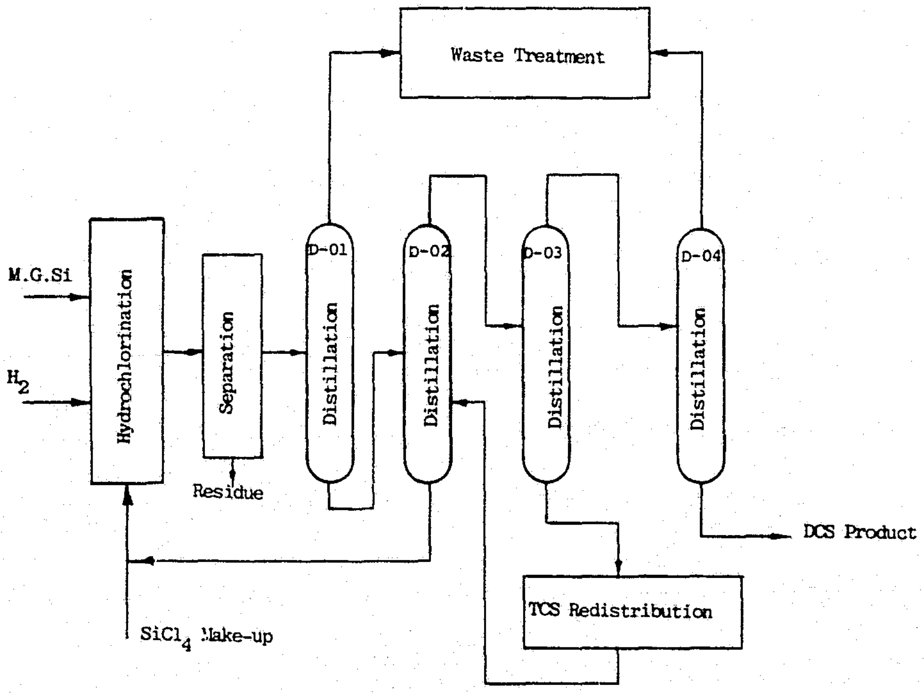
Hemlock Semiconductor Corp. Program

- CHEMICAL ENGINEERING ANALYSIS
    - BASED ON INITIAL DCS PRODUCTION (DICHLOROSILANE)
    - UTILIZATION OF DCS AS SILICON SOURCE MATERIAL IN HSC PROGRAM (HEMLOCK SEMICONDUCTOR CORP.)
    - DICHLOROSILANE PRODUCTION VIA DCS PROCESS - CASE A
- ECONOMIC ANALYSIS
    - BASED ON CHEMICAL ENGINEERING ANALYSIS RESULTS FOR DCS PROCESS - CASE A
    - PROVIDE ECONOMICS (PRODUCT COST, SALES PRICE) OF DICHLOROSILANE AS SILICON SOURCE MATERIAL

Chemical Engineering Analysis: Progress and Status

		PRIOR	CURRENT
1.	BASE CASE CONDITIONS	35%	100%
2.	REACTION CHEMISTRY	30%	100%
3.	PROCESS FLOW DIAGRAM	20%	100%
4.	MATERIAL BALANCE	5%	100%
5.	ENERGY BALANCE	5%	100%
6.	PROPERTY DATA	2%	100%
7.	EQUIPMENT DESIGN	0%	100%
8.	MAJOR EQUIPMENT LIST	0%	100%
9.	PRODUCTION LABOR	0%	100%
10.	FORWARD FOR ECONOMIC ANALYSIS	0%	100%

Process Flow Sheet for DCS Process: Case A



Economic Analysis: Progress and Status

		PRIOR	CURRENT
1.	PROCESS DESIGN INPUTS	0%	100%
2.	BASE CASE CONDITIONS	0%	100%
3.	RAW MATERIAL COSTS	0%	100%
4.	UTILITY COST	0%	100%
5.	MAJOR PROCESS EQUIPMENT COST	0%	100%
6.	PRODUCTION LABOR COST	0%	100%
7.	PLANT INVESTMENT COST	0%	100%
8.	PRODUCT COST	0%	100%

Preliminary Cost Sensitivity Analysis: Progress and Status

		PRIOR	CURRENT
1.	BASE CASE CONDITIONS	0%	100%
2.	RETURN ON ORIGINAL INVESTMENT	0%	100%
3.	DISCOUNTED CASH FLOW RATE OF RETURN	0%	100%
4.	PLANT INVESTMENT COST VARIATION	0%	100%
5.	RAW MATERIAL COST VARIATION	0%	100%
6.	UTILITY COST VARIATION	0%	100%
7.	LABOR COST VARIATION	0%	100%
8.	EFFECT OF INFLATION	0%	100%
9.	COST AND PROFITABILITY ANALYSIS SUMMARY	0%	100%

IMPURITY EFFECTS IN SILICON

WESTINGHOUSE ELECTRIC CORP. R&D CENTER

Technology Impurity effects in silicon	**Report Date** 9/24/80
Approach Analysis of silicon material and solar cells with controlled impurity additions **Contractor** Westinghouse Electric Corp., R&D Center	**Status** Phase IV experimental program underway **Preliminary Results:** • Threshold for impurity-induced structure breakdown lower in poly than single crystal ingots • Less grain boundary segregation evident for Ti as metal content is lowered from 2×10^{14} to 5×10^{13} cm^{-3} • Impurity threshold for performance reduction projected lower in high efficiency cells • Solar cells made from DCS silicon comparable in efficiency to baseline solar cells • Accelerated aging tests indicate rate of performance degradation of impurity-doped cells in order: Cr > Ag > Nb > Ti
Phase **Goals** Evaluate impurity effects in: • Polycrystalline silicon • High efficiency cells • Experimental silicon materials • Cells subjected to processing, e.g. gettering • Cells treated to simulate long term behavior	

Polycrystalline Solar Cells

Impurity-dependent lifetime behavior is essentially the same as observed in single-crystal material.

The electrical activity of grain boundaries is virtually unaffected by impurities.

High impurity concentrations in poly cells result in considerable junction shunting.

Impurity segregation to grain boundaries is negligible.

Polycrystalline ingots suffer structural breakdown at lower impurity concentrations than do single crystal ingots.

C-3

Gettering of Impurities

Gettering appears to be diffusion-controlled and is therefore most effective for fast-diffusing impurities.

IMPURITY	DIFFUSION CONSTANT(900 C)
Copper	10^{-6}
Iron	6 10^{-6}
Chromium	10^{-7}
Silver	2 10^{-10}
Vanadium	8 10^{-10}
Titanium	2 10^{-11}
Molybdenum	$< 10^{-14}$
Tungsten	$< 10^{-14}$

Permanence and Aging Effects in Solar Cells

Projected Behavior

Ingot	Activation Energy (ev)	Time to Failure (hrs) (100°C)
Baseline	1.42	6.3 10^{12}
W077Mo001	2.03	4.4 10^{19}
W123Ti008	3.47	7.6 10^{39}
W072Cr005	0.25,0.55	1.0 10^{5}
W192Ag001	0.59	3.3 10^{5}
183Nb002	0.77	7.4 10^{6}
W135Fe005	-	-
W166Fe007	-	-
W167Nb001	0.79	1.0 10^{7}

- Time to failure is defined as the time for efficiency to drop 10%.
- Twenty years equals 1.75 10^{5} hours.

High-Efficiency Solar Cells

SOLAR CELL PERFORMANCE DEPENDS PRIMARILY ON THE ELECTRONIC PROPERTIES AND THE SPATIAL ARRANGEMENT OF THE SEVERAL N-TYPE AND P-TYPE REGIONS WHICH MAKE UP THE DEVICE.

THE MOST IMPORTANT PARAMETERS ARE THE MINORITY CARRIER DIFFUSION LENGTHS (OR LIFETIMES) AND THE CARRIER MOBILITIES.
THESE, IN TURN, DEPEND IN AN INTRICATE WAY ON THE CONCENTRATION OF THE DONOR AND ACCEPTOR DOPANTS, THE CONCENTRATION OF UNINTENTIONAL TRACE IMPURITIES, AND ON CRYSTAL AND SURFACE PERFECTION.

THE MODEL ANALYSIS CHARACTERIZES CARRIER RECOMBINATION AND COLLECTION IN TERMS OF INTERNAL VELOCITY PARAMETERS (S_E) FROM WHICH ARE DETERMINED THE VOLTAGE AND CURRENT OBSERVED AT THE CELL TERMINALS.

IMPURITY EFFECTS IN SILICON SOLAR CELLS

C.T. SAH ASSOCIATES

TECHNOLOGY
IMPURITY EFFECTS IN SILICON SOLAR CELLS

REPORT DATE
80/09/24

APPROACH
Theoretical-numerical analysis of the performance of silicon solar cells doped with specific impurities, using the transmission line circuit model as well as the experimental dopant impurity profiles and experimental recombination impurity energy levels, emission and capture rates.#

CONTRACTOR
C. T. SAH ASSOCIATES

GOALS
Predict the maximum allowable recombination impurity concentration at a given one AM1 sun efficiency for:

- N+/P/P+ and P+/N/N+ cells
- Different impurity species
- Optimum cell thickness
- One and two optical passes

#Detailed in Technical Reports 1,2,3 and summarized on pp.27-30, 14th PIM Proceeding.

STATUS
(1) TECHNICAL REPORTS 1, 2 AND 3 GIVE:

- Effects of substrate and surface dopant impurity concentration.
- Effects of two-level recombination center and position variation of the impurity concentration.
- Effects of high illumination levels.
- Effects of back surface field.
- Effects of interband Auger recombination.
- Effects of enhanced impurity solubility
- Good agreement between theory and experiments in Ti-doped cells.
- Prediction of maximum zinc density for 17% AM1 efficiency (<4-7x10^{11} Zn/cm^3)

(2) CURRENT RESULTS

- Prediction of optimum cell thickness: 80 microns for one optical pass and 40 microns for two optical passes.

SILICON MATERIAL TASK

SILICON MATERIALS RESEARCH LABORATORY

JET PROPULSION LABORATORY

Silicon Material

TECHNOLOGY

CONSOLIDATION OF SILICON POWDER

IMPURITY EFFECTS IN SILICON

APPROACH

- CONSOLIDATION - USING CZ AND FLOAT-ZONE
- IMPURITY EFFECTS - USING THERMALLY STIMULATED CAPACITANCE (TSCAP)

CONTRACTOR

JPL IN-HOUSE (A. YAMAKAWA)
(R. COCKRUM)

GOALS

- DEVELOPMENT OF A METHOD TO CONSOLIDATE SUB-MICRON SILICON POWDER
- EVALUATE IMPURITY EFFECTS IN PROCESS DEVELOPMENT SAMPLES

REPORT DATE

09-25-80

STATUS

CONSOLIDATION

- TEST APPARATUS USING HF FLOAT-ZONE APPARATUS AS THE HEAT SOURCE DEMONSTRATED

IMPURITY EFFECTS

- FACILITIES AND EQUIPMENT REQUIRED TO FABRICATE SCHOTTKY DIODES FOR TSCAP MEASUREMENTS COMPLETED

Silicon Material Research Laboratory (SMRL)

FACILITIES AT SMRL INCLUDE

- CRYSTAL GROWING AND REFINING EQUIPMENT
- INGOT SLICING EQUIPMENT
- CHEMICAL CLEAN ROOM
- HIGH TEMPERATURE FURNACE
- METALLIZATION EQUIPMENT
- ELECTRICAL TEST EQUIPMENT
- CHEMICAL TEST EQUIPMENT

- AN ADDITIONAL RESPONSIBILITY OF THE SMRL IS TO PREPARE PROCESS DEVELOPMENT SAMPLES FOR TESTING BY OUTSIDE CONTRACTORS

Status of SMRL

- MOVE-IN STARTED JUNE 1979
- ALL EQUIPMENT EXCEPT CHEMICAL TEST EQUIPMENT HAVE BEEN DELIVERED
- ALL DELIVERED EQUIPMENT EXCEPT HIGH TEMPERATURE FURNACE ARE CONNECTED AND OPERATING
- HIGH TEMPERATURE FURNACE WILL BE COMPLETED WITHIN 2 WEEKS
- CHEMICAL TEST EQUIPMENT EXPECTED BY END OF CALENDAR YEAR
- CONSOLIDATION EXPERIMENTS HAVE STARTED
- ELECTRICAL MEASUREMENTS HAVE STARTED

Impurity Effects

- ANALYSIS OF IMPURITY EFFECTS IS PERFORMED USING TSCAP
- TSCAP MEASURES VARIATIONS IN CAPACITANCE WITH TEMPERATURE TO DERIVE ELECTRICALLY ACTIVE IMPURITY CONCENTRATIONS AND ACTIVATION ENERGIES
- TSCAP IS CAPABLE OF DETECTING IMPURITY CONCENTRATIONS FOUR ORDERS OF MAGNITUDE LESS THAN THE SUBSTRATE DOPING CONCENTRATION
- TSCAP USES A SIMPLE EXPERIMENTAL SET-UP

TSCAP Measurement Sequence

- I-V CURVE (ROOM TEMPERATURE)
- C-V CURVE (ROOM TEMPERATURE)
- TEMPERATURE-CAPACITANCE CURVE (LOW TEMPERATURE)
- IN-DEPTH T-C CURVE (LOW TEMPERATURE)

Consolidation

- EXPERIMENTS ARE BEING PERFORMED BY DR. A. YAMAKAWA
- DR. YAMAKAWA IS DEVELOPING A METHOD OF CONSOLIDATE SUB-MICRON SILICON POWDER PRODUCED BY THE FSR OF THE UCC PROCESS
- THE METHOD CONSISTS OF MELTING THE POWDER ON TOP OF A PEDESTAL, FOLLOWED BY UNIDIRECTIONAL SOLIDIFICATION
- A TEST APPARATUS HAS BEEN CONSTRUCTED USING A HIGH FREQUENCY FLOAT-ZONE APPARATUS AS THE HEAT SOURCE
- ADDITIONAL EXPERIMENTS ARE PLANNED USING CZ FURNACE

Chemical Analysis

- BY ZEEMAN ATOMIC ABSORPTION SPECTROMETER
- BY INDUCTIVELY COUPLED PLASMA EMISSION SPECTROMETER

Problems and Concerns

- THE MAJOR PROBLEM WITH THE SMRL HAS BEEN IN THE AREA OF STAFFING
- ANY ADDITIONS TO THE SMRL WILL REQUIRE NEW POWER LINES - ALL AVAILABLE POWER HAS BEEN ALLOCATED

Large-Area Silicon Sheet Task

TECHNOLOGY SESSION

J. Liu, Chairman

Advanced Czochralski: Kayex Corp.

Process automation techniques utilizing microprocessor-controlled crystal growth are under development and are aimed at reducing cost and improving process yield.

Development priorities have been issued by JPL as follows:

Priority 1: Microprocessor controls
Priority 2: Accelerated growth
Priority 3: Accelerated meltback: chunk material utilizing cold crucible premelter.

A series of single-batch crystal growth runs have been made using microprocessor control. The runs have been demonstrated using 12-in.-dia crucibles and 4-in.-dia crystal growth.

A molybdenum heat sink has been designed and fabricated. Several crystal growth runs have been made, i.e. batch and recharge, using this heat sink.

A successful 150 kg 6-in.-dia crystal growth run has also been demonstrated.

The cold crucible premelter system has been assembled and melting trials have been successfully undertaken on a bench scale. Interfacing of the equipment with the crystal grower is ongoing.

Advanced Czochralski: Siltec Corp.

During the past months, several demonstration runs incorporating continuous melt replenishment were performed, growing individual crystals of 150 mm dia weighing 40, 52 and 65 kg per ingot. Growth conditions were extremely stable. Average growth velocity deviations were only ±0.25 in./h. Typical solidification rates during these runs were 3.5 to 4.0 kg/h.

Structural problems occurred typically about 23 to 15 in. below the ingot shoulder, which was attributed to silicon monoxide particles interfering with crystal growth. However, it was possible to grow monocrystalline, dislocation-free material after several ingots had already been pulled and half the melt had already been in the crucible for more than 60 h. This is a significant result; it shows that it is possible to grow large portions of the 150-kg material monocrystalline, provided the silicon monoxide level in the furnace interior is kept to a minimum. This is usually accomplished when leak rates of the total system are kept below 10^{-4} torr ℓ/sec.

Semicrystalline Casting: Semix Inc.

"Semicrystalline Casting Process Development and Verification" is a three-year cooperative agreement between Semix Incorporated and the United States Department of Energy. The goals of this agreement are to demonstrate Commercial Readiness of a silicon-sheet manufacturing process compatible with the 1982 price goal of \$2.80/W_p and to demonstrate Technology Readiness to meet the 1986 price goal of \$.70/W.

The initial effort is aimed at economic evaluation of the projected 1982 and 1986 technologies in order to pinpoint critical process subsystems and set specific technical objectives for achieving the price goals. Equipment and process development will be carried out to meet the yields, throughput, productivity and other process parameters necessary to support program goals. A continuous verification procedure will be maintained to insure technical and economic viability of each development change. Current SAMICS analyses show that projected Semix semicrystalline technology can produce sheet material to meet 1982 and 1986 price goals.

Enhanced ID Slicing: Siltec Corp.

Experimentation with ingot rotation and minimum exposed blade area continued during the past months. Although average cutting feed rates of 13 to 15 mm/min for slices 100 mm in diameter, 250 μm thick, with kerfs of 152 μm were produced, these results could not be demonstrated consistently. Problems usually occurred after the cutting edge had penetrated 0.7 in. into the ingot, in the form of fracture lines, following the curvature of the cutting edge. This problem persisted for a wide range of cutting parameters and was identified as the result of high-frequency vibrations of the cutting edge.

The effectiveness of the cutting-edge position control system was further evaluated. Blade deflection values for 250 μm wafers, cut with 152 μm kerfs, were typically reduced by one order of magnitude. The effect of damping vibrations of the blade cutting edge through the deflection control mechanism was minimal, but cutting rates could be increased from 15 to 25 mm/min in the first 0.5 to 0.7 in. of radial cutting edge penetration.

Multiblade Slurry Slicing (MBS): P. R. Hoffmann Co.

Results of the tests performed indicate that the present state of the art of multiblade slurry wafering does not provide for successful wafering of 1 m^2/kg of 10-cm-dia silicon ingot. The major problems to be overcome are related directly to blade wear, feed force control, and abrasive slurry characteristics. Other major factors in accomplishing the goals of the Large-Area Silicon Sheet Task are the cost of consumables and wafer cleaning and handling.

Fixed Abrasive Slicing Technique (FAST): Crystal Systems Inc.

A new slicing head was designed and fabricated. The salient features of this blade head are a very high degree of rigidity and accurate alignment. The blade head has been enlarged to accommodate 750 wires (25 wires/cm).

Initial testing with the new blade head has shown that 500 ft/min surface speeds can be achieved. Increased speed is limited by the drive unit rather than the blade head. Slicing tests using the blade head with electroplated wires has resulted in average slicing rates of 5.1 mils/minute (0.13 mm/min) with 83% yield.

Blade development has continued. Along with the 45 m diamonds used for slicing, smaller filler diamonds were used to prevent erosion of the matrix.

Partial Pressure of Reactant Gases: University of Missouri Rolla

Analysis of data obtained on the oxygen content of the silicon furnace purge gases in the JPL and Mobil Tyco facilities indicates that equilibrium conditions do not exist between their purge gases and the molten silicon. Therefore it is possible to use inert gases containing levels of oxygen much higher than the equilibrium oxygen partial pressure without seriously contaminating the molten silcon with oxide. This is true for several reasons. First, much of the purge gas never reaches the temperature of the molten silicon, and thus the oxygen has insufficient time to react before being exhausted from the system. Second, the portion of the oxygen that thermally accommodates with the 1700°K graphite surfaces in the furnace is quickly converted to CO. Finally, in the case of the Mobil Tyco ribbon-pulling system, the oxides that do form on the surface of the silicon reservoir remain there as a skin, while the silicon used in the formation of the ribbon is drawn from below this floating oxide skin through the die where it is exposed only to graphite and not to the surrounding atmosphere, maintaining an extremely low oxygen activity until it emerges from the top of the die where it freezes very quickly, before oxidation can occur.

Silicon Solar Cell Fabrication and Analysis: Applied Solar Energy Corp.

The objective of this program is to investigate, develop, and utilize technologies appropriate and necessary for improving the efficiency of solar cells made from various unconventional silicon sheets. Silicon sheets processed included EFG ribbons, dendritic web, SOC and wafers from HEM cast ingots and ingots from semi-continuous Cz growth techniques.

The effect of grain sizes and BSF on solar cell parameters are discussed. Performance summaries of all sheet cell evaluations are included.

LARGE-AREA SILICON SHEET TASK

INGOT GROWTH: COST REDUCTION

KAYEX CORP.

TECHNOLOGY - INGOT GROWTH	REPORT DATE: SEPT. 24, 1980 START DATE: MARCH 12, 1979
PROGRAM 1. LOWER THE COSTS OF THE MELT DOWN AND GROWTH PROCESSES. 2. REDUCE LABOR COSTS AND IMPROVE YIELDS.	**OBJECTIVE** FASTER MELT DOWN. INCREASED GROWTH RATE. USE 1 PRODUCTION OPERATOR PER 6 GROWERS. COMBINATION OF THE ABOVE WILL REDUCE THE CZ ADD ON COSTS TO: LOW COST CZ (ROD FEED)= 15.36/KG (1980) =$0.1083 ¢/PEAK WATT LOW COST CZ (POLY CHUNK FEED)=14.95/KG (1980) =$0.1054 ¢/PEAK WATT APPROXIMATELY 27.2% 29.1% COST REDUCTION COMPARED TO COLD FILL PROCESS

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS:	ROD FEED	POLY LUMP FEED
C1 EQPT = 0.49/YR - $EQPT	$107,310	$102,410
C2 SQFT = $97/YR - $SQFT	9,700	9,700
C3 DLAB = $2.1/YR - $DLAB	22,245	22,245
C4 MATS = $1.3/YR - $MATS	101,037	101,818
C5 UTIL = $1.3/YR - $UTIL	19,533	19,811
TOTAL	$259,825	$255,984
QUAN (TOTAL CHARGED X % YIELD) (KG)	16,918	17,122
THRUPUT	2.25 KG/HR	2.28 KG/HR

PROJECTION

1. LOW COST CZ (ROD FEED) WITHOUT SILICON = $15.36/KG ADD ON COST =$0.1083¢/PEAK WATT.
2. COST WITH $85/KG POLY ROD (CURRENT COST) $138.2/KG ADD ON COST =$0.9747¢/PEAK WATT
3. NO PROJECTED COST FOR SILICON POLY ROD

1. LOW COST CZ (POLY LUMP FEED) WITHOUT SILICON = $14.95/KG ADD ON COST =$0.1054¢/PEAK WATT
2. COST WITH $65/KG SILICON LUMP (CURRENT COST) $108.8/KG ADD ON COST =$0.7673¢/PEAK WATT
3. COST WITH $14/KG SILICON LUMP (PROJECTED LSA GOAL) $35.2/KG ADD ON COST =$0.2483¢/PEAK WATT

CZ Growth Methods

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

SAMICS-IPEG Input Data and Cost Calculation for Low-Cost Cz (Rod Feed) vs Low-Cost Cz (Poly Lump Feed)

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

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

TECHNOLOGY: INGOT GROWTH JPL CONTRACT 955270	REPORT DATE: SEPT. 24, 1980 START DATE: MARCH 12, 1979
APPROACH EQUIPMENT AND PROCESS IMPROVEMENTS FOR PRODUCTION OF LOW COST SOLAR SILICON SHEET BY THE CZOCHRALSKI METHOD.	GOALS 1. CONTINUOUS GROWTH OF 150 KGS OF SINGLE CRYSTAL UTILIZING MELT REPLENSIHMENT TECHNIQUES EMPLOYING INDUCTION MELTING OF POLY RODS OR Si LUMP BY COLD CRUCIBLE MELTING. 2. DIAMETER OF 15 CMS. 3. GROWTH RATE OF 15 CM/HR USING HEAT SINK. 4. PULLED YIELD OF 90% USING MICRO-PROCESSOR CONTROL. 5. SOLAR CELL EFFICIENCY OF 14% AMI 6. TECHNOLOGY TRANSFER READINESS BY 6/30/80.

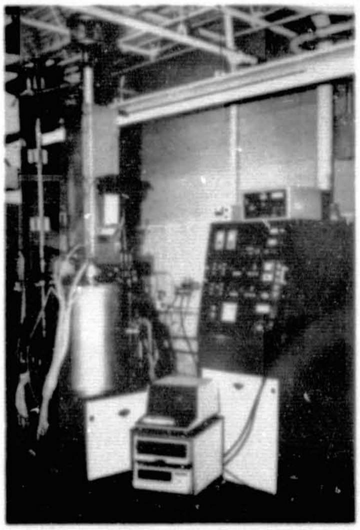
Overall Program Progress

TECHNOLOGY - INGOT GROWTH	REPORT DATE: SEPT 24, 1980 START DATE: MARCH 12, 1979
PROGRAM 1. ACCELERATED MELT 2. ACCELERATED GROWTH 3. COLD CRUCIBLE 4. MICROPROCESSOR CONTROL	PROGRAM GOAL A) DECREASE CRUCIBLE DEVITRIFICATION B) ACHIEVE FASTER MELT RATES, I.E. 25 + KG/HR INCREASE GROWTH RATE TO 15 CM/HR FOR 15.25 CM DIAMETER CRYSTAL GROWTH. A) MAINTAIN MELT PURITY LEVEL INTO CRUCIBLE B) PREVENT CRUCIBLE DEVITRIFICATION A) REDUCE LABOR COSTS BY PROCESS AUTOMATION B) IMPROVE YIELD

APPROACH	STATUS
EQUIPMENT AND PROCESS IMPROVEMENT FOR PRODUCTION OF LOW COST SOLAR SILICON SHEET BY THE CZOCHRALSKI METHOD.	JPL ISSUED TECHNICAL DIRECTION MEMO - APRIL 1980 PRIORITIES FORMULATED. 1. MICROPROCESSOR CONTROL - DEMONSTRATED. 2. ACCELERATED GROWTH - PARTIALLY DEMONSTRATED. ANCILLARY ADVANTAGES DEMONSTRATED. 3. COLD CRUCIBLE - DEMONSTRATED OFF THE PULLER INTERFACE ASSEMBLY READY. 4. R.F. MELTING OF POLY ROD RECHARGE - DE-EMPHASIZED. PROBLEMS DUE TO: AVAILABILITY OF SUITABLE POLY RODS (CRACK, TAPER AND BOW FREE) AVAILABILITY OF POLY RODS AT A COST EFFECTIVE PRICE.

Program: Microprocessor Control

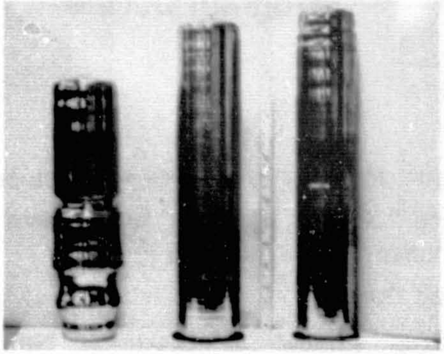
APPROACH	GOALS
EQUIPMENT AND PROCESS COST IMPROVEMENT FOR PRODUCTION OF LOW COST SOLAR SILICON SHEET BY THE CZOCHRALSKI METHOD.	DEVELOP MICROPROCESSOR CONTROL OF THE CZOCHRALSKI PROCESS TO: A. REDUCE LABOR COSTS. B. IMPROVE YIELD BY REDUCING OPERATOR DEPENDENCE.



Advanced Cz Puller With Microprocessor Unit

STATUS

1. MICROPROCESSOR CONTROL OF THE SHOULDER AND STRAIGHT GROWTH PROCESSES DEMONSTRATED FOR 4" AND 6" DIAMETER CRYSTALS.
2. OPERATOR PROMPTING OF MELT DOWN AND MELT STABILIZATION REQUIRED.
3. MANUAL CONTROL OF THE SEEDING AND NECK GROWTH PROCESSES THROUGH THE MICROPROCESSOR.
4. MANUAL TAPER OUT CONTROLLED THROUGH MICROPROCESSOR.

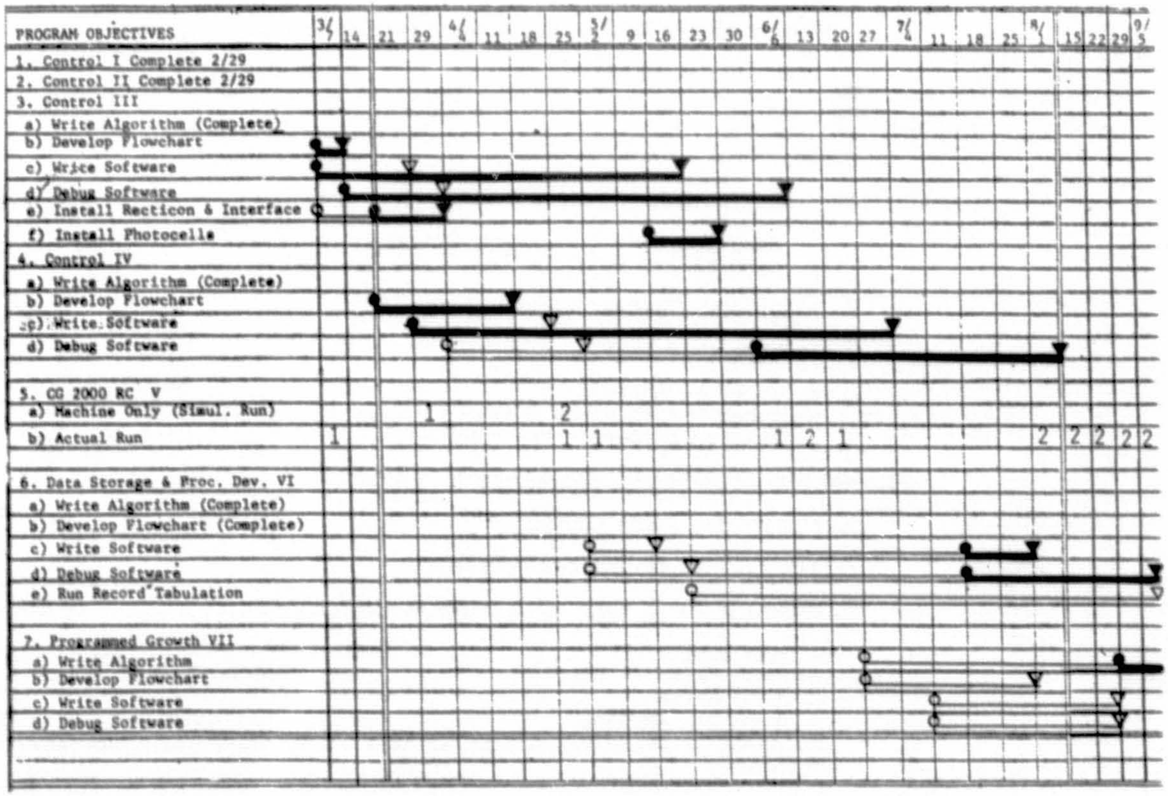


Crystals Grown With MPU Control: Run #32

SUMMARY

1. CONTROL DEMONSTRATED FOR 4" AND 6" MICROPROCESSOR DIAMETERS.
2. EFFECTIVE COST REDUCTION AND YIELD IMPROVEMENT BY TOTAL AUTOMATION OF THE GROWTH PROCESS REQUIRES ADDITIONAL DEVELOPMENT.

Microprocessor Control Program Plan



Program Outline

I. CONTROL I

- A. GOALS
  1. PROMPT OPERATOR FOR PROPER SEQUENCE OF OPERATION.
  2. CAUSE "CRUCIBLE ROTATION" TO BE UNDER CONTROL.
     - A. MOTOR CONTROL ROUTINE
  3. CAUSE "CRUCIBLE LIFT" TO POSITION CRUCIBLE.
  4. PERFORM "BAKEOUT" BY OPERATOR DETERMINED PARAMETERS.
     - A. TEMPERATURE LEVEL (ENTERED)
     - B. SOAK TIME (ENTERED)
     - C. CRUCIBLE POSITION (ENTERED)
  5. PERFORM "MELTDOWN" BY OPERATOR DETERMINED PARAMETERS.
     - A. TEMPERATURE LEVEL (ENTERED) MELTDOWN
     - B. SOAK TIME (ENTERED) MELTDOWN
     - C. CRUCIBLE POSITION (ENTERED) MELTDOWN
     - D. TEMPERATURE LEVEL (ENTERED) STABILIZE
     - E. SOAK TIME (ENTERED) STABILIZE
     - F. CRUCIBLE POSITION (ENTERED) STABILIZE
  6. MONITOR ALARM SENSORS AND SHUTDOWN IF MAJOR.
     - A. WATER FLOWS (MAJOR)
     - B. WATER TEMPERATURES (MINOR)
     - C. PRESSURES (MINOR/RAPID RISE MAJOR)
     - D. POSITIONING (MINOR)
- B. MINIMUM ACCEPTANCE: (SCHEDULED 2/22/80)
  1. PROMPTING
  2. CRUCIBLE MOTIONS
  3. AUTO; BAKEOUT, MELTDOWN & STABILIZATION

II. CONTROL II

- A. GOALS:
  1. ALLOW CONTROL OF ALL MOTORS (SPEED ONLY)
     - A. CRUCIBLE LIFT & ROTATION (NO JOG)
     - B. SEED LIFT & ROTATION (NO JOG)
  2. ALLOW FOR TEMPERATURE VARIATIONS
  3. ROUTINE EXIT
     - A. ABORT BY OPERATOR
     - B. ABORT DUE TO MAJOR ALARM
     - C. EXIT TO AUTO-DIAMETER CONTROL
- B. MINIMUM ACCEPTANCE: (SCHEDULED 2/29/80)
  1. ALL MOTORS UNDER CONTROL
  2. TEMPERATURE VARIATIONS POSSIBLE
  3. OPERATOR TO BE ABLE TO PERFORM MANUAL GROWTH
     - A. DIP SEED
     - B. GROW NECK
     - C. GROW CROWN
     - D. SHOULDER CRYSTAL
     - E. ABORT BY OPERATOR OR EXIT TO AUTO (THIS STAGE STILL ABORTS)

CONTROL III

III. CONTROL III

A. GOALS:

1. CONTROL SEED LIFT VIA DIAMETER INPUT.
    - A. OPERATOR CAN CHANGE DIAMETER REQUIRED
    - B. RETICON (OR PHOTOCELLS IF RETICON UNACCEPTABLE) DIAMETER INPUT. (RETICON INSTALLED & TESTED).
2. LOCKOUT OPERATOR ATTEMPTS TO CHANGE ROTATIONAL SPEEDS. OPERATOR MAY ABORT OR EXIT TO AUTO OR MANUAL.
3. CRUCIBLE LIFT A FUNCTION OF SL, CAL. XTAL WEIGHT, AND CRUCIBLE SIZE.
4. ABORT DUE TO MAJOR ALARM.

B. MINIMUM ACCEPTANCE: (SCHEDULED 3/28/80)

1. CONTROL SEED LIFT BY DIAMETER INPUT.
2. SLAVE CRUCIBLE LIFT TO SL, XTAL WEIGHT, AND C. SIZE.
3. LOCKOUT UNACCEPTABLE OPERATOR COMMANDS.
    - A. ROTATIONAL SPEED CHANGES. (ABORT OR FULL AUTO OR MAN. ALLOWED)

IV. CONTROL IV

A. GOALS:

1. INCREASE AND DECREASE TEMPERATURE SET POINT AS A FUNCTION OF THE AVERAGE DEVIATION OF THE SEED LIFT FROM THE SEED LIFT SET POINT.
2. OPERATOR ALLOWED TO:
    - A. ABORT
    - B. EXIT MANUAL
    - C. EXIT AUTO DIAMETER
    - D. CHANGE SL OR DIAMETER SET POINTS.
3. ABORT DUE TO MAJOR ALARM.

B. MINIMUM ACCEPTANCE: (SCHEDULED 4/18/80)

1. TEMPERATURE SET POINT A FUNCTION OF AVERAGE SEED LIFT DEVIATION FROM ITS SET POINT.
2. OPERATOR MAY ABORT ON EXIT TO CONTROLS II OR III.
3. OPERATOR MAY CHANGE SEED LIFT OR DIAMETER SET POINTS.

V. CG 2000 RC USAGE

A. SIMULATED RUNS:

1. REQUIRES ALL MACHINE FUNCTIONS EXCEPT FOR TEMPERATURE & DIAMETER SENSING.
2. TEMPERATURE CHANGES PERFORMED BY MONITORING THE APPROPRIATE D/A OUTPUT. (COMPARE VOLTAGE TO AN ACTUAL VALUE FOR THE SAME SET POINT READING.)
3. DIAMETER TESTING BY VARIOUS FORMS OF LIGHT SOURCES.
4. TEST ACTUAL MOTOR SPEEDS VERSUS REQUIRED AND DISPLAYED ACTUAL.

B. ACTUAL RUNS:

1. REQUIRES:

   A. BAKEOUT - FROM COLD MACHINE
   B. MELTDOWN - FROM FINISH OF BAKEOUT
   C. VARIOUS STAGES OF ACTUAL CRYSTAL GROWTH, I.E. NECK ONLY OR NECK & CROWN, ETC.

2. GROWER SHOULD NOT BE IN USE FOR MORE THAN ONE SHIFT IN MOST CASES.

VI. DATA STORAGE AND PROCESS DEVELOPMENT

A. GOALS:

1. TO STORE RUN DATA AT FIXED TIME INTERVALS (UND. AS YET).

   A. ALL MOTOR SETTINGS
   B. ALL MOTOR TACH READINGS
   C. DIAMETER SETTING
   D. TEMPERATURE SET POINT
   E. ACTUAL DIAMETER (REQ. RETICON OR SIMILAR)

2. TO STORE RUN DATA WHEN OPERATOR CAUSES A CHANGE TO OCCUR, I.E. ENTERS NEW SET POINT.

3. PRODUCE A HARD COPY OF ALL RUN DATA FROM THE FLOPPY DISK.

   A. SUITABLE FORMAT TO BE USED FOR EASE IN ANALYSES OF DATA

B. MINIMUM ACCEPTANCE: (SCHEDULED 8/1/80)

1. RUN DATA STORAGE ON FLOPPY DISK.

VI. PROGRAMMED GROWTH

A. GOALS:

1. ALLOW OPERATOR TO ENTER RUN DATA POINTS.

   A. PARTICULAR DATA POINTS, I.E. SL, CR, ETC.
   B. PARAMETERS FOR USE OF DATA POINTS, I.E. TIME INTO RUN OR XTAL WEIGHT OR BOTH, ETC.

2. ALLOW FOR PERMANENT STORAGE OF DATA POINTS.

3. RETRIEVAL OF STORED FOR USE IN SUCCESSIVE RUNS.

   A. ELIMINATES NEED FOR OPERATOR ENTRY AT START OF EACH RUN

4. ALLOW OPERATOR TO EDIT AND CHANGE GROWTH PROGRAM.

5. ALL ENTRY AND EDIT FEATURES TO BE IN PLAIN ENGLISH AND ENGINEERING UNITS SO AS TO REQUIRE <u>NO</u> PROGRAMMING KNOWLEDGE ON THE OPERATOR'S PART.

B. MINIMUM ACCEPTANCE: (SCHEDULED 8/1/80)

1. ALL GOALS LISTED PREVIOUSLY.

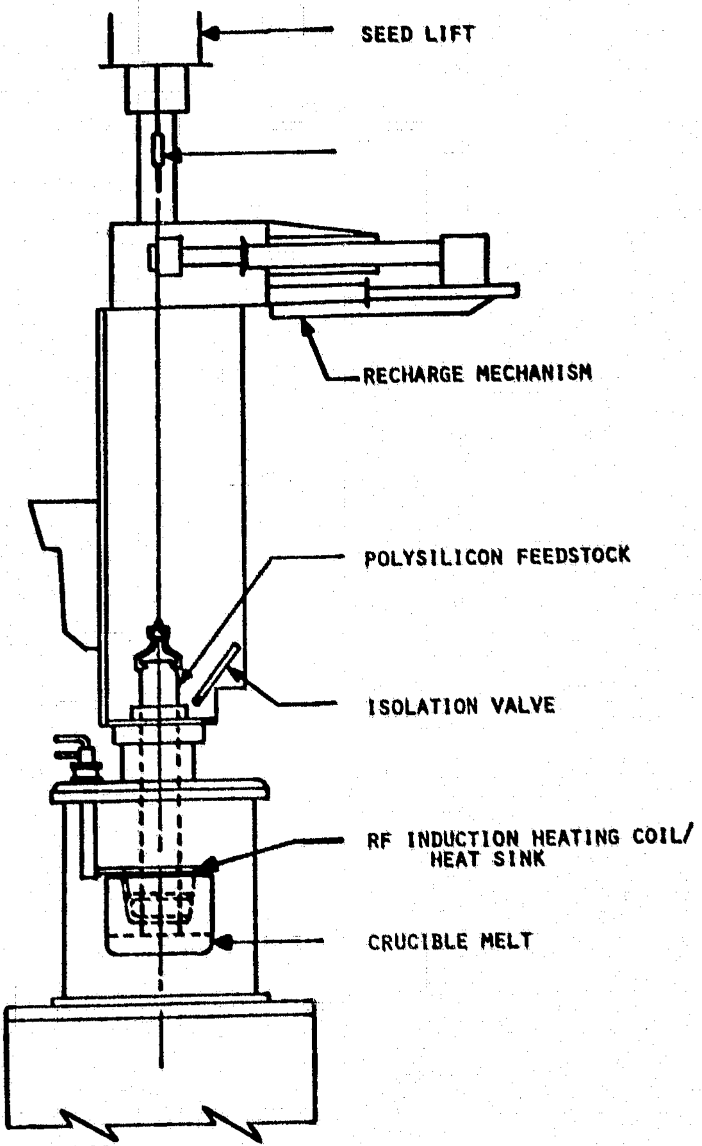
2. OPTION TO POSTPONE UNTIL LATER DATE DUE TO PROCESS DEVELOPMENT PROBLEMS.

3. IF POSTPONED, THEN SOME FORM OF PROGRAMMED TAILING OPERATION OF CRYSTAL TO BE DEVELOPED TO JPL CONTRACT REQUIREMENTS.

LARGE-AREA SILICON SHEET TASK

Program: Accelerated Melting of Si Poly Rods

TECHNOLOGY - INGOT GROWTH	REPORT DATE: SEPT 24, 1980 STATE DATE: MARCH 12, 1979
APPROACH DEVELOPMENT OF CRUCIBLE RECHARGE TECHNIQUES UTILIZING R.F. MELTING OF 5" DIAMETER POLYCRYSTALLINE SILICON RODS.	STATUS JPL ISSUED TECHNICAL DIRECTION MEMO IN APRIL DE-EMPHASIZING THIS PROGRAM. PROBLEMS 1. TECHNICAL PROBLEMS DUE TO ARCING IN GROWTH ATMOSPHERE. 2. AVAILABILITY OF SUITABLE QUALITY CRACK-FREE, TAPER AND BOW FREE POLY RODS IS A MAJOR PROBLEM. 3. AVAILABILITY OF POLY RODS AT A COST EFFECTIVE PRICE.



CG2000 RECHARGE MODE

Problems and Concerns

MELTING OF 25 KG/HR OF POLY ROD UTILIZING AN RF INDUCTION HEATING WORK COIL POSES TECHNICAL PROBLEMS:

A) ARCING OCCURS UTILIZING NORMAL VACUUM/ARGON ATMOSPHERE (PRIMARILY ARGON IONIZATION)

B) ARCING CORRECTED BY MELTING IN A HELIUM PRESSURE ATMOSPHERE, BUT IS COSTLY AND PRODUCES MORE OXIDE BUILD-UP ON COIL AND CHAMBER WALLS.

C) POLY ROD CRACKS - SLOW TEMPERATURE PREHEAT ESSENTIAL, BUT TIME CONSUMING.

D) POLY ROD BOW AND TAPER - DIFFICULT TO CENTER IF RF COIL, CAUSING ARCING IF TOO CLOSE TO COIL; VARIABLE MELTING RATE OCCURS DUE TO RF COUPLING VARIATION.

Program: Accelerated Growth

TECHNOLOGY - INGOT GROWTH

REPORT DATE: SEPT. 24, 1980
START DATE: MARCH 12, 1979

APPROACH

EQUIPMENT AND PROCESS COST IMPROVEMENT FOR PRODUCTION OF LOW COST SOLAR SILICON SHEET BY THE CZOCHRALSKI METHOD.

GOALS

ACHIEVE A GROWTH RATE OF 15 CM/HR. USING A HEAT SINK TO ABSORB ENERGY RELEASED BY HEAT OF FUSION.

STATUS

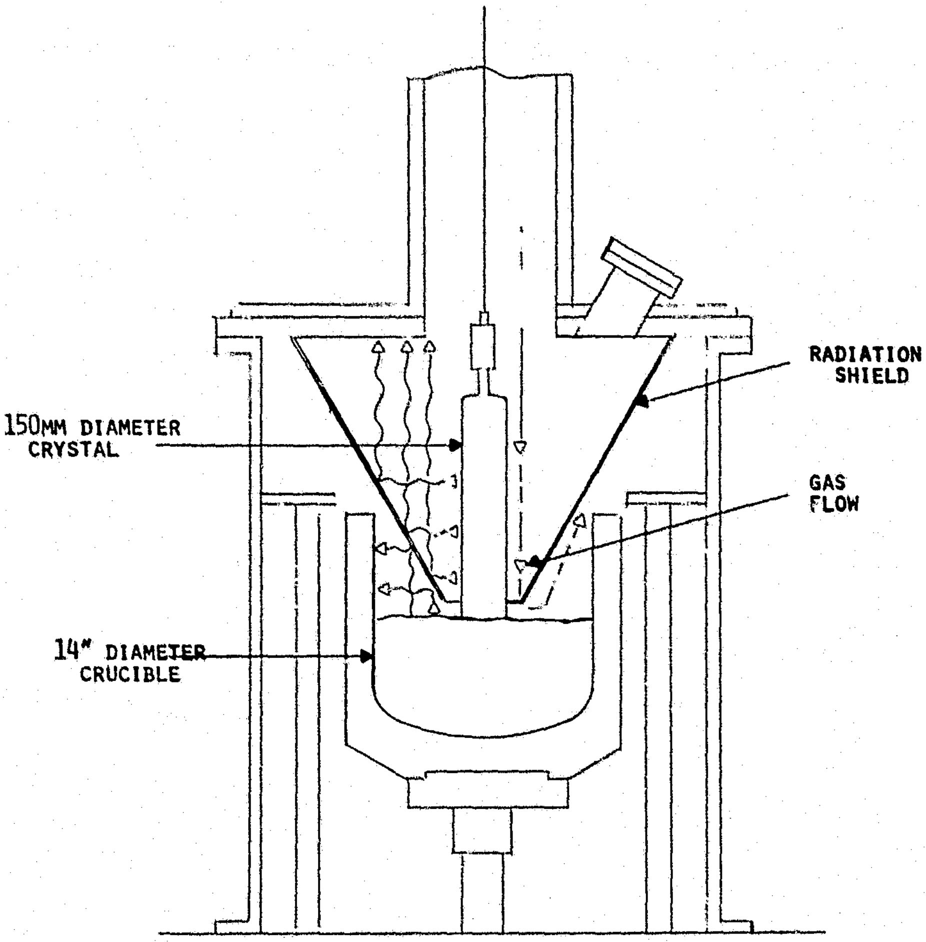
1. USE OF R.F. COIL AS HEAT SINK DISCONTINUED.
   GROWTH RATE IMPROVEMENT OBTAINED.
   OXIDE FLAKING CAUSED STRUCTURE LOSS.
2. MOLYBDENUM HEAT SHIELD FABRICATED
   GROWTH RATE IMPROVEMENT OBTAINED.

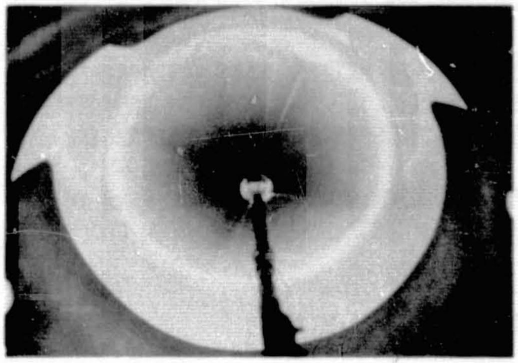
ANCILLARY BENEFITS OBTAINED:

A) REDUCED OXIDE BUILD UP ON CRUCIBLE WALL

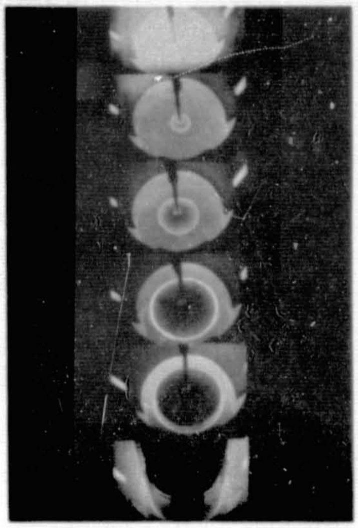
B) ELIMINATION OF OXIDE FORMATION ON CRYSTAL.

Cz Furnace Radiation Shield

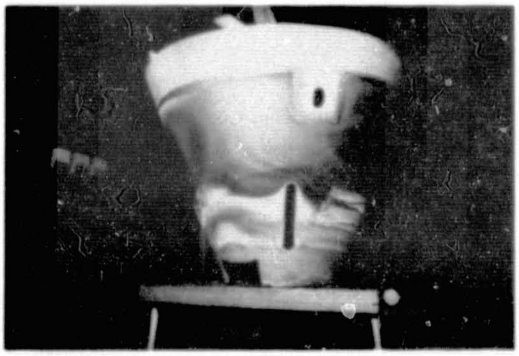




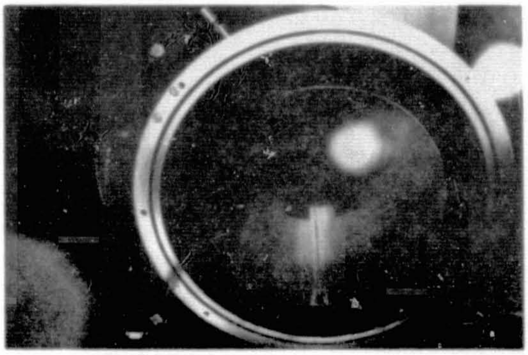
Cryštal Growing Through Shield



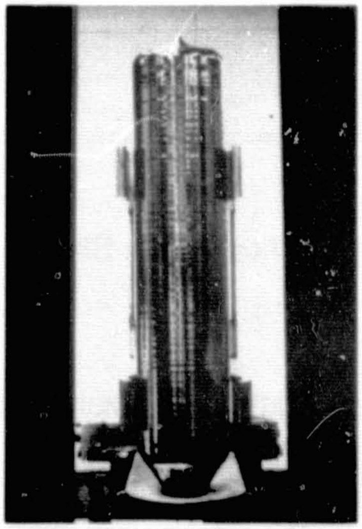
Growth Sequence



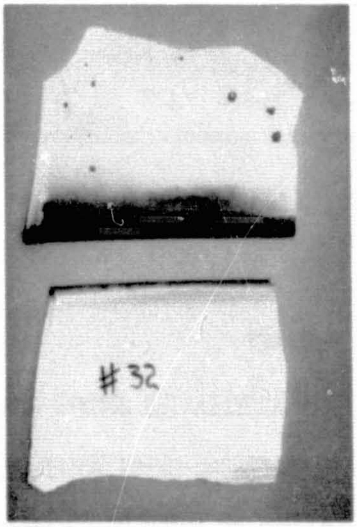
Radiation Shield With Slots



Shield in Position (No Slots)



Crystal Grown in Run #33



Crucible Oxide Comparison

ORIGINAL PAGE IS
OF POOR QUALITY

Program: Radiation Shield to Accelerate Growth

1. MORE EFFECTIVE COOLING OF CRYSTAL DURING GROWTH.
2. REDUCED OXIDE BUILD UP ON CRUCIBLE WALL AND FURNACE TANK COVER PLATE.
3. CRUCIBLE WALL IS KEPT HOT BY RADIATION FROM MELT SURFACE BEING REFLECTED BY RADIATION SHIELD BACK TO CRUCIBLE WALL. THE REFLECTED BY RADIATION SHIELD PREVENTS THIS HEAT FROM BEING RADIATED BACK ON TO THE CRYSTAL.
4. RADIATION SHIELD REFLECTS HEAT FROM THE GROWING CRYSTAL AWAY FROM THE GROWTH REGION. THIS HEAT IS EFFECTIVELY ABSORBED BY THE WATER COOLED COVER PLATE.
5. ARGON FLOW REQUIREMENT TO VIEW PORT WINDOWS ELIMINATED.

6-in.-Dia Growth Rate Comparison

STANDARD GROWTH CONDITIONS						RADIATION SHIELD GROWTH CONDITIONS					
(1) Crystal ID Run-Xtal #	(2) Crystal Length (in)	(3) Straight Growth (hrs)	(4) Growth Rate St. Growth (inch/hr)	(5) Avg. 1st half growth rate (inches/hr)	(6) Avg total run growth rate (inches/hr)	(1)	(2)	(3)	(4)	(5)	(6)
70-1	22-3/4	8.25	2.75			30-1	23-1/2	6.7	3.51		
70-2	21-1/2	7.25	2.97			30-2	22	6.3	3.49		
70-3	24	8.50	2.82	2.84		30-3	20-1/4	6.75	3.00	3.33	
70-4	25-1/2	9.50	2.68			30-4	26	9.7	2.68		
70-5	23 1/4	9.90	2.35			30-5	24-1/4	8.5	2.85		
70-6	24	10.00	2.40		2.64	30-6	25-1/2	9.8	2.60		2.96
72-1	21-1/2	7.50	2.87								
72-2	23	7.80	2.95								
72-3	22	8.70	2.53	2.77							
72-4	20	8.00	2.50								
72-5	24	9.20	2.61								
72-6	26-1/2	11.50	2.30		2.60						

Program: Accelerated Growth Using Radiation Shield

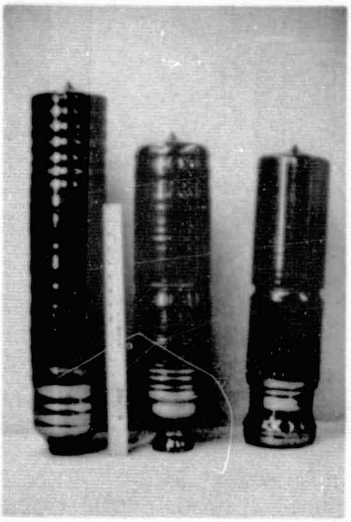
SUMMARY

1. ACCELERATED GROWTH PARTIALLY DEMONSTRATED. FURTHER DEVELOPMENT NECESSARY.
2. REDUCED OXIDE BUILD-UP ON CRUCIBLE WALL.
3. OXIDE BUILD-UP ON CRYSTAL ELIMINATED.
4. IMPROVED MONOCRYSTALLINE YIELD.

Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
*2-1	16	13.7	13	81.3	16	100	5.3	3.02"/HR 7.67CM/HR	63.7
*2-2	13-1/2	9.9	10 1/2	77.8	13 1/2	100		2.7"/HR	
*2-3	21	13.8	13	61.9	14 1/2	69	6.5	3.23"/HR 8.20 CM/HR	
*2-4	10	9.0	4 1/2	45.0	7	70	3.5	2.86"/HR 7.26 CM/HR	
*2-5	18	12.5	5 1/2	30.6	7	38.9	6.7	2.69"/HR 6.83 CM/HR	
*2-6	4-3/4	3.0	2	42.0	4 3/4	100	1.5	3.17"/HR 8.05 CM/HR	
*2-7	9-1/2	7.1	2	21.1	5	52.6	4.3	2.21"/HR 5.6 CM/HR	
*2-8	24	15.4	1 3/4	7.3	10	41.7	9.0	2.67"/HR 6.78 CM/HR	
*2-9	23	15.9	CROWN	0	11 1/4	48.9	10.0	2.3"/HR 5.84 CM/HR	
TOTAL	139.75	100.3			89		46.8		

Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
4-1	17.5	12.6	12	68.6	13.5	77.1	4.25	4.12"/HR 10.46CM/HR	
4-2	11.5	8.1	2	17.4	4.5	39	2.5	4.6"/HR 11.68CM/HR	6.21
TOTAL	29	20.7			18		6.75		
20-1	20	19.45	NONE	100	NONE	100	6.7	2.99"/HR 7.59CM/HR	100
21-1	27.5	27.7	7	25.4	9	32.7	8	3.44"/HR 8.74CM/HR	32.7
22-1	24 1/4	22.8	NONE	100	NONE	100	7.0	3.46"/HR 8.79CM/HR	100
22-2	16 1/4	14.2	NONE	100	NONE	100	4.9	3.32"/HR 8.43CM/HR	
TOTAL	40.5	37.0			40.5		11.9		

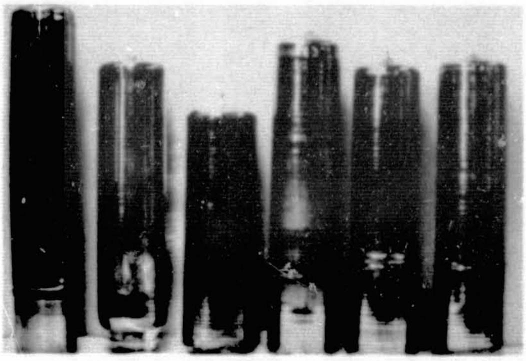
Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
23-1	24 + 2" TAPER	22.2	NONE	100	24 + 2	100	7.8	3.07"/HR 7.80 CM/HR	92.9
23-2	18¼ +4" TAPER	18.7	16	87.7	18	98.6	5.0	3.65"/HR 9.27 CM/HR	
23-3	21¼ NO TAPER	18.6	15 1/4	71.8	17	80.0	5.5	3.09"/HR 7.85 CM/HR	
TOTAL	63.5	59.5				59	18.3		



Crystals Grown in Run #23

Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
27-1	22" +2½" TAPER	22.8	NONE	100	22	100	7.0	3.15"/HR 8.00 CM/HR	61.9
27-2	22"+3/4" TAPER	21.8	11	50	12	54.5	7.4	2.97"/HR 7.54 CM/HR	
27-3	15½"	15.4	2-1/2	16.1	3-1/2	22.6	4.0	3.88"/HR 9.86 CM/HR	
27-4	5	5.2	CROWN	0	3	60	1.6	3.13"/HR 7.95 CM/HR	
TOTAL	64.5	65.2			40.5		20		

Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
30-1	23-1/2 + 3" TAPER	24.0	NONE	100	23-1/2 + TAPER	100	6.7	3.51"/HR	(FIRST THREE CRYSTALS 77/2)
30-2	22 + 2" TAPER	24.1	10	45	13	59	6.3	3.49"/HR 8.86 CM/HR	
30-3	20-1/4 + 3/4" TAPER	23.3	13	64	15	74	6.75	3.00"/HR 7.62 CM/HR	
30-4	26 + 0	26.1	CROWN	0	3	11.5	9.7	2.68"/HR 6.81 CM/HR	45.6
30-5	24-1/4 + 1/2" TAPER	24.7	2-1/2	10.3	7	28.9	8.5	2.85"/HR 7.24 CM/HR	
30-6	25-1/2 + 0	26.3	CROWN	0	3	11.8	9.8	2.60"/HR 6.61 CM/HR	
TOTAL	141.5	148.5			64.5		47.75		



Crystals Grown in Run #30

Crystal ID# Run-Xtal #	Crystal Length (in)	Crystal Weight (kg)	Pt. of Dislocation (in)	%OD	Inches of Single Xtal (in)	% of Single Xtal	St. Growth (hrs)	Growth Rate St. Growth	Total-Single Xtal % of Run
32-1	22½ + 0	21.0	11	48.9	13	57.8	8.7	2.59"/HR 6.58 CM/HR	
32-2	27 + 0	26.2	1 ½	5.6	6"	22.2	9.9	2.73"/HR 5.93 CM/HR	32.2
32-3	28¼ + 0	24.8	1	3.5	6"	21.2	9.9	2.85"/HR 7.24 CM/HR	
TOTAL	77.75	72			25		28.5		

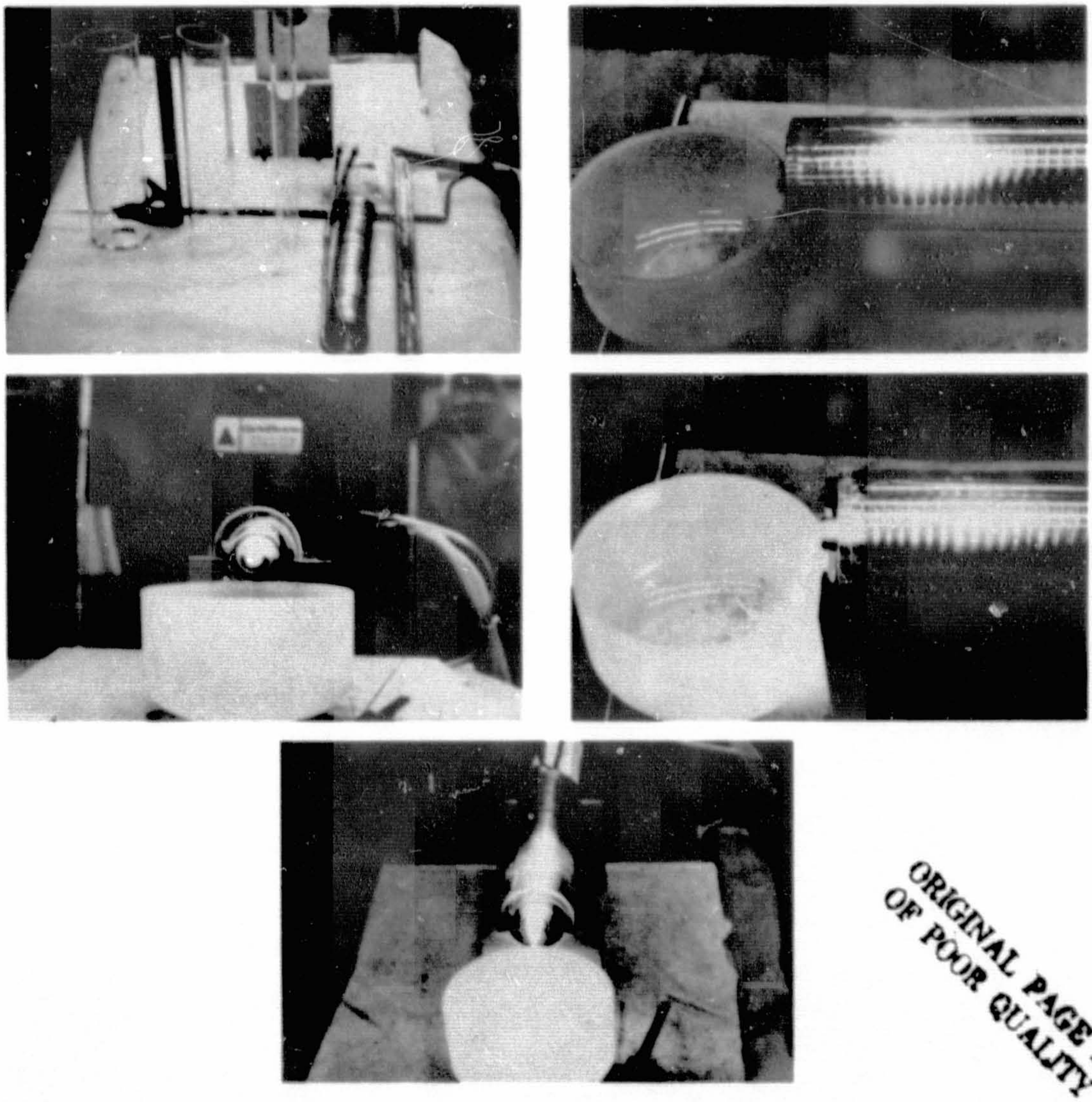
1ST 9½" UNDER MICRO GROWN OD AT 3.17"/HR

1ST 15½" UNDER MICRO AT 3.0"/HR

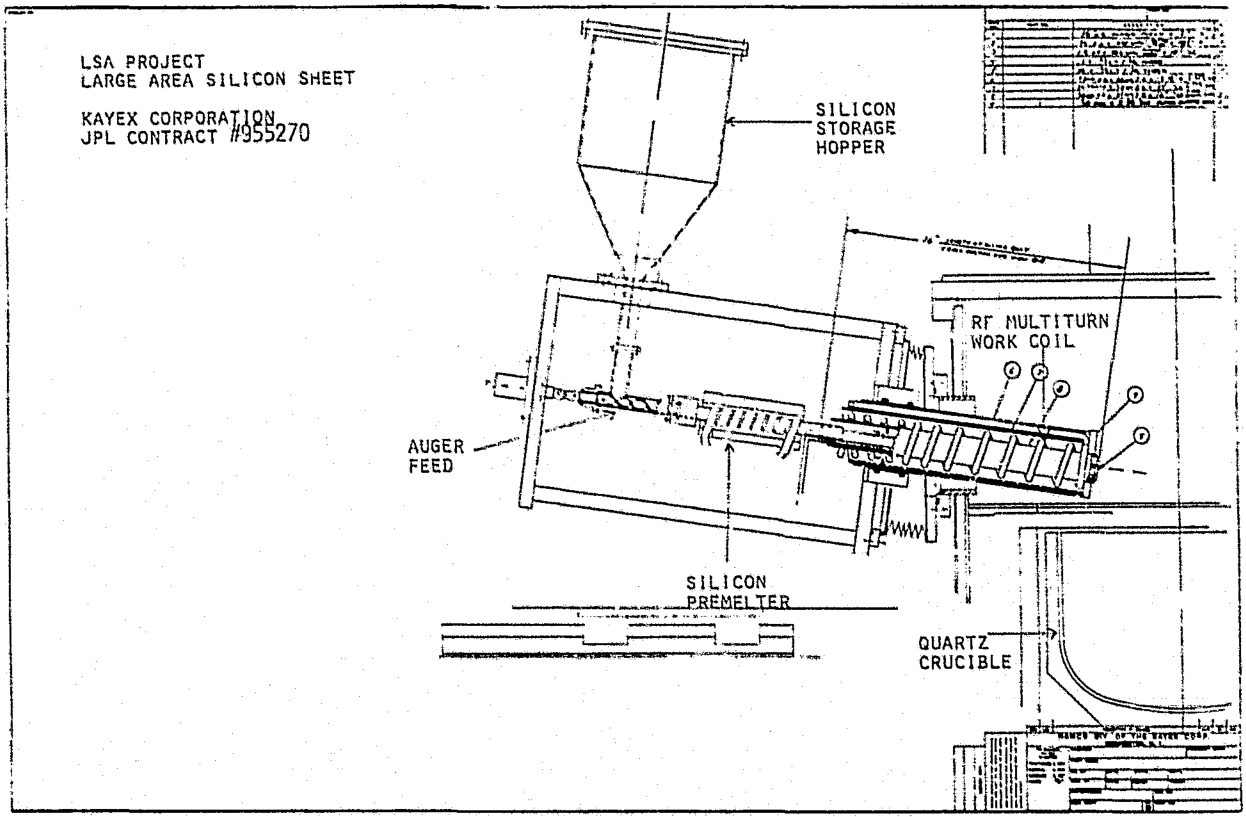
Crucible Thickness Comparison

Cold Crucible Premelter System

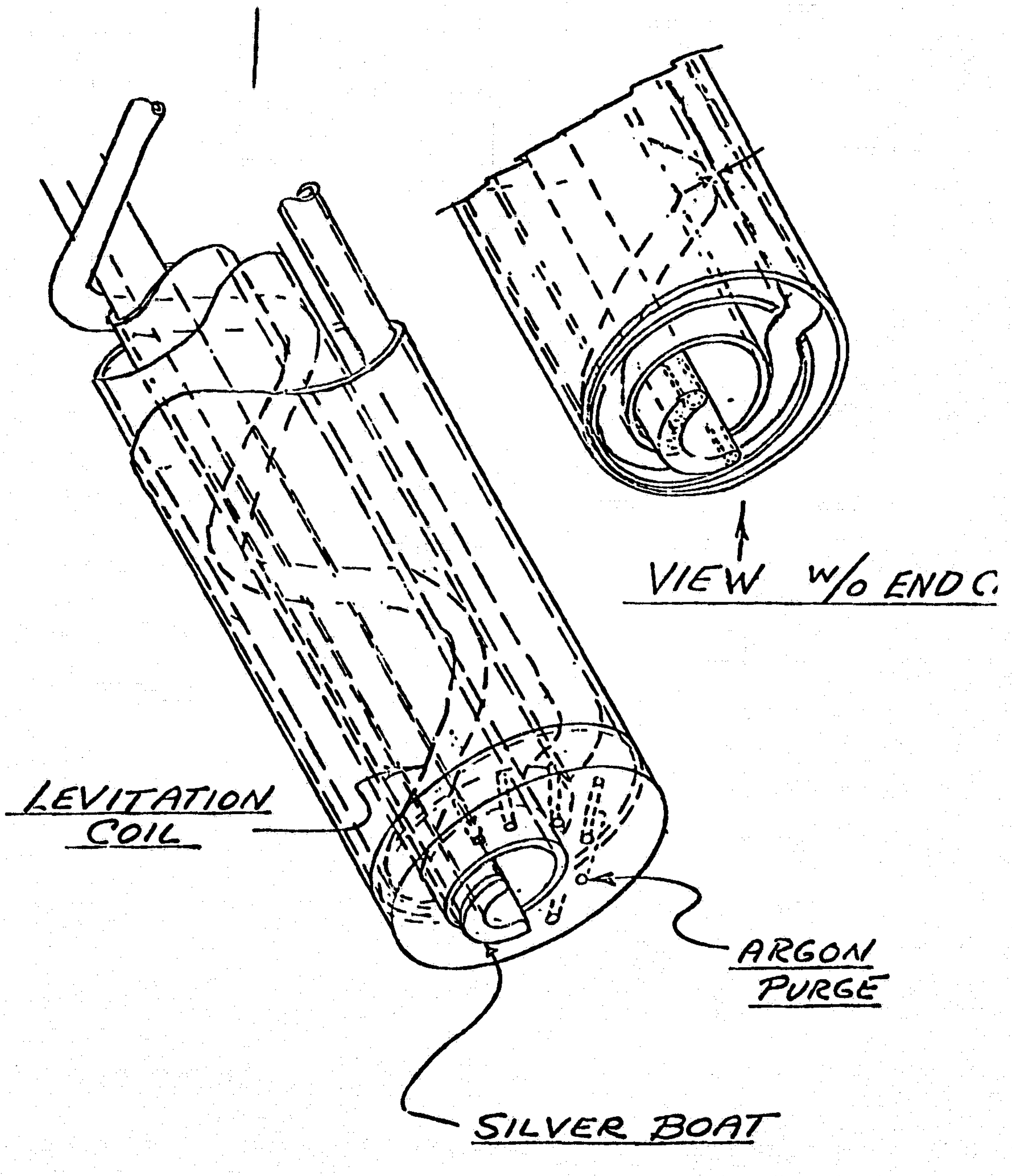
GOALS	
1. COLD CRUCIBLE DESIGN	COMPLETE 3/28/80
2. MODIFIED FURNACE TANK	COMPLETE 4/11/80
3. SILVER BOAT/R.F. COIL ASSEMBLY	COMPLETE 5/8/80
4. MELT/LEVITATION/MELT TRANSFER EXPERIMENTS.	COMPLETE 8/15/80
5. COLD CRUCIBLE/CRYSTAL PULLER INTERFACE	ONGOING



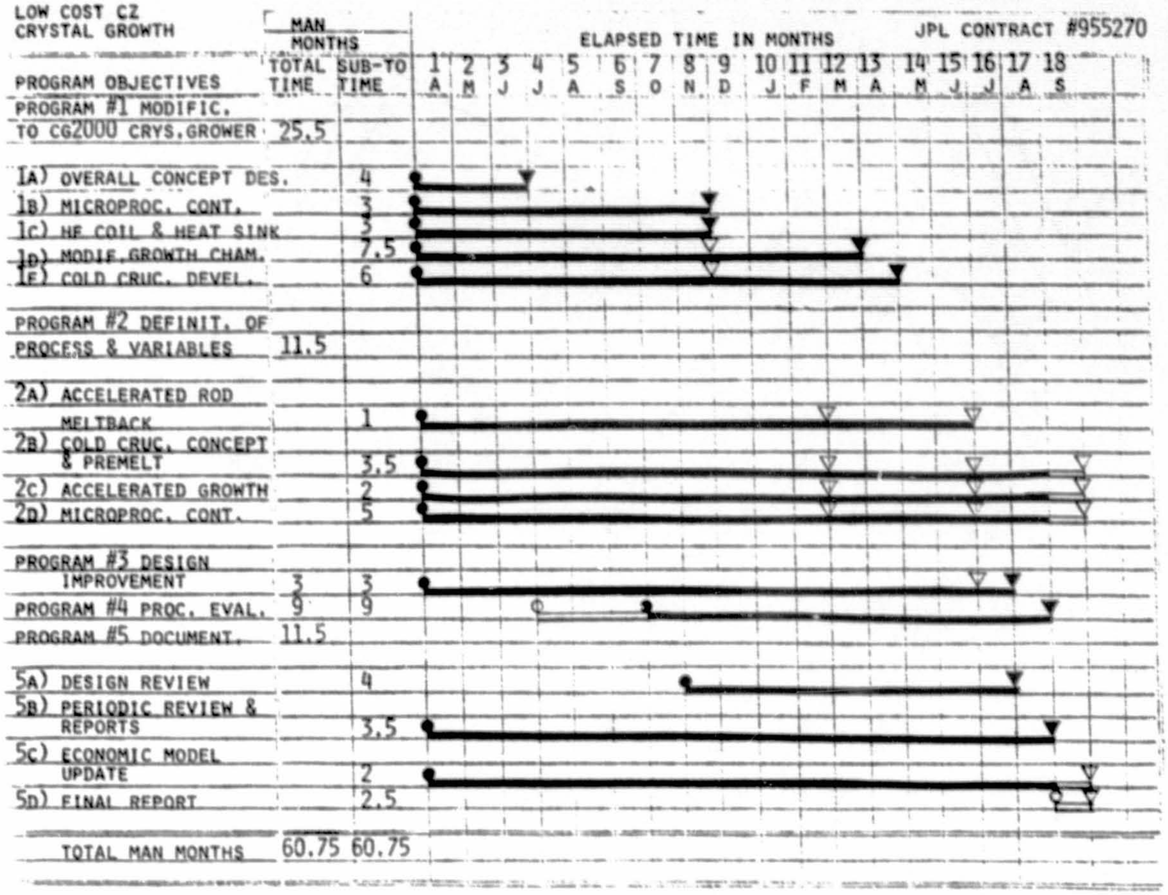
Cold Crucible Views


LSA PROJECT
LARGE AREA SILICON SHEET
KAYEX CORPORATION
JPL CONTRACT #955270
SILICON STORAGE HOPPER
RF MULTITURN WORK COIL
AUGER FEED
SILICON PREMELTER
QUARTZ CRUCIBLE

Cold Crucible Premelter Silver Boat Assembly



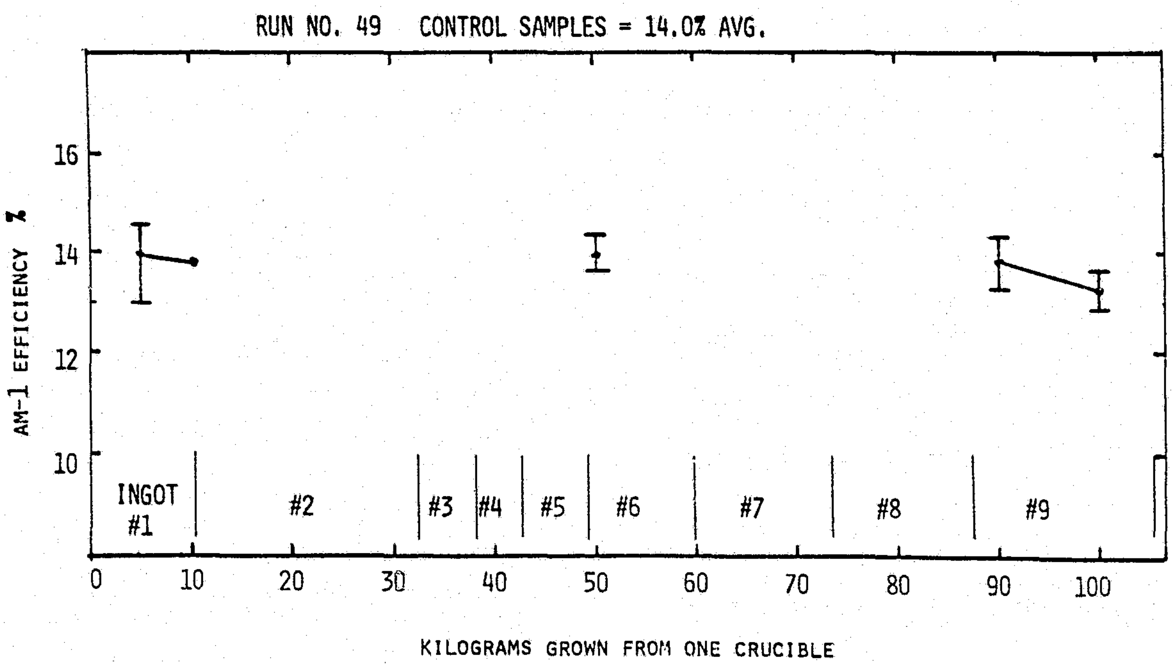
Program Plan: Low-Cost Cz Crystal Growth

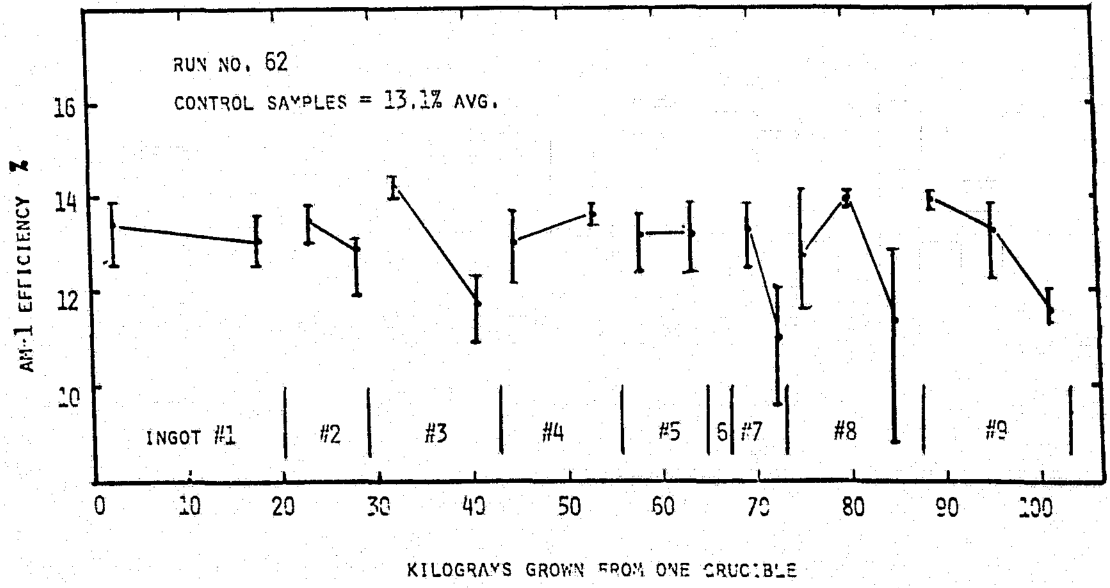


Overall Program Summary

PROGRAM	STATUS
1. MICROPROCESSOR CONTROL	SHOULDER AND STRAIGHT GROWTH DEMONSTRATED FOR 4" AND 6" GROWTH.
2. ACCELERATED GROWTH	PARITALLY DEMONSTRATED
3. COLD CRUCIBLE	ANCILLARY BENEFITS GAINED: A) CLEANER CRYSTALS B) REDUCED OXIDE ON CRUCIBLE WALL
4. ACCELERATED MELTING OF POLY RODS USING R.F. COIL	DEMONSTRATED OFF THE CRYSTAL PULLER TOTAL INTERFACE OF EQUIPMENT TO CRYSTAL PULLER AVAILABLE. PROGRAM DE-EMPHASIZED BY J.P.L.

Solar Efficiency vs Kilograms Grown



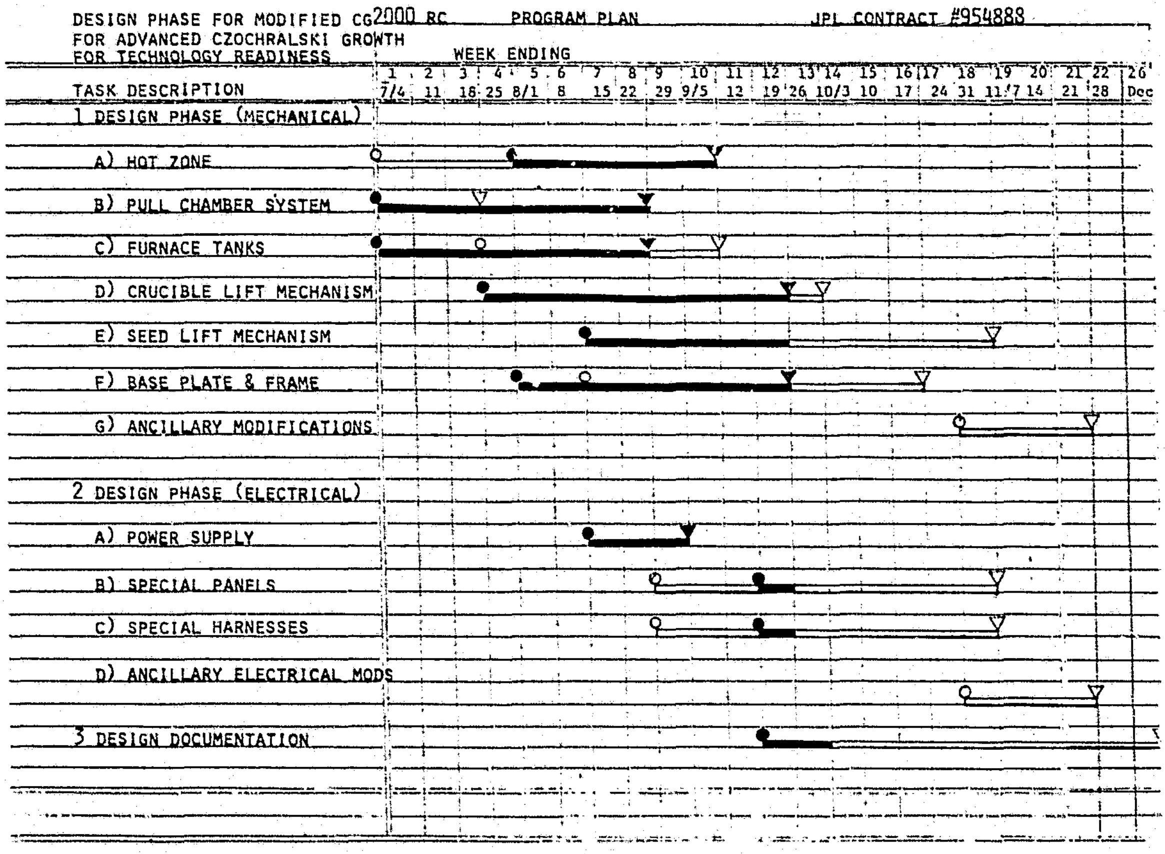


INGOT GROWTH: ADVANCED CZOCHRALSKI

KAYEX CORP.

TECHNOLOGY - INGOT GROWTH	REPORT DATE: SEPTEMBER 24, 1980 START DATE: JULY 1, 1980
<u>APPROACH</u>: DESIGN OF A MODIFIED CG 2000 RC CRYSTAL GROWER FOR ADVANCED CZOCHRALSKI GROWTH FOR TECHNICAL READINESS.	<u>GOALS</u>: DESIGN A MODIFIED CG 2000 RC CRYSTAL GROWER WITH A CAPABILITY OF PULLING FIVE CRYSTALS, EACH OF 30 KG WEIGHT, 150 MMS DIAMETER FROM A SINGLE 16" DIAMETER CRUCIBLE. MODIFICATIONS TO BE AS FOLLOWS: A. OVERALL EQUIPMENT DESIGN B. PROCESS AUTOMATION WITH MPU C. SENSOR DEVELOPMENT: MELT LEVEL; MELT TEMPERATURE; CRYSTAL DIAMETER D. RADIATION SHIELD TO ACCELERATE GROWTH E. RECHARGE RATE OF 25 KG/HR USING SILICON CHUNKS OR GRANULAR SILICON UTILIZING A RECHARGE HOPPER F. MODIFIED GROWTH CHAMBER SUITABLE FOR USE AS A PRODUCTION FACILITY WITH A THROUGHPUT CAPABILITY OF 2.5 KG/HR OF MACHINE THROUGHPUT

Program Plan



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<tr><td>TECHNOLOGY
INGOT GROWTH</td><td>REPORT DATE START DATE
SEPT. 24, 1980 JULY 1, 1980</td></tr>
<tr><td>APPROACH:
EQUIPMENT DESIGN OF A MODIFIED CG 2000 RC CRYSTAL GROWER FOR ADVANCED CZOCHRALSKI GROWTH FOR TECHNOLOGY READINESS.
CONTRACTOR: KAYEX CORPORATION
CONTRACT NO: 954888</td><td rowspan="2">STATUS:
MECHANICAL: DESIGNS COMPLETE FOR ALL MAJOR COMPONENTS AND HOT ZONES.
SEED LIFT DESIGN ONGOING - COMPLETE BY 10/3/80

ELECTRICAL: POWER SUPPLY MODIFICATION REQUIREMENTS COMPLETE.
SPECIAL HARNESSES, PANELS DESIGN ONGOING - COMPLETE BY 10/3/80.
DESIGN DOCUMENTATION: ONGOING - COMPLETE BY 10/31/80.</td></tr>
<tr><td>GOALS:
A. OVERALL EQUIPMENT DESIGN
B. DESIGN DOCUMENTATION</td></tr>
</table>

Thermal American Fused Quartz Co.
incorporated

MAIN OFFICE:
Route 202, Montville, New Jersey 07045
Tel: 201-334-7770 Telex: 136477

TO:
Hamco Machine
1000 Millsteadway
Rochester, NY 114624

Attention: Elwyn Roberts

DATE: May 12, 1980

REFERENCE:

We are pleased to quote as follows:

QUANTITY	DESCRIPTION	UNIT PRICE	TOTAL
	VITREOSIL A.M. CRUCIBLE		
50	16" OD x 12" High 3" Corner Radium/16" Bottom Radius	* $391.00/ea.	
150/mo for 15 mos.		340.00/ea.	
50	15" OD x 12" High w/3" Corner Radius/16" Bottom Radius	322.00/ea.	
150/mo. for 15 mos.		280.00/ea.	
50	14" OD x 12" High w/3.5" Corner Radius/14" Bottom Radius	230.00/ea.	
	Delivery: *Estimated Selling Price for Evaluation Only.		

This quotation is valid for a period of 30 days from the date hereof. However, we reserve the right to revise upon notification to you during this period.

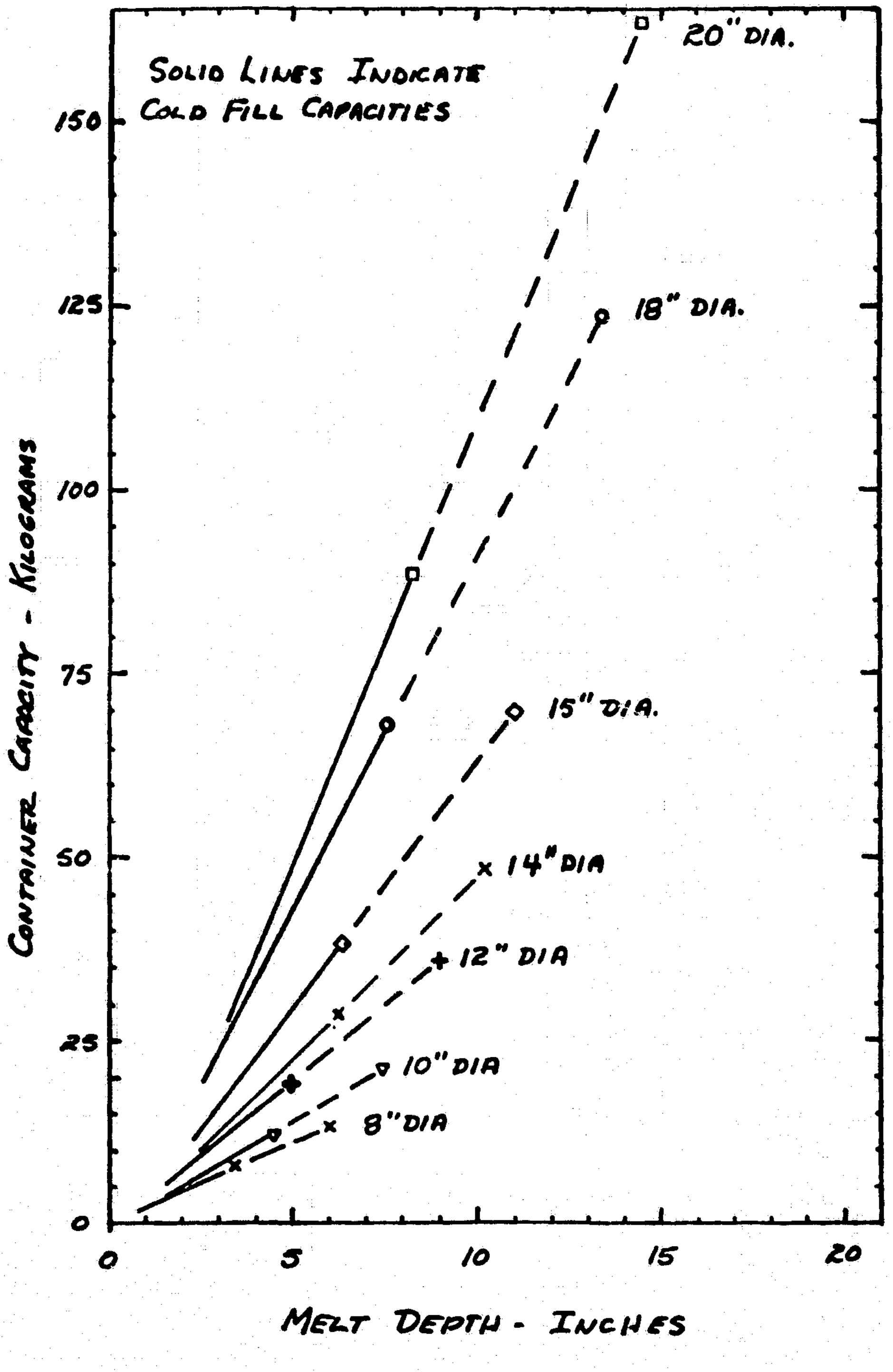
THERMAL AMERICAN FUSED QUARTZ CO.

By: Frank Rusignuolo
Frank Rusignuolo
Title: Salesman

TERMS: 30 Days Net
F.O.B.: Shipping Point

Manufacturers of Transparent & Opaque Fused Silica

Container Capacities



Cz Growth Parameters

LOW COST CZ (POLY LUMP FEED)
15 CMS DIAMETER

CONDITIONS (PER CYCLE)	3"/HR GROWTH	4"/HR GROWTH
CRUCIBLE SIZE (INS)	16	16
CRYSTAL DIAMETER (CMS)	15	15
GROWTH RATE (CMS/HR)	7.62	10.16
TOTAL POLY MELTED (KG)	157.5	157.5
TOTAL CRYSTAL PULLED (KG)	150	150
PULLEY YIELD (%)	95.2	95.2
YIELD AFTER CG (%)	85	85
NO. OF CRYSTALS/CRUCIBLE	4	4
CYCLE TIME (HR)	68.7	57.9

REPORT DATE: SEPT. 24, 1980
START DATE: JULY 1, 1980

Process Time Cycle

OPERATION	LOW COST CZ (3"/HR)		LOW COST CZ (4"/HR)	
1. PREPARATION		180 MINS		180 MINS
LOAD POLY	25		25	
CLOSE FURNACE	5		5	
PUMP DOWN	10		10	
MELT	140		140	
2. GROWTH CYCLE (INITIAL)		826 MINS		664 MINS
LOWER SEED *	15 *		15 *	
STABILIZE TEMP.	30		30	
SEED & CROWN GROWTH	90		90	
STRAIGHT GROWTH	646		484	
TAPER END	60		60	
3. RECHARGE & GROWTH CYCLES		2958 (3 CYCLES)		2472 (3 CYCLES)
COOL CRYSTAL	30		30	
REMOVE CRYSTAL	10		10	
LOAD HOPPER	15		15	
LOWER HOPPER	5		5	
MELT POLY LUMP	100		100	
LOWER SEED *	15 *		15 *	
STABILIZE TEMPERATURE	30		30	
SEED GROWTH	30		30	
CROWN GROWTH	60		60	
STRAIGHT GROWTH	646		484	
TAPER END	60		60	

* COMPLETED DURING MELT TEMPERATURE STABILIZATION

	LOW COST CZ (3"/HR)		LOW COST CZ (4"/HR)	
4. SHUT DOWN CYCLE		160 MINS		160 MINS
COOL FURNACE	80		80	
REMOVE CRYSTAL *	10 *		10 *	
CLEAN, SET UP	80		80	

* COMPLETED DURING FURNACE COOLING TIME.

