MASTER

Progress Report 12

for the Period January 1979 to April 1979

and Proceedings of the
12th Project Integration Meeting

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

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REA

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Prepared by the Jet Propulsion Laboratory, California Institute of Technology,
for the Department of Energy through an agreement with the National
Aeronautics and Space Administration.

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

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ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period January through April 1978. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at, the Project Integration Meeting held April 4-5, 1979.

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ABBREVIATIONS AND TERMS

AR	Antireflective
BSF	Back-surface field
B-T	Bias/temperature
B-T-H	Bias/temperature/humidity
CLF	Continuous liquid feed
CSA	Department of Energy Office of Conservation and Solar Applications
CVD	Chemical vapor deposition
CZ	Czochralski (classical silicon crystal growth method)
DCF	Discounted cash flow
DLTS	Deep-level transient spectroscopy
DS/RMS	Directionally solidified/refined metallurgical silicon
EB	Electron beam
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EPR	Ethylene propylene rubber
EPSDU	Experimental process system development unit
ESB	Electrostatic bonding
EVA	Ethylene vinyl acetate
FPUP	Federal Photovoltaics Utilization Program
GRC	Glass-reinforced concrete
HEM	Heat exchanger method (silicon crystal ingot growth method)
IPEG	Interim Price Estimation Guidelines
I_{sc}	Short-circuit current
I-V	Current-voltage

LAPSS	Large-area pulsed solar simulator
LCP	Lifetime cost and performance
LSA	Low-Cost Solar Array
MBS	Multiblade sawing
MWS	Multiwire sawing
NDE	Nondestructive evaluation
NOCT	Nominal operating cell temperature
PDU	Process development unit
P/FR	Problem/failure report
PIM	Project Integration Meeting
PMMA	Polymethylmethacrylate
$P_{\max}$	Maximum power
ppba	Parts per billion atoms
ppma	Parts per million atoms
PRDA	Program Research and Development Announcement
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RFP	Request for proposal
RFQ	Request for quotation
RMS	Refined metallurgical-grade silicon
RTR	Ribbon-to-ribbon (silicon crystal growth method)
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Solar Array Manufacturing Industry Simulation
SERI	Solar Energy Research Institute
SOC	Silicon on ceramic (crystal growth method)
TD&A Lead Center	Photovoltaics Program Technology Development and Applications Lead Center

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SECTION I

PROJECT SUMMARY

A. INTRODUCTION

This report describes the activities of the Low-Cost Solar Array Project during the period December 1978 through March 1979, including the 12th LSA Project Integration Meeting (PIM) held April 4-5, 1979.

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

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic modules at a rate greater than 500 MW/yr and at a price of less than \$500 (in 1975 dollars) per peak kilowatt by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. OVERVIEW

In the analysis and integration area, the Solar Array Manufacturing Industry Costing Standards (SAMICS) methodology was applied to several contractor production processes in support of Production Process and Equipment Area activities. Review of the SAMICS indirect requirements matrix was initiated, also in cooperation with PP&E. A major presentation was made at Department of Energy describing SAMICS. Later, at the 12th Project Integration Meeting, projections of potential module prices for the late 1980s and late 1990s were shown (see Section III). The results of the first verification runs of the Lifetime Cost and Performance (LCP) model were also presented at the PIM.

The planning and costing of Battelle Memorial Institute's process development unit was carried out for its fabrication, procurement, installation, startup and developmental operation. Union Carbide's process design-phase activities concluded during this reporting period, and contract negotiations began for the 100 MT/yr experimental process support development unit phase. Union Carbide's free-space reactor was operated at five times the design output rate to produce about 30 kg of Si powder, which was two to three times as dense as powder produced at the design output rate. Impurity levels were less than 10 ppba. Westinghouse's arc heater equipment for the reduction of SiCl_4 by Na neared completion, and shakedown tests at

reduced power levels were successful. At the end of the reporting period, work was stopped because of cost overruns and efforts were being made to fund the program to completion. The final report on J.C. Schumacher's investigation into the production of Si from bromosilanes indicated that two closed-loop SiHBr_3 processes demonstrated by laboratory-scale experiments were feasible. The Schumacher contract lapsed in February due to lack of available funds.

In ingot technology, Kayex Corporation (Hamco) completed its chunk silicon feeder and a 100-kg multiple ingot run using a 30 cm dia. crucible was made. Ingot diameter was 12 cm, with an average growth rate of 8 cm/h. Loss of crystal structure remains a problem. A melt transfer/crystal-growth run was attempted by Siltec Corp., yielding ingots of 21 kg to 70 kg. Maximum growth rate achieved was 1.29 kg/h.

In shaped sheet investigations, Mobil Tyco's EFG process was modified to achieve a greater width of 10 cm at a slower speed of 5 cm/h than in previous demonstrations. Westinghouse, using its web dendritic approach, made more than 40 experimental growth runs, demonstrating a throughput of $22 \text{ cm}^2/\text{min}$. Melt replenishment, with simultaneous web growth, was used for a period of more than one hour. Motorola obtained significant improvements in material quality in 7.5 cm wide ribbons using the RTR process. Solar cell efficiencies of $>10\%$ at AM1 with areas of $>1 \text{ cm}^2$ were achieved.

Candidate encapsulation material systems and fabrication processes having the potential of meeting the Project cost, performance and lifetime goals have been identified, and during this period intensive experimental evaluation and system development was begun. A 12 in x 16 in minimodule effort will examine the effectiveness of a large variety of materials in many component combinations. Materials and processes that were the subject of major special investigations included ethylene/vinyl acetate, electrostatic bonding, silicone-based materials, glass-reinforced concrete, and anti-reflective coatings.

In junction formation, Sensor Technology demonstrated the ability of spray-on doping techniques to produce both boron- and phosphorus-doped junctions. Spire Corp. has determined reproducible and uniform beam parameters intended for post-ion-implantation electron-beam annealing of 7.6-cm dia. wafers with a single pulse. Westinghouse reports that most consistent back-surface field results have been achieved by sputtering deposition of aluminum.

Kinetic Coatings, Inc., and Spectrolab, Inc., have optimized or defined process sequences they are developing, and a contract was awarded to Sensor Technology to establish a processing sequence for polysilicon cells.

Bernd Ross Associates has compounded fritless inks to produce metal contacts using base metals or base metal dilutions or noble

metals, and OCLI is continuing investigation of the use of copper in contact formation. Sol/Los, Inc., investigated a metallization system that will produce a molybdenum-tin contact. Westinghouse has found deterioration in all properties when an electroless palladium-nickel-conductive layer is substituted for the standard titanium-palladium-silver system.

In surface preparation, Motorola has constructed a module made entirely of cells whose front-surface ohmic contact grid pattern was etched through the silicon nitride dielectric by plasma technique through a mechanical mask.

OCLI is in the process of developing a p-on-n, 14% efficient module. Most recently, 15.6% efficient cells have been reported. ARCO Solar is designing machines that will solder interconnects at a rate of 12 per minute and produce 12 laminates per hour. A final design review has been completed of OCLI's four-fold tooling, which provides semi-automation of the antireflective coating application, cell testing, back contact soldering, and vacuum pick-up.

During this reporting period, 44.4 kW of photovoltaic modules were shipped to JPL under Block III procurement. This represented 89% of the contracted total of 214 kW, and completed the requirement for three of the five manufacturers contributing to the procurement. Proposals for the Block IV module design contracts were evaluated and negotiations with eight potential contractors were begun. Most testing done during this period was on flat-plate PRDA-38 modules. Significant findings were that 1) most modules showed excellent hailstone survivability and 2) hipot tests during environmental exposure showed a high incidence of failure of electrical resistance to ground. Reference cells were delivered to the PRDA test program at JPL and MIT/LL. Testing during this period resulted in a modification of test procedures using reference cells. JPL assumed responsibility this period for 12 module test sites originally established by Lewis Research Center. These sites, located in diverse locations between Alaska and Panama, will be the subject of visits and an updated test plan by JPL personnel.

SECTION II

AREA REPORTS

A. PROJECT ANALYSIS AND INTEGRATION

1. Planning and Integration

A critique of, and response to, the American Physical Society's report on photovoltaics was submitted to Project management and to the Technology Development and Applications Lead Center. This was combined with the Lead Center's response and forwarded to the APS and DOE. As a result, a dialogue has developed between LSA, Lead Center, DOE and APS that should be very helpful in dispelling misconceptions and keeping all parties informed.

Support of the Lead Center continued with reviews of the supply-side economic assessment implementation plan and contributions to the Program planning and integration plans as well as the Multiyear Program Plan. In addition, LSA contributed support to the Lead Center in the effort to develop a system-level price allocation methodology and breakdown structure for Program-wide application.

The Project Analysis and Integration area has been exploring ways to aid Project management in decision-making by applying some decision analysis methods to the LSA planning process. The application of these methods shows promise for clarifying Project goals and identifying appropriate action to attain those goals.

2. Array Technology Cost Analysis

The SAMICS methodology was applied to the evaluation of several contractor production processes in support of Production Processes and Equipment Area activities. Several runs were made on CdS processes in connection with discussions at JPL with a CdS module manufacturer.