TOTAL TIME (MIN)	4124	3476
(HRS)	687	579

SAMICS/IPEG INPUT DATA AND COST CALCULATION

CONDITIONS (PER CYCLE)	3"/HR GROWTH	4"/HR GROWTH
TOTAL SI MELTED (KG)	157.5	157.5
CRYSTAL WEIGHT (KG)	37.5	37.5
NO. CRYSTALS/CRUCIBLE	4	4
DIAMETER OF CRYSTALS (CM)	15	15
GROWTH RATE (CM/HR)	7.62	10.16
CYCLE TIME (HRS)	68.7	57.9
CRUCIBLE SIZE (INS)	16	16

INPUT DATA ($1980)

CAPITAL EQUIP. COST (EQPT)	167500	167500
MANUFACTURING FLOOR SPACE (SQFT)	100	100
ANNUAL DIRECT SALARIES		
PROD OP. (0.65 PERSONS/YR)	8554	8554
ELECT. TECH. (0.33 PERSONS/YR)	5082	5082
INSPECTOR (0.1 PERSONS/YR)	1155	1155
TOTAL D/LAB	14791	14791

Calculation: 4 × 37.5 kg Crystals × 6-in. Dia Using Mod. CG 2000 RC and 16-in. Crucibles @ $391 ea.

IPEG PRICE

C1 EQPT = $ 0.49/YR = $ EQPT	$ 82075	$ 82075
C2 SQFT = $ 97/YR = $ SQFT	9700	9700
C3 DLAP = $ 2.1/YR = $ DLAB	31061	31061
C4 MATS = $ 1.3/YR = $ MATS	123819	134377
C5 UTIL = $ 1.3/YR = $ UTIL	39213	38917
ANNUAL COST	$285868	$296130

QUAN (TOTAL CHARGE X % YIELD) (KG) =	14458 KG	17163 KG
THROUGHPUT =	1.95 KG	2.3 KG
ADD ON COST ($KG OR $M^2	$ 19.77	$ 17.25
(ASSUME 1 KG = 1 M^2)		

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS: PRODUCING 4 x 37.5 KG CRYSTALS FROM A 16" DIAMETER CRUCIBLE

	LOW COST CZ (3"/HR GROWTH)	LOW COST CZ (4"/HR GROWTH)
C1 EQPT = $0.49/YR = $EQPT	$ 82,075	$ 82,075
C2 SQFT = $97/YR = $SQFT	9,700	9,700
C3 DLAB = $2.1/YR = $DLAB	31,061	31,061
C4 MATS = $1.3/YR = $MATS	123,819	134,377
C5 UTIL = $1.3/YR = $UTIL	39,213	38,917
TOTAL =	$ 285,868	$ 296,130
QUAN (TOTAL CHARGED × % YIELD)(KG)	=14,458KG	=17,153KG
THROUGHPUT	= 1.95/KG	= 2.3/KG

PROJECTION

ASSUME $1M^2$ = 1 KG

LOW COST CZ (3"/HR GROWTH)	LOW COST CZ (4"/HR GROWTH)
CZ ADD ON COST =	CZ ADD ON COST =
$ 19.77/KG	$ 17.25/KG
= $ 0.1394/PEAK WATT	= $ 0.1217/PEAK WATT

DIRECT USED MATERIALS & SUPPLIES 85% USAGE/YEAR		
CYCLES/YR HRS/CYCLE	108/687	1282/57.9
POLY-KG/YR CHARGED	17010	20191.5
SEED ($20)	1080	1282
DOPANT (NOT COSTED)		
ARGON (100FT^3/CYCLE HR @ $0.02/FT^3)	14839	14845
CRUCIBLES (16" @ $3.91 EA.)	42228	50126
MISCELLANEOUS (INCLUDING GRAPHITE AT $5/CYCLE HR)	37098	37114
MATERIALS TOTAL (MATS)	$ 95245	$ 103367
UTILITIES (PROCESS)		
ELECTRICITY (100 KW x 0.035/KW)(CYCLE TIME - 3 HRS) X (# OF CYCLES)	$ 24834	$ 24633
COOLING WATER (100 KW x 0.0074/KW)(CYCLE TIME - 2 HRS) X (# OF CYCLES)	$ 5330	$ 5303
UTILITIES TOTAL (UTIL)	$ 30164	$ 29936

Cz Growth Parameters

LOW COST CZ (POLY LUMP FEED)
15 CMS DIAMETER

CONDITIONS (PER CYCLE)	3"/HR GROWTH	4"/HR GROWTH
CRUCIBLE SIZE (INS)	15	15
CRYSTAL DIAMETER (CMS)	15	15
GROWTH RATE (CMS/HR)	7.62	10.16
TOTAL POLY MELTED (KG)	157.5	157.5
TOTAL CRYSTAL PULLED (KG)	150	150
PULLED YIELD (%)	95.2	95.2
YIELD AFTER CG (%)	95	85
NO. OF CRYSTALS/CRUCIBLE	5	5
CYCLE TIME (HRS)	74.75	64.0

Process Time Cycle

OPERATION	LOW COST CZ (3"/HR)		LOW COST CZ (4"/HR)	
1. PREPARATION		165 MINS		165 MINS
LOAD POLY	25		25	
CLOSE FURNACE	5		5	
PUMP DOWN	10		10	
MELT	125		125	
2. GROWTH CYCLE (INITIAL)		772 MINS		643 MINS
MELT POLY LUMP	75		75	
LOWER SEED *	15 *		15 *	
STABILIZE TEMP.	30		30	
SEED & CROWN GROWTH	90		90	
STRAIGHT GROWTH	517		388	
TAPER END	60		60	
3. RECHARGE/GROWTH CYCLES		3,388		2,872
COOL CRYSTAL	30	(4 CYCLES)	30	(4 CYCLES)
REMOVE CRYSTAL	10		10	
LOAD HOPPER	15		15	
LOWER HOPPER	5		5	
MELT POLY LUMP	90		90	
LOWER SEED *	15 *		15 *	
STABILIZE TEMP.	30		30	
SEED GROWTH	30		30	
CROWN GROWTH	60		60	
STRAIGHT GROWTH	517		388	
TAPER END	60		60	

* COMPLETED DURING STABILIZATION OF MELT TEMPERATURE

OPERATION	LOW COST CZ (3"/HR)		LOW COST CZ (4"/HR)	
4. SHUT DOWN CYCLE		160 MINS		160 MINS
COOL FURNACE	80		80	
REMOVE CRYSTAL**	10**		10**	
CLEAN, SET UP	80		80	

** COMPLETED DURING FURNACE COOLING TIME

TOTAL TIME	(MIN)	4485	(MIN)	3840
	(HRS)	74.75	(HRS)	64

SAMICS/IPEG INPUT DATA AND COST CALCULATION

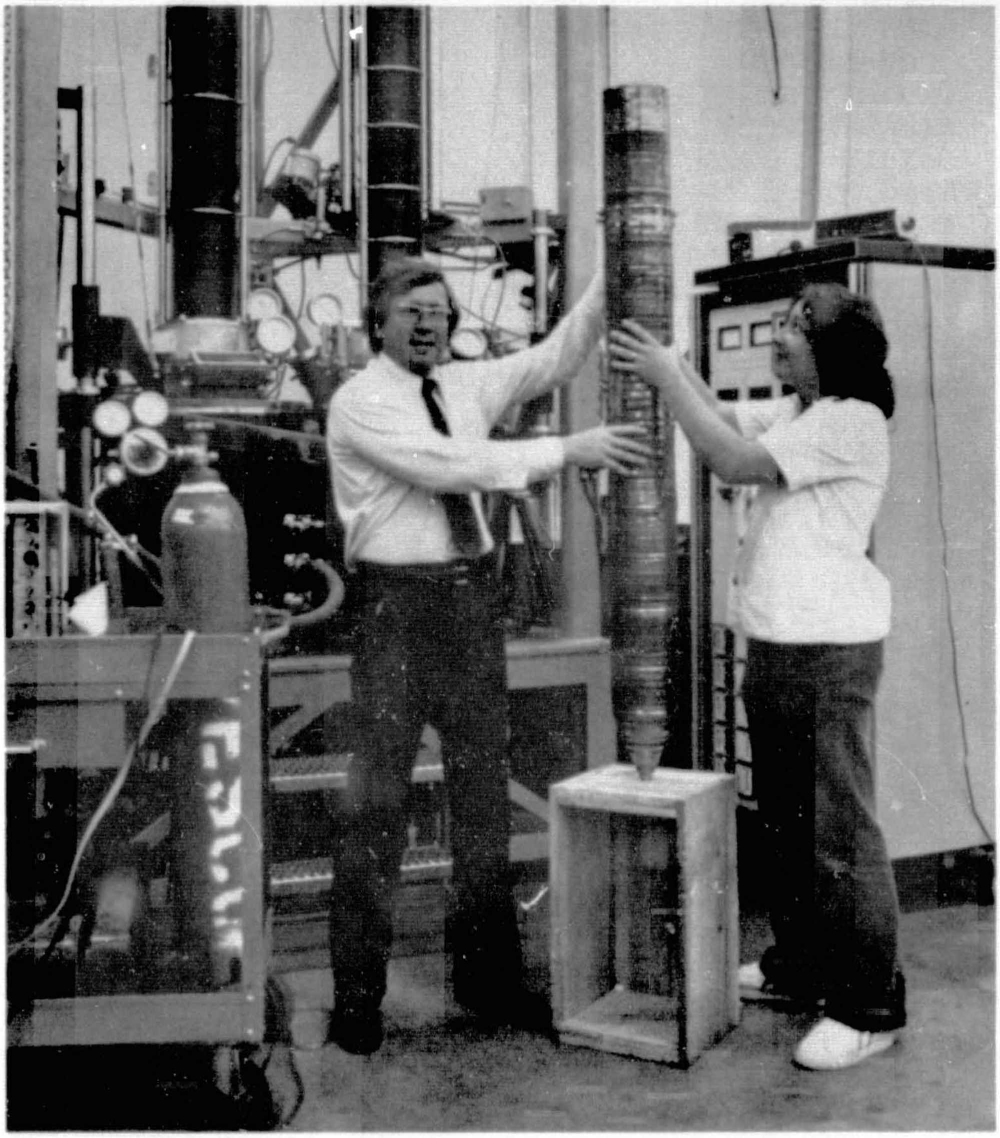
CONDITIONS (PER CYCLE)-3"/HR GROWTH		4"/HR GROWTH
TOTAL Si MELTED (KG)	170	170
CRYSTAL WEIGHT (KG)	37.5	37.5
NO. CRYSTALS/CRUCIBLE	4	4
DIAMETER OF CRYSTAL (CMS)	15	15
GROWTH RATE (CM/HR)	7.62	10.16
CYCLE TIME (HRS)	73.8	62.3
CRUCIBLE SIZE (INS)	15"x 12"	15" x 12"

INPUT DATA ($1980)	167500		
	100		
CAPITAL EQUIP. COST (EQPT)		167,500	167,500
MANUFACTURING FLOOR SPACE (SQFT)		100	100
ANNUAL DIRECT SALARIES			
PROD. OP. (0.65 PERSONS/YR)		8,554	8,554
ELECT. TECH. (0.3 PERSONS/YR)		5,082	5,082
INSPECTOR (0.1 PERSONS/YR)		1,155	1,155
TOTAL D/LAB		14,791	14,791

DIRECT USED MATERIALS & SUPPLIES 85% USAGE/YEAR	LOW COST CZ (3"/HR GROWTH)	LOW COST CZ (4"/HR GROWTH)
CYCLES/YE HRS/CYCLE	99.3/74.75	116/64
POLY-KG/YR CHARGED	15640	18270
SEED ($20)	993	1160
DOPANT (NOT COSTED)	14845	
ARGON (100 FT^3/CYCLE HR @ $0.02/FT^3)	31974	14848
CRUCIBLES (15" @ $322 EA.)	29691	37352
MISCELLANEOUS (INCLUDING GRAPHITE AT $4/CYCLE HR)		29696
MATERIALS TOTAL (MATS)	$ 77503	$ 83056
UTILITIES (PROCESS)		
ELECTRICITY (100 KW x 0.035/KW)(CYCLE TIME - 3 HRS) X (# OF CYCLES)	$ 24936	$ 24766
COOLING WATER (100 KW x 0.035/KW)(CYCLE TIME - 2HRS) X (# OF CYCLES)	$ 5346	$ 5322
UTILITIES TOTAL (UTIL)	$ 30282	$ 30088

IPEG PRICE	LOW COST CZ (3"/HR GROWTH)	LOW COST CZ (4"/HR GROWTH)
C1 EQPT = $0.49/YR - $EQPT	82075	82075
C2 SQFT = $97/YR - $SQFT	9700	9700
C3 DLAB = $2.1/YR - $DLAB	31061	31061
C4 MATS = $1.3/YR - $MATS	100754	107973
C5 UTIL = $1.3/YR - $UTIL	39366	39114
ANNUAL COST	$ 262956	$ 269923

QUAN.(TOTAL CHARGE X % YIELD)(KG)	=	13294 KG	15529 KG
THROUGHPUT	=	1.79 KG/HR	2.09 KG/HR
ADD ON COST ($KG OR $M^2) (ASSUME 1 KG = 1 M^2)	=	$ 19.78	$ 17.38
	=	$0.1395/PEAK WATT	$ 0.1226/PEAK WATT



Cost Projections (1980 $) SAMICS/IPEG

ASSUMPTIONS:

Equipment cost $160,000 (machines in quantity, with μprocessor control)
1 operator/4 pullers
90% equipment utilization
10 cm/hr growth velocity (6"∅ , 4 kg/hr)
56.85 hrs run cycle time
150 kg run size 3 ingots/run, 86% growing yield

PROJECTION

$12.75/kg crystal add on cost
$\$11.88/\mathrm{m}^2$ (25 slices/cm)

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS: PRODUCING 5 X 30 KG CRYSTALS FROM A 15" DIAMETER CRUCIBLE

	LOW COST CZ (3"/HR GROWTH)	LOW COST CZ (4"/HR GROWTH)
C1 EQPT = $0,49/YR = $EQPT	$ 82,075	$ 82,075
C2 SQFT = $97/YR = $SQFT	9,700	9,700
C3 DLAB = $2.1/YR = $DLAB	31,061	31,061
C4 MATS = $1.3/YR = $MATS	106,754	107,973
C5 UTIL = $1.3/YR = $UTIL	39,366	39,114
TOTAL	=$ 262,956	=$269,923
QUAN (TOTAL CHARGED X % YIELD)(KG)	= 13,294KG	= 15,529KG
THROUGHPUT	= 1.79KG	2.09KG

PROJECTION

ASSUME $1M^2$ = 1KG

LOW COST CZ (3"/HR GROWTH)
CZ ADD ON COST = $ 19.78/KG
= $ 0.1395/PEAK WATT

LOW COST CZ(4"/HR GROWTH)
CZ ADD ON COST = $17.38/KG
= $ 0.1226/PEAK WATT

CONTINUOUS LIQUID-FEED Cz GROWTH

SILTEC CORP.

TECHNOLOGY ADVANCED CZOCHRALSKI	REPORT DATE 09/25/80
APPROACH CONTINUOUS LIQUID FEED CZ - GROWTH CONTRACTOR SILTEC CORPORATION	STATUS
GOALS . 150 KG OF INGOTS/CRUCIBLE . 15 CM DIAMETER INGOTS . 2 KG/HR GROWTH RATE . AUTOMATION . 90% YIELD . 16.9% SOLAR CELL EFFICIENCY . TECHNICAL FEATURES DEMO 03/31/80 . TECHNOLOGY READINESS 11/30/81	INDIVIDUAL ACCOMPLISHMENTS . 100 KG OF INGOT/CRUCIBLE . 15 CM DIAMETER INGOTS . 2.5 KG/HR GROWTH RATE . UNDER DEVELOPMENT (50% COMPLETE) . 85% YIELD . SOLAR CELL EFFICIENCY (DATA NOT YET AVAILABLE) SIMULTANEOUS ACCOMPLISHMENTS . 48 HOURS (2.1 KG/HR) THROUGHPUT

Problems and Concerns

PRODUCTION PROTOTYPE DEMONSTRATION IS TO BE ACCOMPLISHED WITHIN EXTREMELY SHORT TIME PERIOD.

SEMICRYSTALLINE CASTING PROCESS DEVELOPMENT AND VERIFICATION

SEMIX-DOE COOPERATIVE AGREEMENT

SEMIX INC.

Z. Putney

Agreement Objectives

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

*** ALLOCATION BASED UPON JPL PRICE GUIDELINES**

Basic Terms

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

Semix Semicrystalline Material

Technical Advantages

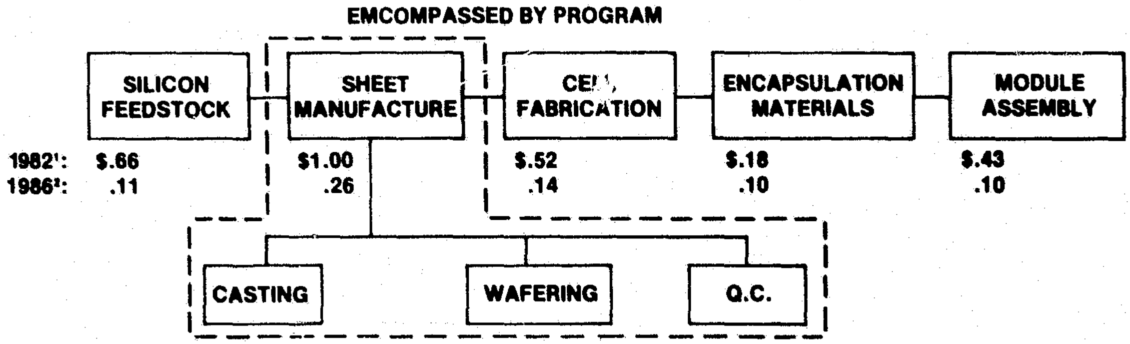
- **ELECTRICAL EFFICIENCY:**
  COMPARABLE -17% DEMONSTRATED (2x2cm.)
  TO CZ - 10-14% PRODUCTION (10x10cm)
- **SILICON MASS YIELD:**
  PROJECTED 98% vs. 85% FOR ROUND CZ
- **AREA RELATED SAVINGS PACKING DENSITY:**
  96% VS. 78% FOR ROUND CZ
- **FASTER SAWING RATE DUE TO FLAT TOP (MBS)**
- **COMPARABLE OR HIGHER MECHANICAL STRENGTH:**
  22.3 K.P.S.I.
  RUPTURE MODULUS VS.
  20.3 FOR SINGLE SRYSTAL
- **HIGH IMPURITY TOLERANCE**
- **LOW ENERGY, EQUIPMENT AND PRODUCTION COSTS**

ALL OF THE ABOVE ELEMENTS WILL BE VERIFIED BY JPL UNDER THIS AGREEMENT

LARGE-AREA SILICON SHEET TASK

Process Flow and Price Allocation

1982[1] $2.80/WP (MODULE)
1986[2] $.70/WP (MODULE)



1. PRICE ALLOCATION GUIDELINES
   J.P.L. LOW CAST SOLAR ARRAY 5101-68
   R.W. ASTER, MAY 12, 1978
2. PRICE ALLOCATION GUIDELINES
   J.P.L. LOW COST SOLAR ARRAY 5101-68 - REVISION A
   R.W.ASTER, JANUARY 15, 1980

Agreement Outline

PHASE I - JUNE 1980 - JUNE 1981

- TASK 1 - DEMONSTRATE PROOF OF CONCEPT FOR SEMICRYSTALLINE PROCESS
- TASK 2 - PROOF OF CONCEPT REPORT
- TASK 3 - PRELIMINARY DESIGN, ANALYSIS AND PROTOTYPE EVALUATION
- TASK 4 - CRITICAL SUBSYSTEM DESIGN, ASSEMBLY AND TEST
- TASK 5 - PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION FOR 1986 GOALS

PHASE II - JUNE 1981 - JUNE 1982

- TASK 6 - DETAILED DESIGN AND EXPERIMENTAL EVALUATION OF CRITICAL SYSTEMS
- TASK 7 - ANALYSIS AND DESIGN OF INTEGRATED PRODUCTION SYSTEM
- TASK 8 - TECHNICAL AND ECONOMIC EVALUATION FOR 1986 GOALS

PHASE III - JUNE 1982 - JUNE 1983

- TASK 9 - EPSDU SYSTEM ASSEMBLY AND CHECKOUT
- TASK 10 - PROCESS VERIFICATION OF COMMERCIAL READINESS FOR 1982 GOALS
- TASK 11 - DEMONSTRATION OF TECHNOLOGY READINESS FOR 1986 GOALS

ENHANCED ID SLICING

SILTEC CORP.

EXPERIMENT NO.	DIA MM	SLICE THICKNESS MILS	KERF MILS	FEED RATE INCH/MIN	NO. OF CUTS	YIELD %	FORM OF CUTTING
15	100	10	10	2.0	100	90%	I.R.
16	100	10	10	1.5	100	95%	I.R.
17	100	10	8	1.0	100	90%	I.R.
18	100	12	8	1.5	100	95%	I.R.
19	100	12	7	0.8	50	70%	I.R.
20	100	10	7	0.6	50	65%	I.R.
21	100	15	6	0.25	20	70%	I.R.
22	100	10	6	0.25	20	50%	I.R.
23	150	12	12	2.0	50	85%	P.C.
24	150	12	10	2.0	25	80%	P.C.

Cost Projections (1980 $) SAMICS-IPEG

ASSUMPTIONS: MACHINE COST $30,000
1 OPERATOR/6 SAWS
150 MM INGOT DIAMETER
PRODUCTIVITY/MACHINE/24 HOURS 900 WAFERS
CUTS/BLADE 2000
SLICING YIELD 95%

PROJECTION

$10.48/$M^2$ WAFERING ADD ON COST - 150 MM
$11.58/$M^2$ WAFERING ADD ON COST - 100 MM

LARGE-AREA SILICON SHEET TASK

TECHNOLOGY ADVANCED INGOT WAFERING	REPORT DATE 09/25/80
APPROACH ENHANCED I.D. SLICING CONTRACTOR SILTEC CORPORATION	STATUS
GOALS . 25 WAFERS/CM OF INGOT (250 μM THICK, 152 μM KERF) . 10 CM DIA WAFERS . 1.0 WAFERS/MIN . 95% YIELD . TECHNICAL FEATURES DEMO 10/31/80 . TECHNOLOGY READINESS 11/30/81	. 22 WAFERS/CM OF INGOT 0.5 WAFERS/MIN, 100 MM DIA . 25 WAFERS/CM OF INGOT 0.25 WAFERS/MIN, 100 MM DIA . 150 CM WAFERS . 0.5 WAFERS/MIN . 90% YIELD

LARGE-AREA SILICON SHEET TASK

INGOT SLICING (MBS)

P.R. HOFFMAN CO.

TECHNOLOGY
INGOT SLICING

APPROACH
MULTI-BLADE SLURRY TECHNIQUE (MBS)

CONTRACTOR
P. R. HOFFMAN CO. (NORLIN IND.)

GOALS
- 10 CM DIAMETER WORKPIECE
- 455 PARALLEL SLICES
- 25 WAFERS/CM
- 95% YIELD
- $13.70/M^2 (1980$)

REPORT DATE
5/23/80

STATUS
- 10 CM DIAMETER WORKPIECE
- 400 PARALLEL SLICES
- 18 WAFERS/CM

DEMONSTRATION
- 95% YIELD
- 1.5 MIL/MIN CUT RATE

Demonstrated Technology (Various Tests)

. 400 WAFERS/RUN	10 CM WORKPIECE
. 100% YIELD	5 CM WORKPIECE
. 20 WAFERS/CM	5 CM WORKPIECE
. 1.5 ML/MIN CUT RATE	10 CM WORKPIECE

EQUIV. 0.17 WAFERS/MIN @ 455 WAFERS/RUN

Cost Projections (1980 $) IPEG

ASSUMPTIONS:

EQUIPMENT COST - $42K/MACHINE
FLOOR SPACE - 36 SQ. FT.
1 OPERATOR/15 UNITS
EXPENDABLES/RUN - $140.89 (BLADE PACK, OIL, ABRASIVE)
455 WAFERS/RUN (20 WAFERS/CM)
45 HOUR RUN TIME
95% YIELD
95% DUTY CYCLE

PROJECTION:
$104.4/$M^2$ VALUE ADDED

Problems and Concerns

- SEVERAL DESIGN IMPROVEMENTS APPEAR NECESSARY TO OPTIMIZE THE MBS TECHNOLOGY INCLUDING: SAW CAPACITY, FEED FORCE CONTROL, INGOT MOUNTING AND WAFER SUPPORT.

- SEVERAL PROCESS IMPROVEMENTS ARE NECESSARY TO OPTIMIZE THE MBS TECHNOLOGY INCLUDING DEFINITION OF OPTIMUM FEED RATES, BLADE HEAD SPEEDS, SLURRY FORMULATION, SLURRY VOLUME AND DELIVERY, AND BLADE ALIGNMENT TECHNIQUES.

- SIGNIFICANT COST REDUCTION IN CONSUMABLE ITEMS MUST BE REALIZED.

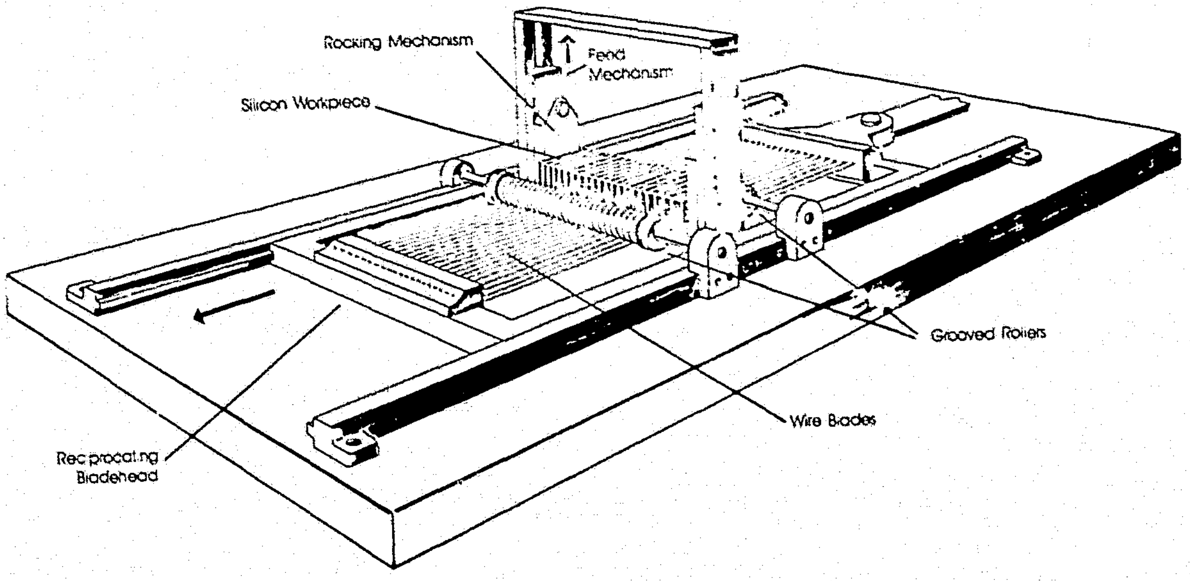
- EVALUATE DESIGN CONSTRAINTS
- DEVELOP DESIGN IMPROVEMENTS
- EVALUATE PROCESS CONSTRAINTS
- DEVELOP PROCESS IMPROVEMENTS
- EVALUATE ALTERNATIVE CONSUMABLES
- DEFINE OPTIMUM SAW DESIGN
- DEFINE OPTIMUM PROCESS
- PROVIDE SAW DESIGN CONSISTENT WITH DEFINITION OF OPTIMIZED PROCESS/DESIGN

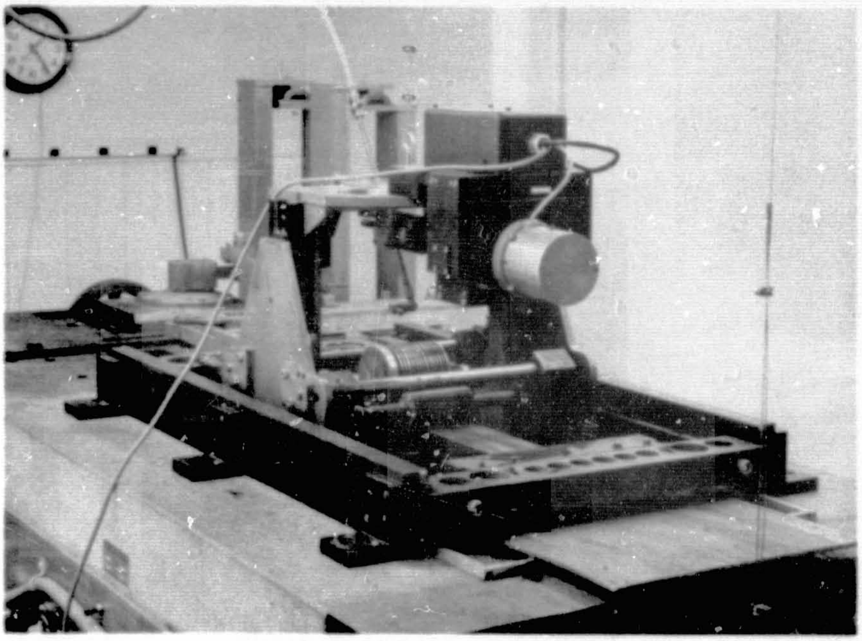
- MICROPROCESSOR FEED FORCE CONTROL
- WAFER LIFT-OFF/SUPPORT DEVICE
- INGOT MOUNTING/DEMOUNTING SYSTEM
- NEW BLADE HEAD DESIGN
- NEW SAW DESIGN
- BLADE PACKAGE SPECIFICATIONS
- ABRASIVE PARTICLE SIZE
- ABRASIVE/VEHICLE RATIO
- SLURRY APPLICATION METHODS (DELIVERY SYSTEM)
- SLURRY APPLICATION METHODS (VOLUME)
- BLADE HEAD SPEED
- FEED FORCE/CUTTING RATE
- EVALUATE VEHICLE RECYCLING
- EVALUATE ABRASIVE RECYCLING
- INVESTIGATE ALTERNATIVE VEHICLES
- INVESTIGATE ALTERNATIVE ABRASIVES

MULTIWIRE SLICING (FAST)

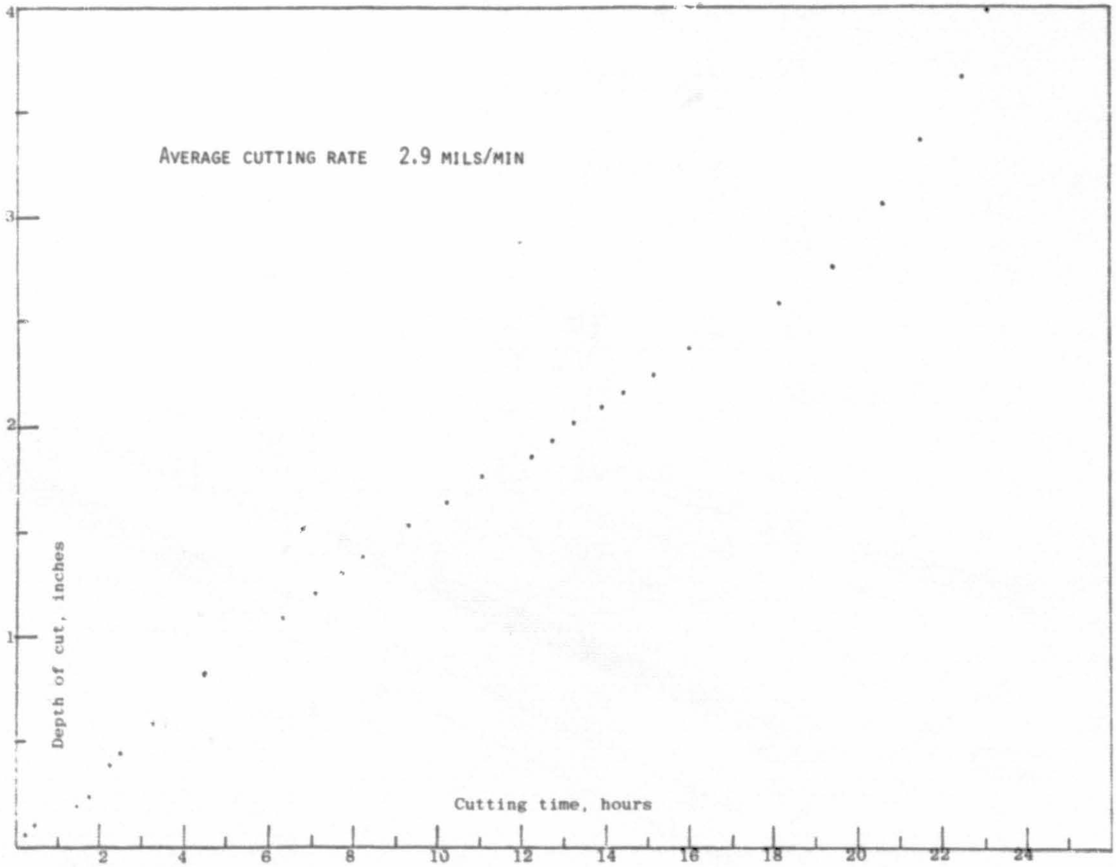
CRYSTAL SYSTEMS, INC.

F. Schmid and C. P. Khattak

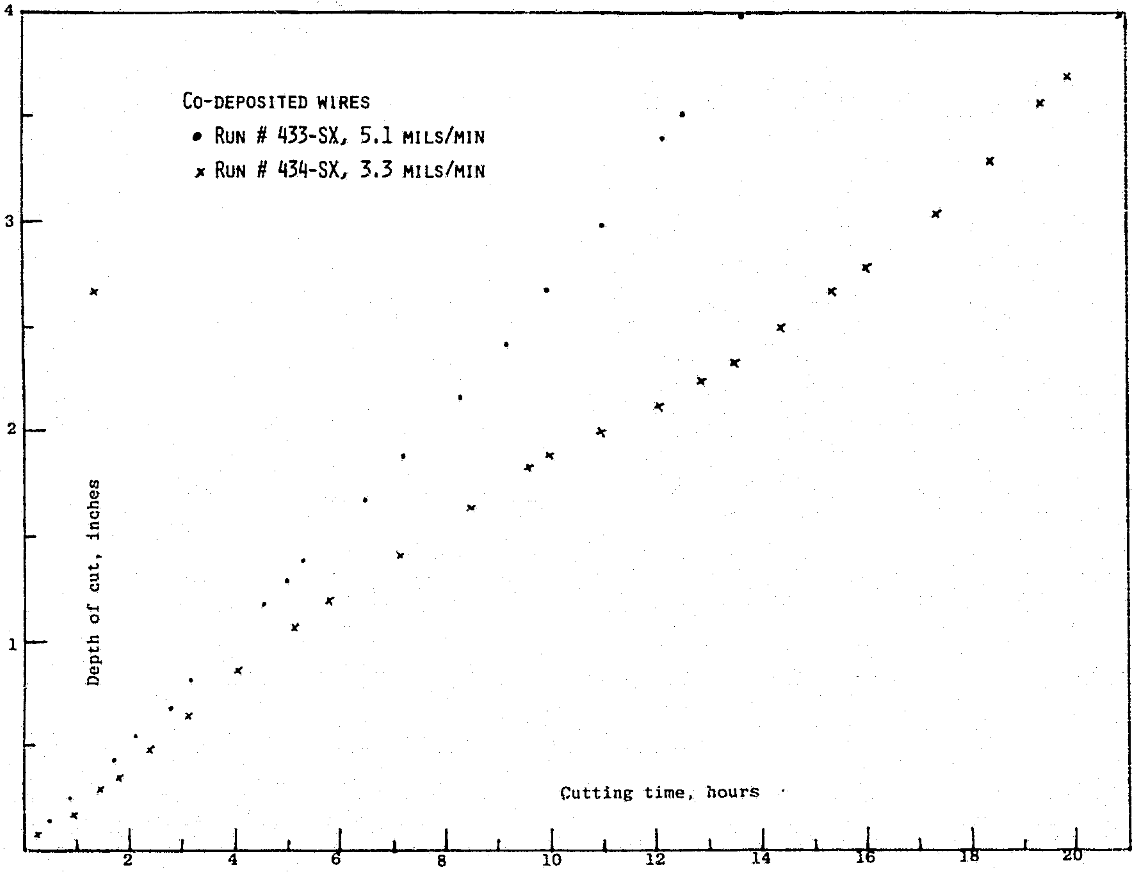


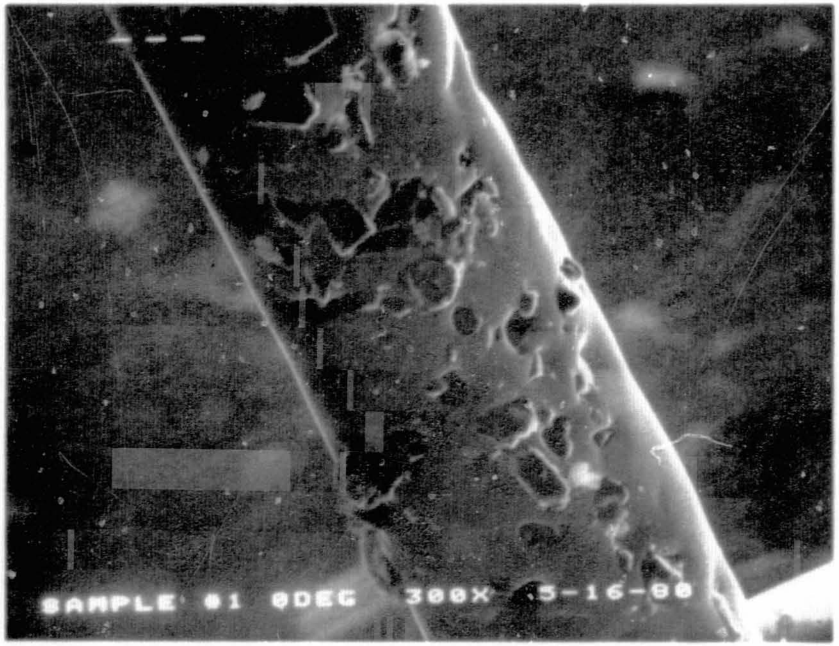


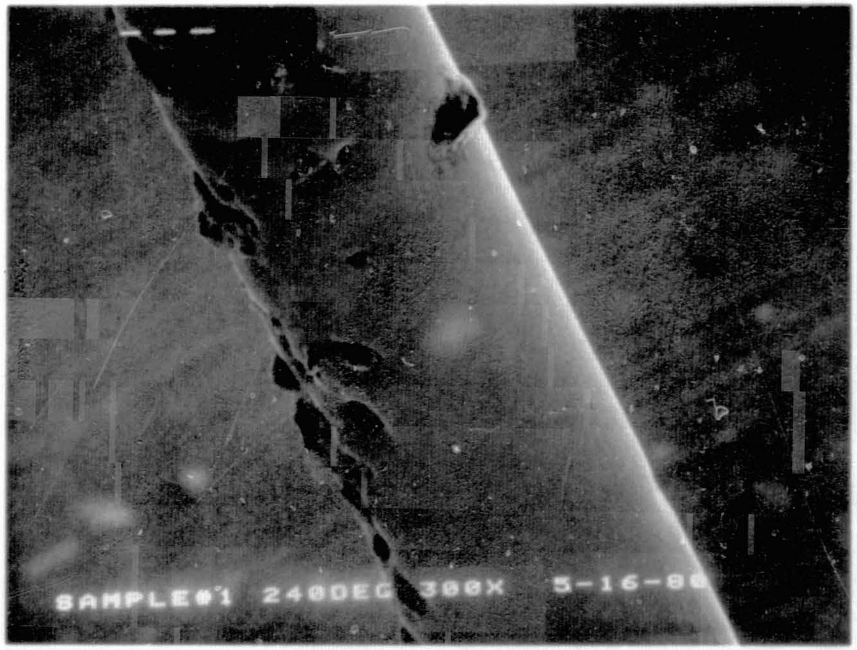
Impregnated Wires (Run #432-SX)

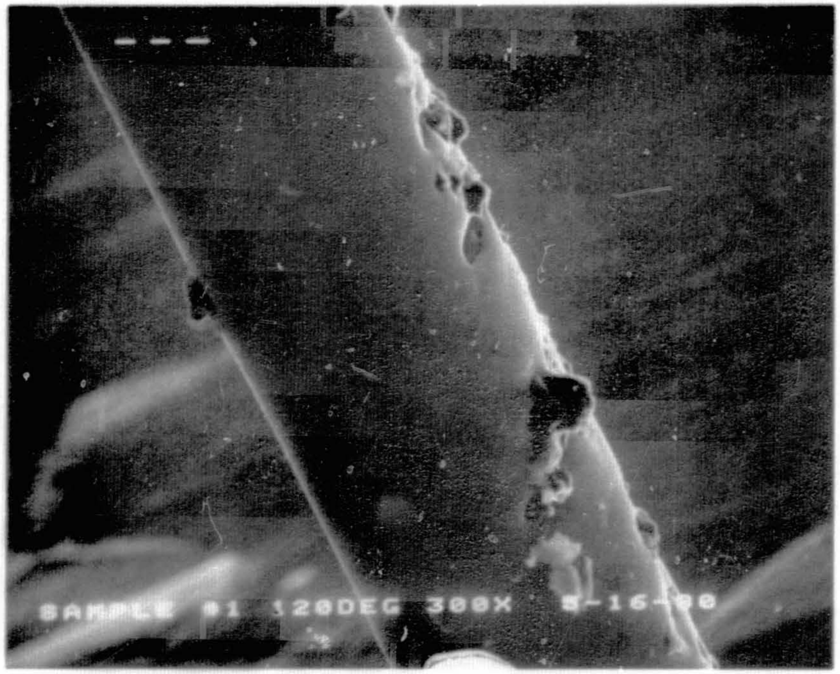


Co-Deposited Wires

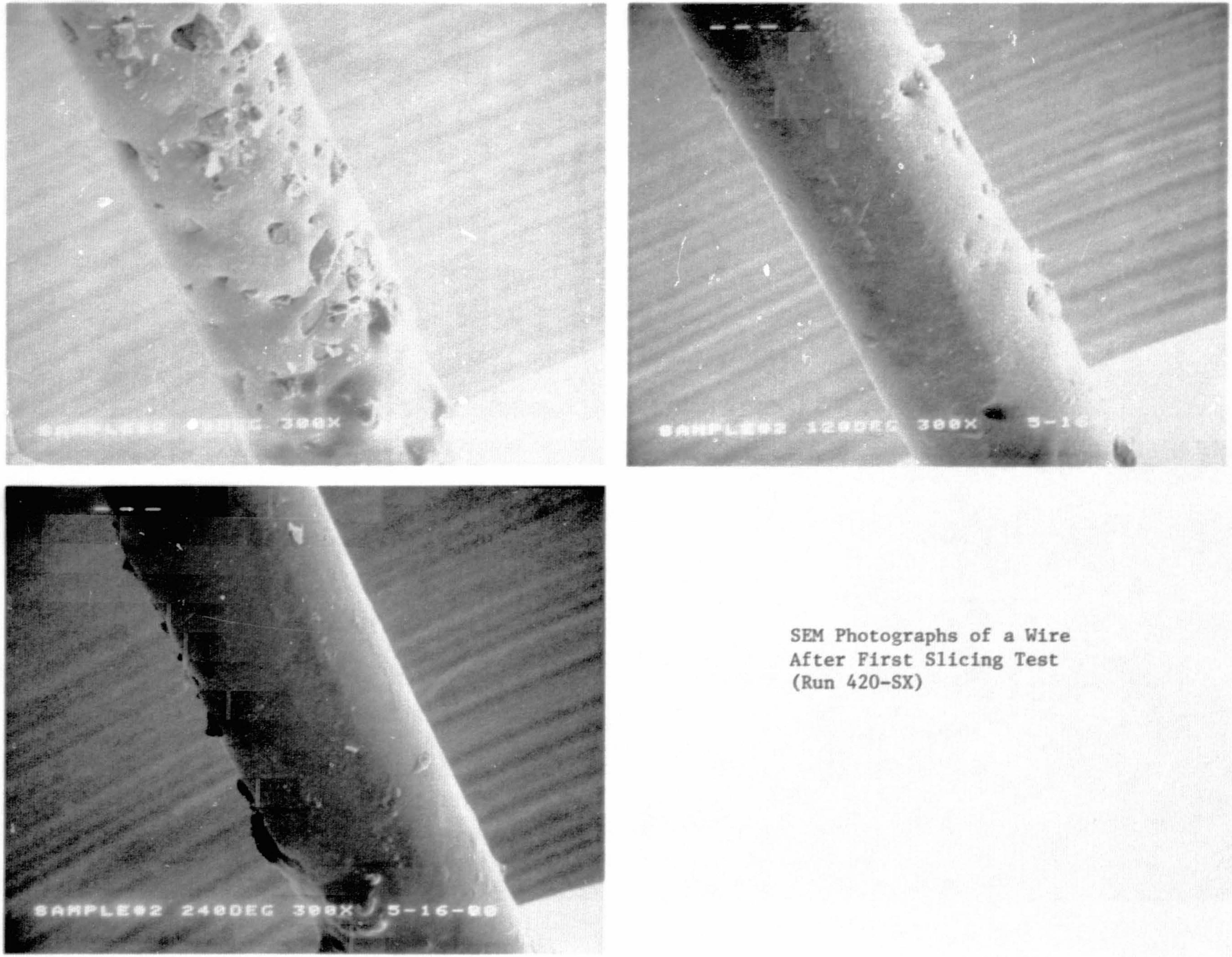




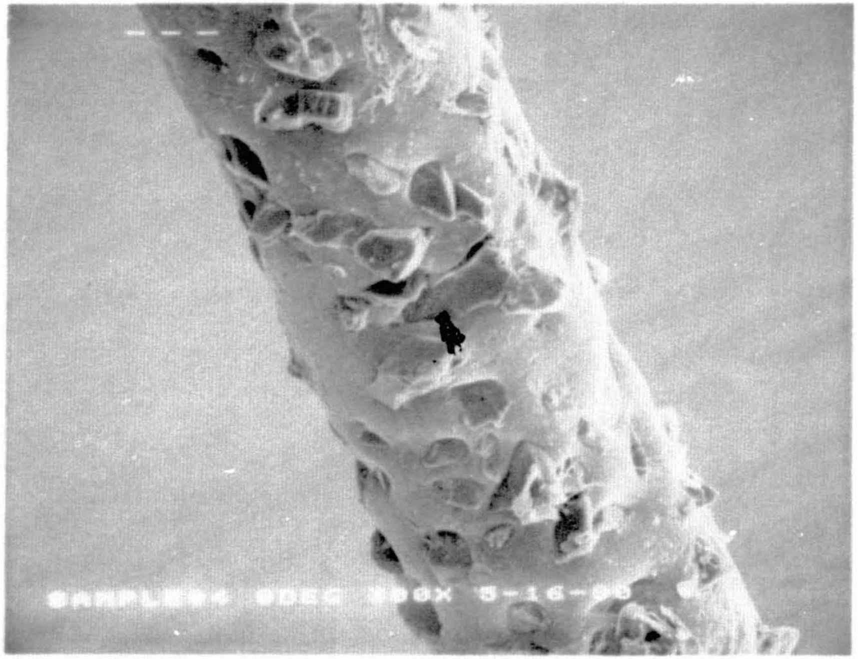


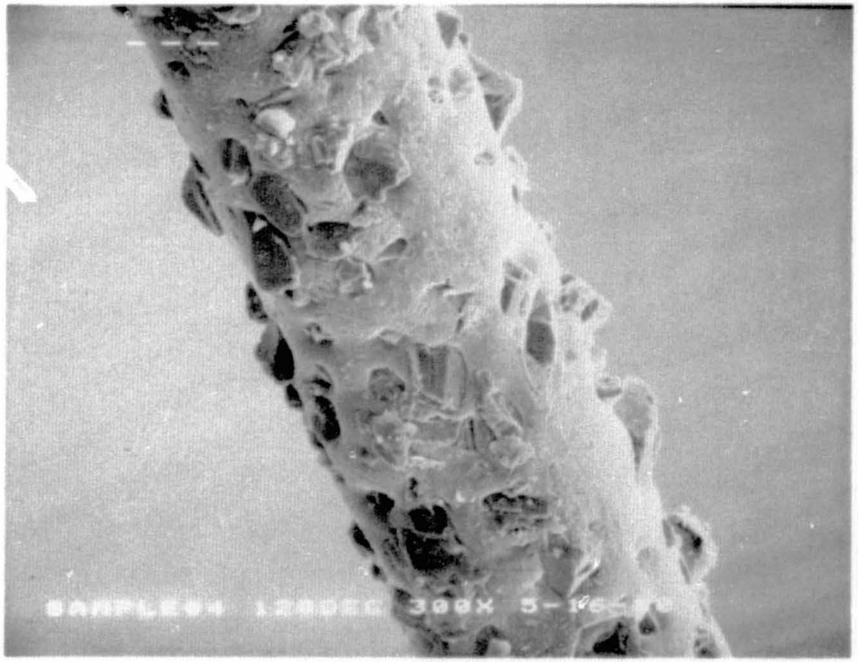


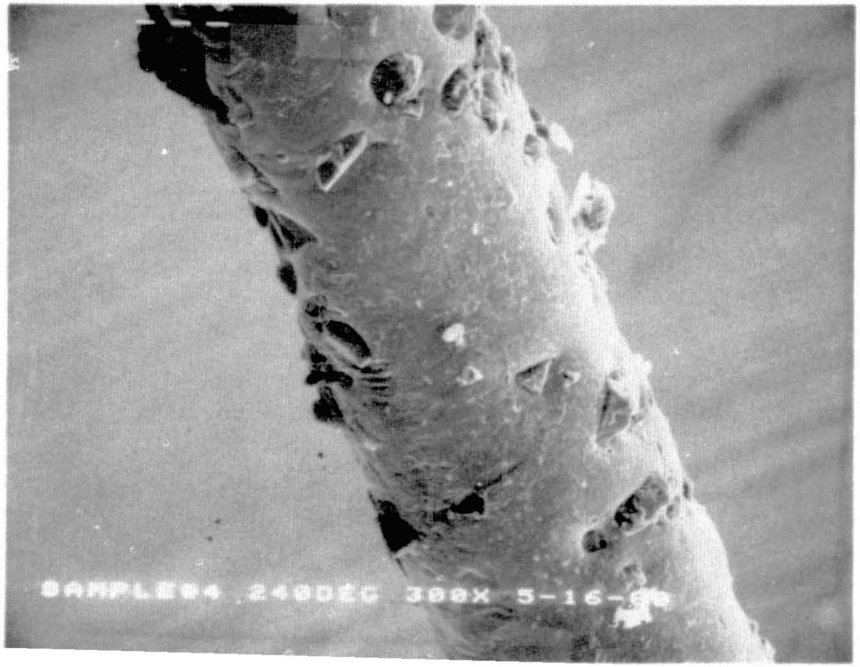
SEM Photographs of Unused Wire, at 120° Rotation of Wire. Wire Was Used in Run 420-SX.



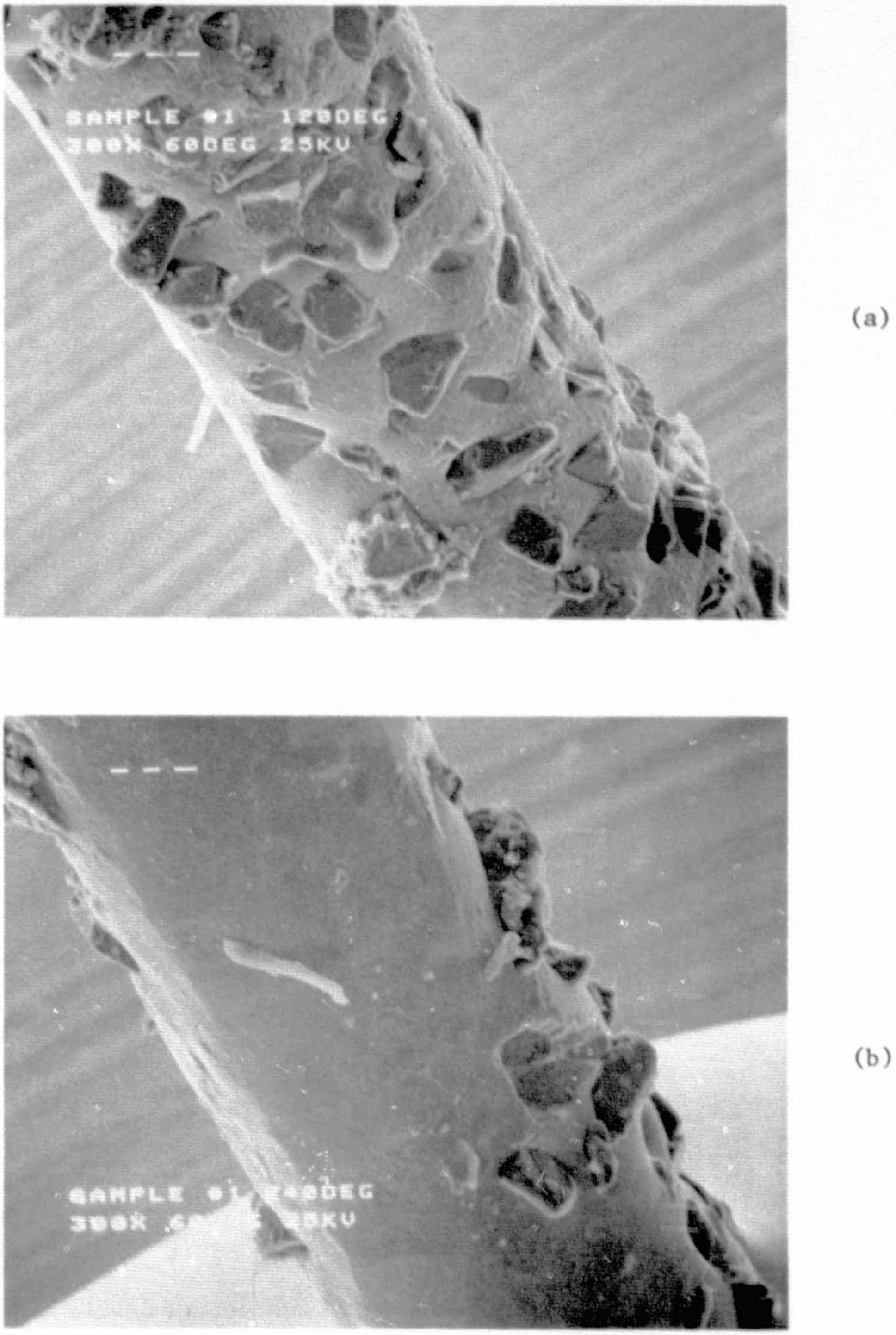
SEM Photographs of a Wire
After First Slicing Test
(Run 420-SX)



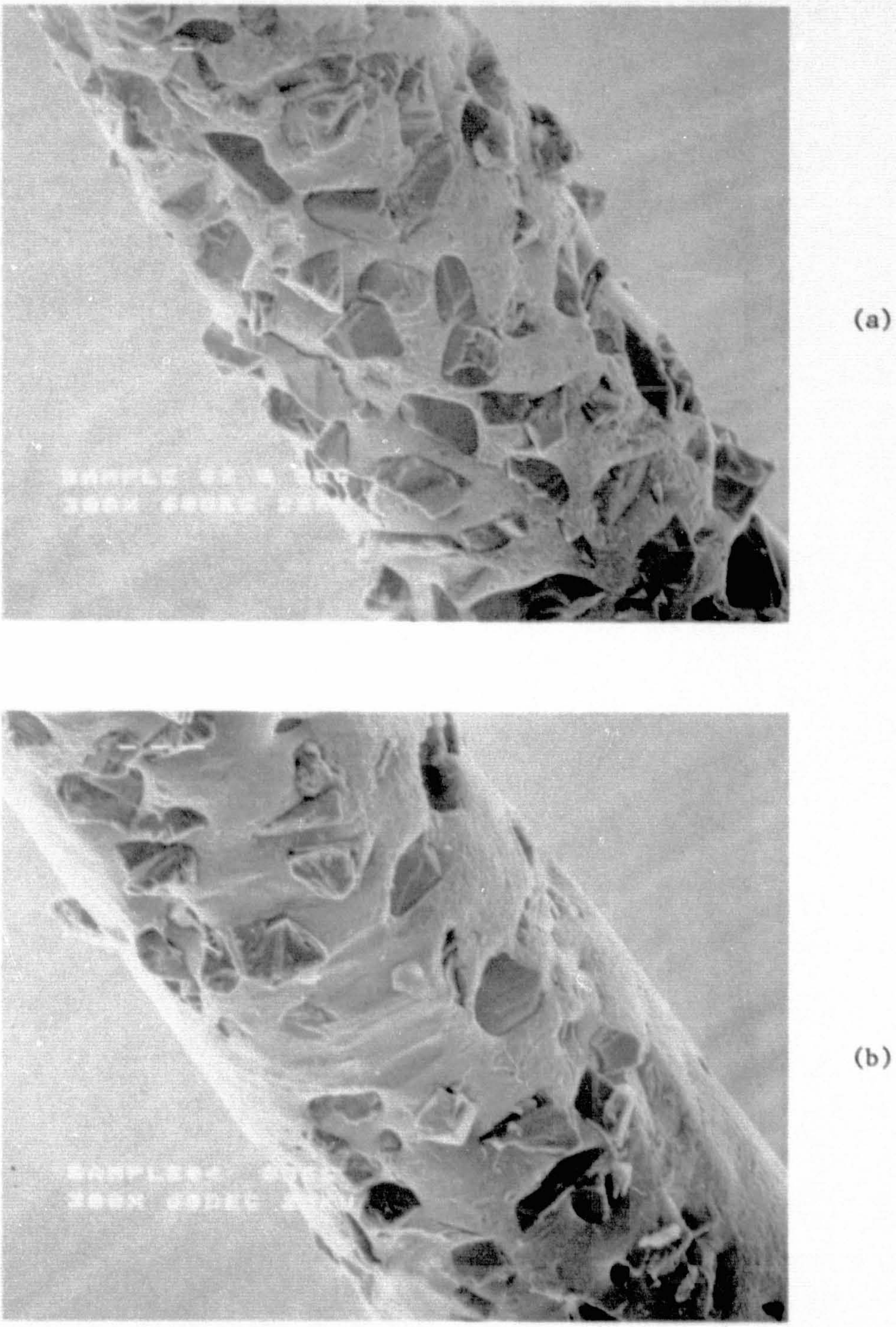




SEM Photographs of a Wire After Second Run (421-SX). This Wire Has Diamond Electroplated Over Its Entire Circumference.



SEM Photographs of a Wire Used in Runs 413-SX through 415-SX, Showing Diamonds Electroplated Only on One Side (300 X). View (b) Shows Wire Rotated 120° From View (a).



SEM Photographs of Wires Taken From Different Locations of the Blade Pack Used in Runs 413-SX Through 415-SX: (a) From the Middle; (b) From the Right Side.

IPEG ANALYSIS FOR VALUE ADDED COSTS OF FAST SLICING USING CONSERVATIVE AND OPTIMISTIC PROJECTIONS OF TECHNOLOGY

	Estimate	
	Conservative	Optimistic
Equipment cost, $	30,000	30,000
Floor space, sq.ft.	80	80
Labor, units/operator	5	10
Duty cycle, %	90	95
Set-up time, hrs	1.5	1.0
Slicing rate, mm/min	0.1	0.14
Slices/cm	22	25
Slices/wire	5	10
Yield	90	95
Expendables/run, $	28	14
Motor power, h.p.	5	3
Conversion ratio, m^2/kg	0.85	1.0
Add-on Price, $/$m^2$	13.13	5.9

SILICON INGOT CASTING: HEAT EXCHANGER METHOD (HEM)

CRYSTAL SYSTEMS, INC.

F. Schmid and C.P. Khattak

TECHNOLOGY INGOT CASTING	REPORT DATE 08/25/80
APPROACH Directional solidification by the Heat Exchanger Method (HEM) CONTRACTOR Crystal Systems, Inc.	STATUS • 34 cm x 34 cm x 20 cm ingot (45 kg)* • 15% cell efficiency demonstrated • 90% single crystal • 12.3 % cell efficiency demonstrated with UMG silicon • Flat plate crucibles demonstrated • 3.1 kg/hr growth rate demonstrated*
GOALS • 30 cm cube ingots (63 kg) • ≥ 15% cell efficiency • > 90% single crystal • ≤ 65 hours cycle time • Technical features demonstration 12/15/80 • Technology readiness 10/01/82	* New achievement

LARGE-AREA SILICON SHEET TASK

OXYGEN PARTIAL PRESSURE

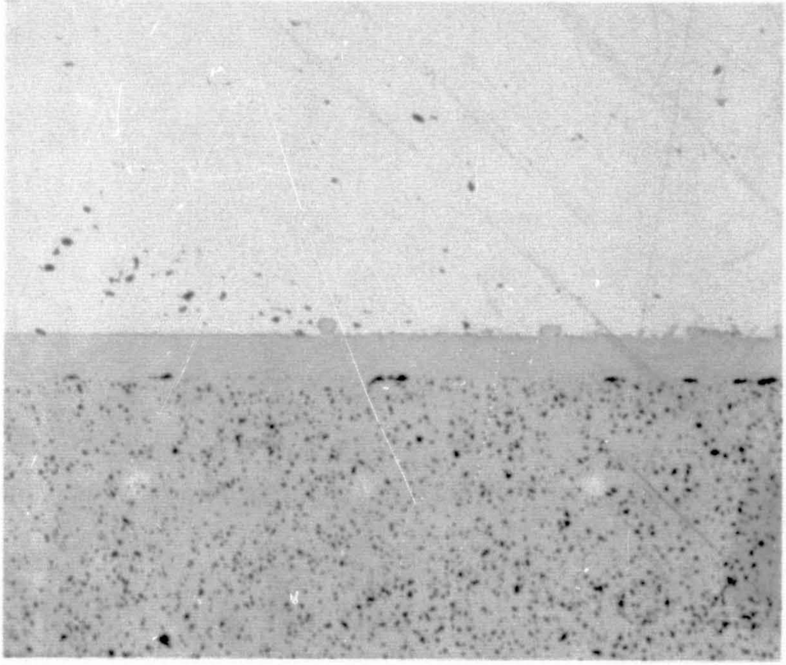
UNIVERSITY OF MISSOURI ROLLA

P. D. Ownby and H. V. Romero

I. H_2H_2O Buffer-Controlled Equilibrium in Sessile Drop Experiments

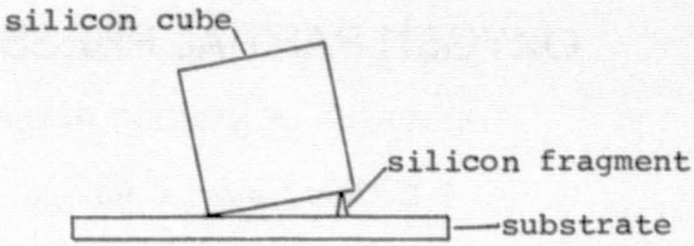
A. Review

1. Review of dependence of silicon-substrate compatability on equilibrium of pre-melt surfaces with buffer atmosphere.

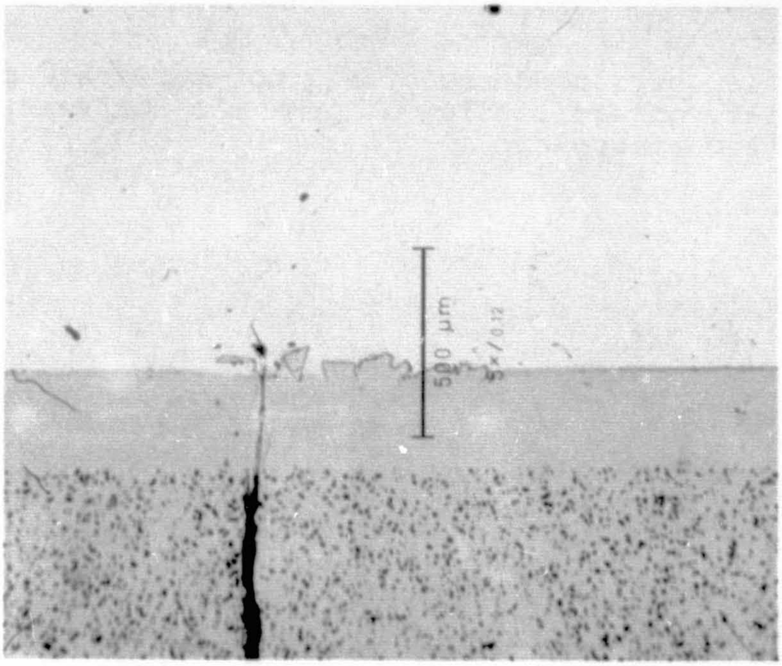


Photomicrograph of polished sections of the silicon-CNTD silicon carbide coating interface showing the abrupt change from practically no interaction on the left side to appreciable interaction on the right beginning precisely at the position of the original silicon cube edge after a 1700°K anneal at $P_{O_2} = 1.8 \times 10^{-20}$ atm.

Experiment:

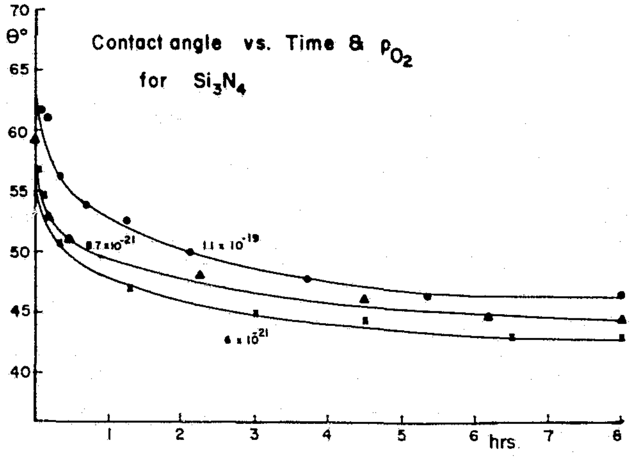


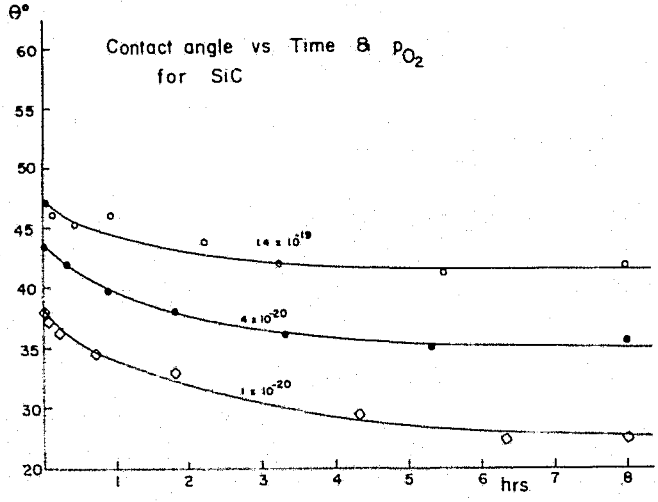
Experimental configuration of silicon cube to allow all surfaces to equilibrate with buffer gas prior to melt.



Results of tilt experiment showing interface degradation only at position of silicon chip.

2. Review of silicon sessile drop contact angle dependence on oxygen partial pressure.



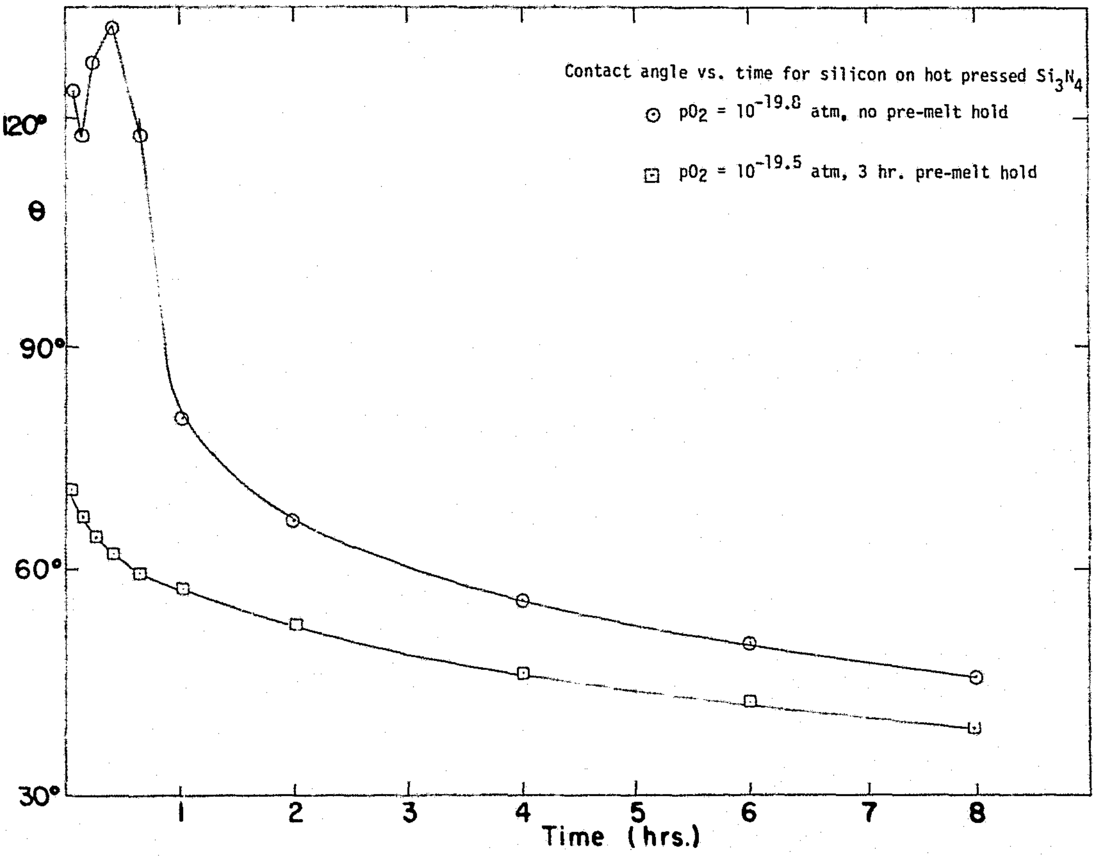


- Lower P_{O_2} gives lower contact angle.

- Initially large decrease in contact angle after melt.

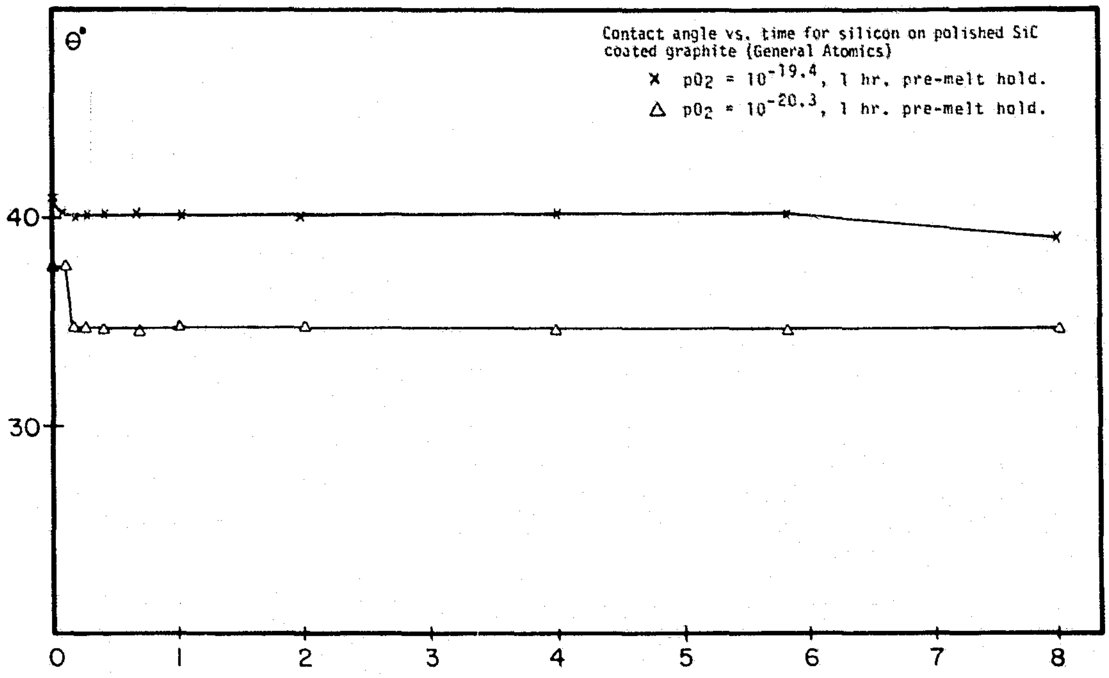
- Continued decrease in contact angle up to 8 hours.

B. Pre-melt hold equilibration of interface precursor surfaces with buffer at melt temperature.

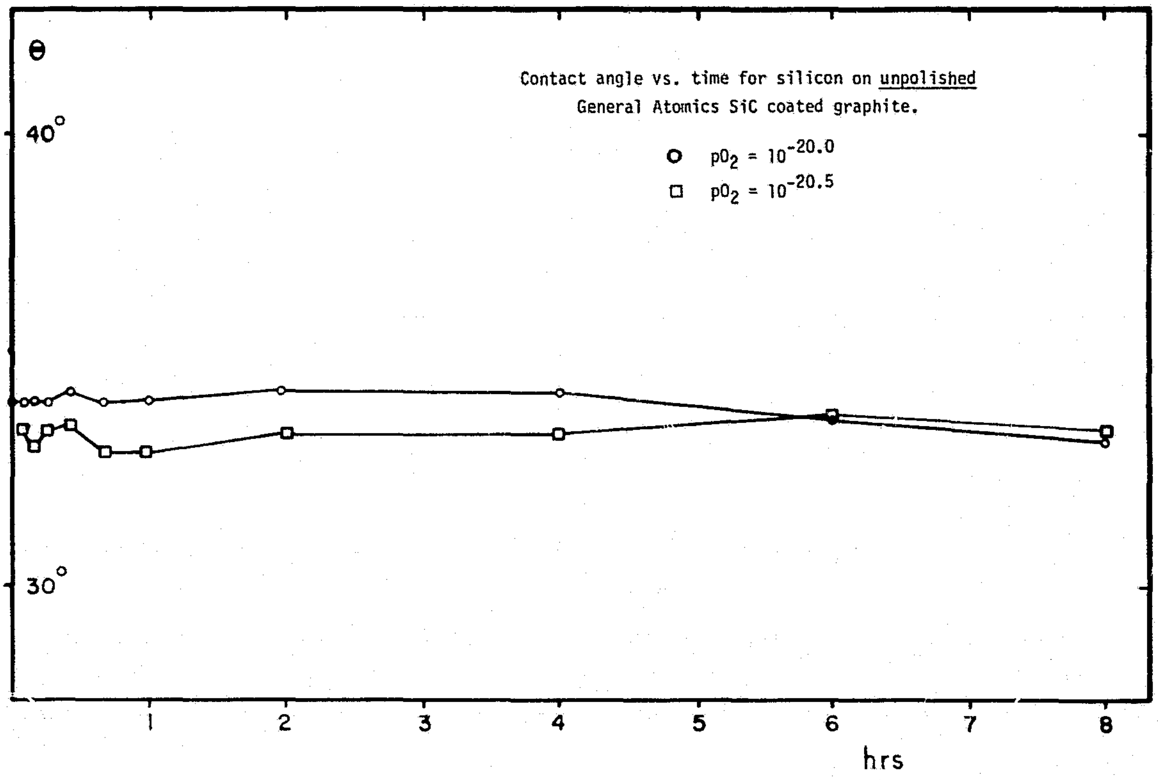


Initial drop in contact angle on silicon nitride is greatly reduced by pre-melt equilibration.

C. Initial and long-term drop in contact angle on SiC is virtually eliminated by pre-melt equilibration.



D. Note that stable contact angle is obtained on the as-coated General Atomic SiC on graphite without further surface preparation. Results are similar to those on polished surfaces except contact angles are lower for the same oxygen partial pressures.



II. Non-Equilibrium Dynamics of Purge Gas in Contact With Hot Graphite

II. Non-Equilibrium Dynamics

A. Analysis of possible non-equilibrium conditions that may exist when a purge gas containing an oxygen impurity flows through a furnace containing hot graphite and then sampled under equilibrium conditions in an oxygen cell.

- Oxygen enters 1700K silicon furnace as impurity A (ppm) in purge gas.
- A fraction x forms 2xA parts CO with furnace graphite leaving A(1 - x) parts O_2 unreacted.
- The non-equilibrated mixture of A(1 - x) parts O_2 and 2xA parts CO enters the oxygen cell and equilibrates at 1273K.

I If $x < 0.5$ (high purge rate)

$$2xA(CO) + xA(O_2) = 2xA(CO_2) + A(1-2x)O_2$$

This leaves A(1 - 2x) parts O_2 unreacted, i.e.
$pO_2 = A(1 - 2x) \times 10^{-6}$ atm.

II If $x > 0.5$ (low purge rate)

$$(2x - \delta)A(CO) + A(1 - x)O_2 = (2x - \delta)A(CO_2)$$

Leaving δA parts CO unreacted. For balance, we require

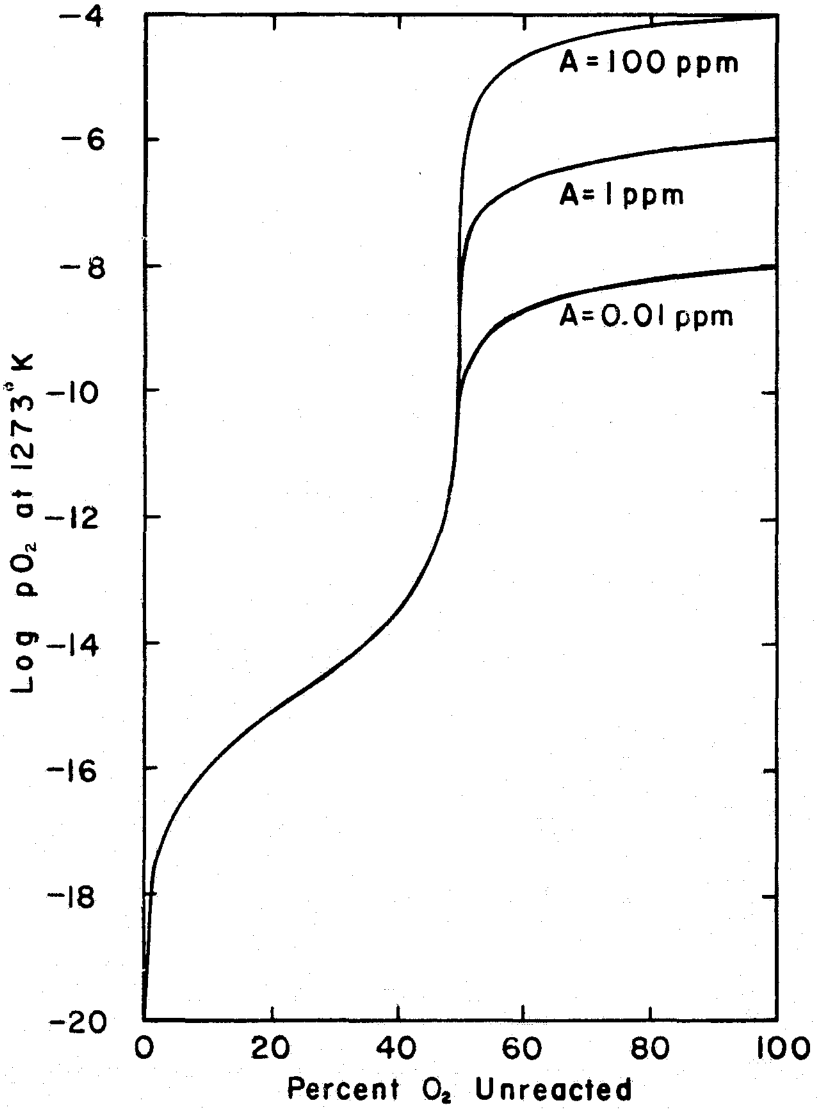
$$(2x - \delta)A = 2A(1 - x) \Rightarrow \delta = 4x - 2$$

The CO/CO_2 ratio is then $\dfrac{\delta}{2x - \delta} = \dfrac{2x - 1}{1 - x}$

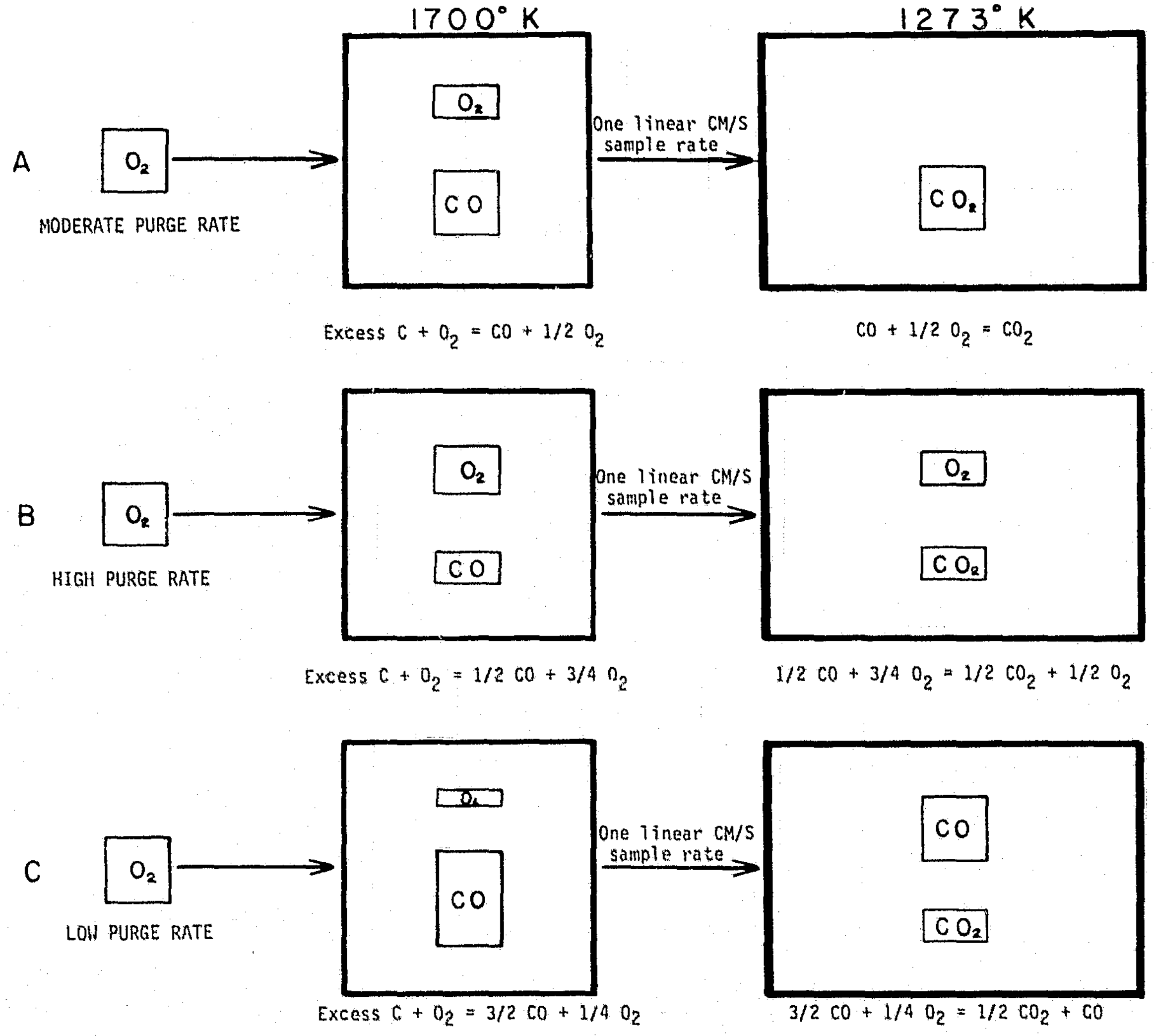
And: $pO_2 = \left(\dfrac{1 - x}{2x - 1}\right)^2 \exp \dfrac{\Delta G}{RT} = \left(\dfrac{1 - x}{2x - 1}\right)^2 \times (7.67 \times 10^{-15})$
if T = 1273K.

B. Calculated equilibrium P_{O_2} expected at $1273^{O}K$ in oxygen cell for varying percentages of oxygen impurity in inert gas passing unreacted through graphite furnace.

Log of equilibrium pO_2 measured by oxygen cell at 1273K vs. percent unreacted O_2 in 1700K silicon furnace. A is the impurity, level of the purge gas entering the silicon furnace.



% O_2 unreacted after passing through furnace containing graphite at 1700K.


1700° K
1273° K
A
O_2
MODERATE PURGE RATE
O_2
CO
One linear CM/S sample rate
CO_2
Excess $C + O_2 = CO + 1/2\ O_2$
$CO + 1/2\ O_2 = CO_2$
B
O_2
HIGH PURGE RATE
O_2
CO
One linear CM/S sample rate
O_2
CO_2
Excess $C + O_2 = 1/2\ CO + 3/4\ O_2$
$1/2\ CO + 3/4\ O_2 = 1/2\ CO_2 + 1/2\ O_2$
C
O_2
LOW PURGE RATE
O_2
CO
One linear CM/S sample rate
CO
CO_2
Excess $C + O_2 = 3/2\ CO + 1/4\ O_2$
$3/2\ CO + 1/4\ O_2 = 1/2\ CO_2 + CO$

D. Experimental results verifying CO concentration dependence on purge gas flow rates expected from calculations.

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

After Mobil Tyco presentation at 15th P.I.M. showing increase of CO for decreasing purge gas flow rates.

Summary

1. EQUILIBRIUM CONTACT ANGLE MEASUREMENTS REQUIRE THAT ALL SURFACES EQUILIBRATE WITH THE LOW OXYGEN PARTIAL PRESSURE ATMOSPHERE AT THE MELT TEMPERATURE PRIOR TO MELT.

2. IMPURITY OXYGEN IN INERT PURGE GASES MAY NOT EQUILIBRATE IN SILICON FURNACES INCORPORATING HOT GRAPHITE.

LARGE-AREA SILICON SHEET TASK

CELL PROCESS DEVELOPMENT, FABRICATION AND ANALYSIS

APPLIED SOLAR ENERGY CORP.

INTRODUCTION

This talk is a review of work to date. Detailed results of recent work were described at the critical review meeting on September 23rd.

A wide range of sheet forms have been evaluated (TABLE I). All these sheets have shown improved quality and increased throughput. In some cases, lower cost starting silicon has been tested.

The evaluation process is shown in Figure 1. The baseline (BL) process is conservative, and provides objective comparative evaluation. The back-up measurements are of diffusion length (L), spectral response, fine light spot scanning, and dark diode characteristics.

Correlation of the baseline evaluation results with sheet properties can:

- Indicate areas where sheet formation can be improved.
- Suggest cell process modifications which can increase efficiency.
- Compare with defect characterization by other groups.

RESULTS

The baseline cell efficiency obtained depended strongly on the L-values of the sheets. The L-value appeared to represent the combined effects of the major defects (crystallographic, impurities, process defects), although efficiency reduction could also be caused by surface defects.

NOTE: Separate work (Dow-Corning-Westinghouse) had shown that certain impurity levels could be tolerated without severe decrease of efficiency, although the tolerance level varied for different impurities.

Improved processes included obvious modifications (better AR coatings, perhaps texturing greater active area, shallower barrier) and defect correcting methods (gettering, grain boundary passivation, surface cleaning, annealing) and use of back surface fields (BSF) or reflectors (BSR).

The "improved" cell efficiency also showed close dependence on L-value, and the sheets with best BL performance could be improved most. (Figure 2)

This suggests that high defect densities in the sheets cannot be easily offset by later cell processing, and may impose similar limits on use of alternative barrier methods such as SIS or pulsed annealing, except that these barrier methods may minimize GB effects.

The highest efficiency values obtainable are more important now that balance-of-systems cost estimates have shown increased importance for area-related costs.

OTHER STUDIES

Grain Size Effects

Using high purity crystals, the BL efficiency dependence on grain size showed that grains $\sim 500 \mu m$ are necessary for good efficiency. (Figure 3)

BSF

Studied BSF effectiveness versus impurity concentration, defect density, and starting L-values. (Figure 4)

Have also identified and corrected some BSF-process induced defects when the Al-alloy method is used. (main problem in leakage of Al to and through front surface).

Use of Lower Cost Silicon

When arc-furnace purified silicon was used for Czochralski or HEM ingots, good cell efficiencies were obtained. However, use of metallurgical grade silicon for HEM growth gave poor cells.

OTHER COMMENTS

Consistency

The importance of consistency for high cell yields has been stressed. Conventional Czochralski sheet and most dendritic web have shown good consistency, the other sheets giving fair consistency.

Continuous grown Czochralski crystals show good consistency for 90% of the crystals, with rapid pull-off for the last 10%, or when polycrystal sections are formed. (Figure 5)

HEM crystals generally have large grains, so that often polycrystalline HEM sheets give good cells. Detailed plotting along and transverse to the growth direction showed that the best areas gave efficiency 0.93 of that of control Czochralski, with an average over the sheet 0.78 (Figure 5).

Throughput

Most ribbon methods report upper limits to solidification ratios, especially when wide or reasonably thick sheets were required. Even so, EFG ribbons have shown impressive throughputs (3 ribbons, 45 cm^2/min, 0-8 m^2/hr).

The ingot methods generally gave $\sim$0.8 m^2/hr (after slicing) but recently large Czochralski ingots have reported growth rates $\sim$2-3 times higher than previous results.

Commercialization

The most promising materials, considering the combination of efficiency, yields, throughput, and use of current cell processing methods are:

Continuous Czochralski
Dendritic Web
(Best) HEM
(Best) EFG
(Perhaps) RTR

INTERACTION WITH LOW COST PROCESSES

Because L-values impose efficiency restrictions, most of the current low cost processes can be applied to the sheets. These process areas include barrier methods, cleaning and handling, AR coatings, measurements, contact metals and methods, interconnection and encapsulation methods.

The most serious process limitation is the mechanical properties of the sheets.

SUMMARY

The evaluation process has proved to be a valuable way to evaluate a variety of sheet materials for their solar cell promise, and to monitor the improvements made in the growth methods.

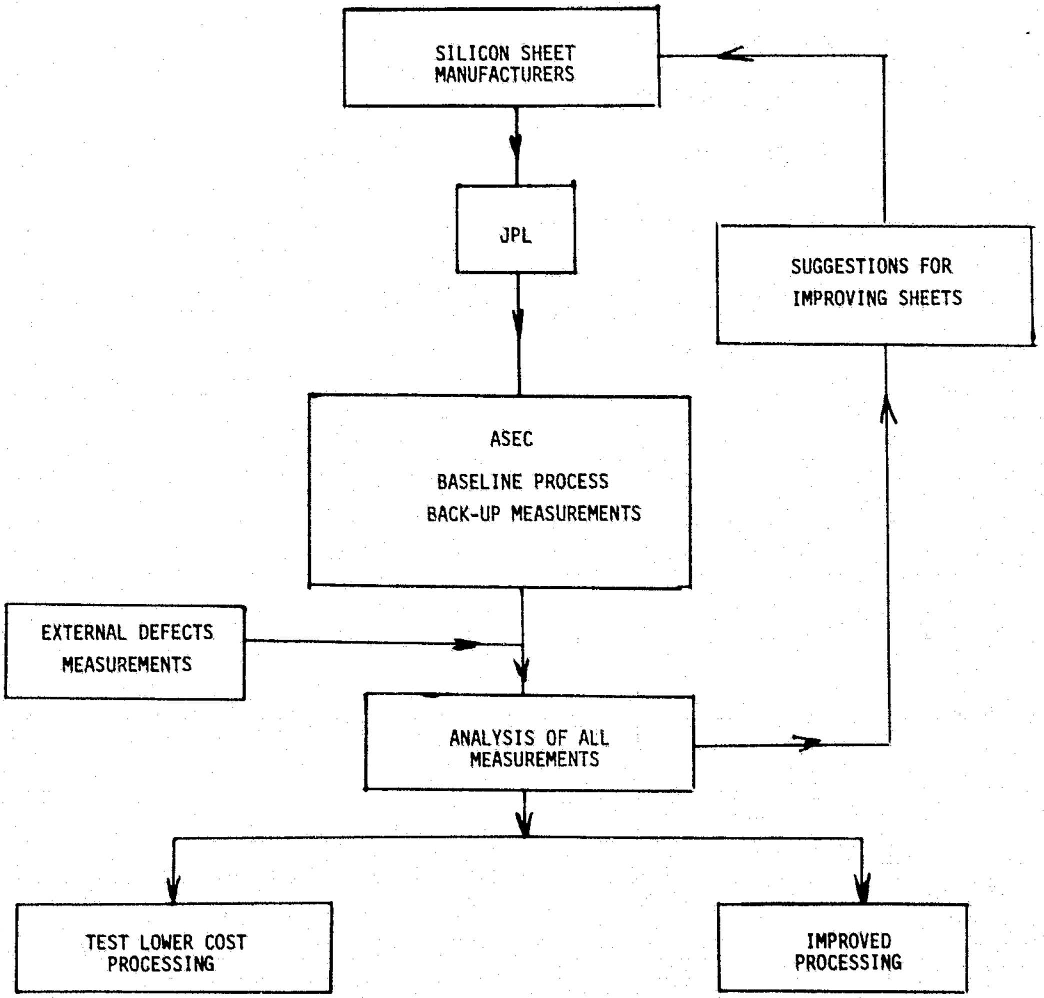
The information required is in directly usable form, including realistic interactions with the cell processes used. The internal consistency of the back-up measurements and the cell results has increased confidence in the analysis.

This is an exciting project, because of the significant advances made by all the sheet manufacturers in the past few years.

Silicon Sheet Forms Evaluated

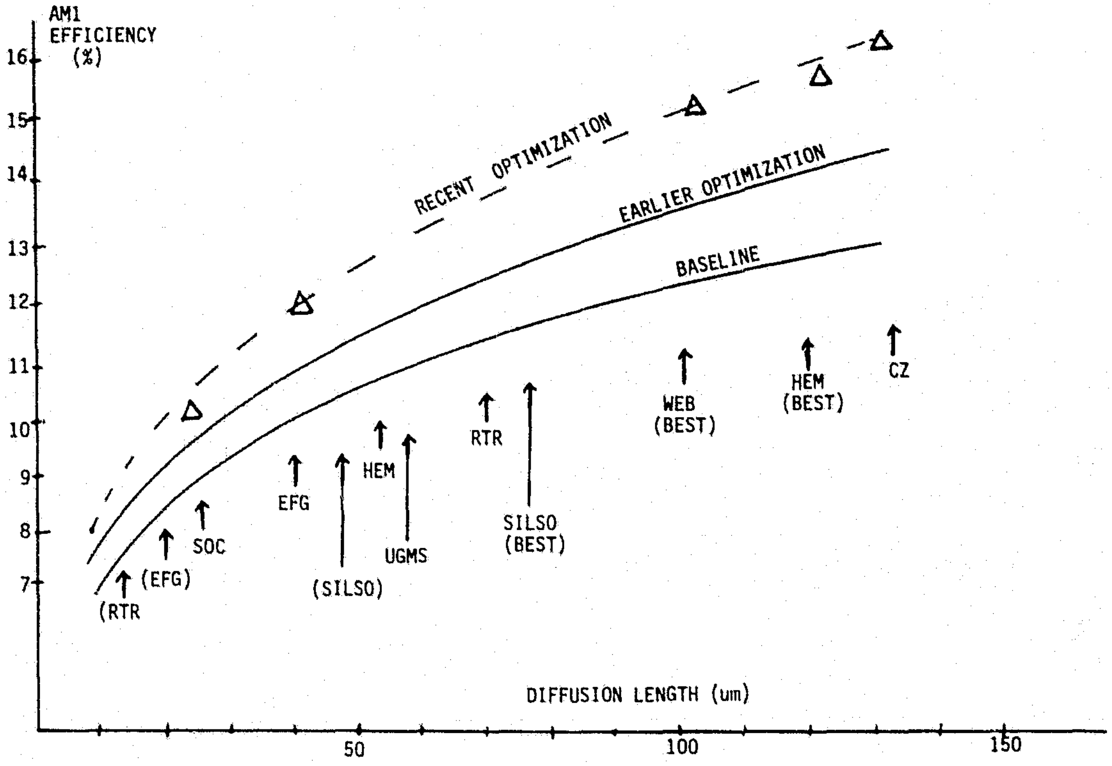
INGOTS:	CZOCHRALSKI	-	STANDARD
		-	SEMICONTINUOUS
	CAST	-	HEM (MOSTLY SINGLE CRYSTAL)
		-	WACKER (POLYCRYSTALLINE)
RIBBONS:	UNSUPPORTED	-	EFG
		-	DENDRITIC WEB
		-	RTR
	SUPPORTED	-	SOC

Evaluation Process

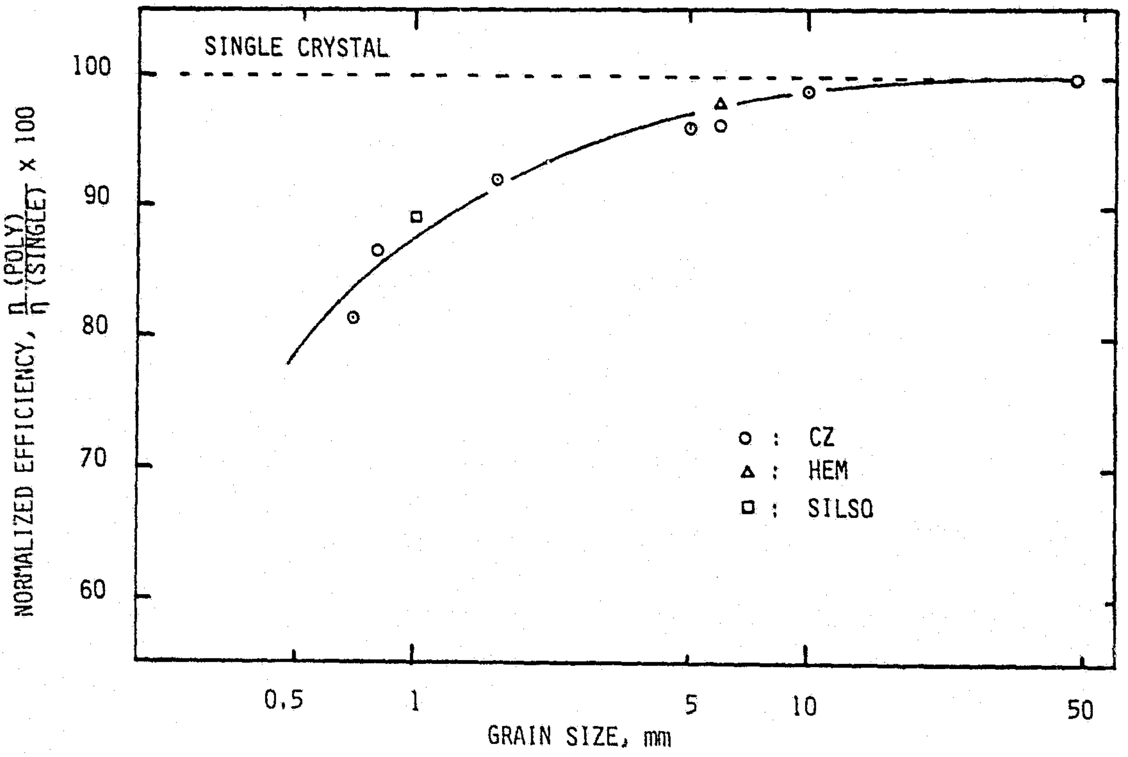


AM1 Efficiency vs Diffusion Length

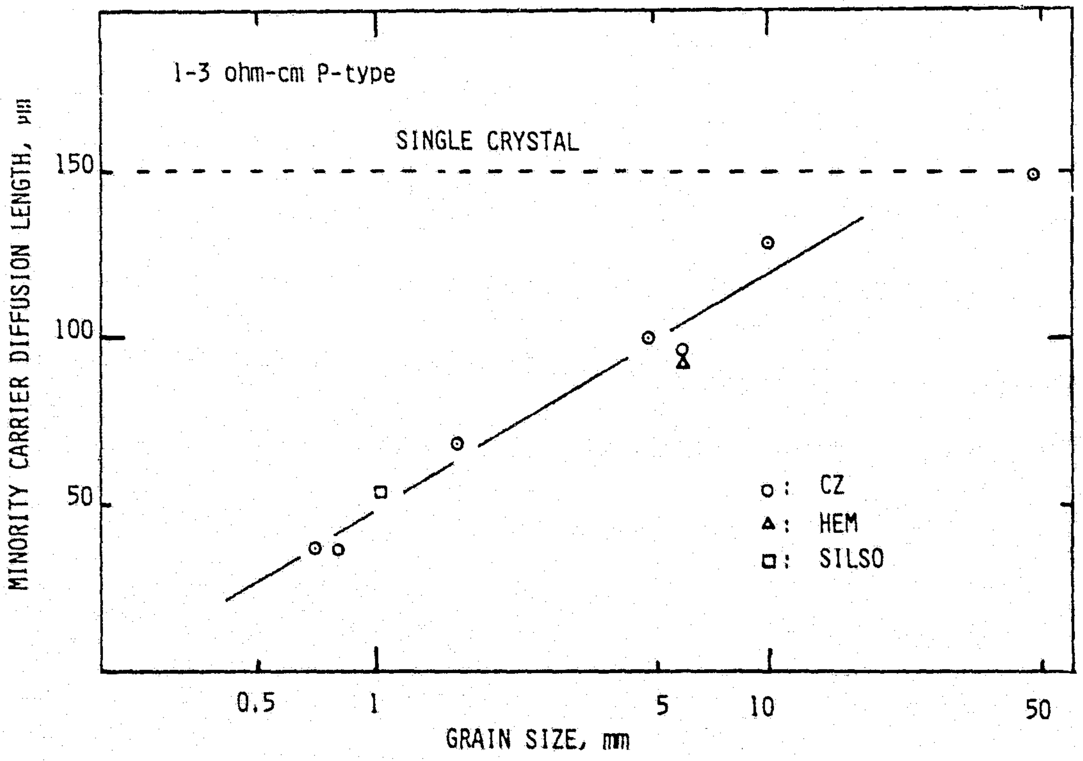
FOR VARIOUS SILICON SHEETS,
BASELINE AND OPTIMIZED PROCESSING



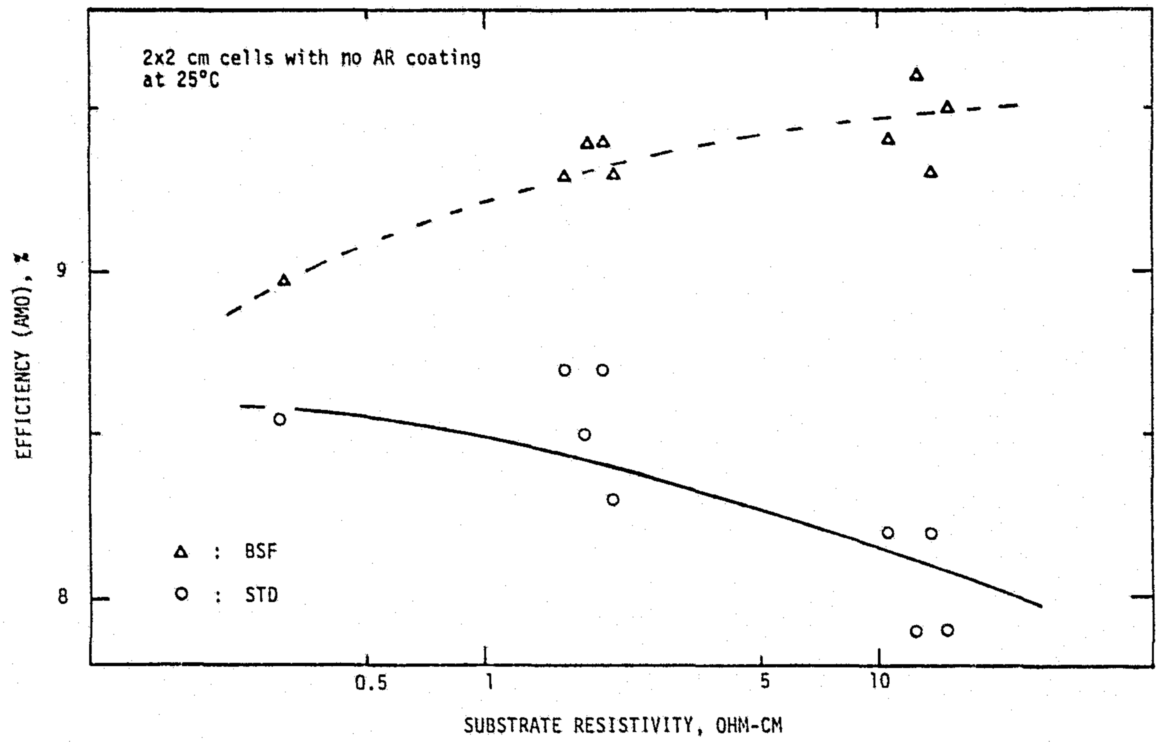
Efficiency vs Grain Size



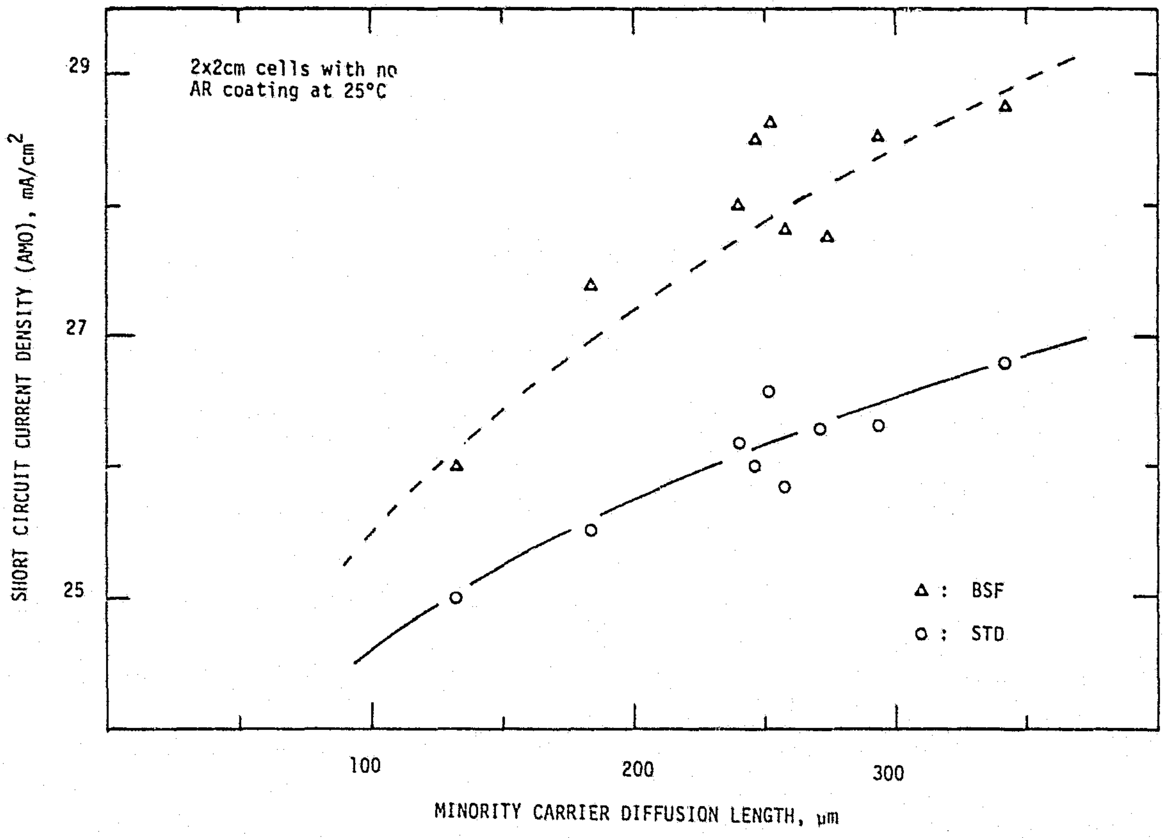
Effective Minority Carrier Diffusion Length vs Grain Size



Effect of BSF Process on Cell Efficiency As a Function of Starting Si Substrate Resistivity



Effect of BSF Process on I_{SC} Density of Cells As a Function of Minority Carrier Diffusion Length



Baseline Process

1. DEEP JUNCTION (0.3 ~ 0.4μm) BY $POCl_3$ SOURCE.
2. METALLIZATION (BOTH FRONT AND BACK) BY EVAPORATION THROUGH METAL SHADOW MASK.
   - Ti-Pd-Ag (THREE LAYER)
   - 90% FRONT ACTIVE AREA
3. AR COATING: EVAPORATED SIO WHICH WILL PROVIDE ABOUT 35% CURRENT GAIN OVER THE BARE SURFACE.
4. CELL SIZE IS 2x2 cm.

AM1 MEASUREMENTS

1. LIGHT SOURCE: SPECTROLAB MODEL XT-10
2. INTENSITY CALIBRATION: A TERRESTRIAL SECONDARY STANDARD (TSS-014, SOLAR CELL) FROM JPL.
3. TEMPERATURE: 28°C TEST BLOCK

Dendritic Web

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF,%	η (AM1) %		
1	543	27.7	76	11.5	BL	12.1
2	582	32.8	75	14.3	SJ+BSF+BSR+MLAR	15.5
CONT	583	27.9	77	12.5	BL	12.7

Earlier EFG (RH)

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1),%		
1	500	18.5	73	6.7	BL	7.2
2	509	19.5	66	6.6	SE + BL	7.2
3	514	18.4	70	6.6	ST + BL	7.1
4	532	21.8	73	8.5	GBP + BL	9.3
5	523	22.9	68	8.1	GET + BL	8.4
6	527	22.0	71	8.2	BL + BSF	9.0
7	533	22.5	75	9.0	SJ + MLAR	10.2
CONT.	588	28.1	76	12.6	BL	13.8

New EFG (RH)

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1) %
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1),%		
8	524	21.4	71	8.1	BL	8.7
9	568	24.3	75	10.3	BL	11.1
10	565	28.4	76	12.1	SJ + BSR + MLAR	13.6

SOC

	AVERAGE CELL PARAMETERS				PROCESS USED	η_B (AM1)%
	Voc, mV	Jsc mA/cm^2	CFF, %	η (AM1),%		
0	532	19.3	66	6.9	PHASE I	7.9
1	524	22.6	65	7.6	STD	8.3
2	523	23.5	64	7.8	SJ+STD	8.2
3	529	23.7	67	8.4	SJ+MLAR	8.9
4	555	24.1	69	9.3	SJ+MLAR	9.6
5	564 (574)	23.0 (23.5)	73 (74)	9.5 (9.9)	HONEYWELL	9.8 (10.2)

STD Process

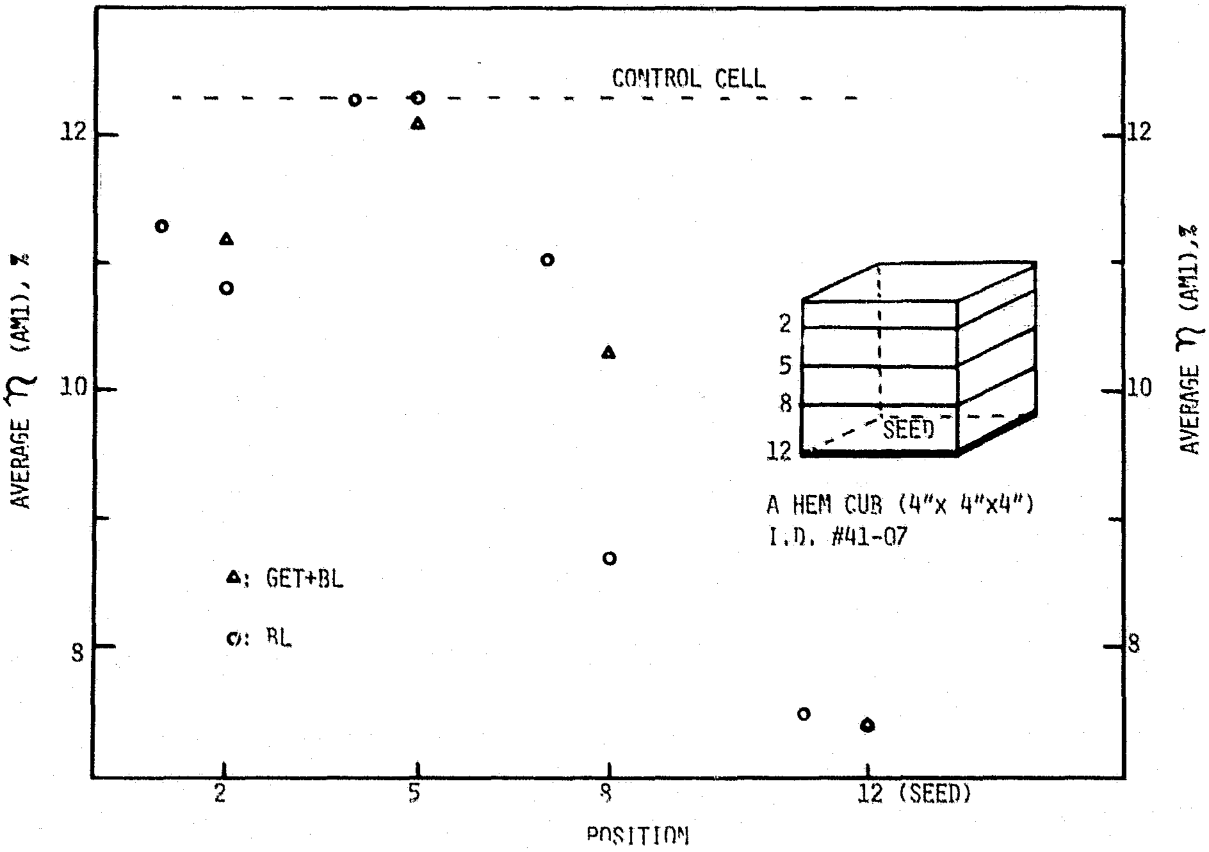
1. EVAPORATION OF Al ON THE BACK.
2. STD DIFFUSION
3. BACK CONTACT EVAPORATION (Ti-Pd-Ag) AND SINTER
4. FRONT CONTACT (Ti-Pd-Ag) BY PHOTORESIST TECHNIQUES.
5. MESA FORMATION
6. AR COATING BY EVAPORATION (SiO)
7. INDIUM-TIN SOLDER FILL IN THE BACK SLOTS.

HEM

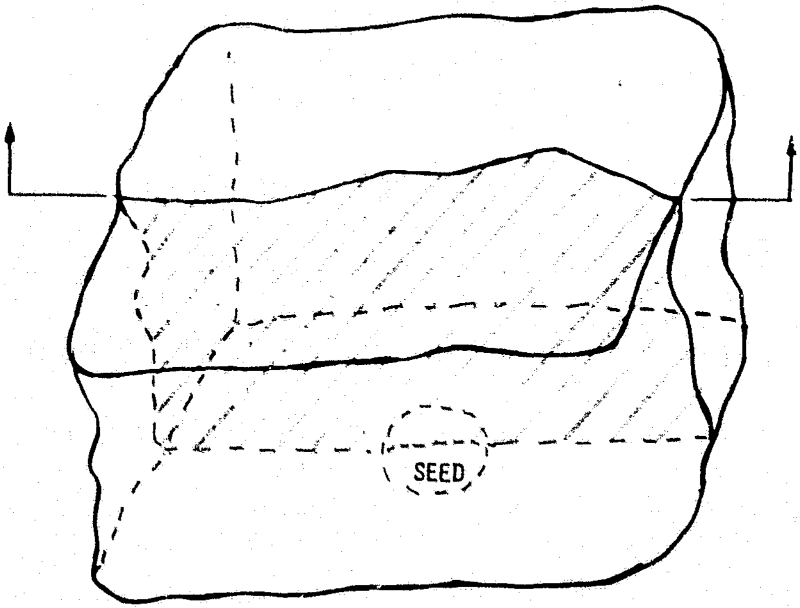
	AVERAGE CELL PARAMETERS (AM1)				PROCESS USED	η_o,%
	Voc, mV	Jsc mA/cm^2	CFF,%	η , %		
1	564	25.9	73	10 .8	BL (I,S)	11.5
2	560	26.0	74	10.8	BL (I,P)	11.5
3	580	25.3	73	10.8	BL (II,S)	12.1
4	580	23.7	63	8.7	BL (II,P)	10.7
5	591	27.7	71	11.7	GET+BL (II,S)	13.5
6	583	26.3	72	11.2	GET+BL (II,P)	12.8
7	550	23.9	74	9.8	BL (III,SP)	12.6
8	557	24.9	73	10.2	GET+BL(III,SP)	12.1
9	597	32.5	78	15.0	GET+SJ+BSF+MLAR	15.7
10	550	23.5	75	9.8	BL (III,SP)	12.8
CONT	588	28.1	76	12.6	BL	13.8

<u>NOTE</u>: 1. #7, 8, and 9 from a cube (4"x 4"x4", Crystal System #41-07)

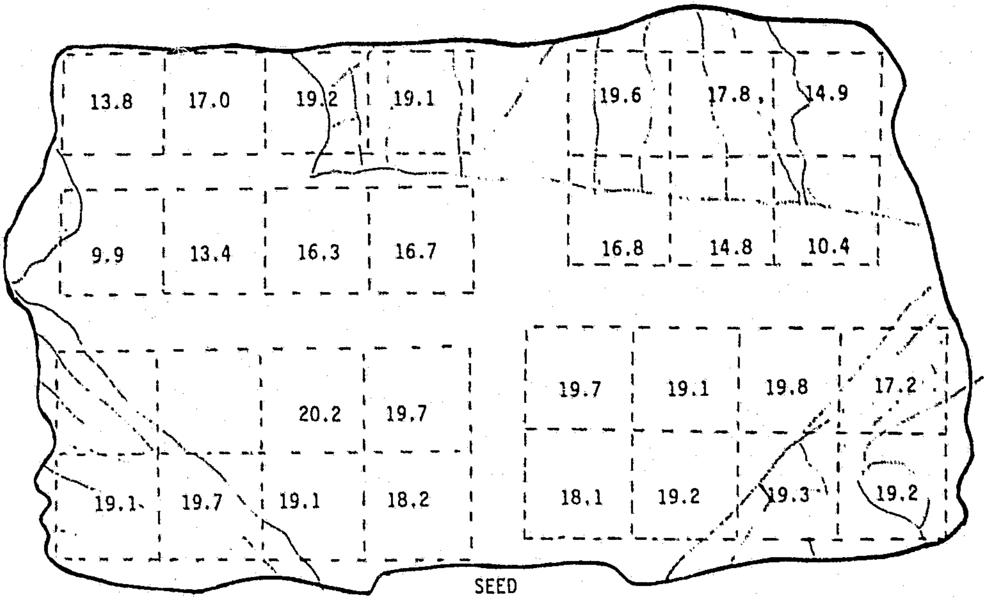
2. #10 from a vertically cut wafer (a whole ingot, Crystal system #41-24)



Cross Section of Vertically Cut HEM Ingot



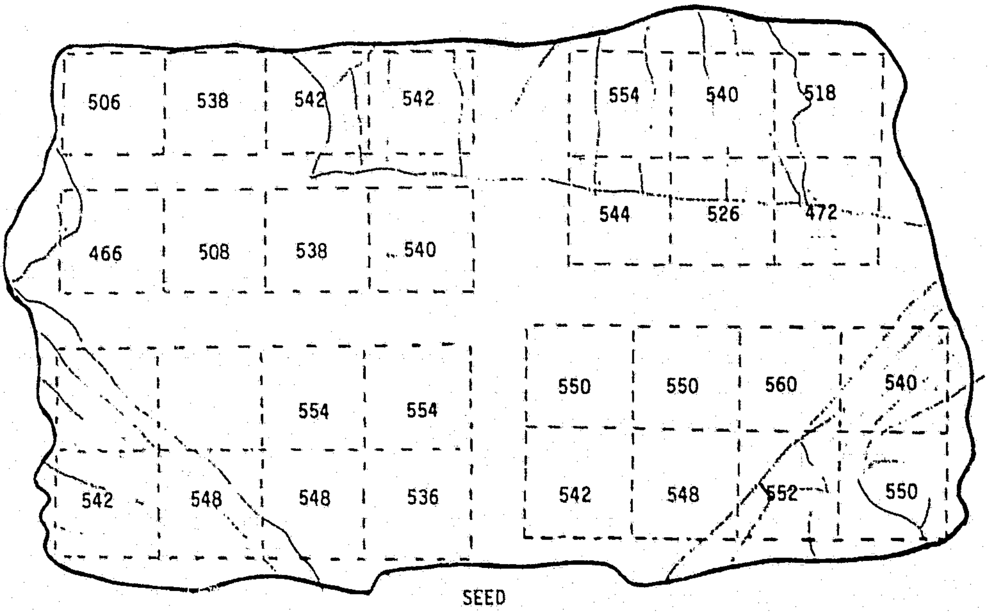
I_{SC} Density (AM1, no AR) Mapping Of Vertically Cut HEM Wafer



NOTE: UNIT: mA/cm^2

Jsc OF CONTROL CELL = 21.3 mA/cm^2

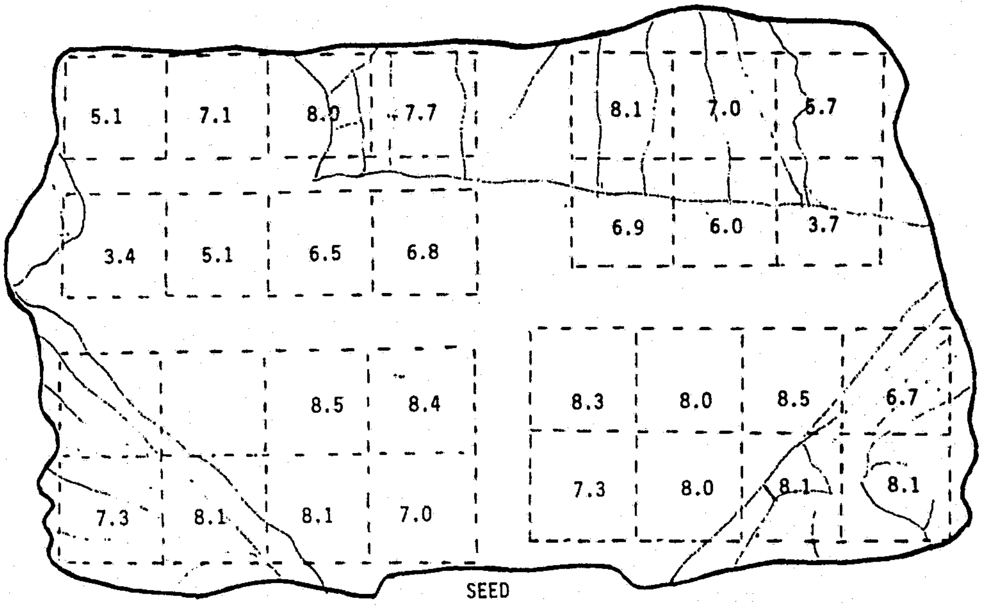
V_{OC} (AM1, no AR) Mapping of Vertically Cut HEM Wafer



NOTE: Unit: mV

Voc of Control Cell = 567 mV

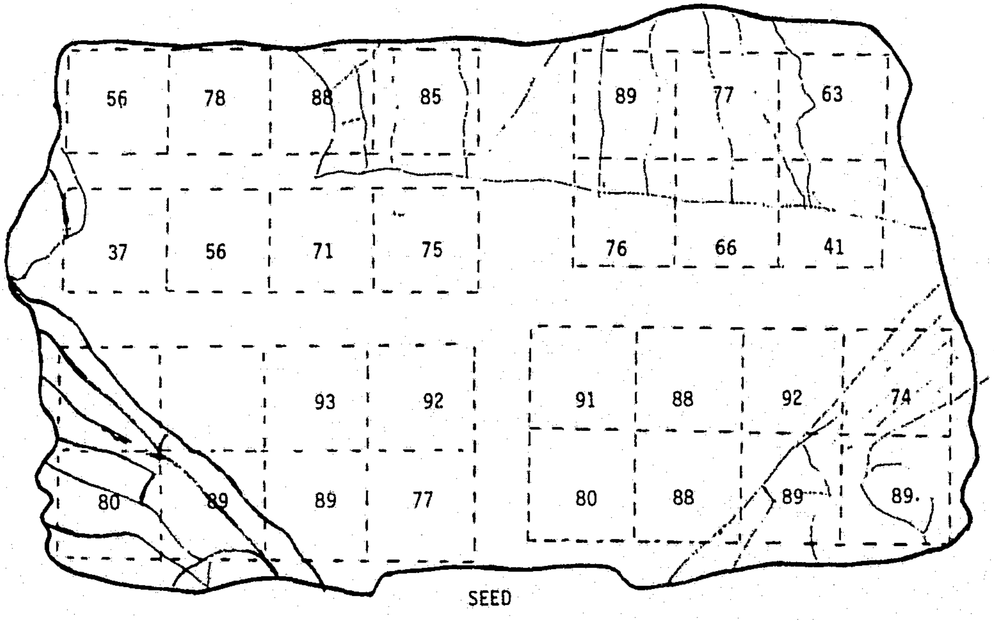
Efficiency (AM1, no AR) Mapping of Vertically Cut Wafer



NOTE: UNIT: %

η OF CONTROL CELL = 9.1

Efficiency (Normalized WRT) to Control Cells) Mapping of Vertically Cut HEM Wafer



NOTE: o UNIT: Percentage

o AVERAGE: 78

Encapsulation Task

TECHNOLOGY SESSION

C.D. Coulbert, Chairman

Continued development and characterization of ethylene vinyl acetate (EVA) as an encapsulant increases confidence in its 20-year life potential. Studies continue at JPL, Springborn, and Spectrolab in characterizing the thermal and UV radiation stability, the processing parameters, and the performance of module designs incorporating EVA as the elastomeric pottant.

These studies include parallel evaluations of alternative candidate module designs and material systems as outlined in Springborn's presentation. Two recent additions to the list of material candidates are a 3M acrylic top-cover film (X-22417) to replace Korad and ethylene methyl acrylate (EMA) produced by Gulf Oil Chemicals as a possible alternative to EVA. Initial evaluation shows EMA to be very similar in cost, performance, and processing to EVA. It may have a somewhat higher temperature stability, which may be crucial in view of recent module hot-spot experience.

The ultraviolet absorber, 5-vinyl tinuvin, developed at the University of Massachusetts has been successfully copolymerized with acrylic polymers to give a non-extractable absorber to be used in the preparation of weatherable UV screening top-cover films. Scale-up and evaluation continues at Springborn.

The module design analysis effort at Spectrolab-Hughes has provided a number of parametric evaluations of the effects of encapsulant properties and configurations on module optical, thermal, electrical and structural performance. These results, which will appear in a forthcoming report, will demonstrate the economic effects of such design parameters as glass-cover properties, module surface emissivities, pottant thickness and modulus, and the use of stiffening ribs on substrate panels.

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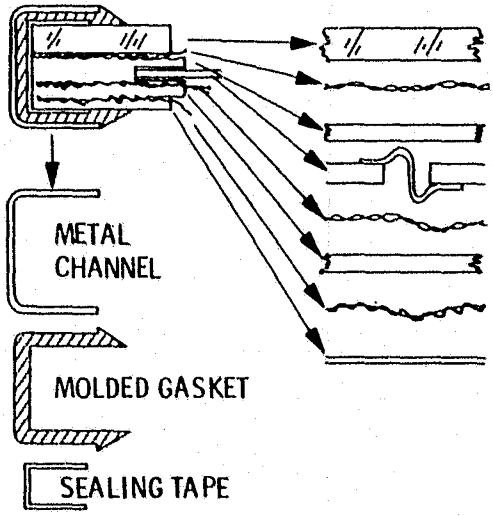
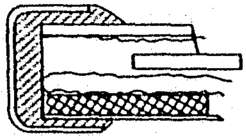
Encapsulant Material Design Candidates

Superstrate Designs



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

SUBSTRATE DESIGN OPTIONS



UV COVER FILM (ACRYLIC OR TEDLAR)
POTTANTS (EVA, EMA, ACRYLIC)
SUBSTRATE (WOOD OR STEEL)
EDGE SEAL & GASKET

MODULE TOTAL
$5.00 - 13.00/M²

Candidate Low-Cost Encapsulation Materials

Continuing Evaluation

SUPERSTRATE DESIGN

CONSTRUCTION ELEMENT	CANDIDATE MATERIAL
STRUCTURAL ELEMENT	SODA-LIME GLASS
ELASTOMERIC PUTTANTS	ETHYLENE VINYL ACETATE ETHYLENE METHYL ACRYLATE ALIPHATIC POLYURETHANE POLY-N-BUTYL-ACRYLATE
BACK COVER FILM	MYLAR TEDLAR ALUMINUM FOIL

- MODULES UNDER CONSTRUCTION AND TESTING

SUBSTRATE DESIGN

CONSTRUCTION ELEMENT	CANDIDATE MATERIAL
TOP COVER FILM	X-22417 ACRYLIC FILM TEDLAR 100 BG 30 UT
ELASTOMERIC POTTANTS	ETHYLENE VINYL ACETATE ETHYLENE METHYL ACRYLATE ALIPHATIC POLYURETHANE POLY-N-BUTYL ACRYLATE
STRUCTURAL PANEL	GLASS REINFORCED CONCRETE MILD STEEL FIBERBOARD (E.G.,"SUPER-DORLUX MASONITE) FLAKEBOARD (POTLATCH)

- MODULES UNDER CONSTRUCTION AND TESTING

Candidate Pottant Under Development

Ethylene/Methyl Acrylate

- PRODUCED BY GULF OIL CHEMICALS
- COST, $0.59 /LB
- VERY HIGH THERMAL STABILITY
- EXCELLENT ADHESION PROPERTIES
- NON-HYDROPHILIC
- AVAILABLE WITH ANTI-BLOCKING ADDITIVE
- CAN BE VACUUM BAG LAMINATED
- TOTAL INTEGRATED TRANSMISSION: 91.5%
- IN THIN FILMS EXTRUDABLE

Outer Cover Materials

NEW CANDIDATE MATERIAL MADE AVAILABLE BY 3M CORPORATION. BIAXIALLY ORIENTED ACRYLIC FILM.

PROPERTIES:

- HIGH TENSILE STRENGTH, 25,000 PSI
- NO SHRINKAGE DURING LAMINATION
- HIGH OPTICAL TRANSPARENCY: 91.5%
- AVAILABLE WITH UV ABSORBER, CUTOFF WAVELENGTH, 385 NM.
- PRELIMINARY INDICATIONS OF GOOD STABILITY, UNCHANGED AFTER 1,500 HRS. RS/4 EXPOSURE
- MINIMODULE PREPARED AND UNDERGOING JPL THERMAL CYCLE TESTING

Outer Cover Candidates for Substrate Design Modules

MATERIAL	COMPOSITION	RS/4 EXPOSURE PERFORMANCE
KORAD 212	ACRYLIC MULTIPOLYMER	BRITTLE AND DEGRADED IN 500 - 1000 HRS.
OF CURRENT INTEREST:		
TEDLAR 100BG30UT	POLYVINYL FLUORIDE	UNCHANGED 3,000 HRS.
3M X-22417	BIAXIALLY ORIENTED[A] ACRYLIC POLYMER	UNCHANGED 1,500 HRS.

A. MODULES HAVE BEEN PREPARED WITH THIS FILM - NO DIFFICULTY TH FILM SHRINKAGE HAS BEEN ENCOUNTERED.

UV Absorbers

5-VINYL TINUVIN
CHEMICALLY REACTIVE UV ABSORBER FROM UNIVERSITY
OF MASSACHUSETTS

- HAS BEEN SUCCESSFULLY COPOLYMERIZED WITH ACRYLIC POLYMERS TO GIVE NON-EXTRACTABLE ABSORBER
- MAY BE USEFUL FOR THE PREPARATION OF OUTER COVER FILMS THROUGH COPOLYMERIZATION OR MASTERBATCH BLENDING.
- SUCCESSFULLY COMPOUNDED AND CURED INTO EVA-EXTRACTION SHOWS ONLY 8% LOSS OF ABSORBER
- DEMONSTRATES CHEMICAL PERMANENCE IS POSSIBLE
- TECHNOLOGY FOR SYNTHESIS HAS BEEN TRANSFERRED TO SPRINGBORN LABORATORIES

Anti-Blocking Treatments

EXTRUSION/GLASS MAT TECHNIQUE

POLYMER EXTRUDED DIRECTLY ONTO "CRANEGLASS" 230 5-MIL NONWOVEN GLASS MAT

ADVANTAGES:

- GLASS MAT AVAILABLE IN ROLL FORM
- EFFECTIVE ANTI-BLOCKING SURFACE
- POSITIVE SPACER FOR MODULE COMPONENTS
- AIDS DEGASSING IN LAMINATION STEP
- PROVIDES INSULATION RESISTANCE
- TOTAL INTEGRATED TRANSMISSION 91% (MOLDED)
- DUE TO INTERNAL LIGHT TRAPPING
- ADD ON COST ONLY 0.78¢/FT^2

* NO DECREASE IN POWER OUTPUT FOUND WHEN PLACED OVER THE CELLS IN SUPERSTRATE MODULE.

Thermogravimetric Analysis of Candidate Encapsulation Materials

TEMPERATURES INDICATE ONSET OF WEIGHT LOSS IN ATMOSPHERES OF AIR AND NITROGEN

MATERIAL	IN AIR (°C)	IN NITROGEN (°C)
SAFLEX-PVB	60	60
KORAD ACRYLIC FILM	220	250
TEDLAR	280	280
EMA (BASE RESIN)	300	370
EVA (ELVAX 150) BASE RESIN	275	300
EVA (A9918) UNCURED	190	210
EVA (A9918) CURRED	260	275

- EMA BASE RESIN VERY THERMALLY STABLE
- TEDLAR SHOWS LITTLE SIGN OF OXIDATION (AIR AND NITROGEN TEMPERATURES THE SAME)
- EVA BASE RESIN APPEARS STABLE TO 275C
- COMPOUNDED RESINS LOSE VOLATILES AT LOWER TEMPERATURES

Primers — Adhesives

MODIFIED PRIMER FORMULATION [A.]

DOW CORNING Z-6030	9.0 PARTS
BENZYL DIMETHYL AMINE	1.0 PARTS
LUPERSOL 101 PEROXIDE	0.1 PARTS

DILUTE TO 10% SOLUTION WITH ANHYDROUS METHANOL, SWAB ON, AIR DRY, 1/2 HOUR.

BOND STRENGTHS(TO EVA)

IN POUNDS PER INCH OF WIDTH

SUBSTRATE	PRIMED	BOILING WATER (2 HOURS)
SODA LIME GLASS	40	24
"SUNADEX"	35	32
MILD STEEL	56	50
TEDLAR KORAD ALUMINUM GALVANIZED STEEL	INEFFECTIVE	

A. NUMBER A11861

Durable Coatings for Steel

RECOMMENDATIONS FROM MILT GLASER[A]

CONSULTANT - COATINGS EXPERT

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

[A] COST/ PERFORMANCE HEIRARCHY FOR COATINGS FOR GALVANIZED STEEL OR CONVERSION COATED MILD STEEL.

Corrosion Studies

RESULTS OF 1600 HOURS OF SALT SPRAY EXPOSURE
(ASTM B-117)

METALS PRIMED WITH SILANE PRIMER [A].

ENCAPSULATED IN EVA

METAL	UNPRIMED	PRIMED
GALVANIZED STELL	MEDIUM CORROSION	HEAVY CORROSION
MILD STEEL	MEDIUM CORROSION	LIGHT CORROSION
COPPER	UNCHANGED	UNCHANGED
ALUMINUM	UNCHANGED	UNCHANGED

- PRIMED METALS GENERALLY BETTER THAN UNPRIMED
- ALUMINUM LEAST EFFECTED OF METALS INVESTIGATED BOTH PRIMED AND UNPRIMED.

[A] PRIMER A11861; SILANE/AMINE/PEROXIDE

ENCAPSULATION TASK

Engineering Design Trends and Guidelines

1) Temperature Controlled Primarily By Emissivity, Not Bulk Thermal Considerations
2) AR Coating On Cell A Must
3) Ribs Are Necessary On Substrate Modules
4) Al Substrate Unsuitable
5) Encapsulant Should Be Elastomeric
6) Low Iron Glass Cost Effective
7) Crane Glas Above Cells Okay
8) Frame Design: 3/8" Bite, 1/16" Gasket
9) Minimum Pottant Thickness Has Structural Dependence
10) Lower Efficient Cells Not Cost Effective

Minimodule and Submodule Weathering Program

STATUS

- JPL SITE COMPLETELY INSTALLED
  - 24 MINI-MODULES
  - 92 SUB-MODULES
  - UV AND OTHER INSTRUMENTATION
  - 2 MONTHS OF WEATHERING
    - NO VISUAL DEGRADATION
    - SLIGHT REDUCTION IN ELECTRICAL OUTPUT OF MINI-MODULES
    - SUB-MODULES NOT TESTED ELECTRICALLY (TEST EQUIPMENT IN PREPARATION)
- GOLDSTONE SITE READY FOR INSTALLATION (WAITING FOR TEST EQUIPMENT)
- POINT VINCENTE SITE UNDER CONSTRUCTION (READY BY 10/1/80)

c-4

PRODUCTION PROCESS AND EQUIPMENT AREA

TECHNOLOGY SESSION

Don Bickier, Chairman

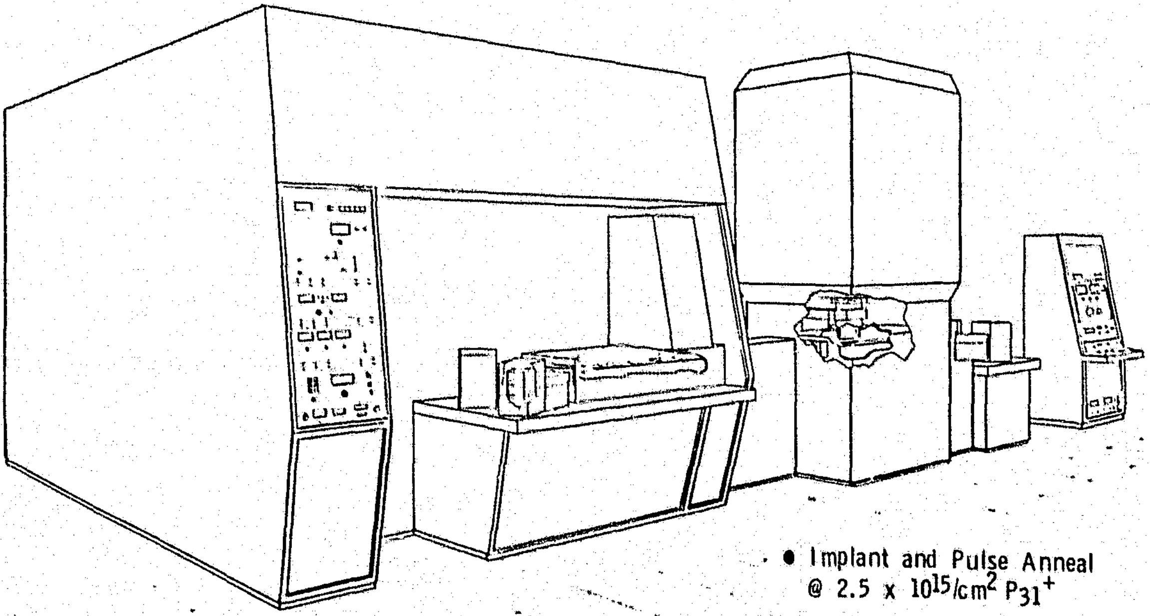
The seven contracts managed by PP&E that originated with the near-term funding group were not reported on at this PIM. Some of the contracts are still listed as active only to complete the required documentation. All significant technical developments in these contracts were reported previously.

Reduction in the number of presentations resulted in a single four hour session for the PP&E Area contractors. This allowed the contractors to participate in the plenary sessions and to interface with the activities in the other areas of the Project.

SOLAR CELL JUNCTION PROCESSING SYSTEM

SPIRE CORP.

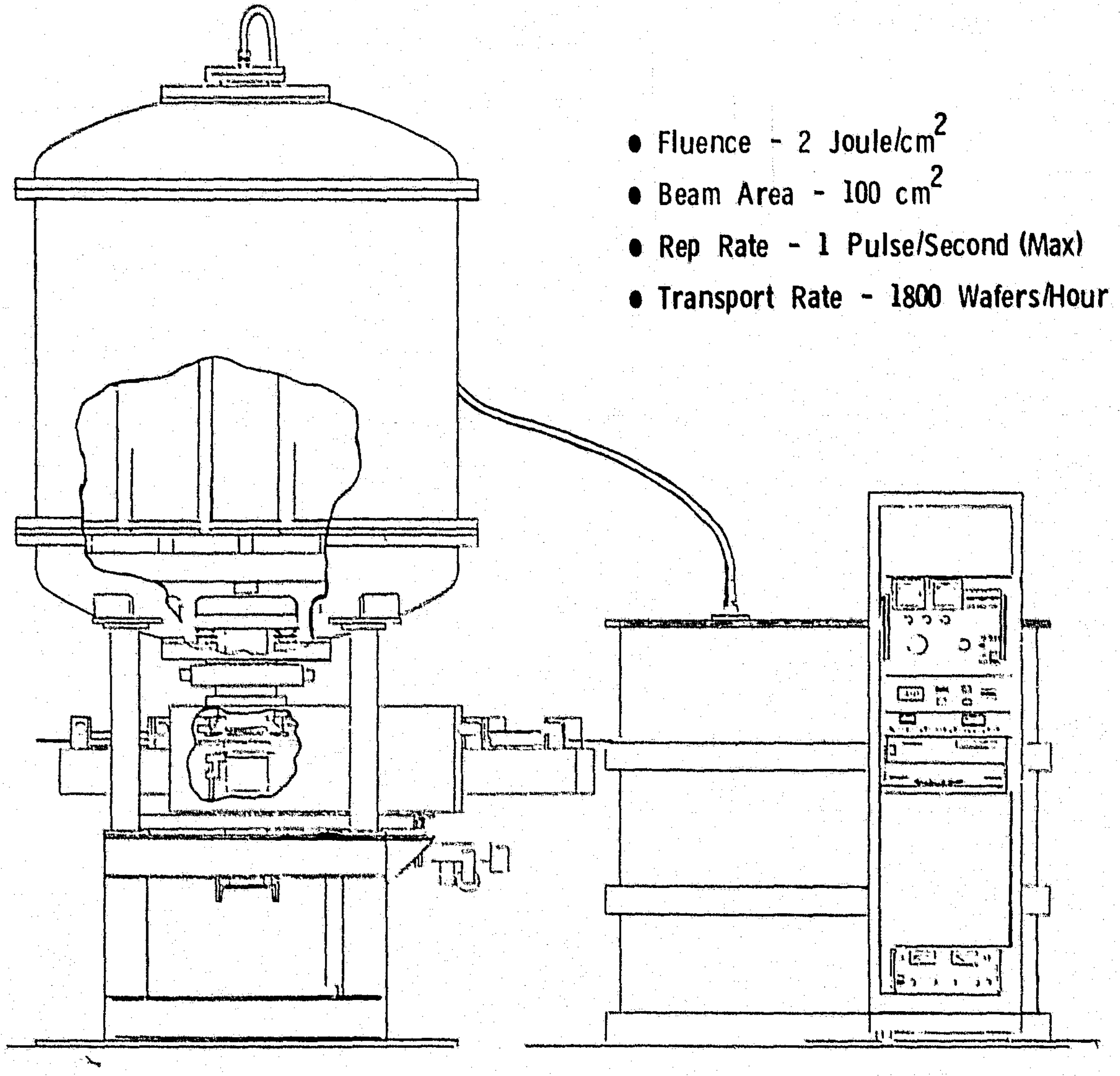
Spire-JPL Junction Processor



- Implant and Pulse Anneal @ $2.5 x 10^{15}/cm^2 P_{31}^{+}$
- 1800 Wafers/Hour
- 100 cm^2 Area per Wafer

PAGE 284 INTENTIONALLY BLANK

SPI - Pulse 7000 Pulse Annealer

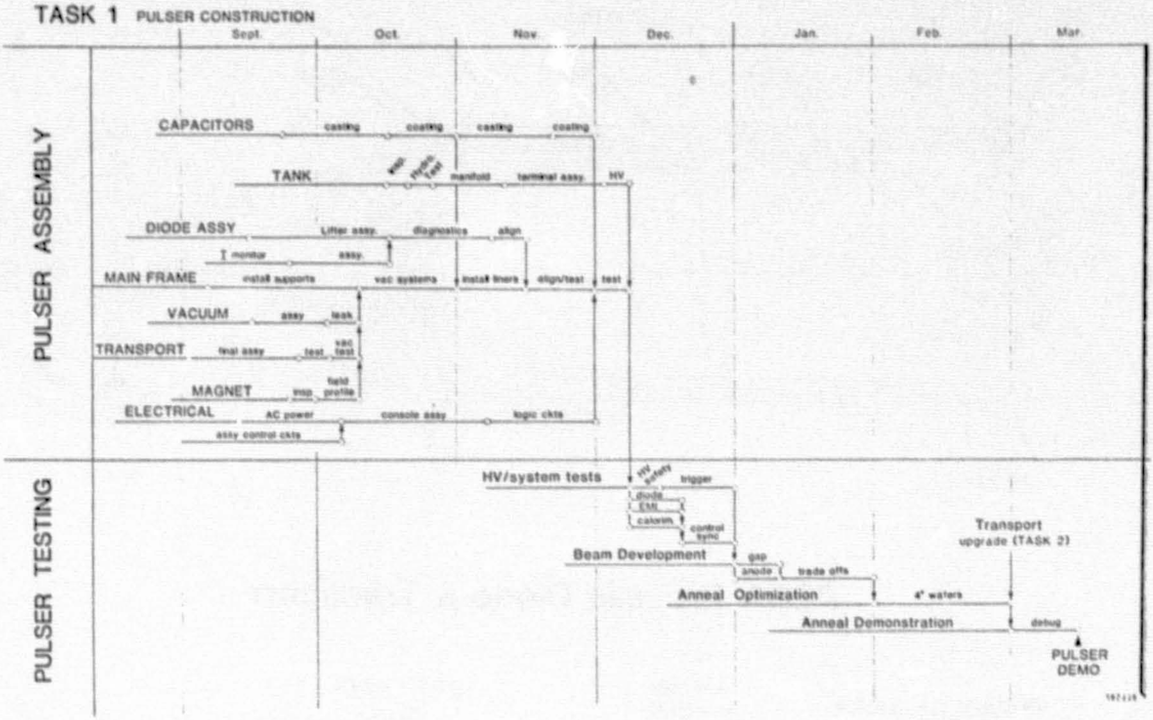


- Fluence - 2 Joule/cm^2
- Beam Area - 100 cm^2
- Rep Rate - 1 Pulse/Second (Max)
- Transport Rate - 1800 Wafers/Hour

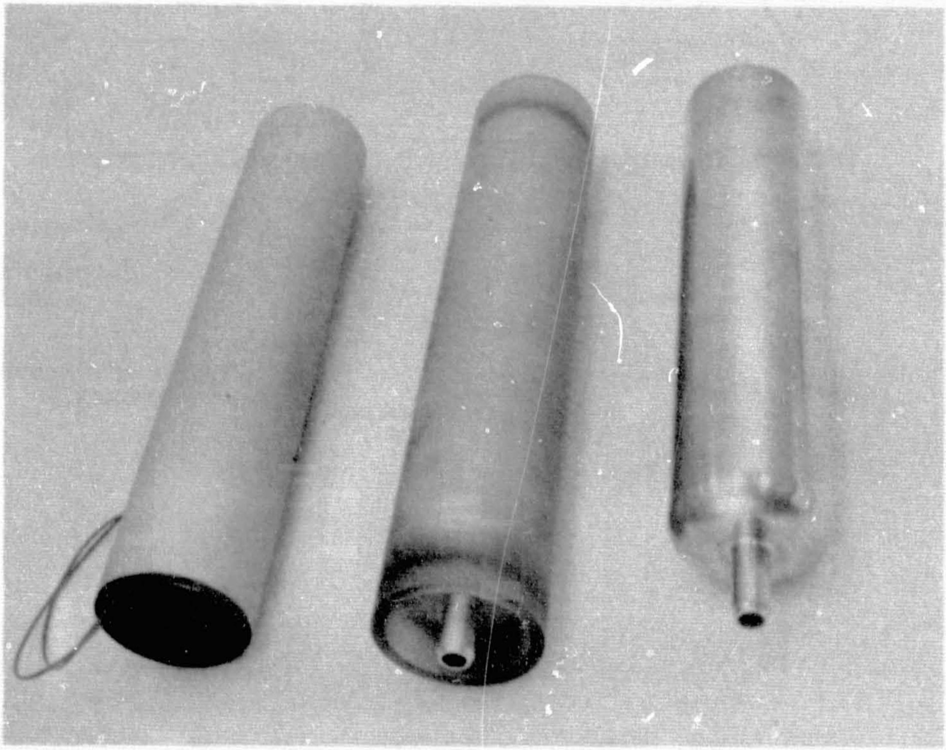
Junction Processor Program Status, September 1980

1. PULSER DETAIL DESIGN COMPLETED JULY 1980
2. ALL COMPONENTS ARE BEING MANUFACTURED
3. FINAL ASSEMBLY TO START SEPTEMBER
4. ASSEMBLY TO BE COMPLETED BY JANUARY 1

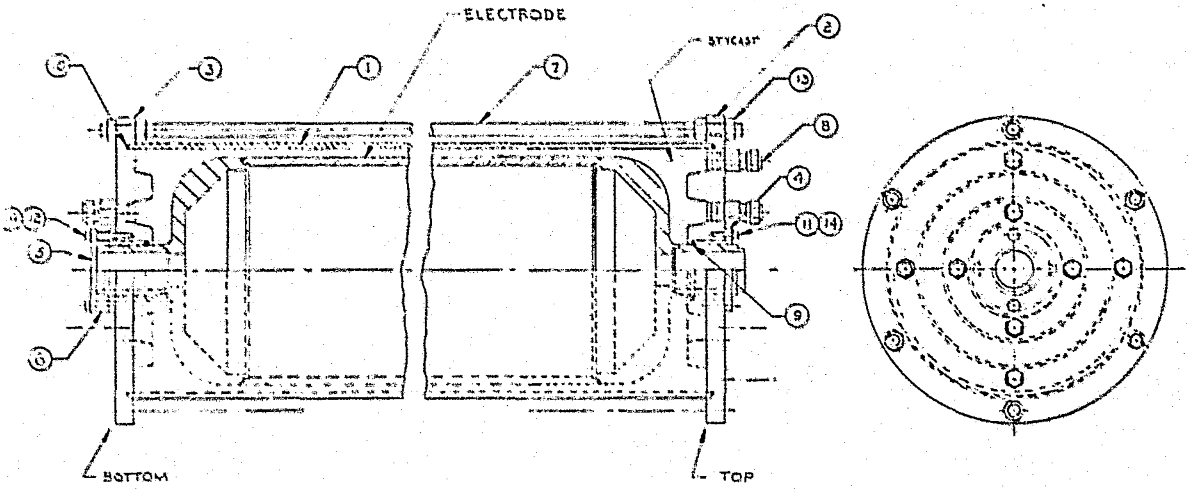
Junction Processor Development



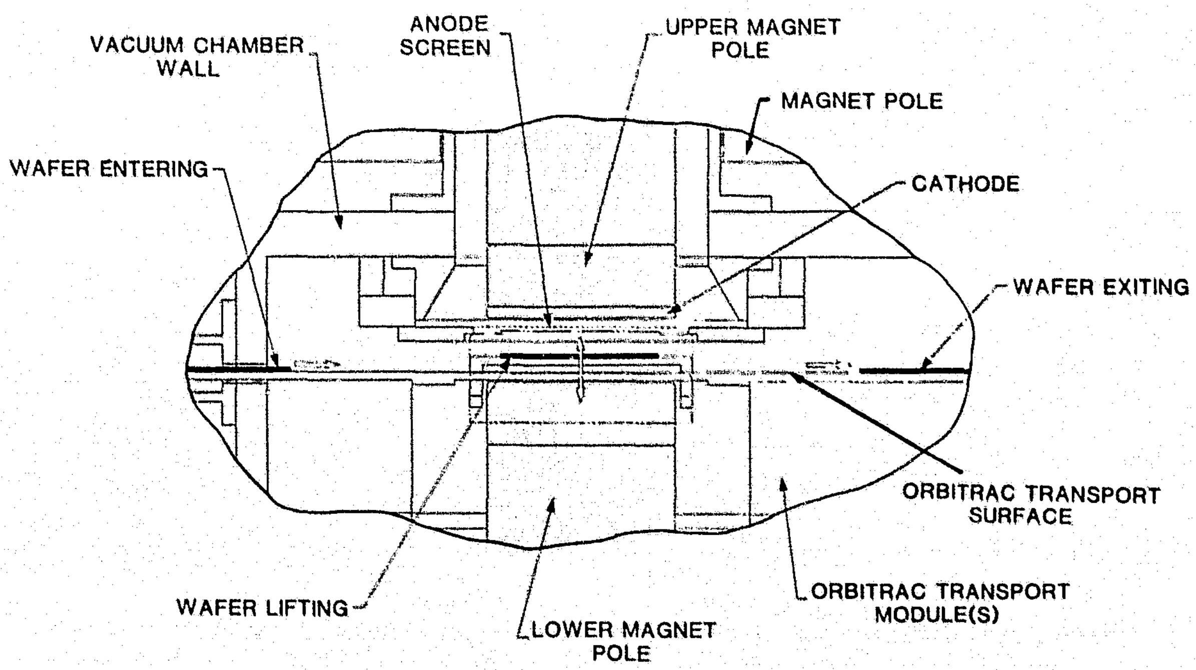
SPI-Pulse 7000 Energy Storage Capacitor Manufacturing Sequence

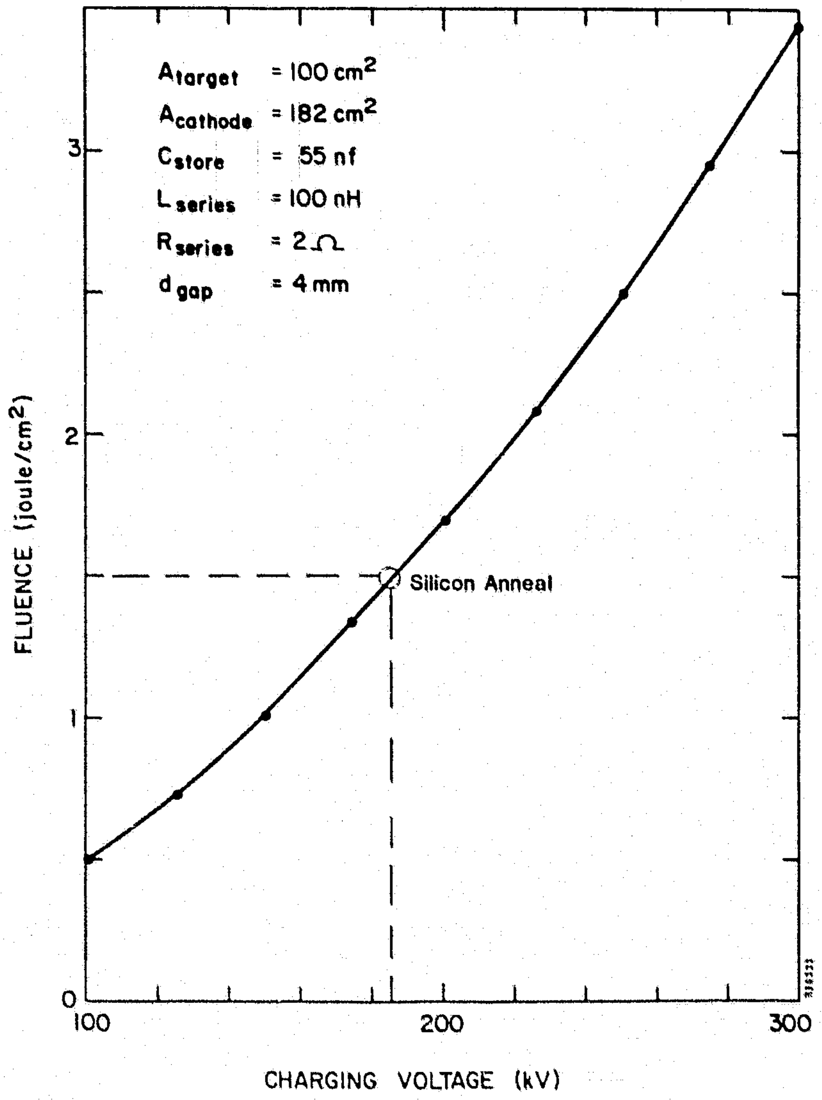


Mold

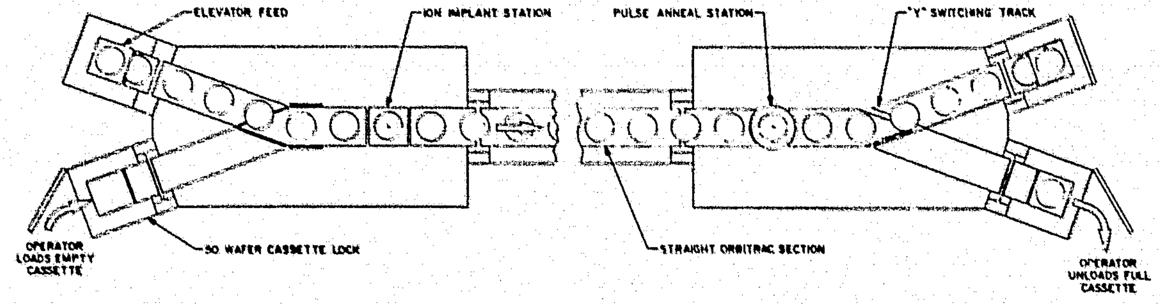


PEBA Process Diode & Transport

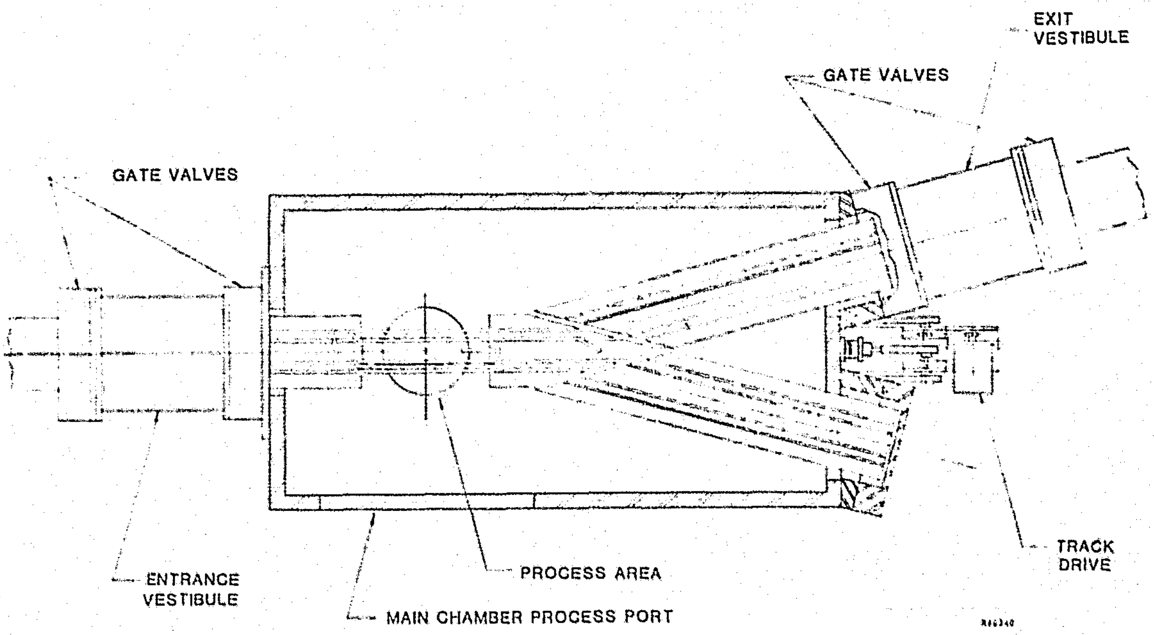




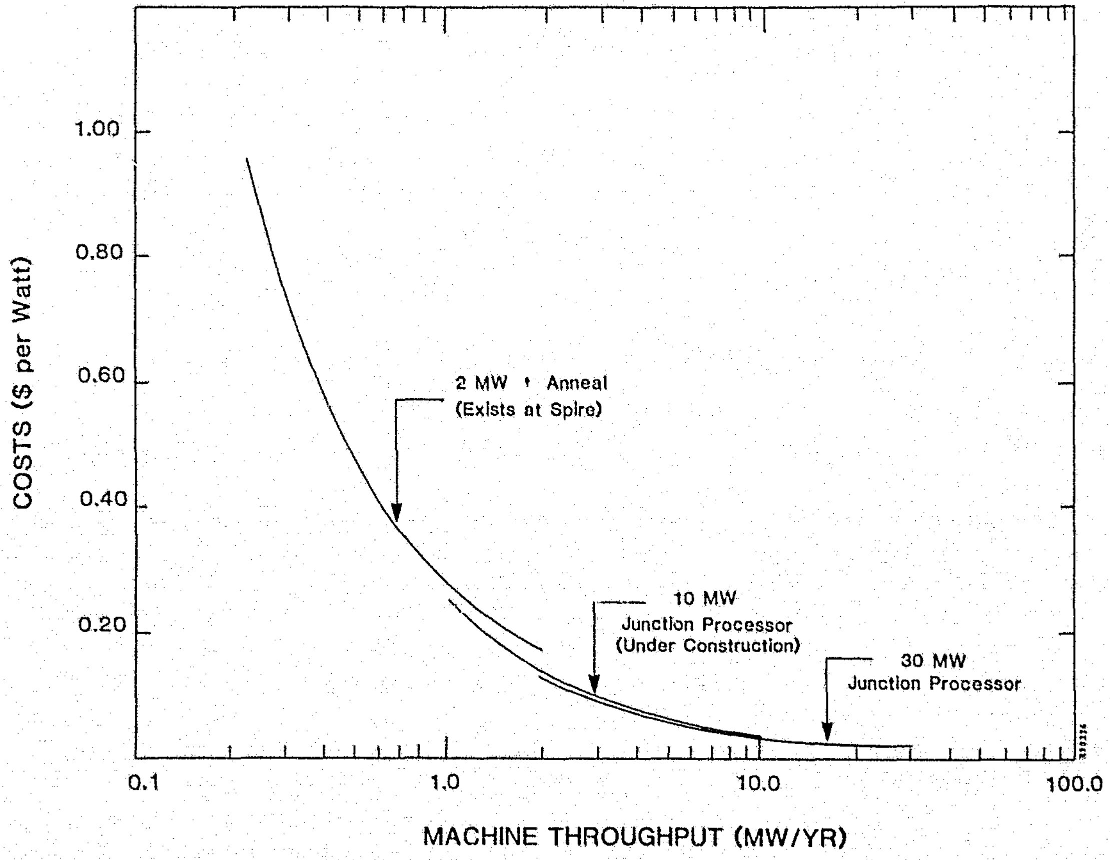
Spire 1800-Wafer/h Vacuum Transport System

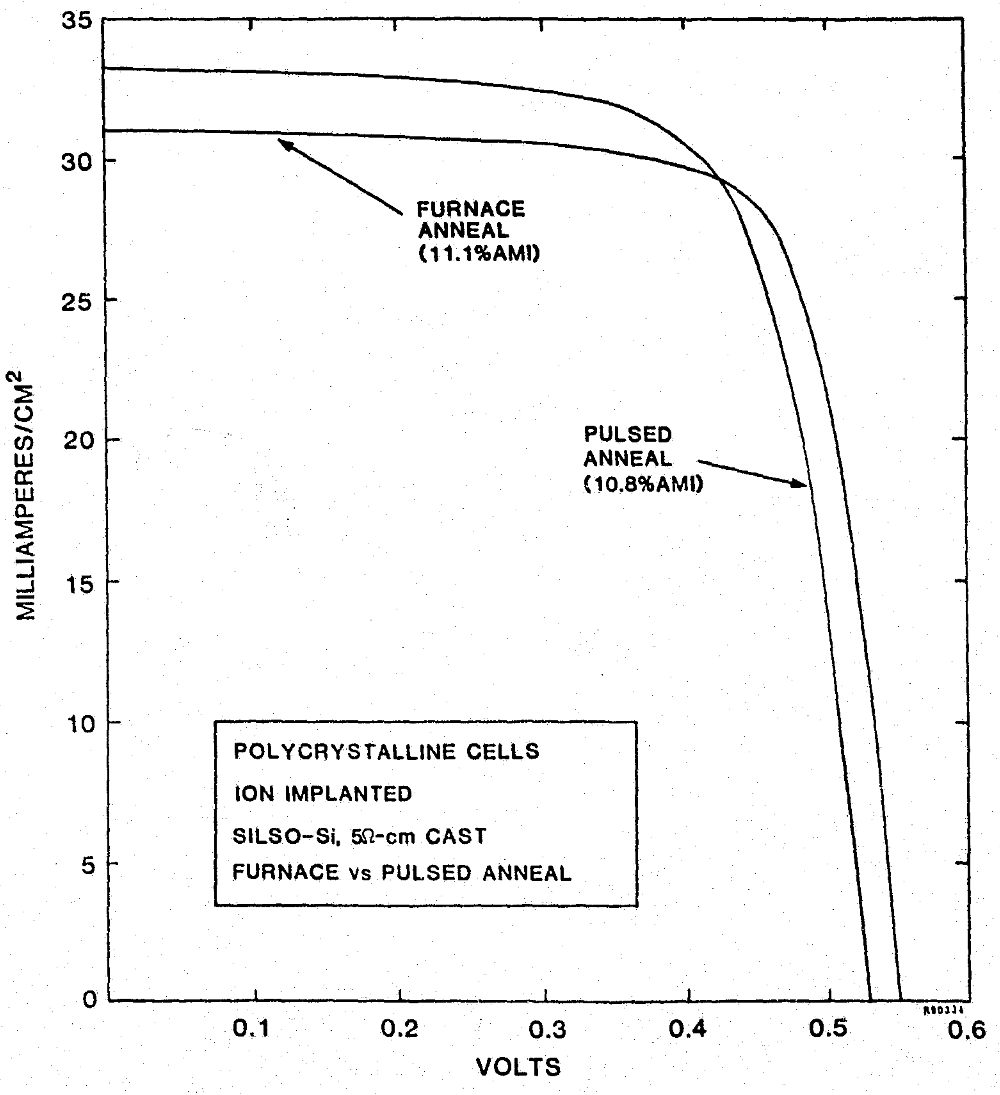


Process Chamber (Top View)

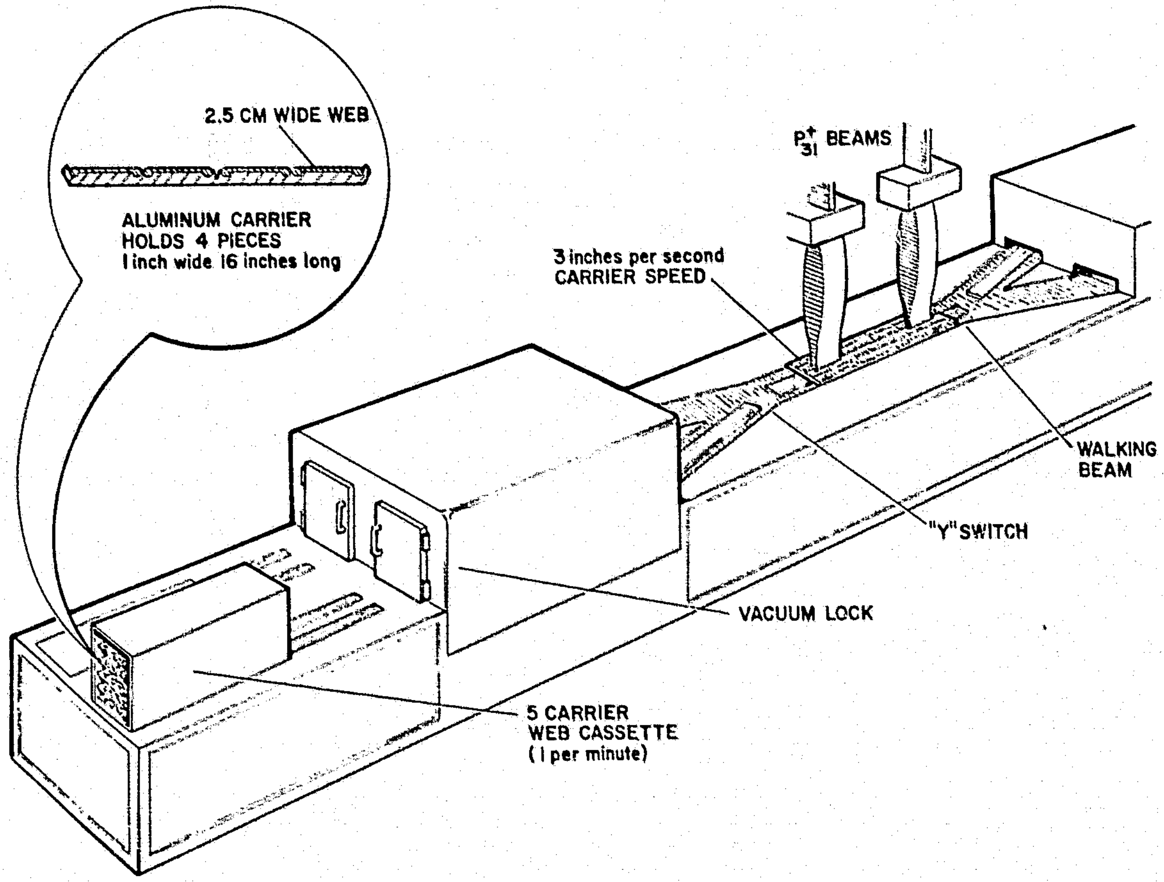


Junction Formation Costs by Ion Implantation



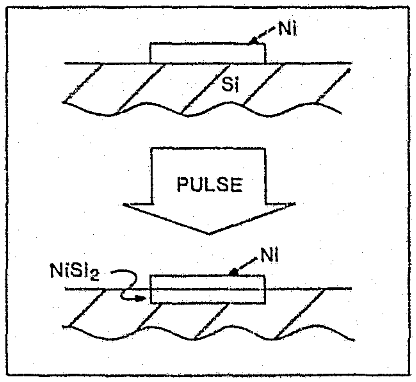

35
30
25
20
15
10
5
0
MILLIAMPERES/CM²
0.1
0.2
0.3
0.4
0.5
0.6
VOLTS
FURNACE
ANNEAL
(11.1%AMI)
PULSED
ANNEAL
(10.8%AMI)
POLYCRYSTALLINE CELLS
ION IMPLANTED
SILSO-Si, 5Ω-cm CAST
FURNACE vs PULSED ANNEAL
R80334

Concept for 30 MW/yr Web Ion Implanter



Other Applications of Pulse Electron Beam Heating

SINTERING



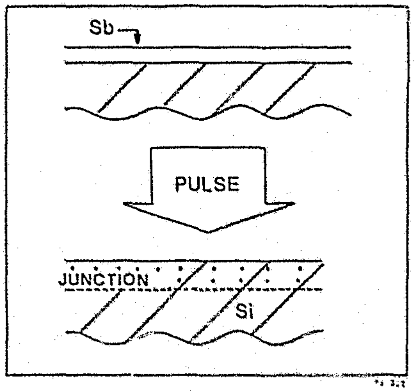
PROCESS:

- Evaporate/Pattern Ni Layer
- Pulse Ni to Near Melt

RESULTS:

- Si Under Ni Alloys
- Exposed Si Not Melted

DIFFUSION



PROCESS:

- Evaporate ≤ 200 A Sb
- Pulse; Melt Sb and Si

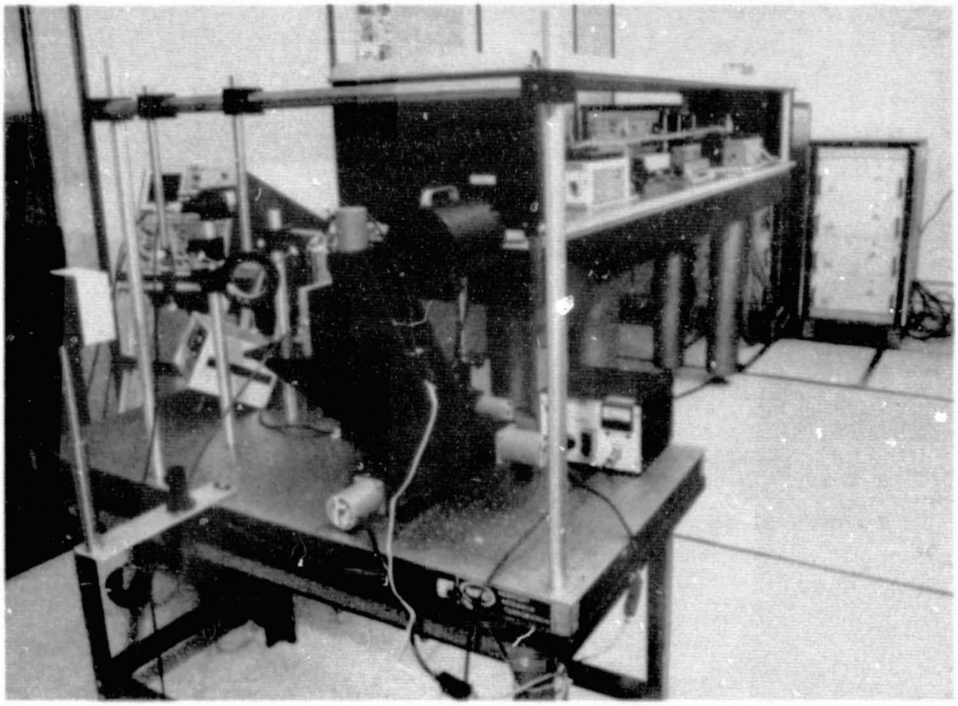
RESULTS:

- Shallow (≤3000 A) Junction
- Sb Substitutional, No Excess

LASER ANNEALING

LOCKHEED MISSILES & SPACE CO., INC.

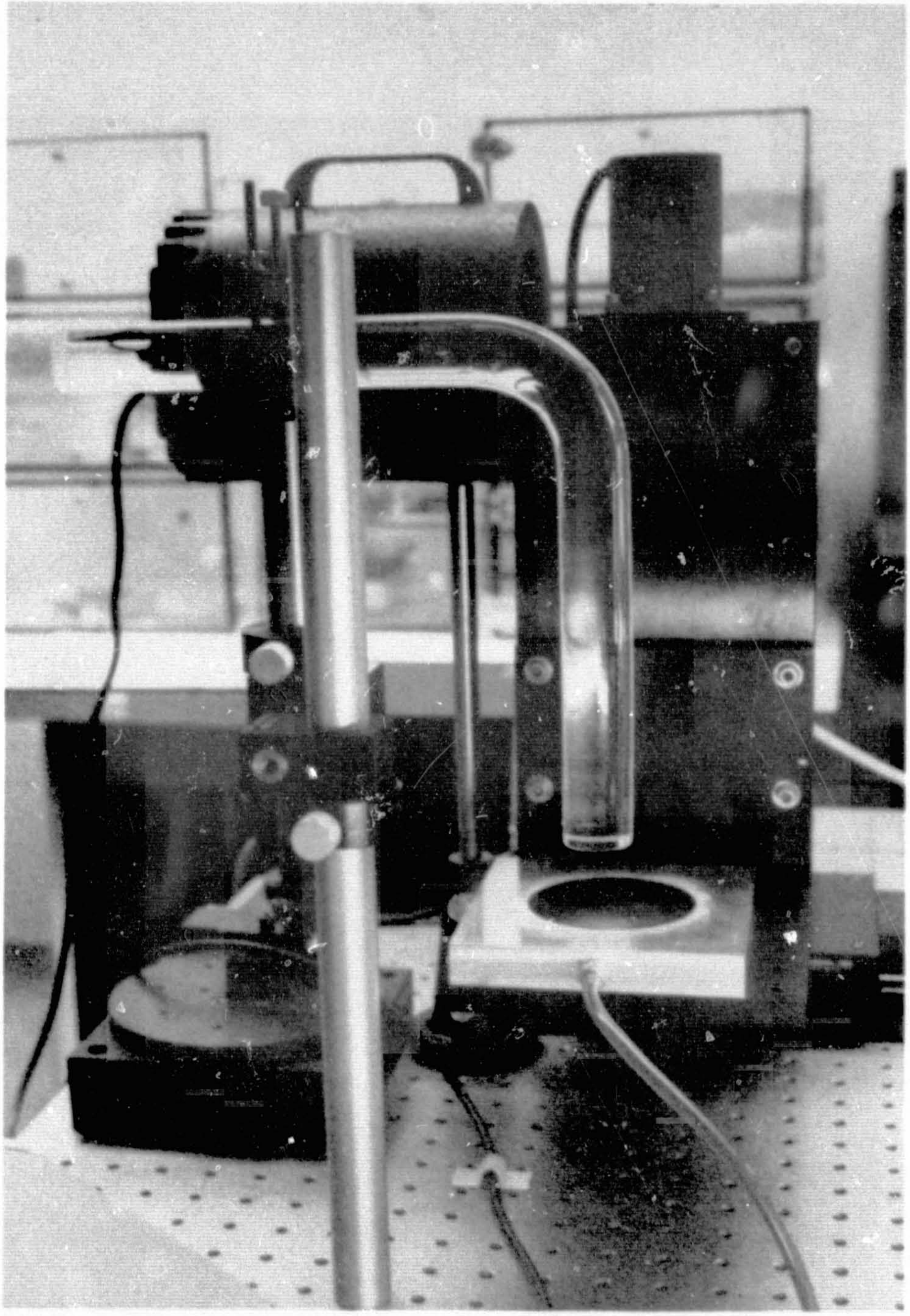
Nd:Glass Laser System



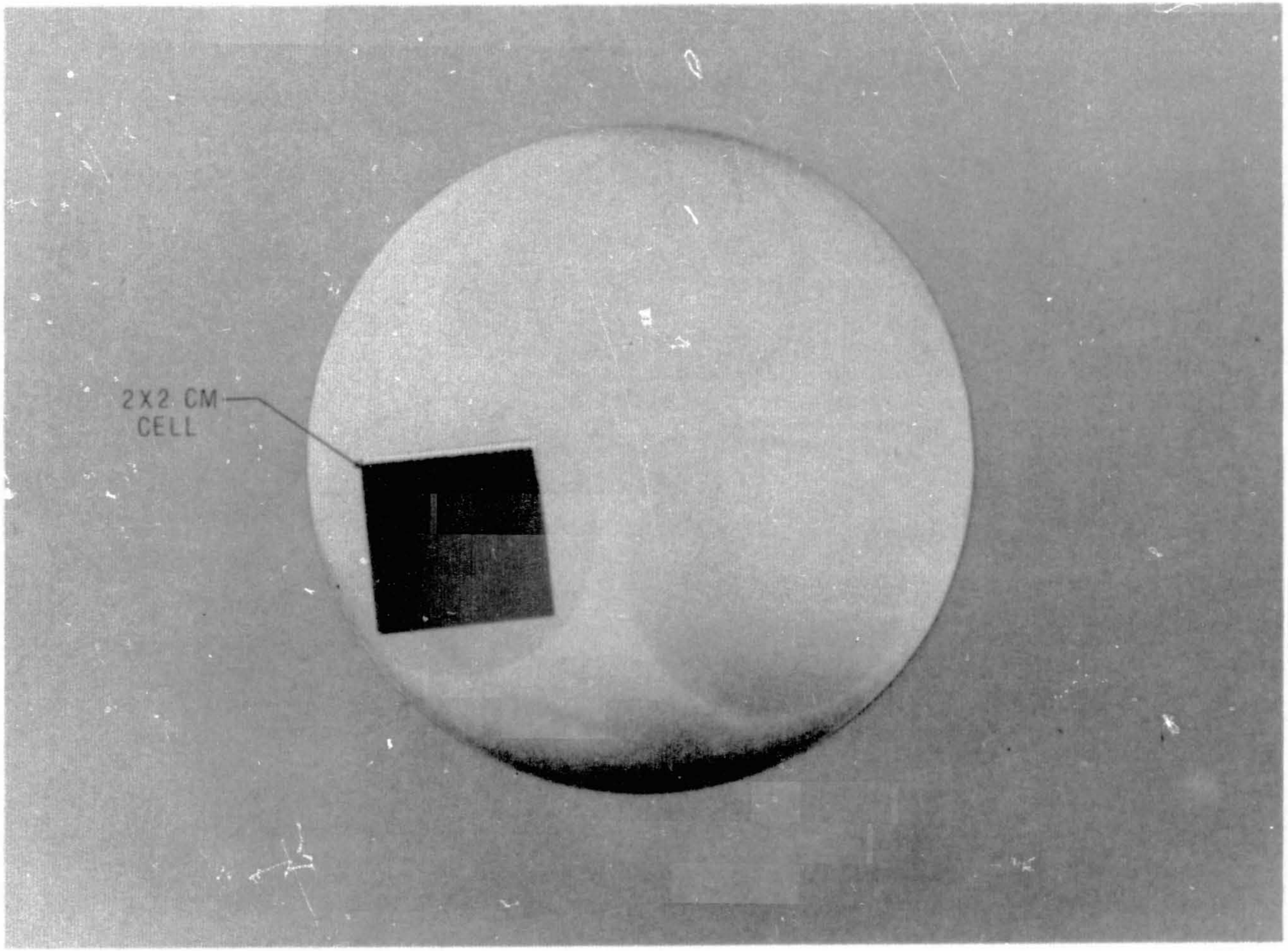
Laser Anneal Parameter Variables

WAVELENGTH	PULSE WIDTH	ENERGY DENSITY
1064 nm		1, 2J/cm^2
		1, 5J/cm^2
532 nm	20-50 nSEC	
		1, 9J/cm^2
1064 nm/532 nm		2, 1J/cm^2

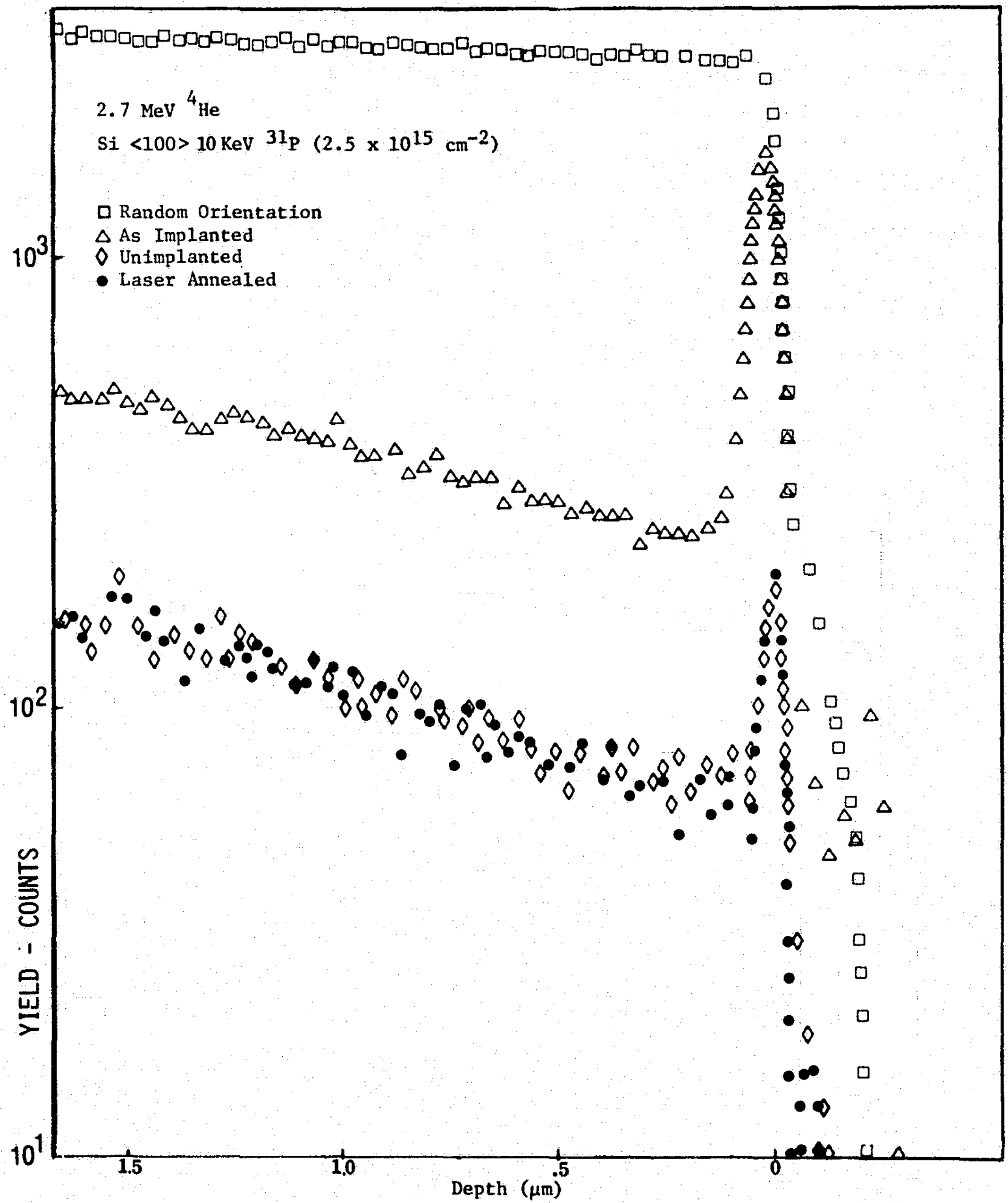
Laser Beam Homogenizer



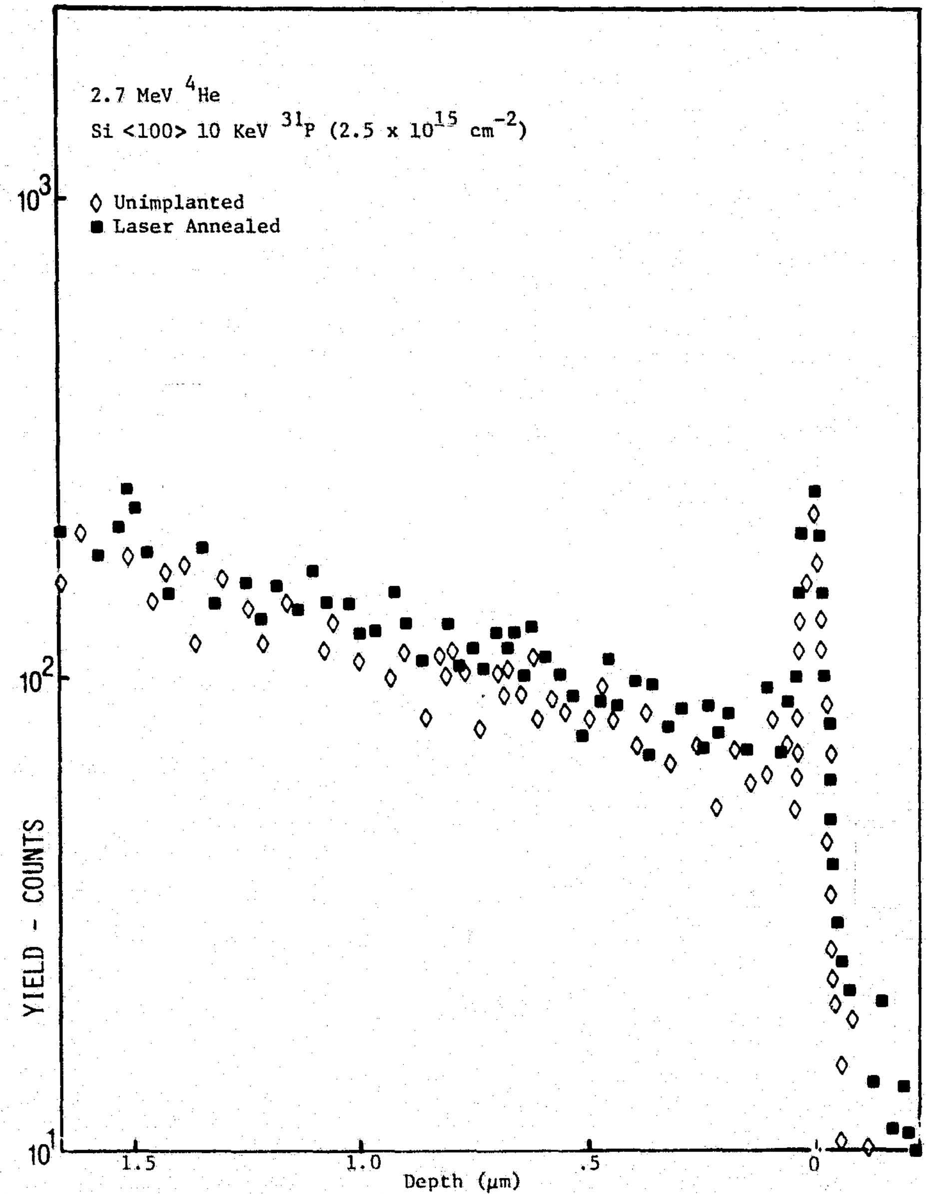
Single-Pulse 30-mm-Dia Laser-Annealed Areas on 3-in.-Dia Wafer



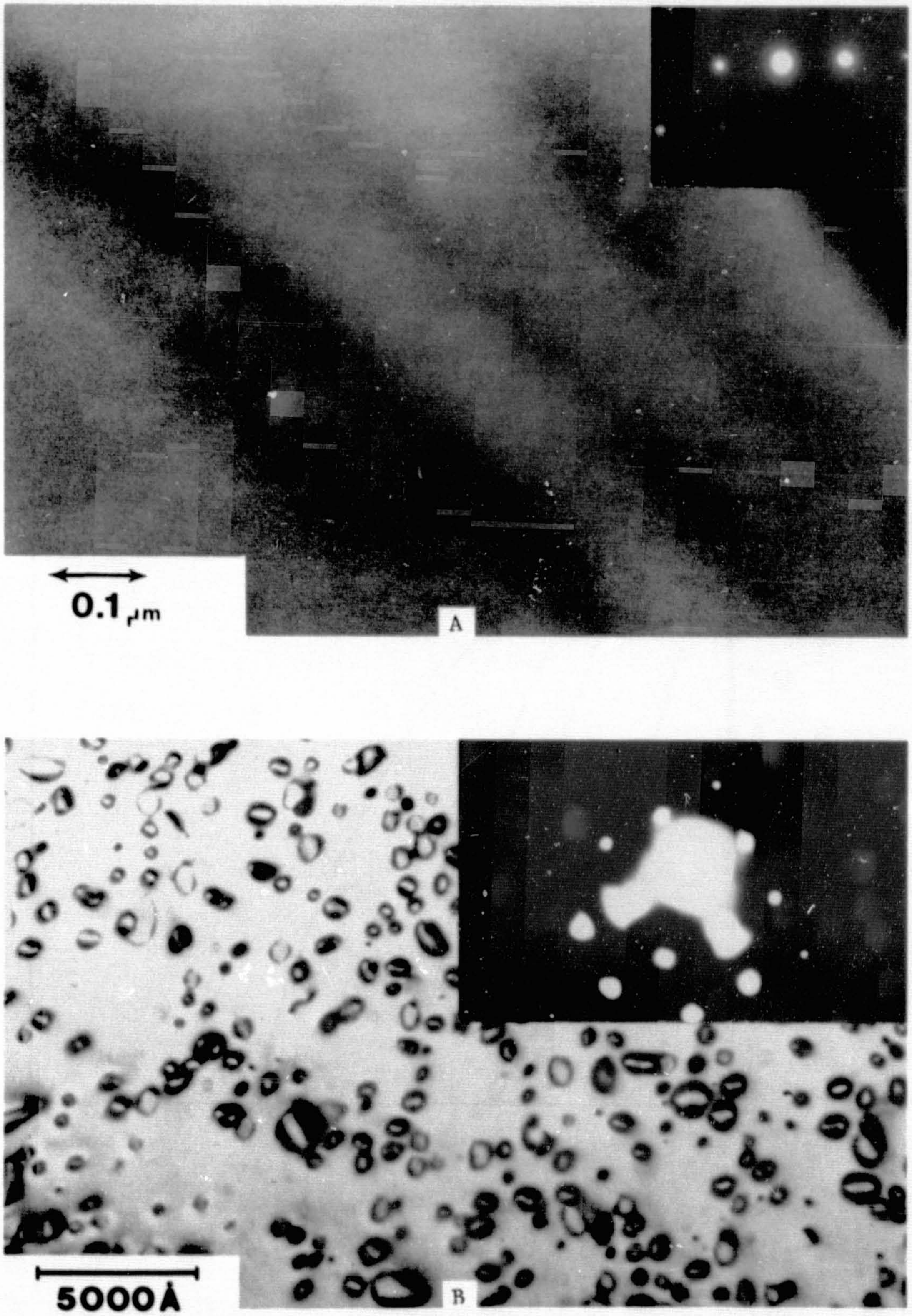
RBS Spectra



BACKSCATTERING SPECTRA OF 100 SILICON WAFERS IN UNIMPLANTED (VIRGIN), AND LASER ANNEAL (2.1 J/cm^2). A RANDOM SPECTRUM FOR THE VIRGIN CRYSTAL IS ALSO SHOWN.