A major presentation was made at DOE describing the SAMICS methodology, validation and working experience. Although the stated purpose of the presentation was a SAMICS methodology review, the subject shifted to several other items including the credibility of the \$0.50/Wp strawman candidate factory.

A review of the SAMICS indirect requirements matrix was initiated and is continuing in close cooperation with the Production Processes and Equipment Area. The results of this review will be more realistic algorithms for computing indirect requirements.

The development of a replacement algorithm for IPEG was initiated. The new algorithm should permit greater flexibility in calculating rough estimates of product prices.

Projections of potential module prices for the late 1980s and late 1990s were presented at the 12th Project Integration Meeting and are shown in the PA&I section of the PIM portion of this report. These prices were not SAMICS analyses, but were based on estimates of what would be possible in that time frame.

A revised SAMICS Input Data Preparation document has been issued. It contains examples of excellent Format A preparation and a checklist of items to consider in Format A preparation.

3. Economics and Industrialization

The results of the first verification runs of the lifetime cost and performance (LCP) model were presented at the 12th Project Integration Meeting. Viewgraphs of this presentation are included in the PIM section of this report. The LCP model development was initiated in the LSA Project and is now being developed jointly by LSA Project and the Lead Center.

Documents of interest published during this reporting period include the Gnostics Concepts, Inc., "Industrialization Study" final report and JPL Document 5101-102, "Energy Systems Economic Analysis (ESEA) Methodology and Users Guide." The latter describes a computer program that has been developed for the rank ordering of alternative energy systems in terms of cost.

B. TECHNOLOGY DEVELOPMENT AREA

1. Silicon Material Task

The objective of the Silicon Material Task is to establish by 1986 an installed plant capability of producing silicon (Si) suitable for solar cells at a rate equivalent to 500 MWp of solar arrays per year and at a price of less than \$10/kg (1975 dollars; \$14/kg in 1980 dollars). One means of meeting this requirement is to devise a process for producing Si material that is less pure than semiconductor-grade Si material.

a. Technical Goals. Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about \$65/kg. A drastic reduction in the price of material is necessary to meet the economic objectives of the LSA Project. One means for meeting this requirement is to devise a process for producing Si material that is less pure than semiconductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for the Project 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 the optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si.

b. Organization and Coordination. As Table 2-1 indicates, the Silicon Material Task effort is organized into four phases. Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si are being demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells are being investigated. This body of information will serve as a guide in developing and assessing processes (in Part III) for the production of solar-cell-grade Si. The process developments in

Table 2-1. Organization of the Silicon Material Task Effort

Phase/Part	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing Si.
Part I	Establish the practicality of processes capable of high-volume production of semiconductor-grade Si.
Part II	Investigate the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells.
Part III	Establish the practicality of processes capable of high-volume production of solar-cell-grade Si.
Part IV	Evaluate the relative commercial potential of the Si-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct EPSDU operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

Parts I and III are being accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III are being evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies, and the most promising processes will have been selected.

Phase II is for obtaining process scale-up information. This is being derived from experiments and analyses involving mass and energy balances; process flows; kinetics; mass transfer; temperature and pressure effects, and operating controls. The basic approach is to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations are also being used. This body of scale-up data will then provide the necessary basis for the design, construction, and operation of experimental process system development units (EPSDUs).

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, EPSDUs will be used to obtain technical and economic evidence of large-scale production potential. In the EPSDU phase (i.e., Phase III) there will be opportunities to correct design errors, to determine energy consumption, to establish practical operating procedures and production conditions for process optimization and steady-state operation, and to evaluate more realistically the requirements for instrumentation, controls, and on-line analyses.

In the final phase of the Silicon Material Task (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The EPSDU and the commercial plant will be operated concurrently for some time so as to permit the use of the EPSDU for investigations of plant operations; i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task are being conducted in supporting efforts. These supporting subtasks are accomplished under contract and by an in-house JPL program.

c. Silicon Material Task Contracts. Fifteen contracts are in progress and are listed in Table 2-2.

d. Silicon Material Task Technical Background

1) Processes for Producing Semiconductor-Grade Si

a) Production of Si by Zinc (Zn) Reduction of SiCl₄ -- Battelle. The contract with Battelle Columbus Laboratories is for development of the reaction for the Zn reduction of silicon

tetrachloride (SiCl_4) using a fluidized bed reactor as an economical means for producing Si.

Table 2-2. Silicon Material Task Contractors

Contractor	Technology Area
AeroChem Research Princeton NJ (JPL Contract No. 954777) (JPL Contract No. 954862)	Investigation of Si halide-alkali metal flames process Model of silicon hydride and halide reactions
Aerospace Corporation El Segundo CA (JPL Contract No. 955201)	Impurity concentration measurements
Battelle Columbus Laboratories Columbus OH (JPL Contract No. 954339)	Zn/ SiCl_4 fluid bed reactor process
Lamar University Beaumont TX (JPL Contract No. 954343)	Technology and economic analyses
Lawrence Livermore Laboratories Livermore CA (NASA Defense Purchase Request No. WO8626)	Measurements of impurity concentrations in Si
Materials Research Salt Lake City UT (JPL PO No. JR-672583)	X-ray analysis of Si wafers
National Bureau of Standards Washington DC (NASA Defense Purchase Request No. WO 8604)	Measurements of impurity concentration in Si
Sah, C. T. Associates Urbana IL (JPL Contract No. 954685)	Effects of impurities on cell performance
Schumacher, J.C. Oceanside CA (JPL Contract No. 954914)	Production of Si from bromosilanes

Table 2-2. Silicon Material Task Contractors (Continued)

Contractor	Technology Area
Solarex Rockville MD (JPL Contract No. 955307)	Effects of impurities on performance of solar cells
SRI International Menlo Park CA (JPL Contract No. 954471)	Sodium (Na) reduction of SiF_4 process
Union Carbide Sisterville WV (JPL Contract No. 954334)	Silane/silicon process
Westinghouse Pittsburgh PA (JPL Contract No. 954331)	Effects of impurities on performance of solar cells
(JPL Contract No. 954589)	Plasma arc heater process

b) Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. The Union Carbide contract is for the development of processes for the production of silane (SiH_4) and for the subsequent deposition of Si from SiH_4 . The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of metallurgical-grade Si and the by-product SiCl_4 to trichlorosilane (SiHCl_3), which can be used as a feed for redistribution. The free-space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

2) Effects of Impurities and Processing on Solar Cell Performance

a) Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. The objective of this program is to obtain a data base for performing cost tradeoff analyses for polycrystalline Si processes and for defining the purity requirements for solar-cell-grade Si.

b) Effects of Impurities -- C. T. Sah Associates. The objective is to develop a model for solar-cell performance, including

the effects of recombination centers. The parameters of the recombination centers are being determined.

c) X-Ray Analysis of Si Wafers -- Materials Research Inc.
This is for a non-destructive study of the crystallographic structure defects in Si wafers deliberately doped with impurities.

d) Analysis of the Effects of Impurities in Si -- Solarex.
This effort consists of measuring and analyzing the performance of solar cells that have been fabricated from impurity-doped Si ingots.

e) Impurity Concentration Measurements in Si -- Lawrence Livermore Laboratories. By means of neutron activation analyses, impurity concentrations in Si materials from process development contractors are being measured.

f) Impurity Concentration Measurements in Si -- National Bureau of Standards. Procedures are being developed for measuring impurity concentrations in the ppba range in Si using neutron activation analysis and spark-source mass spectroscopy.

g) Composition Measurements by Analytical Photon Catalysis -- Aerospace. The purpose of this work is to establish the capabilities of analytical photon catalysis for the measurement of impurity concentrations in Si in the ppba range.

3) Processes for Producing Solar-Cell-Grade Si

a) Production of Si from H_2SiF_6 Using Na Reduction of SiF_4 Process -- SRI International. This contract is for the development of a two-step process for the production of Si from SiF_4 , which can be made from H_2SiF_6 , a byproduct from the fertilizer industry. The steps are (1) the reduction of silicon tetrafluoride (SiF_4) by Na to produce high-purity Si and (2) the further purification of this product.

b) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. This contract is for the development of a process for the production of Si using the reduction of $SiCl_4$ by Na, employing electric-arc heaters.

c) Production of Si from Bromosilanes -- J. C. Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes as the appropriate intermediates to produce Si.

4) Supporting Contracts

a) Evaluation of Si Production Processes -- Lamar University.