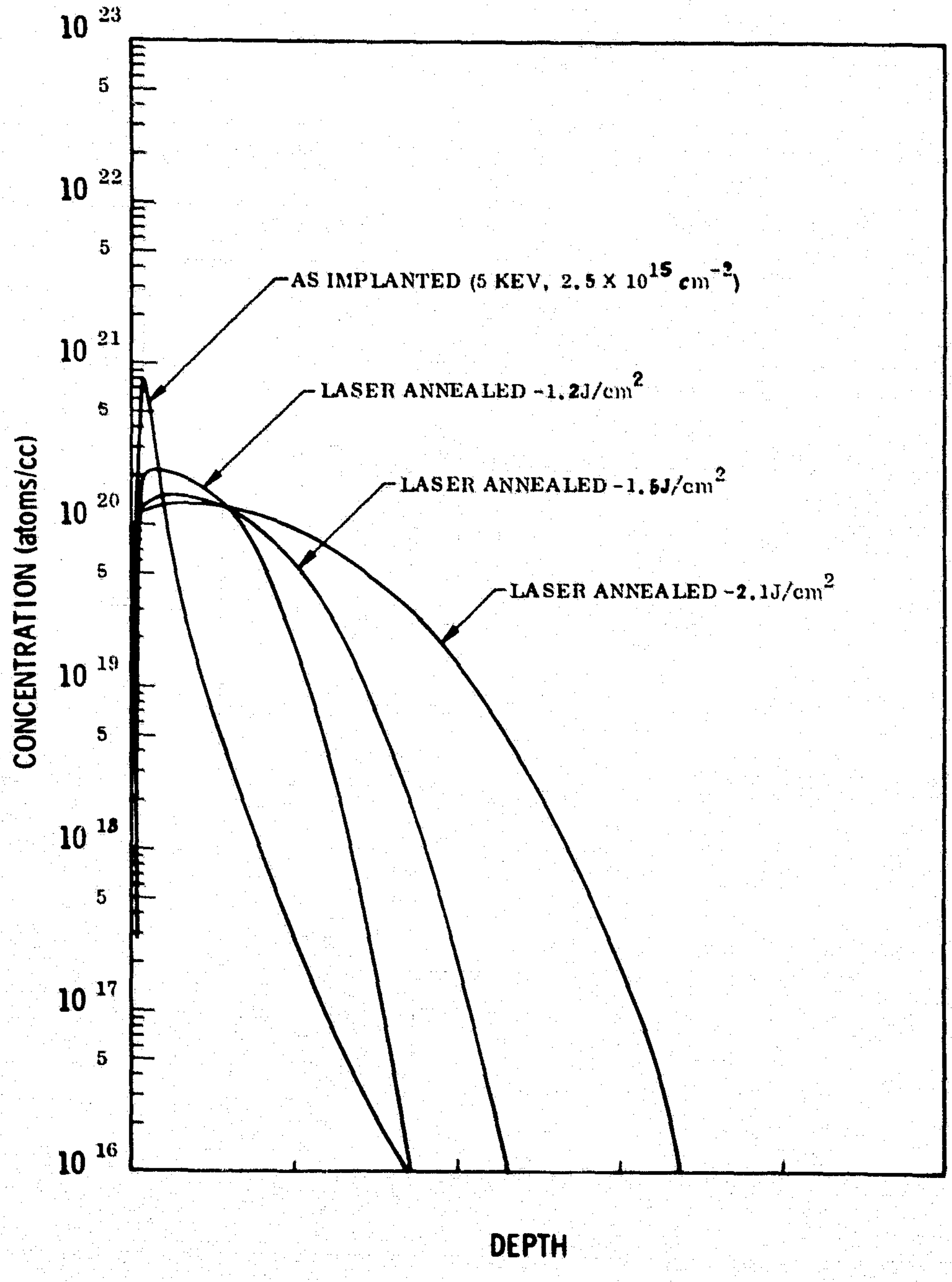


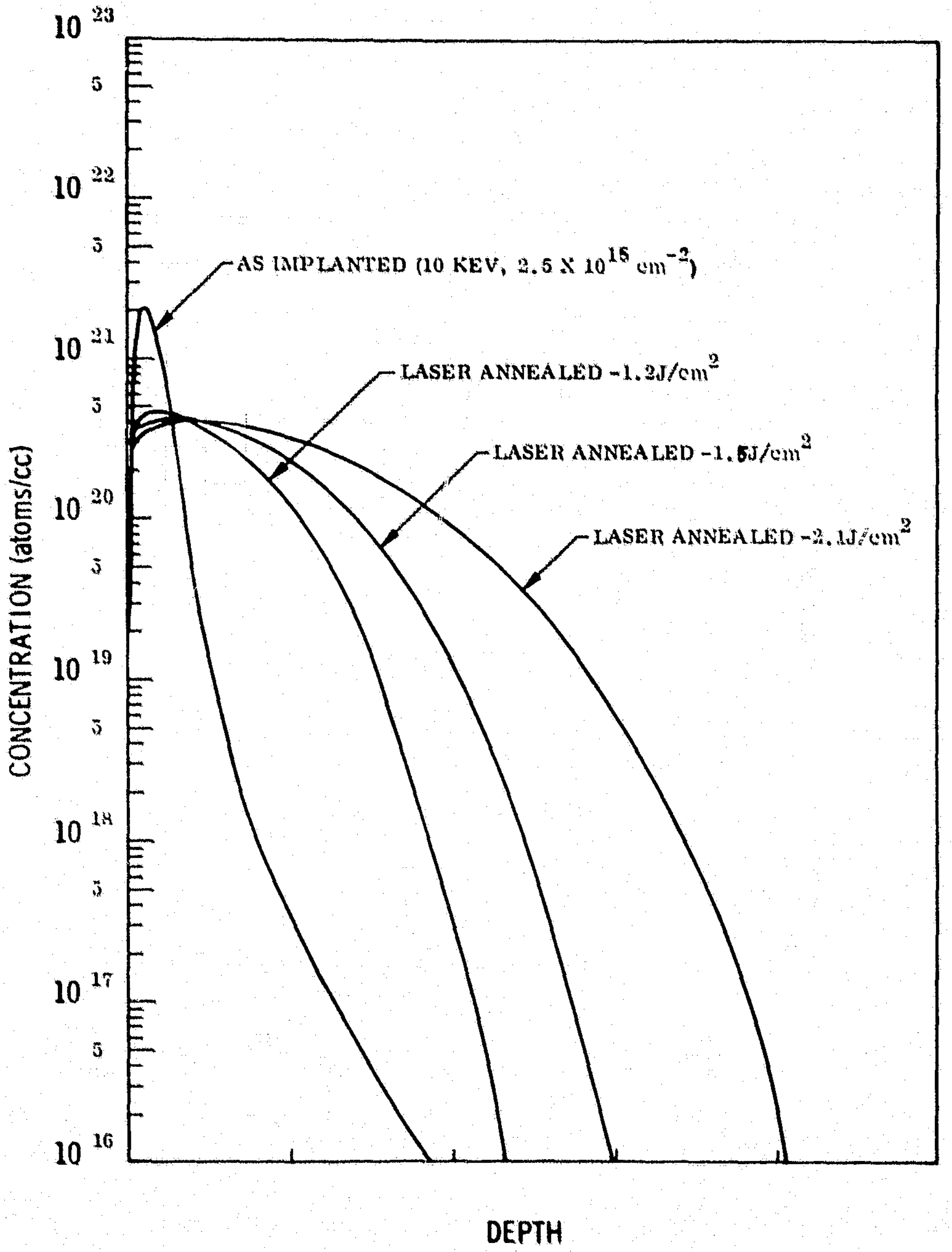
BACKSCATTERING SPECTRA OF 100 SILICON WAFERS IN UNIMPLANTED (VIRGIN), AND LASER ANNEAL (1.5 J/cm^2) STATES.



TEM Micrographs of ^{31}P Implanted Silicon After Laser Annealing (A), and After Furnace Annealing 900°C / 20 minutes (B).

SIMS Profiles




10 23
5
10 22
5
10 21
5
10 20
5
10 19
5
10 18
5
10 17
5
10 16
CONCENTRATION (atoms/cc)
AS IMPLANTED (10 KEV, 2.5 X 10^15 cm^-2)
LASER ANNEALED -1.2J/cm^2
LASER ANNEALED -1.5J/cm^2
LASER ANNEALED -2.1J/cm^2
DEPTH

Cell Variables

SURFACE VARIABLES	IMPLANTATION VARIABLES	CELL PROCESSING	LASER ANNEAL VARIABLES
CHEM. POLISHED	5 KEV/2.5 X 10^{15} cm^{-2} 10 KEV/2.5 X 10^{15} cm^{-2}	STANDARD	1.2J/cm^2
		BF_2 BSF ELECTRON BEAM ANNEALED	1.5J/cm^2
FLASH ETCHED	5 KEV/2.5 X 10^{15} cm^{-2} 10 KEV/2.5 X 10^{15} cm^{-2}		1.9J/cm^2
TEXTURE ETCHED	10 KEV/4 X 10^{15} cm^{-2}	BF_2 BSF ELECTRON BEAM PLUS LASER ANNEALED	2.1J/cm^2

Laser-Annealed Solar Cells (2 x 2)

FRONT IMPLANT PARAMETERS (2.5 X 10^{15})	WAFER SURF. CONDITION	BSF	LASER ENERGY DENSITY (J/cm^2)	Voc (mV)	Isc (mA)	FF	CONV. EFF.	Jsc (mA/cm^2)
10 KEV	PO	NONE	FURNACE 875°/20 min	550, 553	126.5, 127.5	77, 78.6	13.7	31.63, 31.88
5 KEV	PO & FE	NONE	1.5	539/556	133.6/136	72.3/77.1	13.3/14.5	33.40/34.00
10 KEV	PO & FE	NONE	1.2	530/549	125.7/133.5	70.5/75.5	12.5/13.1	31.43/33.38
10 KEV	PO & FE	NONE	1.5	545/555	126/132	72.8/77.9	12.9/13.9	31.50/33.00
10 KEV	PO & FE	NONE	1.9	549/556	125/131.5	75.8/77.3	13.3/14.1	31.25/32.88
5 KEV	PO	BF_2, EB ANNEALED	1.5	555	132.7, 133.6	76.9, 77.6	14.2, 14.4	33.18, 33.40
5 KEV	PO	BF_2, EB & LASER	1.5	575	139	73.7	14.7	34.75
5 KEV	PO	BF_2, EB & LASER	1.9	573	136	73.8	14.4	34.00
10 KEV	PO & FE	BF_2, EB	1.2	534/550	127/132.5	72/78.2	12.6/13.9	31.75/33.13
10 KEV	PO & FE	BF_2, EB	1.5	540/557	127/131	68.9/78.1	11.8/14	31.75/32.75
10 KEV	PO & FE	BF_2, EB & LASER	1.5	560/571	127.5/134	74/78.7	14/14.2	31.88/33.50
10 KEV	PO & FE	BF_2, EB	1.9	552/556	126/132	71.4/78.2	12.9/14	31.50/33.00
10 KEV	PO & FE	BF_2, EB & LASER	1.9	560, 565	126.7, 133	72.9, 78.1	13.6/14	31.68, 33.25

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

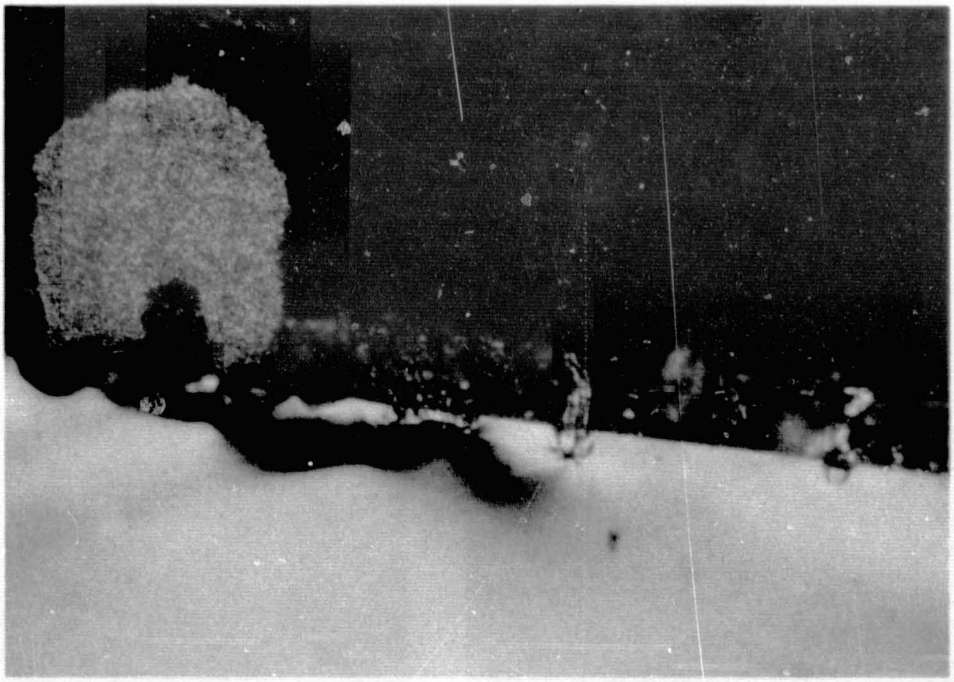
BERND ROSS ASSOCIATES

PROGRESS TO DATE

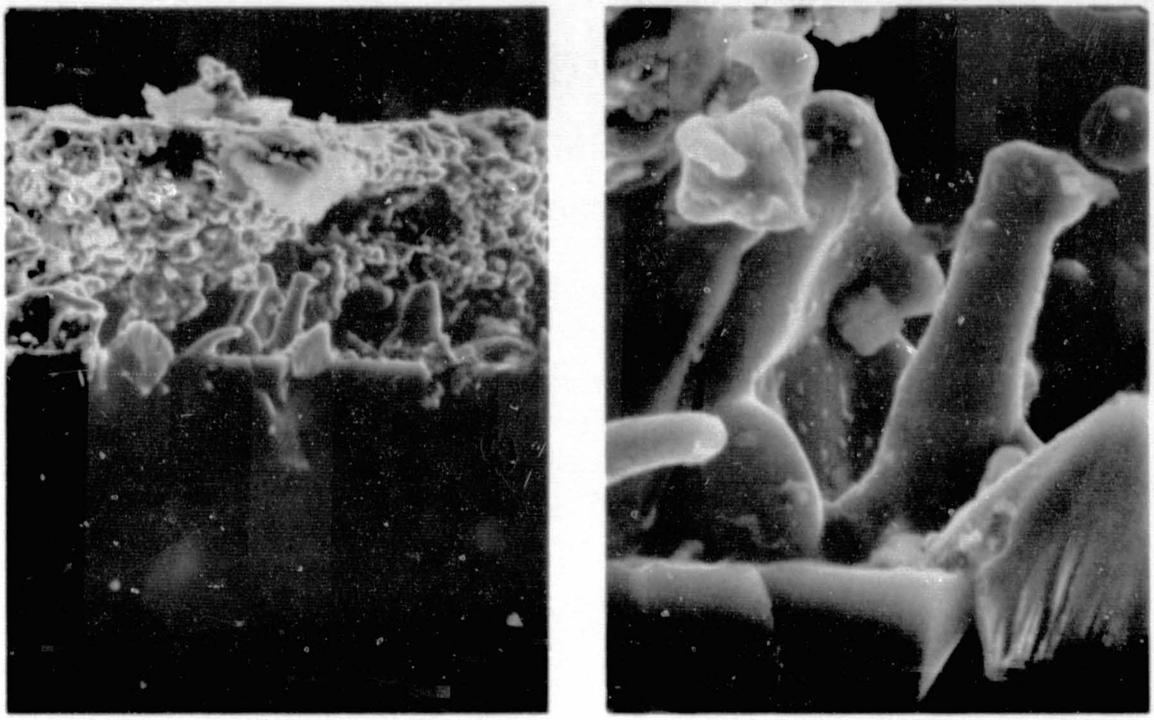
- NEW MATERIALS ORDERED AND RECEIVED
- PASTES BASED ON COPPER POWDER FABRICATED INCLUDING FORMULATION FOR FRONT CONTACT
- OBSERVATION OF UNEXPECTED MICROSTRUCTURE DURING CROSS SECTIONAL ANALYSIS
- IDENTIFICATION OF STRUCTURE
- SOLAR CELL FRONT CONTACT EXPERIMENT IN PROCESS

RESULTS OF ANALYSIS

WHILE LOOKING FOR REGROWN ALUMINUM DOPED SILICON DURING THE ANALYSIS OF CROSS SECTIONS OF ELECTRODES THE STRUCTURE SHOWN IN THE FOLLOWING ILLUSTRATIONS WAS OBSERVED.

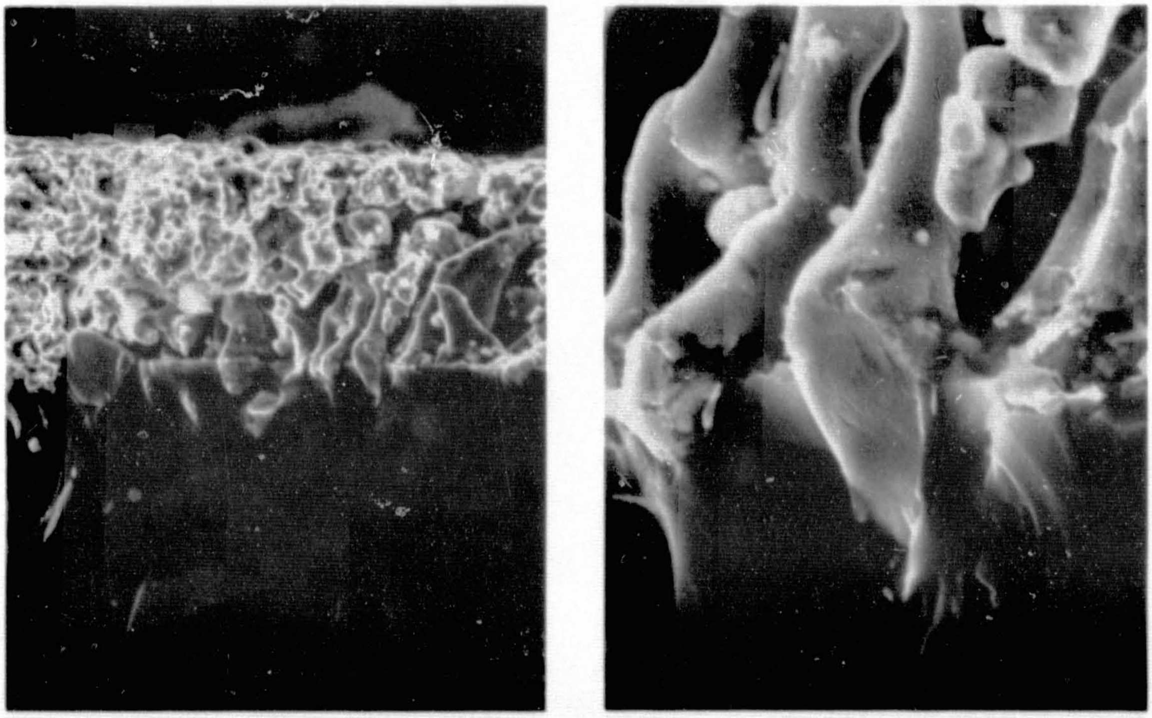


Optical micrograph of S080 paste approximately 85 wt. % copper, 5 wt. % silver fluoride, 5 wt. % germanium-aluminum eutectic, 5 wt. % lead. Combined optical and photographic enlargement about 1600x. Color of spikes suggests semiconductor material.



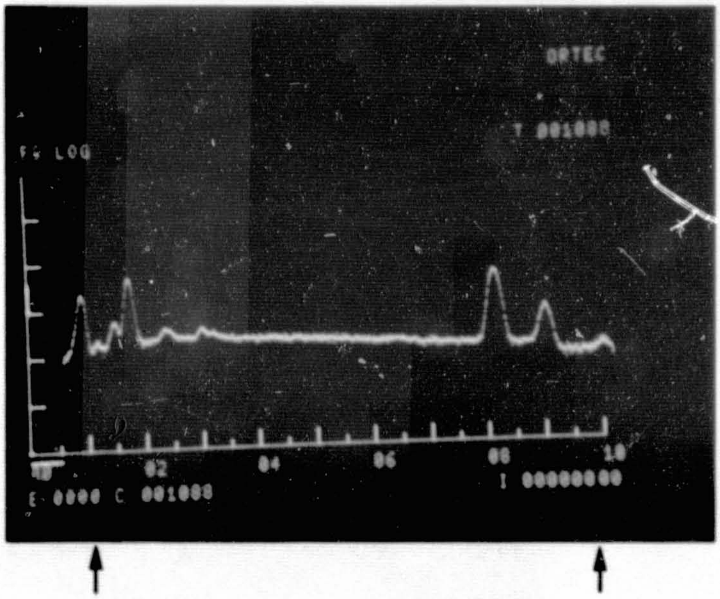
870x 4400x

Cross section of S079 electrodes fired at 550°C



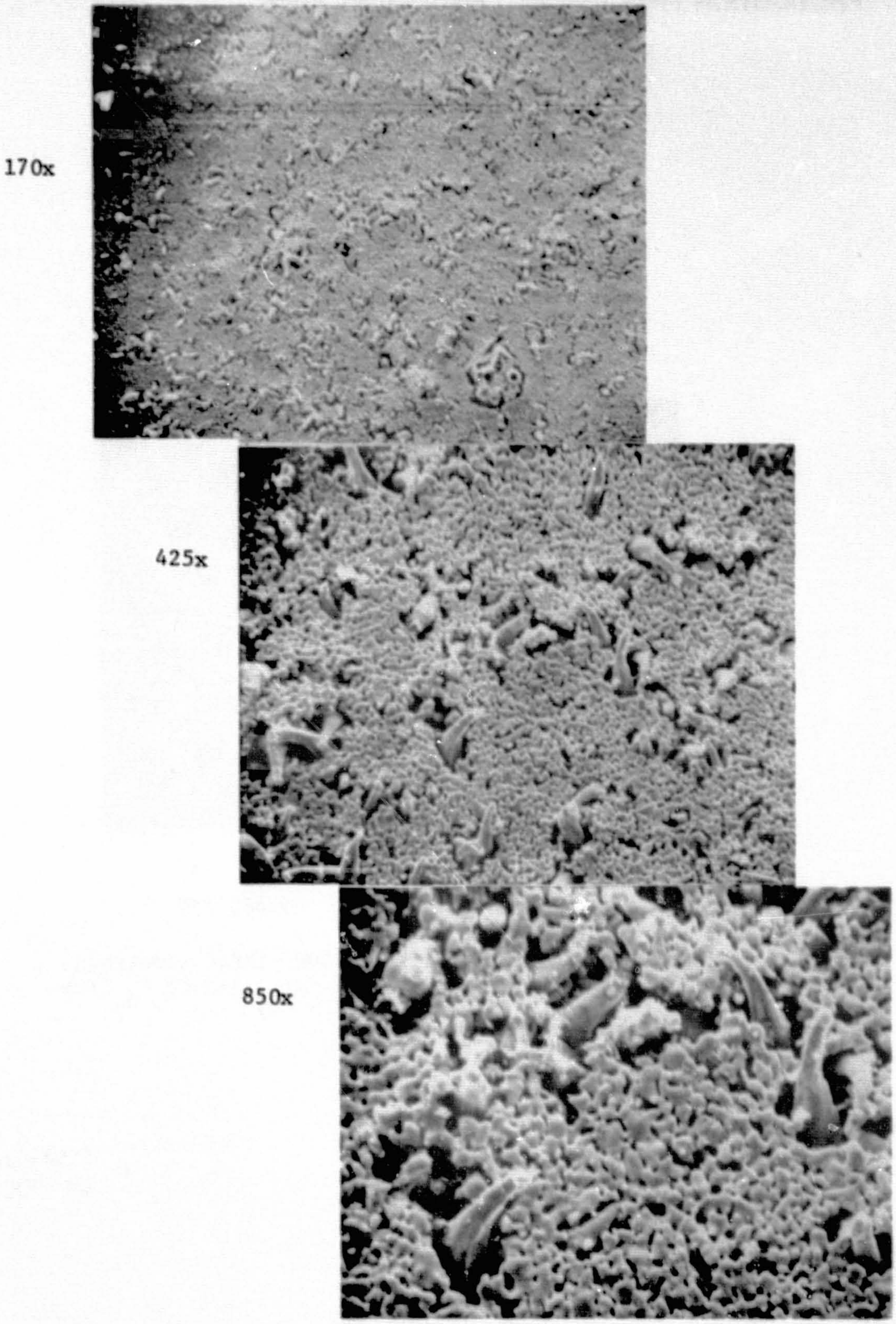
890x 15 4400x

Similar to above. Note subsurface structure below spikes

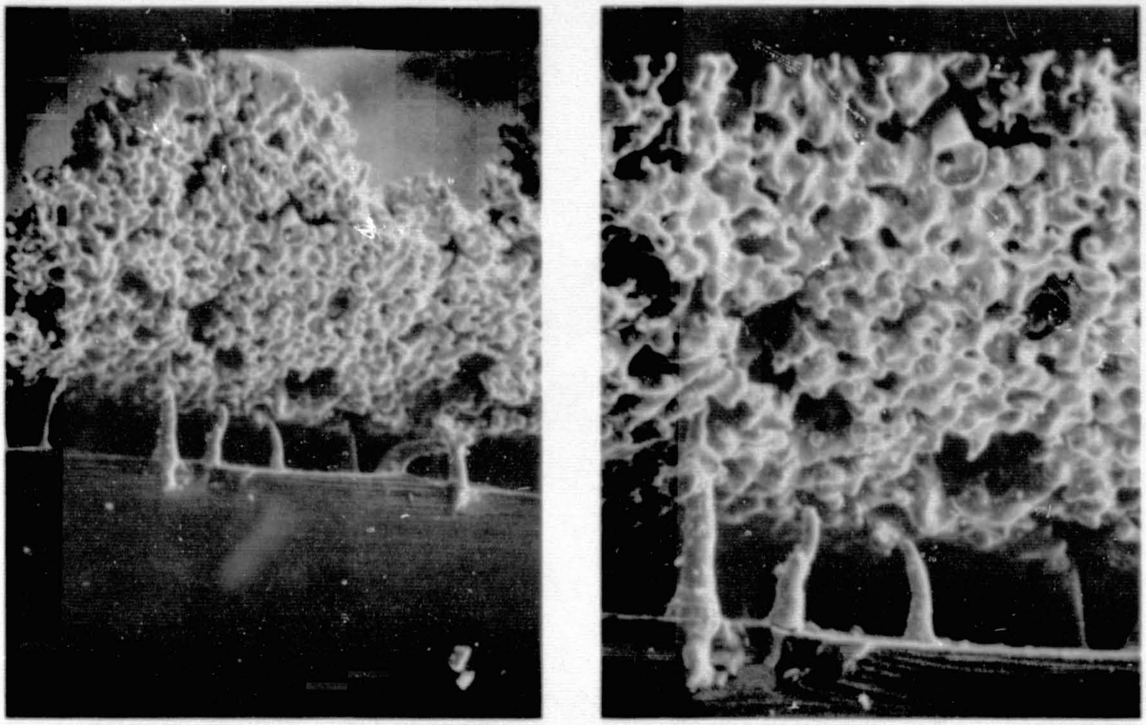


1.186 KeV 9.885 KeV

Xray fluorescence spectral scan of S080 fired electrode cross section. Indicated peaks are GeL$_{\alpha_1}$ and GE K$_{\alpha_1}$ lines



Sequence of photomicrographs of S071-A9, fired at 600°C in forming gas



450X

825X

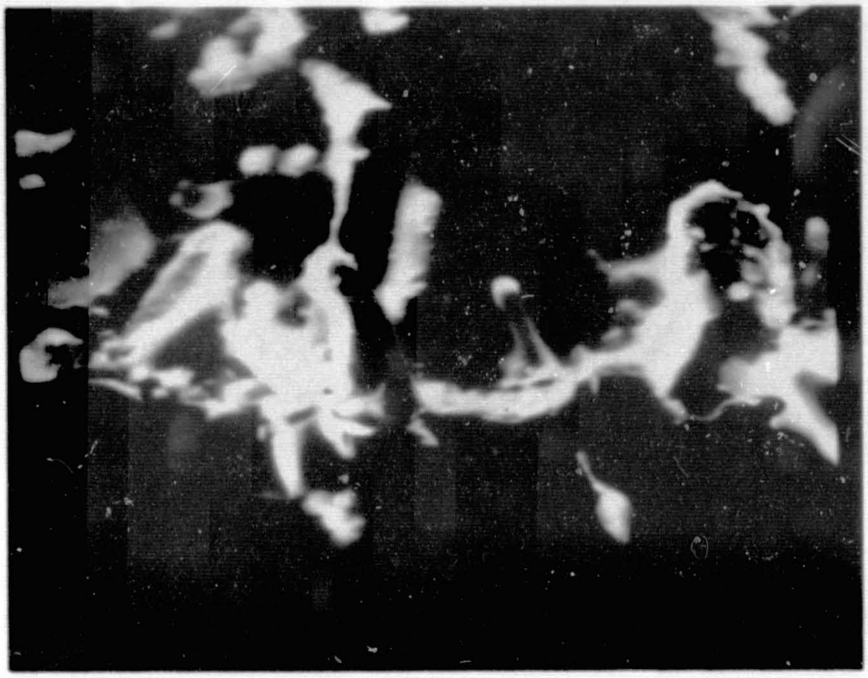
S071 Electrode partially pulled from substrate (in cross section)

Conclusions and Problems

1. SOLAR CELLS APPEAR TO BE TOLERANT TO HIGH TEMPERATURE HEAT TREATMENT (550^{0}C AT 13 MIN.) DESPITE EXISTENCE OF INTEGRAL PORTION OF SILICON-COPPER EUTECTIC ON FACE OPPOSITE JUNCTION.

2. PROBLEMS EXIST IN ACHIEVING REPRODUCIBILITY IN RHEOLOGY AND METALLURGY OF COPPER PASTES.

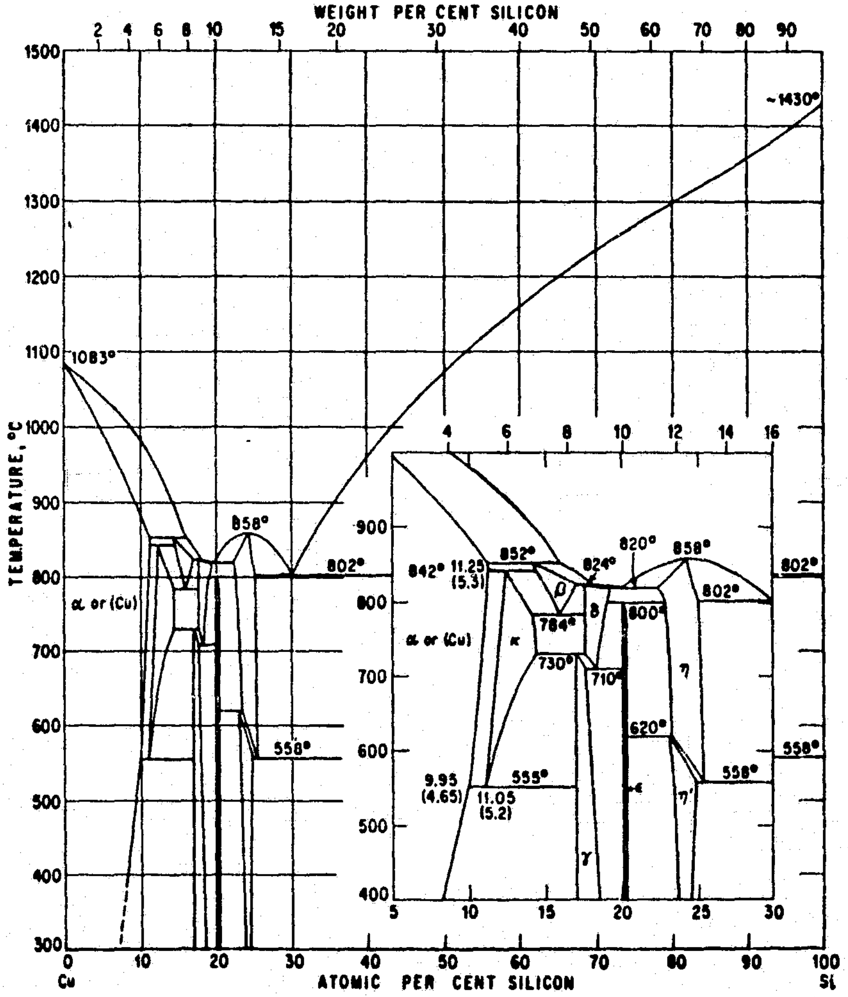
3. VIABILITY OF COPPER PASTE FOR FRONT CONTACT AND POSSIBLE FIRING THROUGH AR COATING REMAINS TO BE DEMONSTRATED (EXPERIMENT IN PROGRESS).



Electron microprobe analysis (CAMECA microprobe) of spike structure; target structure photographed in CAMEBAX at 2000x, paste S079

Composition According to Microprobe

	Needle	General
Silver	0.38 at %	0.84 at %
Copper	63.45	81.08
Silicon	29.80	3.79
Lead	0.17	6.76
Aluminum	1.20	7.54



From M. Hansen and K. Anderko, "Constitution of Binary Alloys," McGraw-Hill, 1958, p. 631

NICKEL-SOLDER METALLIZATION

SOLAREX CORP.

Electroless Nickel Plating on Silicon

EXPERIMENTAL TASKS

- ENVIRONMENTAL STRESSES
  FOUR SELECTED THERMAL STRESS TESTS
- PLATING ON SILICON OXIDE
  DOES OXIDE AFFECT PLATING?
- EFFECT OF PLATING SOLUTION ON CELLS
  DOES SOLUTION INFLUENCE CELL PROPERTIES?
- NICKEL PENETRATION OF SILICON
  HOW MUCH SINTERING IS TOLERABLE?
- EVALUATION OF MOTOROLA PROCESS RELATIVE
  TO SINGLE STEP ELECTROLESS NICKEL PLATING

Environmental Stress Task Observations

1 B-T-H (85°C - 85% RH - 0.45 VOLT) 1074 HOURS
- VISUAL INSPECTION - LIGHT I-V CURVES - TAB PULL TESTS
  NO EVIDENCE OF DEGRADATION

2 150°C - 1008 HOURS
- DEGRADATION AND CONTACT LIFTING IN MOST CELLS
- CELLS WHICH LOOK PERFECT SHOW LITTLE CHANGE IN
  ELECTRICAL PROPERTIES
- CONTACTS FAIL AT Si-Ni INTERFACE
  NO EVIDENCE OF Si DAMAGE

3 THERMAL CYCLE (-65°C TO +150°C) 100 CYCLES - IN AIR
- LIFTING OF CONTACTS IN ALL CELLS
- SOME SILICON DAMAGE EVIDENT

4 THERMAL SHOCK (-65°C TO +150°C) 25 CYCLES
- LIFTING OF CONTACTS IN MOST CELLS
- SILICON DAMAGE EXTENSIVE
- SOME CELLS LOOKED PERFECT AND SHOWED LITTLE CHANGE IN LIGHT I-V CURVES, BUT TAB PULL TESTS INDICATED WEAKENED CONTACTS.

5 METALLIZATION DOES SURVIVE 763 HOURS AT 100°C AND 25 CYCLES OF THERMAL SHOCK (-40°C TO +100°C)

Results of Thermal Stress Tests (-40°C, +100°C)

	TAB PULL STRENGTHS (G)	
	MEAN	STD DEV
CONTROL GROUP	431	248
THERMAL SHOCK 25 CYCLES -40°C TO +100°C	384	165
763 HOURS AT 100°C	453	282

CHANGES ARE WELL WITHIN EXPERIMENTAL ERROR

Environmental Stress Task Conclusions

1. CELLS SURVIVED B-T-H TEST PERFECTLY.
2. TEMPERATURE EXTREMES OF -65°C AND +150°C WERE TOO SEVERE.
3. TAB PULL MEASUREMENTS APPEARED TO BE A MORE SENSITIVE MEASURE OF CONTACT QUALITY THAN DID ELECTRICAL MEASUREMENTS.
4. DIFFERENT MODES OF FAILURE OBSERVED WITH DIFFERENT STRESSES INDICATE AT LEAST TWO DIFFERENT FAILURE MODES OPERATING.
5. METALLIZATION BEHAVES WELL UNDER MORE MODERATE TEMPERATURE EXTREMES OF -40°C AND +100°C.

Electroless Nickel Plating on Oxide Films

- OXIDE GROWTH - THERMAL IN OXYGEN
- MEASURE OXIDE THICKNESS BY ELLIPSOMETRY
- NICKEL PLATING SOLUTION DISSOLVES OXIDE DOWN TO 50 ANGSTROMS OR LESS BEFORE DEPOSITING NICKEL

Oxide Dissolution by Nickel Plating Solution

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

Tab Pull Data on Oxidized Silicon

	AVERAGE PULL STRENGTH (G)		
SINTER TEMP (1 MIN)	70 Å OXIDE 10 MIN PLATE	NO OXIDE 10 MIN PLATE	NO OXIDE 6 MIN PLATE
NONE	549	801	358
200°C	536	683	727
250°C	731	490	853
300°C	593	519	756

Oxide Effect on Cell Properties

	MEAN CHARACTERISTICS	
	OXIDE (35-80 Å)	OXIDE REMOVED
V_{OC} (mV)	558	551
I_{SC} (mA)	763	740
P_M (mW)	280	253
TAB PULL STRENGTH (G)	794	765

DIFFERENCES ARE LESS THAN ONE STANDARD DEVIAITION

Effect of Plating Solution on Solar Cells

DOES EXPOSURE TO PLATING SOLUTION HARM CELL JUNCTION?

FABRICATE CELLS USING A RANGE OF NI PLATING TIMES (4-14 MIN)

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

Illuminated I-V Characteristics

CELLS PLATED FOR 6, 8, 10 MIN BETTER THAN CELLS PLATED FOR 4, 12, 14 MIN
CORRELATES WITH QUALITY OF METAL ADHESION ON THESE CELLS

Dark I-V Characteristics

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

Conclusions

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

Etching of Silicon by Plating Solution

- WEIGH Si - PLATE Ni
  DISSOLVE Ni - WEIGH AGAIN
- WEIGHT LOSS EQUIVALENT TO 0.12 MICRON Si
- SHEET RESISTIVITIES OF DIFFUSED WAFERS ALSO INCREASE AFTER PLATING AND STRIPPING NICKEL

PLATING SOLUTION ETCHES SILICON BEFORE DEPOSITING NICKEL

POSSIBILITY OF DAMAGE TO VERY SHALLOW JUNCTIONS

Nickel Penetration of Silicon on Sintering

PLATE - SINTER - ANGLE LAP
MICROPROBE ANALYSIS

NO EVIDENCE OF NICKEL PENETRATION UP TO
425°C, 12 MIN
450°C, 2 MIN

EXTENSIVE NICKEL PENETRATION AT
450°C, 20, 30, 40 MIN

CONSISTENT WITH LEAKAGE CURRENT DATA SHOWING LITTLE CHANGE AFTER 30 MIN AT 350°C OR 2 MIN AT 450°C, BUT SUBSTANTIAL INCREASE AFTER LONGER TIMES AT 450°C

Motorola Process

- COMPLEX AND LENGTHY
- ELECTROLESS NICKEL PLATING PRECEDED BY THREE STEPS OF IMMERSION PALLADIUM PLATING AND ONE STEP OF ELECTROLESS PALLADIUM PLATING PLUS TWO HEAT TREATMENT STEPS AND SEVERAL CLEANING AND RINSING STEPS.
- DESIGNED FOR REPRODUCIBLE HIGH QUALITY METALLIZATION

Comparison of Motorola Process With Simple Electroless Nickel Plating

DIRECT COMPARISON BY PARALLEL EXPERIMENTS

- REPRODUCIBILITY OF RESULTS IS SOMEWHAT BETTER WITH SIMPLE ELECTROLESS NICKEL PLATING
- ETCHING OF SILICON APPEARS GREATER WITH MOTOROLA PROCESS (SHEET RESISTANCE CHANGES)
- TAPE PEEL TESTS AND TAB PULL TESTS GIVE IDENTICAL RESULTS WITH BOTH PROCESSES
- EFFECTIVE DIODE N-FACTORS ARE THE SAME
- ELECTRICAL CHARACTERISTICS OF CELLS PROVIDE NO BASIS FOR CHOOSING BETWEEN THE TWO PROCESSES

Electrical Characteristics of Cells

PROCESS		V_{OC} MV	I_{SC} MA	P_M MW
MOTOROLA	MEAN	543.7	1370	445
	(S.D.)	(6.4)	(78)	(59)
NICKEL	MEAN	550.6	1337	472
ONLY	(S.D.)	(10.7)	(39)	(24)

- BOTH PROCESSES EQUALLY GOOD
- MOTOROLA PROCESS LENGTHY AND CUMBERSOME

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

SPECTROLAB, INC.

Nick Mardesich

Program Tasks

I. ESTABLISH MIDFILM PROCESS AT SPECTROLAB

II. FABRICATION OF MODULES

III. ENVIRONMENTAL TEST

IV. ALTERNATE MATERIALS

Standard Cell Processing

SURFACE PREPARATION - 30% NAOH

JUNCTION FORMATION - SPIN-ON DIFFUSION SOURCE

ALUMINUM BACK SURFACE FIELD - SCREEN PRINTED ALUMINUM PASTE

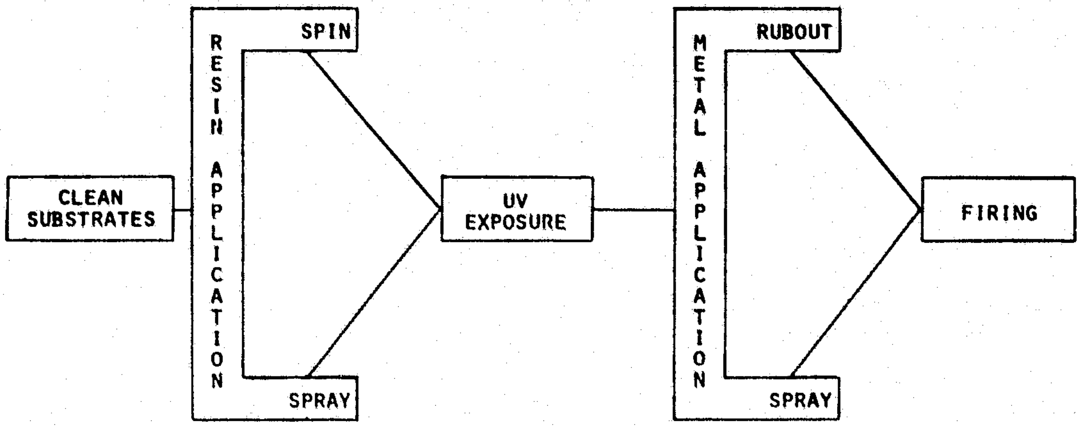
CLEAN RESIDUAL ALUMINUM AND DIFFUSION OXIDE - HF AND BRUSH

JUNCTION CLEAN - LASER SCRIBE

FRONT CONTACT - MIDFILM

AR COAT - EVAPORATED SiO_X

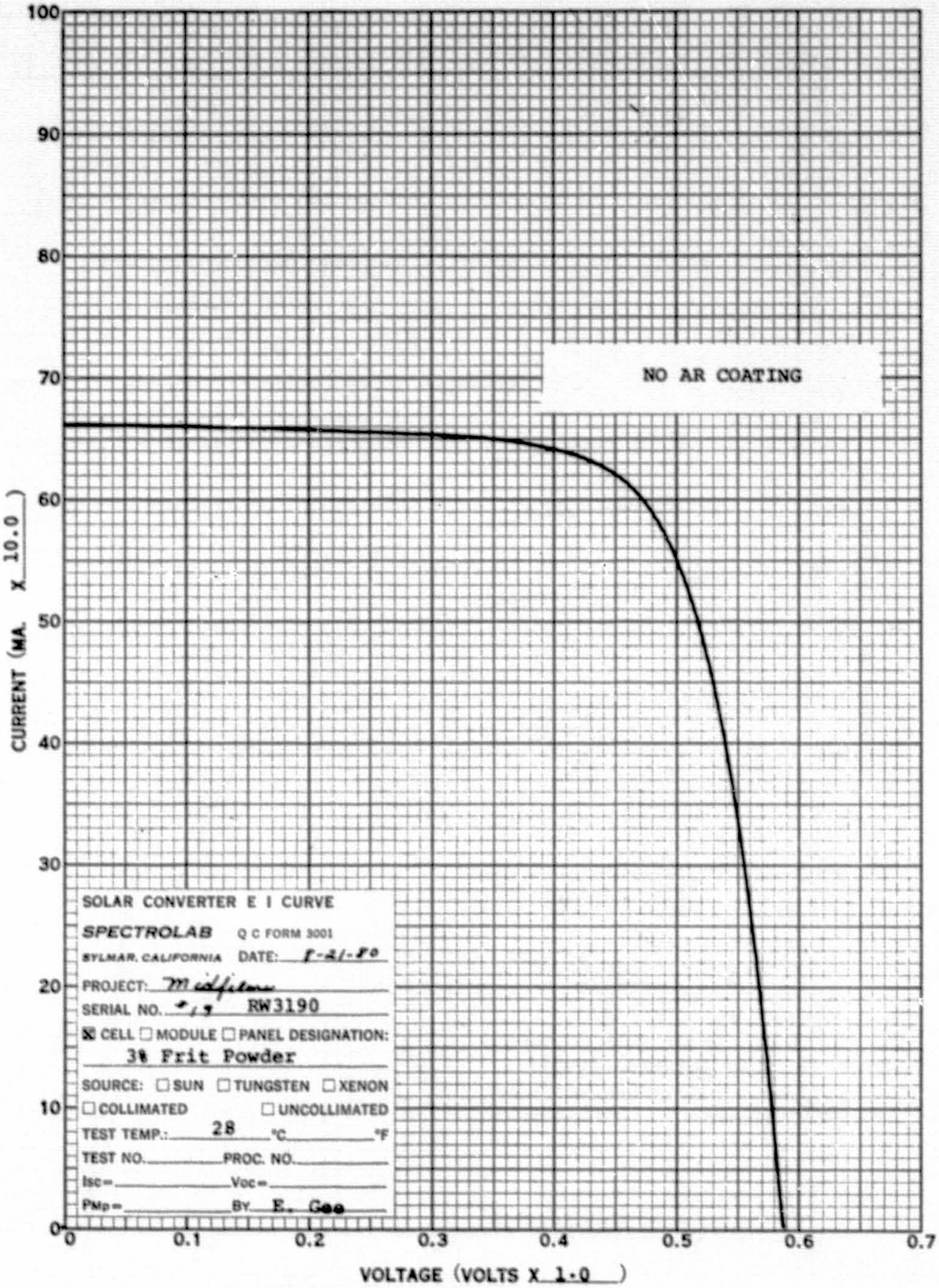
Ferro E-100 Midfilm Process



Silver Powder Compositions	Evaluation
1. 98% TFS Spherical Type Powder; 2% 3347 TFS Frit	High Series Resistance (100-200 mΩ) Solder Leaches Silver
2. 97% TFS Spherical Type Powder; 3% 3347 TFS Frit	High Series Resistance (100-200 mΩ) Solder Leaches Silver
3. 95% TFS Spherical Type Powder; 5% 3347 TFS Frit	Lower Series Resistance (80-110 mΩ)
4. 90% TFS Spherical Type Powder; 10% 3347 TFS Frit	Lower Series Resistance (80-110 mΩ)

Resin	
1. Ferro RC 4851	Does Not Meet OSHA Standard
2. Ferro RW 3190	Humidity Sensitive
3. Ferro RG-4933	

3% Frit Powder



SOLAR CONVERTER E I CURVE

SPECTROLAB Q C FORM 3001

SYLMAR, CALIFORNIA DATE: 8-21-80

PROJECT: Midfilm

SERIAL NO. #19 RW3190

☒ CELL ☐ MODULE ☐ PANEL DESIGNATION:

3% Frit Powder

SOURCE: ☐ SUN ☐ TUNGSTEN ☐ XENON

☐ COLLIMATED ☐ UNCOLLIMATED

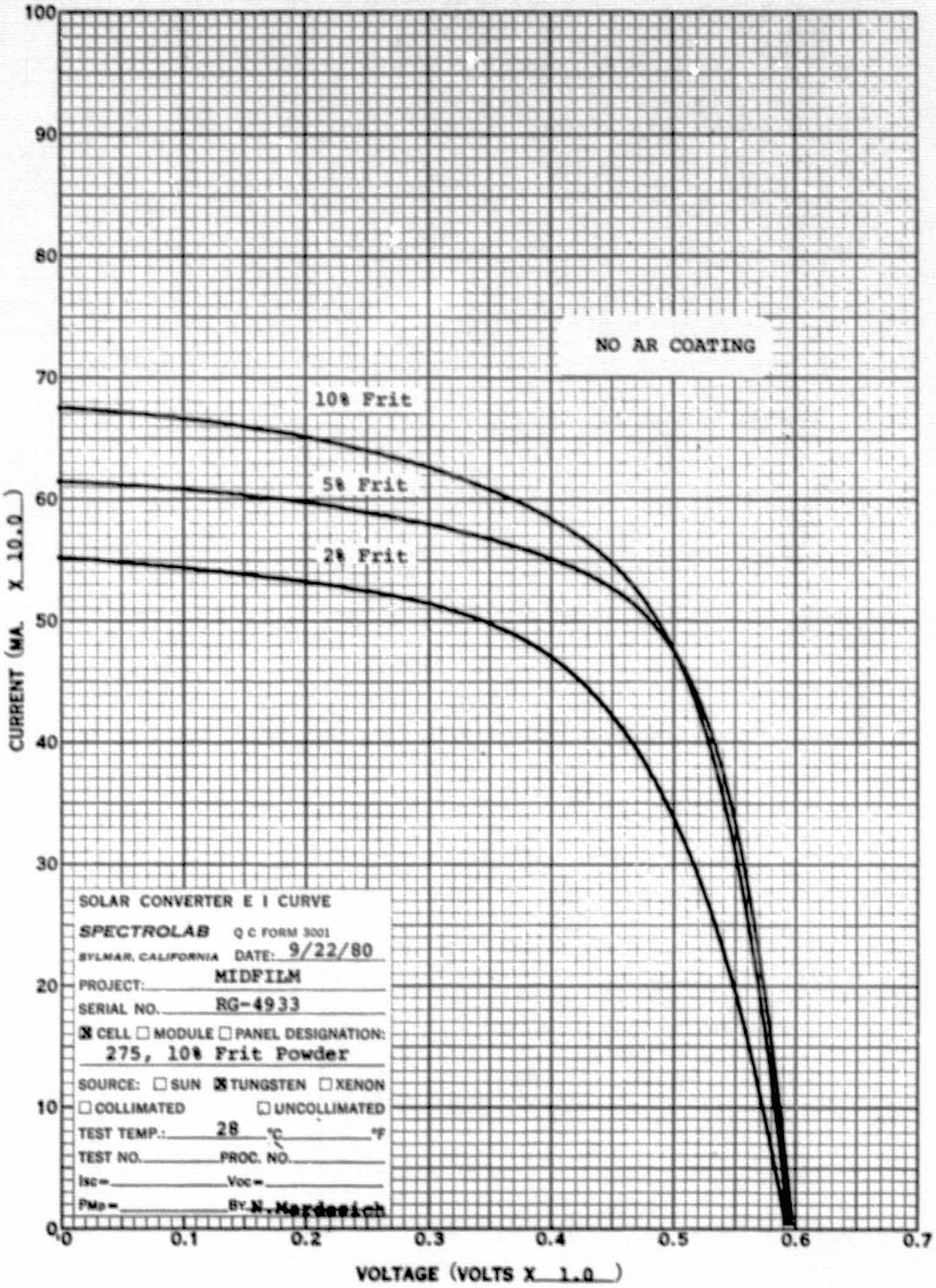
TEST TEMP.: 28 °C ______ °F

TEST NO. ______ PROC. NO. ______

Isc= ______ Voc= ______

PMp= ______ BY E. Gee

275, 10% Frit Powder



SOLAR CONVERTER E I CURVE

SPECTROLAB Q C FORM 3001

SYLMAR, CALIFORNIA DATE: 9/22/80

PROJECT: MIDFILM

SERIAL NO. RG-4933

☒ CELL ☐ MODULE ☐ PANEL DESIGNATION:
275, 10% Frit Powder

SOURCE: ☐ SUN ☒ TUNGSTEN ☐ XENON

☐ COLLIMATED ☐ UNCOLLIMATED

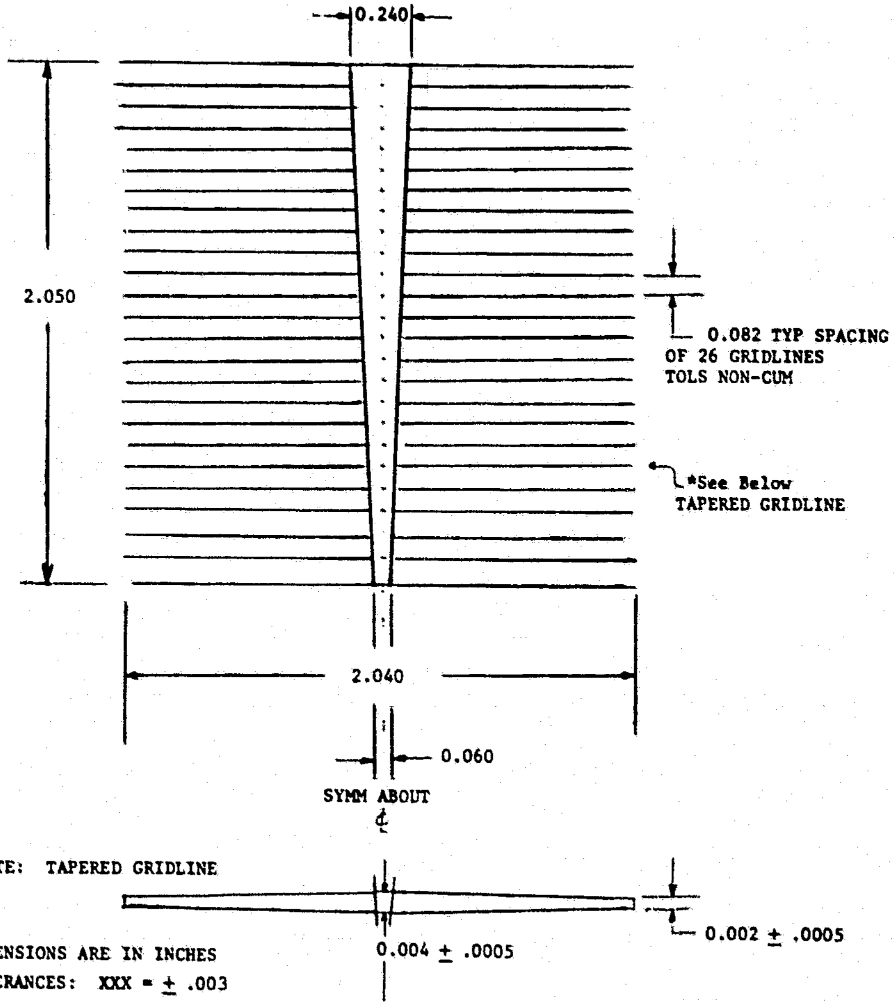
TEST TEMP.: 28 °C ______ °F

TEST NO. ______ PROC. NO. ______

Isc= ______ Voc= ______

PMP= ______ BY N. Mardesich

Front Contact Grid Line Pattern



*NOTE: TAPERED GRIDLINE

DIMENSIONS ARE IN INCHES
TOLERANCES: XXX = ± .003

Series Resistance Calculation

A) 3 Ω-cm Base Silicon	3.48 mΩ
B) 35 Ω/□ Diffused Surface Layer	4.59 mΩ
C) Gridline Resistance	10.59 mΩ
D) Center Ohmic Collector	20.38 mΩ
Total	39.04 mΩ

Cost Effectiveness

PR = (0.49:EQPT + 97·SQFT + 2.1·DLAB + 1.3·MATS + 1.3·UTIL)/QUAN.

EQPT = $210,000 + 6,000 - 10,000 = $206,000

SQFT = 1,500

DLAB = 1.0 PRSN.YRS./SHIFT x 4.7 x $8,100
+ 0.4 PRSN.YRS./SHIFT x 4.7 x 11,000 = $58,750/YR

MATS = (0.025 GM AG POWDER a $0.58/GM
+ 0.205 ML RESIN a $.01717/ML)
x 55,890,000 CELLS/YR
= $1,007,129/YR

UTIL = .0055 KWH/CELL x 55,890,000 CELLS/YR x $.0452/KWH
= $13,894/YR

QUAN = 7500 CELLS/HR x .90 x 8280 HR/YR x
= 55,890,000 CELLS/YR

PR = (100,940 + 145,500 + 123,375 + 1,309,268 + 18,062)/55,890,000

= 0.0304/CELL

IF η = .13

POWER/CELL = $(10.16)^2$ CM^2 x .1 x .13

= 1.342 WATTS/CELL

PR = 0.0226/WATT

ASSUMING NO YIELD LOSS.

AUTOMATED MODULE ASSEMBLY USING AN INDUSTRIAL ROBOT

MBAssociates

DIRECT FOLLOW-ON TO JPL CONTRACT NO. 945882: AUTOMATED CELL LAYUP AND INTERCONNECT USING AN INDUSTRIAL ROBOT

FIVE PHASE PROGRAM:

PHASE ONE – IMPROVEMENTS TO EXISTING SYSTEM
- SPEED UP CYCLE TIME TO 10 SEC/CELL
- IMPROVE SOLDER PASTE DISPENSING
- IMPROVE SOLDER BOND

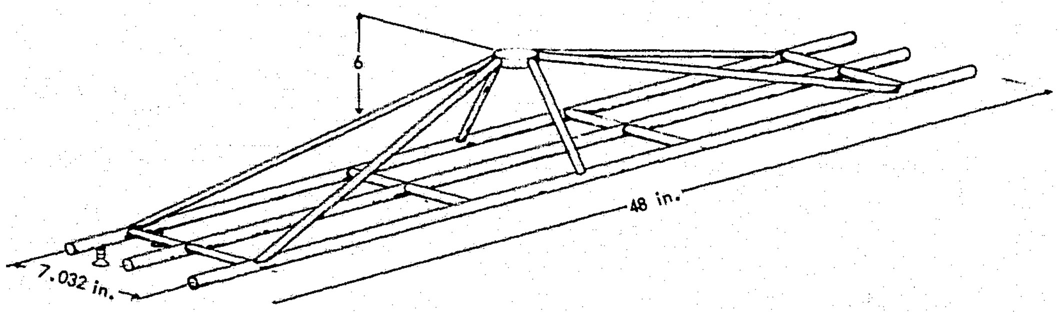
PHASE TWO – EXPAND CAPABILITY
- BROKEN CELL DETECTION AND DISPOSAL
- POST SOLDER TESTING

PHASE THREE – AUTOMATED ENCAPSULATION STATION
- LAMINATION PREPARATION STATION
- VACUUM PLATEN
- AUTOMATED LAMINATION CHAMBER

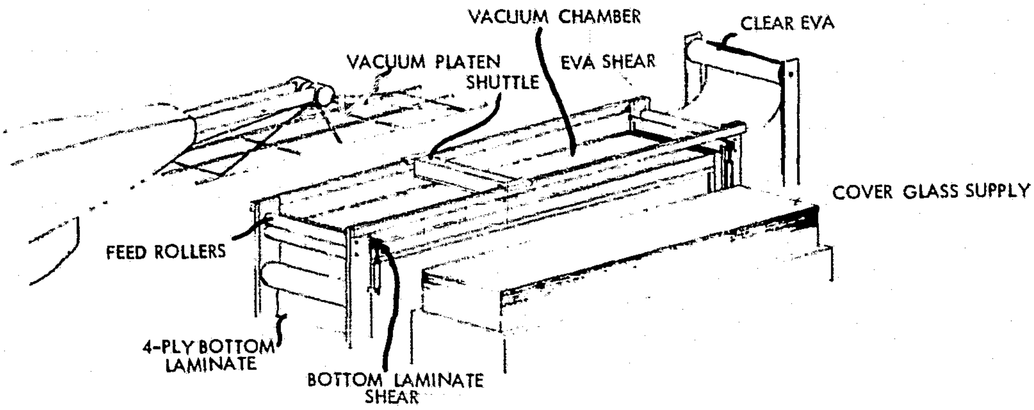
PHASE FOUR – FINAL ASSEMBLY STATION
- APPLY EDGE SEAL
- GRC

PHASE FIVE – FABRICATION
- SIX 1' x 4' MODULES USING EQUIPMENT DEVELOPED UNDER BOTH CONTRACTS

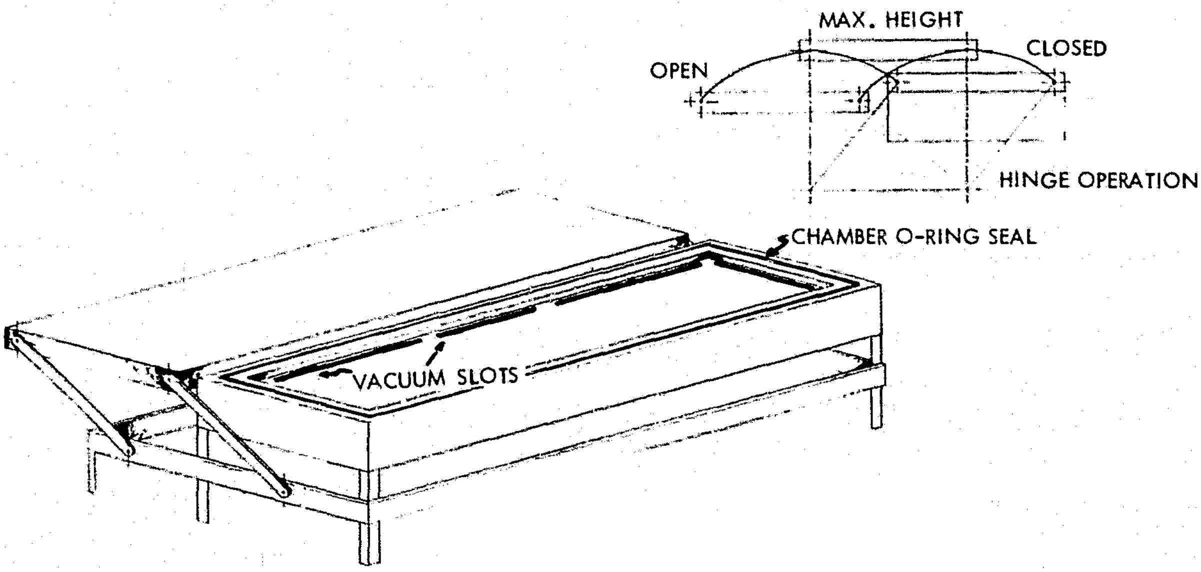
Vacuum Platen End Effector Concept



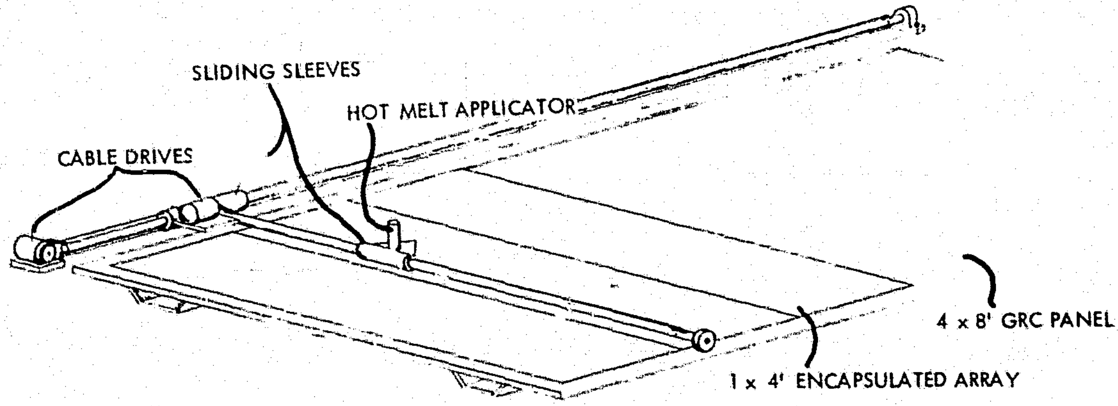
Automated Lamination Station Concept



Automated Lamination Chamber With Low Profile Cover (Concept)



Automated Edge Seal Application Concept



SILICON DENDRITE WEB MATERIAL PROCESS DEVELOPMENT

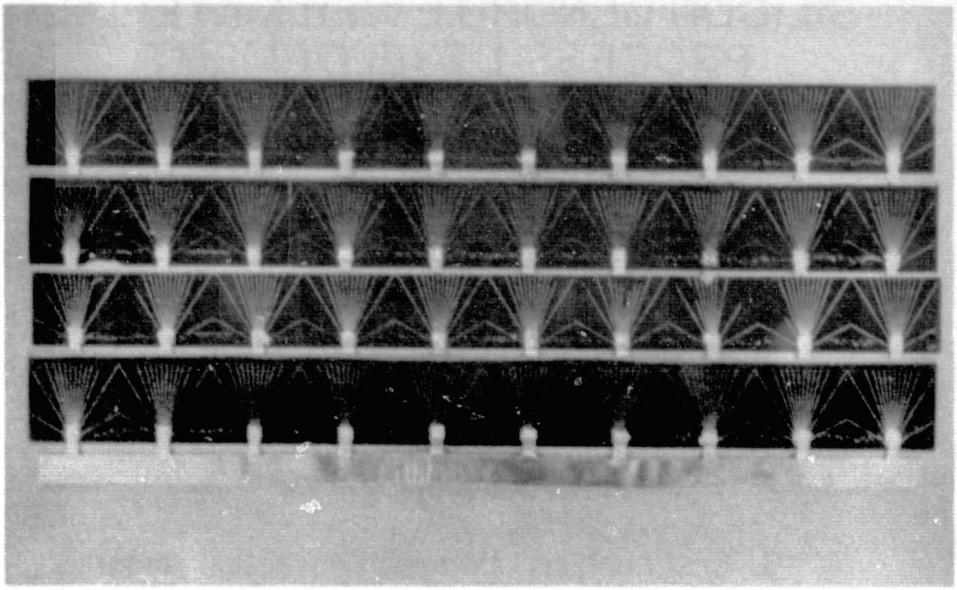
WESTINGHOUSE R&D CENTER

Tasks

1. **Ultrasonic Seam Bonding**
2. **Lamination - Ethylene Vinyl Acetate, And Polyvinyl Butyral**
3. **Cost Analysis - Updated Conceptual Factory**
4. **Module Fabrication - 30 cm × 60 cm**

Advantages of Ultrasonic Bonding

- **Clean - No Flux - No Waste Products**
- **No Metal Build Up**
- **No Material Cost**
- **Automatable**
- **Rapid, Cost Effective**
- **Low Energy Requirements**
- **Moderate Capital Cost**
- **Reliable**



Survey of Ultrasonic Seam-Bonded Al Ribbon to Metallized Dendritic Web Solar Cells

Metal System	Front/Back	Cell Type	Av. Pull Strength (Grams)	Std. Deviation	No. of Bonds Tested
Ti Pd Cu (1)	Front	B-BSF	85	33	49
Ti Pd Cu (1)	Front	Al-BSF	80	25	48
Ti Pd Cu (1)	Back	B-BSF	75	37	33
Ti Pd Cu (2)	Back	Al-BSF	80	16	8
Al (3)	Back	Al-BSF	90	28	43

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(1) Evaporated Ti Pd; Electroplated Cu

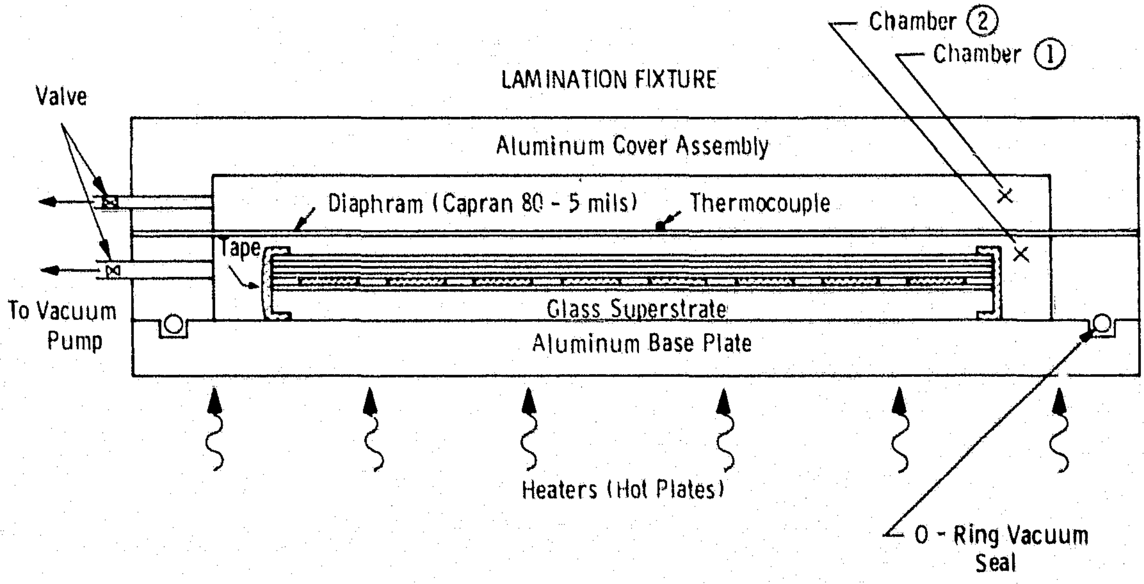
(2) Excess Al Etched Off Back; Remetallized Ti Pd Cu

(3) Al Evaporated On Back Surface After Oxides Removed

Ultrasonic Bonding Conclusions

- **Bonds Can Be Made Without Cell Fracture With Suitable Bonding Parameters**
- **Bonds Made With Pull Strength Equal To Half Ultimate Strength Of 0.001 Inch Aluminum Foil**
- **Cells Interconnected By Ultrasonic Bonding Have Been Successfully Laminated**
- **Contact Resistance Of Bonds < 1 Milliohm**

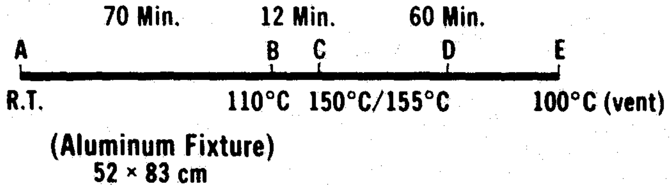
Lamination Fixture



Lamination

- **EVA And PVB Tested**
- **Fixturing For Modules Up To 30 cm × 60 cm Fabricated**
- **Curing Cycles Determined**

(⊣ ⊢ 5 minutes) **Cure Cycle - 30 × 60 cm Module**



A to B	RT to 110°C (70 minutes), Vent Top Chamber At B
B to C	110°C to 150°C (12 minutes), Turn-Off Hot Plates
C to E	150°C to 100°C (60 minutes), Vent Bottom Chamber, Slow Cool to RT (~ 4 hours)

Cost Analysis, Conceptual Factory

Assumptions

- 25 MW/Yr Production
- Module Size - 16" × 48" (Nominal)
- 12% Module At 28°C And 100 mW/cm^2 Insolation
- Dendritic Web Silicon Sheet Input At $0.24/Peak Watt (1980 $)
- 85% Overall Yield With 90% Cell Yield And 95% Module Assembly Yield
- All Capital Equipment Costed As Second Copy

25 MW/Yr Production

Total Capital -	4,620 K $
Direct Labor -	96 Py or 1,560 K $
Materials -	13,737 K $
Utilities -	267 K $
Space - (All Types)	6300 Sq. Ft.

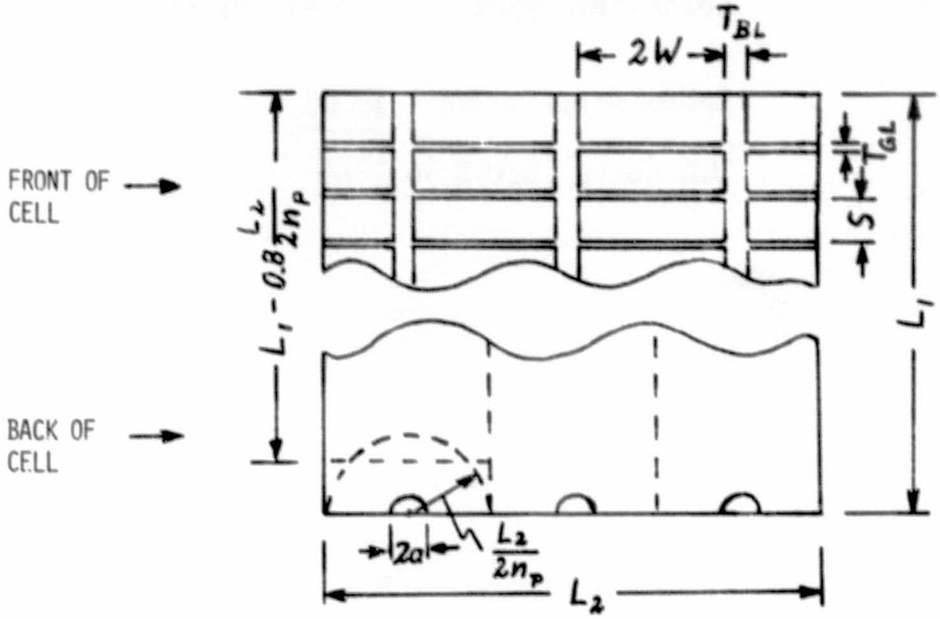
Selling Price Per Watt - $0.66

(All Costs 1980 $ in 1986)

Process No.	Process	$/Watt-Peak (1980 $)
1	Pre-Diffusion Clean + Si	0.280
2	$POCl_3$ Diffusion	0.016
3	AL-BSF	0.018
4	Antireflection/Photoresist Deposition	0.016
5	Expose/Develop/Etch	0.020
6	Metallize-Front & Back Ti Pd	0.032
7	Rejection/Cuplating	0.041
8	Laser Scribe/Break	0.015
81	Yield Dummy - 90% Cell Yield	0
9	Interconnect	0.018
10	Lamination/Test	0.179
101	Yield Dummy - 95% Module Yield	0
11	Crating	0.026
		$0.66/Watt-Peak

ANALYSIS AND EVALUATION OF PROCESSES AND EQUIPMENT

UNIVERSITY OF PENNSYLVANIA



ρ_B = RESISTIVITY OF SEMICOND. BASE LAYER

$R_{SH,B}$ = SHEET RESISTANCE OF BACK METALLIZATION

$R_{SH,DIFF}$ = SHEET RESISTANCE OF SEMICOND. FRONT LAYER

$R_{SH,GL}$ = SHEET RESISTANCE OF GRID LINE

ρ_{BL} = RESISTIVITY OF BUS LINE (ROUND WIRE, DIA. = T_{GL})

N_p = NUMBER OF INTERCONNECTS TO BACK

N_{GL} = $\frac{L_1}{S+T_{GL}}$ = NUMBER OF GRID LINES

N_{BL} = $\frac{L_2}{2W+T_{BL}}$ = NUMBER OF BUS LINES

F = GEOMETRY FACTOR = $\left\{\begin{array}{l} 1 \text{ FOR PARALLEL} \\ \frac{3}{4} \text{ FOR FULLY TAPERED} \end{array}\right\}$ GRID LINES

RELATIVE POWER LOSS:

$$\frac{\Delta P}{P} = \frac{1}{V_{MP}J_{MP}L_1L_2}\left(A_{ACT}\Delta V_{EFF} + A_{SHADE}V_{MP}\right)J_{MP} \;;$$

$$\approx \frac{\Delta V_{EFF}}{V_{MP}} + \frac{A_{SHADE}}{L_1L_2}$$

$$\Delta V_{EFF} = \frac{1}{3}J_{MP}\left\{\underset{\text{SEMICOND. FRONT LAYER}}{R_{SH,DIFF}\left(\frac{S}{2}\right)^2} + \underset{\text{GRID LINES}}{FR_{SH,GL}\frac{S}{T_{GL}}W^2}\right.$$

$$+ \underset{\text{BUS LINES}}{\frac{4\rho_{BL}}{\pi}\;\frac{S}{S+T_{GL}}\;\frac{2W}{T_{BL}{}^2}\;L_1{}^2} + \underset{\text{SEMICOND. BASE LAYER}}{3\rho_B D}$$

$$\left. + \underset{\text{BACK METALLIZATION}}{R_{SH,B}L_1{}^2\left(1 - \frac{L_2}{L_1N_P}\left[\frac{2}{5} - \frac{1}{\pi}\left(\frac{LN\left(\frac{L_1}{2N_PA}\right)}{1-\left(\frac{2N_PA}{L_1}\right)^2} - \frac{1}{2}\right)\right]\right)}\right\}$$

$$A_{SHADE} = L_1L_2\frac{2W}{2W+T_{BL}}\left(\underset{\text{GRID LINES}}{\frac{S}{S+T_{GL}}\;\frac{T_{GL}}{S}} + \underset{\text{BUS LINES}}{\frac{T_{BL}}{2W}}\right);$$

$$A_{ACT} = L_1L_2 - A_{SHADE} \quad L_1L_2$$

Design Rules

DESIGN		OPTIMUM	NEAR OPTIMUM	THIN Cu	THIN Ni	PLATED BUS LINES	NEAR OPTIMUM	SCREEN PRINTED Ag
NO. OF BUS LINES (SPACING)	- (CM)	7 (1.428)	→	→	→	→	3 (3.333)	→
BUS LINE WIDTH (DIAMETER)	MM	0.255 DIA	→	→	→	0.75	0.361 DIA	→
BUS LINE THICKNESS (GAUGE)	μM (B&S)	(30 GA.)	→	→	→	10 (Cu)	(27 GA.)	→
NO. OF GRID LINES (SPACING)	- (MM)	65 (1.53)	→	→	→	→	40 (2.50)	→
GRID LINE WIDTH	μM	12.5	25	→	→	→	→	127
GRID LINE THICKNESS	μM	5	10	2	10	→	→	10 (FIRED)
GRID MATERIAL	-	Cu		→	Ni	Cu	→	SINTERED Ag
BUS SHADING	%	1.79	1.79	1.79		5.25	1.08	1.08
BUS LOSS	%	0.96	0.94	0.94		4.46	1.12	1.03
GRID SHADING	%	0.82	1.63	1.63		1.55	1.00	5.08
GRID LOSS	%	0.42	0.10	0.51		0.09	0.94	0.49
FRONT LAYER LOSS	%	0.41	0.41	0.41		0.39	1.11	0.98
BASE LOSS (200 μM 1ΩCM; 10 μM Cu)	%	0.46	0.46	0.48	1.82	0.44	0.49	0.47
TOTAL POWER LOSS	%	4.9	5.3	5.8	7.1	12.2	5.7	9.1
CELL EFFICIENCY	%	16.36	16.29	16.20	15.98	15.10	16.22	15.63
MODULE EFFICIENCY	%	15.34	15.27	15.19	14.98	14.16	15.21	14.65
CELL VALUE	$/M^2	86.31	85.46	84.49	81.93	71.94	84.73	77.91
	¢/W(PK)	56.3	56.0	55.6	54.7	50.8	55.7	53.2
DIFFERENCE IN VALUE	$/M^2	REFERENCE	-0.85	-	-	-	-1.58	-
			REF.	-0.97	-3.53	-13.52	REFERENCE	-6.82

1. $$W = \frac{1}{2}\left(\frac{3}{\pi^2}\;\frac{\rho_{BL}^2}{R_{SH,GL}^3}\;\frac{V_{MP}}{J_{MP}}\right)^{1/8}, L_1^2$$

2. $$T_{BL} = \left(\frac{32}{3\pi}\;\frac{J_{MP}\rho_{BL}}{V_{MP}}\;L_1^2W^2\right)^{1/3}$$

3. $$S \leq 2\left[3^{1/2}\;F\;\frac{R_{SH,GL}^{1/2}}{R_{SH,DIFF}}\left(\frac{V_{MP}}{J_{MP}}\right)^{1/2} W\right]^{1/2}$$

(SELECT S AS SMALL AS POSSIBLE IN VIEW OF TECHNICAL LIMITATIONS ON T_{GL} (SEE 4 BELOW), BUT NOT SIGNIFICANTLY LARGER THAN GIVEN BY THE ABOVE RELATIONSHIP FOR S.)

4. $T_{GL} = \left(\frac{1}{3} R_{SH,GL} \frac{J_{MP}}{V_{MP}} \right)^{1/2} WS$

   (IF TECHNICAL LIMITATIONS REQUIRE A VALUE FOR T_{GL} LARGER THAN RESULTING FROM RELATIONSHIPS 3.) AND 4.), USE THE SMALLEST PRACTICAL VALUE FOR T_{GL}, IF PATTERN RESOLUTION IS LIMITING. IF GRID LINE WIDTH-TO-THICKNESS RATIO IS LIMITING, REDUCE THICKNESS (INCREASE $R_{SH,GL}$), TO FIND T_{GL} AND $R_{SH,GL}$ VALUES FOR LEAST POWER LOSS.

5. ARRANGE GRID LINES NORMAL TO BUS LINES.

6. SELECT CONDUCTOR METAL OF THE HIGHEST PRACTICAL CONDUCTIVITY.

7. SELECT DEPOSITION PROCESSES WHICH APPROACH BULK CONDUCTIVITY AS CLOSELY AS PRACTICAL.

8. EACH HIGHER LEVEL IN THE HIERARCHY OF CONDUCTORS NEEDS A MUCH LOWER SHEET RESISTANCE THAN THE PRECEDING LEVEL. THIS LEADS TO THE "SKY SCRAPER RULE" FOR THE BUS LINES: BUILD HIGH RATHER THAN WIDE.

9. THE "EFFECTIVE VOLTAGE DROP" OF FULLY TAPERED LINES IS 3/4 THAT OF UNIFORM WIDTH LINES OF EQUAL SHADING, OR 1/2 OF THE "END-POINT VOLTAGE DROP".

10. CARELESS METALLIZATION DESIGN IS COSTLY.

ANALYSIS OF PANEL DESIGN CONCEPTS USING LIGHT TRAPPING

SCIENCE APPLICATIONS, INC.

Briefing Outline

- INTRODUCTION
- LIGHT TRAPPING OPTICS
- SIMPLIFIED DESIGN EQUATIONS
- CASE STUDY

Goals of Contract

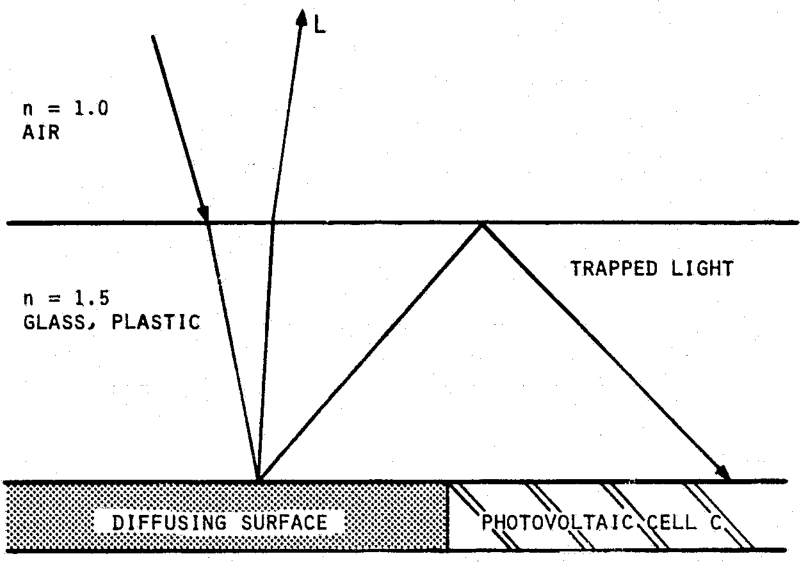
- SUMMARIZE PRIOR SAI COMPUTER SIMULATION AND TESTS OF LIGHT TRAPPING IN DESIGN GUIDE TO INCLUDE:
  - SIMPLIFIED OPTICAL EQUATIONS
  - GRAPHS
  - TABLES
- APPLY DESIGN GUIDE CONCEPTS BOTH TO EXISTING MODULES AND INNOVATIVE POSSIBILITIES
- PERFORM COST/BENEFITS ANALYSIS TO INCLUDE:
  - COST OF MANUFACTURING PANELS
  - COST OF BUILDING SYSTEMS
  - COST OF O&M
- DEVELOP COST-EFFECTIVE DESIGN RECOMMENDATIONS

Task I Objectives

- DEVELOP SIMPLIFIED OPTICAL PERFORMANCE EQUATIONS FOR A GENERIC FLAT PLATE PV MODULE
- USE AS BASELINE A MODULE WITH NO OPTICAL TRAPPING

Light-Trapping Concept

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



Closed-Form Approximate Solution

- ASSUMPTIONS:
  - SINGLE TRAPPING LAYER
  - NO ABSORPTION IN LAYER
  - NO FRESNEL REFLECTIONS
  - HOMOGENEOUS MIXTURE OF DIFFUSING LAYER AND CELLS
  - PERFECT DIFFUSE (LAMBERTIAN) REFLECTION BETWEEN CELLS

- METHOD—SERIES SOLUTION TO RAY PROPAGATION

$$G_0(N_1) = 1/(C+L - LC)$$

C = CELL PACKING FRACTION

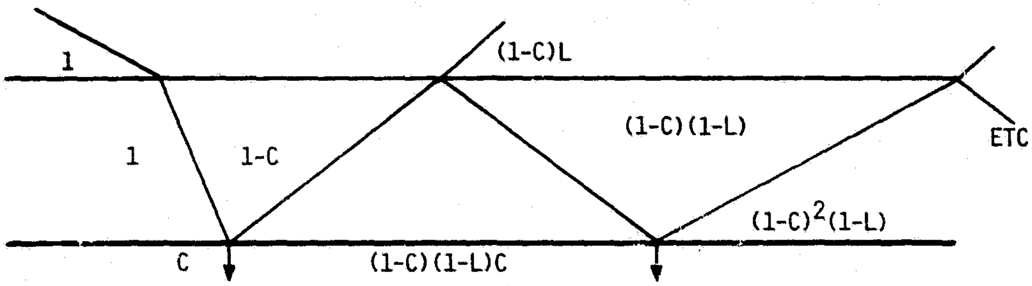
L = LOSS DUE TO LESS THAN CRITICAL ANGLE REFLECTION

$$1 - \sin^2\theta_C = \left(\frac{n_1}{n_2}\right)^2 \equiv (N_1)^2$$

$$G_0(N_1) = 1/(N_1)^2;\ C \rightarrow 0$$

$$= (n_2/n_1)^2$$

Derivation of Closed-Form Solution



$$G = \left[1 + \underbrace{(1-C)(1-L)}_{1-C-L+LC} + (1-C)^2(1-L)^2 \cdot \cdot \cdot\right]$$

$$G = \sum_{n=0}^{\infty} (1-C-L+LC)^n = \sum_{n=0}^{\infty} X^n = \frac{1}{1-X} = \frac{1}{C+L-LC}$$

Computer Model for Simulation of Light Propagation and Diffusion by Monte Carlo Methods

- PROPAGATION OF LIGHT IN THREE DIMENSIONS INCLUDES FRESNEL LOSSES, ABSORPTION LOSSES, AND DIFFUSION LOSSES
- DIFFUSED RAYS GIVEN ANGLES AND ENERGIES WHICH EFFECTIVELY SAMPLE THE REAL DISTRIBUTION OF DIFFUSED LIGHT
- VARIOUS DIFFUSION PATTERNS INCLUDING LAMBERTIAN DISTRIBUTION

Preliminary Simplified Design Equations

1) GAIN WITH NO FRESNEL REFLECTIONS

$$G_0 = 1/(C+L-LC)$$

2) GAIN WITH FRESNEL REFLECTION AT TOP LAYER

$$G_0 = 1/(C+L-LC-LF+CLF)$$

3) GAIN WITH FINITE REFLECTIVITY $R \leq 1.0$

$$G(R) = 1 + \left[G_0(R=1)-1\right]R; \quad R \leq 1.0$$

4) GAIN FOR LESS THAN OPTIMUM THICKNESS $T \leq T_0 = \ell/4$

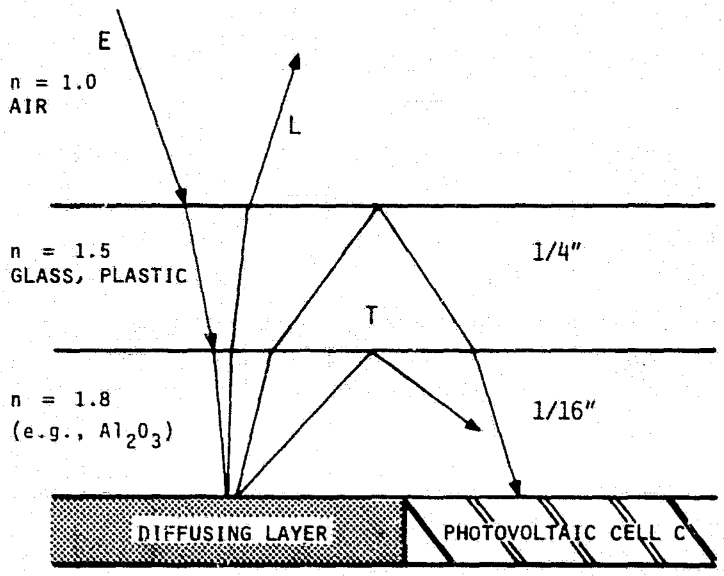
$$G(T) = 1 + \left[G_0(T=T_0)-1\right]\left(\frac{T}{T_0}\right)^{1/2}; \quad T \leq T_0$$

5) EFFECTS OF R, T AND ADDITIONAL LAYERS ARE MULTIPLICITIVE

$$G(N_1, N_2 \cdots, R, T) = 1+\left[G_0(N_1)\, G_0(N_2) \cdots - 1\right] R\left(\frac{T}{T_0}\right)^{1/2}$$

Multilayer Light Trapping

- HIGHER N LAYERS ARE LOCATED CLOSER TO CELL
- LIGHT TRAPPING IS DETERMINED BY HIGHEST N MATERIAL
- MONTE CARLO PROGRAM IS CAPABLE OF MODELING MULTIPLE LAYERS
- SIMPLIFIED DESIGN RULES WILL BE VALIDATED



Typical Gains for Block III Modules Using Simplified Design Equations

SUPPLIER	AS CONFIGURED	WITH τ = 1/2"
ARCO	1.08	1.17
MOTOROLA	1.10	1.20
SENSOR TECHNOLOGY	1.12	1.24
SOLAR POWER	1.06	1.13
SOLAREX	1.13	1.26

Scope of Further Effort

- IN ORDER TO UTILIZE LIGHT TRAPPING AS AN EFFECTIVE MEANS OF INCREASING GAIN, THE FOLLOWING ARE BEING EXAMINED:
  - GENERIC CELL ENCAPSULATION AND ATTACHMENT SCHEMES
  - CELL SIZES, SHAPES, EFFICIENCIES
  - INTRACELL AREAS—REFLECTIVITY, ANGULAR PATTERN
  - INTERCELL AREAS--INTERCONNECTIONS, TERMINALS, CELL GRID PATTERNS, GEOMETRIES AND BLOCKAGE
  - CELL EFFICIENCIES AS A FUNCTION OF ILLUMINATION
  - ANTI-REFLECTION COATINGS

ENGINEERING AREA
OPERATIONS AREA

JOINT TECHNOLOGY SESSION

R.G. Ross Jr. and
Larry Dumas, Chairmen

OPERATIONS AREA

LSA Environmental Test Director John Griffith presented an update on recent test results and pointed out some needed improvements in both the modules and the tests themselves. Prototype modules for seven of 10 Block IV designs have now been tested, and most will need changes in design or processing. The problems encountered have typically not been catastrophic, but seem to indicate once again that reliability and durability in hardware is seldom achieved on the first try.

Some difficulties in obtaining repeatable Nominal Operating Cell Temperatures (NOCT) in outdoor testing were noted. The results from indoor simulation of these tests suggest that wind speed and direction may be more critical than had been believed. Field results also indicate that the effects of reverse voltage bias and of extended duirnal thermal cycling can cause failures that are undetected in the current series of qualification tests. A cell hot-spot test is being added to the qualification sequence to correct the former deficiency; resolution of the latter is under study.

Results of this year's survey of modules at the endurance test sites were presented by Field Test Director Peter Jaffe. During the past year three modules have failed and six additional modules show electrical degradation among the 167 Block II modules at these sites. Hot, humid, and salty environments are the most harmful to the modules; dry and cool climates, such as those at high elevations, are the least harmful. Cracked cells, corrosion of exposed metallic surfaces, and encapsulation delamination are the most common forms of physical deterioration.

Status reports for Test and Applications Projects were given by Edwin T. Muckley of NASA LeRC, Calvin B. Rogers of Sandia Laboratories, Ron Baisley of JPL, and Steve Forman of MIT/LL. Until recently, NASA LeRC field experience with arrays in remote stand-alone systems has been excellent. Open-circuit failures at Upper Volta and Schuchuli villages are of present concern, however. LeRC is stressing market development for remote stand-alone systems to provide near-term mass markets for PV products.

The Sandia-monitored PRDA-35 (concentrator) and PRDA-38 (flat-plate) application experiments are nearing installation. The four flat-plate experiments, using Solarex and Solar Power modules, will provide valuable experience with large-scale intermediate-load systems in a variety of new applications.

A recent survey of the 60-kW array at Mt. Laguna has revealed a continuation of the module problems reported earlier for this site. Although the incidence of newly cracked cells from reverse voltage bias heating has slowed, the module failure rate from this condition has increased. Evidence of this degradation mode has now also been seen on the second of the two types of modules in the array, which has construction features similar to those of the first but much lower cell shunt resistance. Impact fractures, which had previously been mainly observed in the latter module type, are now becoming evident in the former as well.

Overall module failure rates at MIT/LL test sites continue to be low. The array at the University of Texas Arlington (UTA), which suffered from the same reverse voltage bias hot-spot problem as that at Mt. Laguna, was replaced after module failures had reached 27%. Techniques for fault detection and isolation in the systems at Natural Bridges National Monument, WBNO (Bryan, Ohio), UTA, and the John F. Long house (Phoenix) were described by Steve Forman.

Steve Sollock, responsible for LSA problem and failure analysis activities, provided an overview of significant findings since the last Project Integration Meeting. Analyses of cracked cover glasses, cell-string shorts, fractured interconnects, and cell heating and cracking have been carried out in the laboratory. On-site array diagnoses at Mt. Laguna and Camp Pendleton were also made by Failure Lab personnel.

SUMMARY

Larry Dumas, Operations Area Manager, reviewed the schedule status for Block IV module design and test contracts, which have typically slipped 7 to 8 months. After recapping some of the more significant negative findings from environmental testing and field-test-and-application project presentations, he offered some observations on the current status of Project reliability and durability goals. Indications are that the 20-year lifetime goal and the methods for assessing and controlling the factors which govern it are not well in hand. Increased emphasis on this aspect of the Program was recommended.

ENGINEERING AREA

R. G. Ross Jr., Engineering Area manager, presented a brief overview of Engineering Area activities. Recently published reports describing activities contracted by Engineering include completed array design requirements studies by Burt Hill Kosar Rittelman Associates on operations and maintenance costs for residential applications, studies by Bechtel National, Inc., of curved-glass modules and electrical isolation requirements, and an assessment of current module output termination methods and requirements by Motorola, Inc. The series-parallel circuit design workshop was repeated for interested program participants on May 19 and 20. As part of the SERI-supported standards effort, documentation of array interim performance criteria and test methods was released as part of IPC-1. A number of ongoing tasks were described briefly in the areas of array requirement studies, array subsystem development, component engineering and reliability studies, and standards development. The detailed status of a number of these activities was described in a technical session held jointly with the Operations Area.

As an update of ongoing array low-cost structures development, Abe Wilson described the improved 8 x 20-ft frame and panel design that was demonstrated at the PIM. Since the last PIM, detailed cost vs quantity sensitivity analyses have been performed, which indicate that substantial savings can be made for the proposed design even in quantities of a few tens of panels and frames. Total installed cost estimates (not including modules) have been developed for 2 x 4-ft and 4 x 4-ft module installations.

Boeing Engineering and Construction presented the results to date of the wind-tunnel testing conducted on a 1/24th-scale model of an array field at Colorado State University. As part of the presentation a film was shown that highlighted the significant effect that proper fencing has on wind loads within an array, especially as the first row, resulting in substantial reductions in normal force coefficient. Future work will include documentation of the results of steady-state wind loading and the beginning of evaluation of the effects of turbulence and array dynamics on design guidelines.

Steve Gasner and Al Wen described photovoltaic/thermal module development work at JPL. The objectives of this activity are development of design requirements for PV/T modules and the development of performance test methods. This effort is part of the SERI-supported Standards and Test Method Project. He also described work toward verifying a new proposed cell-temperature test procedure.

Allan Levins, Underwriters Laboratories, Inc., discussed progress in the UL contract to study photovoltaic module and array safety concerns. a goal of this study is the development of preliminary standards for product requirements for protection of personnel and equipment from hazards of shock, fire and casualty. Of particular interest were results of recently conducted fire-resistance tests on representative Block III modules. An additional area of discussion was design of suitable ground-fault detection and interruption circuits for PV systems.

G. R. Mon described a JPL in-house investigation of electrical insulation design requirements. Both theoretical considerations and results of empirical tests of a variety of module types were discussed.

Cell hot-spot heating was discussed in the last two presentations. JPL has recently completed fabrications of a five-bay cell hot-spot endurance test facility. This facility is being used to evaluate proposed methods for conducting hot-spot tests is part of future module qualifications test sequences. The procedures under evaulation were described along with reverse quadrant data for representative Block II and III modules. Clemson University provided a detailed discussion of a thermal model that has been developed to describes the temperature performance of cells subjected to second-quadrant heating.

ENVIRONMENTAL TESTING

JET PROPULSION LABORATORY

John S. Griffith

Contents

- TYPES OF TESTS, A BRIEF REVIEW
- RECENT QUALIFICATION TEST RESULTS
  - BLOCK III, TASK 4, PRDA 38
  - BLOCK IV
- PROBLEMS IN ENVIRONMENTAL TESTING
- TESTS PLANNED FOR THE NEAR FUTURE
- SUMMARY

Types of Tests

- QUALIFICATION TEST – ENVIRONMENTAL EXPOSURES REQUIRED IN THE PROCUREMENT SPECIFICATION

• TEMPERATURE CYCLING	+90°C, -40°C, 100°C/hr, 50 TIMES
• HUMIDITY CYCLING	+40°C, +23°C, 90% R.H., 5 DAYS
• WIND SIMULATION	±2400 PASCALS (50 lb/ft^2), 10,000 CYCLES
• TWIST	±2 cm/100 cm OUT-OF-FLAT
• HAIL	1.9 cm (0.75 inch) HAILSTONES AT 20 m/s (45 mph)
• ELECTRICAL ISOLATION	2000 VDC AT LESS THAN 50 μA LEAKAGE

- EXPLORATORY TESTS – TESTS FOR SPECIAL ENVIRONMENTS OR DEVELOPMENT OF NEW QUALIFICATION TESTS
  - HEAT/RAIN, HUMIDITY/HEAT, HUMIDITY/FREEZE, SALT FOG
- ADDITIONS TO EXPLORATORY TEST SERIES UNDER CONSIDERATION
  - HOT CELL TESTS
  - ADDITIONAL TEMPERATURE CYCLING TO DETECT INTERCONNECT FATIGUE

Qualification Tests Completed Recently

- Y TYPE HIGH DENSITY, LATE BLOCK III
- M TYPE, TASK 4
- Y TYPE, PRDA 38, RETEST OF PHASE 1 MODULE
- SEVEN OF THE TEN TYPES OF BLOCK IV PROTOTYPE MODULES

Results of Qualification Tests

- Y TYPE, HIGH DENSITY, LATE BLOCK III – SATISFACTORY
- M TYPE, HIGH EFFICIENCY, TASK 4 – TWO SMALL CELL CRACKS, ONE MODULE FAILED HIPOT
- Y TYPE, PRDA 38, RETEST OF PHASE 1 MODULE

TEMPERATURE CYCLING	PVC J-BOXES DISTORTED AT 105°C ONE MODULE UNSTABLE WITH POWER LOSS UP TO 15%
WIND	ONE MODULE HAD 6% ELECTRICAL LOSS
TWIST	MORE ELECTRICAL LOSS AND TWO OTHERS HAD MARGINAL ELECTRICAL LOSSES

Block IV Module Type GR (Shingle)

• MODULE CONSTRUCTION TOP TO BOTTOM	4.4-mm GLASS, CELLS BONDED WITH SILICONE, WHITE SILICONE ENCAPSULANT, WEATHER-PROOFED CARDBOARD BACK. FLEXIBLE PORTION IS TWO LAYERS OF POLYESTER SCRIM REINFORCED WHITE HYPALON WITH A CORE OF POLYETHYLENE CLOSED-CELL FOAM. THREE MODULES MOUNTED ON A SIMULATED ROOF SECTION
• TEST RESULTS	
• TEMPERATURE CYCLING	OPEN CIRCUIT, UNEXPLAINED. FORWARD CURRENT OF 2A CORRECTED THIS. SOME DELAMINATION AT INTERCONNECTS AND ADJACENT CELLS
• HUMIDITY CYCLING	ALL DUMMY SHINGLES WARPED
• CONCLUSION	MODULES PASS BUT IMPROVEMENTS IN DUMMY SHINGLES NEEDED

MS Module

(Two Sets Tested)

● CONSTRUCTION	4.8-mm GLASS, PVB, CELL, PVB, .1 mm TEDLAR. SOLDER-PLATED COPPER-MESH INTERCONNECT CONTACTS CELL AT CENTER. EXTRUDED ALUMINUM ALLOY FRAME.	
● TEST RESULTS	SET 1 (4 MODULES)	SET 2 (3 MODULES)
• TEMPERATURE CYCLING	CELL CRACKS IN 4 MODULES, 3, 7, 9, AND 15, RESPECTIVELY	2 CELLS CRACKED IN ONE MODULE. 10% ELECTRICAL DEGRADATION IN ANOTHER
• HUMIDITY	FRAME SEAL DELAMINATION	ELECTRICAL RECOVERY
• WIND	MORE CRACKS, 14% ELECTRICAL DEGRADATION IN ONE MODULE	SATISFACTORY
• TWIST	MORE CRACKS	SATISFACTORY
• HAIL	MORE CRAKCS	ONE SMALL SEMICIRCULAR CRACK IN A CELL FROM HAILSTONE IMPACT
● CONCLUSION	FURTHER REDUCTION IN CELL CRACKING AND RETEST NEEDED	

RS Module

● CONSTRUCTION	3.2-mm TEMPERED GLASS, PVB, CELLS, PVB, WITH A BACK-SURFACE SANDWICH OF 0.025 mm TEDLAR/ 0.008 ALUMINUM/0.025 mm TEDLAR. BENT-UP FRAME OF STAINLESS SHEET. BUTYL RUBBER GLASS-TO-FRAME SEAL
● TEST RESULTS	
• TEMPERATURE CYCLING	SEALANT BETWEEN GLASS AND FRAME EXTRUDED
• HUMIDITY CYCLING	TWO CELLS CRACKED
• WIND	ONE CELL CRACK. ONE FRAME CORNER BROKEN OFF AT MOUNTING HOLE
• HIPOT	3 OF 5 MODULES FAILED HIPOT TEST. ONE FAILED GROUND CONTINUITY TEST
• MODIFIED MODULES TESTED	FAILED HIPOT
● CONCLUSION	IMPROVED MODULES TO BE SUPPLIED FOR TESTING

SS Module

● CONSTRUCTION	3.2-mm GLASS, EVA, CELLS, EVA, POLYESTER RIPSTOP, MYLAR/ALUMINUM BACKING, 244 SCOTCHCLAD BACKSPRAY. STAINLESS STEEL FRAME
● TEST RESULTS	
• TEMPERATURE CYCLING	STRIPPED J-BOX THREADS, ONE CELL CRACKED, SMALL BLISTERS OF THE MODULE BACK COVER FOUND ON ONE MODULE
● CONCLUSION	SATISFACTORY AFTER FIXING SCREW-THREAD PROBLEM. IMPROVE LAMINATION PROCESS CONTROL

YR Module

● CONSTRUCTION	4.7-mm TEMPERED GLASS, EVA, POLYCRYSTALLINE CELLS, EVA, TEDLAR BACK SURFACE. RUBBER GASKET EDGE, NO FRAME SUPPLIED
● TEST RESULTS	
• TEMPERATURE CYCLING	ALL MODULES HAD BACKSIDE TEDLAR DELAMINATION, BLISTERS. ONE CRACKED CELL. ONE WITH MARGINAL ELECTRICAL DEGRADATION
• HUMIDITY CYCLING	ONE WITH MARGINAL ELECTRICAL DEGRADATION BUT WITH RECOVERY LATER
• WIND	BLISTERS ENLARGED
● CONCLUSION	IMPROVED PROCESSING AND MODULE,RETEST NEEDED

YS Module

● CONSTRUCTION	4.8-mm GLASS, EVA, POLYCRYSTALLINE CELLS, EVA, TEDLAR BACKING. ALUMINUM ALLOY FRAME
● TEST RESULTS	
• TEMPERATURE CYCLING	AIR BUBBLES
• HUMIDITY CYCLING	TWO WITH TEDLAR DELAMINATION
● CONCLUSION	IMPROVED PROCESSING AND RETEST OF MODULES NEEDED

ZS Module

● CONSTRUCTION	0.05-mm POLYESTER TOP COVER, EVA, CELL, EVA, FIBERGLASS SCRIM, 0.12-mm ACRYLIC, EVA, PORCELANIZED STEEL PAN, ALUMINIZED STEEL BACK STRUCTURE.
● TEST RESULTS	
• TEMPERATURE CYCLING	ENCAPSULANT LIFTED OFF ENAMELED STEEL PAN IN SEVERAL PLACES. THREE OF FOUR MODULES HAD CELL CRACKS. ONE MODULE HAD CORNER DELAMINATION
• HUMIDITY CYCLING	ONE CELL CRACK
• WIND	TWO MODULES HAD CRACKED CELLS, DELAMINATION FROM THE PAN, AND ONE WITH MARGINAL ELECTRICAL DEGRADATION
• HAIL	FAILED
● CONCLUSION	REDESIGN AND RETEST OF MODULES NEEDED

Problems in Environmental Testing

- DETERMINATION OF NOMINAL OPERATING CELL TEMPERATURE (NOCT)
  - JPL VARIATIONS FROM VENDOR MEASUREMENTS
  - CONTROLLED NOCT TESTS IN THE 25-FOOT SOLAR SIMULATOR
- STANDARD QUALIFICATION TESTS DO NOT DETECT POTENTIAL HOT CELL PROBLEMS
  - A HOT-CELL TEST IS UNDER DEVELOPMENT BY THE ENGINEERING AREA
- STANDARD QUALIFICATION TEST AND/OR INSPECTION METHODS DO NOT DETECT LONG-TIME INTERCONNECT FATIGUE
  - SOMETIMES STRESS DAMAGE AFTER 50 CYCLES CAN BE SEEN AT HIGH MAGNIFICATION
  - SECTIONING INTERCONNECTS AFTER TEMPERATURE CYCLING MAY BE NECESSARY
  - TEMPERATURE CYCLING MAY HAVE TO BE EXTENDED WELL PAST 50 CYCLES

Testing Planned for Near Future

- COMPLETE THE BLOCK IV QUALIFICATION TESTS
- TEST 4 TYPES OF MODULES FROM THE WORLD BANK/HALCROW
  - TWO U.S. MODULES, ONE FRENCH, ONE FROM INDIA
  - ULTRAVIOLET EXPOSURE TESTS ARE DONE IN ENGLAND
  - QUALIFICATION TESTS ARE TO BE RUN AT JPL PLUS HUMIDITY-HEAT AND HUMIDITY-FREEZE IF TIME PERMITS
- EXPLORATORY TESTS ON BLOCK IV MODULES, ADDING HOT-CELL TESTS AND MORE TEMPERATURE CYCLING
- TEST MODULES FROM THE THREE MIT-MANAGED RESIDENTIAL EXPERIMENT STATIONS

Summary

- SEVEN OF THE TEN TYPES OF BLOCK IV MODULES HAVE BEEN RECEIVED AND QUALIFICATION TESTS COMPLETED. ONE TYPE HAS BEEN RETESTED.
  - FIVE OF THE SEVEN FAILED TO QUALIFY. IMPROVEMENTS AND RETEST NEEDED.
- DIFFICULTIES IN MEASURING NOCT PERSIST
  - TEST REFINEMENTS ARE UNDER CONSIDERATION
- STANDARD QUALIFICATION TESTS HAVE NOT DETECTED HOT-CELL AND INTERCONNECT FATIGUE PROBLEMS
  - EXTENDING THE QUALIFICATION TEST SEQUENCE IS UNDER STUDY

REAL-TIME ENDURANCE TESTING
Status Report on Modules at Continental Remote Sites

JET PROPULSION LABORATORY

Peter Jaffe

Continental Remote Sites

CATEGORY	LOCATION	LATITUDE (degrees)	ALTITUDE (feet)	KEY FEATURES
EXTREME WEATHER	CANAL ZONE (FT. CLAYTON)	9	~0	TYPICAL TROPIC: HOT AND HUMID; 100 INCH-PER-YEAR RAINFALL
	ALASKA (FT. GREELY)	64	1,270	SEMI-ARCTIC: DRY, COLD AND WINDY; -30°F WINTERS
MARINE	KEY WEST, FLA.	25	0	HOT AND HUMID: CORROSIVE SALT SPRAY
	SAN NICHOLAS ISLAND, CALIF.	34	0	SOMEWHAT MILDER THAN KEY WEST
MOUNTAIN	MINES PEAK, COLORADO	40	13,000	CLEAR AND COLD; HIGH-VELOCITY WINDS; MAXIMUM UV
HIGH DESERT	ALBUQUERQUE, NEW MEXICO	35	5,200	DRY WITH CLEAR SKIES; AN ABUNDANCE OF UV
	DUGWAY, UTAH	40	4,300	COLD WINTERS, HOT SUMMERS; ALKALINE SOIL
MIDWEST	CRANE, INDIANA	39	~0	TYPICAL MIDWEST: HOT HUMID SUMMERS, COLD SNOWY WINTERS
NORTHWEST	SEATTLE (FT. LEWIS)	47	~0	TYPICAL NORTHWEST: MILD TEMPERATURES AND AN ABUNDANCE OF RAIN
UPPER GREAT LAKES	HOUGHTON, MICHIGAN	47	750	MILD SUMMERS, SEVERE WINTERS
URBAN COASTAL	NEW LONDON, CONNECTICUT	41	0	TYPICAL NEW ENGLAND COASTAL
	NEW ORLEANS, LOUISIANA	30	~0	HOT AND VERY HUMID; HIGH POLLUTION ENVIRONMENT

Typical Data from Portable I-V Data Logger

```
                              PORTABLE IV DATA

MEDIA SERIAL NR: 1002     MEDIA RECORD NR:  5   STORAGE FILE NAME: DK1:AL801

LOG NUMBER: 2516         ID NUMBER:  131         DATE:  7/18/80    TIME: 1024

THERMOCOUPLE DATA (DEG F):       97     97        134   134

PYRANOMETER DATA:          9.73     9.72          0.08     0.00

REFERENCE CELL DATA:     102.1    102.4         153.1    153.1

NUMBER OF RAW DATA POINTS:    53           NUMBER OF MERGED DATA POINTS:    48

ISC=1.829    VOC=20.38    PEAK-PWR=25.66    V@PEAK-PWR=15.62    FILL-FAC=0.688

                              I-V DATA

   I        V            I        V            I        V            I        V
0.000   20.380       0.071   20.270       0.143   20.180       0.214   20.070
0.286   19.970       0.357   19.850       0.429   19.740       0.500   19.620
0.572   19.490       0.643   19.370       0.715   19.230       0.786   19.090
0.857   18.940       0.929   18.780       1.000   18.610       1.072   18.430
1.143   18.230       1.215   18.010       1.286   17.780       1.358   17.490
1.429   17.180       1.492   16.790       1.501   16.800       1.569   16.260
1.572   16.310       1.641   15.560       1.643   15.620       1.693   14.770
1.707   14.650       1.726   13.970       1.739   13.820       1.747   13.180
1.761   12.390       1.763   12.800       1.771   11.600       1.780   10.810
1.787   10.020       1.792    9.230       1.798    8.440       1.803    7.650
1.806    6.860       1.810    6.060       1.814    5.270       1.817    4.480
1.821    3.690       1.823    2.900       1.827    2.110       1.829    1.320
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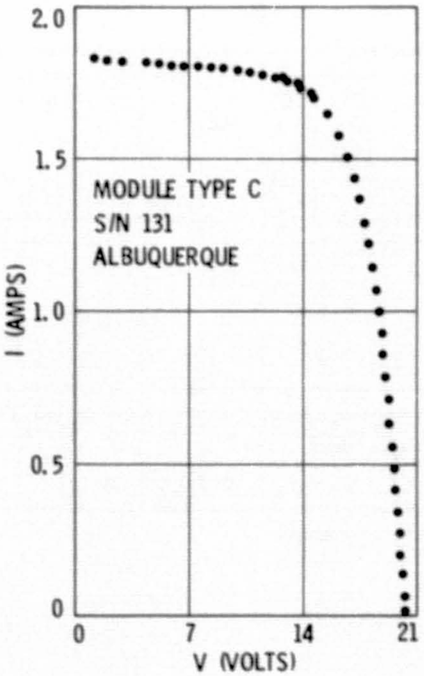


Typical I-V Summary Data

```
                    SUMMARY OF DATA FOR SPECTROLAB  MODULE  131 TAKEN AT ALBUQUERQUE
                   ----------------------------------------------------------------

REFERENCE CONDITIONS FOR CORRECTED DATA:  INSOLATION (MW/CM*CM) = 100.0    MODULE TEMPERATURE (DEG C) = 28.0
MODULES INSTALLED IN FIELD --3/23/78--                       PRE-INSTALLATION DATA:  1.84  23.6  30.97  .7132