The objective of this contract is to evaluate the potentials of the processes being developed in the program of the Silicon Material Task. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing economics. The evaluations will be performed during all phases of the Task, using information that becomes available from the various process-development contracts.

b) Development of a Model and Computer Code to Describe Si Production Processes -- AeroChem Research. This contract is for the formulation of a model and a computer code for the description of several of the Si processes now under development.

c) Investigation of Si Halide/Alkali Metal Flames -- AeroChem Research. The objective is to study high-temperature reactions of alkali metals with Si halides, evaluating product separation and collection processes, measuring heat release parameters for scaling purposes, and determining the effects of the reactants and products on materials of construction.

e. Summary of Progress

1) Production of Si by Zn Reduction of SiCl_4 -- Battelle Columbus Laboratories. The planning and costing of the Process Development Unit (PDU) was carried out and a proposal was prepared for the PDU fabrication, procurement, installation, start-up, and developmental operation. The PDU consists of the critical portions of the Experimental Process System Development Unit (EPSDU), and it will be operated in a batch mode to prove out its principal items (Zn vaporizer, reactor byproduct condenser, and ZnCl_2 electrolysis cell). Development continued on these three items. The power efficiency of the electrolysis cell was raised to 42.5% from a level of about 32%.

2) Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. The Phase II (Process Design) activities ended on March 31, and the final report on this work was completed. Contract negotiations for Process Support R&D for Phase III (100 MT/yr EPSDU program) were started. A unilateral contract modification was issued by JPL to cover the period between the two phases.

The free-space reactor was operated at five times the design output rate to produce about 30 kg of Si powder. This powder was two to three times as dense as powder produced at the design output

rate. Analysis of electrical resistivity data for Si crystals made by melting the powder produced in the free-space reactor indicates electrically active impurity levels of less than 10 ppba.

3) Determination of the Effects of Impurities and Process Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. Deep-level transient spectroscopy (DLTS) and detailed I-V measurements made on gettered, Ti-doped solar cells indicate that as cell performance improves, bulk lifetime increases and the density of Ti recombination centers ($E_V + 0.3\text{eV}$ level) diminishes. Thus, in this case gettering deactivates the recombination centers rather than changing the level of the recombination center. The Ti trap density fell by about a factor of four after gettering for five hours at 1100°C .

Studies of potential impurity anisotropy in 3-inch-dia. Mn-doped and Ti-doped wafers were extended to provide detailed edge-to-center and seed-to-tang maps of cell performance. No systematic or preferential impurity distribution was noted except a slight seed-to-tang buildup due to impurity segregation during crystal growth. Performance variation across or along the ingots was within $\pm 10\%$ of the average ingot cell efficiency. This was consistent with the map of ingot bulk lifetime, which indicated that the maximum variation of impurity content is less than a factor of 2 in both types of ingots.

Initial studies of impurity aging effects on solar cells were done for temperatures up to 800°C and times as long as 100 h. For uncontacted cells, no cell performance degradation due to aging effects in Mo-doped or Ti-doped cells was noted even at the longest times and highest temperatures. However, cell efficiency reduction occurred in contacted cells after 10 hours at 500°C due to interdiffusion of the contact metals and Si base material.

4) Effects of Impurities -- C.T. Sah Associates. Computer model studies were made of the effects of phosphorus-vacancy recombination centers in the phosphorus-diffused back-surface field (BSF) region, of boron-defect complex centers in the diffused emitter, and of surface recombination at the front and back surfaces in BSF cells. These recombination mechanisms are not as important as recombination at the Ti center in the base region. Computer calculations showed that to get AM1 efficiency of 16% in the Si $P^+/N/N^+$ cell, which is less sensitive to Ti than the corresponding P-base cell, the Ti concentration must be smaller than about 6×10^{12} atoms/cc.

The second technical report, covering the past year's work, was completed for distribution in May.

5) X-ray Analysis of Si Wafers -- Materials Research. Samples from Al-doped and Mn-doped ingots were examined by the Lang transmission technique and the results were correlated with the performance of solar cells made from other slices of the same materials. The Al-doped samples were by far the cleanest with respect to dislocations. However, there were varying amounts of precipitate clusters scattered at random in the samples. Correlations with the cell performance indicate that the Al-doped Si solar cell behavior is not structure-defect-sensitive but rather is affected by electronic properties.

6) Effects of Impurities on Solar Cells -- Solarex. This effort was started in this period. A draft program plan, including quality assurance provisions, for the cell fabrication program was prepared and submitted to JPL.

7) Composition Measurements by Analytical Photon Catalysis -- Aerospace Corp. Analysis of NBS standard Si (Standard Reference Material #57) by the analytical photon catalysis method indicates that the composition of the vapor reflects the composition of the original solid sample; these results demonstrate the validity of the method. The following impurities were identified in this material: Al, Ca, Cr, Cu, Fe, Mn, Mg, and Na. For Ti analysis, sensitivity was found to be 10^4 atoms/cc, or 1 ppb.

8) Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 -- SRI International. For the process using Na (s) and SiF_4 (g), the effects of various sizes, geometries, and feed rates of Na slices on reaction efficiencies were investigated. It was found that the presence of Na in the reaction product was minimized when the slice thickness was ≤ 3 mm. All impurities in the Si product were below the limits of detection by emission spectroscopy.

9) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. Assembly and installation of test system equipment for the process demonstration continued and neared completion. Shakedown tests were conducted on several subsystems, including cooling water, electrical, and effluent disposal. The first reactor shakedown tests, made at reduced power levels, were successful. In the first test, only argon (Ar) gas was employed as the working fluid (no H_2 , Na, or $SiCl_4$ being introduced). In the second test a mixture of H_2 and Ar was used, and a power level of 750 kW (about half of the normal operating power) was attained.

In mid- February JPL was notified by Westinghouse that the contract funding would be exhausted by about the end of February because of a projected overrun. Consequently, after the second test was done on March 2 the work was stopped. Efforts are under way to

reach a suitable contracting agreement to assure completion of the effort while still limiting the additional funding required.

10) Production of Si from Bromosilanes -- J.C. Schumacher. Tests were performed on the synthesis of tribromosilane (SiHBr_3), which is used as feedstock for Si production in this process. The yield was found to be sensitive to such variables as residence time of the reactants in the hot zone, H_2 -to- SiBr_4 feed ratio, catalytic agents, and temperature. In other tests the production of Si by the H_2 reduction of SiHBr_3 was studied.

The final report was issued. The study indicates that two closed-loop SiHBr_3 processes (the thermal decomposition process and the hydrogen reduction process) for the production of pure Si were demonstrated by laboratory-scale experiments to be technically feasible. These processes appear to have some significant advantages, such as reductions in both homogeneous nucleation and wall deposition of Si, over chlorosilane-based processes.

This contract was allowed to lapse in February because of lack of available funds.

11) Silicon Halide/Alkali Metal Flames -- AeroChem Research. A larger-scale reactor system was designed, built, and tested. Experiments on the compatibility of pyrolytic graphite-coated graphite with Na vapor were completed. Tests were made at 1700 K and 1200 K, a Na pressure of 0.5 atm, and flow velocities ranging from 3 m/sec to 10 m/sec. At 1200 K, tests showing that the coated graphite samples were extensively damaged and lost their structural strength were consistent with earlier tests with refluxing Na. The experiments at 1700 K showed no substrate damage, but the coating peeled and cracked.

12) Development of a Model and Computer Code to Describe Si Production Processes -- AeroChem Research. Coefficients needed to describe the transport of Si vapor and droplets from the interior to the walls of reactors, such as those in the Westinghouse arc heater process and in the AeroChem flame process, were calculated. It was found that for extremely large temperature gradients near the wall (conditions that occur in some of the reactors to be used in producing Si, particularly the Westinghouse reactor), the deposition of Si droplets in the diameter range $0.01\ \mu\text{m}$ to $1.0\ \mu\text{m}$ within a viscous sublayer region close to the wall will be controlled by thermal diffusion (thermophoresis or Soret diffusion). Work also proceeded on debugging and developing the modified LAPP (Low Altitude Plume Program) code and the boundary layer code.

13) JPL In-House Si Processing Technologies. Initial testing of the modified continuous-flow pyrolyzer (CFP) system was conducted. The particle feed subsystem was tested successfully at particle temperatures up to 840°C and at feed rates of about 5 g/min. Tests were then made with the CFP system. One test lasted 1.7 h, during which particles were fed for 0.7 h at temperatures as high as 850°C. The results indicate that the difficult problem of continuously feeding fine Si powder at elevated temperature has been solved.

Tests were conducted in the one-inch-diameter quartz fluidized bed reactor (FBR) to determine the concentration and temperature dependence for homogeneous nucleation of Si from silane (SiH_4). The conditions ranged from 700°C to 850°C in the bed and 1% to 6% SiH_4 in H_2 , at about 6.5 times the minimum fluidization velocity. For these conditions, less than 1% of the Si formed in the reactor was collected at the outlet as fines, indicating that reasonably high concentrations of SiH_4 can be employed in the FBR without producing excessive quantities of fines.

2. Large Area Silicon Sheet Task

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the capability of several processes to produce large areas of Si sheet material suitable for low-cost, high-efficiency solar photovoltaic energy conversion. To meet the objectives of the LSA Project, sufficient technology development must be accomplished on these processes to allow the capability of producing large areas of silicon sheet. The final sheet growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

a. Technical Goals. Current solar cell technology is based on the use of Si 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 Si wafers is tailored to the needs of large-volume semiconductor products (i.e., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of Si high-volume production techniques that would result in low-cost electrical energy.

Growth of Si 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), etc., are possible candidates for the growth of solar cell material. The growth of large ingots requiring less consumables would also appear plausible. However, it appears that to meet productivity requirements in cutting large ingots into wafers it will be necessary to increase throughput; one way to achieve this is by multiple-cutting techniques.

Technology development on ribbon, film and ingot growth plus multiple-blade, multiple-wire and enhanced ID cutting initiated in 1975-76 is in progress.

b. Organization and Coordination. At the time the LSA Project was initiated (January 1975) a number of methods potentially suitable for growing Si crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured. The Large-Area Silicon Sheet Task effort is organized into four phases: feasibility demonstration of sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1979-82); development, fabrication, and operation of production growth plants (1981-86).

c. Large-Area Silicon Sheet Task Contracts. Advanced development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 2-3.

d. Large-Area Silicon Sheet Task Technical Background

1) Shaped Ribbon Technology: EFG Method -- Mobil-Tyco Solar Energy Corp. The EFG technique is based on feeding molten Si through a slotted die as illustrated in Figure 2-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material that is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 5 cm/min and a width of 10 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

2) Shaped Ribbon Technology: Laser Zone Growth in a Ribbon-to-Ribbon (RTR) Process -- Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 2-2). The polysilicon ribbon is fed into a preheated region that is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

3) Shaped Ribbon Technology -- Westinghouse. Dendritic web is a thin, wide ribbon form of single-crystal Si. "Dendritic" refers to the two wire-like dendrites on either side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film supported by the bounding dendrites. Dendritic web is particularly suited for fabrication into photovoltaic converters for a number of reasons, including the high efficiency of the cells that can be fabricated from it, the excellent packing factor of the cells into subsequent arrays, and the cost-effective conversion of raw Si into substrates (Figure 2-3).

Table 2-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
SHAPED SHEET TECHNOLOGY	
Mobil-Tyco Solar Energy Waltham MA (JPL Contract No. 954355)	Edge-defined film-fed growth (EFG)
Motorola, Inc. Phoenix AZ (JPL Contract No. 954376)	Ribbon growth, laser zone regrowth
Westinghouse Research Pittsburgh PA (JPL Contract No. 954654)	Dendritic web process
Honeywell Corp. Bloomington MN (JPL Contract No. 954356)	Si on ceramic substrate (SOC)
ARCO Solar, Inc. Chatsworth CA (JPL Contract No. 955325)	Vacuum die casting
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem MA (JPL Contract No. 954373)	Heat exchanger method (HEM) of cast ingot and multiwire fixed abrasive slicing technique (FAST)
Kayex Corp. (Hamco) Rochester NY (JPL Contract No. 954888) (JPL Contract No. 955270)	Advanced Cz growth Advanced Cz growth
Siltec Corp. Menlo Park CA (JPL Contract No. 954886) (JPL Contract No. 955282)	Advanced Cz growth Enhanced ID slicing
Varian Vacuum Division Lexington MA (JPL Contract No. 954374) (JPL Contract No. 954884)	Multiblade slurry sawing Advanced Cz growth

Table 2-3. Large-Area Silicon Sheet Task Contractors (Continued)

Contractor	Technology Area
DIE AND CONTAINER MATERIALS STUDIES	
Battelle Labs Columbus OH (JPL Contract No. 954876)	Silicon nitride for dies
Coors Porcelain Golden CO (JPL Contract No. 954878)	Mullite for container and substrates
Eagle Picher Miami OK (JPL Contract No. 954877)	CVD silicon nitride and carbide
RCA Labs Princeton NJ (JPL Contract No. 954901)	CVD silicon nitride
Tylan Torrance CA (JPL Contract No. 954896)	Vitreous carbon
MATERIAL EVALUATION	
Optical Coating Laboratory City of Industry CA (JPL Contract No. 955089)	Cell fabrication and evaluation
Spectrolab Sylmar CA (JPL Contract No. 055055)	Cell fabrication and evaluation
UCLA Los Angeles CA (JPL Contract No. 954902)	Material evaluation
Materials Research Inc. Centerville UT (JPL Contract No. 957977)	Quantitative analysis of defects and impurity technique evaluation
Cornell University Ithaca NY (JPL Contract No. 954852)	Characterization--Si properties

Figure 2-1. Edge-Defined Film-Fed Growth (EFG) -- Mobil-Tyco

Figure 2-2. Laser Zone Regrowth -- Motorola

Figure 2-3. Schematic Section of Web Growth --Westinghouse

4) Supported Film Technology -- Honeywell. The purpose of this program is to investigate the technical and economic feasibility of producing solar-cell quality sheet Si by coating inexpensive ceramic substrates with a thin layer of polycrystalline Si. 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 Si can be caused to wet only that graphite-coated face and produce uniform thin layers of large-grain polycrystalline Si; thus, only a minimal quantity of Si is consumed.

5) Ingot Technology: Heat Exchanger Method (HEM) -- Crystal Systems. The Schmid-Vicchnicki technique (heat exchanger method) has been developed to grow large single-crystal sapphire (Figure 2-4). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of He (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.

Growth of a crystal by the heat exchanger method:

- (a) Crucible, cover, starting material, and seed prior to melting.
- (b) Starting material melted.
- (c) Seed partially melted to insure good nucleation.
- (d) Growth of crystal commences.
- (e) Growth of crystal covers crucible bottom.
- (f) Liquid-solid interface expands in nearly ellipsoidal fashion.
- (g) Liquid-solid interface breaks liquid surface.
- (h) Crystal growth completed.

Figure 2-4. Crystal Growth Using the Heat Exchanger Method -- Crystal Systems

The goal of this program is to determine if the heat-exchanger ingot casting method can be applied to the growth of large shaped Si crystals (30 cm cube) 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 Si.

6) Ingot Technology: Advanced Cz -- Varian, Texas Instruments, Siltec, and Kayex. In the advanced Cz contracts efforts are geared toward developing equipment and a process to achieve the cost goals and demonstrate the feasibility of continuous Cz solar-grade crystal production (Figure 2-5). Varian will modify an existing furnace for continuous growth using granular Si for recharging (molten Si will also be considered), and a new puller is to be designed. Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Kayex will demonstrate the growth of 100 kg of single crystal material using only one crucible by periodic melt replenishment.

Figure 2-5. Continuous Cz Crystal Growth Machines

7) Ingot Technology: Multiwire Sawing (MWS) -- Crystal Systems; Multiblade Sawing (MBS) -- Varian. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a large cost factor in producing solar cells. The multiblade and multiwire slicing operations employ similar reciprocating blade-head motion with a fixed workpiece. Multiblade slicing is accomplished with a slurry suspension of cutting fluid and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheath, which is impregnated with diamond as an abrasive.

8) Contact Material -- Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, and Tylan. In the crystal-growing processes, a refractory crucible is required to hold the molten Si, while in the ribbon processes an additional refractory shaping die is needed. The objective of these contracts is to develop and evaluate cost-effective refractory die and container materials. The material must be

mechanically stable to temperatures above the melting point of Si, must not excessively contaminate the Si processed through it, be amenable to the fabrication of dies and containers with close tolerances and of varying geometries, and be cost-effective. Two of the contracts in this area, RCA and Tylan, are to develop a substrate material for supported film growth and a coating for substrates, dies, and containers.

9) Material Evaluation -- Optical Coating Lab (OCLI), Spectrolab, UCLA and Materials Research Inc. Proper assessment of potential low-cost Si sheet materials requires the fabrication and testing of solar cells using reproducible, 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 Si sheet be impartially evaluated in solar cell manufacturing environments with well-established techniques and standards. Two solar cell manufacturers, OCLI and Spectrolab, have been retained to satisfy this need.

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

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

e. Summary of Progress

1) Ingot Technology

a) Kayex Corporation (Hamco). The design for the chunk Si feeder was completed and the fabrication work was initiated. A 100-kg multiple-ingot run using a 30 cm (12") dia. crucible was made. Ingot diameter was 12 cm, with an average growth rate of 8 cm/h. The total run time was 80 h. Another run totaling 50 kg (2 ingots) was made using a 35.5 cm (14") dia. crucible. Loss of crystal structure remains a major problem.

b) Siltec Corporation. The recharging of solid Si particles into the melt-down chamber during a melt transfer/crystal growth run was attempted. Recharging was slow, crystal removal was difficult and an excessive oxide build-up in the meltdown chamber obscured the view inside the furnace. Several growth runs were tried for 100 kg multiple-ingot growth using the liquid transfer system. Yields varying

from 21 kg to 70 kg were obtained. Maximum growth rate achieved was 1.29 kg/h (contract goal >2.0 kg/h). Major problems were the erratic heat control because of SiO deposition on the sensor surface and the melt transfer tube failure. An add-on phase is currently being negotiated.

c) Varian Associates. After detailed discussions between Varian and JPL it was decided that the work on the prototype construction would continue. No further development work or growth runs will be funded under this phase of the contract.

d) Crystal Systems (HEM). Design work on modifications of the present furnace was completed. Construction of a larger heat zone is under way. Several 20 cm dia. ingots (5 kg, 6.5 kg, etc.) were cast at growth rates of 1 kg/h (contract goal is 2.5 kg/h), with single crystal yield of 80%. Delivery of a 15 cm x 15 cm shaped crucible is awaited by CSI. Uniformity of the graded crucibles is affecting growth yield.

e) Crystal Systems (FAST). A 10 cm x 10 cm x 5 cm ingot (cut from a 15 cm dia. HEM ingot) was cut in the high-speed slicer using commercial (impregnated and plated diamonds) Lastec variety blades at 20 slices/cm spacing. Yields dropped rapidly (to 50%) at the latter half of the run because of binding in the ingot-feed mechanism. Modification for 25 slices/cm is being planned. Blade development work will continue. Another run on an older Varian 686 machine yielded 100% of 4 cm x 4 cm wafers cut at 25 wafers/cm. Blade pack with 100 blades was used for five runs, giving good blade life.

f) Varian Associates (MBS). A new 1,000-blade package was assembled and tried, but the run was aborted due to bearing trouble. Complete overhaul is planned. Mineral oil slurries with and without lubricity additive (lard) have been studied. Runs on a Varian 686 (standard machine) with 300-blade pack, 100 m thick blades and 300 m spacers (25 wafers/cm) gave low yields due to sample holder rocking and blade breakage. A water-based slurry run with additives is showing some promise. A recycled abrasive run is also planned.

g) Siltec (Advanced ID). Work has been started on design and hardware fabrication. Operation is anticipated to start by late May.