<-------------------------------RAW DATA--------------------------------->  <-----------CORRECTED DATA----------->

  DATE    TIME   ISC     VOC   PK-PWR FILFAC  REFCL   PYRO    TAIR  TBACK   REFCLV TCELL   ISC    VOC  PK-PWR FIL-FAC

 7/18/80  1024  1.829  20.38  25.66  0.688  102.3  102.2   97.0  134.0    95.6  145.1  1.909  23.47  31.71  0.708
 7/18/80  1024  1.829  20.37  25.63  0.688  102.5  102.1   97.0  134.0    95.5  145.1  1.910  23.49  31.71  0.707
 7/18/80  1024  1.833  20.36  25.68  0.688  102.7  102.2   97.0  133.0    95.6  144.1  1.912  23.41  31.66  0.707
 7/21/80   903  1.708  21.62  25.97  0.703   98.2   96.5   84.5  103.0    90.2  113.5  1.892  23.36  31.41  0.711
 7/21/80   903  1.702  21.60  25.92  0.705   98.2   96.4   84.5  103.5    90.1  114.0  1.887  23.36  31.42  0.713
 7/21/80   903  1.703  21.57  25.88  0.704   98.2   96.3   85.0  104.0    90.1  114.4  1.890  23.36  31.43  0.712
```

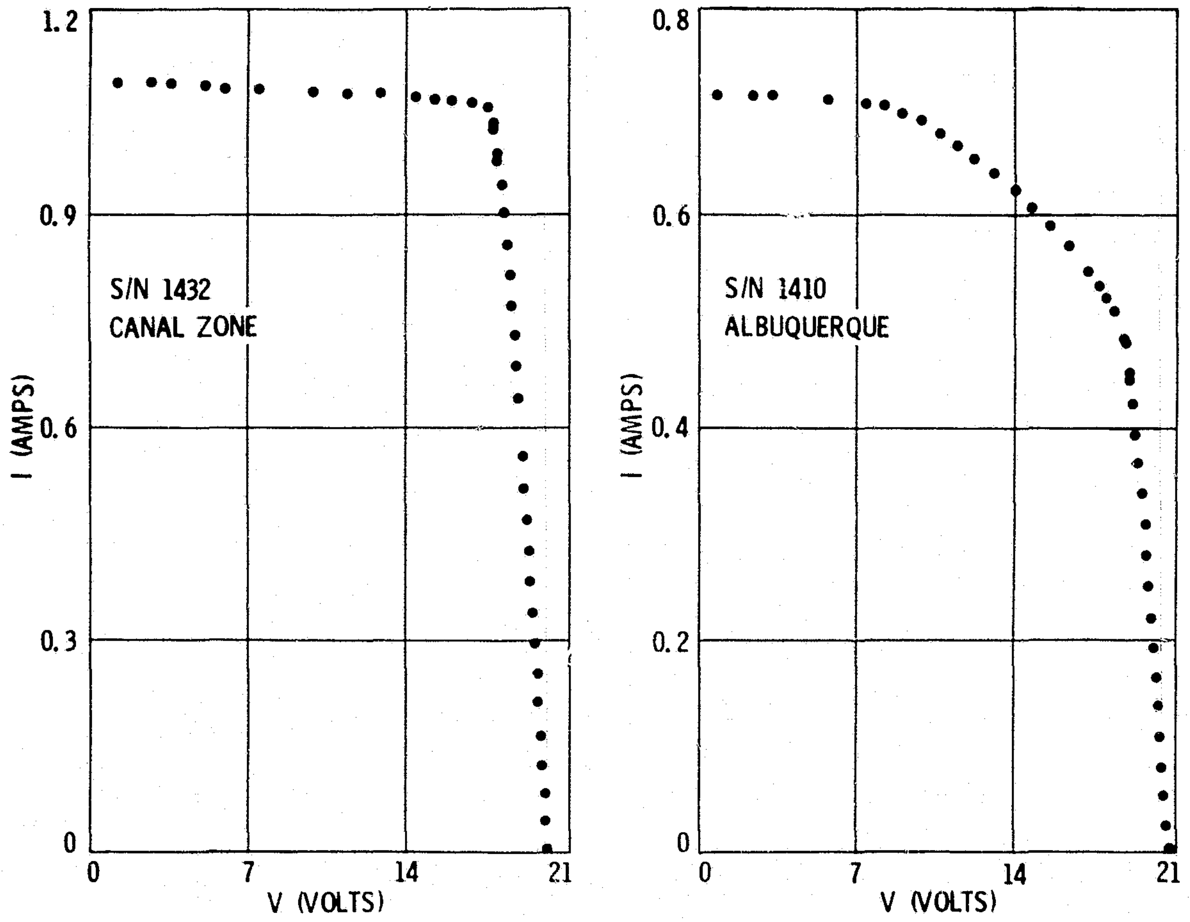
Electrical Performance Summary of Remote-Site Modules

OLD → ⧄ ← NEW

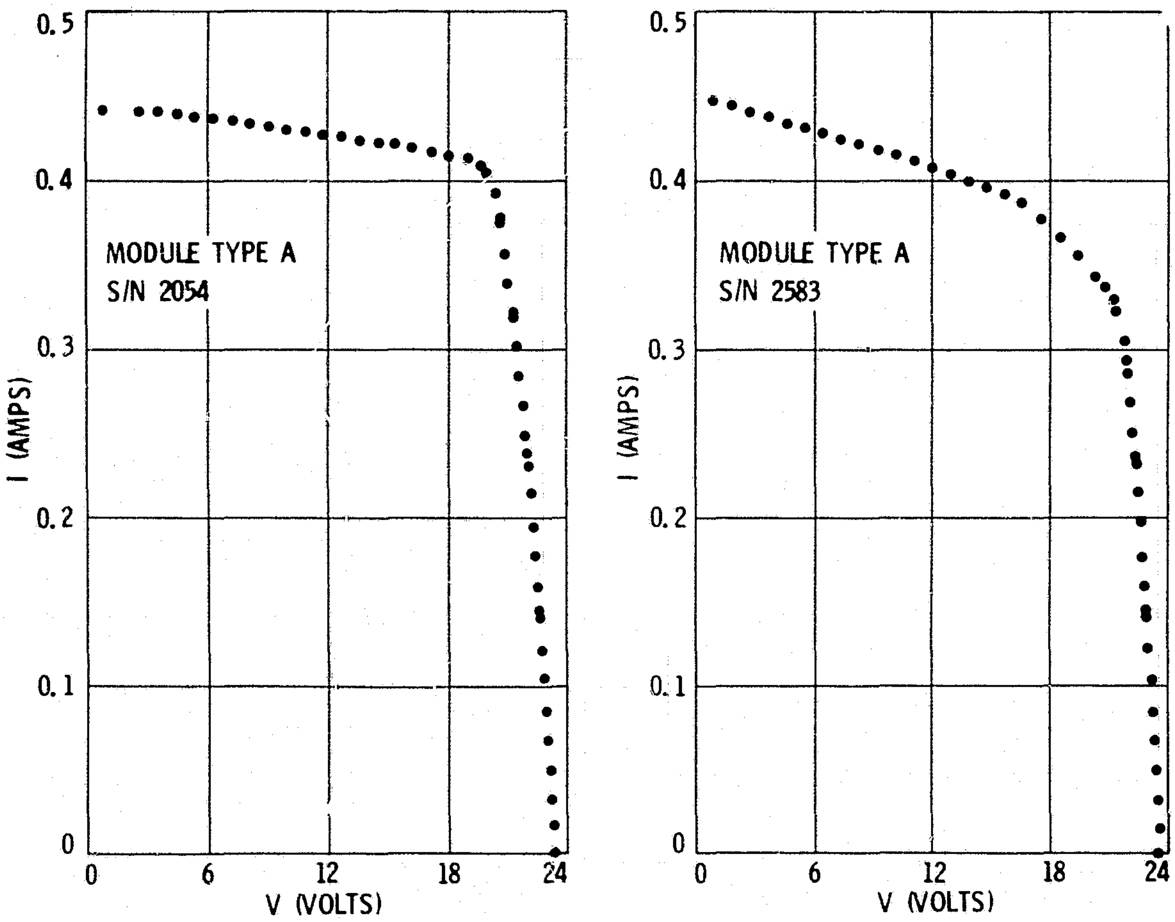
		CANAL ZONE	KEY WEST	NEW ORLEANS	CRANE	HOUGHTON	NEW LONDON	ALBUQUERQUE	DUGWAY	ALASKA	SEATTLE	SAN NICHOLAS	TOTALS
TYPE A	NUMBER OF MODULES	4	4	2	4	3	4	4	4	4	4	4	41
	FAILED												0
	DEGRADED					/2							/2
TYPE B	NUMBER OF MODULES	4	3	4	4	4	4	4	4	4	4	2*	41
	FAILED												0
	DEGRADED												0
TYPE C	NUMBER OF MODULES	4	3	4	4	4	4	4	4	4	4	4	43
	FAILED	1/1	/1	/1				1/					2/3
	DEGRADED	1/		/1		1/2		1/					3/3
TYPE D	NUMBER OF MODULES	4	4	4	4	4	4	4	4	4	4	2	42
	FAILED												0
	DEGRADED										/1*		/1*
	TOTAL FAILED	1/1	/1	/1	0	0	0	1/	0	0	0	0	2/3
	TOTAL DEGRADED	1/	0	/1	0	1/4	0	1/	0	0	/1*	0	2/6

*MODULE INCURRED MASSIVE PHYSICAL DAMAGE

Typical I-V Curves of Degraded Type C Modules



I-V Curves of Degraded Modules Resulting From Impact Cracks at Houghton



Comments on Methods of Determining Physical Change

OVER THE PAST 2 YEARS, THE PROCESS HAS EVOLVED FROM RECORDING PHYSICAL DEFECTS BY CATEGORY TO COMPARING THE PHYSICAL STATE OF EACH MODULE TYPE ON A SITE-BY-SITE BASIS

MODULES ARE INSPECTED USING A PRIORI KNOWLEDGE OF "PREVALENT DEFECTS"—OBSERVED PROBLEMS COMMON TO A SPECIFIC DESIGN

INSPECTION DATA FOR EACH MODULE TYPE ARE COLLECTIVELY REDUCED TO SET OF RELATIVE INDICES WHICH DEPICT THE STATE OF THE "PREVALENT DEFECTS"

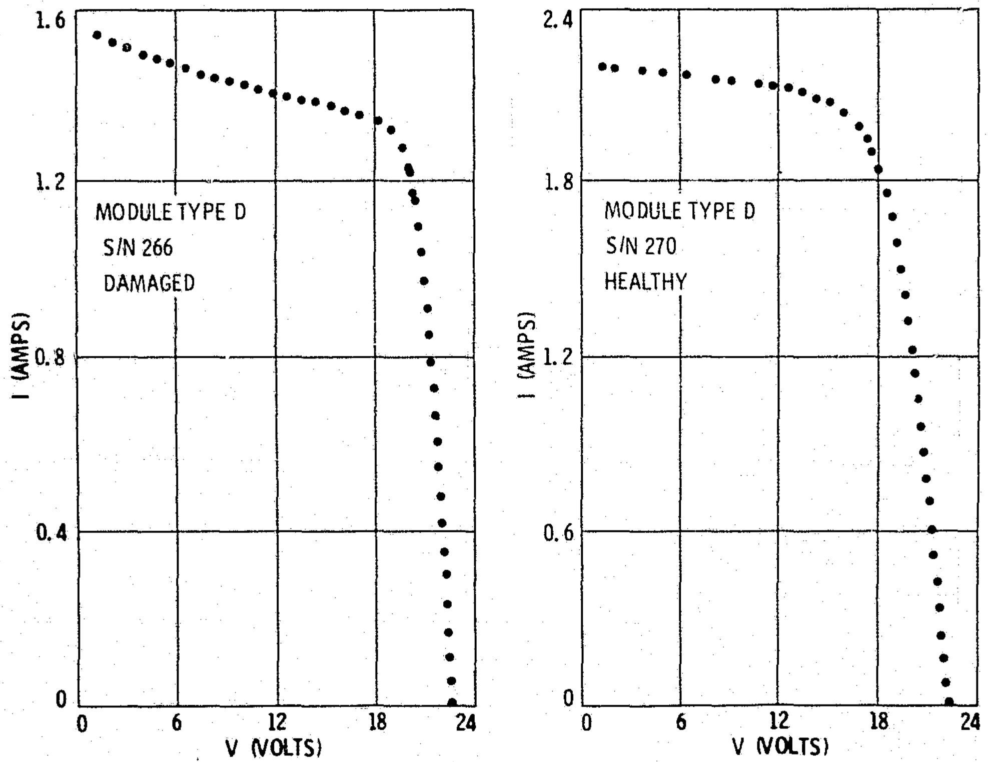
OBJECTIVITY IS INCREASED BY USING CONSENSUS OF SEVERAL OBSERVERS

SINGLE EVENTS, VANDALISM AND NON-NATURAL WEATHERING DAMAGE, SUCH AS BIRD DAMAGE, ARE NOT INCLUDED

PROCEDURE COULD BE IMPROVED BY HAVING A WHAT-TO-LOOK-FOR LIST AHEAD OF TIME, PROVIDED BY MATERIAL AND DESIGN SPECIALISTS

DETERMINING AND REPORTING PHYSICAL CHANGE IS A LEARNING, EVER-REFINING PROCESS—NO ESTABLISHED PROCEDURE EXISTS

I-V Curves of Damaged and Healthy Glass Modules



Physical Inspection Summary of Remote-Site Modules

	PREVALENT PHYSICAL DEFECTS	PROBABLE EFFECT	CANAL ZONE	KEY WEST	NEW ORLEANS	CRANE	HOUGHTON	NEW LONDON	ALBUQUERQUE	DUGWAY	ALASKA	SEATTLE	SAN NICHOLAS
TYPE A	CRACKED CELLS	a				○	◑	○				○	
	GROUND TERMINAL CORROSION	u	◑	●	◑	●		○	○			◑	●
	PROTECTIVE TERMINAL BOOT DETERIORATION	d				○		○	○	○			
	OUTPUT TERMINAL HARDWARE CORROSION	d				○							◑
	EMBEDDED DIRT	b	○	○	◑	○	○	○	○		○	○	○
TYPE B	CRACKED CELLS	a			○								
	CELL GRID AND COLLECTOR DISCOLORATION	d	◑	○	◑	○	○	○	○	○	○	○	○
	MODULE FRAME CORROSION	c	○	○	○			○				○	○
	J-BOX AND OUTPUT CONNECTOR CORROSION	c	○	●	◑			○		○			◑
	EMBEDDED DIRT	b	○	○	◑	○	○	○	○		○	○	○
TYPE C	CRACKED CELLS	a	○		○		○				○	○	
	FRAME SEAL/SUBSTRATE DELAMINATION	a	◑	◑	◑	○	○	○	●	●		○	○
	INTERCONNECT/CELL SURFACE CORROSION	u	○		○				○	◑	○	○	
	OUTPUT INTERCONNECT/SOLDER JOINT CORROSION	u	◑	◑		◑		○	○	○	○	◑	○
	HARD-COAT CRAZING	c				○	◑		○	○	○		○
	INTERCONNECT BREAKTHROUGH	u										○	
	SUBSTRATE DETERIORATION	c	○	◑	○	○	○		◑	○		○	
	EMBEDDED DIRT	b	○	○	◑	○		○				○	○
TYPE D	TERMINAL STRIP/SOLDER JOINT DISCOLORATION	d	○	◑	○	○	○	○				○	○
	RUBBER OUTPUT CONNECTOR DETERIORATION	u				○	○	○	○	◑	○		
	FRAME SCREW FASTENER CORROSION	c	◑	●	○	○		○				◑	
	MODULE FRAME CORROSION	c	○	○	○	○		○		○		○	○

PROBABLE EFFECTS

a POTENTIAL ELECTRICAL FAILURE
b RESULTS IN POWER DECREMENT
c PRIMARILY COSMETIC
d LIKELY NOT SERIOUS
u UNKNOWN

SEVERITY SCALE

NONE
SOME
○ MODERATE AMOUNT
◑ SIGNIFICANT AMOUNT
● EXTREME CONDITION

Physical Inspection Data Indicate Things to Avoid

- DISSIMILAR METAL COMPONENTS IN CONTACT WITH ONE ANOTHER
- NEOPRENE ELECTRICAL CONNECTORS AND PROTECTIVE DEVICES
- GALVANIZED MATERIALS FOR NEAR-OCEAN APPLICATIONS
- SINGLE INTERCONNECTS BETWEEN CELLS AND TERMINALS
- MODULE DESIGNS WHICH COULD RETAIN WATER BETWEEN FRAME AND ENCAPSULANT

Summary and Conclusions

- HOT HUMID ENVIRONMENTS APPEAR TO BE THE MOST DAMAGING; COLD, DRY ENVIRONMENTS THE MOST BENIGN
- ALL ELECTRICAL FAILURES AND 6 OF THE 9 MODULES THAT DEGRADED WERE OF TYPE C
- FAILURES PROBABLY DUE TO CRACKED INTERCONNECTS, INTERCONNECT SOLDER JOINT FAILURES, OR CRACKED CELLS
- SOME PREVALENT PHYSICAL DEFECTS HAVE BEEN IDENTIFIED BUT SO FAR NO CORRELATION WITH ELECTRICAL CHANGE HAS BEEN OBSERVED
- TWO SUCCESSFUL DESIGN FEATURES WORTHY OF COMMENT ARE:
    - WRAP-AROUND FRAME ENCAPSULANT CONTAINMENT DESIGN OF TYPE B MODULES
    - THE PVB LAMINATED CONSTRUCTION OF TYPE D MODULES
- GLASS MODULES HAVE SUPERIOR NON-SOILING AND SELF-CLEANING CHARACTERISTICS
- MODULE DEFICIENCIES APPEAR TO BE EITHER DESIGN-RELATED OR THE RESULT OF POOR FABRICATION PRACTICE—NO INHERENT LIFE-LIMITING PROBLEMS HAVE BEEN IDENTIFIED

PV STAND-ALONE APPLICATIONS PROJECT: PV APPLICATION EXPERIENCE

NASA LEWIS RESEARCH CENTER
Edwin T. Muckley

DOE PV Stand-Alone Applications Project

OBJECTIVE: ACCELERATE PENETRATION OF PHOTOVOLTAIC SYSTEMS IN NEAR-TERM AND INTERMEDIATE MARKETS (ESPECIALLY INTERNATIONAL) TO STIMULATE PV INDUSTRY GROWTH TOWARD DOE GOALS

APPROACH:

- DEVELOP AND DEMONSTRATE, IN PARTNERSHIP WITH HOST COUNTRIES AND USERS, STAND-ALONE APPLICATIONS WHICH REPRESENT A POTENTIALLY LARGE MARKET FOR PHOTOVOLTAICS
- DEVELOP THE SUPPORTING SYSTEM, SUB-SYSTEM, AND COMPONENT TECHNOLOGY

RESOURCES:

FY 80 FUNDS	$3 M
FY 81 FUNDS	$4.4 M

Why Remote Stand-Alone Applications Are Important

- EARLY MARKET FOR PHOTOVOLTAIC SYSTEMS NEEDED TO SUPPORT GROWTH OF PV INDUSTRY
- REMOTE STAND-ALONE APPLICATIONS CONSTITUTE FIRST MARKET FOR PHOTOVOLTAIC SYSTEMS
  - NEED NOT COMPETE WITH UTILITY POWER IN COST
  - ARE NOW COST COMPETITIVE WITH ALTERNATIVE POWER SOURCES IN IMPORTANT SELECTED USES IN THE DEVELOPING WORLD

ENGINEERING AND OPERATIONS AREAS

Major Activities

- o MARKET DEMONSTRATIONS
- o MARKET STUDIES
- o SYSTEM TECHNOLOGY DEVELOPMENT
- o SUPPLIER DEVELOPMENT

Summary: Single Applications

APPLICATION CATEGORY	USE	USER	DATE OPERATIONAL	LOCATION	POWER LEVEL, Wp
INSTRUMENT	WEATHER DATA	USCG	DECEMBER 1972	CLEVELAND, OH	30
INSTRUMENT	WEATHER DATA	NOAA	AUGUST 1973	MAMMOTH MT., CA	60
COMMUNICATIONS	RADIO REPEATER	USFS	JULY 1974	WHITE MT., CA	16
COMMUNICATIONS	EDUCATIONAL TV	GOVT. INDIA	JULY 1976	1) AHMEDABAD, INDIA 2) SAMBALPUR, INDIA	55 55
REFRIGERATION	FOOD PRESERVATION	USNPS	JUNE 1976	ISLE ROYALE, MI	220
REFRIGERATION	MEDICAL	VILLAGE RESIDENTS	JULY 1976	SIL NAKYA, AZ PAPAGO TRIBE	330
INSTRUMENT	WEATHER DATA	NOAA	APR-SEPT 1977	1) NEW MEXICO; 2) NEW YORK; 3) HAWAII; 4) ALASKA; 5) MAINE; 6) FLORIDA	75-150
HIGHWAY	DUST STORM WARNING SIGN	DOT-AZ	APRIL 1977	CASA GRANDE, AZ	116
INSTRUMENT	INSECT SURVEY TRAPS	USDA	MAY 1977	COLLEGE STATION, TX	23 & 163
REFRIGERATION	WATER COOLER	INTERAGENCY VISITOR CENTER	OCTOBER 1977	LONE PINE, CA	446
INSTRUMENT	AIR POLLUTION MONITOR	NJ-DEP	NOVEMBER 1979	LIBERTY PARK, NJ	360
INSTRUMENT	SEISMIC MONITORS	USGS	JANUARY 1980	KILAUEA VOLCANO, HI	18 & 18

Major Current Market Demonstrations

LOCATION	APPLICATION CATEGORY	SERVICES	SPONSORS	STATUS
SCHUCHULI, AZ.	VILLAGE SERVICES	LIGHTS REFRIGERATORS WATER PUMP WASHING MACHINE SEWING MACHINE	DOE, PAPAGO TRIBE	OPERATING SINCE DECEMBER 1978
4 VILLAGES IN GABON	VILLAGE SERVICES	WATER PUMPS REFRIGERATORS INDOOR LIGHTS OUTDOOR LIGHTS	DOE, GABON	PROJECT DEFINITION IN WORK OPERATION PLANNED FOR MID 1982
COLOMBIA GAMBIA INDIA IVORY COAST MALDIVE ISLANDS PERU	HEALTH: VACCINE PRESERVATION	REFRIGERATORS	DOE, CENTER FOR DISEASE CONTROL, PAN AMER. HEALTH ORG.	OPERATION SCHEDULED FOR EARLY 1982

PV Applications Projects Managed by NASA-LeRC for the Agency for International Development

LOCATION	APPLICATION CATEGORY	SERVICES	SPONSORS	STATUS
TANGAYE, UPPER VOLTA	VILLAGE SERVICES	WATER PUMP GRAIN MILL	AID, UPPER VOLTA	OPERATING SINCE MARCH 1979
TUNISIA	VILLAGE SERVICES	WATER PUMP LIGHTING DOMESTIC APPLIANCES DRIP IRRIGATION	AID, TUNISIA	OPERATION SCHEDULED FOR MARCH 1982
ECUADOR GUYANA KENYA	HEALTH SERVICES (MEDICAL POSTS)	LIGHTS REFRIGERATOR AUTOCLAVE DENTAL EQUIPMENT ETC	AID, HOST COUNTRY	PROJECTS BEING DEFINED

Operational History

	SYSTEM PEAK POWER Wp	INSTALLED	MODULE TYPE (1)	TOTAL No.	MODULE EXPERIENCE (2)	OTHER COMPONENT EXPERIENCE
ISLE ROYAL	220	MAY 76	SX(I)	24	NO PROBLEMS	NO PROBLEMS
SIL NAKYA	330	JUL 76	SX(I)	30	2 - OPEN CIRCUIT 1 - CRACKED CELL	REFRIGERATOR DEFICIENT (3) VOLTAGE REGULATOR DEFICIENT- REPLACED
FOREST TOWERS	294	OCT 76	SX(I)	64	NO PROBLEMS	NO PROBLEMS
RAMOS	75-150	APR-OCT 77	SX(I)	64	3 - CRACKED CELLS (IN SERVICE) 5 - VANDALISM	VOLTAGE REGULATOR DEFICIENT - REPLACED ENVIRONMENTAL CORROSION PROBLEM AT SSNY - CORRECTED
ADOT SIGN	116	APR 77	ST(I)	20	1 - VANDALISM	NO PROBLEMS
USDA INSECT TRAPS	23-163	MAY 77	ST(I)	64	1 - OPEN CIRCUIT (INFANT MORTALITY)	NO PROBLEMS
LONE PINE	446	SEP 77	ST(II)	48	NO PROBLEMS	VOLTAGE REGULATOR FAILED - REPLACED W/REDESIGNED REG.
SCHUCHULI	3,500	NOV 78	SX(II)	192	34 - OPEN CIRCUIT BET. 7/79 AND 8/80 (27 REPLACED)	CONTROL SYSTEM FAILURES - CORRECTED REFRIGERATOR: MOTORS - REPLACED FREON LEAKS - CORRECTED
UPPER VOLTA	1,800	MAR 79	SX(II)	100	26 - OPEN CIRCUIT BET. 10/79 & 9/80 (1 REPLACED 1979, 23 REPLACEMENTS INSTALLED 9/80)	BURR MILL EXCESSIVE WEAR - REPLACED WITH HAMMER MILL
NJ DEP	360	NOV 79	ARCO(III)	20	NO PROBLEMS	NO PROBLEMS
HVO	40	JAN 80	ST(II)	4	NO PROBLEMS	NO PROBLEMS

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(1) SX = SOLAREX CORP. ARCO - ARCO SOLAR INC.
ST = SENSORTECH CORP. NUMBER IN PARENTHESIS REFER TO JPL BLOCK BUY MODEL

(2) UNLESS OTHERWISE NOTED, ALL FAILED MODULES REPLACED

(3) OUT OF SERVICE PENDING REPLACEMENT

Market Development of PV Products

- IDENTIFY PROMISING MATURE OR NEARLY-DEVELOPED PV POWERED SYSTEMS AND SUPPORT THEIR PENETRATION INTO WORLDWIDE MARKETS
- ISSUE "ANNOUNCEMENT OF OPPORTUNITY" OR EQUIVALENT, SOLICITING COST-SHARED MARKETING APPROACHES FOR PV SYSTEMS
- EMPHASIS ON ACTIVITY SHALL BE ON MARKETING OF PRODUCT
  - LIMITED PRODUCT DEVELOPMENT POSSIBLE
- MULTI-CONTRACTS TO BE ISSUED WITHIN ONE YEAR

STATUS OF FLAT-PLATE PV PROJECTS

SANDIA LABORATORIES

Calvin B. Rogers

Sandia Application Projects

- FOUR PRDA-38 FLAT PLATE PROJECTS
- FIVE PRDA-35 CONCENTRATOR PROJECTS
- THE SAN BERNARDINO COMM. DEV. PROJECT

New Mexico Solar Energy Institute, Newman Power Station, El Paso, Texas

- SIZE IS 18 KW
- COST IS $471 K, $26/WATT
- SOLAR POWER G-361 MODULES
- NO INVERTER - DC SYSTEM
- LOAD IS UPS BATTERY BANK
- OPERATIONAL DEC 1980

Lea County Electric, Lovington, New Mexico

- SIZE IS 100 KW
- COST IS $2.7 M, $27/WATT
- SOLAR POWER G-361 MODULES
- TWO DECC INVERTERS
- NO STORAGE, COOPERATIVE UTILITY INTERFACE
- OPERATIONAL FEB 1981

Solar Power, Beverly High School, Beverly, Mass.

- SIZE IS 100 KW
- COST IS $2.7 M, $27/WATT
- SOLAR POWER G-361 MODULES
- TWO DECC 60 KW INVERTERS
- NO STORAGE, COOPERATIVE UTILITY INTERFACE
- OPERATIONAL FEB 1981

SAI-Oklahoma Center for Science and Arts, Oklahoma City

- SIZE IS 135 KW
- COST IS $2.7 M, $20/WATT
- SOLAREX SEMI-CRYSTALLINE MODULES
- WINDWORKS 150 KVA INVERTER
- NO STORAGE, COOPERATIVE UTILITY INTERFACE
- OPERATIONAL MARCH 1981

San Bernardino, Calif., Westside Community Development

- SIZE IS 35 KW
- COST IS $983 K, $28/WATT
- SOLAREX 36 CELL SQUARE PANELS
- THREE 10 KVA SUNVERTERS BY ABACUS
- NO STORAGE, COOPERATIVE UTILITY INTERFACE
- OPERATIONAL NOV 1981

STATUS REPORT: MT. LAGUNA AIR FORCE STATION

JET PROPULSION LABORATORY

Ron Baisley

History

- DEDICATION – AUG 15, 1979
- FULLY OPERATIONAL SINCE
- PERIODIC FIELD AUDITS

Array Characteristics

- ARRAY POWER – 64 kW PEAK (60 kW SYSTEM AC OUTPUT)
- ARRAY BUS VOLTAGE – 230 V
- 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)

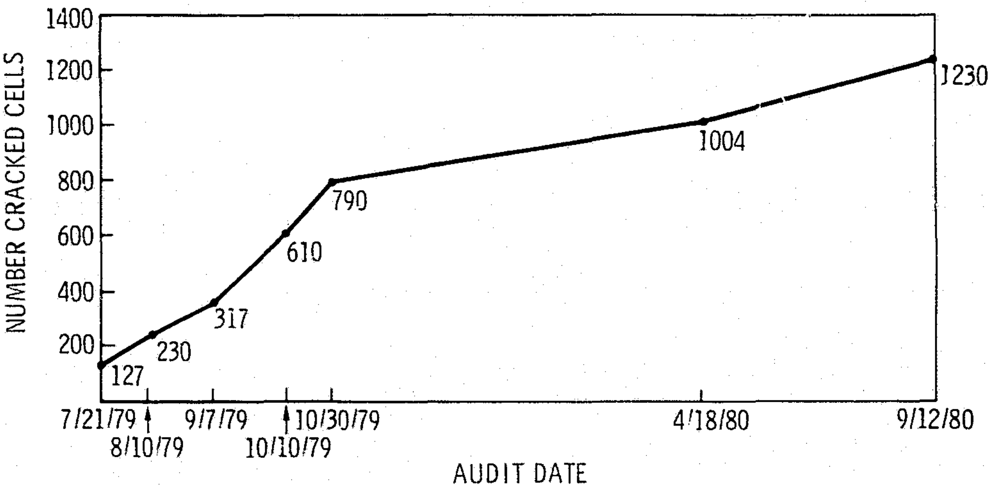
Visual Observations

Cracked Cells, Burst-Type Fractures: 30-W Module

- OCCURRENCE – 1230 CELLS (671 MODULES)
- DISTRIBUTION: NON-UNIFORM
- DELAMINATION –
  - CELL – 411 CELLS
  - EDGE – 1485 MODULES

Visual Observations

Cracked-Cell, Burst-Fracture History: 30-W Module



Visual Observations

Cracked Cells, Impact Fractures: 20-W Module

- 195 CRACKED CELLS IN 141 MODULES
- TYPICAL OF IMPACT CRACKS
- HAILSTORM
- SOME BURST-TYPE FRACTURES

- BURST-CELL PHENOMENON
  - CONTINUING
  - SPREADING TO 20-W MODULE
- IMPACT FRACTURES
  - PROBABLE CAUSE: HAILSTORMS
  - ALSO OBSERVED IN 30-W MODULES
- MODULE DEGRADATION
  - INCREASING
  - ARRAY PERFORMANCE NOTICEABLY AFFECTED

MODULE FAILURES AT MIT/LL TEST SITES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORIES

S. E. Forman

Data Up to 8/80

MFG. START	NEB (7/77)	RES STF (11/78)	ROOF STF (5/77)	UTA (8/78)	CHIC (7/77)	WBNO (8/79)	NBNM (1/80)	TOTALS
A (I)	-	-	15/945	-	0/288	-	-	15/1233
A (II)	-	-	-	-	-	-	0/720**	0/720
B (II)	-	-	5/64	65/240	-	-	-	70/304
C (II)	35/1512	15/700	0/36	-	-	-	-	50/2248
C (III)	-	6/372	-	4/640*	-	-	-	10/1012
D (II)	31/728	-	-	-	-	-	-	31/728
D (III)	-	5/194	1/74	-	-	4/800	-	9/1068
E (III)	-	-	-	-	-	-	1/1740	1/1740
F (III)	-	-	-	-	-	-	28/2064	28/2064
	2.95%	2.05%	1.9%	27%	0%	0.5%	0.6%	214/11117
				0.6%				1.93%

* ARRAY START DATE 4/80

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

SITE	STARTING DATE	NO. OF FAILURES/TOTAL BLOCK I	BLOCK II	BLOCK III
NEB	7/77	--	66/2240	--
RES STF	11/78	--	15/700	11/556
ROOF STF	5/77	15/945	5/100	1/74
UTA	8/78-4/80	--	65/240	--
UTA	4/80	--	--	4/640
CHIC	8/79	0/288	--	--
WBNO	8/79	--	--	4/800
NBNM	1/80	--	0/720**	29/3804
TOTALS		15/1233 (1.22%)	150/4000 (3.75%)	49/5884 (0.83%)

**NOTE: 52 MODULES HAVE BEEN FOUND WITH CRACKED GLASS COVER SHEETS.

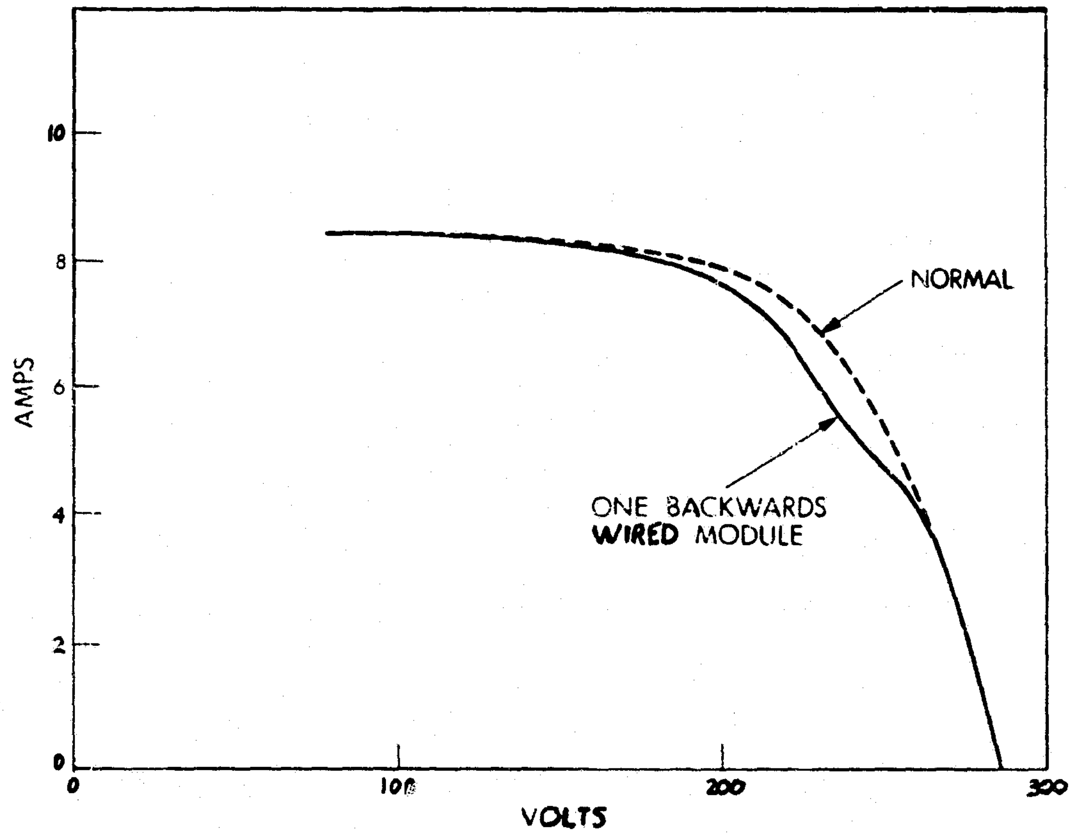
Principal Causes of Module Failures

1. CELLS CRACKED DUE TO WEATHERING OR INTERNAL MODULE STRESSES.
2. FAILED SOLDER JOINTS.
3. INTERCONNECTS NOT SOLDERED TO REAR SIDES OF CELLS AT ASSEMBLY.
4. CELL STRING SHORTED TO SUBSTRATE.
5. BROKEN OR SPLIT INTERCONNECTS.

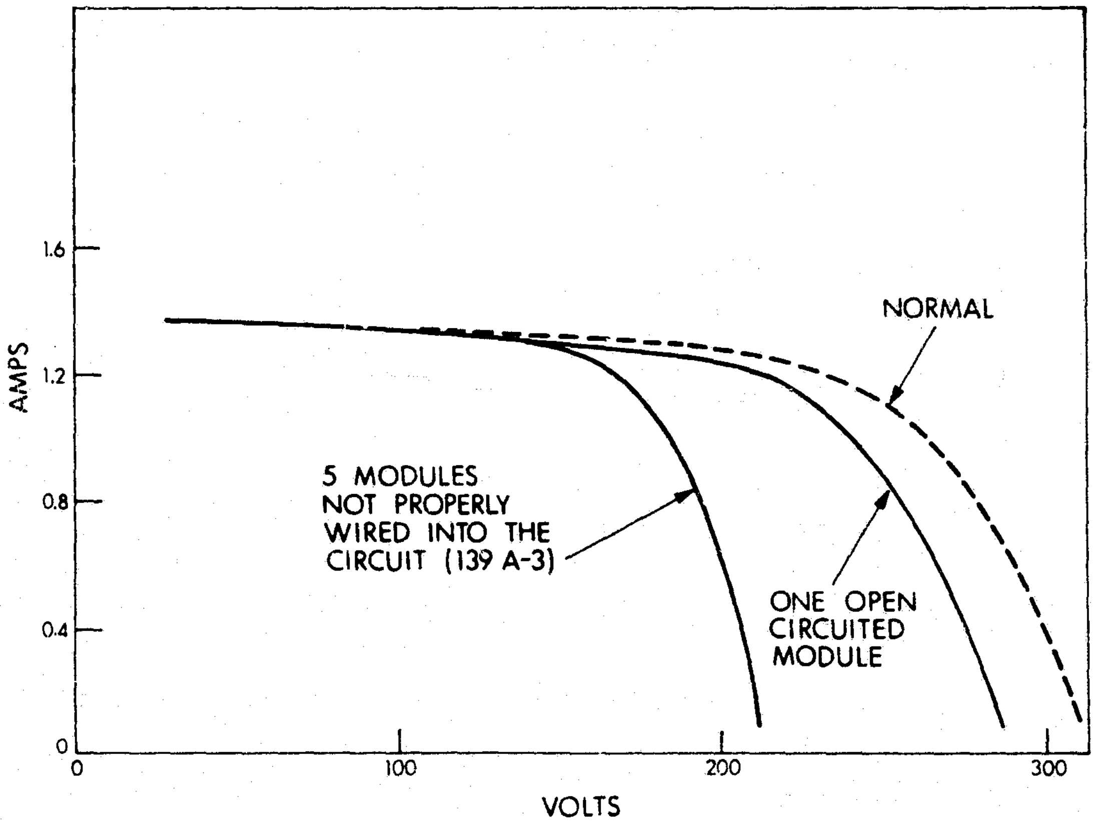
Natural Bridges National Monument System Characteristics

MODULES (GLASS)	1740 E (III)	2064 F (III)	720 A (II)
NO. OF BRANCH CIRCUITS	116	43	10
BRANCH CIRCUIT CONFIGURATION	15 IN SERIES	48 IN SERIES	5 IN PARALLEL BY 14 IN SERIES
DIODES	ONE PER MODULE	ONE PER MODULE	ONE PER GROUP OF 5 IN PARALLEL

NBNM 6/24/80: Branch Circuit No. 102



NBNM 6/24/80: Branch Circuit No. 144B-4



WBNO System Characteristics

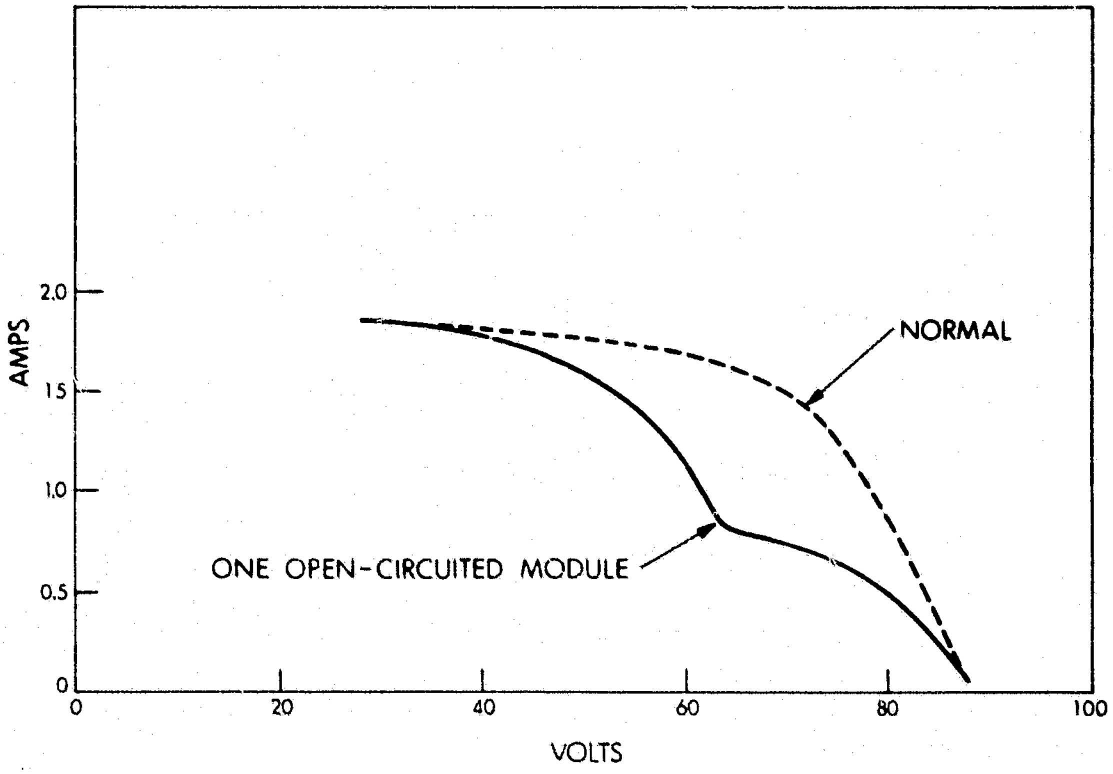
MODULES - 800 MFG D (III) RTV

NO. OF BRANCH CIRCUITS - 100

BRANCH CIRCUIT CONFIGURATION - 4 IN SERIES PARALLELLED WITH 4 IN SERIES

DIODES - EACH MODULE HAS ONE DIODE

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



University of Texas Austin System Characteristics

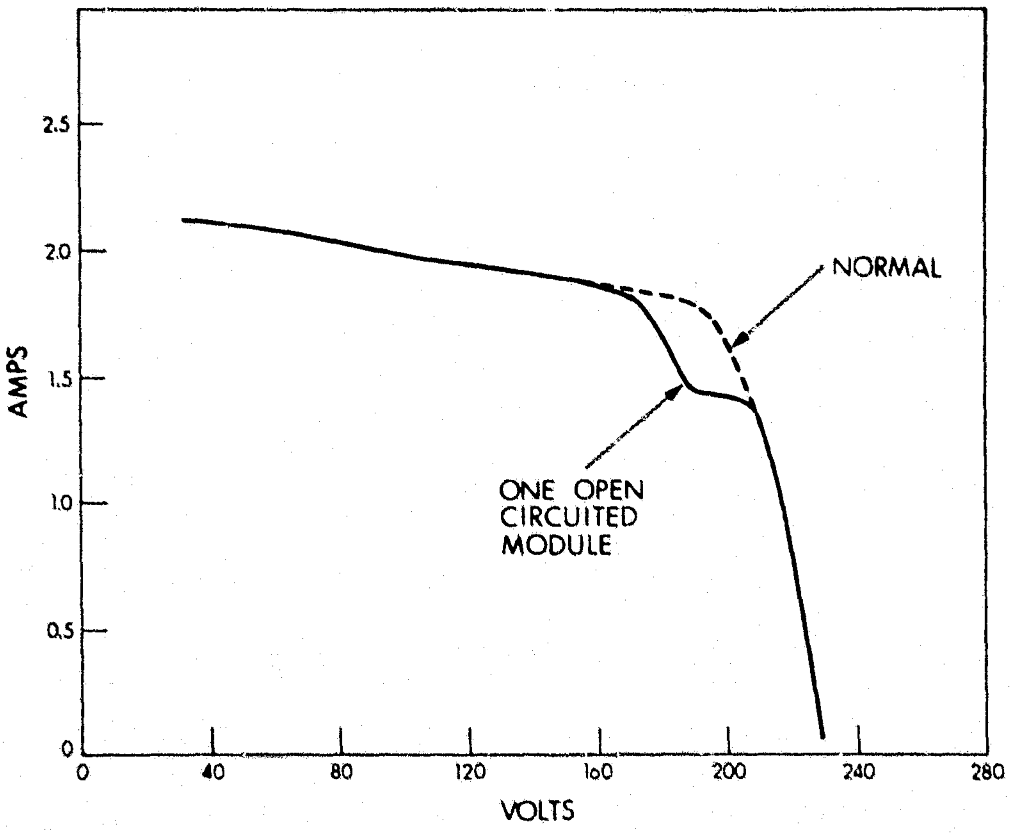
MODULES - 640 MFG C (III) RTV

NO. OF BRANCH CIRCUITS - 16

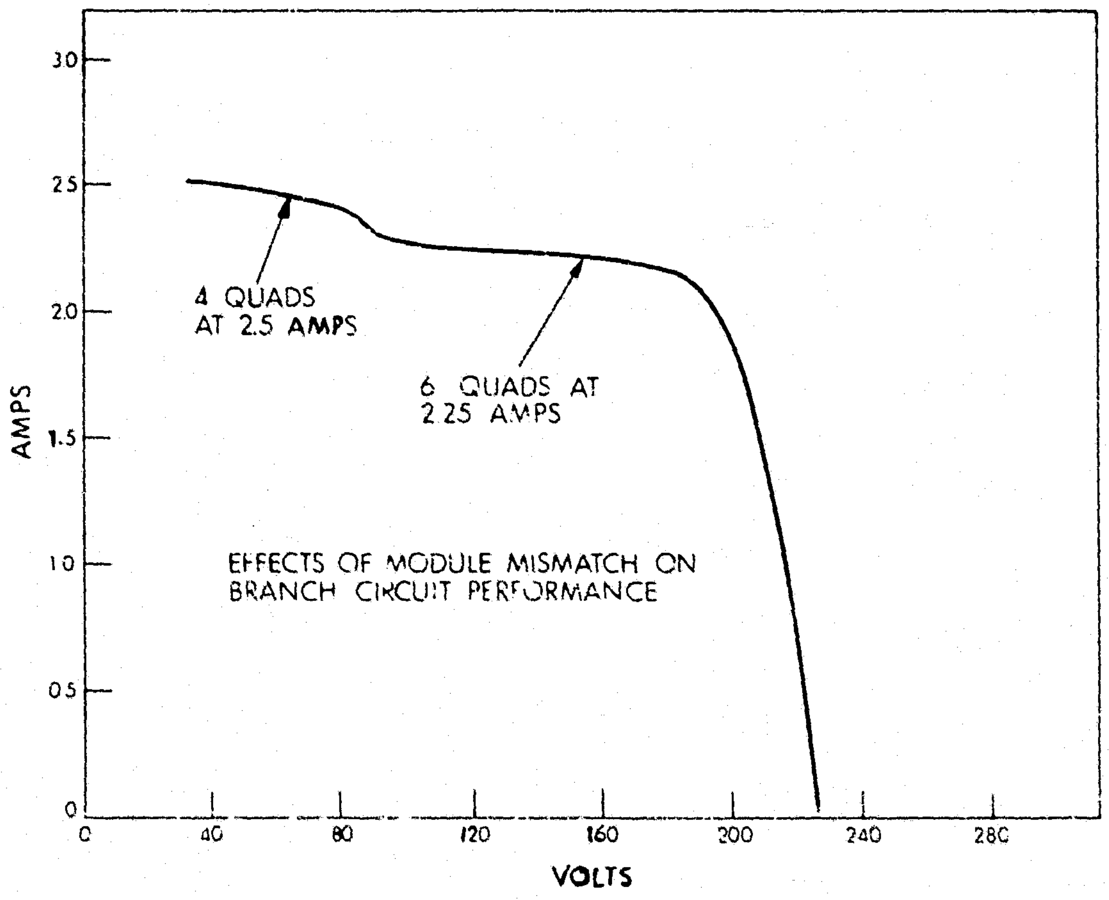
BRANCH CIRCUIT CONFIGURATION - 4 IN PARALLEL BY 10 IN SERIES

DIODES - EACH GROUP OF 4 IN PARALLEL HAS ONE DIODE

UTA 4/16/80: Branch Circuit No. 11



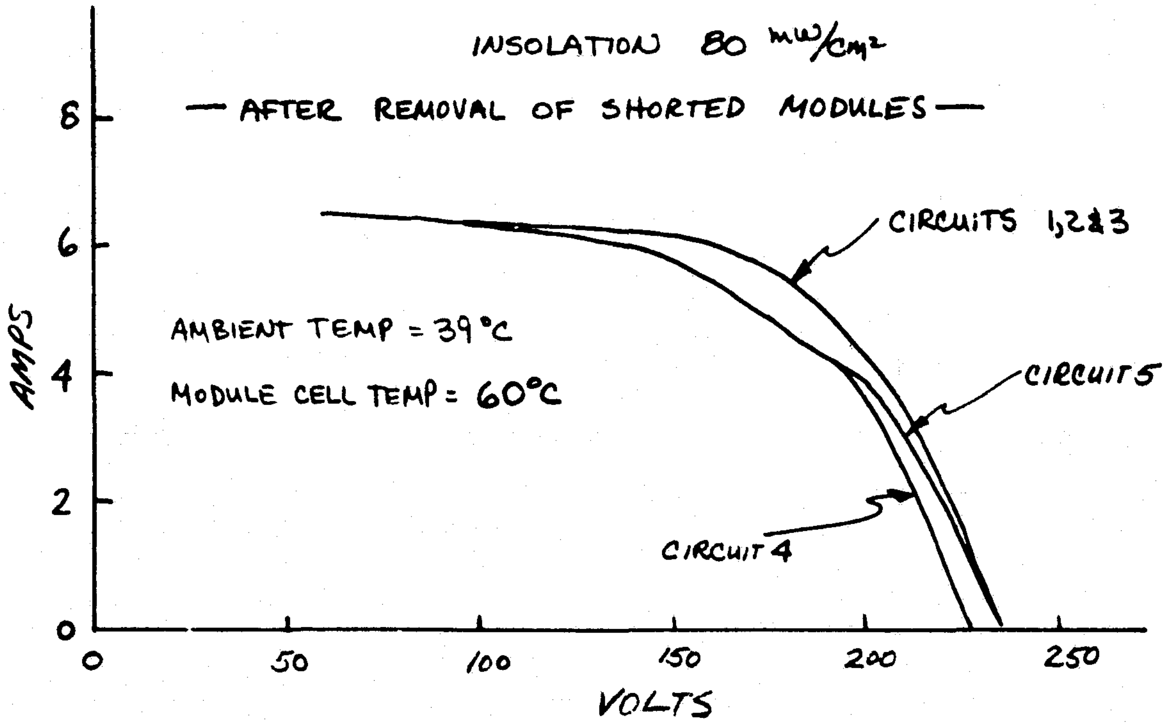
UTA 4/16/80: Branch Circuit No. 16



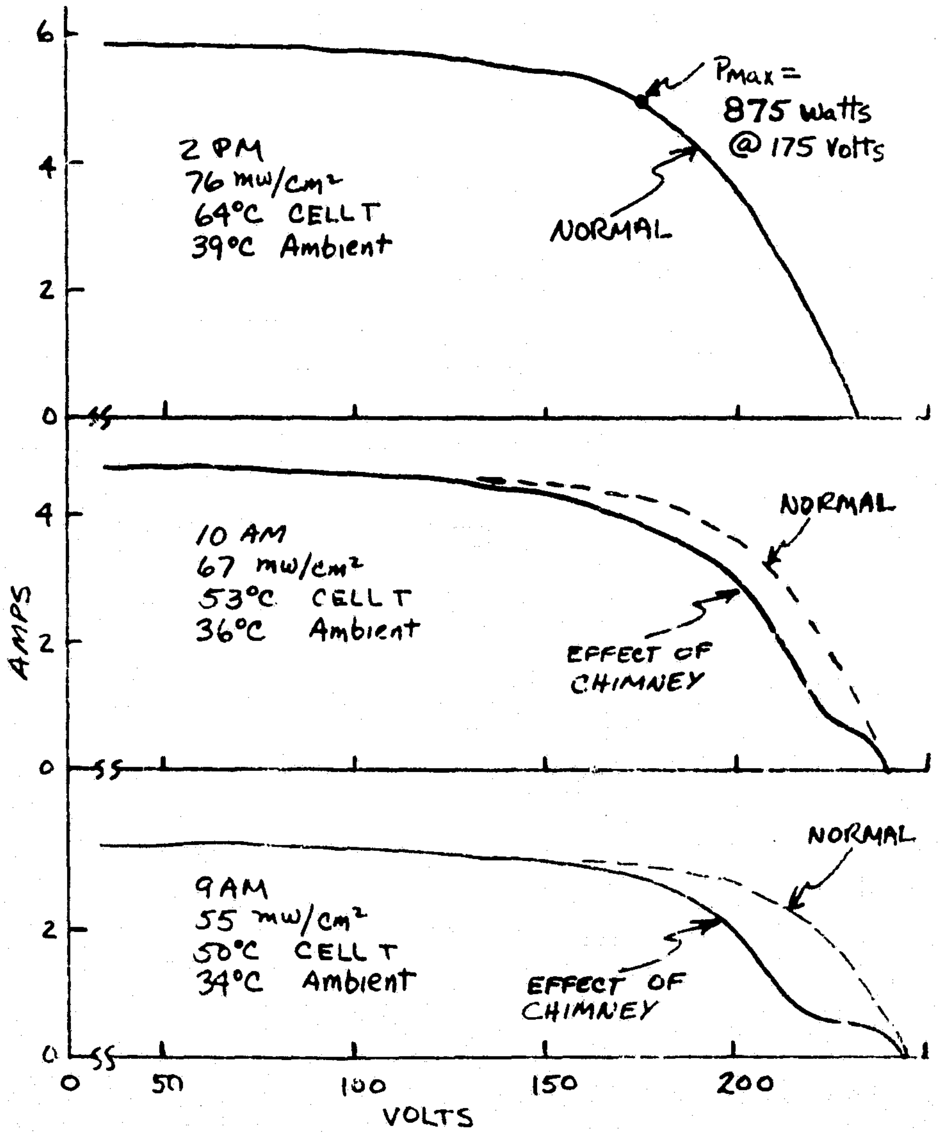
John F. Long House System Characteristics

MODULES	120 E (IV)
NO. OF BRANCH CIRCUITS	5
BRANCH CIRCUIT CONFIGURATION	24 MODULES IN SERIES
DIODES	ONE PER MODULE
MEASURED ARRAY PMAX AT NOCT AND 80 MW/CM^2	4.6 kW

John Long House 7/30/80, 11:30 a.m.



John Long House 7/31/80



PROBLEM-FAILURE ANALYSIS

JET PROPULSION LABORATORY

S. G. Sollock

- Problem/Failure Reporting System Status
- Block II - Laminated Glass Superstrate
- Block III - Glass-Stainless Steel Case
- Block II - 20 Watt Module
- Residential - Batten Seam
- Mt Laguna Field Analysis Results
- Camp Pendleton Marine Base Repeater Arrays

Problem-Failure Report (P-FR) Status

VENDOR	MODULE TYPE	NO. PFR'S	NO. CLOSED	PROBLEM/FAILURE ORIGIN		
				ENVIRONMENTAL TEST	JPL FIELD TEST	APPLICATIONS PROJECTS
V	BLOCK I	21	19	9	7	5
	BLOCK II	101	91	57	3	41
	BLOCK III	35	21	31		4
W	BLOCK I	51	45	27	5	18
	BLOCK II	16	15	15		1
Y	BLOCK I	40	33	21	7	13
	BLOCK II	38	24	7	4	27
	BLOCK III	27	8	13	1	13
	BLOCK IV	6		6		
Z	BLOCK I	75	66	31	21	23
	BLOCK II	53	39	25	4	24
	BLOCK III	39	21	28		11
	BLOCK IV	9		9		
U	BLOCK III	30	19	30		
R	BLOCK III	40	32	29		11
	BLOCK IV	13	10	13		
S	BLOCK IV	4		4		
K	BLOCK IV	2	2	2		
M	BLOCK IV	19		19		
DEVELOPMENT & COMMERCIAL		154	88	153	1	
PRDA		94	86	94		
TOTAL		867	619	623	53	191

Problem-Failure Analysis

- Laminated Glass Superstrate Block II Modules (28 of 720)

Natural Bridges National Monument

Problem: Glass Cover Broken

Cause: Edge Chip/Temperature

Problem-Failure Analysis

- Glass Stainless Steel Case Block III Modules (26 of 2256)

    Natural Bridges National Monument

    Problem: Short to Ground

    (1) Edge Foil to Pan Shorts (8 ea.)

    (2) Terminal to Foil Solder Joints (2 ea.)

    (3) Feed Through Insulator Damage (1 ea.)

    Cause: Workmanship/Handling.

- 20 Watt Block II Modules

    Schehuli Indian Reservation (34 of 192)

    Tangaya South Africa (20 of 100)

    Problem: Open Circuit Intermittant

    - Fractured Interconnects
    - Cracked Cells

    Cause: Workmanship/Design

- Batten Seam Residential Module

    John F. Long Installation, Az. (15 of 120)

    Problem: Cell Heating & Cracking

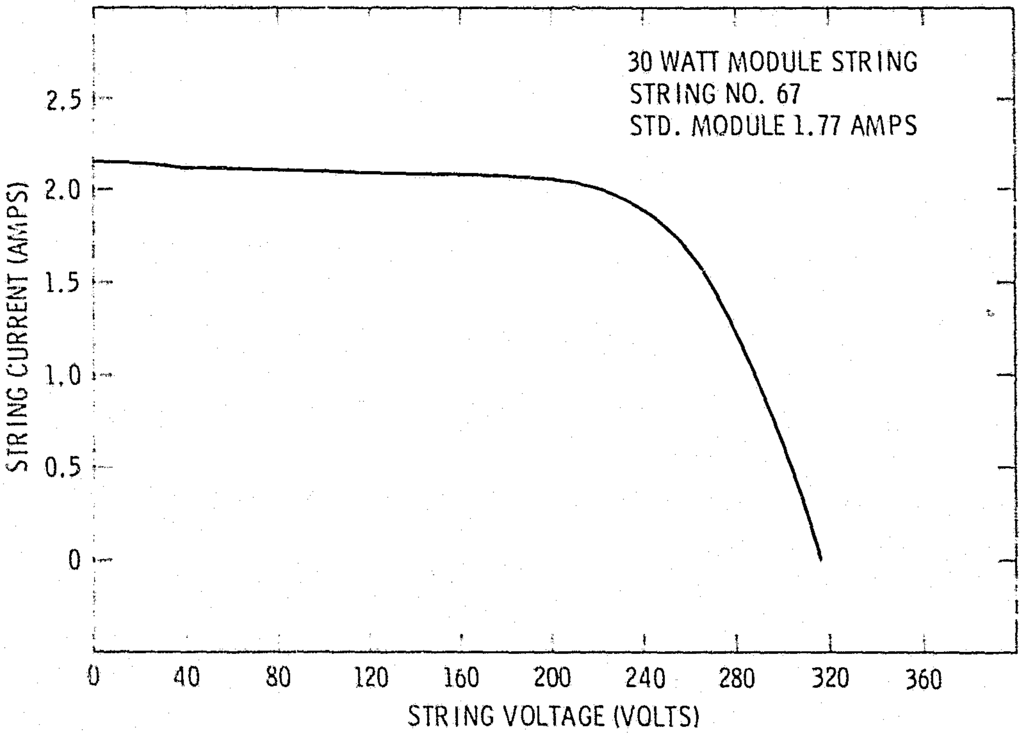
    - Reverse Bias
    - Encapsulant Outgasing

Field Performance Analysis of Mt. Laguna

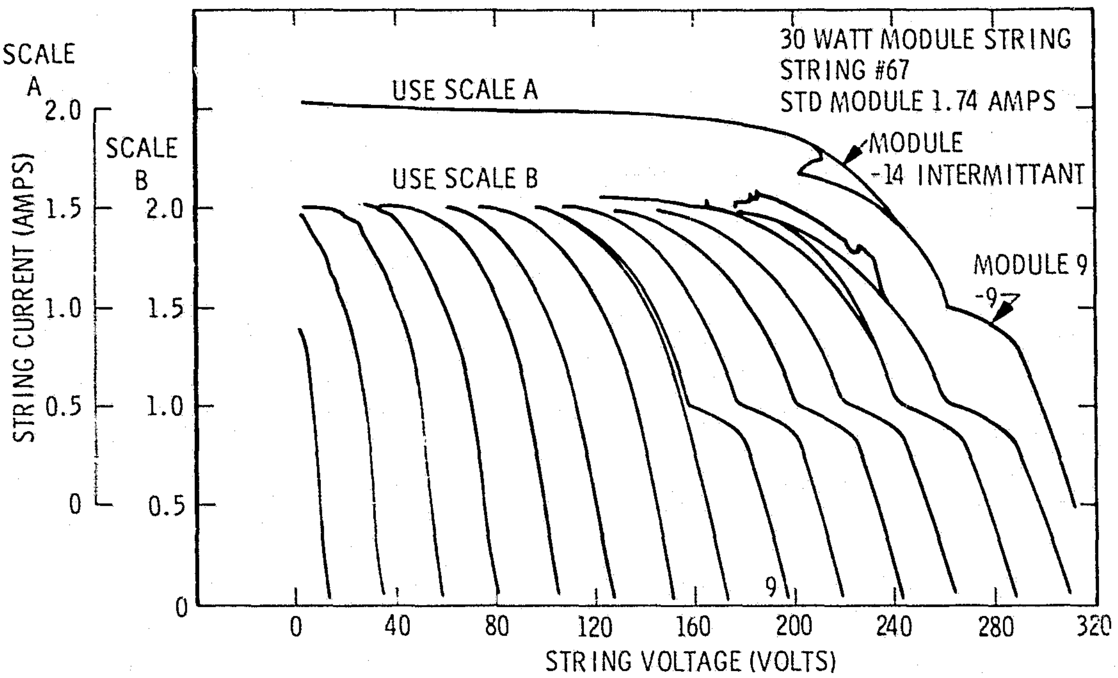
Data Taken of Individual String and Module

- IV Curves
- Module Bypass Test

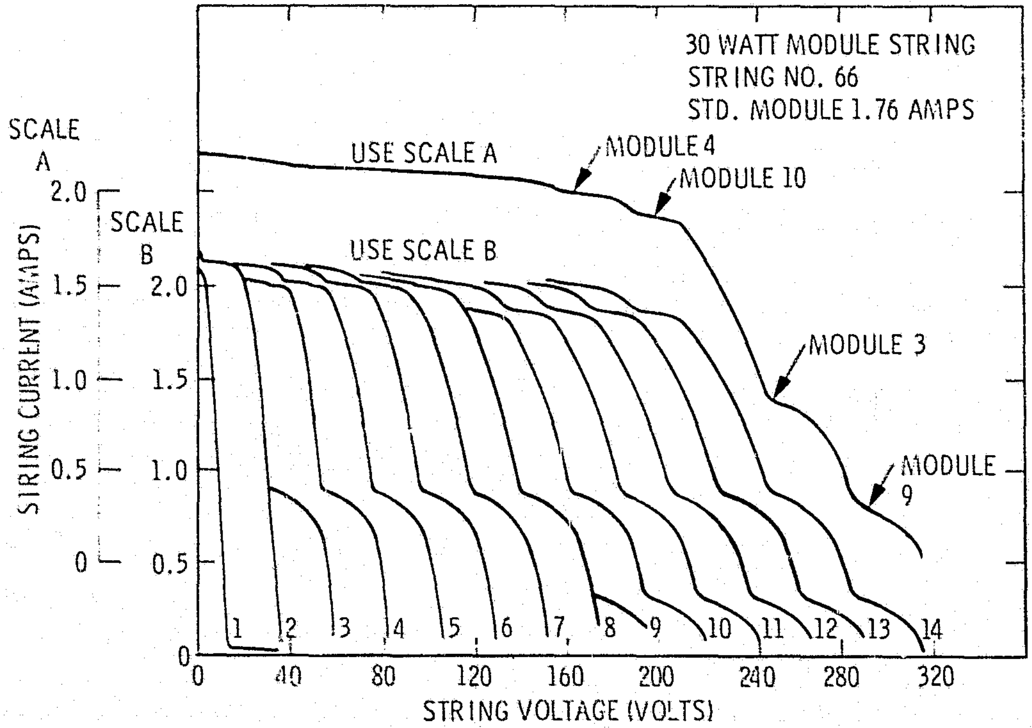
March 1980



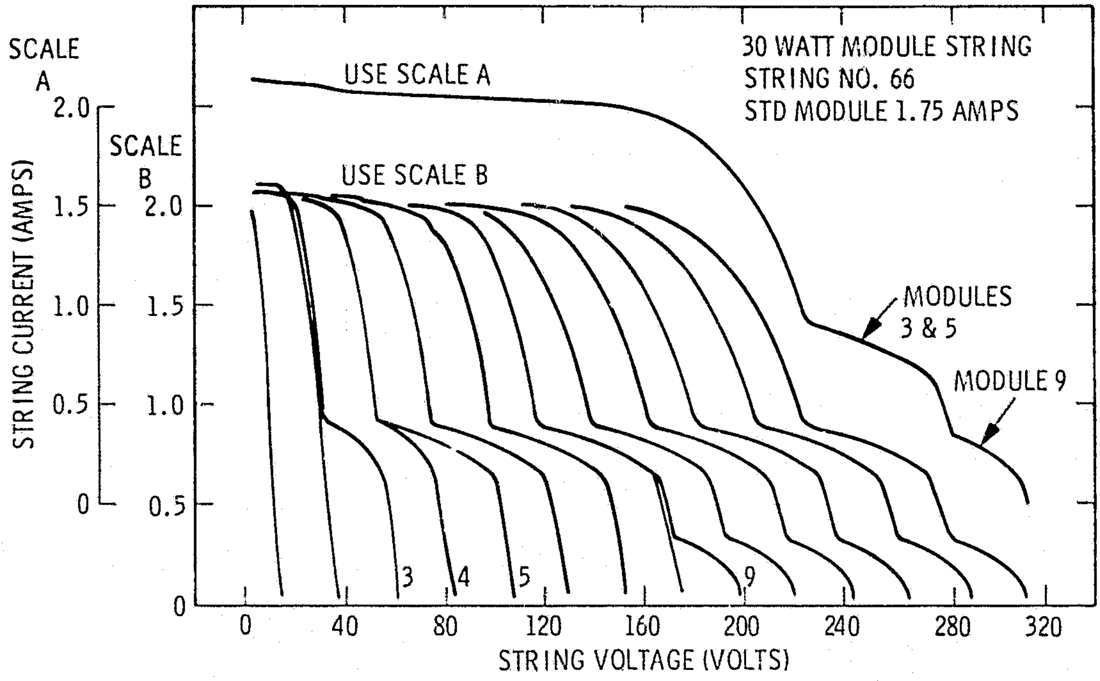
August 1980



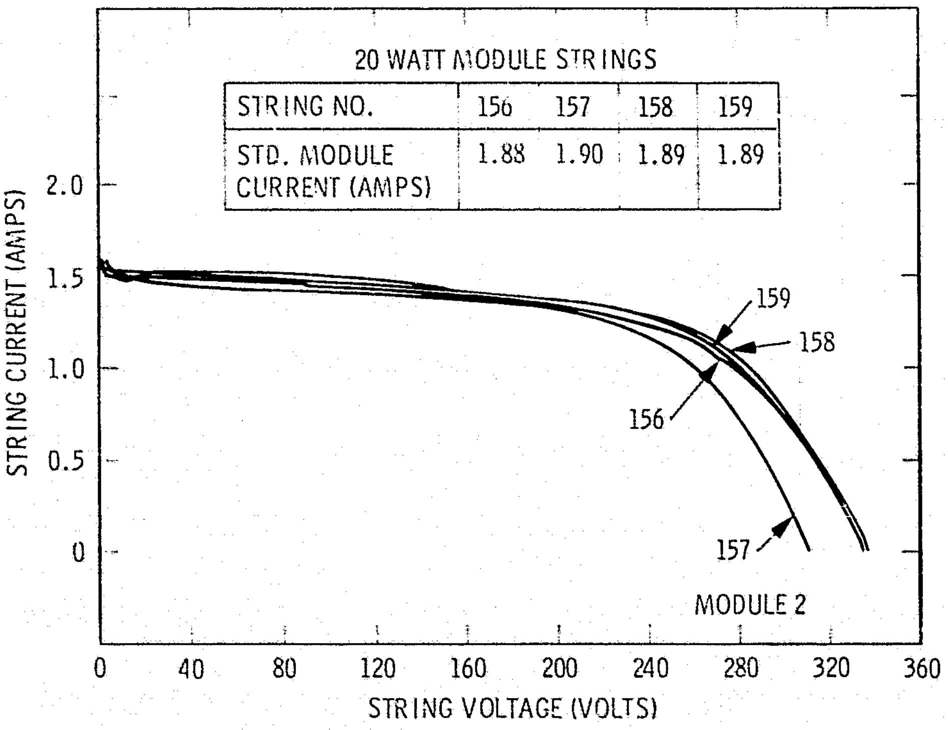
March 1980



August 1980

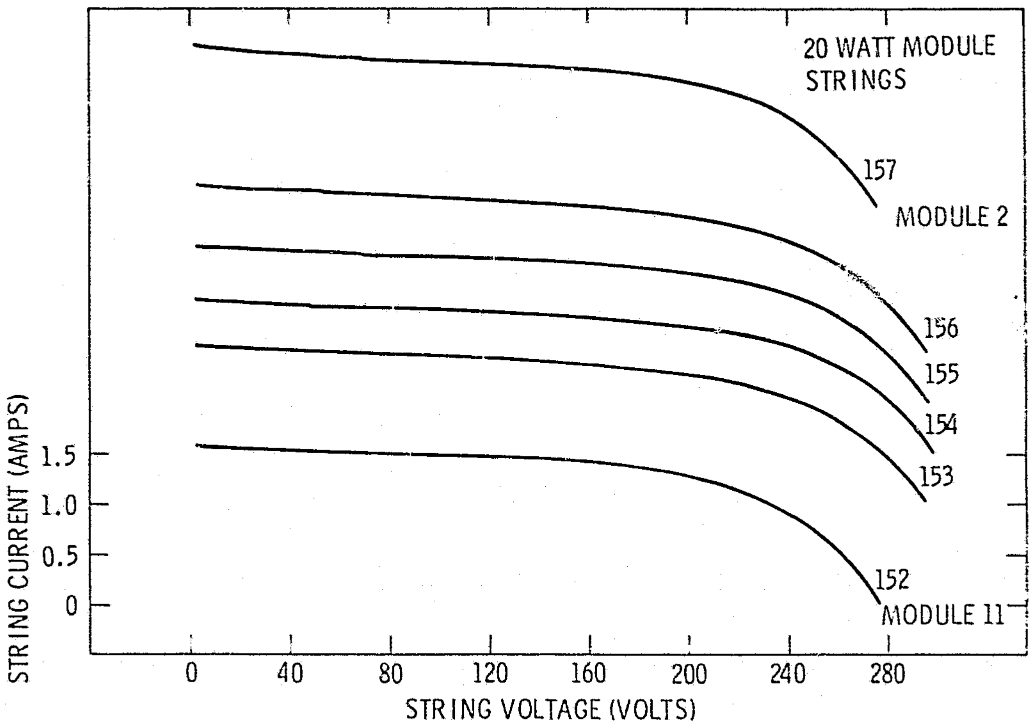


March 1980



STRING NO.	156	157	158	159
STD. MODULE CURRENT (AMPS)	1.88	1.90	1.89	1.89

August 1980

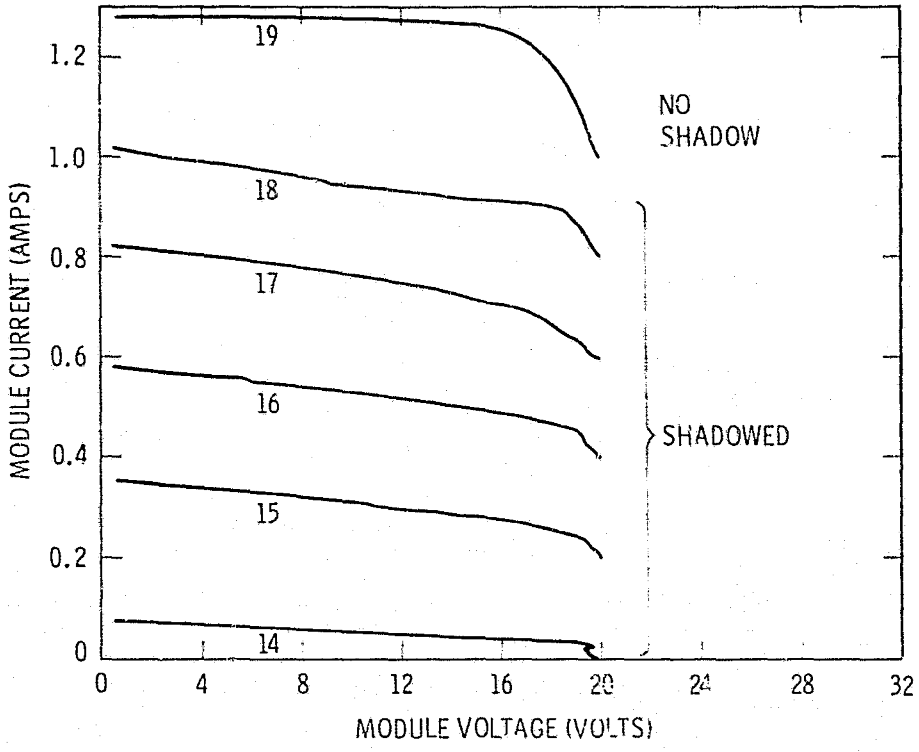

20 WATT MODULE STRINGS
157
MODULE 2
156
155
154
153
152
MODULE 11
STRING CURRENT (AMPS)
1.5
1.0
0.5
0
0
40
80
120
160
200
240
280
STRING VOLTAGE (VOLTS)

Field Performance Analysis of Camp Pendleton Repeater Array

Problem: Array Not Operating at Peak Efficiency

Cause: Fence Shadowing

PMO Repeater



BLOCK IV FINAL DESIGN REVIEW STATUS

JET PROPULSION LABORATORY

Larry Dumas

	ORIGINAL PLAN	ACTUAL, OR CURRENT PLAN
APPLIED SOLAR ENERGY	1/80	8/19/80
ARCO SOLAR	3/80	11/80
GENERAL ELECTRIC	2/80	3/31/80
MOTOROLA	2/80	8/25/80
PHOTOWATT	12/79	10/80
SOLAR POWER	2/80	9/80
SOLAREX	1/80	9/80
SPIRE	1/80	8/21/80

Summary Observations

- BLOCK IV SCHEDULE SLIPS & ENVIRONMENTAL TEST RESULTS SUGGEST DIFFICULTIES IN ASSIMILATING TECHNOLOGY DEVELOPMENT AND INDUSTRY GROWTH
- FIELD RESULTS INDICATE THAT TYPICAL BLOCK I-III MODULE DESIGNS DO NOT MEET PROJECT 1986 RELIABILITY/DURABILITY GOALS
- ANALYSIS OF LABORATORY AND FIELD RESULTS SHOWS THAT PROBLEMS ENCOUNTERED TO DATE ARE ALL CORRECTABLE OR CONTROLLABLE BY KNOWN TECHNIQUES. MOST HAVE ALREADY BEEN CORRECTED
- COMPLETE METHODOLOGIES FOR PREDICTING AND CERTIFYING MODULE RELIABILITY AND LIFETIME ARE NOT IN HAND
- FIELD TESTS ARE AN ESSENTIAL FINAL ELEMENT IN THE DEVELOPMENTAL PROCESS

C-5

ENGINEERING AREA STATUS

(SEPTEMBER 1980)

JET PROPULSION LABORATORY

R.G. Ross, Jr.

RECENTLY COMPLETED ACTIVITIES

- REQUIREMENTS DEVELOPMENT
  - RESIDENTIAL O&M COST STUDY (BURT-HILL)
- ARRAY SUBSYSTEM DEVELOPMENT
  - CIRCUIT DESIGN GUIDELINES (WORKSHOP)
- ARRAY COMPONENT ENGINEERING
  - CURVED GLASS MODULE REPORT } (BECHTEL)
  - ELECTRICAL INSULATION REPORT } (BECHTEL)
  - ELECTRICAL TERMINATION REPORT (MOTOROLA)
- ARRAY STANDARDS
  - INTERIM PERFORMANCE CRITERIA INPUT
  - ARRAY REFERENCE CONDITION STUDY

ONGOING ACTIVITIES

- REQUIREMENT DEVELOPMENT STUDIES
  - SAFETY DESIGN REQUIREMENTS (UL)
  - PRODUCT LIABILITY REQ (CARNEGIE-MELLON)
  - COMMERCIAL BUILDING CODES (BURT-HILL)
  - WIND LOADING (BOEING/CSU)
- ARRAY SUBSYSTEM DEVELOPMENT
  - LARGE GROUND MOUNTED ARRAYS (JPL)
  - INTEGRATED RESIDENTIAL ARRAYS (GE AND AIA)
- COMPONENT ENGINEERING/RELIABILITY STUDIES
  - OVERALL RELIABILITY ANALYSIS (JPL/IITRI)
  - ELECTRICAL INSULATION (JPL)
  - GLASS BREAKAGE (JPL)
  - INTERCONNECT FATIGUE (JPL)
  - HOT-SPOT ENDURANCE (JPL)

ONGOING ACTIVITIES (CON'T)

- COMPONENT ENGINEERING/RELIABILITY STUDIES (CON'T)
    - CELL RELIABILITY TESTING (CLEMSON)
    - CELL FRACTURE MECHANICS (JPL)
    - ACCELERATED SUNLIGHT TESTING (DSET)
    - LONG-TERM HUMIDITY TESTING (WYLE)
    - CORROSION ENDURANCE (WYLE)
    - SOILING (JPL)
- STANDARDS ACTIVITIES
    - ARRAY TASK GROUP MANAGEMENT (FOR SERI)
    - PV-T PERFORMANCE TEST DEVELOPMENT (JPL)
    - CONCENTRATOR PERFORMANCE TEST DEVEL (ASU)

ARRAY STRUCTURE COST REDUCTION STUDY

JET PROPULSION LABORATORY

Abe Wilson

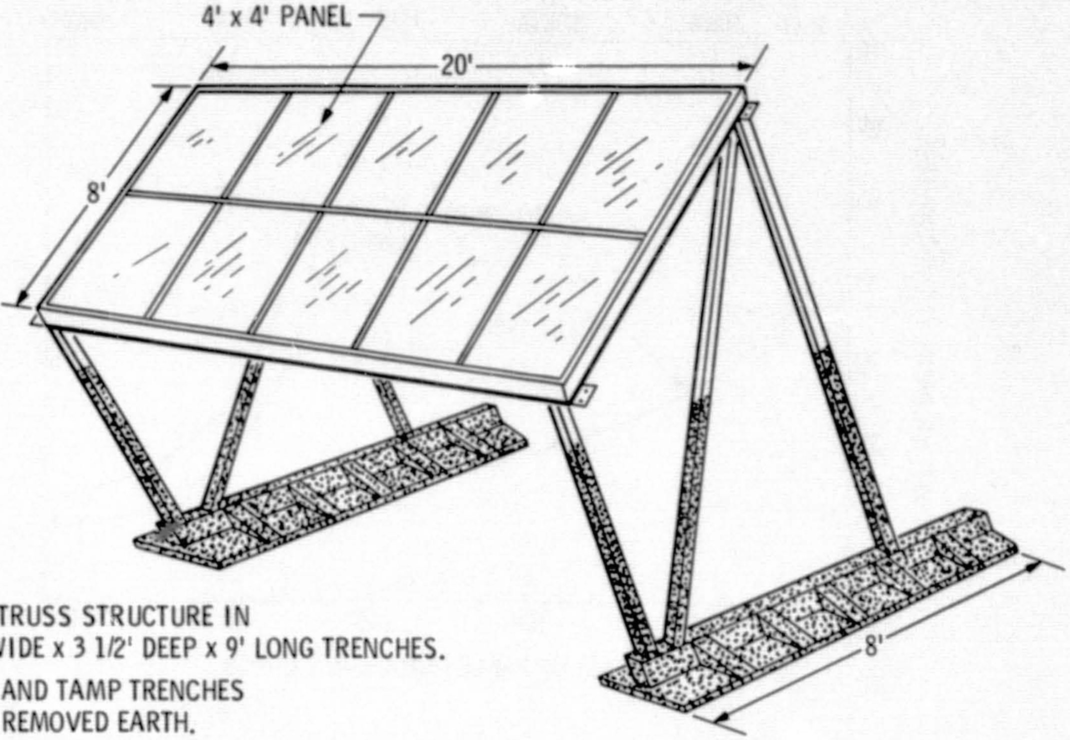
Objective

- IDENTIFY MEANS FOR REDUCING THE COST OF FLAT PLATE ARRAY STRUCTURES FOR LARGE INDUSTRIAL/CENTRAL STATION ARRAYS
    - PANEL FRAME
    - ARRAY STRUCTURE
    - ARRAY FOUNDATION
    - ASSEMBLY OF MODULES, FRAMES AND STRUCTURES
- DEVELOP DATA ON SIMILAR ARRAYS APPLICABLE TO CURRENT ILC ARRAY DESIGNS (1 KW TO 1 MW)

Approach

- REVIEW PERFORMANCE AND COST OF PANEL FRAME DEMONSTRATED AT APRIL 1980 PIM
- MODIFY DESIGN TO IMPROVE PERFORMANCE AND/OR REDUCE OVERALL COST
- FABRICATE PANEL FRAME PER MODIFIED DESIGN AND PROOF TEST
- REVIEW PERFORMANCE AND COST OF FOUNDATION AND SUPPORT STRUCTURE DEMONSTRATED AT APRIL 1980 PIM
- MODIFY DESIGN TO IMPROVE PERFORMANCE AND/OR REDUCE OVERALL COST
- FABRICATE AND TEST MODIFIED FOUNDATION AND SUPPORT STRUCTURE
- INVESTIGATE PROBLEMS OF ASSEMBLING MODULES ON PANEL FRAME
    - GASKETS
    - ASSEMBLY LABOR
    - SHIPMENT COSTS
    - INSTALLATION LABOR

Low-Cost Array Structure Displayed at 16th PIM
(Demonstrating Framed & Unframed Module Mounting)

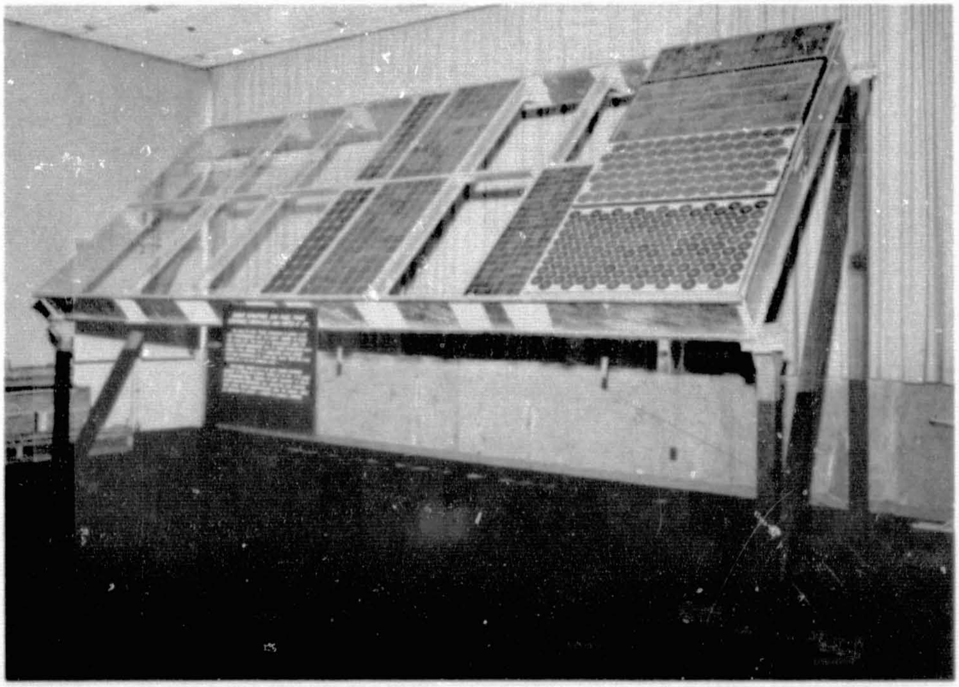


NOTE:

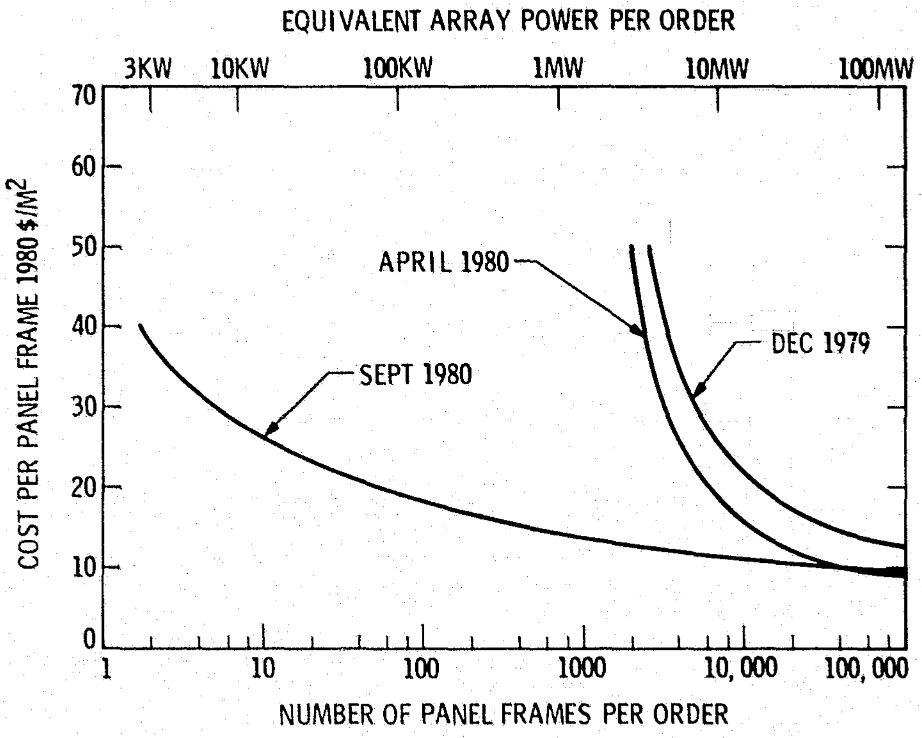
PLACE TRUSS STRUCTURE IN 1 1/2' WIDE x 3 1/2' DEEP x 9' LONG TRENCHES.

REFILL AND TAMP TRENCHES USING REMOVED EARTH.

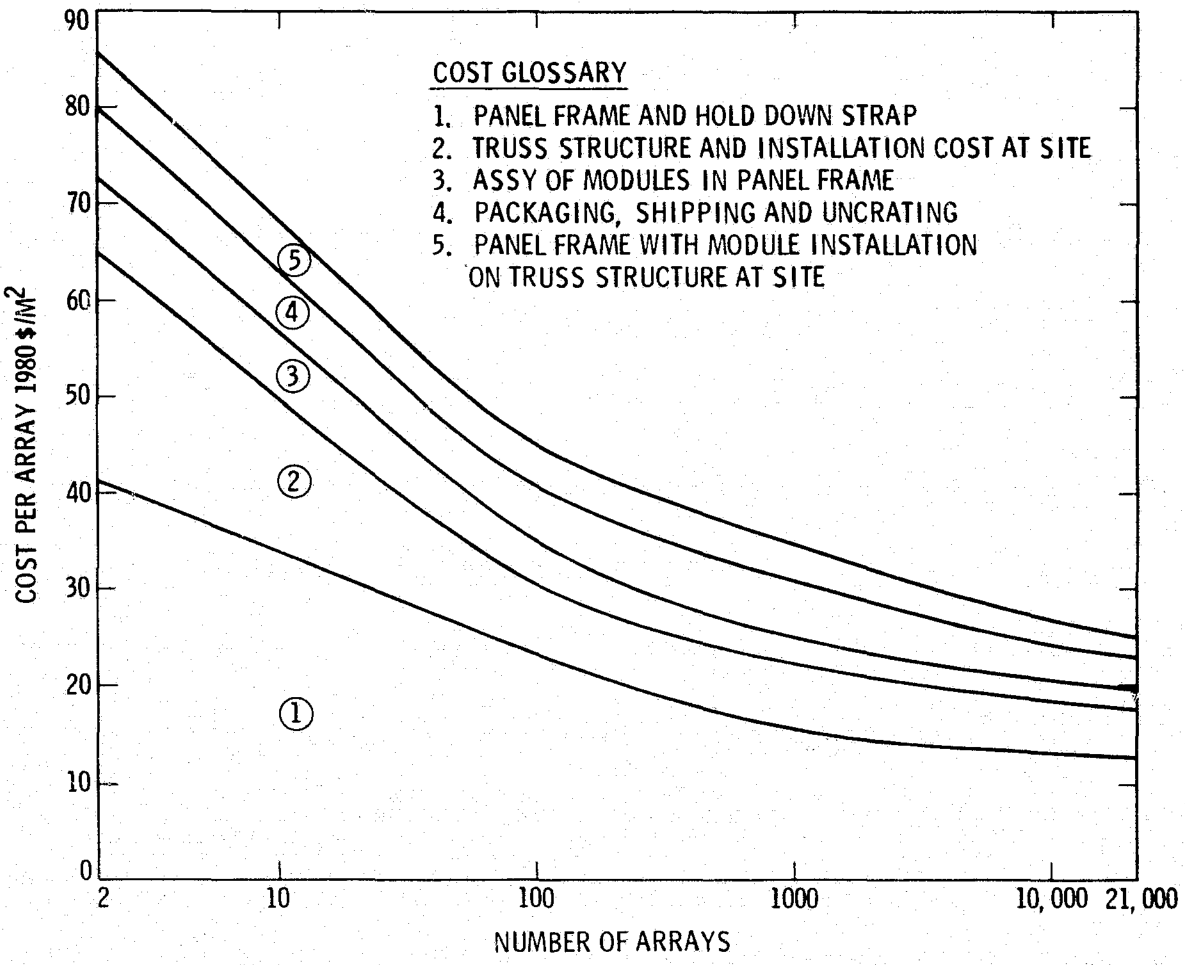
SHADED PORTION OF STRUCTURE IS BELOW GROUND LEVEL.



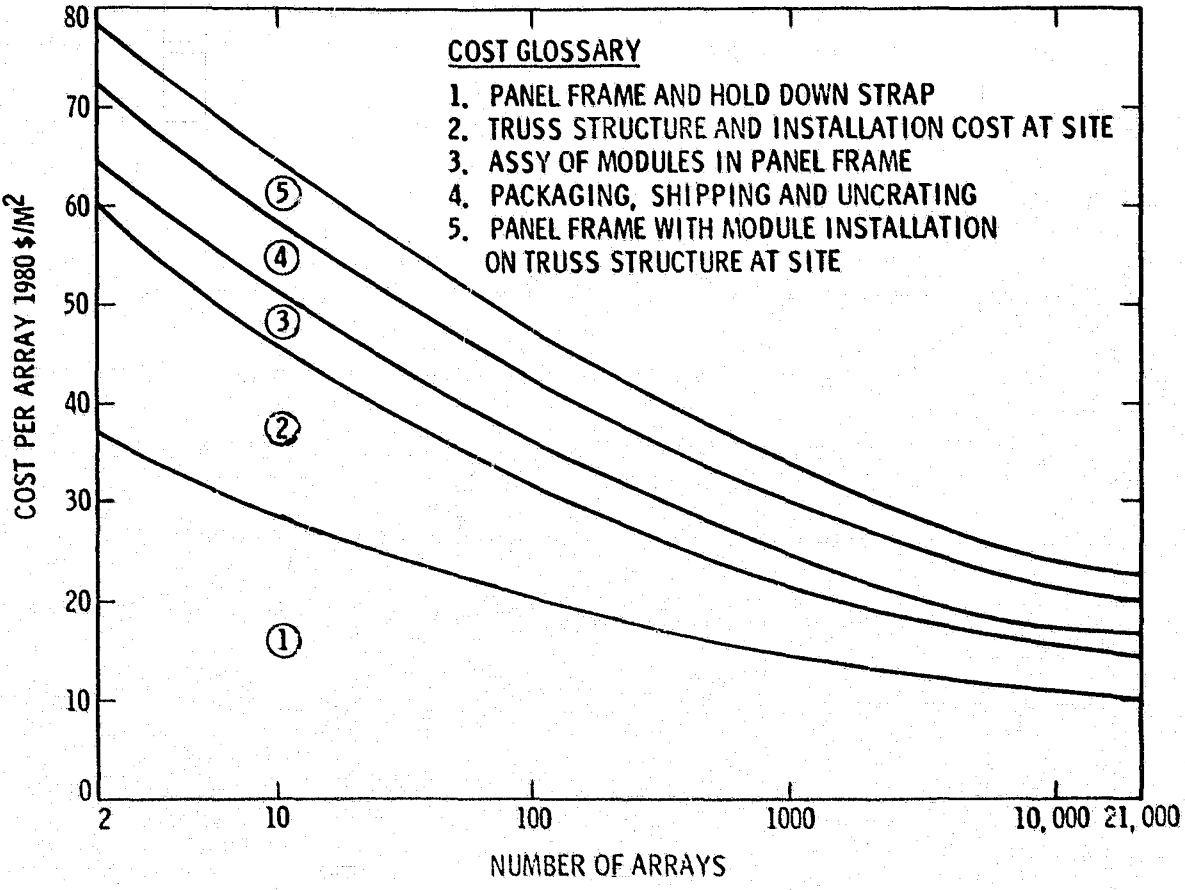
Panel Frame Cost/Quantity Sensitivity



Based on Twenty 2 x 4-ft Modules per Frame



Based on Ten 4 x 4-ft Modules per Frame



Preliminary Study Results (1980 $/m^2)

DATE OF ESTIMATE	(1) BARE PANEL FRAME	(2) ARRAY AND STRUCTURE FOUNDATION	(3) CONNECTORS MODULE ASSEMBLY SHIPPING AND FIELD INSTALLATION	(4) TOTAL (1) + (2) + (3)
*AUGUST 1978	$18.90	$40.32	$9.52	$68.74
*NOVEMBER 1979	$13.45	$7.56	$9.52	$30.53
*APRIL 1980	$9.80	$8.90	$9.52	$28.22
**SEPTEMBER 1980	$10.77	$5.50	$7.63	$23.90

* BASED ON 50,000 FRAMES

** BASED ON 20,000 FRAMES

Future Work

- ARRAY STRUCTURE
  - SIMPLIFY SECTION TO REDUCE WELDING
  - VERIFY NEED FOR CROSS BRACES
- ARRAY FOUNDATION
  - EFFECT ON PERFORMANCE OF SOIL TYPE
- INTERFACE WITH MODULE SUPPLIER
  - ASSEMBLY OF MODULES ON PANEL FRAME
  - CRATING AND SHIPPING OF THESE ASSEMBLIES

WIND LOADS ON FLAT-PLATE PV ARRAY FIELDS

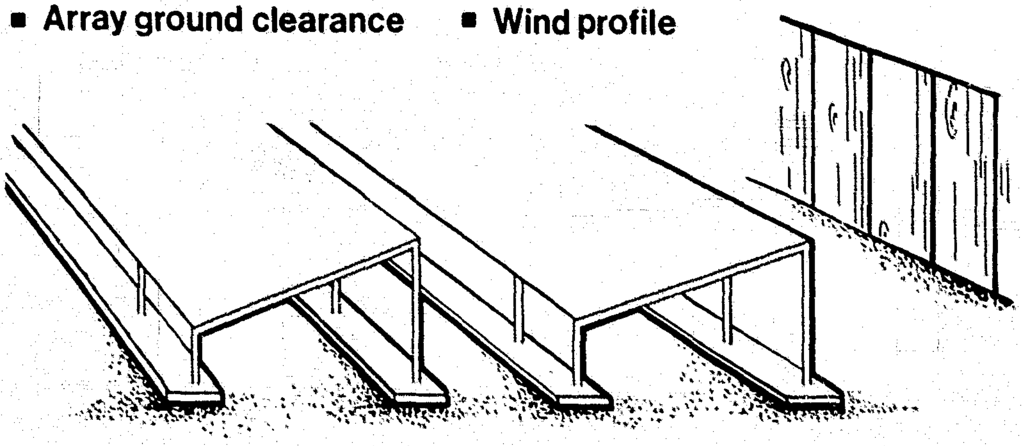
BOEING ENGINEERING & CONSTRUCTION

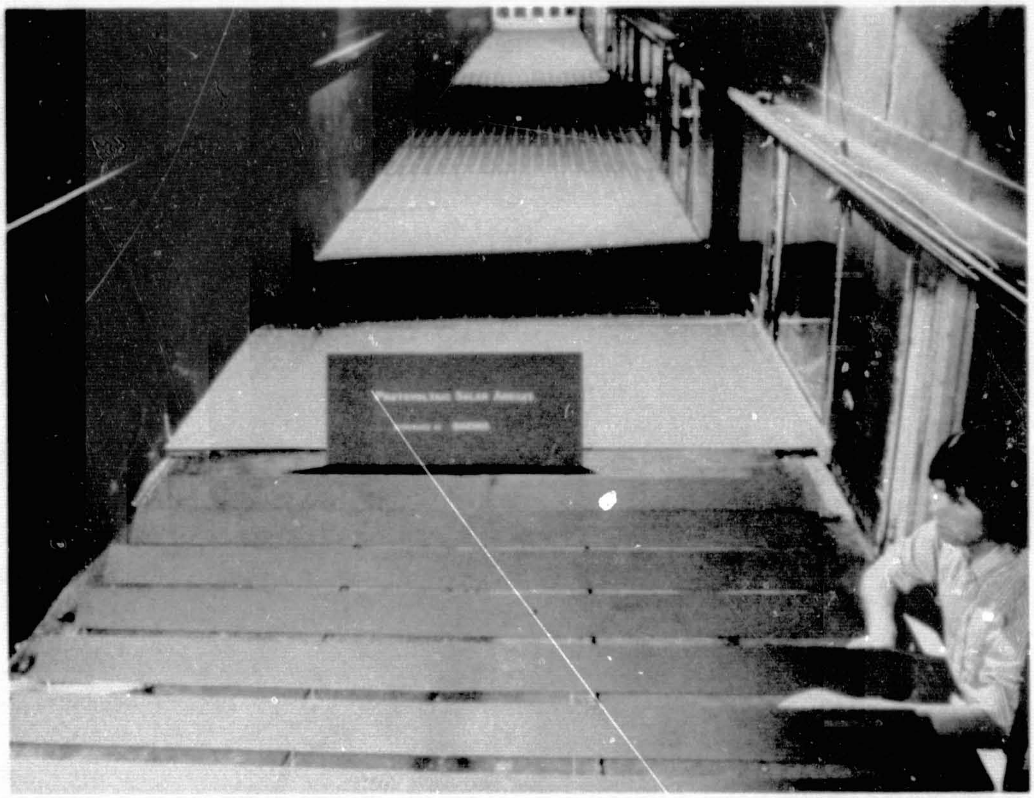
Objective:
- Develop more refined estimates of wind loading on flat-plate photovoltaic modules and array support structures and develop design guidelines

Approach:
- Theoretical [Phase II-Report No. DOE/JPL954833-79/2]
  - Literature search
  - Separated flow analysis
- Experimental [Wind Tunnel Test - Phase III]
  - Colorado State University environment tunnel
  - 1/24 scale model

Parameter Variation

- Tilt angle
- Array spacing
- Array ground clearance
- Fence-array spacing
- Fence height
- Wind profile

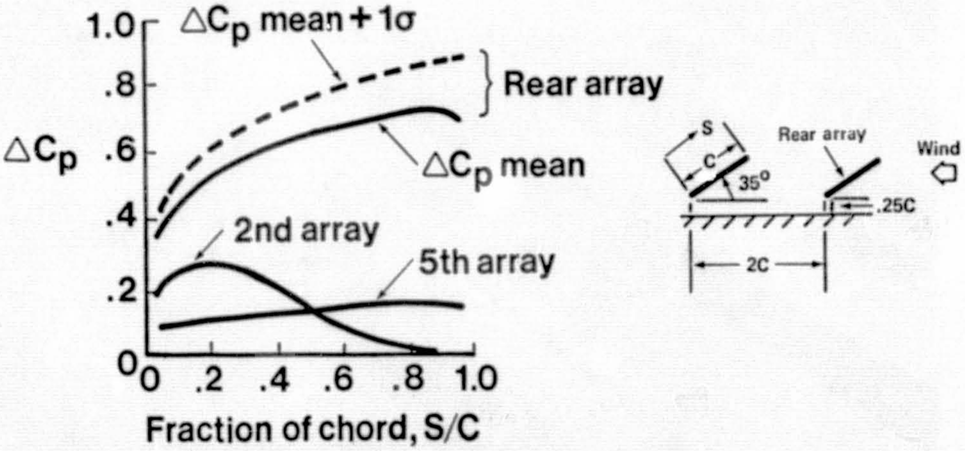


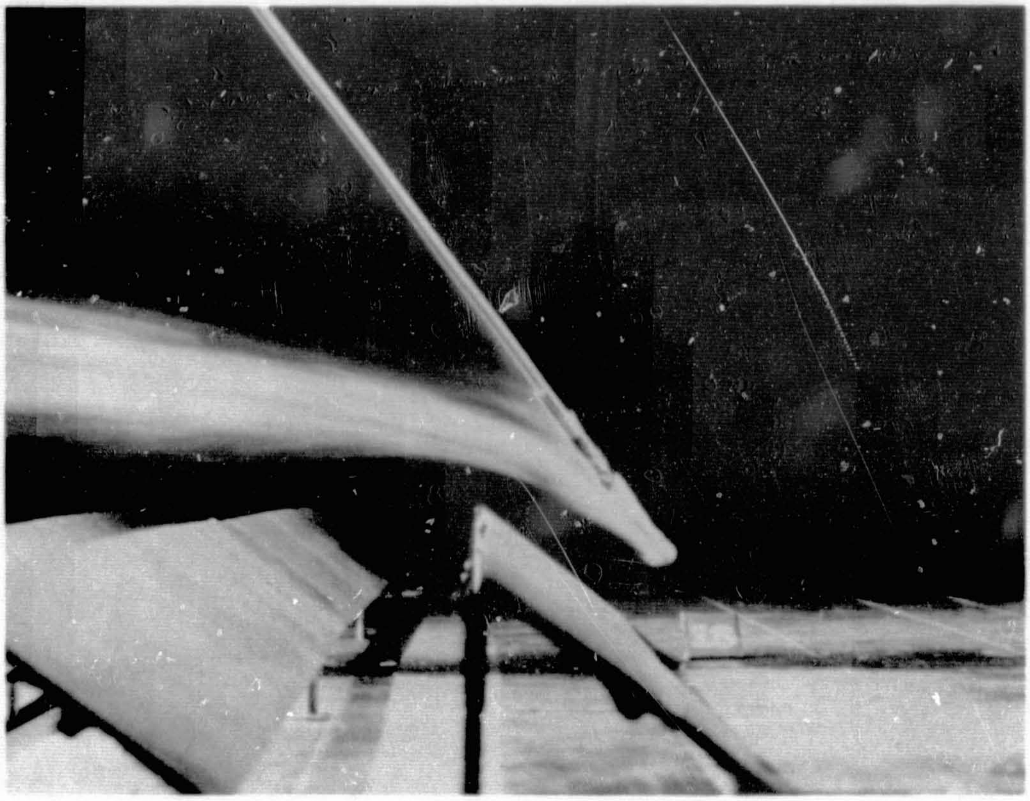


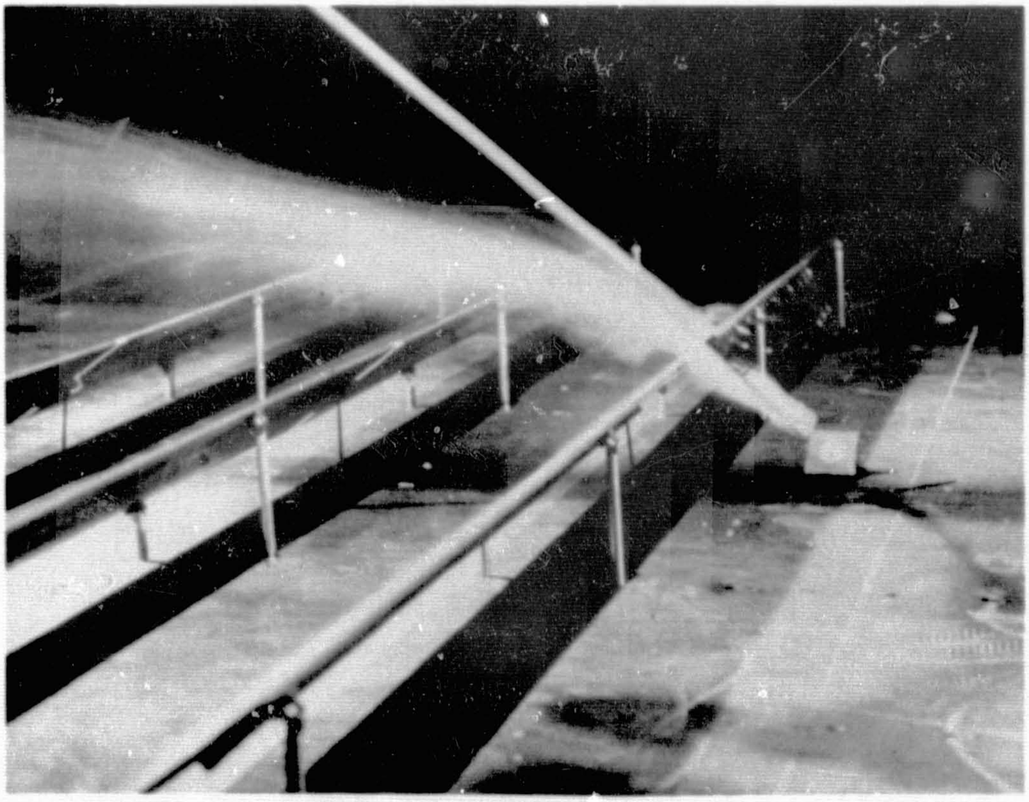
Typical Wind-Tunnel Test Results

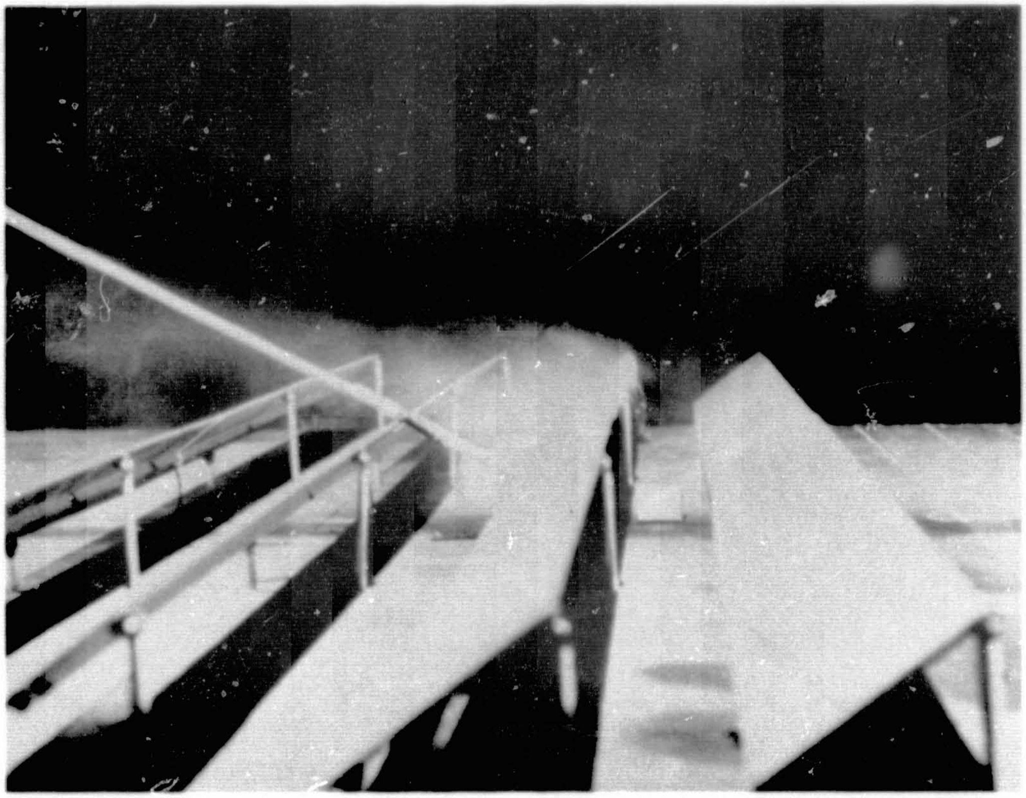
Without a Fence

- 1/7 power law wind velocity profile
- Wind from rear

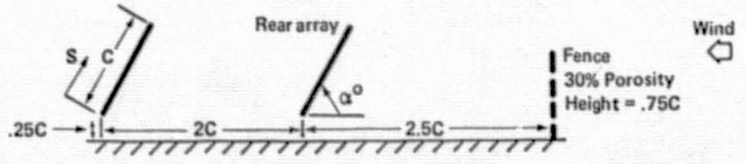




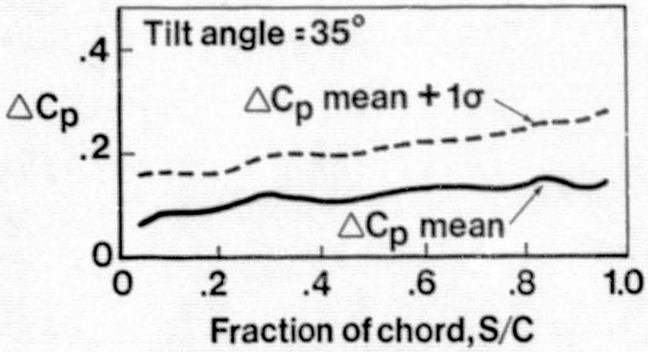


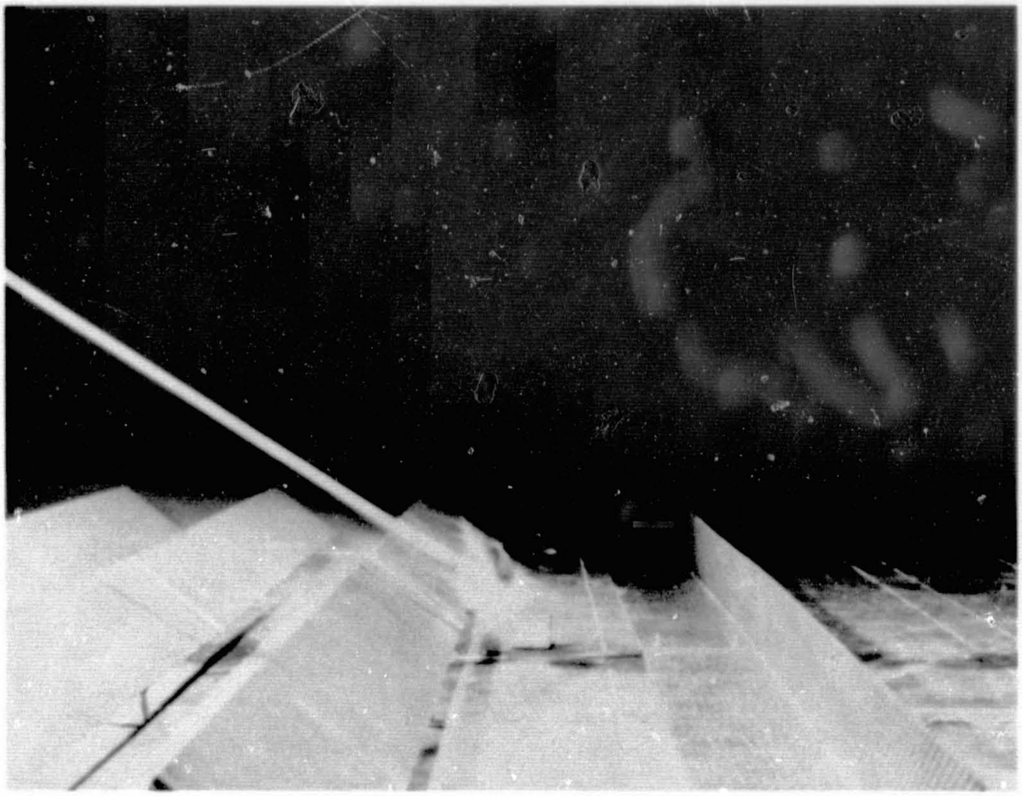


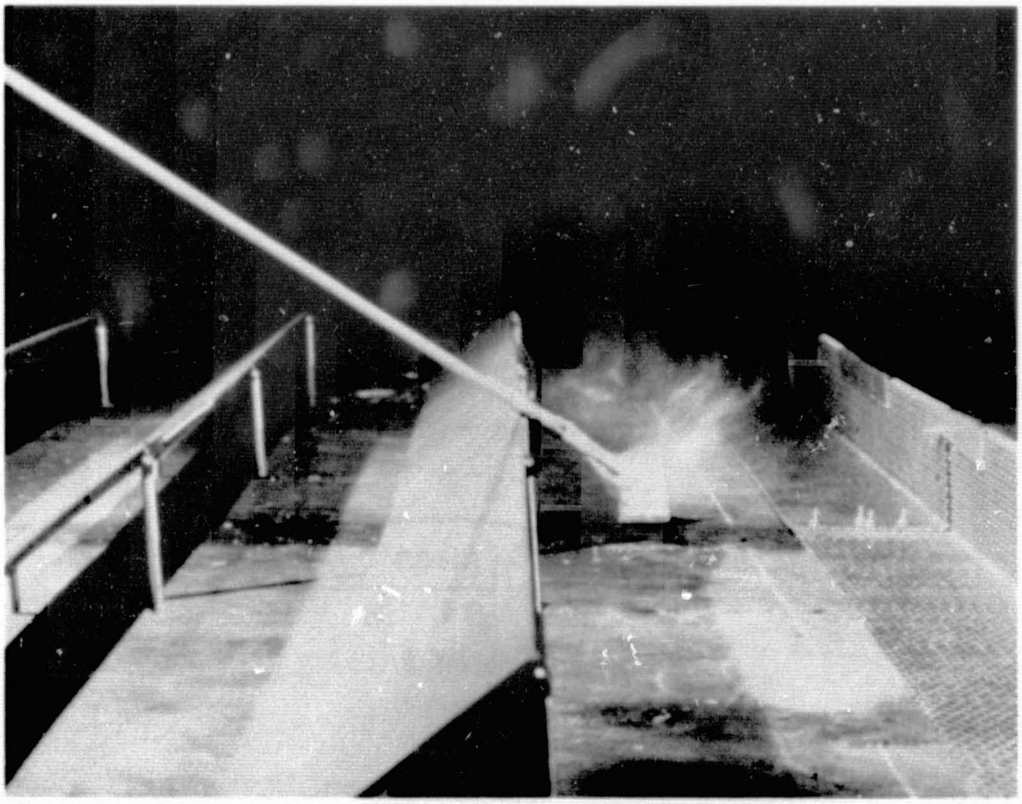
With a Fence



Rear array



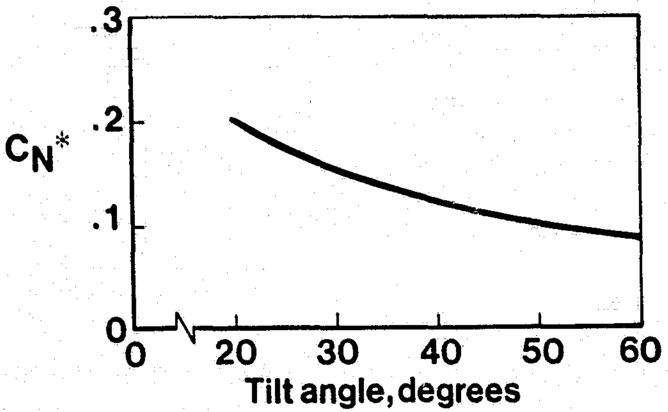




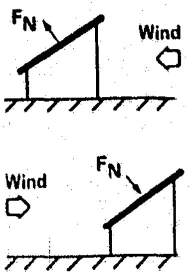
Design Guidelines

Normal Force Coefficient

- **Interior arrays**
- **Arrays behind a protective wind barrier**
- **Steady state wind**



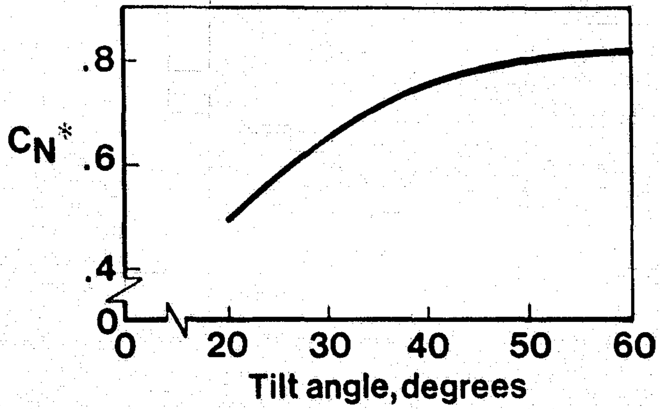
* C_N based on wind reference velocity at 10 meters



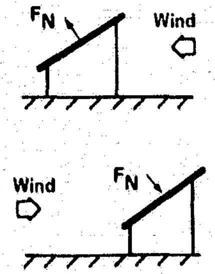
(Not valid within two slant heights from side edge)

- **Boundary arrays without a protective wind barrier**

- **Steady state wind**



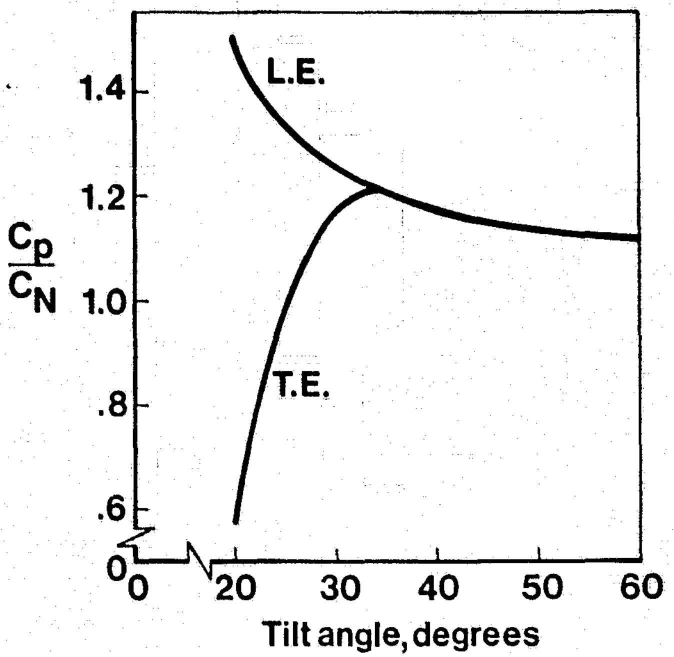
* C_N based on wind reference velocity at 10 meters

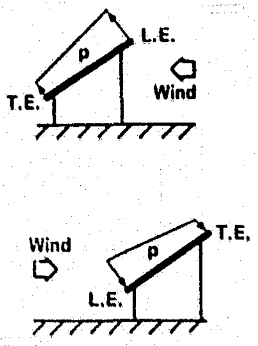


(Not valid within two slant heights from side edge)

Normalized Pressure Coefficients

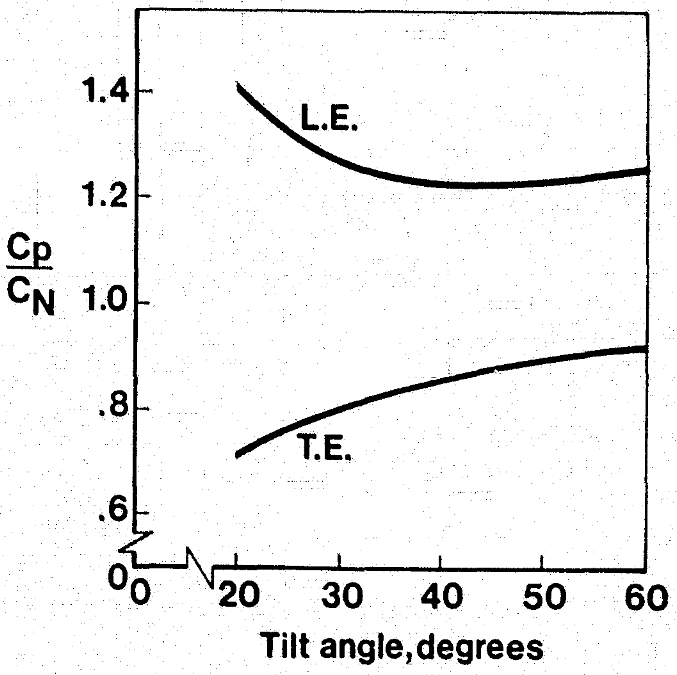
- **Interior arrays**
- **Arrays behind a protective wind barrier**
- **Steady state wind**

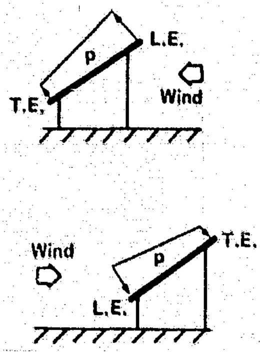




(Not valid within two slant heights from side edge)

- **Boundary arrays without a protective wind barrier**
- **Steady state wind**





(Not valid within two slant heights from side edge)

Remaining Work

- Complete wind tunnel test
- Develop design guidelines for array side edges
- Complete documentation for steady state wind loads
- Evaluate effects of turbulence and array dynamics on design guidelines

PHOTOVOLTAIC/THERMAL MODULE DEVELOPMENT AT JPL

JET PROPULSION LABORATORY
S. Gasner and A. Wen

- DEVELOPMENT OF DESIGN REQUIREMENTS AND GENERATION OF OPTIMUM PV/T MODULE DESIGNS
- DEVELOPMENT OF PERFORMANCE TEST METHODS FOR PV/T MODULES IN SUPPORT OF SERI'S STANDARDS & TEST METHOD PROJECT

Performance Test Method Development

- COMMITTEE OF INDUSTRY, UNIVERSITIES, AND GOVERNMENT LABS FORMED TO DEVELOP TEST METHODS AND STANDARDS FOR FLAT PLATE AND CONCENTRATOR PV/T SYSTEMS

- CANDIDATE PERFORMANCE TEST METHODS IDENTIFIED
  - ELECTRICAL PERFORMANCE
    - FLAT PLATE (JPL)
    - CONCENTRATOR (E-SYSTEMS/ASU)
  - THERMAL PERFORMANCE
    - MODIFIED ASHRAE TEST

- TEST METHOD PROOF-OF-CONCEPT EXPERIMENTS IN PROGRESS
  - E-SYSTEMS
  - JPL
  - MIT/LL
  - SANDIA

PV/T Module Testing

- FLAT PLATE
  - I-V PERFORMANCE vs (S, T_{cell})
  - T_{cell} vs $(S, T_{air}, T_{in},$ WIND$)$
  - THERMAL - ASHRAE TEST

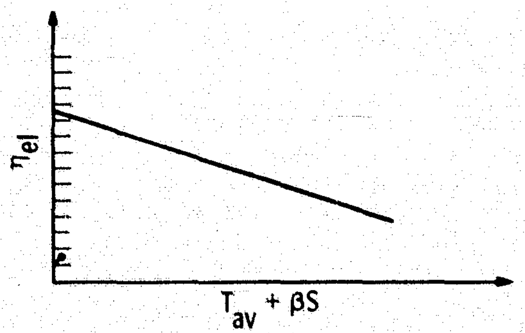
- CONCENTRATOR
  - I-V PERFORMANCE vs $(S, T_{air}, T_{in}, \Delta T)$
  - THERMAL - ASHRAE TEST

Electrical Performance Test For Actively Cooled Concentrators

- COLLECT THE FOLLOWING DATA:
  - INLET FLUID TEMPERATURE (T_i)
  - TEMPERATURE INCREASE ACCROSS THE COLLECTOR (ΔT)
  - IRRADIANCE (S)
  - MAX POWER
- CONSTRUCT PLOT OF

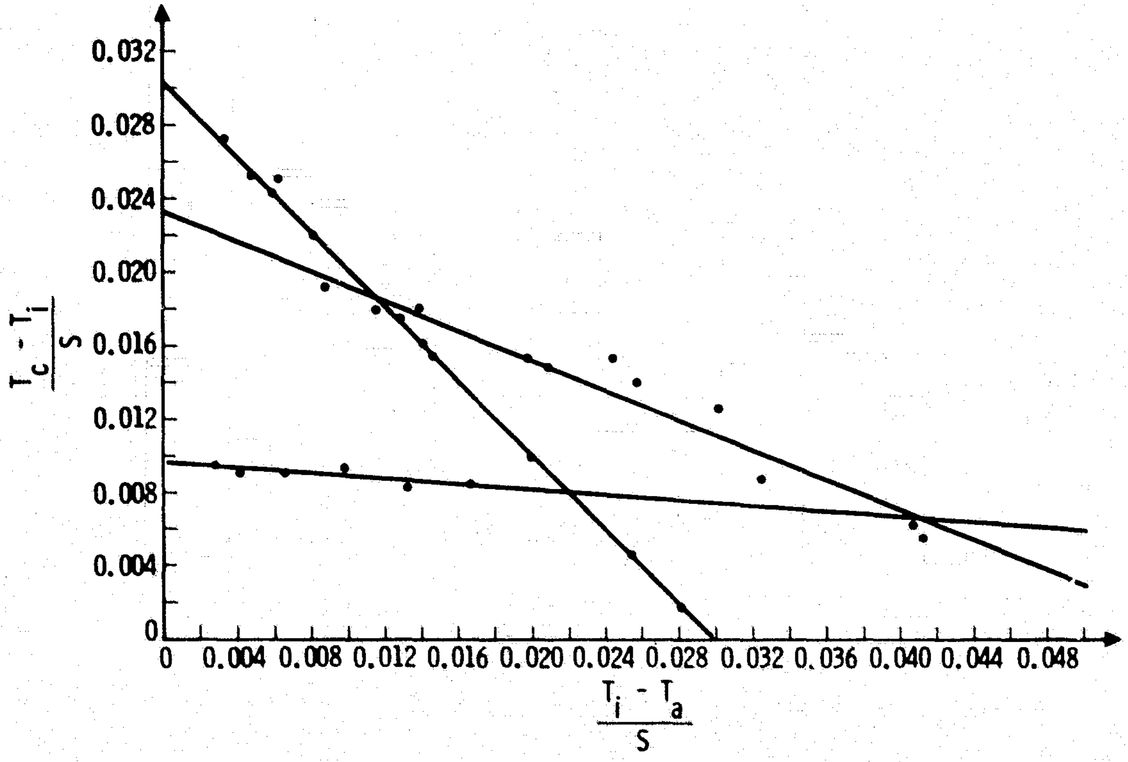
  η_{el} vs $T_{average} + \beta S$

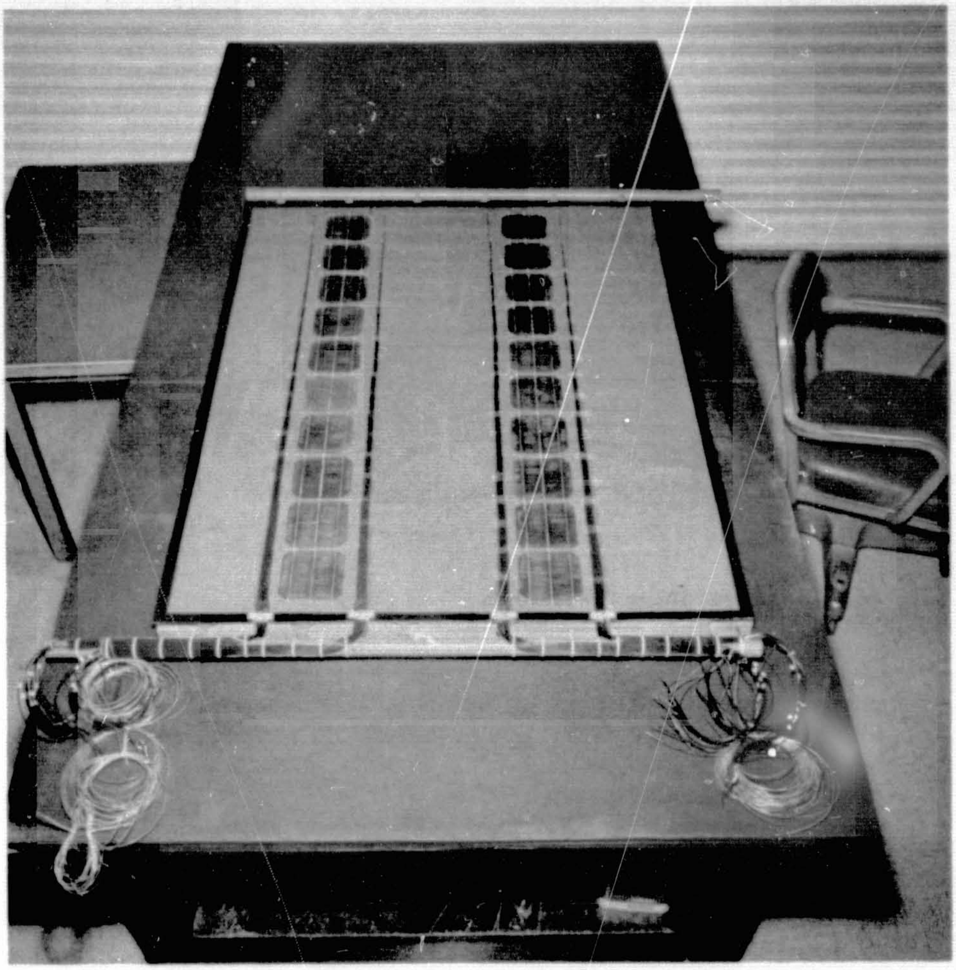
- INTERPOLATED LINE DEFINES η_{el} AS A FUNCTION OF T_{av}, S
- (HAS DRAWBACK OF NOT TAKING AMBIENT TEMPERATURE INTO ACCOUNT)

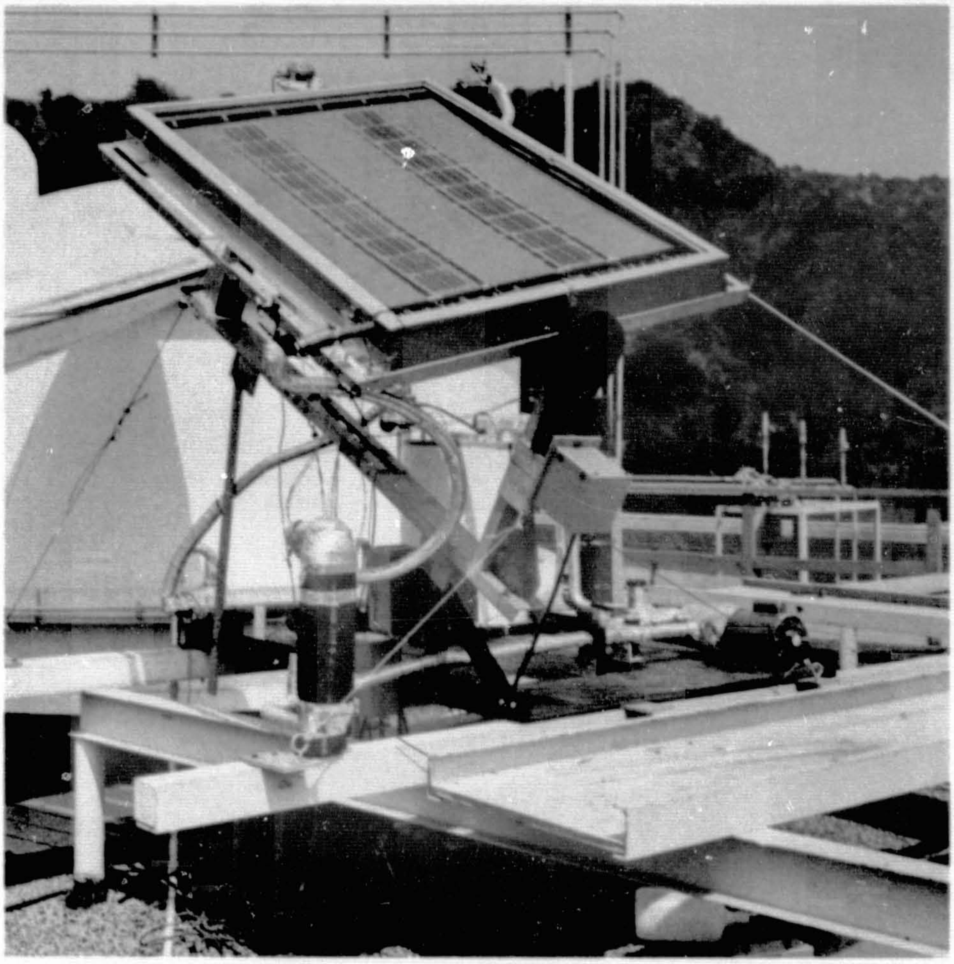


Cell Temperature Test Results

(Three Prototype Collectors)

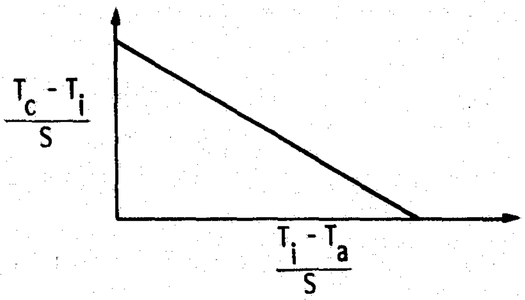






Flat-Plate PV/T Cell Temperature Test

- COLLECT THE FOLLOWING DATA
  - INLET FLUID TEMPERATURE (T_i)
  - CELL TEMPERATURE (T_c)
  - AMBIENT AIR TEMPERATURE (T_a)
  - IRRADIANCE (S)
- CONSTRUCT PLOT:



- INTERPOLATED LINE DEFINES T_c AS A FUNCTION OF T_i, T_a, S

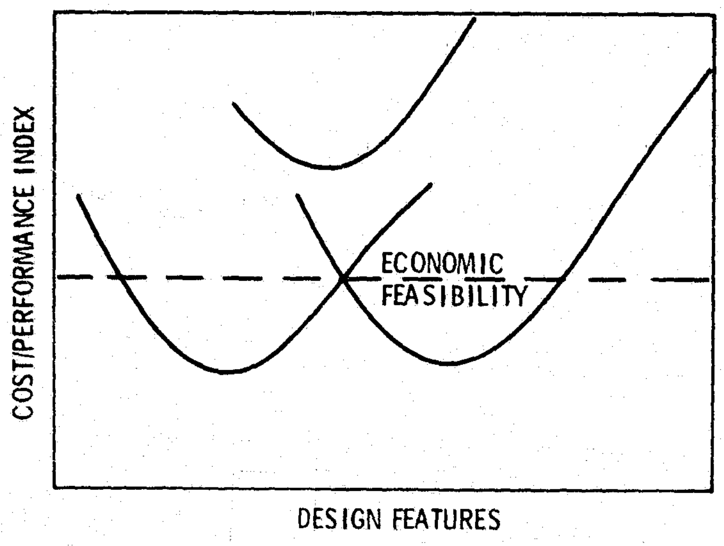
PV/T MODULE DESIGN REQUIREMENTS

Objectives

- DETERMINE "OPTIMAL" DESIGN FEATURES FROM COST/PERFORMANCE SENSITIVITY STUDIES

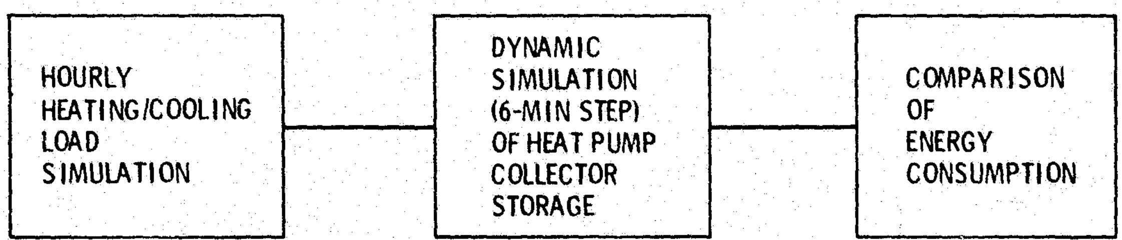
- ESTABLISH "JUSTIFIED COST" FOR PV/T MODULES BASED ON OVERALL PERFORMANCE AND INTEGRATED ENERGY DISPLACEMENT (kWh)

Approach



- PV/T MODULE CHARACTERISTICS
- APPLICATIONS
- SYSTEM ARRANGEMENT/SIZING

Methodology



HOURLY HEATING/COOLING LOAD SIMULATION

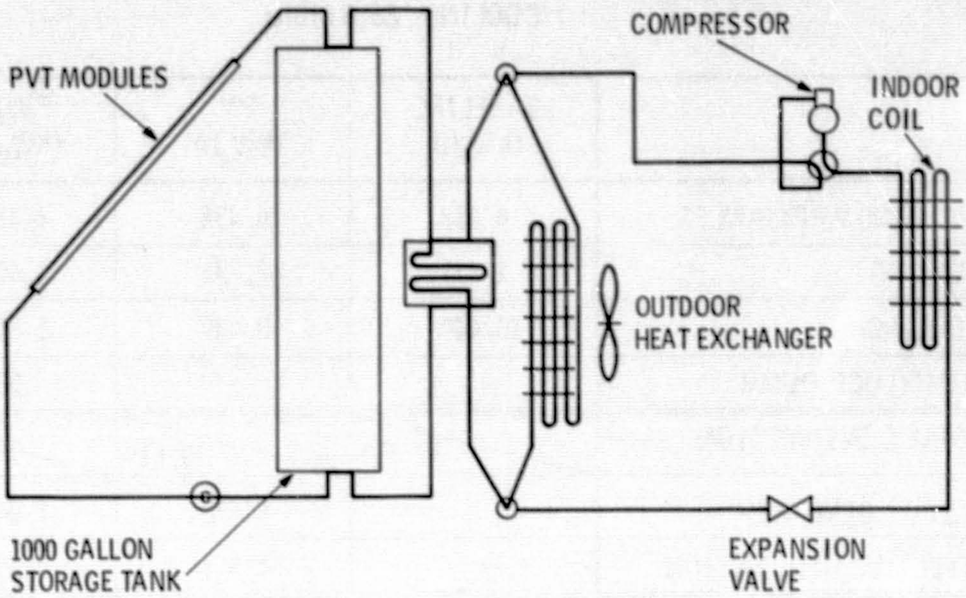
DYNAMIC SIMULATION (6-MIN STEP) OF HEAT PUMP COLLECTOR STORAGE

COMPARISON OF ENERGY CONSUMPTION

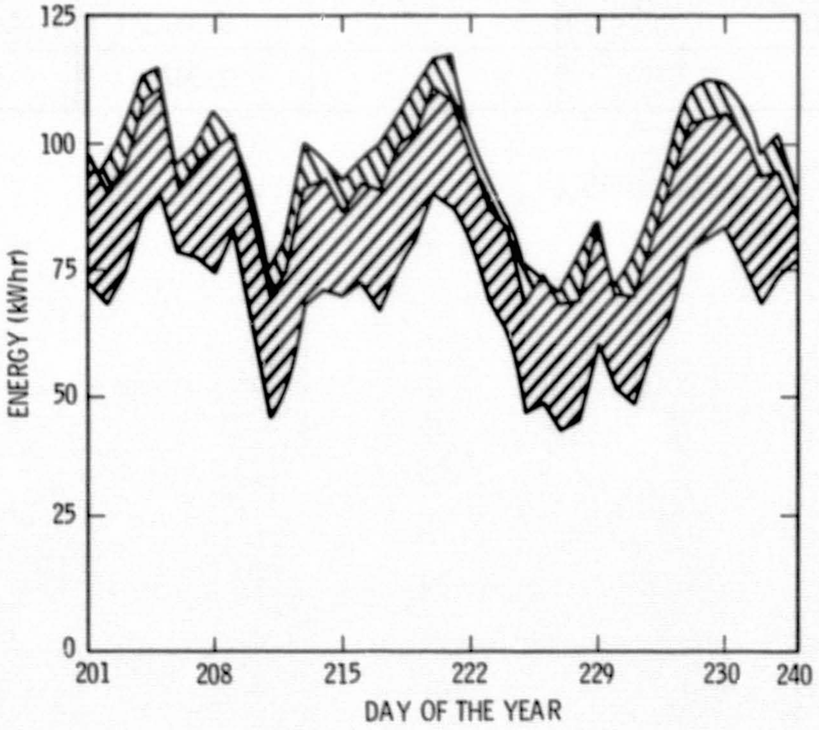
- ASHRAE BUILDING MODEL
- SOLMET WEATHER TAPE
- THERMAL INERTIA CONSIDERED
- LIGHTING/APPLIANCE LOAD DISTRIBUTION

- PV/T MODULE
- HYDRONIC HEAT PUMP
- STRATIFIED STORAGE

- BASELINE
- PV MODULE
- PV/T MODULE



System Arrangement



SAMPLE RESULTS OF ANNUAL ENERGY CONSUMPTION
LOCATION: <u>FORT WORTH</u> HEATING: 17.6 MBtu
COOLING: 86.6 MBtu

	BASELINE (kW_eh)	PV (kW_eh)	PV/T* (kW_eh)
LIGHTING/APPLIANCES	6, 438	6, 438	6, 438
HEATING	2, 731	2, 731	1, 498
COOLING	10, 449	10, 449	8, 885
FLUID LOOP PUMP	–	–	530
TOTAL CONSUMPTION	19, 619	19, 619	17, 312
ENERGY GENERATION	–	6, 838	7, 043
EFFECTIVE UTILIZATION	–	4, 531	4, 258
ANNUAL ELECTRIC BILL	19, 619	15, 088	13, 063
DIFFERENCE	–	4, 531	4, 531 + 2, 025
CREDIT	–	2, 307	2, 785

*47.57 m^2 UNGLAZED MODULE

SAMPLE RESULTS OF ANNUAL ENERGY CONSUMPTION
LOCATION: BOSTON HEATING LOAD 62.5 MBtu
COOLING LOAD 28.7 MBtu

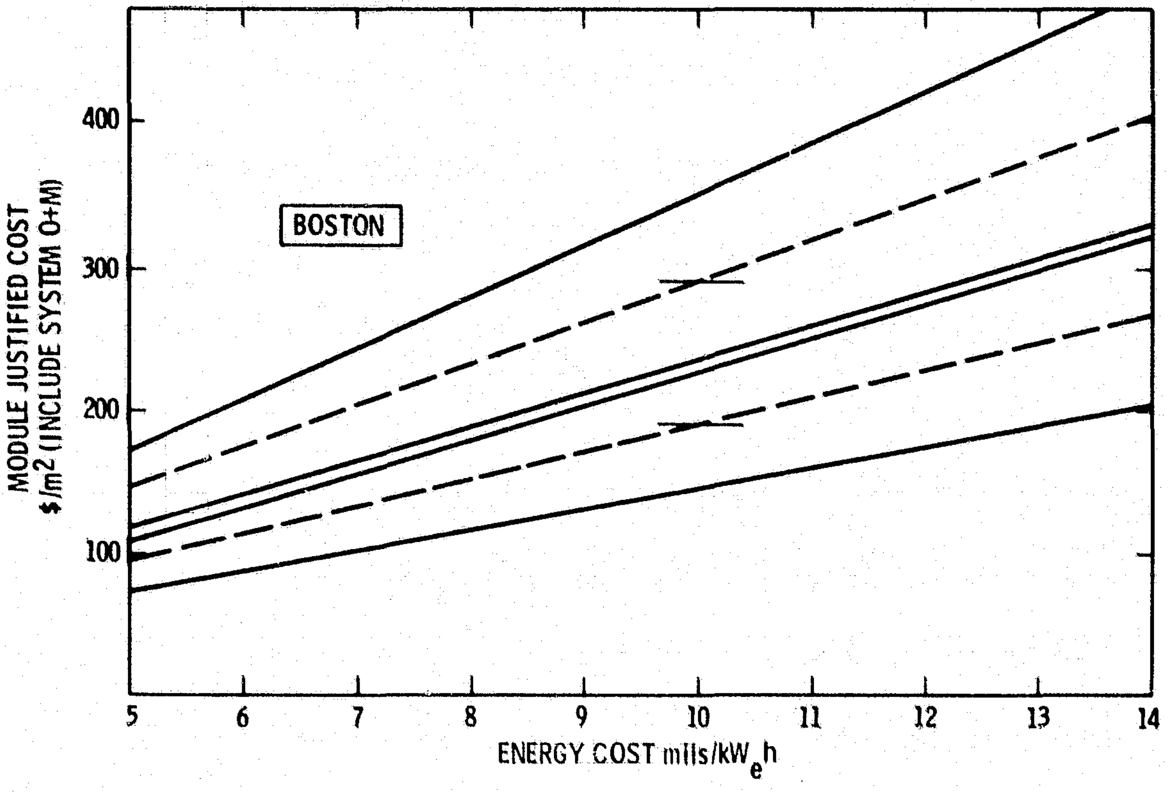
	BASELINE (KW_eH)	PV (KW_eH)	PV/T (KW_eH)*
LIGHTING/APPLIANCES	6, 438	6, 438	6, 438
HEATING	9, 890	9, 890	7, 950
COOLING	3, 240	3, 240	2, 387
FLUID LOOP PUMP	–	–	293
TOTAL CONSUMPTION	19, 569	19, 569	17, 029
ENERGY GENERATION	–	5, 676	5, 882
EFFECTIVE UTILIZATION	–	3, 457	3, 104
ANNUAL ELECTRIC BILL	19, 569	16, 112	14, 101
DIFFERENCE	–	3, 457	3, 457 + 2, 011
CREDIT	–	2, 219	2, 777

*47.57 m^2 UNGLAZED MODULE

SAMPLE RESULTS OF ANNUAL ENERGY CONSUMPTION
LOCATION: SANTA MARIA HEATING LOAD 6.3 MBtu
COOLING LOAD 9.3 MBtu

	BASELINE (KW$_e$H)	PV (KW$_e$H)	PV/T (KW$_e$H)*
LIGHTING/APPLIANCES	6,438	6,438	6,438
HEATING	993	993	342
COOLING	1,036	1,036	720
FLUID LOOP PUMP	—	—	203
TOTAL CONSUMPTION	8,468	8,468	7,663
ENERGY GENERATION	—	7,971	8,205
EFFECTIVE UTILIZATION	—	2,466	2,198
ANNUAL ELECTRIC BILL	8,468	6,002	5,465
DIFFERENCE	—	2,466	2,466 + 537
CREDIT	—	5,505	6,007

*47.57 m^2 UNGLAZED MODULE



Discussions

- PRELIMINARY ANALYTICAL RESULTS SHOW THAT UNGLAZED PV/T MODULES ARE WORTH AT LEAST 30% - 60% MORE THAN CORRESPONDING PV MODULES

- APPLICATIONS USING GLAZED PV/T MODULES SHOULD CONSIDER TECHNICAL CONSTRAINTS AND SUMMER OPERATING CONDITIONS

- INCLUDING POTENTIAL FOR DOMESTIC HOT WATER HEATING, VALUE COULD BE SIGNIFICANTLY ENHANCED

PV MODULE AND ARRAY SAFETY STUDY

UNDERWRITERS LABORATORIES INC.
Allan Levins

DEVELOPMENT AND APPLICATION OF PRODUCT REQUIREMENTS FOR
PROTECTION AGAINST DESTRUCTION OF:
PROPERTY
HUMAN LIFE
AS A RESULT OF:
SHOCK
FIRE
CASUALTY

Points to Be Covered

1) NATIONAL ELECTRICAL CODE - ARTICLES AND SECTIONS RELATIVE TO PV INSTALLATIONS AND APPLICATIONS
2) ROOF FIRE TESTS
   A) PROCEDURE
   B) RESULTS OBTAINED
3) PROPOSED STANDARD (OF PARTICULAR INTEREST TO MODULE AND PANEL MANUFACTURERS)
   A) AREAS TO BE ADDRESSED
   B) EVALUATION OF CURRENT MODULES
4) FUTURE ACTIVITIES

THE RESULTS OF UL'S WORK ARE PROMULGATED IN DOCUMENTS RELATED TO PRODUCT SAFETY.

1) BUILDING AND ELECTRICAL CODE (NEC) ARTICLES DESCRIBING REQUIREMENTS FOR PRODUCT INSTALLATION AND APPLICATION DOCUMENTS USED BY (MUNICIPAL INSPECTORS) IN EVALUATING PRODUCT INSTALLATIONS.
2) UL STANDARDS FOR FACTORY BUILT ITEMS DOCUMENT USED BY UL IN LABORATORY EVALUATIONS.

AT PRESENT NO UL OR CODE REQUIREMENTS OR PROVISIONS FOR PV MODULES OR ARRAYS, BUT CERTAIN SECTIONS OF ELECTRICAL CODE MIGHT BE APPLICABLE TO PARTS OF PV SYSTEM.

BECAUSE OF LACK OF SPECIFIC DIRECTIVES INSPECTORS WOULD BE AT LIBERTY TO RENDER THEIR OWN JUDGEMENTS ON ACCEPTABILITY OF INSTALLATION, AND INDIVIDUAL JUDGEMENTS MAY BE INCONSISTENT WITH EACH OTHER.

IT IS DESIRABLE TO ELIMINATE VOID IN THE NEC TO:

1) REMOVE INCONSISTENCIES AS CONCERNS INSPECTOR JUDGEMENT.
2) DIRECT AND EDUCATE LOCAL INSPECTORS.
3) ALLOW UNIFORMITY IN THE PRODUCTS.

NEC COMMITTEE BEING FORMED TO CONSIDER REQUIREMENTS TO PV ARRAYS.

National Electrical Code

CURRENT ARTICLES AND SECTIONS CONSIDERED PERTINENT TO PHOTOVOLTAIC SYSTEMS.

GENERAL -	110-7;	INSULATION INTEGRITY
	110-11;	DETERIORATING AGENTS
	110-12;	MECHANICAL EXECUTION OF WORK
	200-6;	IDENTIFICATION OF GROUNDED CONDUCTORS
	215-2;	FEEDER RATINGS AND SIZES

SPECIFICS:

110-16 (A) AND 110-34 (A); WORKING CLEARANCES AND SPACES
110-17 AND 110-34 (C); GUARDING OF LIVE PARTS
200-2; GROUNDED CONDUCTORS
200-3; CONNECTION TO GROUNDED SYSTEM
200-10; TERMINAL IDENTIFICATION
200-22 (C); MAXIMUM LOADS
225-4; CONDUCTOR COVERING
225-6; OVERHEAD SPANS
225-10; WIRING ON BUILDINGS
225-11; CIRCUIT EXIT AND ENTRANCES
225-12; OPEN CONDUCTOR SUPPORTS
225-14; OPEN CONDUCTOR SPACINGS
225-15; SUPPORT OVER BUILDINGS
225-16; POINT OF ATTACHMENT TO BUILDINGS
225-17; MEANS OF ATTACHMENT TO BUILDINGS
225-18; CLEARANCE FROM GROUND
225-19; CLEARANCE FROM BUILDINGS AND ZONE FOR FIRE

ENGINEERING AND OPERATIONS AREAS

LADDERS
225-20; MECHANICAL PROTECTION OF CONDUCTORS
225-21; CABLES ON BUILDINGS
225-22; RACEWAYS ON BUILDINGS
230-26; POINT OF ATTACHMENT
230-27; MEANS OF ATTACHMENT
230-29; SUPPORT OVER BUILDINGS
230-43; WIRING METHODS
230-50; PROTECTION OF CONDUCTORS
230-51; MOUNTING SUPPORTS
230-52; CONDUCTORS ENTERING BUILDINGS
230-53; DRAINING OF RACEWAYS
230-54; CONNECTIONS AT SURFACES
230-70; GENERAL (AS APPLIED TO DISCONNECTING MEANS)
230-71; MAXIMUM NUMBER OF DISCONNECTS
230-82; EQUIPMENT CONNECTED TO THE SUPPLY SIDE OF A SERVICE DISCONNECT
230-95; GROUND FAULT PROTECTION

OVERCURRENT PROTECTION

240-21; OVERCURRENT DEVICE; LOCATION IN CIRCUIT

GROUNDING

250-21; OBJECTIONABLE CURRENTS
250-22; POINT OF CONNECTION
250-26; SEPARATELY DERIVED SYSTEMS
250-42; EQUIPMENT FASTENED IN PLACE
250-51; EFFECTIVE GROUNDING PATH
250-72; METHOD OF BONDING SERVICE EQUIPMENT
250-91; MATERIAL (FOR GROUNDING CONDUCTORS)

X X X X

300-15; BOXES OR FITTINGS
310-5; MINIMUM SIZE CONDUCTORS
310-10(B); CONDUCTOR IDENTIFICATION
318; CABLE TRAYS
320; OPEN WIRING
480; STORAGE BATTERIES

RATIONALES:

110-16(A) AND 110-34(A); WORKING CLEARANCES AND SPACES - TO PROVIDE SUFFICENT AREAS TO SAFELY AND PROPERLY FUNCTION.

110-17 AND 110-34(C); GUARDING OF LIVE PARTS - TO PROTECT AGAINST PERSONAL CONTACT WITH HAZARDOUS ENERGY PARTS. SUGGEST 30 VOLTS AND 30 MA DC AS HAZARD LEVEL, BASED IN PART ON NEC LIMIT FOR WET LOCATIONS, CLASS 2 CIRCUITS, TABLE 725-31(B), NOTE 5.

APPLICATION PROBLEMS:

SECTION 200-2; "ALL PREMISES WIRING SYSTEMS SHALL HAVE A GROUNDED CONDUCTOR". PROBLEM IF TRANSFORMERLESS CONDITIONER, AS ONLY VIRTUAL GROUNDING OF ARRAY WIRING MAY BE POSSIBLE.

SECTION 200-3; IS WIRING FROM A REMOTE ARRAY OR CONDITIONER A "SUPPLY SYSTEM"? IF SO THERE MAY BE A PROBLEM COMPLYING WITH THIS SECTION FOR A SYSTEM WITH A TRANSFORMERLESS CONDITIONER.

SECTION 200-10; IS IT THE INTENT OF THIS REQUIREMENT TO INCLUDE TERMINAL IDENTIFICATION STIPULATIONS FOR EQUIPMENT THAT GENERATES ELECTRICAL POWER? UL PROPOSES YES.

ARTICLE 210; BRANCH CIRCUIT - SUGGEST THAT THE PROVISIONS OF THIS ARTICLE APPLY TO THE WIRING BETWEEN THE SERVICE ENTRANCE AND THE CONDITIONER.

SECTION 210-22(C); CONTINUOUS LOADS ON A BRANCH CIRCUIT ARE GENERALLY RESTRICTED TO 80% OF RATING, SUGGEST THIS SAME STIPULATION ALSO BE APPLIED TO THE CONDITIONER CIRCUIT.

SECTION 225-19(D); ZONE FOR FIRE LADDERS, UL SUGGESTS THAT SIMILAR IDEA BE APPLIED TO ROOF MOUNTED MODULES.

SECTIONS 225-14(A) AND (B): MAY NOT NEED TO BE APPLIED CONSIDERING "STATE OF THE ART" INSULATIONS AND THE LIMITED POTENTIAL FAULT CURRENTS FROM PV ARRAYS.

SECTION 230-95; GROUND FAULT PROTECTION - NEED TO INTERRUPT PV SOURCE AS WELL AS UTILITY SUPPLY.

SECTION 240-21; STIPULATION THAT A CONDUCTOR BE PROTECTED BY AN OVERCURRENT DEVICE WHERE IT RECEIVES ITS SUPPLY IS LIKELY UNWARRANTED FOR PV SOURCE, AS OVERCURRENT CONDITION FROM PV CAN NOT EXIST.

ARTICLE 250; GROUNDING - LIKELY THAT AN ARRAY WITH A TRANSFORMERLESS SUPPLY CAN SATISFY GROUNDING REQUIREMENTS WITH A "VIRTUAL GROUND". HOWEVER THIS MEANS THAT POTENTIAL FAULT CURRENTS FROM EXTERNAL SOURCES MUST BE ELIMINATED OR AT LEAST MINIMIZED, THEREFORE POWER LINES SHOULD NOT CROSS OVER ARRAYS.

SECTION 250-26; GROUNDING SEPARATELY DERIVED SYSTEMS IS NOT APPLICABLE, A UTILITY INTERACTIVE SOURCE IS NOT SEPARATELY DERIVED.

ADDITIONAL BONDING PATHS MAY RENDER GROUND FAULT SENSING AND RELAYING EQUIPMENT INEFFECTIVE AND/OR PLACE EXCESSIVE FAULT CURRENTS ON GROUNDING CONDUCTORS.

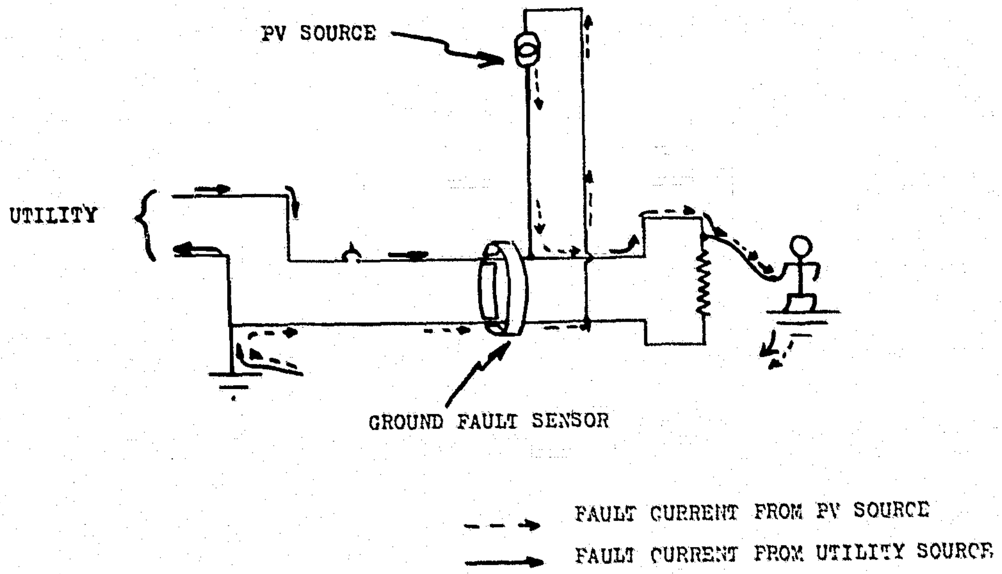
SECTION 450-4; THREE PHASE SOURCE SHALL NOT SINGLE PHASE INTO A THREE PHASE SYSTEM.

X X X X X

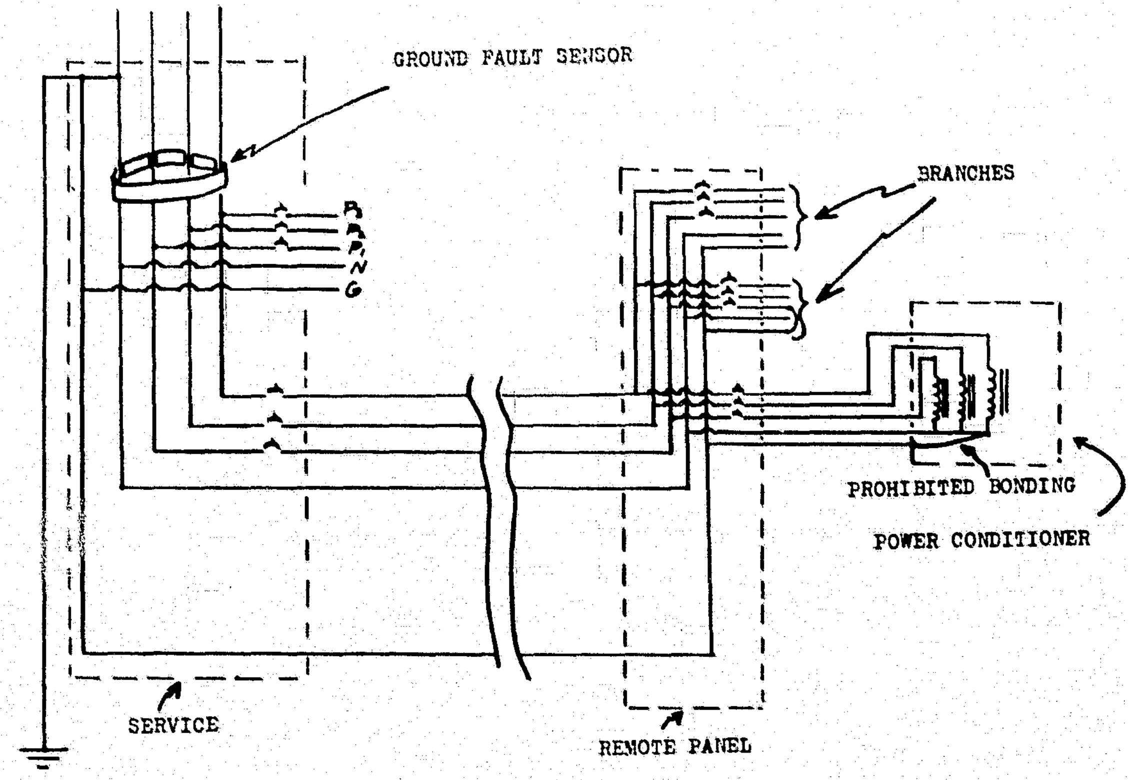
NON HARDWIRED UTILITY INTERACTIVE SOURCE AND REQUIRED GROUND FAULT PROTECTION, PROBLEM UNLESS PROPER (2 POLE) GFCI CONFIGURATION.

CIRCUIT GROUNDING IS WARRANTED, TO STABILIZE CIRCUIT VOLTAGES WITH RESPECT TO EARTH. GROUNDING WILL DISSIPATE INDUCED CHARGES, SO AS TO PREVENT INSULATION BREAKDOWNS.

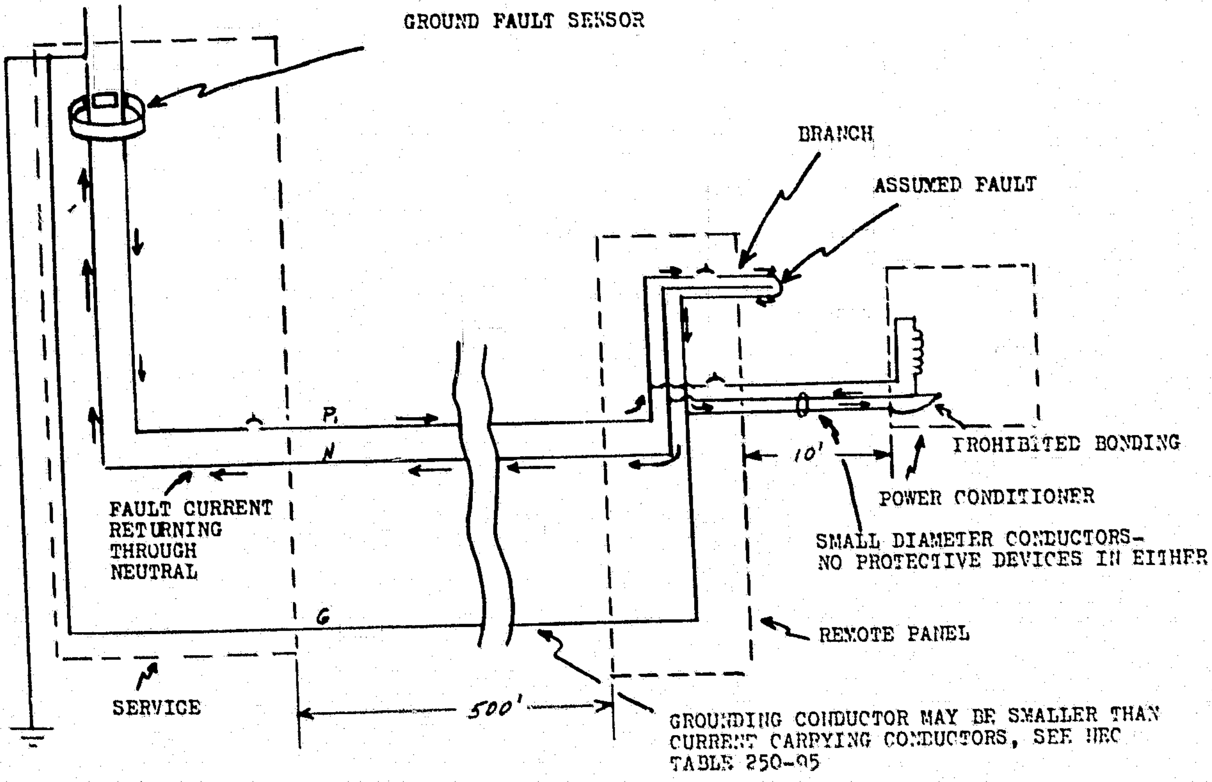
CASUALLY CONNECTED PHOTOVOLTAIC SOURCE



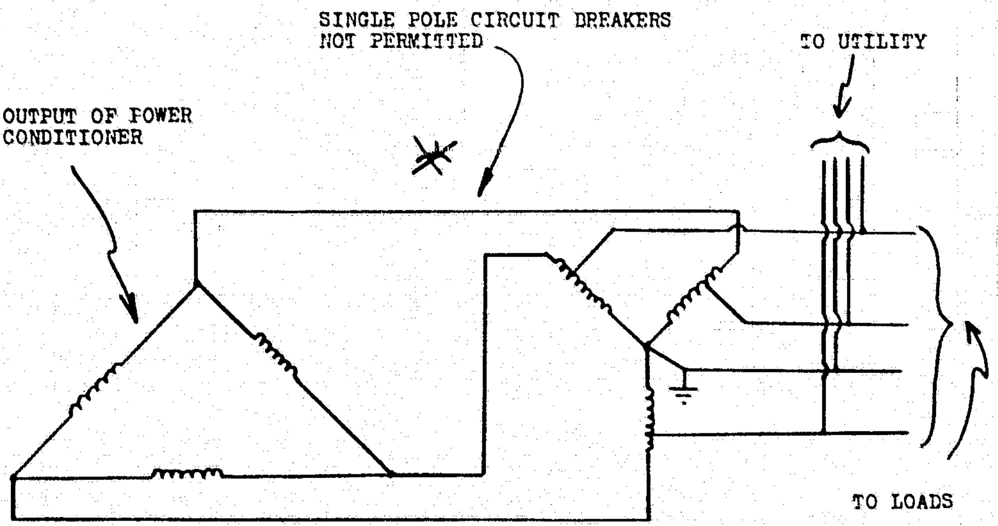
GROUNDING SEPARATELY DERIVED SYSTEMS



GROUNDING SEPARATELY DERIVED SYSTEMS



CIRCUIT INTERRUPTING DEVICES IN INTERFACE



BUILDING CODE PROVISIONS

FIRE RESISTANCE OF ROOF COVERING MATERIALS (UL 790)

ROOF RATING

CLASS	FIRE RESISTANCE	TYPICAL APPLICATIONS
A	MOST RESISTANT	COMMERCIAL AND INDUSTRIAL BLDGS. MULTI-FAMILY RESIDENTIAL BLDGS. SCHOOLS, HOSPITALS
B	MODERATELY RESISTANT	ONE OR TWO FAMILY RESIDENCES IN HIGHER FIRE RISK LOCALES
C	LIGHT RESISTANT	ONE OR TWO FAMILY RESIDENCES

ARRAY TESTING PER UL 790 - ON ROOF -

INTERMITTENT FLAME TEST - REPRESENTS LAPPING OF FLAMES FROM OTHER BURNING PARTS. GAS BURNER IS IGNITED AND EXTINGUISHED FOR A SPECIFIED NUMBER OF CYCLES.

SPREAD OF FLAME TEST - REPRESENTS PRESUMED IGNITION OF ONE PART OF ROOF, DETERMINATION OF EASE OF SPREAD OF FLAMES. GAS BURNER ON CONTINUOUSLY.

BURNING BRANDS TEST - REPRESENTS BURNING PIECES ALIGHTING ON ROOF FROM NEARBY FIRES. GAS BURNER NOT PRESENT. BURNING BRANDS PLACED ON ROOF.

ACCEPTANCE CRITERIA - FIRE TESTS

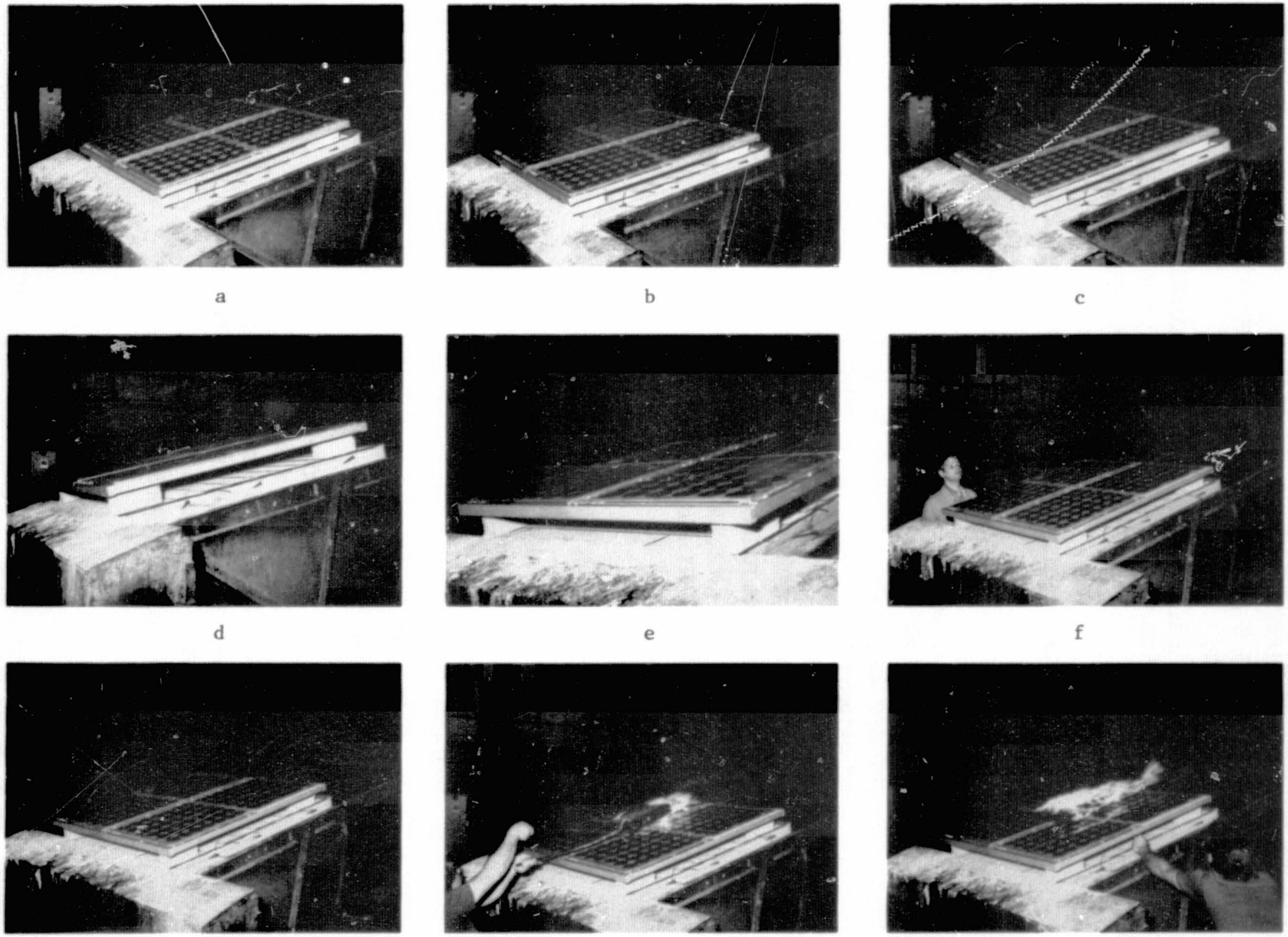
1) DURING AND AFTER THE TEST NO PORTION OF ROOF COVERING SHALL HAVE BLOWN OR FALLEN FROM THE TEST DECK IN THE FORM OF FLAMING OR GLOWING BRANDS OR PARTICLES.

2) ROOF DECK SHALL NOT BE EXPOSED BY BREAKING, SLIDING, CRACKING OR WARPING OF THE ROOF COVERING.

CONCLUSION

PERMITTING AIR CIRCULATION BETWEEN ROOF DECK AND PV PANELS IS NOT RECOMMENDED FROM A FIRE SAFETY STANDPOINT. THE USE OF FIRE STOPS MAY ALLEVIATE THIS CONDITION, HOWEVER, THIS MAY BE AT THE COST OF ELEVATED TEMPERATURES AND THEREFORE DETERIORATED PERFORMANCE OF THE ARRAY.

Brand Test
Solarex Modules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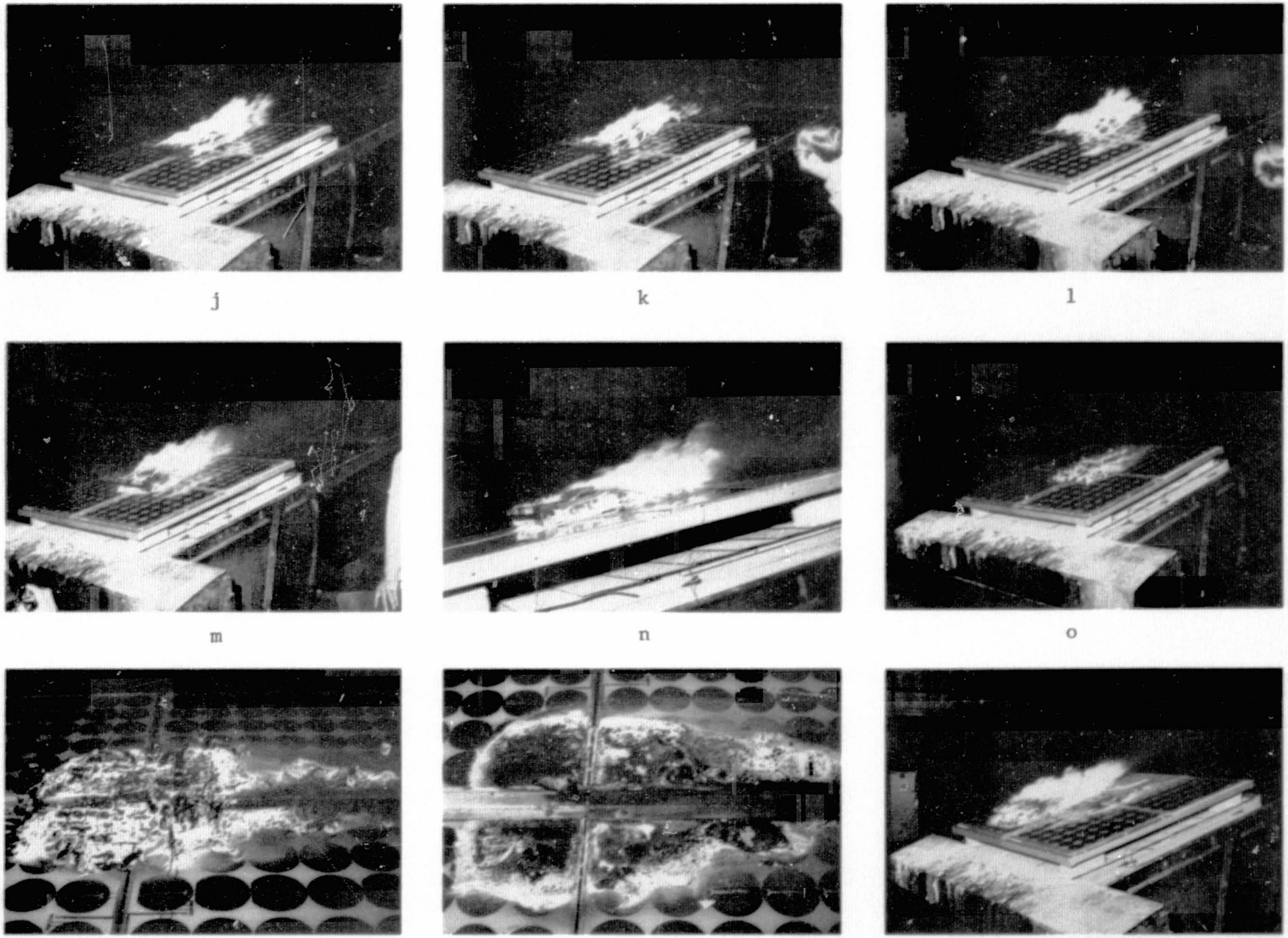

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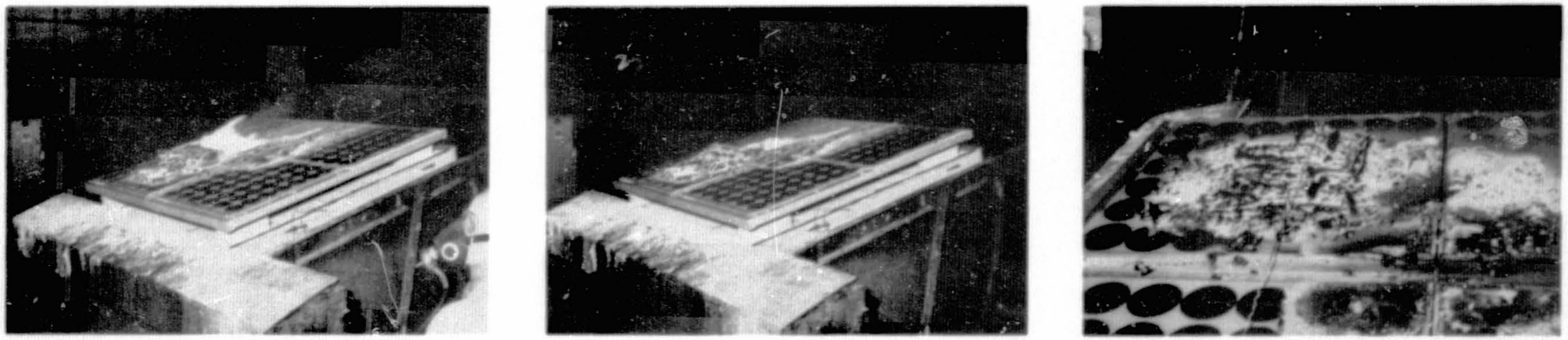

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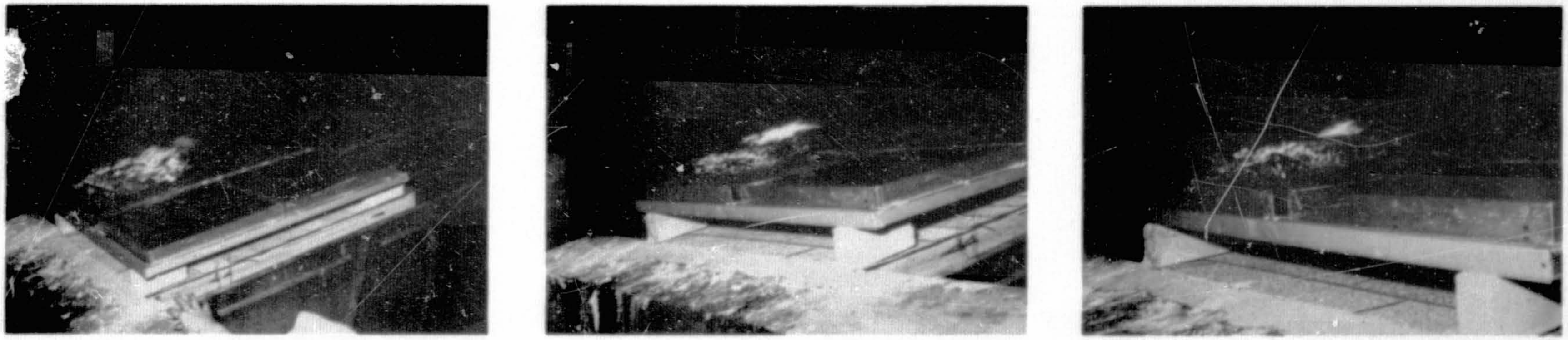
Brand and Spread of Flames
Motorola Modules



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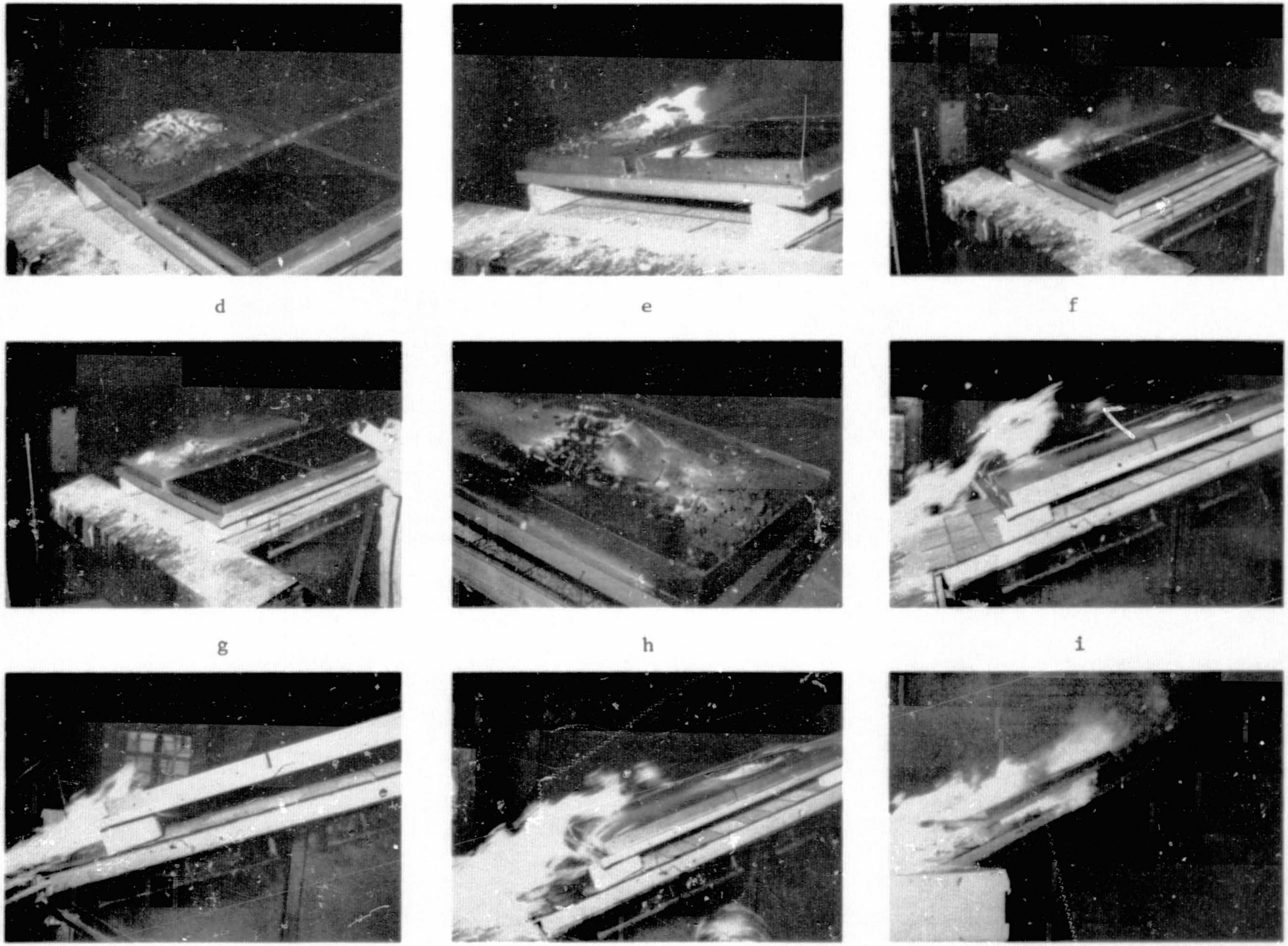

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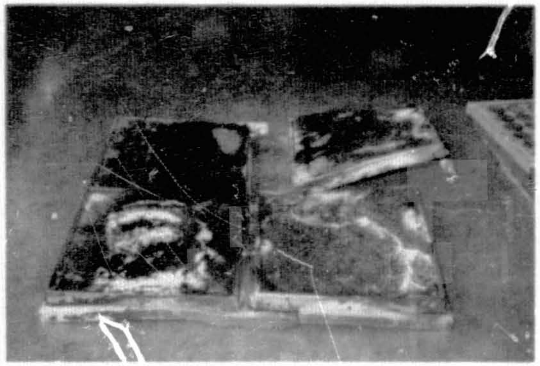

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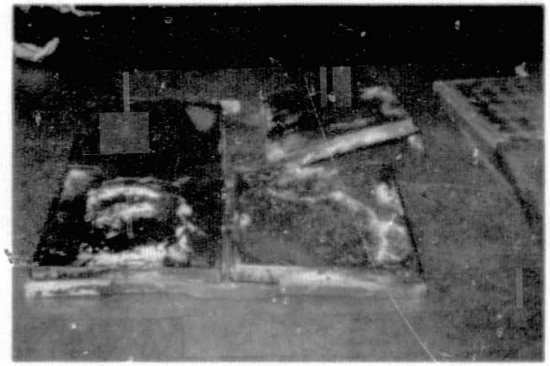

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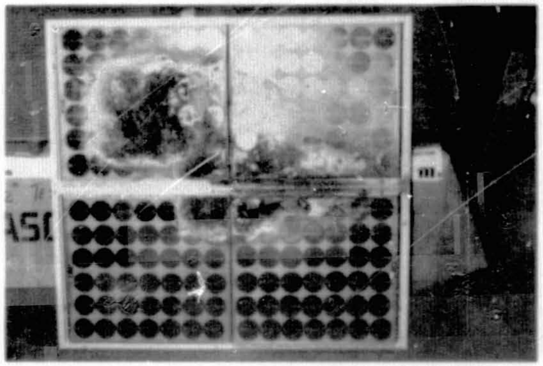

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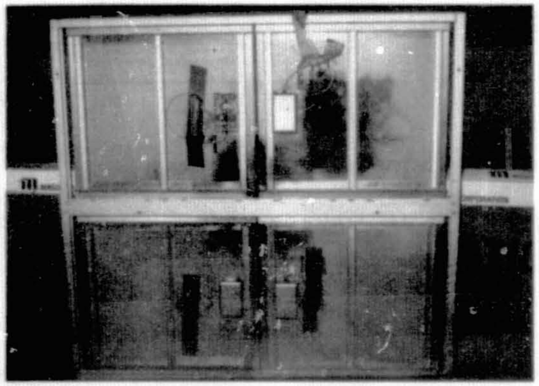

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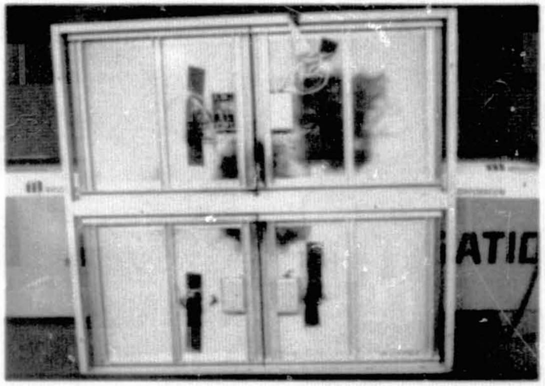

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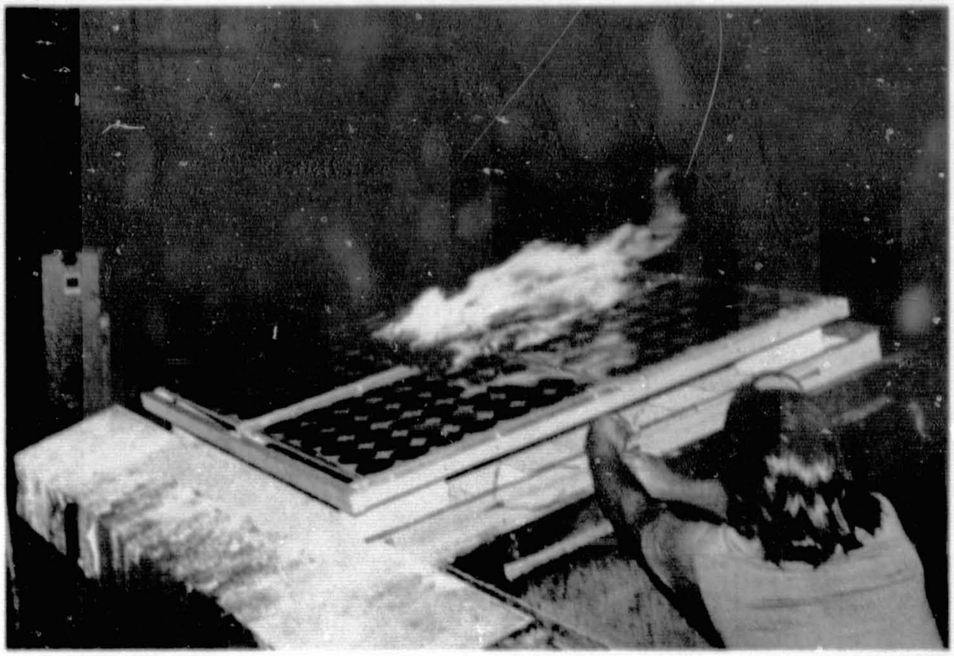
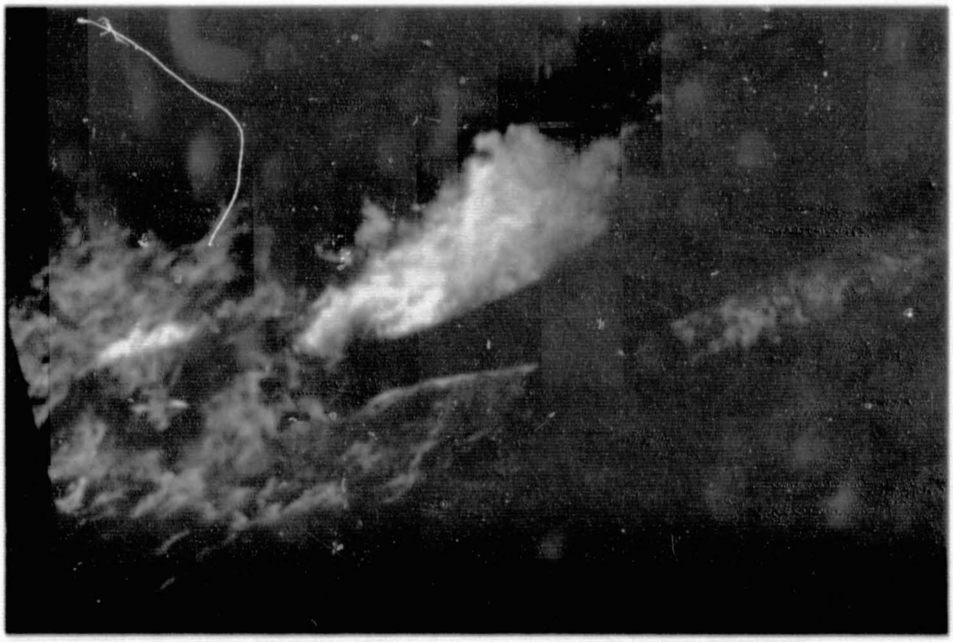




POINTS TO BE ADDRESSED IN UL STANDARD

GENERAL - WHERE POSSIBLE ACCEPTANCE TO BE BASED ON PERFORMANCE RATHER THAN CONSTRUCTION.

1) INSTALLATION
    - A) COMPATABILITY WITH NEC, E.G. - WIRING MEANS, TERMINAL IDENTIFICATION, PROVISIONS FOR GROUNDING
    - B) INSTRUCTIONS TO MINIMIZE HAZARDS TO INSTALLER
2) RESISTANCE TO MECHANICAL ABUSE, E.G. - CELL ENCAPSULANT TO PROTECT AGAINST PERSONAL CONTACT WITH HAZARDOUS ENERGY DURING AND AFTER PRESCRIBED IMPACTS AND CUTTING ATTEMPTS.
3) TEMPERATURES OF MATERIALS DURING OPERATION AVOID RAPID DETERIORATION
4) ELECTRICAL CHARACTERISTICS OF INSULATION, E.G. - IMPULSE VOLTAGE WITHSTAND, DIELECTRIC VOLTAGE WITHSTAND AND LEAKAGE CURRENT LEVELS
5) EFFECTS OF CORROSIVE ATMOSPHERES, E.G. - SALT SPRAY, HYDROGEN SULPHIDE
6) ROOF FLAME TESTS
7) SHARPNESS OF EDGES, TO REDUCE RISK OF CUT HAZARD
8) MARKINGS
9) FACTORY DIELECTRIC WITHSTAND

FUTURE ACTIVITIES

DEVELOP SAFETY SYSTEM CONFIGURATIONS

EXAMPLE:

1) GROUND FAULT DETECTION WITH DISABLING OR INTERRUPTION

2) GROUNDING

3) DOUBLE INSULATION

DEVELOP PROCEDURES FOR INSTALLATION AND SERVICING

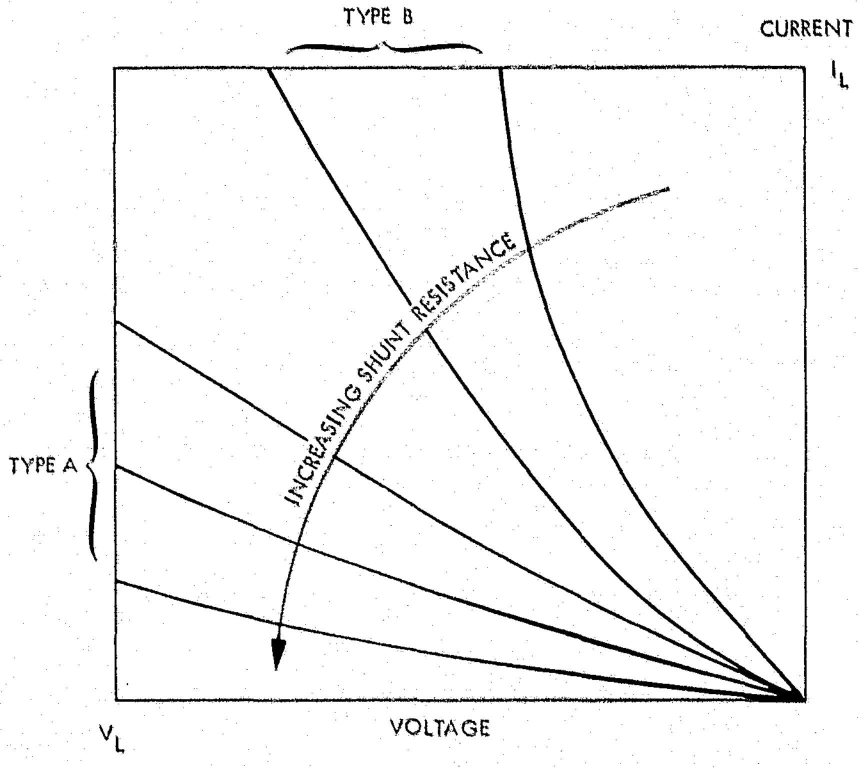
EVALUATE GROUNDING SCHEMES

CONDUCT ADDITIONAL FIRE TESTS

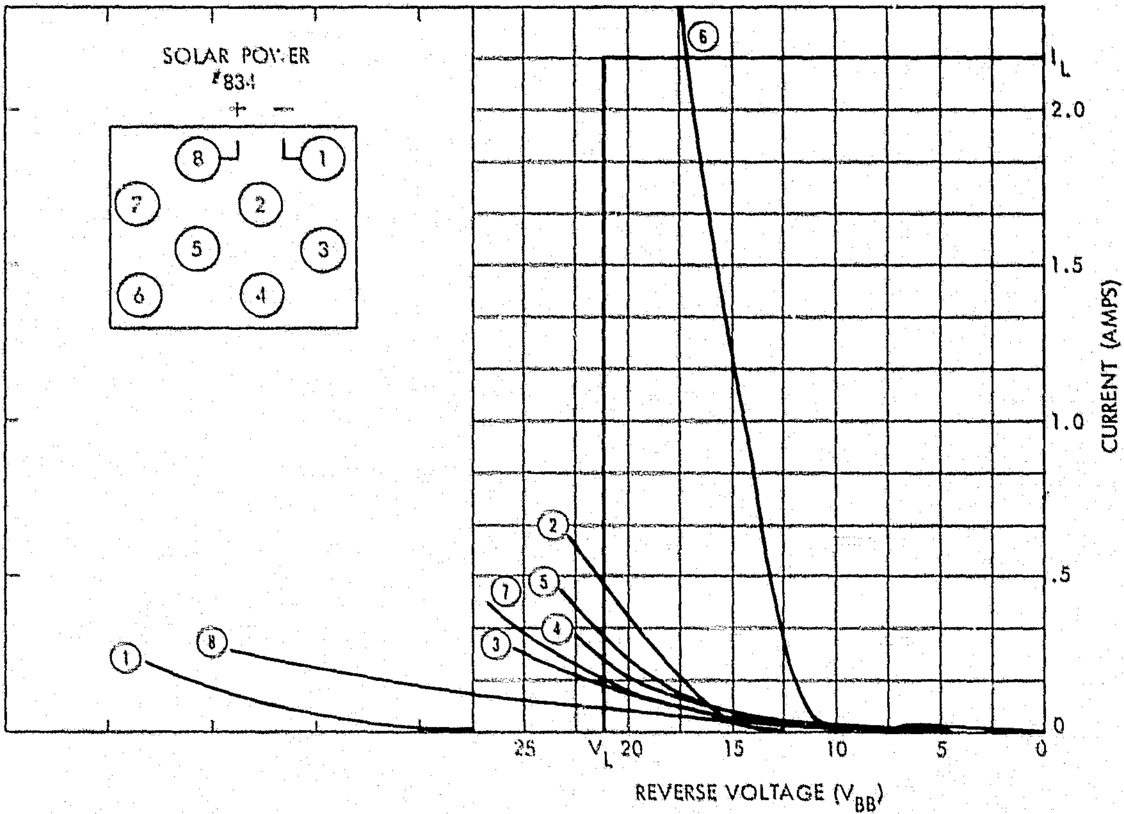
MODULE HOT-SPOT TESTING RESULTS

JET PROPULSION LABORATORY
J.C. Arnett

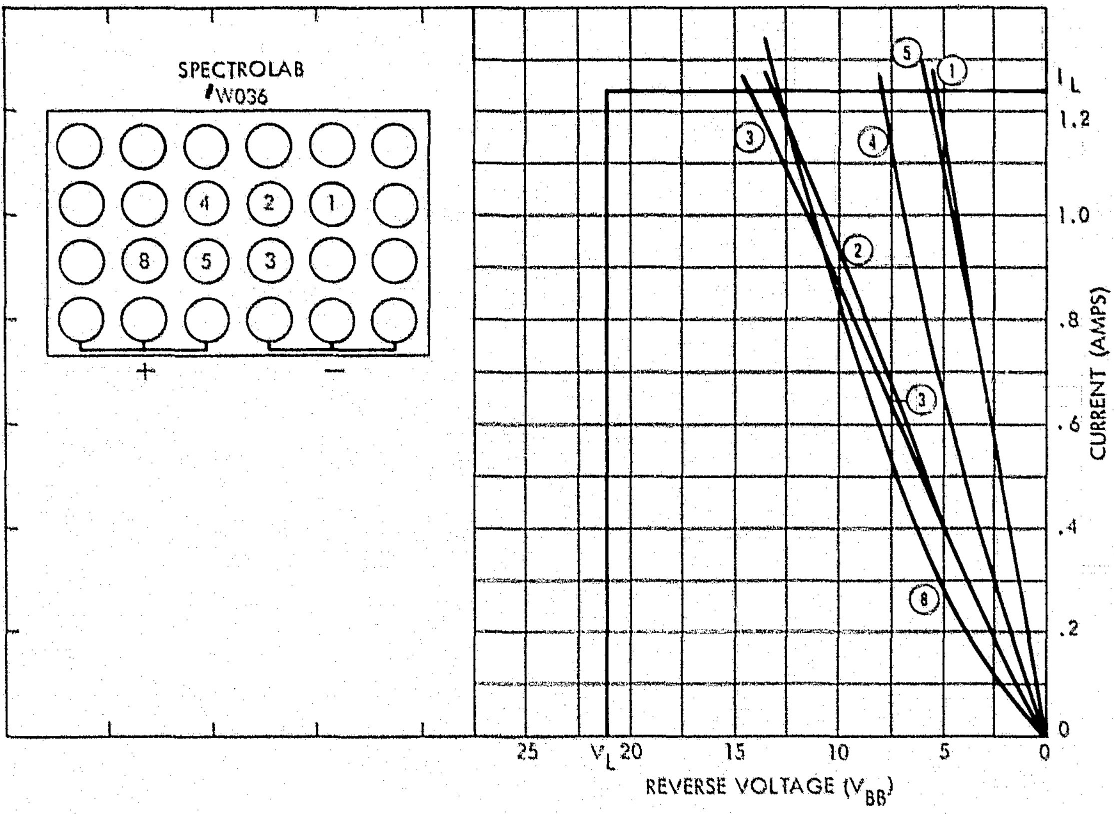
Typical Cell Reverse-Bias I-V Curves



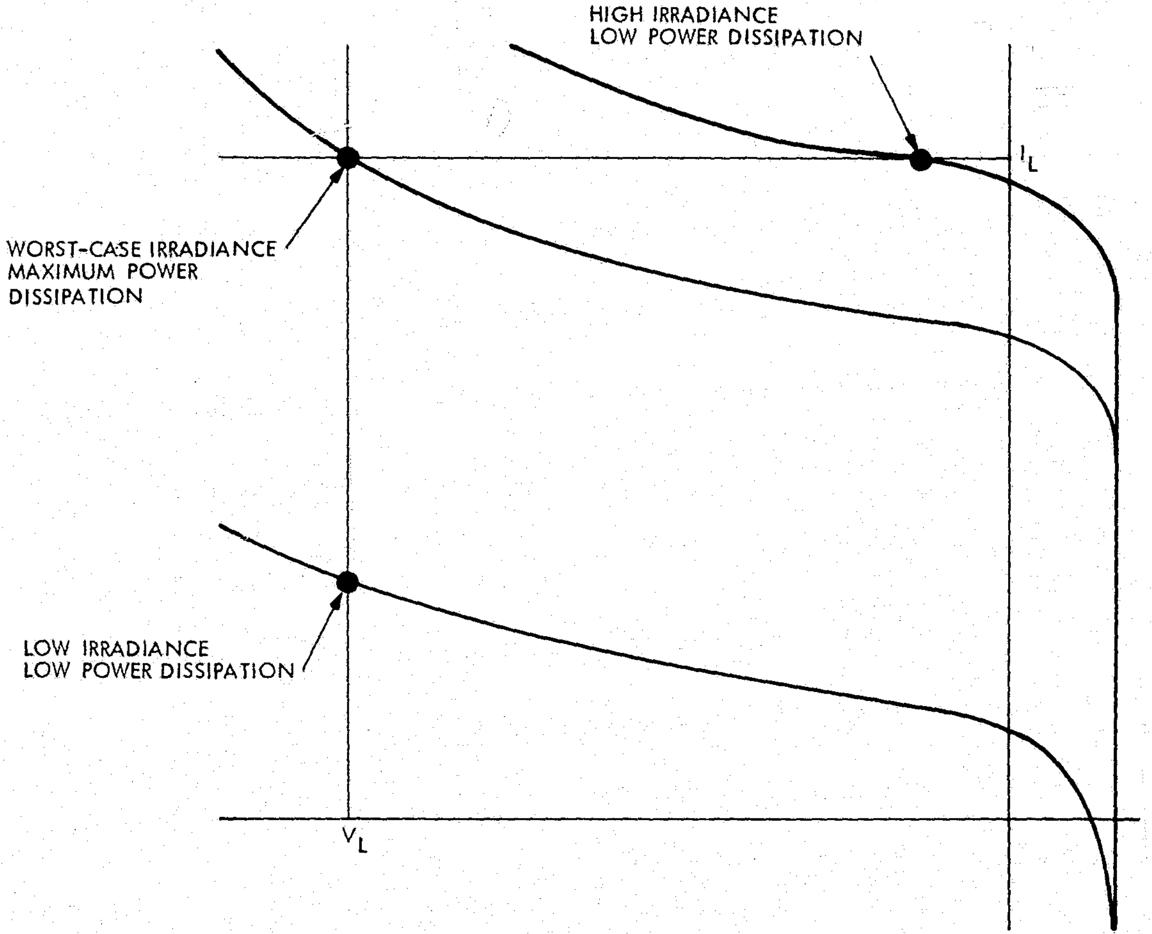
Solar Power No. 834



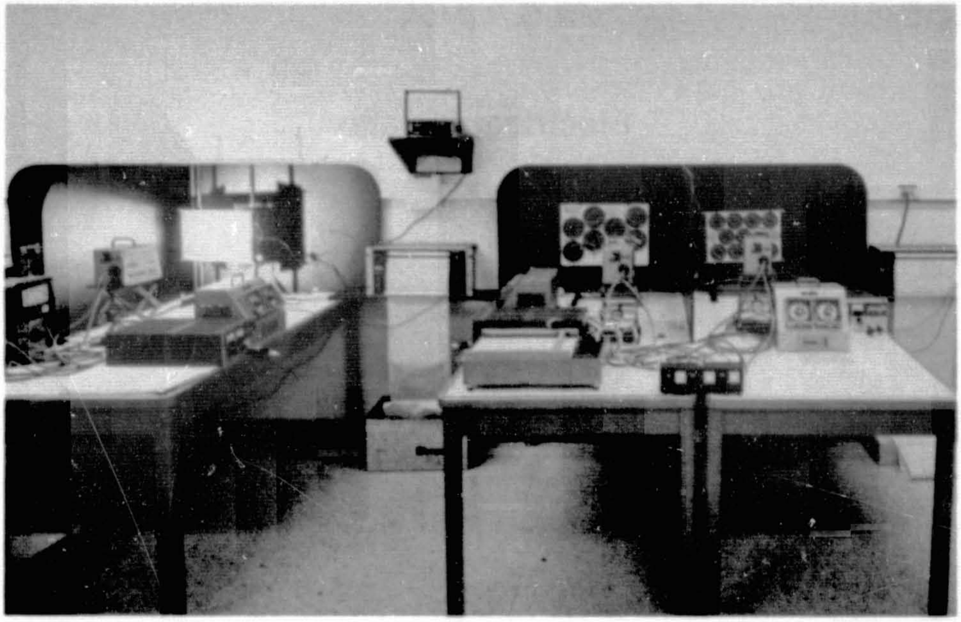
Spectrolab No. W036



Effect of Test-Cell Illumination Level On Hot-Spot Power Dissipation



Hot-Spot Test Facility



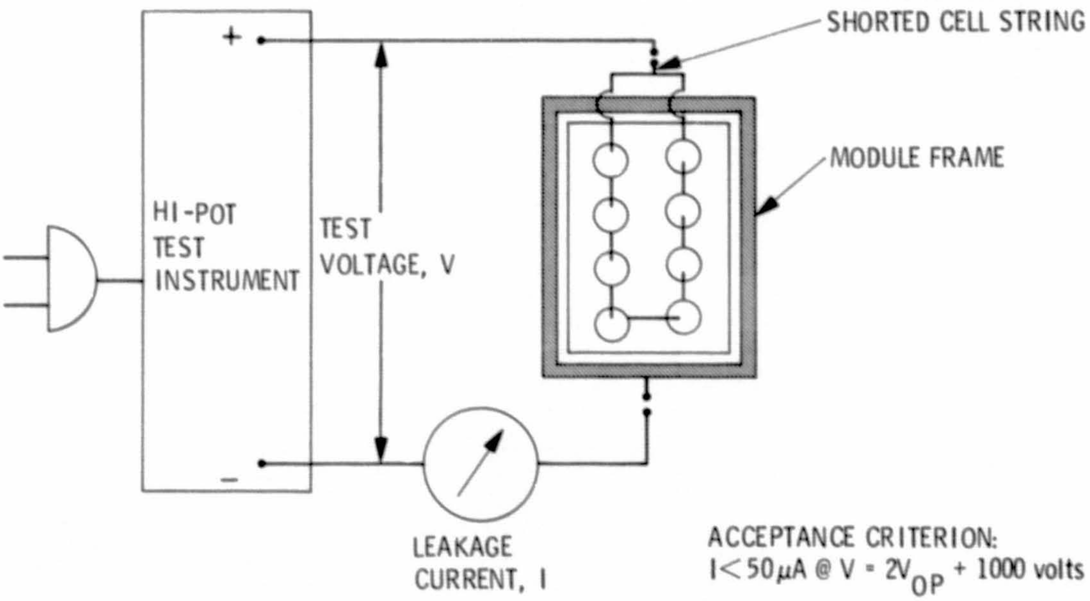
MODULE INSULATION VOLTAGE BREAKDOWN STUDY

JET PROPULSION LABORATORY
G.R. Mon

Electrical Isolation

- DESIGN METHODS (SIZING)
- DURABILITY/RELIABILITY
- INITIAL PERFORMANCE EVALUATION

Hi-Pot Test Schematic and Acceptance Criterion



ACCEPTANCE CRITERION:
$I < 50 \mu A$ @ $V = 2V_{OP} + 1000$ volts

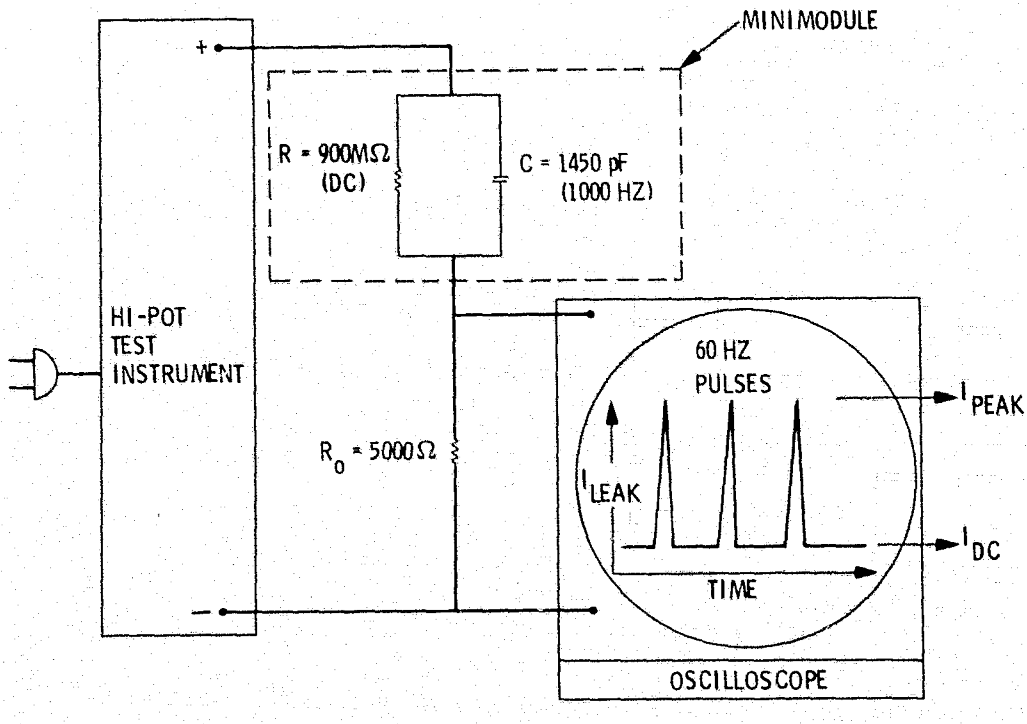
Comparison of Test Results for Two Different Test Instruments

MODULE NO.	VOLTAGE (volts)	
	INSTRUMENT NO. 1	INSTRUMENT NO. 2
1	500	1400
2	300	1450
3	200	2000
4	10,000	460
5	4000	4500
6	700	1750
7	1900	1300

REJECTION CRITERIA:

INSTRUMENT NO. 1 → $I > 100 \mu A$
INSTRUMENT NO. 2 → $I > 50 \mu A$

Hi-Pot Test Circuit and Leakage Current Wave Form



Calculated and Measured Peak Leakage Currents
(Metal Substrate Module)

V (kV)	I_{DC} (μA)	INSTRUMENT NO. 1*		INSTRUMENT NO. 2**
		MEASURED I_{peak} (μA)	CALCULATED I_{peak} (μA)	CALCULATED I_{peak} (μA)
2.0	4.6	44	55	27
6.0	13.8	152	164	82
10.0	29.0	260	273	136

*5% RIPPLE VOLTAGE (RATED)

**2 1/2% RIPPLE VOLTAGE (RATED)

SAMPLE CALCULATION:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(60)(1450 \times 10^{-12})} = 1.829 M\Omega$$

$$I_{peak} = \frac{V \times \text{ripple factor}}{X_C} = \frac{2000 \times 0.05}{1.829 \times 10^{6}} = 55 \mu A$$

Conclusions and Recommendations on Hi-Pot Testing

CONCLUSION:

- RIPPLE VOLTAGE FROM HI-POT TEST INSTRUMENT INTERACTS WITH MODULE CAPACITANCE TO PRODUCE HIGH AC RIPPLE CURRENTS WHICH CAN LEAD TO IMPROPER MODULE REJECTION

RECOMMENDATION:

- MEASURE/MONITOR ONLY DC COMPONENT OF LEAKAGE CURRENT

CONCLUSIONS:

- HIGH AC RIPPLE CURRENTS WILL FLOW IN ARRAY GROUND CIRCUIT IF POWER CONDITIONER FEEDS RIPPLE ONTO THE ARRAY. THESE HIGH AC CURRENTS MAY MAKE DETECTION OF DC GROUND FAULT CURRENTS DIFFICULT

Quantification of Module Breakdown Voltage

OBJECTIVE

DEVELOP NON-DESTRUCTIVE TEST WHICH QUANTIFIES MODULE INSULATION STRENGTH

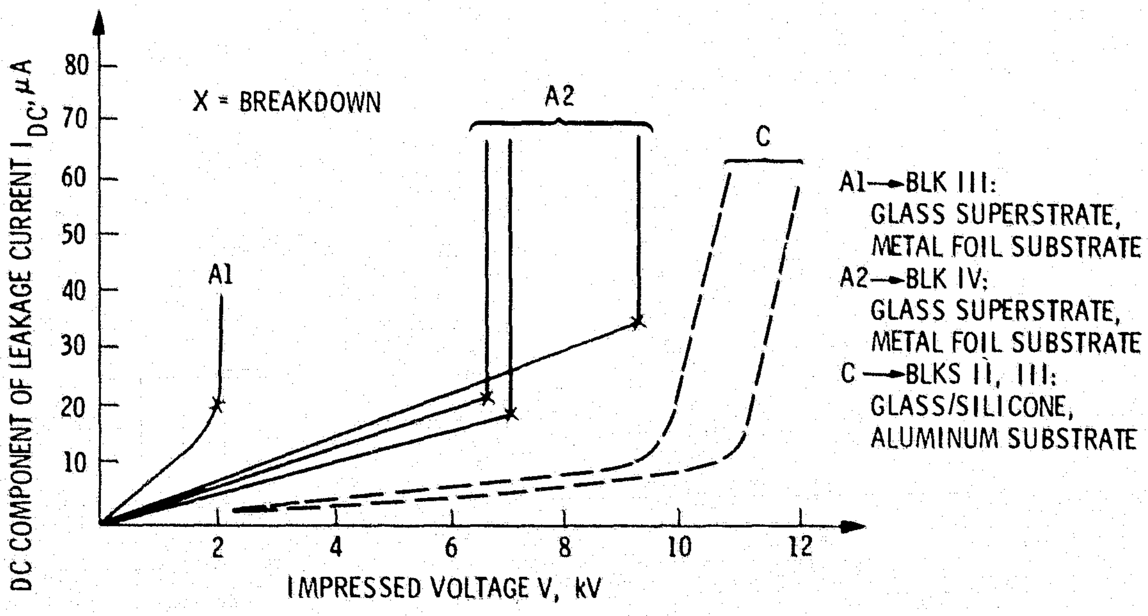
CANDIDATES

- LEAKAGE CURRENT AT FIXED VOLTAGE (HI-POT)
- INSULATION RESISTANCE
- VOLTAGE AT FIXED PARTIAL DISCHARGE (CORONA) LEVEL

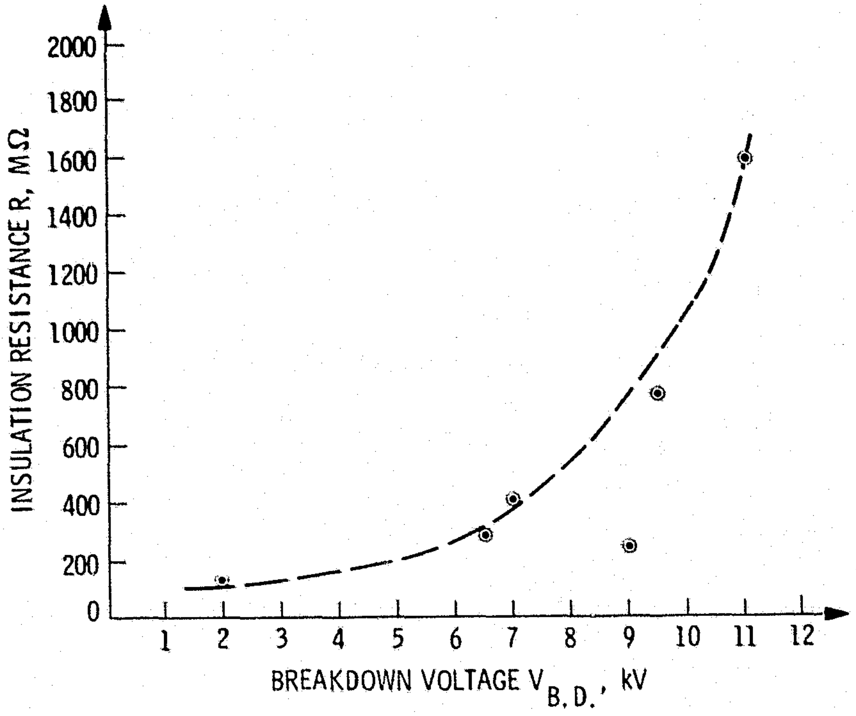
APPROACH

SEEK CORRELATION BETWEEN CANDIDATE VARIABLES AND BREAKDOWN VOLTAGE (OR STRESS) LEVELS

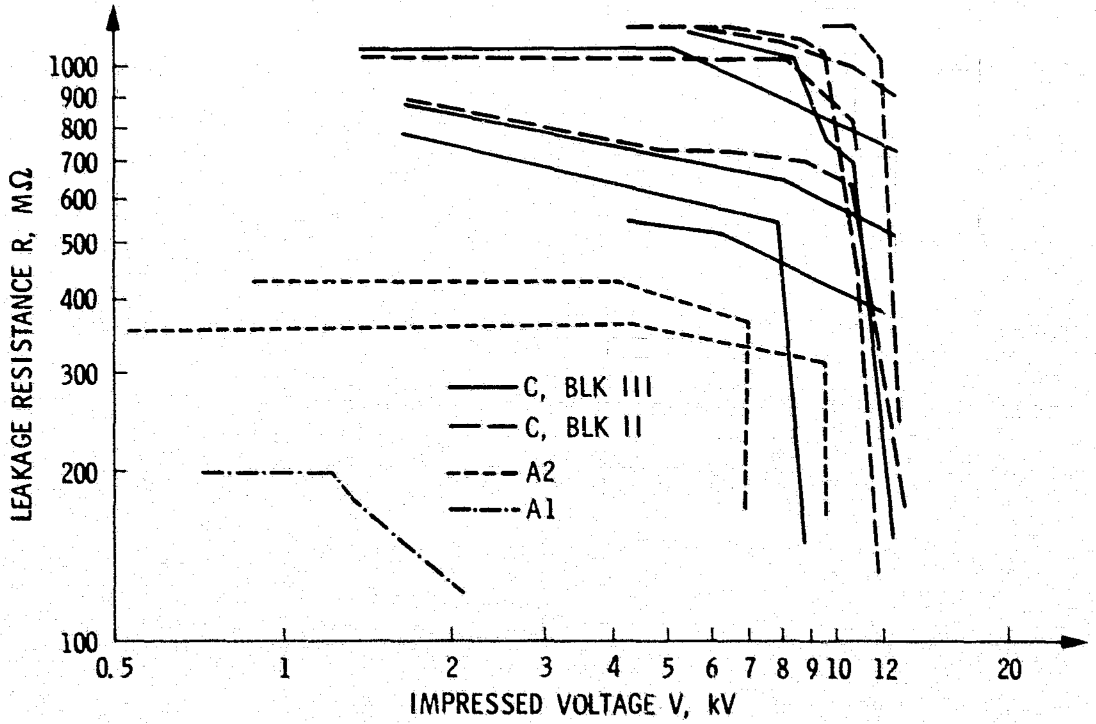
Dc Component of Leakage Current vs Applied Voltage



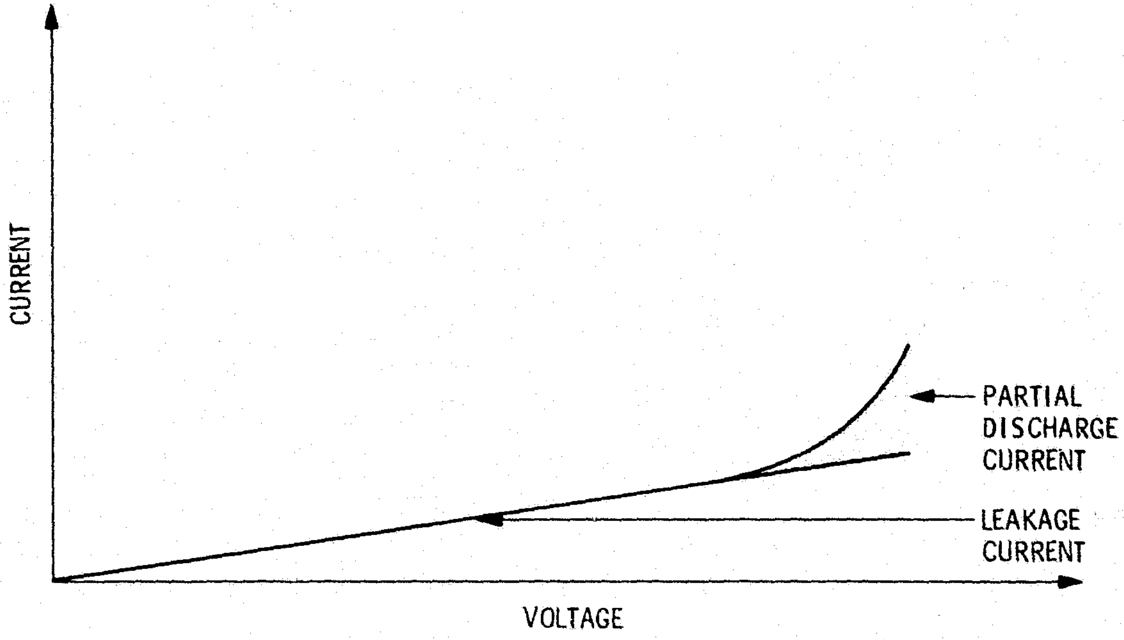
Module Insulation Resistance vs Breakdown Voltage



Module Leakage Resistance vs Applied Voltage



Partial Discharge Detection



Conclusions

- LOW LEAKAGE RESISTANCE CORRELATES LOOSELY WITH LOW BREAKDOWN VOLTAGE, BUT THE CORRELATION IS NOT SUFFICIENT TO JUSTIFY USING LEAKAGE RESISTANCE TO QUANTIFY BREAKDOWN STATISTICS

- PARTIAL DISCHARGE DETECTION SYSTEMS APPEAR TO PROVIDE A MEANS FOR NON-DESTRUCTIVE DETERMINATION OF MODULE INSULATION STRENGTH. SUCH SYSTEMS, HOWEVER, ARE EXPENSIVE: $25K-$50K.

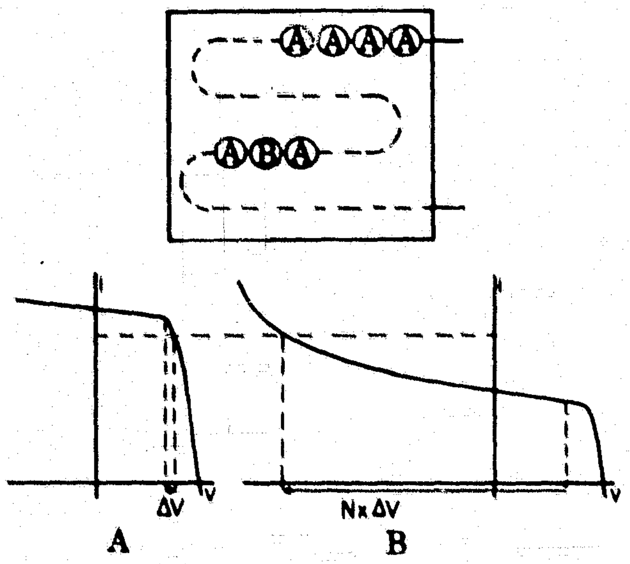
SECOND-QUADRANT EFFECTS IN SILICON SOLAR CELLS

CLEMSON UNIVERSITY
R.A. Hartman
J.W. Lathrop

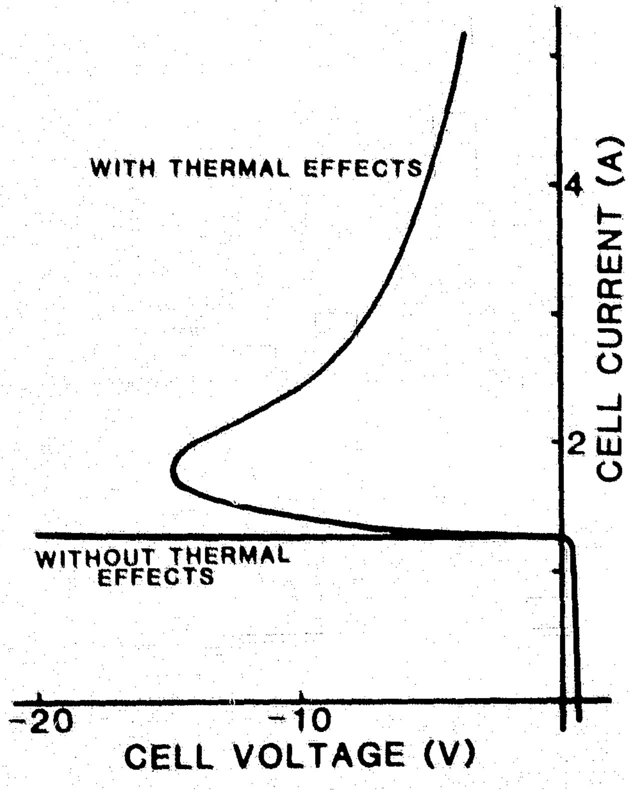
Outline

- o INTRODUCTION
  - o WHEN DOES IT OCCUR
  - o THERMAL EFFECTS
  - o PHYSICAL BACKGROUND
  - o TEMPERATURE DEPENDANCE OF IV-CURVE
- o MODEL AND OBSERVATIONS
  - o MODEL
  - o IV-CURVE
  - o TEMPERATURES
  - o HOT SPOT
- o ENCAPSULATED CELLS
  - o STRUCTURE
  - o IV-CURVE
  - o DAMAGE
  - o INTEGRATED DIODE SOLAR CELL
- o CONCLUSIONS

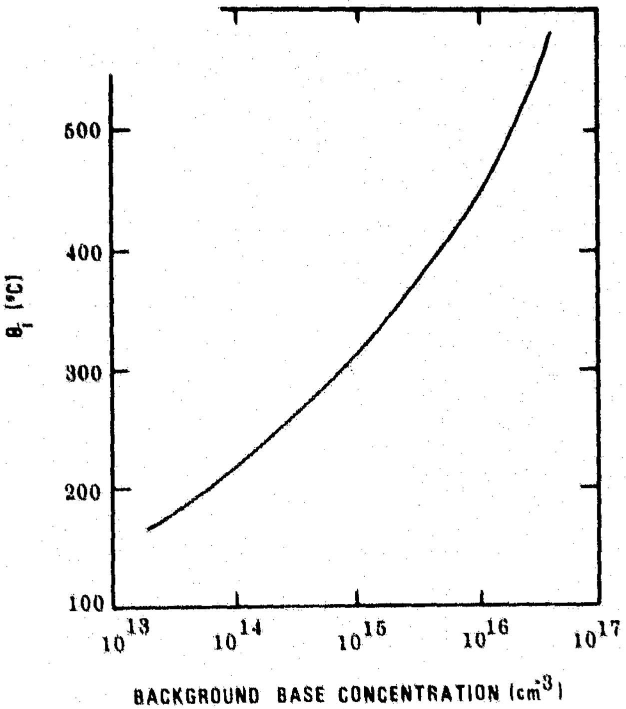
N Cells in Series With a Cell With an Anomalous I-V Curve



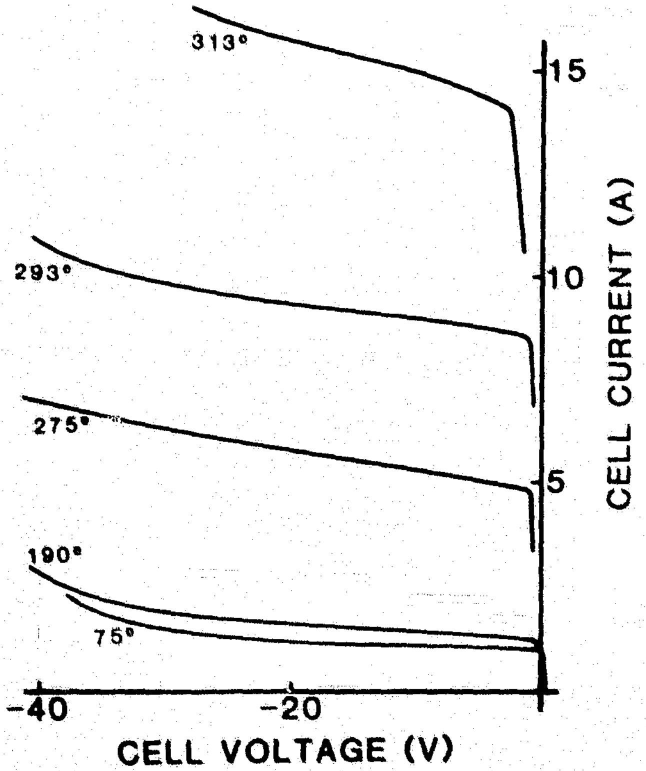
I-V Curve of Unencapsulated Cell With And Without Thermal Effects



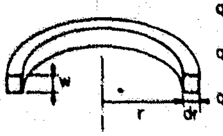
Intrinsic Temperature vs Doping Level



I-V Curve of a Cell: Uniform Temperature



Model for a Cell in the Second Quadrant



$$q_{in\ at\ r} = -2\pi r w k \frac{\partial T}{\partial r}$$

$$q_{generated} = 2\pi r\, dr \{ jV - h(T - T_{air}) + ILL \}$$

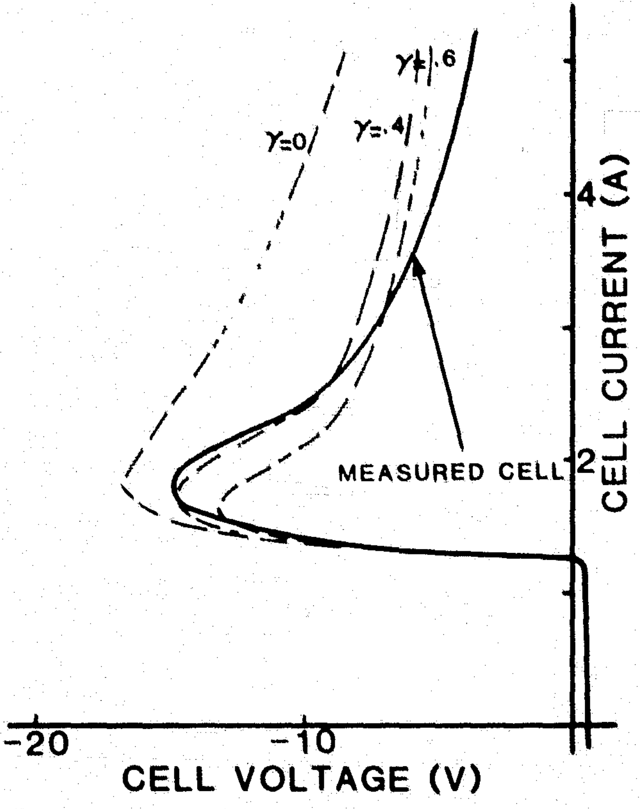
$$q_{out\ at\ r+dr} = -2\pi (r+dr) w \left\{ k \frac{\partial T}{\partial r} \right|_{r+dr}$$

$$q_{stored} = 2\pi r\, dr\, w \rho c \frac{\partial T}{\partial t}$$

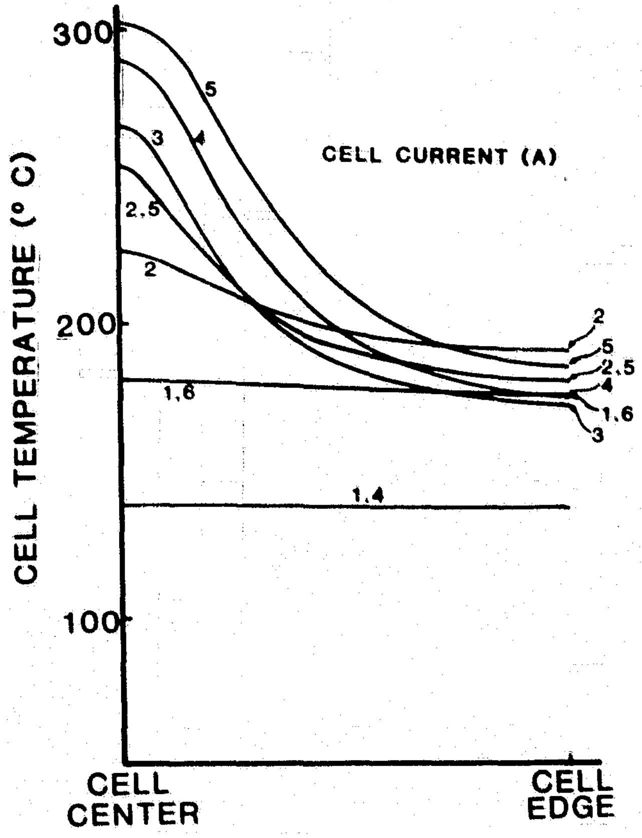
$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{k}\frac{dk}{dT}\left(\frac{dT}{dr}\right)^2 + \frac{jV - h(T - T_{air}) + ILL}{kw} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$\alpha = k/\rho c$ $\qquad$ $j = j(T, V, f(\gamma))$

I-V Curve of Unencapsulated Cell Compared With the Model



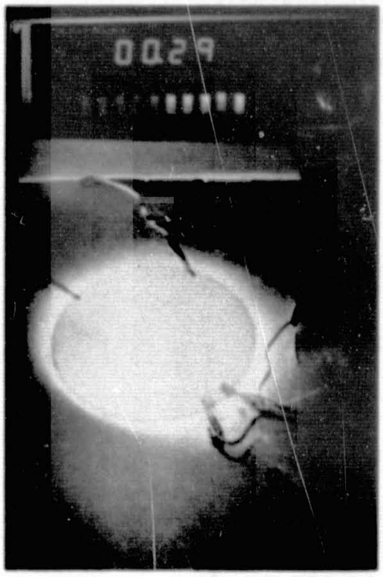
Temperature Profiles of Unencapsulated Cell: Model



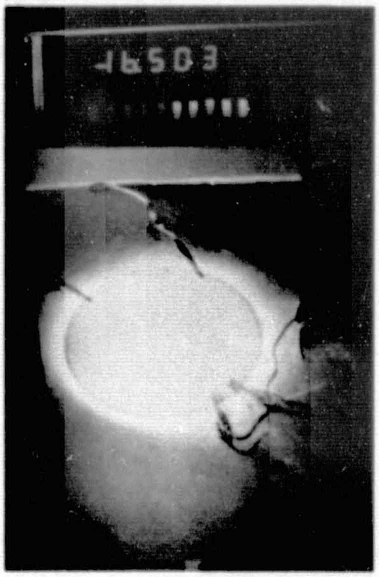
Temperatures of an Unencapsulated Cell Compared With the Model

CURRENT	TEMPERATURES ° C	
A	MEASURED	MODEL
1.3	100	90
1.4	140	138
1.6	180	182
1.8	200	206
2.0	230	225
2.5	270	253
3.0	280	268
4.0	310	287
5.0	325	304

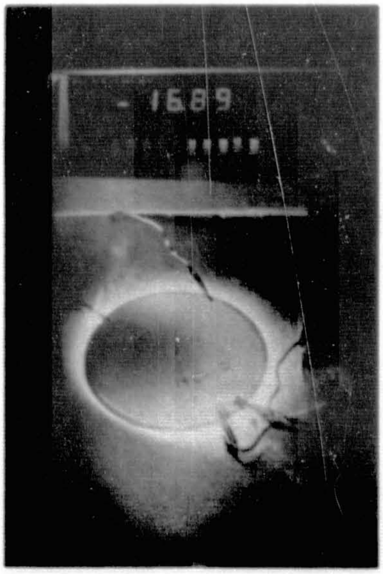
Development of Hot Spot



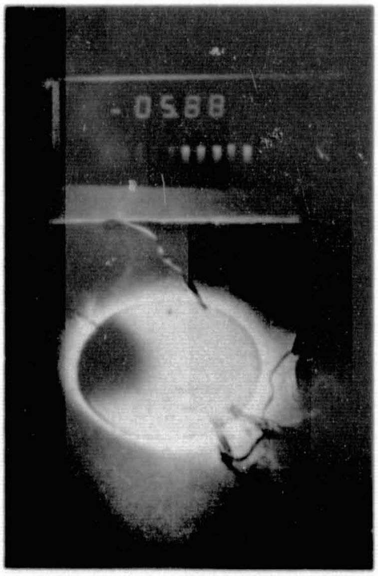
At OV



Before the Knee



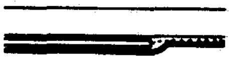
Over the Knee



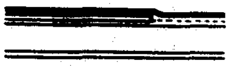
At High Currents

Structure of Minimodules

GLASS SUPERSTRATE



MASONITE SUBSTRATE

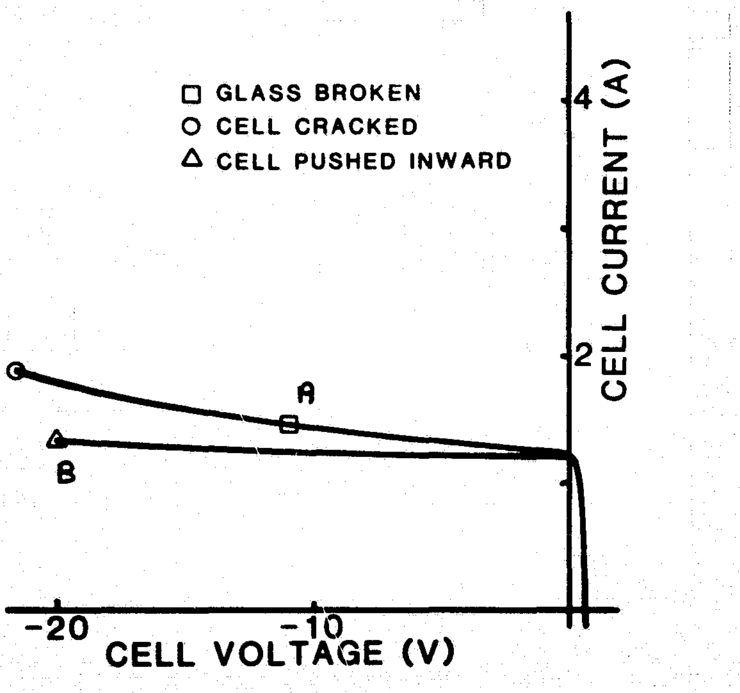


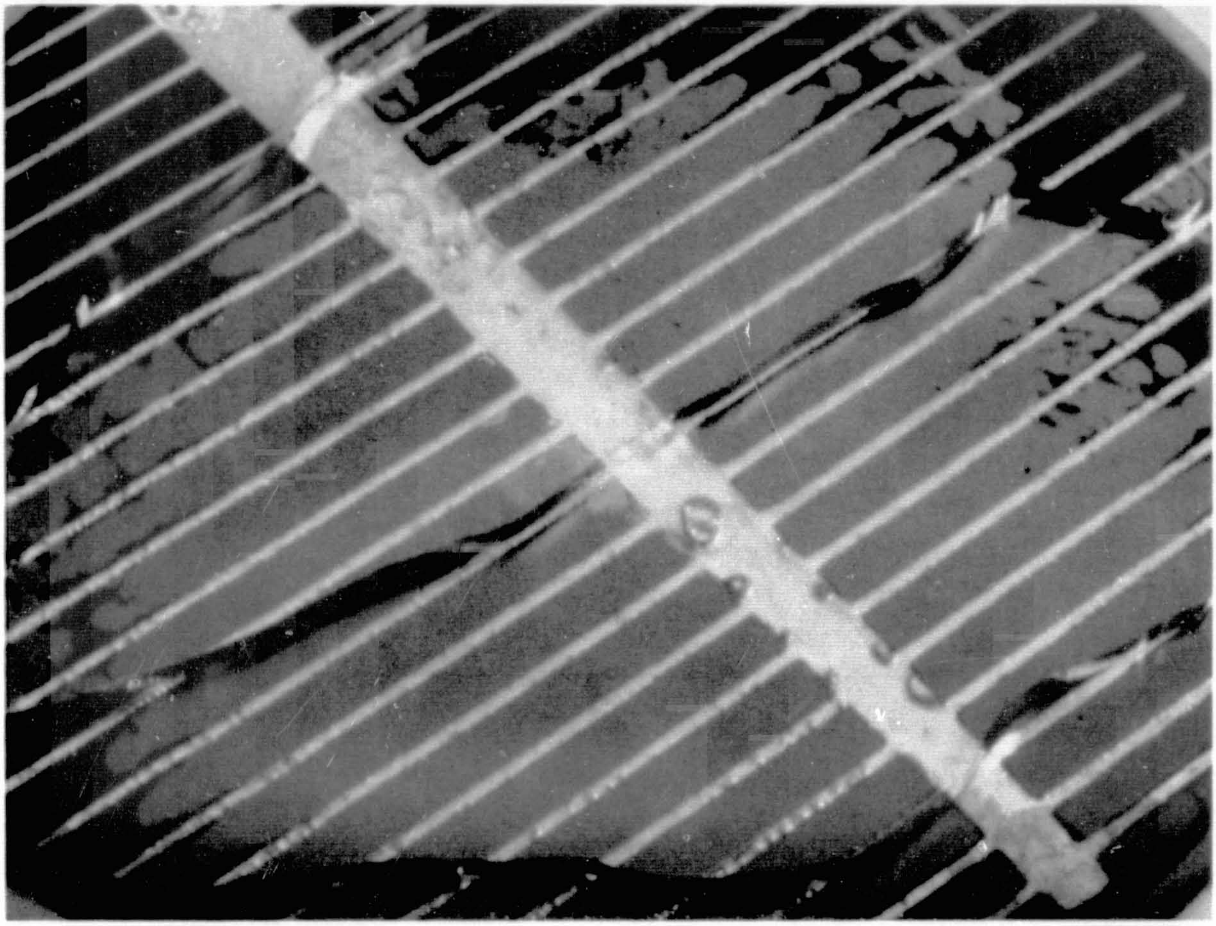
	THICKNESS (MM)	THERMAL CONDUCTIVITY (W/° C.CM) X 10^{-3}
GLASS	3.175	8.37
EVA	0.445	2.62
CELL	0.485	k = k(T)
EVA[□]	0.254	2.62
ALUMINUM	0.025	2360

	THICKNESS (MM)	THERMAL CONDUCTIVITY (W/° C.CM) X 10^{-3}
KORAD	0.076	1.93
EVA	0.432	2.62
CELL	0.485	k = k(T)
EVA[□]	0.254	2.62
SUPER DORLUX	3.175	1.67
EVA	0.254	2.62

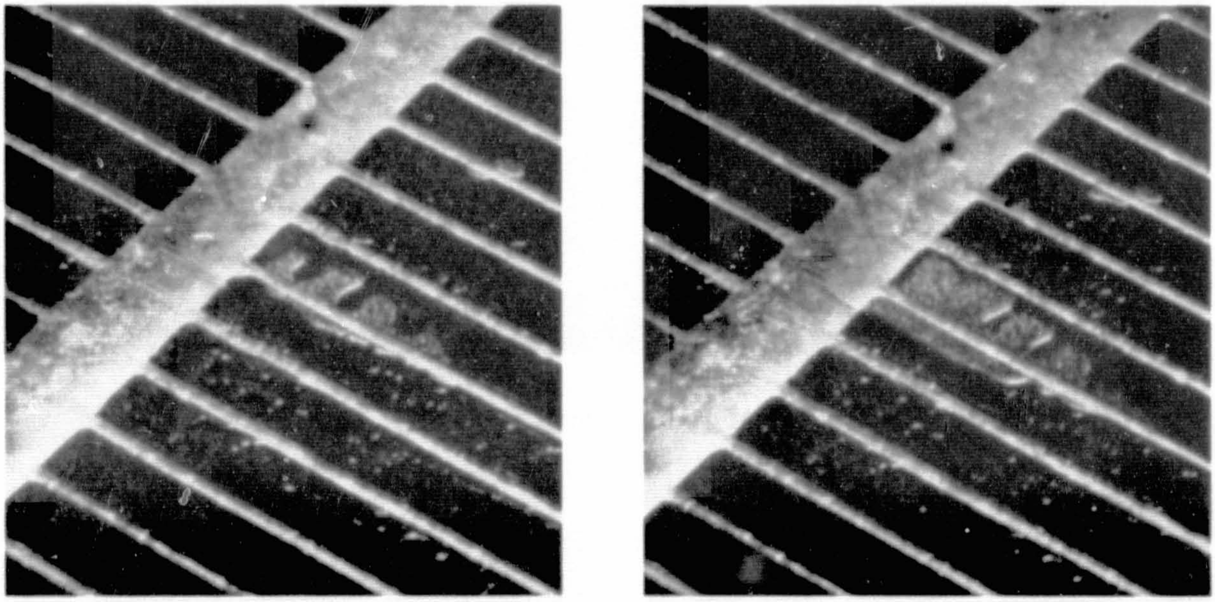
[□] EVA WITH GLASSMAT AND WHITE PIGMENT

I-V Curve of Glass-Encapsulated Cell



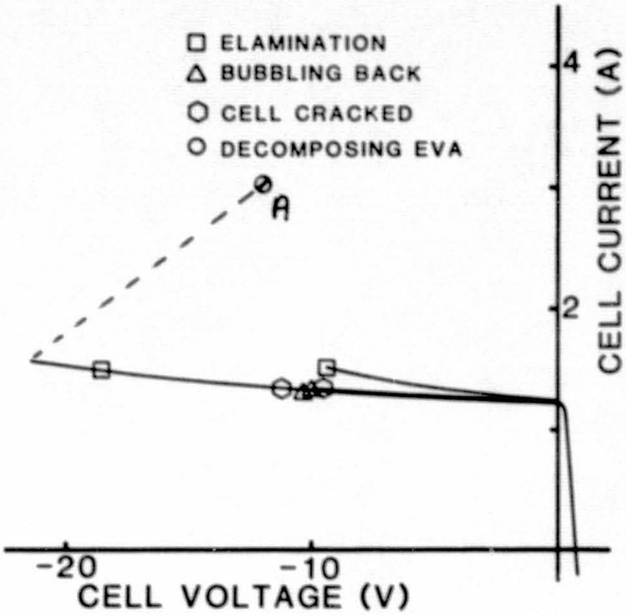


Broken Superstrate and Cell Delamination, Point A of the Curve

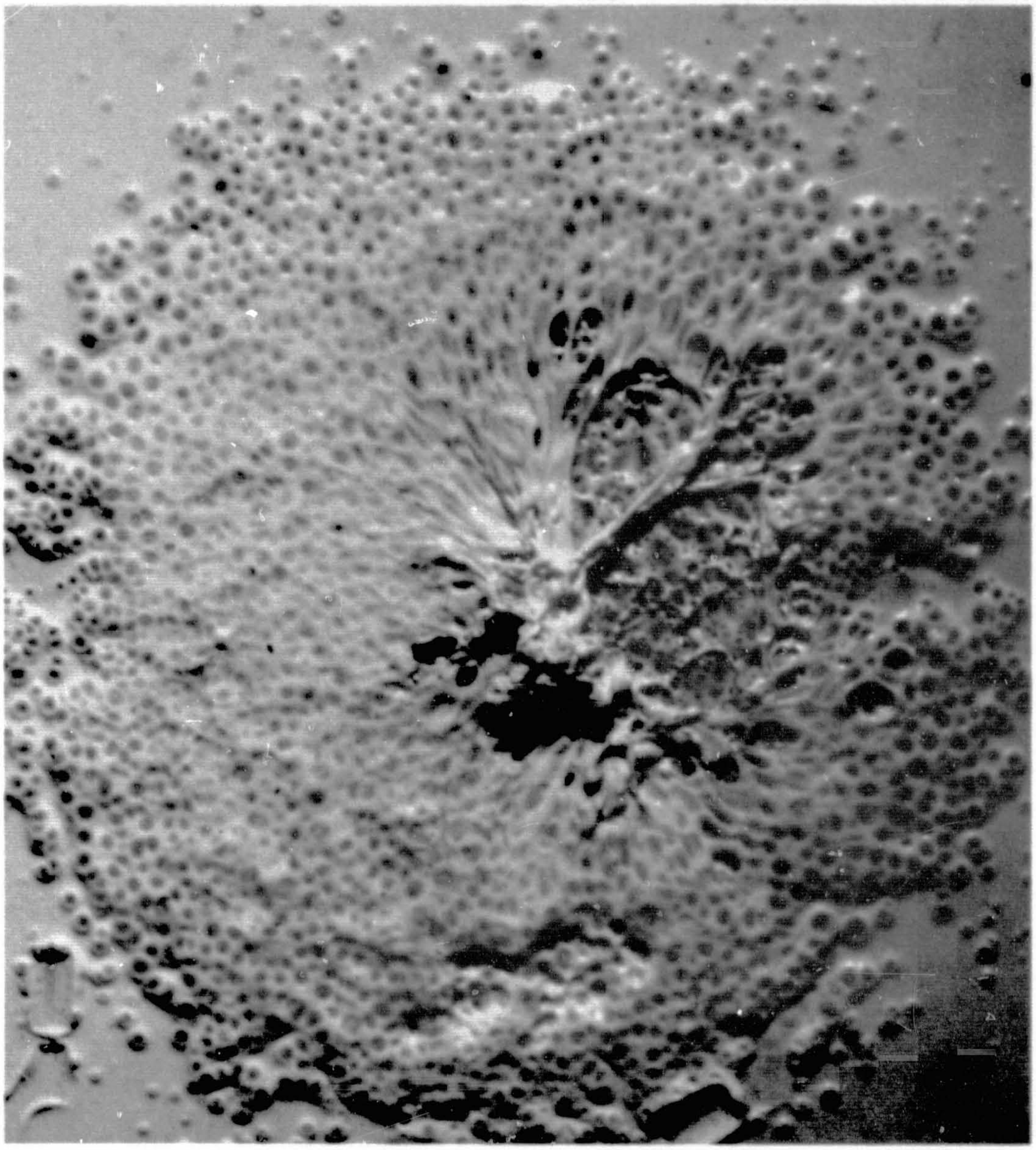


Cell Being Pushed Into the Backing at Point B of the Curve

I-V Curve of Masonite-Encapsulated Cell

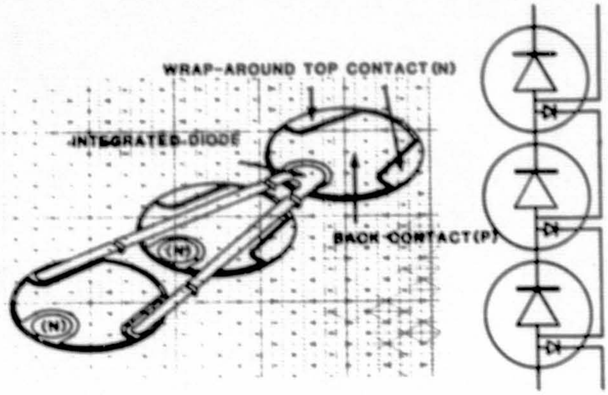


Back of Masonite After Three Hours at 10 V Reverse Bias



Degradation of the Encapsulation After a 5-Minute Power Dissipation of Approximately 35 W, at Point A of Curve

Design of Integrated Diode Solar Cell With Wraparound Top Contact



Conclusions

- o MODEL DESCRIBES THE BEHAVIOR OF AN UNENCAPSULATED CELL ADEQUATELY
- o GLASS ENCAPSULATED CELLS DO NOT WITHSTAND 20V BACKWARD BIAS, FAILURE OF ENCAPSULANT AS LOW AS 10V HAS BEEN OBSERVED
- o DEGRADATION OF MASONITE ENCAPSULATED CELLS STARTS AT 10V
- o INTEGRATED DIODE SOLAR CELL IS A POSSIBLE SOLUTION

PROJECT ANALYSIS AND INTEGRATION AREA

Technology Session

Paul K. Henry, Chairman

A discussion of Technical Readiness of \$2.80/W_p technology was presented in the plenary session. The discussion examined the way in which the most widely used technology in the industry, Czsochralski ingot, could meet the 1982 \$2.80/W_p commercial production milestone in the National Photovoltaics Program.

The analysis of energy payback time for photovoltaic module manufacturing responds to an increasing number of requests to the LSA Project for estimates of energy payback time and inquiries regarding conflicting estimates from other sources. The discussion described how energy payback time computation is incorporated in SAMIS and how the energy content of materials is being assembled into a data base in the Cost Account Catalog.

The latest addition to the SAMICS family of models, IPEG4, was introduced by Robert Chamberlain and Paul Firnett. IPEG is a major expansion in the capabilities, flexibility and simplicity of applying SAMICS, and it is cheap. A single SAMIS run is used to generate input data for IPEG4. Sensitivities can than be run quickly for any of the process input parameters.

TECHNICAL READINESS \$2.80 W_p

JET PROPULSION LABORATORY
Paul K. Henry

Agenda

1. BACKGROUND

2. 1980 PRODUCTION TECHNOLOGY - WHERE ARE WE NOW?

3. 1982 PRODUCTION TECHNOLOGY - WHAT DOES IT TAKE TO GET TO \$2.80/W_p?

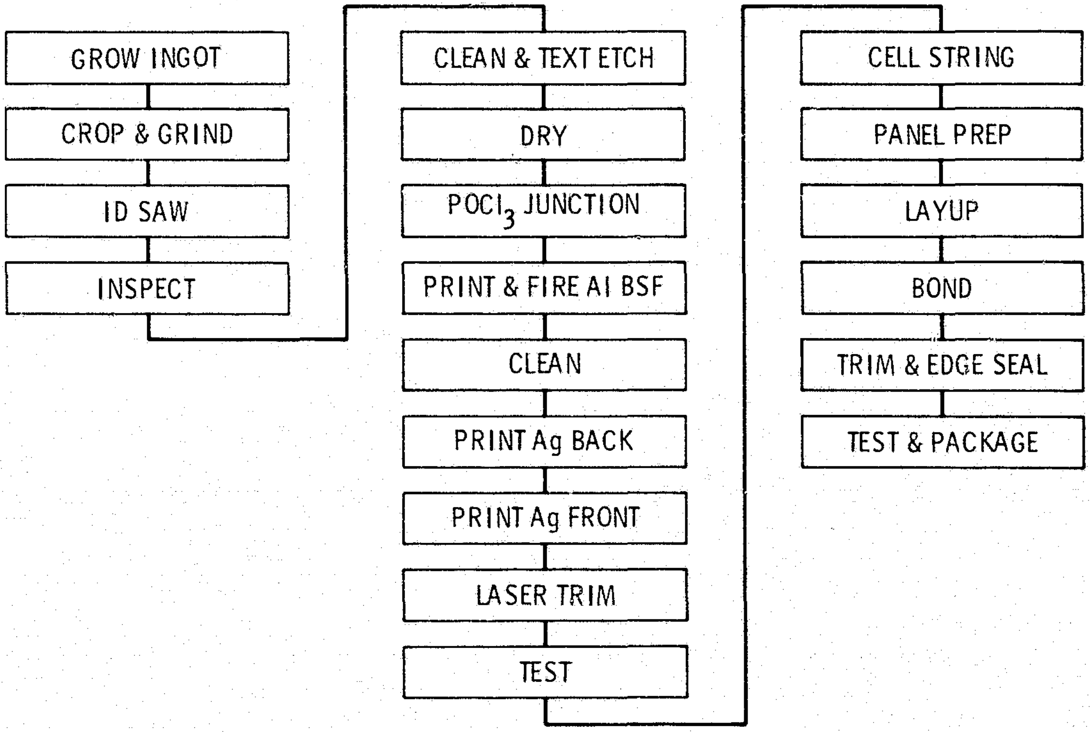
   a) 1982 BASELINE CASE - A CONSERVATIVE ESTIMATE

   b) SENSITIVITY TO VARIOUS PARAMETERS

Financial Parameters That Apply for All Cases

AFTER-TAX RATE OF RETURN I EQUITY CAPITAL	20%/YR
INTEREST RATE ON CORPORATE DEBT	9 1/4%/YR
COMBINED STATE/FEDERAL CORPORATE INCOME TAX RATE	50%
MAXIMUM INVESTMENT TAX CREDIT	11%
PROPERTY TAX RATE	2%/YR
INSURANCE PREMIUM RATE	4%/YR
GENERAL INFLATION RATE (AFTER 1980)	7%/YR
CONSTRUCTION AND EQUIPMENT CONTINGENCIES	15%
AVERAGE TIME IN INVENTORY FOR RAW MAT'LS & FINISHED GOODS	2 WEEKS
DAYS COMPANY CLOSED	20 DAYS
DAYS PER WORKER'S WEEK	5 DAYS
PAID DAYS OFF (HOLIDAYS, VACATION, SICK LEAVE, JURY DUTY, ETC.)	39 DAYS

Process Sequence Applied to Both 1980 and 1982 Cases



1980 Commercial Production Case Ground Rules

- ALL EQUIPMENT AND PROCESSES MUST PRESENTLY BE IN USE IN FULL-SCALE PRODUCTION SOMEWHERE IN THE INDUSTRY
- ALL EQUIPMENT AND PROCESSES NEED NOT PRESENTLY BE COLOCATED

1980 Commercial Technology Assumptions

GENERAL:

- PRODUCTION YEAR – 1980
- FACTORY SIZE – 5 MW/yr
- 3 SHIFTS/DAY, 7 DAYS/WEEK FOR INGOT GROWTH & SLICING
- 1 SHIFT/DAY, 5 DAYS/WEEK FOR ALL OTHER WORK STATIONS

SILICON MATERIAL:

- POLYSILICON COST – $84/Kg

PROJECT ANALYSIS AND INTEGRATION AREA

MODULE DESIGN AND PERFORMANCE:

- CELL DIAMETER - 4.015 INCH (102 mm)
- 2.5 FT x 4 FT MODULE (0.76m x 1.22m)
- GLASS SUPERSTRATE, PVB, CRANE GLASS, TEDLAR
- EXTRUDED ALUMINUM FRAME
- PACKING FACTOR – 77%
- MODULE EFFICIENCY – 9.47%
- ENCAPSULATED CELL EFFICIENCY – 12.3%
- MODULE PERFORMANCE - 88 W_p/MODULE
- SERIES-PARALLELING – 11 CELLS/STRING, 8 PARALLEL STRINGS
- BYPASS DIODE

INGOT GROWTH:

- ONE 20 kg Cz INGOT PER CRUCIBLE

INGOT SAWING:

- ID SAWING - 25 mils/SLICE PLUS KERF
- SAWING RATE - 1.5 in/min
- SAWING YIELD – 95%
- SAWS/OPERATOR – 3
- BLADE LIFE – 2500 SLICES

CELL PROCESSING:

- TEXTURE ETCHED
- $POCl_3$ JUNCTION FORMATION
- ALUMINUM BSF
- CLEAN & BRUSH
- PRINTED SILVER FRONT AND BACK CONTACTS ($18.40/oz SILVER)
- CELL PROCESSING YIELD ~ 87%

MODULE ASSEMBLY:

- CELL STRINGER – $75K EACH
- CELL STRINGERS/OPERATOR – 1
- MODULE TEST YIELD – 90%

1980 Commercial Technology Value Added (1980$)

	VALUE ADDED ($/$W_p$)
INGOT GROWTH (INCL. SILICON)	2.86
SAWING	0.83
CELL PROCESSING	0.65
MODULE ASSEMBLY (INCL. ENCAPSULATION MAT'L)	1.20
	$5.54/$W_p$

1982 Commercial Technology Ground Rules

- 1982 BASELINE CASE:

  ALL EQUIPMENT AND PROCESSES MUST BE PRESENTLY IN USE OR PROVEN AND AVAILABLE FOR PURCHASE, INSTALLATION AND COMMERCIAL OPERATION BY LATE 1982. ALL PARAMETERS VERY WELL KNOWN.

- SENSITIVITY CASES:

  SUBSTITUTE OPTIMISTIC OR PESSIMISTIC VALUES FOR CERTAIN KEY PARAMETERS

1982 Commercial Technology Assumptions

GENERAL:

- * FULL-SCALE PRODUCTION STARTS LATE 1982
- * FACTORY SIZE – 30 MW/yr
- * 3 SHIFTS/DAY, 7 DAYS/WEEK FOR ALL WORK STATIONS

*INDICATES A DEPARTURE FROM 1980 COMMERCIAL TECHNOLOGY CASE

MODULE DESIGN AND PERFORMANCE:

- CELL DIAMETER - 4.015 INCH (102mm)
- *4ft x 4ft MODULE (1.22m x 1.22m)
- GLASS SUPERSTRATE, *EVA, CRANE GLASS, TEDLAR
- *NO FRAME
- *PACKING FACTOR - 78% (ROUND CELLS)
- *MODULE EFFICIENCY - 9.6%
- ENCAPSULATED CELL EFFICIENCY - 12.3%
- *MODULE PERFORMANCE - 143 W_p/MODULE
- *SERIES-PARALLELING - 11 CELLS/STRING, 13 PARALLEL STRINGS
- BYPASS DIODE

*INDICATES A DEPARTURE FROM 1980 COMMERCIAL TECHNOLOGY CASE

SILICON MATERIAL:

- POLYSILICON COST - $84/Kg ($1980)

INGOT GROWTH:

- *TWO 26 Kg Cz INGOTS PER CRUCIBLE

INGOT SAWING:

- *ID SAWING - 20 mil/SLICE PLUS KERF
- *SAWING RATE - 2.0 in/min
- SAWING YIELD - 95%
- *SAWS/OPERATOR - 5
- *BLADE LIFE - 3100 SLICES

*INDICATES A DEPARTURE FROM 1980 COMMERCIAL TECHNOLOGY CASE

CELL PROCESSING:

- TEXTURE ETCHED
- $POCl_3$ JUNCTION FORMATION
- ALUMINUM BSF
- CLEAN AND BRUSH
- PRINTED SILVER FRONT AND BACK CONTACTS ($18.40/oz SILVER)
- *CELL PROCESSING YIELD – 89.1%

MODULE ASSEMBLY:

- *CELL STRINGER – $200K EACH
- *CELL STRINGERS/OPERATOR – 4
- *MODULE TEST YIELD – 99%

*INDICATES A DEPARTURE FROM 1980 COMMERCIAL TECHNOLOGY CASE

1982 Commercial Technology Value Added (1980$)

	VALUE ADDED ($/$W_p$)
INGOT GROWTH (INCL. SILICON)	1.63
SAWING	0.37
CELL PROCESSING	0.36
MODULE ASSEMBLY (INCL. ENCAPSULATION MAT'L)	0.34
	$2.70/$W_p$

$\$/W_p$ Effect of Changes Between 1980 and 1982 Technologies

PROCESS STEP	PARAMETERS	1980	1982	$0\$/W_p$
INGOT GROWTH	INGOTS/CRUCIBLE	1	2	\$0.40
SAWING	SLICE + KERF (D+K)	25	20	0.39
	SAWS/OPERATOR	3	5	0.18
	BLADE LIFE (SLICES)	2500	3100	0.02
ALUMINUM BACK	YIELD	98%	99%	0.04
	PRINTERS/OPERATOR	2	3	0.02
SILVER FRONT/BACK	YIELD (EACH)	98%	99%	0.08
	PRINTERS/OPERATOR	2	3	0.04
LAMINATION	THROUGHPUT RATE (MODULES/MIN)	0.2	0.3	0.03
EDGE TRIM & SEAL	FRAME	FRAME	NO FRAME	0.48
MODULE TEST	YIELD	90%	99%	0.50
				\$2.18
	SHIFTS/DAY	3-INGOT & SAW 1 REST OF PLANT	3 (7 DAYS/WK)	0.54
	MISC			0.12
	BOTTOM LINE ($\$/W_p$)	\$5.54 –	\$2.70 =	\$2.84

Total Initial Capital Investment

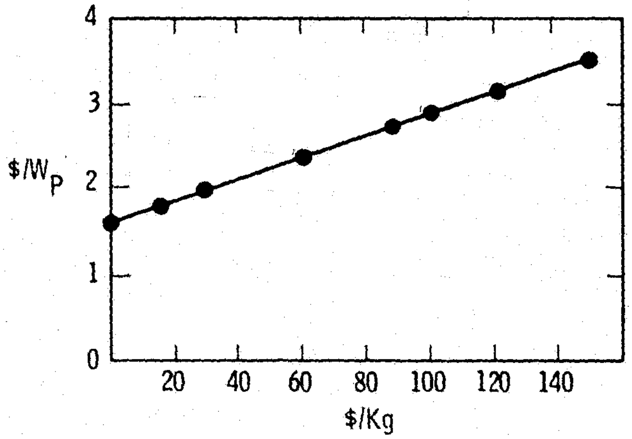
PLANT DESCRIPTION	TOTAL INVESTMENT (MILLIONS)	DIVIDED BY OUTPUT (\$/W)
1980 5 MW	12.6	2.5
1982 5 MW (4 SHIFTS)	7.8	1.6
1982 15 MW (4 SHIFTS)	17.6	1.2
1982 30 MW (4 SHIFTS)	32.7	1.1

°IN 1980 DOLLARS. INCLUDES EQUIPMENT, WORKING CAPITAL, ALL FACILITIES AND LAND.

Silicon Price Sensitivity

BASED ON THE $2.70/W CASE WITH THE 2 INGOTS/CRUCIBLE
Cz FURNACE AND 20 mil D+K ID SAWS:

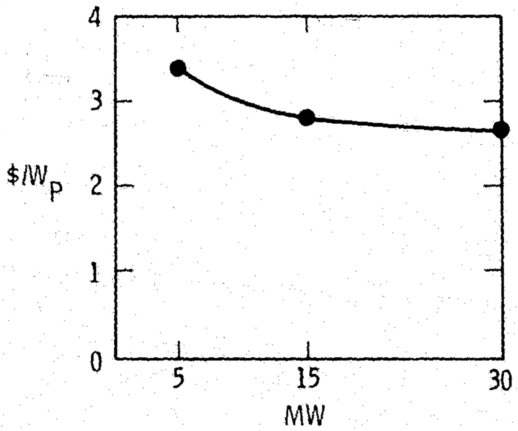
Si PRICE ($/kg)	MODULE PRICE ($/W)
0	1.55
14	1.74
28	1.93
60	2.37
84	2.70
100	2.92
120	3.19
150	3.60



Factory Size Sensitivity

BASED ON THE $2.70/W CASE WITH THE 2 INGOT/CRUCIBLE
Cz FURNACE, 20 mil D+K SAWS:

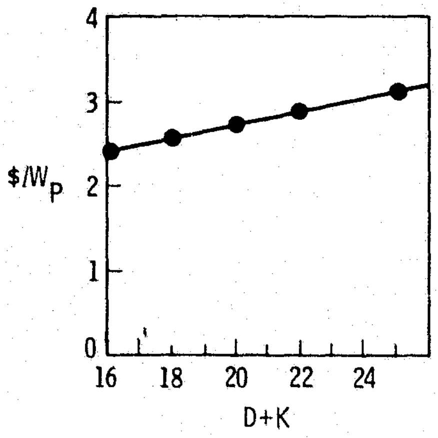
FACTORY SIZE (MW)	MODULE PRICE ($/W$_P$)
5	3.35
15	2.82
30	2.70



Saw Slice + Kerf (D + K) Sensitivity

BASED ON THE \$2.70/W_p CASE WITH THE 2 INGOT/CRUCIBLE
Cz FURNACE, 2 INCH/MINUTE PLUNGE RATE:

D+K (MILS)	MODULE PRICE \$/W_P
25	3.09
22	2.86
20	2.70
18	2.54
16	2.39



Major Components of Capital Investment*

COMPONENT	1980 (5 MW)	1982 (5 MW)	1982 (15 MW)	1982 (30 MW)
WORKING CAPITAL	2.8	1.8	4.8	9.3
FACILITIES	2.7	1.8	3.1	5.3
SAWS	1.6	1.1	3.2	6.4
Cz EQUIPMENT	1.2**	1.0	3.0	6.0
PRINTERS + DRYERS	0.6**	0.2	0.4	0.6
OTHER CELL EQUIPMENT	2.4**	1.1	1.8	2.9
REMAINING EQUIPMENT	1.2**	0.7	1.2	2.1
TOTAL EQUIPMENT	7.0	4.1	9.6	18.0

*IN MILLIONS OF 1980 DOLLARS.

**OPERATED 40 HOURS/WEEK. OTHER EQUIPMENT OPERATED 160 HOURS/WEEK.

Options for Further Price Reductions

- NONPRECIOUS METALS
- PLATING METALLIZATION
- SEMIX INGOT GROWTH
- HEM INGOT GROWTH
- WEB RIBBON
- EFG RIBBON
- IMPROVED SAWING

Summary

- PATH FROM 1980 COMMERCIAL TECHNOLOGY TO 1982 COMMERCIAL TECHNOLOGY CLEARLY DISCERNIBLE – AUTOMATION, YIELDS, MODULE DESIGN
- ALL ASSUMPTIONS QUITE CONSERVATIVE - NO OPTIMISTIC ASSUMPTIONS NECESSARY
- MODULE ENGINEERING – IMPORTANT FACTOR
- BY 1982, CELL AND MODULE PROCESSING WITHIN FACTOR OF 2 OF 1986 GOAL
- INGOT GROWTH AND SAWING WILL BE LARGE 1982 COST DRIVERS
- POLYSILICON WILL CONTRIBUTE OVER $1.00/W TO 1982 PRICE

Conclusions

- TECHNICAL READINESS FOR $\$2.80/W_p$ COMMERCIAL PRODUCTION IN 1982 HAS BEEN ACHIEVED

- SEVERAL OPTIONS EXIST WHICH COULD DRIVE THE PRICE WELL BELOW $\$2.80/W_p$ BY LATE 1982 OR 1983

PRELIMINARY ENERGY PAYBACK ANALYSIS FOR A PV MANUFACTURING INDUSTRY

JET PROPULSION LABORATORY

Erin D. Muha

?

ENERGY PAYBACK TIME (PBT) $\overset{>}{\underset{=}{\textcircled{<}}}$ **SOLAR ARRAY LIFETIME**

Energy Content of Materials

SAMICS REFERENT	MATERIAL	ENERGY CONTENT	SAMICS REFERENT	MATERIAL	ENERGY CONTENT
EG1056D	ACETATE, CHROMIUM	19.7 kW/lb	EAID	HYDROGEN FLUORIDE	147.8 kWh/ft^3
EG1058D	ACETATE, NICKEL	19.7 kW/lb	E1128D	INK SOLVENT (BUTYL ACETATE)	1.73 kW/lb
EG1064D	ACETATE, SODIUM	19.7 kW/lb	E1360D	KORAD A (76.2 mm thick)	0.66 kWh/lb
E1016D	ACID, ACETIC	2.95 kW/lb	E1382D	LUCITE	0.66 kWh/lb
E1400D	ACID, NITRIC	4.25 kW/lb	EG30D	MYLAR (5 mil thick)	0.00642 kWh/ft^2
E1640D	ACID, SULFURIC	0.15 kWh/lb	E1796D	NITROGEN GAS	0.036 kWh/ft^3
E1352D	ALCOHOL, ISOPROPYL	16.5 kWh/gal	EG55D	NITROGEN, LIQUID	1.27 kWh/l
EG52D	ALCOHOL, METHANOL	1.26 kWh/l	E1448D	OXYGEN GAS	0.028 kWh/ft^3
E0001D	ALCOHOL, METHYL	4.77 kWh/gal	EM1460D	PHOSPHINE GAS	1.42 kWh/ft^3
E1096D	ALUMINUM	31.9 kWh/lb	E1502D	POCL$_3$ (PHOSPHORUS OXYCHLORIDE)	63.5 kWh/lb
E1108D	AMMONIA GAS	0.18 kWh/ft^3	EG1D	POLYVINYL BUTYRAL (0.01 mil thick)	1.479e^{-4}kWh/ft^2
E1110D	AMMONIUM HYDROXIDE	37.4 kWh/ft^3	EG1007D	RESIST, PLATING	19.7 kWh/gal
E1112D	ARGON GAS	0.028 kWh/ft^3	EG1586D	SILICON (POLYCRYSTALLINE MG)	23.97 kWh/kg
EP1044D	CERAMIC BLOCK	0.824 kWh/block	E1586D	SILICON (POLYCRYSTALLINE Se-G)	621 kWh/kg
EG16D	COPPER STRIP	0.036 kWh/ft	E1592D	SILVER	0.441 kWh/g
E5009D	COVER FILM, POLYESTER (2 mil thick)	2.56E-3 kWh/ft^2	E1632D	STYCAST (1269A)	0.659 kWh/lb
E1284D	GLASS, TUBING	3274.27 kWh/$	E1664D	TANTALUM PENTOXIDE	0.11 kWh/g
E1812D	GLASS, FLOAT	4.89 kWh/ft^2	E1672D	TEDLAR (1 mil thick)	0.00651 kWh/ft^2
E1480D	GLASS, PLEXIGLASS	52.6 kWh/m^2	E1704D	TITANIUM	59.73 kWh/lb
EP12D	GLASS, SEALING	0.83 kWh/m^2	ES002D	TITANIUM DIOXIDE	11.27 kW/lb
E1828D	GLASS, TEMPERED FLOAT	4.89 kWh/ft^2	EG4D	TOLUENE	3.9 kWh/gal
EG1018D	GRAPHITE BEAM MOUNT	2.8 kWh/each	E1716D	TRICHLOROSILANE	73.9 kWh/lb
E1144D	HYDROGEN GAS	2.34 kWh/m^3	EG1900D	VACUUM PUMP OIL	71.42 kWh/gal

Payback Time Factor

$$\text{pbtf} = \frac{G \cdot \text{CHPY}}{1000} = 1.7531617 \left(\frac{\text{hr}}{\text{yr}}\right)\left(\frac{\text{kW}_e}{\text{W}_p}\right)$$

$$G = \text{SOLAR ENERGY USAGE (\%)} = 0.20 \ \frac{\text{W}_e\text{hr}}{\text{W}_p\text{hr}}$$

$$\text{CHPY} = \text{CALENDAR HOURS PER YEAR} = 8765.8128 \ \frac{\text{hr}}{\text{yr}}$$

$$1000 = \text{CONVERSION FACTOR} = \frac{\text{W}_e}{\text{kW}_e}$$

Example: Energy Payback Analysis Using SAMICS

PARAMETERS:

(1) Cz INGOT GROWTH

(2) ID SAWING

(3) 4-in. ROUND INGOT

(4) 15% ENCAPSULATED CELL EFFICIENCY

(5) MANUFACTURING YEAR IS 1986

(6) 100 MEGAWATTS PRODUCED PER YEAR

RESULT:

NET ENERGY PAYBACK = 2.962 YEARS

*DESIGNATES SAMICS CATALOGUE ITEMS WITH VALUE FOR ENERGY CONTENT

SAMIS DIRECT REQUIREMENTS	
REFERENT	DESCRIPTIVE NAME
D1032D	ACID, POISONOUS
*E1640D	ACID, SULFURIC
C2032D	AIR, COMPRESSED
*E1352D	ALCOHOL, ISOPROPYL
E1112D	ARGON GAS
E1204D	BLADES, DIAMOND
EG1024D	BLADE DRESSING
EA4D	BUS BAR, COPPER
E1100D	CHANNEL, ALUMINUM
E1080D	COATING, ANTIREFLECTIVE
E1180D	CRATES, WOODEN
*C1032B	ELECTRICITY
E1232D	EDGE SEAL
EF1015D	EVA FILM, 0.015 IN. THICK
*E1829D	GLASS, TEMPERED FLOAT
E1526B	GRAPHITE
EG13D	GRINDING WHEEL
EP20D	INTERCONNECTS, COPPER
EF1017	MYLAR/ALUMINUM FILM BACK
C1064B	NATURAL GAS
*E1416D	NITROGEN GAS, REG.
*E1448D	OXYGEN GAS
EP27D	PASTE, ALUMINUM
E1064D	PASTE, SILVER 80%
*E1504D	POCL3, PHOSPHOROUS
*E1520D	QUARTZ
E1576D	SCREEN
E1600D	SODIUM HYDROXIDE
EG1600D	SOLDER PASTE
E1608D	SPARE PARTS
*E1586D	SILICON, POLYCRYSTALINE, (SG
EG14D	SILICON SEED CRYSTAL
D1096B	WASTE, SOLID
C1128D	WATER, COOLING
C1144D	WATER, DEIONIZED
C1016B	WATER, DOMESTIC
D1048D	WATER, POLLUTED

How Energy Payback Time Is Calculated By the SAMICS Program

$$PBT = \frac{ENERGY}{f * IS * pbtf}$$

PBT = ENERGY PAYBACK TIME FOR A COMPANY (OR A WORK STATION)

ENERGY = AMOUNT OF ENERGY PER YEAR FROM NATURAL RESOURCES NEEDED IN THE MANUFACTURING OF PRODUCT X (MEASURED IN $kW_e hr/yr$ OF ACTUAL ELECTRICAL ENERGY)

f = RATIO OF A PRODUCT X PRODUCED BY AN INDIVIDUAL COMPANY TO THE TOTAL AMOUNT OF PRODUCT X PRODUCED BY THE WHOLE PRODUCT X INDUSTRY

IS = INDUSTRY SIZE (W_p/yr)

pbtf = PAYBACK TIME FACTOR; CONVERTS W_p OF ENERGY MANUFACTURED BY THE WHOLE PRODUCT X INDUSTRY TO Whr OF ENERGY PRODUCED BY PRODUCT X OVER AN AVERAGE YEAR OF PRODUCT X'S USE (hr/yr) (kW_e/W_p)

IPEG4: IMPROVED PRICE ESTIMATION GUIDELINES

COMPUTER PROGRAM IMPLEMENTATION

JET PROPULSION LABORATORY

Robert G. Chamberlain

- WHAT IS IPEG AND SO WHAT?
- LET SAMIS DO THE SCUT WORK
- WHEN TO USE SAMIS, WHEN IPEG
- HOW TO USE IPEG4

What Ever Happened to IPEG2 and IPEG3?

ORIGINAL IPEG - INTERIM PRICE ESTIMATION GUIDELINES
(JPL DOC 5101-33, 9/10/77, BY R. W. ASTER)

- $PRICE = (0.49\ EQPT + 97\ SQFT + 2.1\ DLAB + 1.3\ MATS + 1.3\ UTIL)/QUAN$
- "INTERIM" MEANT "WHILE SAMIS PROGRAMMING WAS COMPLETED"
- RESULTS COMPARE WELL WITH SAMIS - BUT "WHAT IF . . . CHANGES?"

IPEG2 - IMPROVED PRICE ESTIMATION GUIDELINES

- $PRICE = (C_{13}\ EQPT_3 + C_{15}\ EQPT_5 + \ldots C_{1,20}\ EQPT_{20} + C_2\ SQFT + C_3\ DLAB + C_4\ MATS + C_5\ UTIL)/QUAN$
- $C_{13} = 0.81$, $C_{15} = 0.61$, $C_{17} = 0.54$, $C_{1,10} = 0.49$, $C_{1,15} = C_{1,20} = 0.47$, $C_2 = 110.61_{\$80}/\mathrm{ft}^2$, $C_3 = 2.14$, $C_4 = C_5 = 1.23$
- SOME SUBMODELS AND DATA IMPROVED
- EQUIPMENT LIFETIME DIFFERENCES AFFECT *PRICE*
- ANALYTIC EXPRESSIONS DERIVED FOR THE *C*'S

IPEG3 - SUPER-IPEG (EXISTS IN CONCEPT ONLY)

- EXPAND CATEGORIES OF SQFT AND DLAB
- INCLUDE OFF-DIAGONAL TERMS IN INDIRECT REQUIREMENT SUBMODEL
- MAY OR MAY NOT BE IMPLEMENTED EVENTUALLY

IPEG4 - COMPUTER VERSION OF IPEG2

- COMPUTES *PRICE* FOR CHANGES IN *EQPT, SQFT, DLAB, MATS, UTIL, QUAN* (TRIVIAL)
- COMPUTES NEW *C*'S FOR CHANGES IN ECONOMIC ASSUMPTIONS (NOT TRIVIAL)
- FACILITATES SENSITIVITY STUDIES
  - PRINTER PLOTS OF (EG) *ROROE* VS *PRICE*
  - MUCH CHEAPER THAN SAMIS: RUN COST≈ \$4 + \$2/CASE
- DOES NOT REPLACE SAMIS
  - IPEG4 HAS SIMPLIFIED ECONOMIC MODEL (EG NO INFLATION)
  - IPEG4 HAS NO NONLINEARITIES OF SCALE

IPEG4 Documentation

JPL DOC 5101-156, *IMPROVED PRICE ESTIMATION GUIDELINES (IPEG) COMPUTER PROGRAM USER'S GUIDE,* PAUL J. FIRNETT, JULY 21, 1980.

JPL DOC 5101-158, *IMPROVED PRICE ESTIMATION GUIDELINES (IPEG) DESIGN DOCUMENT,* ROBERT W. ASTER, ET AL, JULY 21, 1980

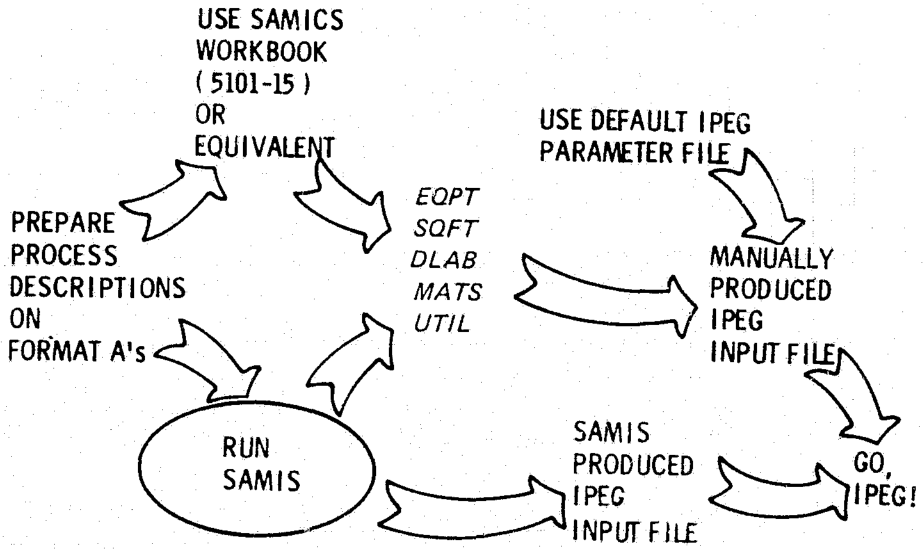
JPL DOC 5101-159, *IMPROVED PRICE ESTIMATION GUIDELINES (IPEG) COMPUTER PROGRAM SOURCE CODE,* ROBERT G. CHAMBERLAIN, ET AL, JULY 21, 1980

IPEG4 Questionees

FOR QUESTIONS ON THE COMPUTER PROGRAM, CONTACT:
PAUL FIRNETT (213) 354-4670

FOR QUESTIONS ON THE MODEL, CONTACT:
BOB ASTER (213) 577-9545

Let SAMIS Do the Scut Work?



Three Ways to Use IPEG

WHO NEEDS A COMPUTER?

- CALCULATE *EQPT, SQFT, DLAB, MATS, UTIL* (SOMEHOW)
- USE IPEG2 VALUES OF COEFFICIENTS: CALCULATE *PRICE*
- CALCULATE EFFECTS OF CHANGES IN *EQPT, SQFT, DLAB, MATS, UTIL*

LET SAMIS CALCULATE DIRECT REQUIREMENTS

- USE SAMIS TO GET *EQPT . . . UTIL* FROM FORMAT A's
- USE IPEG2 BY HAND, OR
- BY COMPUTER VIA DEFAULT IPEG PARAMETER FILE
- COMPUTE (AND PLOT?) SENSITIVITIES TO INPUTS AND PARAMETERS

USE SAMIS TO TAILOR THE IPEG PARAMETERS

- USE SAMIS TO GET *EQPT . . . UTIL* FROM FORMAT A's
- LET SAMIS ADJUST IPEG PARAMETERS FOR ECONOMIES OF SCALE, DETAILED INDIRECT STRUCTURE, FACILITY REQUIREMENTS, ETC.

How to Read SAMIS Output (to Get IPEG Inputs)

WHAT HAS TO BE FOUND:

EQPT = PURCHASE COST OF EQUIPMENT IN MFG YEAR $

SQFT = DIRECT FLOOR AREA NEEDED BY EQUIPMENT AND OPERATORS IN SQUARE FEET.

DLAB = ANNUAL COST OF DIRECT LABOR (INCLUDING FRINGE BENEFITS) IN MFG YEAR $

MATS = ANNUAL COST DIRECT MATERIALS AND SUPPLIES IN MFG YEAR $

UTIL = ANNUAL COST OF DIRECT (MFG PROCESS REQUIRED) UTILITIES IN MFG YEAR $

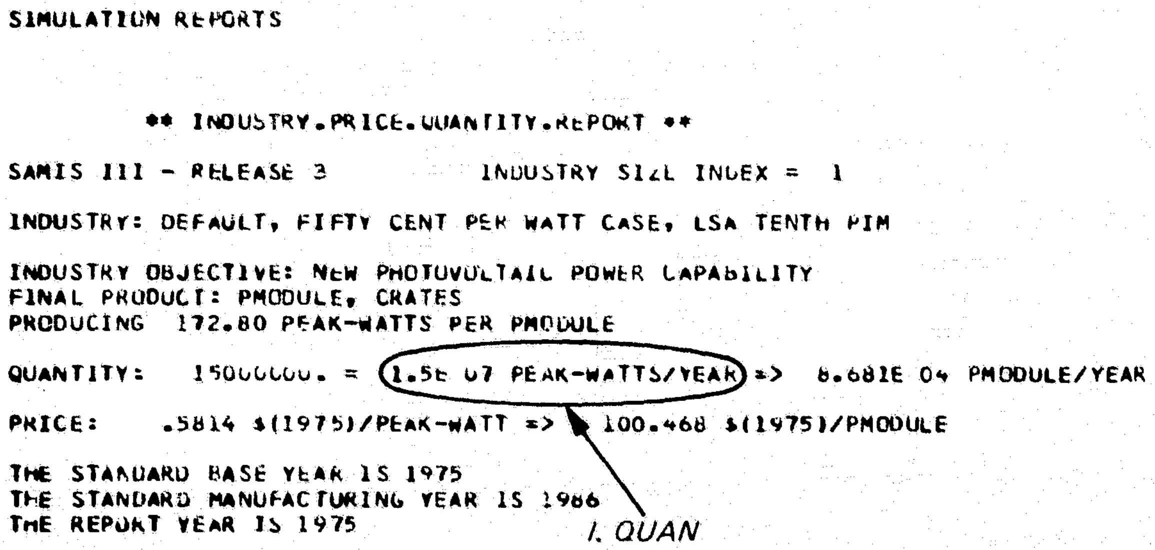
I. QUAN = ANNUAL PRODUCTION QUANTITY ASSOCIATED WITH *EQPT, SQFT, DLAB, MATS, UTIL* EXPRESSED IN PEAK WATTS PER YEAR .

P. QUAN = ANNUAL PRODUCTION QUANTITY EXPRESSED IN PRODUCT UNITS (EG: MODULES OR CELLS) PER YEAR.

G = INFLATION RATE IN FRACTION/YEAR.

How to Read SAMIS Output: Warnings

- IPEG CAN BE APPLIED AT COMPANY LEVEL OR PROCESS LEVEL
  - DO NOT MIX INPUTS, BUT *I.QUAN* COMES FROM INDUSTRY LEVEL REPORT AND *G* COMES FROM COMPANY LEVEL REPORT
- IPEG DOES NOT DEAL WITH INFLATION - SO *EQPT, DLAB, MATS,* AND *UTIL* (AND C_2) MUST BE IN SAME YEAR DOLLARS AS *PRICE* (BUT THE INFLATION RATE, *G*, IS NEEDED NONETHELESS)
- BYPRODUCT EXPENSES AND REVENUES, IF ANY, ARE TO BE INCLUDED IN *MATS.*
- IPEG WILL ALLOW YOU TO VARY *EQPT* (FOR EXAMPLE) WITHOUT VARYING *DLAB* (FOR EXAMPLE). IF YOU MEAN TO INCREASE THE NUMBER OF MACHINES WITHOUT CHANGING THE NUMBER OF MACHINES PER OPERATOR, YOU MUST ALSO INCREASE *DLAB.* IPEG CONTAINS NO RELATIONSHIPS BETWEEN ITS INPUTS.



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SIMULATION REPORTS


        ** INDUSTRY.PRICE.QUANTITY.REPORT **

SAMIS III - RELEASE 3          INDUSTRY SIZE INDEX =  1

INDUSTRY: DEFAULT, FIFTY CENT PER WATT CASE, LSA TENTH PIM

INDUSTRY OBJECTIVE: NEW PHOTOVOLTAIC POWER CAPABILITY
FINAL PRODUCT: PMODULE, CRATES
PRODUCING  172.80 PEAK-WATTS PER PMODULE

QUANTITY:   15000000. = 1.5E 07 PEAK-WATTS/YEAR =>  6.681E 04 PMODULE/YEAR

PRICE:    .5814 $(1975)/PEAK-WATT =>  100.468 $(1975)/PMODULE

THE STANDARD BASE YEAR IS 1975
THE STANDARD MANUFACTURING YEAR IS 1986
THE REPORT YEAR IS 1975
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I. QUAN

Company Data

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SIMULATION REPORTS                                                                10:11 AM  06/25/80  PAGE
                                                                                          COMPANY: $.50/WATT


         ** $.50/WATT: COMPANY.SUMMARY.REPORT **

COMPANY: $.50/WATT, $.50 PER WATT

PRODUCT    QUANTITY SOLD            NORMATIVE PRICE
---------- -------------            ------------------
PMODULE    8.661E 04 CRATED PM @    100.468 $(1975)/CRATED PM =    .5614 $(1975)/PEAK-WATT

  ENERGY ADDED PAYBACK TIME =    .190 YEARS
  COMPANY MARKUP =    1.687 TIMES (DIRECT EXPENSES PLUS EXTERNAL PRODUCT COSTS)
  COMPANY PROFIT =       942,814. $(1975) = 10.6% OF SALES REVENUES = 101.5% OF EQUITY

    CAPITAL VALUES
           INFLATOR (1975 TO 1986)= 2.1024  DEFLATOR (1986 TO 1975)=  .4757
           ---------- IN $(1986)----------   --------- IN $(1975)---------
              INITIAL      BOOK   TAXABLE       INITIAL      BOOK   TAXABLE
    FACILITIES 2121787.   473470.   406972.      1009234.   225207.   194529.
    EQUIPMENT  4825429.  1870008.  1106394.      2295229.   669475.   526259.
    WORKING   [illegible] 1889965.  1889965.       898967.   898967.   898967.
    LAND         50415.    50415.    50415.        23980.    23980.    23980.
              --------- --------- ---------     --------- --------- ---------
      TOTAL    8887596.  4283857.  3455746.      4227411.  2037629.  1643735.

    FINANCIAL PARAMETERS
     COST OF    RATE OF RETURN      DEBT          LEVERAGE       INCOME TAX   CONSTRUCTION CONTINGENCIES
     CAPITAL      ON EQUITY    INTEREST RATE   (TOTAL/EQUITY)      RATE        FACILITIES    EQUIPMENT
   -CALCULATED-    -INPUT-        -INPUT-         -INPUT-       -CALCULATED-     -INPUT-      -INPUT-
      17.44%       20.00%          9.25%           1.20           49.75%         15.00%       15.00%

    TIME PARAMETERS
    CONSTRUCTION LEAD TIME = 2.00 YEARS, STARTUP PERIOD = 1.00 YEARS
    RAW MATERIAL INVENTORY TIME (INPUT)          =  .040 YEARS (  14.6 DAYS)
    BETWEEN PROCESS INVENTORY TIME (INPUT)       = 0.    YEARS (   0.  DAYS)
    INPROCESS INVENTORY TIME (CALCULATED)        =  .004 YEARS (   1.6 DAYS)
       (MULTIPLIED BY 1.0 FOR WORKING CAPITAL CALCULATION)
    FINISHED GOODS INVENTORY TIME (INPUT)        =  .040 YEARS (  14.6 DAYS)
    ACCOUNTS RECEIVABLE TURNOVER TIME (INPUT) = 1.000 YEARS ( 365.2 DAYS)
    ACCOUNTS PAYABLE TURNOVER TIME (INPUT)       =  .990 YEARS ( 361.6 DAYS)
                                                 --------------------------
    WORKING CAPITAL TIME LAG (CALCULATED)        =  .094 YEARS (  34.4 DAYS)

      ALL COMPANY EXPENSES ARE IN $(1975)                           $(1975)/PEAK-WATT
      COMPANY DIRECT EXPENSES                  5,169,115.                  .3446
         COMPANY DIRECT LABOR EXPENSES                    789,273.         .0526
         COMPANY DIRECT MATERIALS AND SUPPLIES          [illegible]        .2846
         COMPANY DIRECT BYPRODUCT EXPENSES                    17.          .0000
         COMPANY DIRECT UTILITIES EXPENSES                110,940.         .0074

      COMPANY INDIRECT EXPENSES                  652,876.                  .0435
         COMPANY INDIRECT LABOR EXPENSES                  534,174.         .0356
```