2) Shaped-Sheet Technology.

a) Mobil Tyco (EFG). The effort directed to increase throughput has been modified to achieve greater width (10 cm) at a slower speed (5 cm/min) (instead of 7.5 cm width x 7.5 cm/min). A multiple ribbon growth effort yielded 10 meters of material per cartridge system. Cell processing is planned.

b) Westinghouse (Web). More than 40 experimental growth runs were made. A throughput of 22 cm²/min was demonstrated. Direction of Ar flow was found to be critical for web quality. Initial problems with cold after-trimmers were eliminated. Melt replenishment, with simultaneous web growth, was used for a period of more than 1 h.

c) Motorola (RTR). The modified furnace for RTR growth of 7.5-cm-wide ribbons was made functional. Several CVD poly feedstock runs were made. Solar cell efficiencies of >10% at AM1 with area 1 cm² have been achieved. Rigid-edge RTR growth was demonstrated. Significant improvement in material quality was obtained.

d) Honeywell (SOC). Some progress was made in thermal-fluid flow configuration in the SCIM coater. Coatings of 30-50 cm² with apparently reasonable structure and thickness were produced. Evaluation for improvement of material quality as evidenced by low values of solar cell short-circuit current was in progress. The best SOC cell has shown 10.1% cell efficiency at AM1.

3) Contact Material.

a) Battelle Labs. Study of Sibeon and Sialon was continued. Effort is in final stage and a completion report is being prepared.

b) Eagle Picher. Si sessile drop studies were extended to higher temperatures (up to 1490°C), longer times (up to 12 h), and lower O₂ partial pressures (down to 10⁻²⁰ atm. P_{O2}). Final die and crucible blanks were submitted to Chemetal for coating. Program effort is being completed.

c) Coors Porcelain Company. About 400 slotted and 300 unslotted mullite substrates have been delivered to Honeywell. Two new compositions were also formulated and test parts delivered to Honeywell. The program effort has been completed.

d) RCA. Difficulties in EFG-type die development were encountered. Capillary rise was accomplished under vacuum conditions.

4) Material Evaluation.

a) OCLI. Solar cells were fabricated and tested using the following materials:

<u>Material</u>	<u>Avg. Efficiency at AMO</u>
EFG (RH) displaced die	6.0% (4.3 - 7.5%)
EFG (RH) standard die	5.4% (2.9 - 7.4%)
WEB	9.6%
SOC	6.8%
HEM (3 Ω -cm)	10.0%
(0.5 Ω -cm)	9.2%

BSF cell processing was not successful.

b) Spectrolab. Material and efficiencies are reported as listed below:

<u>Material</u>	<u>Efficiency AMO (%)</u>
Wacker	9-10
EFG	5-7
Web	8.5-9.7

HEM and RTR material were in the process of fabrication. Similar efforts in process optimization are under way.

c) Materials Research. Good progress was made in sample defect characterization. 200 cm² of ribbon were evaluated using a QTM (Quantimet). No cost extension of the contract may be needed for upgrading the image-analyzer QTM720 data-acquisition system by adding a PDP-1103. It will be possible to analyze Honeywell samples now.

3. Encapsulation Task

a. General Progress

Candidate encapsulation material systems and fabrication processes having the potential of meeting the LSA Project cost, performance and lifetime goals have been identified and are undergoing intensive experimental evaluation and system development. The Encapsulation Task now has two major goals: 1) the development and evaluation of candidate encapsulation material systems and 2) the development and validation of a module life prediction method. Current progress and testing results give increasing confidence that the LSA 1986 cost and performance goals can be met and technology readiness can be demonstrated by 1982.

An experimental mini-module (12 in x 16 in) demonstration and evaluation task is being conducted to qualify and optimize the several candidate low-cost encapsulation systems. Four basic material system concepts have been defined for the purpose of detailed analysis and

experimental evaluation during the coming year. These, with their functional element variations, are summarized below:

- Glass superstrate design
- Wood product (e.g. Super Dorlux) substrate design
- Metal substrate design
- Concrete substrate design.

Within these design concepts the following potential variations may be examined within the mini-module task:

<u>Superstrate glass</u>	-Soda lime (window glass) -Borosilicate -Low-iron (tempered/untreated)
<u>Pottant/Adhesives</u>	-Ethylene vinyl acetate -Aliphatic urethane -Polyvinyl butyral -Ethylene propylene rubber -Poly N-butyl acrylate -Silicone/acrylic blend -Low-cost silicone elastomer -Polyvinyl chloride plastisol
<u>Front cover films</u>	-Korad 201/R -Tedlar UT -Tailored UV screening -Films of acrylic -UV screening films of silicone resin -Abrasion resistant coatings
<u>Substrate panels</u>	-Wood fiber hardboard (coated) -Glass reinforced concrete -Steel, galvanized or organic coating
<u>Back-cover films and insulators</u>	-Mylar -Tedlar -Acrylics -Aluminum foil (plus flexible laminates of the above)

Current R&D experience and test results with the low-cost encapsulant candidates show that thermal-expansion differences between single-crystal Si solar cells and the structural panel materials such as glass, steel, hardboard, and concrete can be accommodated by a low-modulus adhesive pottant of reasonable thickness (e.g., less than 0.015 in). Excellent adhesive bonding of these different system materials appears practical with the application of selected primers and coupling agents. The prospect is good for incorporating the coupling agent directly into the pottant formulation.

A major new two-year Encapsulation Task subcontract will be awarded in the next quarter with the goal of integrating and optimizing encapsulation system candidates relative to cost, performance and durability. Studies to determine the thermal, optical, electrical and structural characteristics of candidate 1986 material systems will be performed and experimentally validated by the contractor.

The photodegradation and environmental stability of these materials are being determined at the material specimen level as well as at the system level with encapsulated solar cells. The corrosion protection provided and the corrosion sensitivity of different solar cell strings is being investigated under a current contract.

A critical question relative to the long-term stability of the low-cost pottants is the ability of UV screening covers and back-surface covers to protect them for 20 years or more. The short-term outdoor exposures and accelerated UV radiation tests have shown strikingly the protective potential of UV and oxygen barriers.

Achievement of a 3,000 V DC insulation to ground can be realized with current candidate material systems. Critical breakdown locations appear to be at terminations, electrical leads and gas bubbles left by the lamination process. Current field testing of degradation of this dielectric property has indicated this may not be a serious problem for long-term utility. Work in this area is continuing. The insertion of a low-cost dielectric scrim of glass or polymeric woven material between the solar cell strings and any conducting surface will be incorporated into selected mini-module designs for evaluation.

An abrasion-resistant organic coating applied to the acrylic UV screening film is being evaluated both for abrasion resistance and ease of dust removal. Glass appears to be almost self-cleaning in contrast to the development of a sticky dark film on some of the current silicone-covered solar modules. The soiling characteristics of several commercial abrasion-resistant coatings are being determined.

The progress of individual LSA subcontracts is presented in the following section. Selected viewgraphs from the 12th PIM contract review sessions on encapsulation are appended in Section III.3.c.

b. Contract Status

1) Materials and Processes

a) Springborn. A detailed plan for the optimization of ethylene/vinyl acetate (EVA) was worked out, and the experimental program begun. This program is being carried out with the cooperation of Dupont, the manufacturer of the base EVA resin. Dupont will report to Springborn on both Dupont's and other industrial experience with regard to the reliability and concerns of employing EVA in engineering applications.

Another major phase of experimental testing was initiated, including the following: 1) accelerated UV exposure of candidate UV screening films and candidate pottants overcoated with the films, 2) corrosion assessment of EVA encapsulated copper, mild steel, galvanized steel, etc., 3) modification of Korad 201/R with long-life UV screening agents, and 4) EVA optimization. Springborn will also initiate development of a second candidate encapsulation pottant, ethylene-propylene rubber.