P.QUAN

TB TM A

$r = TM - TB$

$G = \sqrt[r]{A} - 1$ (NEEDED FOR PROCESS DATA, TOO)

EQPT

DLAB

ADD TO GET *MATS*

UTIL

(NEXT PAGE) BYPRODUCT INCOME (0) SUBTRACT THIS

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SIMULATION REPORTS                                                                                   10:11 AM  08/25/80  PAGE   5
                                                                                                        COMPANY: $.50/WATT

     EFG        SX-9          .139 $/RIBBON    =     .171 $/PEAK-WATT   29.49
                                                   --------------------
     TOTAL VALUE ADDED:     100.409 $/CRATED PM =     .581 $/PEAK-WATT

          ** $.50/WATT: BRIEF.FIRM.NEEDS.REPORT **

        THIS COMPANY, $.50/WATT, HAS THE FOLLOWING (ANNUAL) REQUIREMENTS:

          ALL PRICES AND COSTS ARE IN $(1975)
```

FOR *SQFT* ADD QUANTITIES FOR A2064D, A2080D, A2096D
FROM THE LIST OF DIRECT REQUIREMENTS

```
          DIRECT REQUIREMENTS
QUANTITY      PRICE       COST  REFERENT   DESCRIPTIVE NAME         QUANTITY      PRICE       COST  REFERENT   DESCRIPTIVE NAME
 1.550E 03    122.38    189691. A2080D     FLOOR SPACE, CLEAN ROO   4.836E 03     39.16    189373. A2064D     FLOOR SPACE, TILE (WIT

 4.106E 01  10326.32    423784. B3672D     CHEMICAL OPERATOR II     8.624E 00   9652.83     83242. B3752D     OPERATOR, PRODUCTION-M
 6.506E 00   8317.87     54117. B3032D     ASSEMBLER, ELECTRONICS   4.172E 00  12117.39     50550. B3736D     MAINTENANCE MECHANIC 1
 4.695E 00   8317.87     39050. B3096D     ASSEMBLER, SEMICONDUCT   2.107E 00   8420.56     17742. B3768D     TESTER, ELECTRONIC COM
 5.616E-01  23618.65     13265. B3224B     ENGINEER, INDUSTRIAL     1.114E 00  11295.87     12586. B3666D     ELECTRONICS MAINTENANC
 5.575E-01  11295.87      6297. B3704D     ELECTRONICS TECHNICIAN   5.627E-01   8317.87      4681. B3064D     ASSEMBLER, GENERAL (EL
 1.431E-01  10063.59      1440. B3056D     PACKAGER, MACHINE        6.373E-03   8471.90        54. B3720D     INSPECTOR, SYSTEMS (QU

 3.594E 06       .03    108834. C1032B     ELECTRICITY              3.097E 05       .01      2057. C1016B     WATER, DOMESTIC
 1.141E 00     42.43        48. C1080D     NITROGEN, LIQUID         1.159E 05      0.           0. C2128B     VENTILATION

 4.208E 00      4.05        17. D61024D    OIL, VACUUM PUMP, USED

 2.459E 06       .78   1920966. E1064D     PASTE, SILVER 80%        6.488E 04      9.99    648031. E1586D     SILICON, POLYCRYSTALIN
 1.417E 06       .25    360440. E1812D     GLASS, ANNEALED, 1/8 I   5.669E 06       .06    351416. E61D       POLYVINYL BUTYRAL (U.V
 1.417E 05       .17    238396. E630D      MYLAR, 5 MIL THICK       1.702E 07       .01    229124. EP20D      INTERCONNECTS, COPPER
 7.973E 03      9.13     72809. E1560D     RTV 615 (SILICONE)       6.275E 04      1.00     62754. E1696D     THERMOCOUPLE
 4.178E 06       .01     60425. E1112D     ARGON GAS                6.351E 05       .06     53487. E1304D     HELIUM GAS
 1.454E 04      3.60     52383. E61700D    TETRAFLUOROMETHANE       3.611E 04      1.00     36112. E6807D     EFG CARTRIDGE MATERIAL
 9.292E 03      3.57     33166. E1576D     SCREEN                   1.772E 05       .16     28148. E639D      TERMINAL BLOCK SETS
 7.873E 04       .35     27540. E1624D     SQUEEGEES                1.813E 03     10.33     18732. E1060D     COATING, ANTIREFLECTIV
 1.417E 06       .01     15897. E1100D     CHANNEL, ALUMINUM        1.063E 06       .01     15012. E637D      WIRE, TERMINAL BUS
 1.387E 04      1.00     13868. E6803D     EFG INSULATION MATERIA   5.241E 01    173.90      9115. E1120D     BOATS, (12" X 4")
 7.197E 03      1.00      7197. E6801D     EFG DIES                 6.921E 03      1.00      6921. E6805D     EFG HEATING ELEMENT
 3.841E 03       .81      3094. EP27D      PASTE, ALUMINUM          2.894E 04       .07      2014. E1180D     CRATES, WOODEN
 1.819E 03       .80      1451. E64D       TOLUENE                  1.148E 05       .00       391. E1416D     NITROGEN GAS, REGULAR
 2.966E-02     75.82         2. E61460D    PHOSPHINE GAS


          INDIRECT REQUIREMENTS
QUANTITY      PRICE       COST  REFERENT   DESCRIPTIVE NAME         QUANTITY      PRICE       COST  REFERENT   DESCRIPTIVE NAME
 3.077E 03     27.73     85319. A21261     OFFICE SPACE, ADMINIST   9.404E 01    817.71     76898. A20061     AIR CONDITIONING FACIL
 9.851E 02     50.85     50105. A20181     CAFETERIA AND LUNCHROO   3.265E 03     11.09     36223. A21321     OFFICE FURNISHINGS
 4.019E 02     67.95     27308. A22561     TOILET AND LOCKER ROOM   2.099E 04      1.00     20990. A21781     MAINTAINENCE AND MACHI
 5.985E 02     33.28     19915. A11921     SANITARY SEWERS          6.344E 04       .31     19575. A10801     LAND
 1.320E 03     11.41     15057. A22721     FLOOR SPACE, WAREHOUSE   6.298E 02     22.82     14372. A20401     WALLS, EXTERIOR
 1.000E 00  14276.51     14277. A56001     FORKLIFTS                8.050E 02     17.04     13719. A21601     PASSAGES AND CORRIDORS
 1.168E 04      1.00     11680. A13621     WALKS, CURBS AND GUTTE   2.021E 02     50.01     10107. A20241     COMPUTER ROOM AND COMP
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SIMULATION REPORTS                                                                                 10:11 AM  06/25/80  PAGE   6
                                                                                                           COMPANY: $.50/WATT
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OR, GET *SQFT* FROM A30321 IN THE INDIRECT LIST

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2.490E 04        .40     10016. A12721    PARKING LOT PAVING (LI   5.797E 02      16.72      9690. A20321    ELECTRICAL EQUIPMENT R
5.790E 02      16.72      9679. A21121    MECHANICAL EQUIPMENT R   1.192E 03       7.75      9236. A11121    ELECTRICAL SERVICE FAC
1.059E 04        .87      9169. A10961    LANDSCAPING AND IRRIGA   2.553E 02      33.28      8496. A12081    STORM DRAINS
1.053E 04        .61      6428. A12561    ROADS, ON-SITE, PAVING   2.728E 02      22.44      6121. A21921    QUALITY CONTROL LABORA
6.170E 02       9.51      5867. A22631    VENTILATION FACILITIES   2.624E 02      21.82      5724. A21761    PLANT MAINTENANCE AND
1.887E 02      23.77      4486. A21441    OFFICE SPACE, MANUFACT   3.829E 03       1.00      3829. A13521    LIGHTING, SITE
6.717E 02       4.28      2874. A10161    FENCING                  6.344E 04        .03      2162. A13481    GRADING
2.000E 03       1.00      2000. A15041    SIGNS AND FLAGPOLE       1.777E 02       9.98      1774. A22061    SHIPPING AND RECEIVING
6.481E 01      19.11      1239. A22401    TELEPHONE EQUIPMENT RO   1.323E 01      73.15       968. A12401    WATER SERVICE FACILITI
5.600E 01      13.04       704. A12241    TELEPHONE LINES          1.019E 02       7.14       727. A13361    SPACE, STORAGE
1.686E 01      36.61       617. A20461    HEALTH SERVICE FACILIT   1.037E 01      11.41       461. A13201    WALLS, STORAGE AREA
1.850E 03        .07       125. A20561    HEATING FACILITIES       1.816E 02        .63       115. A11281    FUEL OIL SERVICE FACIL
1.141E 00        .74         1. A11601    LIQUID NITROGEN SERVIC   6.386E 03         0.         0. A30321    FLOOR SPACE, TOTAL MAN
1.532E 04         0.         0. A30161    FLOOR SPACE, TOTAL FAC   6.932E 03         0.         0. A30481    FLOOR SPACE, TOTAL SUP
0.000E 00         0.         0. A10321    FIRE LOOP AND SECONDAR   0.000E 00         0.         0. A12861    SECURITY CONTROL FACIL

3.422E 00   13549.67     45662. B33601    CHEMICAL PROCESS FOREM   4.700E 00    7188.26     33785. B3576D    FORKLIFT TRUCK OPERATO
8.370E-01   20907.64     17500. B11281    EMPLOYMENT INTERVIEWER   8.370E-01   20907.64     17500. B14481    SUPERVISOR, TRAINING
8.370E-01   20537.95     17191. B22081    PURCHASING AGENT         8.370E-01   20537.96     17191. B32881    ENGINEER, RESEARCH (EL
1.276E 00   11655.29     14858. B14441    SECRETARY III (UPPER M   1.477E 00   10012.25     14788. B14321    SECRETARY I (LOWER MAN
1.674E 00    8482.17     14200. B13521    PERSONNEL CLERK          9.803E-01   14376.57     14093. B33201    ASSEMBLY FOREMAN
8.370E-01   14376.57     12034. B20081    ACCOUNTANT               4.185E-01   24132.09     10100. B32088    ENGINEER, ELECTRONICS
4.185E-01   24132.09     10100. B32408    ENGINEER, MECHANICAL     7.166E-01   13863.12      9935. B34001    MACHINE SHOP FOREMAN
4.185E-01   23618.65      9885. B32568    PRODUCTION PLANNER       4.185E-01   23618.65      9885. B32728    QUALITY CONTROL ENGINE
4.185E-01   23618.65      9885. B32248    ENGINEER, INDUSTRIAL     2.790E-01   33846.54      9444. B10801    DIRECTOR, OFFICE ADMIN
9.843E-02   90675.00      8925. B13841    PRESIDENT                8.370E-01   10266.98      8595. B20321    BOOKKEEPER
4.891E-01   17457.26      8539. B33361    ASSEMBLY OPERATIONS SU   7.899E-01   10679.73      8436. B14401    SECRETARY II (MIDDLE M
8.370E-01   10063.59      8424. B21601    PROCUREMENT CLERK        1.466E-01   53912.14      7905. B33041    VICE PRESIDENT, MANUFA
5.560E-01   13246.96      7392. B13361    NURSE, PROFESSIONAL (G   1.348E-01   53912.14      7268. B14641    VICE PRESIDENT, ADMINI
1.976E-01   36249.48      7164. B23481    CONTROLLER AND CHIEF A   8.370E-01    8482.17      7100. B10481    CLERK, GENERAL OFFICE
8.370E-01    8482.17      7100. B12401    MAIL CLERK               8.370E-01    8482.17      7100. B21441    PAYROLL CLERK
7.659E-01    9035.69      6921. B12721    MAINTENANCE MAN (PLANT   2.096E-01   32860.72      6886. B31441    DIRECTOR, MANUFACTURIN
2.790E-01   24645.54      6875. B31288    ENGINEER, CHEMICAL       1.286E-01   53398.64      6865. B22721    VICE PRESIDENT, FINANC
2.485E-01   24132.09      5997. B34961    PRODUCTION SUPERINTEND   2.790E-01   20537.95      5730. B33521    PRODUCTION SUPERVISOR,
4.115E-01   13863.11      5704. B34401    MECHANICAL MAINTENANCE   2.790E-01   20024.50      5587. B20961    FINANCIAL ANALYST
6.127E-01    9036.70      5537. B11921    JANITOR                  4.185E-01   13041.59      5458. B31921    DRAFTSMAN, MECHANICAL
3.917E-01   13863.11      5430. B34521    MATERIALS-HANDLING FOR   1.395E-01   38611.33      5386. B10161    ADMINISTRATIVE ASSISTA
4.185E-01   11295.87      4725. B32161    ENGINEERING AIDE         1.395E-01   33846.54      4722. B11121    DIRECTOR, PUBLIC RELAT
1.395E-01   33846.54      4722. B22551    TREASURER                4.195E-01   10885.11      4556. B14001    RECEPTIONIST
1.453E-01   30800.94      4477. B21921    PURCHASING ADMINISTRAT   1.628E-01   27212.79      4429. B13041    MANAGER, PERSONNEL
1.395E-01   28755.14      4011. B31761    DIRECTOR, RESEARCH AND   5.168E-01    7290.97      3723. B11601    GUARD (SECURITY)
1.046E-01   33846.54      3541. B10641    DIRECTOR, INDUSTRIAL R   1.395E-01   24132.10      3367. B12361    LAWYER, CORPORATE (BUS
1.395E-01   21770.23      3037. B10321    AUDITOR, INTERNAL        2.790E-01   10885.11      3037. B20801    DIGITAL COMPUTER OPERA
1.395E-01   21154.09      2951. B20181    ACCOUNTING SUPERVISOR    2.790E-01    9036.70      2521. B21121    KEY PUNCH OPERATOR
1.761E-01   13863.12      2442. B35121    QUALITY CONTROL FOREMA   7.301E-02   32860.72      2399. B31601    DIRECTOR, QUALITY CONT
1.198E-01   16943.81      2029. B34801    PRODUCTION MACHINE SHO   1.208E-01   16019.61      1935. B12561    MAINTENANCE FOREMAN (P
1.393E-01   13863.12      1931. B35641    ELECTRONICS MAINTENANC   1.395E-01   12836.22      1791. B13561    PERSONNEL CLERK, SUPER
8.370E-02   20024.51      1676. B22401    SYSTEMS ANALYST          8.370E-02   18176.09      1521. B21761    PROGRAMMER, BUSINESS
4.650E-02   27212.79      1255. B12861    MANAGER, COMPENSATION,   6.975E-02   17970.71      1254. B22241    PURCHASING SUPERVISOR
6.120E-02   16943.61      1037. B34641    PROCESS MAINTENANCE SU   8.510E-02   11295.87       961. B11761    GUARD CHIEF
3.431E-02   27212.79       934. B13201    MANAGER, SECURITY AND    3.178E-02   27212.79       865. B21251    MANAGER, DATA PROCESSI
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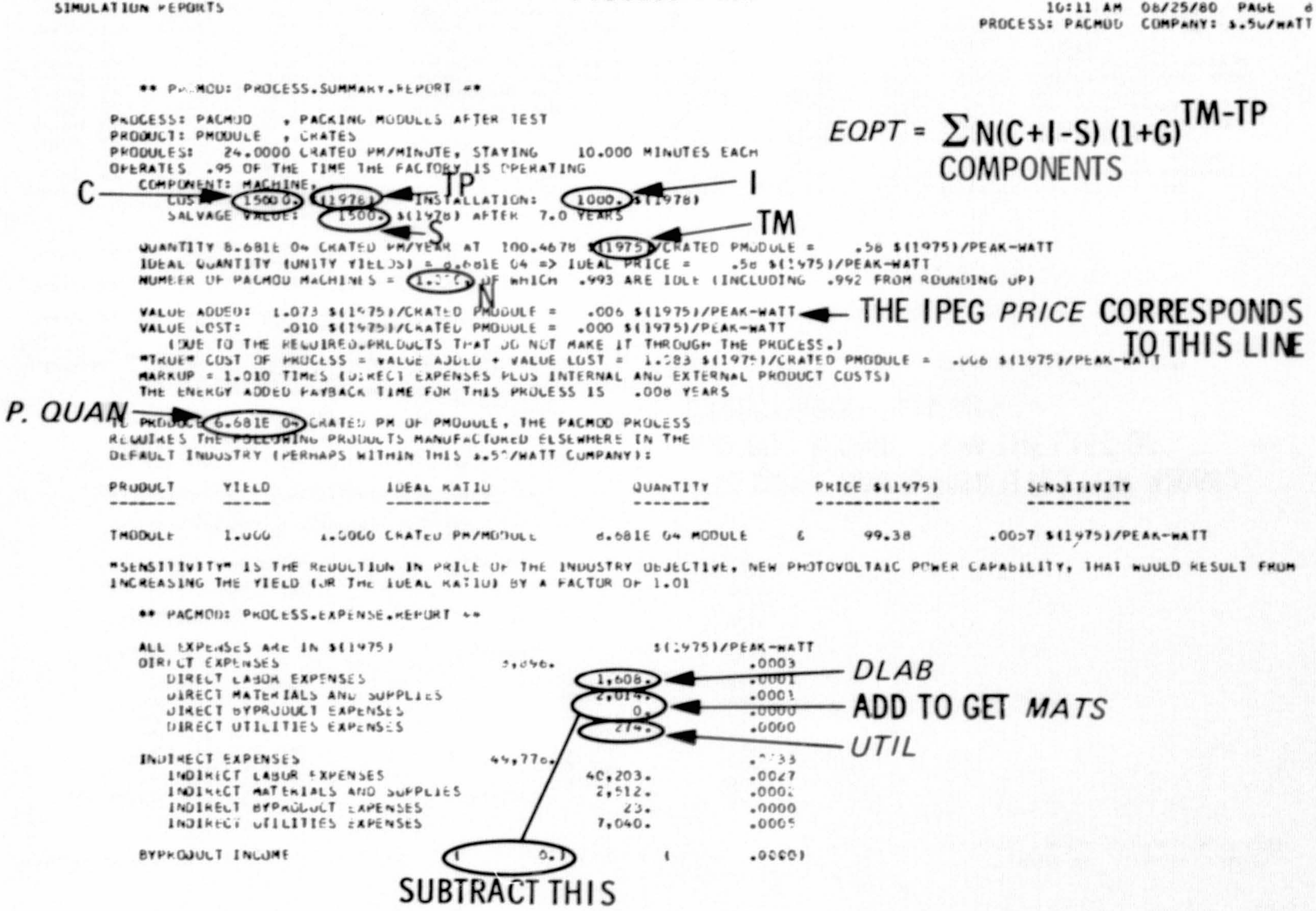
Process Data

$$EQPT = \sum_{\text{COMPONENTS}} N(C+I-S)\,(1+G)^{TM-TP}$$



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SIMULATION REPORTS                                                      10:11 AM  06/25/80  PAGE   6
                                                                   PROCESS: PACMOD  COMPANY: $.50/WATT

     ** PACMOD: PROCESS.SUMMARY.REPORT **

   PROCESS: PACMOD   , PACKING MODULES AFTER TEST
   PRODUCT: PMODULE  , CRATES
   PRODUCES:   24.0000 CRATED PM/MINUTE, STAYING    10.000 MINUTES EACH
   OPERATES  .95 OF THE TIME THE FACTORY IS OPERATING
      COMPONENT: MACHINE,
         COST:  15000. $(1978)     INSTALLATION:   1000. $(1978)
         SALVAGE VALUE:    1500. $(1978) AFTER  7.0 YEARS

      QUANTITY 6.681E 04 CRATED PM/YEAR AT  100.4678 $(1975)/CRATED PMODULE =     .58 $(1975)/PEAK-WATT
      IDEAL QUANTITY (UNITY YIELDS) = 6.681E 04 => IDEAL PRICE =     .58 $(1975)/PEAK-WATT
      NUMBER OF PACMOD MACHINES = 1.[illegible] OF WHICH  .993 ARE IDLE (INCLUDING  .992 FROM ROUNDING UP)

      VALUE ADDED:  1.073 $(1975)/CRATED PMODULE =   .006 $(1975)/PEAK-WATT
      VALUE LOST:     .010 $(1975)/CRATED PMODULE =  .000 $(1975)/PEAK-WATT
         (DUE TO THE REQUIRED.PRODUCTS THAT DO NOT MAKE IT THROUGH THE PROCESS.)
      "TRUE" COST OF PROCESS = VALUE ADDED + VALUE LOST =  1.083 $(1975)/CRATED PMODULE =  .006 $(1975)/PEAK-WATT
      MARKUP = 1.010 TIMES (DIRECT EXPENSES PLUS INTERNAL AND EXTERNAL PRODUCT COSTS)
      THE ENERGY ADDED PAYBACK TIME FOR THIS PROCESS IS   .008 YEARS

   TO PRODUCE 6.681E 04 CRATED PM OF PMODULE, THE PACMOD PROCESS
   REQUIRES THE FOLLOWING PRODUCTS MANUFACTURED ELSEWHERE IN THE
   DEFAULT INDUSTRY (PERHAPS WITHIN THIS $.50/WATT COMPANY):

   PRODUCT      YIELD          IDEAL RATIO              QUANTITY            PRICE $(1975)       SENSITIVITY
   -------      -----          -----------              --------            -------------       -----------

   TMODULE      1.000      1.0000 CRATED PM/MODULE      6.681E 04 MODULE     &      99.38        .0057 $(1975)/PEAK-WATT

   "SENSITIVITY" IS THE REDUCTION IN PRICE OF THE INDUSTRY OBJECTIVE, NEW PHOTOVOLTAIC POWER CAPABILITY, THAT WOULD RESULT FROM
   INCREASING THE YIELD (OR THE IDEAL RATIO) BY A FACTOR OF 1.01

      ** PACMOD: PROCESS.EXPENSE.REPORT **

      ALL EXPENSES ARE IN $(1975)                                     $(1975)/PEAK-WATT
      DIRECT EXPENSES                          3,896.                       .0003
         DIRECT LABOR EXPENSES                            1,608.            .0001
         DIRECT MATERIALS AND SUPPLIES                    2,014.            .0001
         DIRECT BYPRODUCT EXPENSES                            0.            .0000
         DIRECT UTILITIES EXPENSES                          274.            .0000

      INDIRECT EXPENSES                       49,776.                       .0033
         INDIRECT LABOR EXPENSES                         40,203.            .0027
         INDIRECT MATERIALS AND SUPPLIES                  2,512.            .0002
         INDIRECT BYPRODUCT EXPENSES                         23.            .0000
         INDIRECT UTILITIES EXPENSES                      7,040.            .0005

      BYPRODUCT INCOME                        (        0.)          (       .0000)
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THE IPEG *PRICE* CORRESPONDS TO THIS LINE

ADD TO GET *MATS*

SUBTRACT THIS

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SIMULATION REPORTS                                                                          10:11 AM  06/25/80  PAGE
                                                                                     PROCESS: PACMOD  COMPANY: $.50/WATT

            CAPITAL EXPENSES                             24,173.                           .0016
               EQUIPMENT REPLACEMENT                                   1,551.              .0001
               FACILITIES REPLACEMENT                                  2,503.              .0002
               AMORTIZED ONE-TIME COSTS                                6,410.              .0004
               INTEREST ON DEBT                                          563.              .0000
               RETURN ON EQUITY                                        6,085.              .0004
               NON-INCOME TAXES                                        2,224.              .0001
               INSURANCE PREMIUMS                                      4,839.              .0003

            INCOME TAXES                                 10,000.                           .0007

            MISCELLANEOUS                                 5,287.                           .0004

            EXTERNAL PRODUCT COST                             0.                           .0000
                                                      ----------                       ---------
            TOTAL ANNUAL EXPENSES                        93,135.                           .0062

            INTERNAL (IMPLICIT) PRODUCT COST          6,627,994.                           .5752

            ** PACMOD: BRIEF.WORK.STATION.NEEDS.REPORT **

         TO PRODUCE 8.681E 04 CRATED MODULES/YEAR, THE PACMOD
            PROCESS REQUIRES:

            ALL PRICES AND COSTS ARE IN $(1975)

            DIRECT REQUIREMENTS
QUANTITY      PRICE      COST  REFERENT  DESCRIPTIVE NAME          QUANTITY      PRICE      COST  REFERENT  DESCRIPTIVE NAME
9.000E 02     39.16    35245.  A2064D    FLOOR SPACE, TILE (WIT

1.431E-01  10063.59     1440.  B3656D    PACKAGER, MACHINE

9.042E 03       .03      274.  C1032B    ELECTRICITY

2.894E 04       .07     2014.  E1180D    CRATES, WOODEN


            INDIRECT REQUIREMENTS
QUANTITY      PRICE      COST  REFERENT  DESCRIPTIVE NAME          QUANTITY      PRICE      COST  REFERENT  DESCRIPTIVE NAME
 1.272E 01   817.71    10403.  A2008I    AIR CONDITIONING FACIL    7.324E 02     11.41     8356.  A2272I    FLOOR SPACE, WAREHOUSE
 5.549E-01 14276.51     7922.  A5000I    FORKLIFTS                 1.210E 02     27.73     3356.  A2126I    OFFICE SPACE, ADMINIST
 3.876E 01    50.85     1971.  A2016I    CAFETERIA AND LUNCHROO    8.520E 01     22.82     1944.  A2040I    WALLS, EXTERIOR
 6.194E 03      .31     1920.  A1080I    LAND                      9.652E 01     17.04     1645.  A2160I    PASSAGES AND CORRIDORS
 1.281E 02    11.09     1421.  A2132I    OFFICE FURNISHINGS        4.080E 01     33.28     1358.  A1192I    SANITARY SEWERS
 1.433E 03      .87     1240.  A1096I    LANDSCAPING AND IRRIGA    3.454E 01     33.28     1149.  A1208I    STORM DRAINS
 1.140E 03     1.00     1140.  A1366I    WALKS, CURBS AND GUTTE    1.581E 01     67.95     1074.  A2256I    TOILET AND LOCKER ROOM
 9.859E 01     9.98      984.  A2208I    SHIPPING AND RECEIVING    1.425E 03       .61      870.  A1256I    ROADS, ON-SITE, PAVING
 8.341E 01     9.51      793.  A2263I    VENTILATION FACILITIES    5.160E 02      1.00      516.  A1352I    LIGHTING, SITE
 7.956E 00    50.01      398.  A2324I    COMPUTER ROOM AND COMP    9.796E 02       .40      394.  A1272I    PARKING LOT PAVING (LI
 2.277E 01    16.72      381.  A2112I    MECHANICAL EQUIPMENT R    2.234E 01     16.72      373.  A2032I    ELECTRICAL EQUIPMENT R
 4.595E 01     7.75      356.  A1112I    ELECTRICAL SERVICE FAC    3.323E 02      1.00      332.  A2178I    MAINTAINENCE AND MACHI
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FOR *SQFT*, ADD QUANTITIES FOR A2064B, A2080D, A2096D FROM THE LIST OF DIRECT REQUIREMENTS

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                                                                                          PROCESS: PALMOD  COMPANY: $.50/WATT
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OR, GET *SQFT* FROM A30321 IN THE INDIRECT LIST

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6.558E 01      4.26      261. A10161   FENCING                  2.706E 02      1.00      271. A13041   SIGNS AND FLAGPOLE
6.194E 03       .03      211. A10461   GRADING                  7.122E 00     23.77      169. A21441   OFFICE SPACE, MANUFACT
1.396E 01      7.14      100. A13361   SPACE, STORAGE           4.154E 00     21.62       91. A21761   PLANT MAINTENANCE AND
1.215E 00     73.15       69. A12401   WATER SERVICE FACILITI   5.141E 00     13.64       70. A12241   TELEPHONE LINES
1.008E 02       .63       64. A11281   FUEL OIL SERVICE FACIL   5.533E 00     11.41       63. A13201   WALLS, STORAGE AREA
2.550E 00     19.11       49. A22401   TELEPHONE EQUIPMENT RO   1.648E 00     22.44       37. A21921   QUALITY CONTROL LABORA
6.629E 01     36.61       24. A20461   HEALTH SERVICE FACILIT   2.503E 02       .07       17. A20561   HEATING FACILITIES
9.000E 02      0.          0. A30321   FLOOR SPACE, TOTAL MAN   2.072E 03      0.          0. A30161   FLOOR SPACE, TOTAL FAC
1.172E 03      0.          0. A30461   FLOOR SPACE, TOTAL SUP

2.608E 00   7188.28    18746. B35760   FORKLIFT TRUCK OPERATO   2.173E-01  13863.11     3013. B34321   MATERIALS-HANDLING FOR
1.036E-01   9036.69      936. B12721   MAINTENANCE MAN (PLANT   6.269E-02   9036.70      749. B11921   JANITOR
3.295E-02  20907.64      689. B14481   SUPERVISOR, TRAINING     3.295E-02  20907.64      689. B11281   EMPLOYMENT INTERVIEWER
3.295E-02  20537.96      677. B22081   PURCHASING AGENT         3.295E-02  20537.96      677. B32081   ENGINEER, RESEARCH (EL
5.002E-02  11655.29      583. B14441   SECRETARY III (UPPER M   6.591E-02   8482.17      559. B13521   PERSONNEL CLERK
5.325E-02  10012.25      533. B14321   SECRETARY I (LOWER MAN   6.907E-02   7295.97      504. B11601   GUARD (SECURITY)
3.295E-02  14376.57      474. B20061   ACCOUNTANT               2.547E-02  16943.81      432. B35441   WAREHOUSE AND MATERIAL
1.648E-02  24132.09      398. B32098   ENGINEER, ELECTRONICS    1.648E-02  24132.09      398. B32408   ENGINEER, MECHANICAL
1.648E-02  23618.65      389. B32248   ENGINEER, INDUSTRIAL     1.648E-02  23618.65      389. B32728   QUALITY CONTROL ENGINE
1.648E-02  23618.65      389. B32568   PRODUCTION PLANNER       1.098E-02  33846.54      372. B10801   DIRECTOR, OFFICE ADMIN
5.850E-03  93675.30      349. B13841   PRESIDENT                3.295E-02  10268.98      338. B20321   BOOKKEEPER
3.295E-02  10063.59      332. B21601   PROCUREMENT CLERK        3.345E-02  10674.73      325. B14401   SECRETARY II (MIDDLE M
5.532E-03  53912.14      298. B14641   VICE PRESIDENT, ADMINI   2.197E-02  13246.98      291. B13361   NURSE, PROFESSIONAL (G
5.373E-03  53912.14      290. B33041   VICE PRESIDENT, MANUFA   7.761E-03  36249.46      282. B20481   CONTROLLER AND CHIEF A
3.295E-02   8482.17      280. B10481   CLERK, GENERAL OFFICE    3.295E-02   8482.17      280. B12401   MAIL CLERK
3.295E-02   8482.17      280. B21441   PAYROLL CLERK            1.096E-02  24645.54      271. B31288   ENGINEER, CHEMICAL
5.061E-03  53398.64      270. B22721   VICE PRESIDENT, FINANC   1.634E-02  16019.61      262. B12561   MAINTENANCE FOREMAN (P
9.355E-03  24132.09      226. B34961   PRODUCTION SUPERINTEND   1.098E-02  20537.95      226. B33521   PRODUCTION SUPERVISOR,
1.098E-02  20024.50      220. B20961   FINANCIAL ANALYST        1.648E-02  13041.59      215. B31921   DRAFTSMAN, MECHANICAL
5.493E-03  36611.33      212. B10161   ADMINISTRATIVE ASSISTA   6.408E-03  32860.72      211. B31441   DIRECTOR, MANUFACTURIN
1.648E-02  11295.87      186. B32161   ENGINEERING AIDE         5.494E-03  33846.54      186. B11121   DIRECTOR, PUBLIC RELAT
5.492E-03  33846.54      186. B22561   TREASURER                1.648E-02  10885.11      179. B14001   RECEPTIONIST
5.721E-03  30806.94      176. B21921   PURCHASING ADMINISTRAT   6.408E-03  27212.79      174. B13041   MANAGER, PERSONNEL
1.192E-02  13863.12      165. B35601   WAREHOUSE FOREMAN        5.492E-03  28753.14      156. B31761   DIRECTOR, RESEARCH AND
4.119E-03  33846.54      139. B10641   DIRECTOR, INDUSTRIAL R   5.492E-03  24132.10      133. B12081   LAWYER, CORPORATE (BUS
1.151E-02  11295.87      130. B11761   GUARD CHIEF              4.642E-03  27212.79      126. B13201   MANAGER, SECURITY AND
8.634E-03  13863.11      120. B34461   MECHANICAL MAINTENANCE   5.493E-03  21770.23      120. B10321   AUDITOR, INTERNAL
1.598E-02  10885.11      120. B20801   DIGITAL COMPUTER OPERA   5.492E-03  21154.09      116. B20161   ACCOUNTING SUPERVISOR
1.098E-02   9036.70       99. B21121   KEY PUNCH OPERATOR       2.746E-03  32860.72       99. B31601   DIRECTOR, QUALITY CONT
9.552E-03   9036.70       86. B11441   GROUNDSKEEPER            5.492E-03  12836.22       71. B13681   PERSONNEL CLERK, SUPER
3.295E-03  20024.51       56. B22401   SYSTEMS ANALYST          3.295E-03  16176.09       60. B21761   PROGRAMMER, BUSINESS
1.547E-03  33846.54       52. B10961   DIRECTOR, PLANT MAINTE   1.831E-03  27212.79       50. B12881   MANAGER, COMPENSATION,
2.746E-03  17970.71       49. B22241   PURCHASING SUPERVISOR    1.251E-03  27212.79       34. B21281   MANAGER, DATA PROCESSI
1.831E-03  16176.09       33. B20641   DATA PROCESSING SUPERV   2.746E-03  10885.11       30. B12241   LEGAL SECRETARY
9.593E-04  16943.81       16. B34641   PROCESS MAINTENANCE SU   2.751E 00      0.          0. B50161   TOTAL DIRECT PERSONNEL
1.295E-01      0.          0. B50641   TOTAL MAINTENANCE PERS   6.914E-01      0.          0. B50481   TOTAL STAFF PERSONNEL
3.295E 00      0.          0. B50501   TOTAL PRODUCTION PERSO   5.442E-01      0.          0. B50491   INDIRECT PRODUCTION PE
4.187E 00      0.          0. B50321   TOTAL PERSONNEL

1.819E 05       .03     5510. C10328   ELECTRICITY              1.207E 05       .01      802. C10168   WATER, DOMESTIC
5.549E 02       .63      348. C10488   FUEL OIL                 1.212E 05       .00      272. C20648   WASTE DISPOSAL, SEWAGE
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When SAMIS? When IPEG?

- USE SAMIS (ONCE) TO PREPARE IPEG INPUT (COUNTING THE COST OF YOUR TIME, IT IS MUCH CHEAPER)
- USE SAMIS TO GET A TAILORED IPEG WHENEVER YOU ARE LOOKING AT A SIGNIFICANTLY DIFFERENT FACTORY (EG: SIZE OR TECHNOLOGY OR INDUSTRY STRUCTURE)
- USE IPEG FOR SENSITIVITY STUDIES OF PROCESS PARAMETERS OR FINANCIAL PARAMETERS.
- USE SAMIS FOR DEFINITIVE, DEFENSIBLE PRICE ESTIMATES.
- USE SAMIS FOR CONTRACTURAL "SAMICS PRICE ESTIMATES" (BUT USE IPEG TO OPTIMIZE PROCESS PARAMETERS)

IPEG4: IMPROVED PRICE ESTIMATION GUIDELINES

HOW TO USE IPEG4, AND WHAT CAN IT DO?

JET PROPULSION LABORATORY

Paul J. Firnett

The IPEG4 Program

- INTERACTIVE COMPUTER PROGRAM
- WRITTEN IN SIMSCRIPT
- INSTALLED ON THE NATIONAL CSS TIMESHARING SYSTEM
- INTERFACES WITH SAMIS VIA THE IPEG INPUT FILE

How to Access the IPEG4 Program

- CONTACT NEAREST NCSS OFFICE (IN L.A. 277-7511) AND ESTABLISH AN ACCOUNT ON THE NCSS SUNY COMPUTER
- GET AT LEAST 1 CYLINDER OF DISK STORAGE SPACE (MORE IF ALSO RUNNING SAMIS)
- GET MINIMAL INSTRUCTION AND MANUALS FROM NCSS ON USING THEIR SYSTEM
- READ AND USE THE IPEG4 USER'S GUIDE
- GET THE DEFAULT IPEG PARAMETER FILE OR USE SAMIS TO GENERATE AN IPEG INPUT FILE (APPENDIX A)
- BRING IPEG4 INTO EXECUTION VIA THE ATTACH COMMAND:

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ATTACH JPLSAMIS SAMIS AS Z
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The IPEG Input File

- NORMALLY GENERATED BY SAMIS
- DEFAULT FILE ON JPLSAMIS WAS PRODUCED WITH THE SYSTEM TEXT EDITOR. IPEG QUANTITIES EQPT, SQFT, ETC. ARE SET TO ZERO; HOWEVER, I.QUAN AND P.QUAN ARE NOT.
- CAN HAVE MULTIPLE CASES ON THE FILE, THAT IS, SEVERAL COMPANIES AND INDUSTRY SIZE VALUES

What Can IPEG4 Do?

- USER CAN PICK A PARTICULAR CASE TO BE PROCESSED FROM THE IPEG INPUT FILE
- IPEG4 WILL AUTOMATICALLY COMPUTE AND PRINT THE IPEG COEFFICIENTS AND PRICE FOR THE CASE SELECTED.
- IPEG4 ENTERS INTO A CYCLIC DIALOGUE WHICH ALLOWS YOU TO PERFORM ONE OR MORE SENSITIVITY STUDIES OF THE CASE BEING PROCESSED. RESULTS CAN BE PRINTED AND/OR PLOTTED AT THE TERMINAL OR ON A LINE PRINTER (OFF LINE).
- IPEG4 ALLOWS YOU TO SELECT ANOTHER CASE

How About an Actual Example?

- USES THE DEFAULT IPEG PARAMETER FILE WITH I.QUAN SET TO 1.5E7 AND P.QUAN SET TO 86810.0 USING THE TEXT EDITOR. THIS IS NECESSARY BECAUSE IPEG4 WILL NOT PRESENTLY ALLOW YOU TO CHANGE THESE VALUES.
- VALUES FOR EQPT, SQFT, DLAB, MATS, AND UTIL ARE SUPPLIED VIA THE IPEG4 "CHANGE" COMMAND.
- SENSITIVITY STUDY OF PRICE AS A FUNCTION OF RATE OF RETURN ON EQUITY (R) WITH ALL OTHER PARAMETERS HELD CONSTANT. RESULTS SENT TO THE USER'S TERMINAL.

Procedure for Obtaining Default IPEG Parameter File From JPLSAMIS

```
13.50.30 >ATTACH JPLSAMIS SAMIS AS T
JPLSAMIS ATTACHED AS T-DISK

**************************************************
RELEASE 3 OF SAMIS HAS BEEN INSTALLED ON JPLSAMIS
SEE DETAILS IN "USER NEWS".
DO NOT ATTEMPT TO RUN SAMIS UNTIL YOUR DATA FILES HAVE BEEN
CONVERTED AND YOU HAVE OBTAINED VERSION 4 OF THE COST ACCOUNT
CATALOG

RELEASE 1 OF THE IPEG PROGRAM HAS BEEN INSTALLED ON JPLSAMIS
SEE DETAILS IN "USER NEWS".
**************************************************

YOU HAVE ATTACHED JPLSAMIS AS T THEREFORE YOU WILL BE PROMPTED FOR
A COMMAND, WHICH MUST BE LIST, COPY (FOLLOWED BY FILENAME, FILETYPE,
AND FILEMODE), OR DONE.

INPUT A COMMAND
>COPY -IPEG IPEG P

INPUT A COMMAND
>DONE
DEV T DETACHED
```

Bringing IPEG4 Into Execution

```
13.21.52 >ATTACH JPLSAMIS SAMIS AS Z
JPLSAMIS ATTACHED AS Z-DISK

*******************************************
RELEASE 3.2 OF SAMIS HAS BEEN INSTALLED ON JPLSAMIS
SEE DETAILS IN "USER NEWS".
DO NOT ATTEMPT TO RUN SAMIS UNTIL YOUR DATA FILES HAVE BEEN
CONVERTED AND YOU HAVE OBTAINED VERSION 4 OF THE COST ACCOUNT
CATALOG

RELEASE 2 OF THE IPEG PROGRAM HAS BEEN INSTALLED ON JPLSAMIS
SEE DETAILS IN "USER NEWS".
*******************************************

YOU HAVE ATTACHED JPLSAMIS AS Z THEREFORE THE IPEG PROGRAM IS BEING
BROUGHT INTO EXECUTION.
DEV V DETACHED
SCRATCH  ATTACHED AS V-DISK
SIM25LIB ATTACHED AS 1-DISK

SIMSCRIPT II.5 (RELEASE 8H) AS OF JUNE 1, 1979

     TYPE "SIMHELP INDEX" FOR A LIST OF ALL SIMSCRIPT COMMANDS.
```

Output

```
WELCOME TO THE IPEG PROGRAM, RELEASE 1

DO YOU WISH TO PROCESS ANOTHER CASE?
>YES
INPUT THE SIZE.INDEX
>D
THE DEFAULT,  1, HAS BEEN ASSUMED.
INPUT THE COMPANY.REFERENT
>D
THE DEFAULT "MODULECO" HAS BEEN ASSUMED.
DO YOU WISH TO DISPLAY THE COMPANY DATA?
>YES


COMPANY: MODULECO, THIS IS A TEST COMPANY FOR THE IPEG PROGRAM

PROCESS.LIST =
 DUMMY *
I.QUAN = 1.50000E 07 PEAK-WATTS
P.QUAN = 86810.00000 MODULES
EQPT =      0.        $/YEAR
SQFT =      0.        SQ. FT.
DLAB =      0.        $/YEAR
MATS =      0.        $/YEAR
UTIL =      0.        $/YEAR
EL =     10.00000 YEARS
EITCR =       .11000 FRACTION/YR
FL =     40.00000 YEARS
BETA = 2.00000E-02 FRACTION/YR
X = 3.00000E-02 FRACTION/YR
NU = 4.00000E-02 FRACTION/YR
Z =      0.       FRACTION/YR
RLAB =       .70000 $/$
RUTIL =      6.00000 $/SQ. FT.
G = 7.00000E-02 FRACTION/YR
W = 1.00000E-01 YEARS
TAU =       .50000 FRACTION/YR
LAMBDA =      1.20000 $/$
IR = 9.25000E-02 FRACTION/YR
R =       .20000 FRACTION/YR
P1 =       .40000 $/SQ. FT.
P2 =     60.00000 $/SQ. FT.
```

PROGRAM DIALOGUE BEGINS HERE

START CASE DEFINITION

NOTE VALUES

```
P3 =     63.79999 $/SQ. FT.
D1 =      6.00000 FRACTION
D2 =      1.40000 FRACTION
GU = 8.00000E-02 FRACTION/YR
GF = 8.00000E-02 FRACTION/YR
Y =      4.00000 YEARS
V = 4.00000E-02 FRACTION/YR
TS =      1.00000 YEARS
TM =  1986.00000 YEAR
TC =      3.00000 YEARS
L =       .63500 FRACTION/YR
TB =  1975.00000 YEAR
A =       .11000 FRACTION/YR
UF =       .67000 FRACTION/YR
LF =       .33000 FRACTION/YR
T =      7.00000 YEARS
M =      5.00000 YEARS
B =      3.00000 YEARS
TLF =       .67000 FRACTION/YR
XEC =       .15000 FRACTION/YR
XFC =       .15000 FRACTION/YR
XOPR = 1.00000E-01 FRACTION/YR
N =      1.25000 FRACTION
INPUT THE PROCESS.REFERENT OR *COMPANY*
>D
THE DEFAULT "*COMPANY*" HAS BEEN ASSUMED.
INPUT THE REPORT.YEAR BETWEEN 1975. AND 1986. (INCLUSIVE)
>1975
DO YOU WISH TO DISPLAY ANY OF THE SAVED VARIABLES?
>NO
DO YOU WISH TO DISPLAY THE TRANSFORMATION MATRIX?
>NO


C(1) =      .48417)   COMPUTED          ENDS
C(2) =   110.60727|      BY             CASE
C(3) =     2.14224}    IPEG4         DEFINITION
C(4) =     1.22917|
C(5) =     1.22917)
PRICE =     .0000 $(1975)/PEAK-WATT =>      .000 $(1975)/MODULE
```

C-6

BEGIN SENSITIVITY STUDY DIALOGUE

```
DO YOU WISH TO PERFORM ANOTHER SENSITIVITY STUDY?
>YES
DO YOU WISH TO REINITIALIZE THE WORKING VARIABLES?
>YES
DO YOU WISH TO CHANGE ANY OF THE WORKING VARIABLE VALUES?
>YES
INPUT A CHANGE COMMAND OR DONE
>C EQPT 5.E5 C SQFT 1.571E4 C DLAB 7.89E5 C MATS 4.238E6 C UTIL 1.5E5
EQPT CHANGED FROM: 0.00000E 00 TO: 5.00000E 05
SQFT CHANGED FROM: 0.00000E 00 TO: 1.57100E 04
DLAB CHANGED FROM: 0.00000E 00 TO: 7.89000E 05
MATS CHANGED FROM: 0.00000E 00 TO: 4.23800E 06
UTIL CHANGED FROM: 0.00000E 00 TO: 1.50000E 05
INPUT A CHANGE COMMAND OR DONE
>DONE
```

PUTTING IN IPEG VARIABLE VALUES

```
THE FOLLOWING VARIABLES HAVE WORKING VALUES DIFFERENT THAN SAVED VALUES:

  VARIABLE      SAVED VALUE    WORKING VALUE
  --------      -----------    -------------
  EQPT               0.          5.00000E 05
  SQFT               0.          15710.00000
  DLAB               0.          7.89000E 05
  MATS               0.          4.23800E 06
  UTIL               0.          1.50000E 05
INPUT AN INDEPENDENT VARIABLE FOR THE SENSITIVITY STUDY
>NONE
```

THIS IS A SPECIAL RESPONSE!

```
C(1) =      .48417
C(2) =   110.60727
C(3) =     2.14224
C(4) =     1.22917
C(5) =     1.22917
PRICE =     .2671 $(1975)/PEAK-WATT =>     49.603 $(1975)/MODULE
```

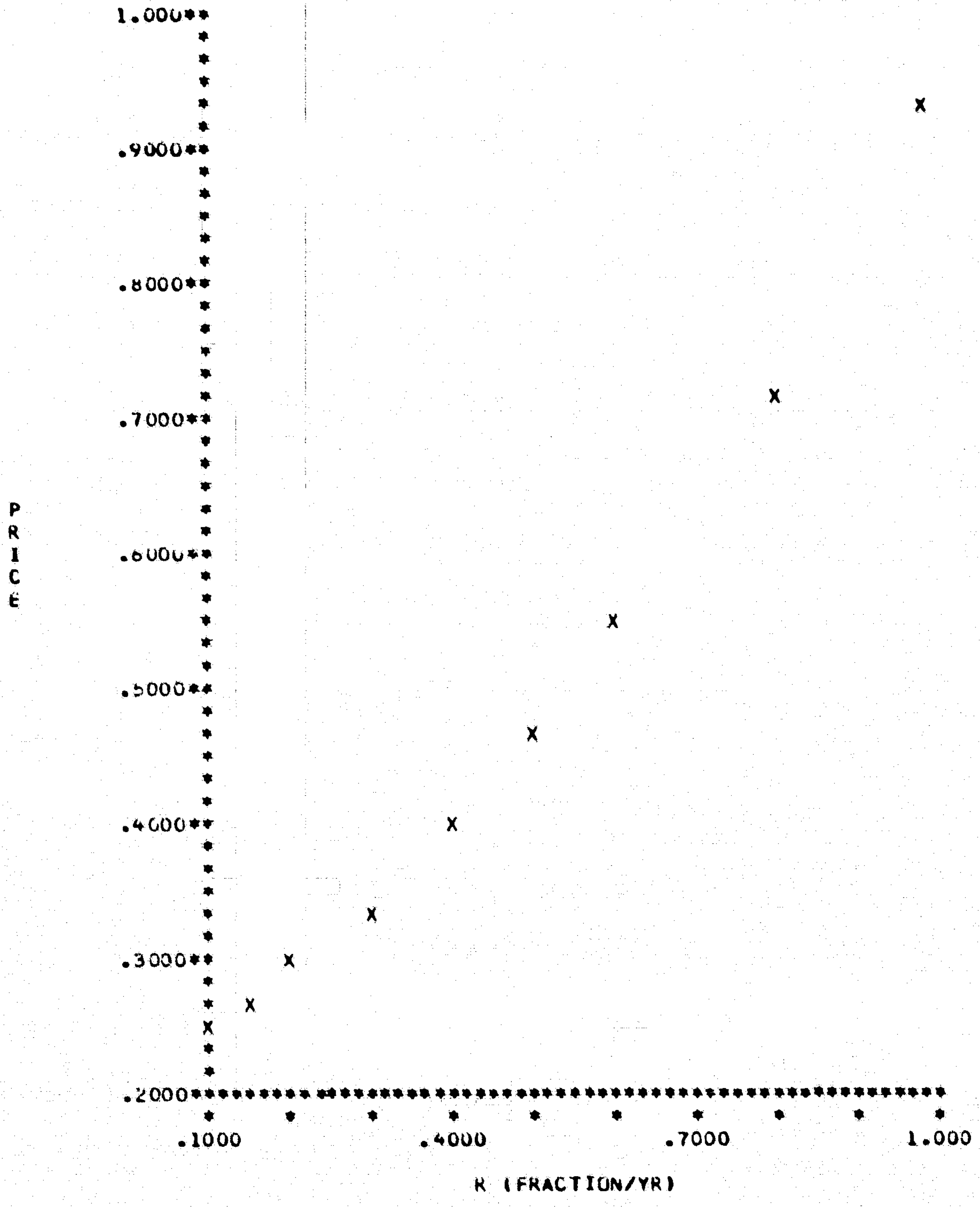
THE IPEG4 PRICE

```
DO YOU WISH TO PERFORM ANOTHER SENSITIVITY STUDY?
>YES
DO YOU WISH TO REINITIALIZE THE WORKING VARIABLES?
>NO
DO YOU WISH TO CHANGE ANY OF THE WORKING VARIABLE VALUES?
>NO
```

```
THE FOLLOWING VARIABLES HAVE WORKING VALUES DIFFERENT THAN SAVED VALUES:

 VARIABLE      SAVED VALUE   WORKING VALUE
 --------      -----------   -------------
 EQPT              0.          5.00000E 05
 SOFT              0.          15710.00000
 DLAB              0.          7.69000E 05
 MATS              0.          4.23800E 06
 UTIL              0.          1.50000E 05
INPUT AN INDEPENDENT VARIABLE FOR THE SENSITIVITY STUDY
>R <------------------------ RATE OF RETURN ON EQUITY
INPUT THE FORM OF THE INDEPENDENT VARIABLE SPECIFICATION
>1
INPUT A LIST OF VALUES ENDING IT WITH "*"
>.1 .15 .2 .3 .4 .5 .6 .8 .99 *
DO YOU WISH TO DISPLAY THE SET OF INDEPENDENT VARIABLE VALUES?
>NO
DO YOU WISH TO PRINT ANY SENSITIVITY STUDY RESULTS?
>YES
DO YOU WISH TO HAVE THE OUTPUT DIRECTED TO YOUR TERMINAL?
>YES
INPUT A REPORT TITLE
>THIS IS A TEST
ENTER A DISPLAY COMMAND FOLLOWED BY THE VARIABLES TO BE DISPLAYED OR ENTER DONE
>DISPLAY C(1) C(2) C(3) PRICE1 PRICE2




THIS IS A TEST                                         1:52 PM  09/18/80  PAGE   1
                                                 SIZE.INDEX:  1  COMPANY: MODULECO

      R             C(1)          C(2)            C(3)         PRICE        PRICE
  FRACTION/YR                                                $(1975)/     $(1975)/
                          THE INPUT VALUE                     MODULE      PEAK-WATT

  1.00000E-01      .30896      62.64798         2.05597     43.70461        .25293
       .15000      .39146      84.69824         2.09720     46.45547        .26685
       .20000      .48417     110.60727         2.14224     49.60300        .28707
       .30000      .70017     174.17253         2.24255     57.17459        .33089
       .40000      .95393     254.90819         2.35369     66.48915        .38479
       .50000     1.23864     353.00024         2.47220     77.49944        .44652
       .60000     1.54726     467.99266         2.59569     90.10446        .52146
       .80000     2.20741     745.66846         2.84525    119.64111        .69240
       .99000     2.85733    1063.57176         3.08004    152.42444        .88213

ENTER A DISPLAY COMMAND FOLLOWED BY THE VARIABLES TO BE DISPLAYED OR ENTER DONE
>DONE
DO YOU WISH TO PLOT ANY SENSITIVITY STUDY RESULTS?
>YES
DO YOU WISH TO HAVE THE PLOTS DIRECTED TO YOUR TERMINAL?
>YES
ENTER A PLOT COMMAND FOLLOWED BY THE VARIABLES TO BE PLOTTED OR ENTER DONE
>PLOT PRICE2
```

SIZE.INDEX: 1 COMPANY: MODULECO

PRICE $(1975)/PEAK-WATT VERSUS R



```
ENTER A PLOT COMMAND FOLLOWED BY THE VARIABLES TO BE PLOTTED OR ENTER DONE
>DONE

DO YOU WISH TO PERFORM ANOTHER SENSITIVITY STUDY?
>NO
DO YOU WISH TO PROCESS ANOTHER CASE?
>NO

DEV Z DETACHED

14.00.08 >LOG
36.30 ARU'S, .17 CONNECT HRS
LOGGED OFF AT 14.00.23 ON 18SEPT80
```

TERMINATES THE RUN

COST OF RUN IS (36.30) (0.20) + (0.17) ($15.) ≃ $9.79