The EVA optimization program has been divided into two phases, designated as system-readiness and life-readiness. System-readiness relates to the selection of its base EVA polymer, curing agents and cure conditions, whitening for pigmented EVA versions, and general qualities of chemical inertness, ease of handling and fabricability, adhesion, and optical transparency. Life-readiness relates to selection of anti-oxidants, UV stabilizers, and outer-cover requirements; module assembly, design techniques, and approaches to maximizing EVA service life. A system-ready EVA formulation should be achieved by early May.

Dr. Plueddemann of Dow Corning Corp., in his capacity as consultant to the Encapsulation Task, will develop an adhesive/primer system that can be physically incorporated into EVA. It is expected that the primer system will be sufficiently general to promote chemical coupling with all surfaces contacted by the EVA in a typical module. The development of such a system would eliminate the need for separate priming steps during module processing.

b) SPIRE. Activities at SPIRE were limited in this quarter pending approval of an 18-month contract extension.

Design modifications to the electrostatic bonder were studied. These included the use of a glass flattener in the post-bonding annealing chamber (which showed significant improvements), a cell alignment fixture incorporating beryllium pins that worked satisfactorily, and a general strengthening of the bonder.

One hundred fifty 5.7 in x 7.7 in hand-rolled Type 7070 glass panels have been completed by Corning. This is the first order of hand-rolled Type 7070 glass. Cast pieces of glass had been used in the past.

Borosilicate glasses from both Owens Corning and Schott Glass have been found satisfactory for electrostatic bonding. Work on these materials will be continued so that competition in the glass field can be increased.

Special evaporation masks for vacuum-depositing contacts have been fabricated. These masks are of a special design for use with square cells intended for future modules.

c) Dow Corning. An interim report has been reviewed by JPL and approved. It should be distributed by Dow Corning within a few weeks.

Phase II of the contract began March 1. This phase is primarily concerned with the fabrication and assessment of large-area modules using silicone-based encapsulation materials identified in Phase I. Phase II includes consideration of automated processing techniques that are applicable for the encapsulation materials. The details of the Phase II program plan were worked out at a joint meeting with Dow Corning, JPL, and Spectrolab. Two Phase II modules were displayed at the April Project Integration Meeting.

Activities to reformulate silicone/acrylic blends were begun. Blends of these polymers are cost-effective, but the selection of the basic polymers and compositions must result in a blend that can survive the JPL qualification tests and outdoor stresses mechanically. The first blend made by Dow Corning cracked during thermal cycling from -40°C to +90°C.

Dow Corning has successfully deposited its anti-abrasion coating (AAC) onto 3-inch square modules having Korad surfaces. The AAC layer could not be abraded by a steel-wool pad; the Korad surface was readily abraded. Dow Corning will now attempt to deposit AAC on an 11 in x 16 in module with a Korad surface.

Dr. Plueddemann of Dow Corning has identified his first candidate adhesive/primer system that can be physically incorporated into EVA, which is to function as a general purpose bonding system for all module interfaces in contact with EVA. Springhorn will evaluate the candidate system.

Dr. Plueddemann is preparing a report on the subject of adhesion and primers for LSA application.

d) Endurex ITW. A statement-of-work for a new contract to develop ion-plated metal patterns in the same process as the AR coatings has been approved. Patent considerations may cause a delay in the planned contract start of late April or early May.

e) MB Associates. Equipment for spraying glass-reinforced concrete (GRC) was received and assembled, and application was begun. Three types of specimens and samples are produced by the GRC equipment: 1) 12 in x 24 in specimens for compression testing to determine optimum mix ratios, thickness, cure rates, etc.; 2) samples for the development of inserts, and 3) samples for the development of molds.

Four-point flexure specimens (12 in x 24 in) for characterization of glass-reinforced concrete formulations were prepared and tested after 7, 28, and 56 days of room-temperature curing. A report on the results of these tests is in preparation.

Substrate design was completed and drawings signed off by JPL. The design will be updated periodically to reflect latest thinking and as more data become available.

A visit was made to Springborn Laboratories to get up-to-the minute data on encapsulation materials. Latest thinking is that encapsulated cell subassemblies will be fabricated (e.g., 24 in x 48 in) then adhesively bonded to the substrate. The subassemblies will have top covers, pottant, and bottom covers only --no substrate or superstrate -- as the most cost-effective approach.

A small module approximately 12 in x 12 in that successfully demonstrated this approach was fabricated. The cells were encapsulated between layers of 3-mil-thick Korad 201/R acrylic film using ethylene/vinyl acetate as adhesive/pottant. Laminated assemblies of this type with dimensions approximately 24 in x 48 in would be secondarily bonded to the GRC substrate with an adhesive to be selected. Because of the relative unavailability of Korad 201/R, it is planned to use Tedlar for fabrication of five mini-modules required by contract to be delivered to JPL in early June. Either Korad or Tedlar could be used on prototype modules to be delivered in December, depending upon availability.

f) Motorola. Two contracts were initiated with Motorola to develop an antireflective (AR) coating for soda-lime glass. The first of these is a Near-Term Cost Reduction contract to develop an AR coating suitable for automated production of 15 MW/year by acid development of a sodium silicate coating. The second is an LSA-funded contract to improve the state of art of producing an improved AR coating on soda lime glass by an acid-leaching process.

g) In-House. Report No. DOE/JPL1012-79/8 (John Repar) "Experience with Silicones in Photovoltaic Modules", dated February 15, 1979, was released.

A draft of a JPL report, "Automated Polymer Processing in Encapsulation," was sent to approximately 20 polymer/automation companies for comment. Some of the companies have expressed an interest in exploring the subject further.

Contacts were made with the Metal-Polymer Laminate Company for encapsulation back-cover film products. A variety of samples were received and placed in test including vapor deposited (VD) aluminum on polyester (Mylar) film, polyester film/aluminum foil/polyester film laminate, VD aluminum on polyester film/paper laminate, and VD aluminum on polyester film/white pigmented PVC laminate.

A permeation cell was designed and tests begun to compare the above materials for resistance to moisture permeation.

2) Life Prediction and Material Degradation

a) Battelle. The Study 5 final report draft entitled "Measurement Techniques and Instruments Suitable for Life-Prediction Testing of Photovoltaic Arrays" was approved. Publication is scheduled for early May.

As discussed in the most recent Project Progress Report, it is desirable to develop a simple method of measuring small changes in electrical characterization of modules at field sites to avoid transportation problems. Series resistance was selected for investigation. Three methods were used to determine values of series resistance of modules taken from the Mead, Nebraska site. These were 1) the Wolf/Rauschenbach (W/R) method (under two levels of illumination), 2) a forward bias (F/B) method (forward bias without illumination), and 3) a two-diode model. While the two-diode model appeared to offer the most potential, the scope of the investigation was limited and the problem too complex for the development of a viable test method within the contract cost and time constraints. To develop a method with the required precision would require extensive development work that is beyond the scope of this contract.

b) Rockwell Science Center. Future work will be on the development and validation of modeling of corrosion as a life-limiting process in encapsulated modules. The effort is in the planning stage, with a follow-on contract in negotiation.

c) Case Western Reserve University. A follow-on contract is in negotiation.

d) California Institute of Technology/In-House. Work has begun in-house to establish a thermomechanical computer model for solar cell modules. A coarse model has been completed and reviewed by Professor W. Knauss of Caltech. Four cases, two boundary conditions simulating winter and summer conditions were run. From these coarse models a high-stress area within the solar module has been identified and chosen for further analyses. A detailed model is being constructed and coded for an ANSYS computer analysis.

e) In-House. Seventeen mini-modules consisting of 11 different designs were subjected to temperature and humidity cycling tests per JPL specification Document 5101-65. These results and the results of other mini-module tests will be given in a forthcoming LSA Project report.

C. PRODUCTION PROCESSES AND EQUIPMENT AREA

During the reporting period, the PP&E Area directed 17 contractor organizations in 25 efforts in pursuit of economical processes for the fabrication of solar cells and modules. The Area's overall schedule is shown in Figure 2-6. A listing of the contractors appears in Table 2-4.

One of the primary functions of the Area is dissemination of process information and procedures evolved as a result of its activities. To obtain such information, contact Mr. Brian Gallagher at (213) 577-9225 or by mail at JPL's Mail Station 512-103. There is no charge for this service; industry is encouraged to make use of it.

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Figure 2-6. Production Processes and Equipment Area Schedule

Table 2-4. Production Process and Equipment Area Contractors

Contractor	Contract Type	Technology Area
ARCO Solar, Inc. Chatsworth CA (JPL Contract No. 955278)		Automated solar module assembly
Bernd Ross Associates San Diego CA (JPL Contract No. 955164)		Thick film solar cell contact
Kinetic Coatings, Inc. Burlington MA (JPL Contract No. 955079)		Ion Implantation
Kulicke & Soffa Ind. Inc. Horsham PA (JPL Contract No. 955287)		Automated solar module assembly
Mobil Tyco Solar Waltham MA (JPL Contract No. 954999)		Development of solar modules
MB Associates San Ramon CA (JPL Contract No. 954882)	Phase II	Process development
Motorola, Inc. Phoenix AZ (JPL Contract No. 954689) (JPL Contract No. 955328) (JPL Contract No. 955324) (JPL Contract No. 954847)	Phase II	Metallization of Si wafers Thin film substrates Wax Patterning Process development
Optical Coating Laboratory City of Industry CA (JPL Contract No. 955217) (JPL Contract No. 955244)		High energy module (unique module assembly) Development of low-cost contacts
RCA Corporation Princeton NJ (JPL Contract No. 954868) (JPL Contract No. 955342)	Phase II	Process sequence development Megasonic cleaning
Sensor Technology Chatsworth CA (JPL Contract No. 955265) (JPL Contract No. 954865) (JPL Contract No. 955266)	Phase II	Polysilicon solar cells Process development Surface Texturizing

Table 2-4. Production Process and Equipment Area Contractors
(Continued)

Solarex Corporation Rockville MD (JPL Contract No. 954854) (JPL Contract No. 955077)	Phase II	Process development Wafer thickness evaluation
Sol/Los Incorporated Los Angeles CA (JPL Contract No. 955318)		Metallization
Spectrolab, Inc. Sylmar CA (JPL Contract No. 954853)	Phase II	Process sequence development
SPIRE Corporation Bedford MA (JPL Contract No. 954786)		Ion implanter
Texas Instruments Dallas TX (JPL Contract No. 954881)	Phase II	Process development
University of Pennsylvania Philadelphia PA (JPL Contract No. 954796)		Automated array
Westinghouse Research Pittsburgh PA (JPL Contract No. 954873)	Phase II	Process sequence development

1. Process Sequence Development

Kinetic Coatings, Inc. has been able to optimize the implantation parameters and those associated with front-contact formation in their Integral Structure-Simplified Process Sequence. Earlier the combined antireflective/hermetic seal/implantation oxide coating and the back contact were optimized.

Sensor Technology has recently been awarded a contract to establish a processing sequence for polysilicon cells. The intent is to process fibrously oriented crystal-grain-structure wafers through a modified sequence. No wafers have been processed to date.

Spectrolab, Inc., has defined a process sequence with only three processes currently having alternate options. These involve the use of plasma etching for diffusion oxide removal, aluminum removal and junction cleaning. Investigation of these options will be done soon and a final process will be evolved. Copies are available for those processes that have been made final.

2. Junction Formation

Sensor Technology has demonstrated the ability of spray-on doping techniques to produce both boron- and phosphorus-doped junctions. Currently efforts are being directed toward spray-on application of antireflective coatings and aluminum for back surface field formation.

SPIRE Corp. has determined reproducible and uniform beam parameters intended for post ion implantation electron beam annealing of 7.6 cm diameter wafers with a single pulse. This has been done for both the junction and back surface field sides of the wafer. There are 500 ion-implanted wafers being processed for characterization and distribution of values. A step and repeat technique has been demonstrated for sheet materials up to 10 cm square.

A new furnace annealing cycle has been evolved by Spire for $10\ \Omega \cdot \text{cm}$ material that reduces the processing time from 255 min. to 75 min.

Westinghouse reports that aluminum that has been deposited by sputtering has yielded the most consistent back-surface field results. Open circuit voltages of 0.585 V and efficiencies of 15.2% have been achieved. When $10\text{--}12\ \Omega \cdot \text{cm}$ dendritic web was used instead of the $12\ \Omega \cdot \text{cm}$ float zone reported above, the average open-circuit voltage reported is 0.570 V and the efficiency averages 14.8%.

3. Metallization

Bernd Ross Associates has been compounding fritless inks to produce metal contacts using base metals or base metal dilutions of noble metals. To verify the general capability of the technique a

silver/silver fluoride system was tried with some success. The recent experiments have shown that use of a Ge powder fraction gives better electrical properties than pastes using B, Al, Ga, In, Sb and Ti as dopants. To date 55 pastes have been formulated.

OCLI is continuing investigation of the use of copper in contact formation. The most promising system to date has been one in which an initial layer of palladium is laid down electrolessly by the bath developed by Motorola under PP&E Area contract. Subsequent electro-deposited layers of chromium and copper are then applied. Good adhesion and conductivity have been shown but some problems have occurred with copper migration after elevated temperature exposure. Work is currently being directed toward improved masking methods.

Sol/Los, Inc., has been investigating a metallization system that will produce a molybdenum-tin contact. The underlying theory is that molybdenum matches the coefficient of expansion of Si closely and tin will provide an easy interconnection system. The fritless ink formed is to be printed and fired in the 800°C-900°C range. This is deemed possible because the molybdenum will be applied as a trioxide.

Initial investigations by Westinghouse have indicated to them that there is a deterioration in all properties when an electroless palladium-nickel conductive layer is substituted for the standard titanium-palladium-silver system.

In addition, optimum grid size and spacing has been determined for a variety of cells by Westinghouse.

4. Surface Preparation

Motorola has constructed a module made entirely of cello whose front-surface ohmic contact grid pattern was etched throughout the silicon nitride dielectric by plasma technique through a mechanical mask. The module produced about 18 W with an open-circuit voltage of 20 V and a short-circuit current of 1.2 A.

RCA has further investigated its in-house formulation of spray-on antireflective coating and has found that the coating, after processing, produced a typical 35% increase in short-circuit current (Figure 2-7). The distribution of short-circuit current vs film thickness is shown in Figure 2-8.

Solarex Corp. has ascertained that wafers sawn with a wire saw and 5 μ m abrasives needed very little saw damage removal. The wafering time rose however, and cost trade-offs are going to be analyzed. A wire diameter of at least 0.006 in. was needed for cost effective use of Solarex's saw.

Figure 2-7. Increase in Short-Circuit Current After Cell Processing with RCA's Anti-Reflective Coating

Figure 2-8. Distribution of Short-Circuit Current vs Film Thickness.

5. Assembly and Test

The Unimate industrial robot is now operational at MB Associates and is being programmed for automation of cell placement and interconnection.

A SAMICS analysis of MB's entire production sequence now indicates a module selling price of \$0.489/Wp. This is predicated upon a price of \$34.90/m² for the input Si.

Sensor Technology has discovered a computational error in its laser scribing and holing SAMICS costing. The current calculation brings the cost down to \$0.00777/Wp for the combined operation. This is in line with the 1986 target goals for Sensor Tech's process sequence. Its current overall SAMICS analysis shows a selling price of \$0.6994/Wp.

6. Module Development

OCLI is in the process of developing a P-on-N, 14% efficient module. Most recently, 15.6% efficient cells have been reported. Work is proceeding on further improvement and currently efforts are directed at production of a back-surface field. The module design size is 22-1/4 in. x 48 in. Sunadex glass, 3/16 in., is being used. The 120 cells will be connected in a four-parallel 30-series system to produce 96.4 W at 15 V. These values are at AM1 and 28°C. OCLI estimates that a gain of 7% is expected from the combined effect of the Sunadex glass and the zero-depth concentrator developed by General Electric under PP&E Area contract.

7. Advanced Equipment Development

ARCO Solar is designing machines to solder interconnects at a rate of 12 per minute and produce 12 laminates per hour. A prototype lamination system has been built and operated. The Contractor Module Design Review was completed in mid-March and the design selected is illustrated in Figure 2-9. Figure 2-10 shows the schematic representation of the Solar Cell Assembly Prototype while the Solar Panel Lamination Prototype is shown in Figure 2-11 with the operating sequence.

Kulicke and Soffa, Inc., presented a design review in the latter part of March and the resultant machine concept is shown in Figure 2-12. The plan is to produce strings of cells by solder interconnection. A vacuum lance will be used to position the string within the module. The cycle target is to process one cell every five seconds.

OCLI has completed a final design review at JPL. The tooling is four-fold in function. It is to cover semi-automation of the antireflective coating application, cell testing, back contact soldering and vacuum pickup.

Figure 2-9. ARCO Solar Module Design

CELL STRINGER

Figure 2-10. ARCO Solar Cell Assembly Prototype

Figure 2-11. ARCO Solar Module Lamination Prototype.

Figure 2-12. Kulicke and Soffa's Machine Concept for Assembly of Solar Modules by Solder Interconnection

D. ENGINEERING AREA

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

1. Array Design/Engineering

Principal in-house work has been upgrading and application of series/paralleling computer programs to perform various analyses. The program was expanded to include cell-failure rates an order of magnitude above and below those previously reported. A statistical method was developed for determining the distribution of failures in an array field based on given expected failure rates. A Monte Carlo technique for analyzing non-uniform location of hot-spot heating cells resulting from distribution of cell shunt resistance was incorporated in the program. An analysis was performed to optimize placement of diodes in module circuits. The module mean environmental operating condition studies reported before are being extended to apply to concentrator systems in response to SERI standards activity. Computer model input parameters for cell characteristics are being modified to include spectral response and theoretical solar spectrum data.

Contractor reports for the Bechtel array-structure study, Boeing wind-loading study, Burt Hill Kosar Rittleman Associates residential requirements study and a recently initiated Motorola module electrical termination requirements study appear in Section III of this report. A contract has been initiated with Underwriters Laboratory to develop photovoltaic module safety-related design criteria.

2. Reliability-Durability Requirements

In-house efforts in the area of cell-fracture mechanics have continued. The four-point twist loading fixture developed by JPL was employed in loading tests of wafers and cells removed from Motorola's cell fabrication line at successive process steps. Results indicate that significant changes in cell fracture resistance can be detected as a result of specific cell fabrication process steps.

Phase I activities were completed and planning for Phase II was initiated in module soiling. Purchase of candidate materials for the outdoor material-soiling experiment, a cooperative effort with the Encapsulation Task, was accomplished and sample preparation and baseline transmission and reflectance measurements made. Deployment of samples to the field is planned for mid-April. The 1500-V electrical stress test of Block II minimodules is continuing at the JPL field site. Corona and leakage current measurements are continuing to be made on a periodic basis. The instrumentation for this test is being modified to detect and count corona or leakage transients with voltage applied. Procurement of an Inframetrics infrared camera for use in hot-spot investigations and field failure detection was initiated. Preliminary results of the use of the camera

to scan the Mead, Nebraska site were discussed at this Project Integration Meeting. Contracted efforts in the Reliability-Durability activity continued on schedule. Current status of the Clemson University cell-reliability study and the DSET Labs module accelerated solar-exposure tests are detailed in the attached summaries.

3. Array Standards and Specifications

A principal activity has been support of the SERI-led Performance Criteria and Test Standards Project. The Task Group I (Array Subsystems) met at JPL in January; Dr. Ron Ross was chairman. Participants included government and industry. The first meeting was addressed to array performance and reliability-durability criteria. A second meeting took place the week before the 12th PIM. Engineering area personnel also participated in Task Group II, which currently addresses itself to the balance of system interface requirements and to system overview requirements. During this period Engineering Area personnel have participated in and provided support to proposal review and assessment for concentrator and flat-plate PRDAs, an Encapsulation Task RFP, and Block IV procurement. Review of designs with respect to applicable specifications was accomplished.

E. OPERATIONS AREA

1. Large Scale Production Task

a. Block III. From December 1978 through March 1979, 44.4 kW of modules were provided to JPL by Block III contractors. The totals delivered by the end of March represented 89% of the requirement. ARCO Solar completed delivery of modules in January. Production detail for the four months ending March 1979 is displayed below.

<u>Contractor</u>	<u>Allocation kW</u>	<u>Shipped Dec.-Mar. kW</u>	<u>Shipped Total kW</u>	<u>Complete %</u>
ARCO Solar	37.15	10.00	37.28	100
Motorola	50.00	21.52	43.82	80
Sensor Technology	42.73	10.46	24.44	57
Solar Power	53.07	2.34	53.51	100
Solarex	<u>31.91</u>	<u>0</u>	<u>31.71</u>	<u>100</u>
Totals	214.86	44.32	190.77	89

Significant modifications to contracts with Sensor Technology, Inc., and Motorola, Inc., that compensated for various changes in the reference cell calibrations used in measuring module power output and for changes in the average power output per module, were negotiated and implemented. In the case of Motorola, the actual power output of an average module was 10% larger than the nominal average power predicted

at the outset of the contract and the number of modules required to deliver the 50 kW on order was reduced from 2381 to 2156.

A continuing shortage of 2-inch dia. Si wafers prevented achievement of the planned module delivery schedule from Sensor Technology, Inc.

b. Block IV

Proposals for Block IV module design contracts were evaluated during this reporting period and negotiations with eight potential contractors were begun. Module designs sought in this procurement were to be for intermediate load applications or for residential applications. Companies submitting proposals for module designs regarded as uniquely residential were ARCO Solar, Inc., GE, and Solarex Corp. Module designs characterized as primarily adapted to intermediate-load applications were submitted by ARCO Solar, Motorola, OCLI, Sensor Technology, Solar Power, Solarex and SPIRE.

The contracts to be negotiated call for the design, fabrication and qualification of modules that incorporate advancements in design and/or processing. Under these contracts, design and processing documentation is to be completed including inspection plans and criteria, the modules are to be subjected to qualification testing, and the SAMICS/SAMIS costing and price analysis demonstrated. Approximately 1 kW of modules will be obtained of each model for qualification testing and limited field testing.

After the successful completion of the design contracts it is expected that purchase orders for limited quantities of each module type, up to 10 kW, will be placed.

2. Module Test and Evaluation

a. Environmental Testing. Most of this period's testing effort was on the PRDA-38 modules. Testing has been completed on some of the 12 types; completion of all tests is expected by the end of April. Details of results will be available after Phase 2 awards are made by DOE. Several general comments about these tests can be made:

1) Hail testing was initiated as one of the qualification tests for this procurement. Most modules had little trouble meeting the requirements except when the field application called for unusually large hailstones.

2) Monitoring of modules for resistance to ground during environmental exposure was also done for the first time during these tests. A considerable number of modules failed this check; this problem was confirmed in most cases by failures in hipot tests after environmental exposure. Poor electrical isolation is a serious problem because it represents a safety hazard in field installations.

Other test results from this period are summarized briefly below:

- (1) ARCO Solar Block III Production Samples: Minor shrinking, cracking and lifting of plastic end channels has continued.
- (2) Sensor Tech Block III Production Samples: Satisfactory.
- (3) Motorola Developmental Module with Multiple Back Contacts: Satisfactory
- (4) Mobil Tyco Developmental Module with Improved Terminals: Many cover glass cracks from cyclic pressure loading.
- (5) Texas Instruments Developmental Module: Cell cracking and one cover glass crack in temperature; more cell cracking in humidity; encapsulant (an oil) leak; one electrical degradation of 12% after cyclic pressure loading.
- (6) OCLI Commercial with PVB Encapsulant: Cover glass crack from temperature cycling.

The Block II Test Report, JPL Document 5101-98, has been issued.

b. Performance Measurements. Reference cells were fabricated, calibrated and delivered to the flat-plate PRDA Program for the JPL test program and to MIT/LL for its field test program. Procurement and fabrication of components for the Block IV reference cells was initiated. It is anticipated that vendor cells will arrive starting in mid-July for the generation of Block IV reference cells.

A need was identified for a higher current capacity dynamic load for the LAPSS system. The present system, though rated at 20 amps, will not function over about 13 amps. Spectrolab was contracted to build a new unit with current capacity to 50 amps. The new unit will be completed in four to six months at a cost of \$25,000. The second LAPSS facility construction is now scheduled for completion in June. The second LAPSS is scheduled to become operational in July. The integration of both LAPSS systems to the central computer system is scheduled for completion in August. Interface hardware and software development for the system integration is continuing.

c. Field Tests. The effort in this period centered on improving the accuracy of the endurance data at the JPL Field Test Site and initiating an inspection tour of the newly acquired Lewis Research Center remote sites.

Two exploratory tests have been performed to provide some basic information regarding the use of reference cells. First, an examination of the influence of the incidence angle (angle between the module normal and the sun) on data accuracy was performed by

collecting I_{SC} and reference cell output data on a large number of modules around solar noon at different tilt angles. A comparison of the ratios of the I_{SC} values and the reference cell values as a function of tilt angle indicated that: 1) there is an angle-of-incidence effect for angles greater than 10° ; 2) the effect can be as great as 2% to 3% at large angles, around 30° ; and 3) there is a time-of-day effect, i.e., the results were different in the morning and afternoon.

The second test entailed performing field calibrations of reference cells. A small group of modules was removed from the field, flashed with the LAPSS system and then re-installed. These modules then provided a baseline for performing a calibration of the reference cells in situ. Over a period of about two weeks data was taken at solar noon on this group of modules. These results provided the data necessary to apply corrections to the reference-cell constants.

At the end of April, as a result of those tests, a revised testing procedure will be implemented. The principal changes will be: 1) the acquisition of the basic daily data will take place at solar noon instead of at some minimum insolation threshold; 2) more module tilt angles will be used throughout the year to ensure that the incidence angles do not exceed 10° ; and, 3) in-field reference cell correction constants will be used.

During February, JPL assumed the responsibility for data collection at the 12 remote endurance test sites originally established by NASA Lewis about a year ago. The sites are located in such diverse spots as Alaska and the Panama Canal Zone and collectively cover virtually all climatic conditions. Each site is the same, having four test stands and the same inventory of modules, four of each of the Block II types. The Area's plan calls for site visits to obtain electrical performance and physical change data on each module, then to generate an updated test plan by the end of FY79. During mid-March, the two high desert sites at Albuquerque, NM, and Dugway, UT, were visited and data taken. A report summarizing these results will be made at the end of April.

d. Failure Analysis. During this reporting period 80 new Problem/Failure Reports were filed and 80 P/FRs were closed out. A summary of this activity is given in Table 2-5.

Table 2-5. Summary of PFR Activity: Module/Problem/Failure
Experience for the Period Jan.-Mar. 1979

<u>MFG</u>	<u>Procure- ment Block</u>	<u>New PFR's</u>	<u>Closed PFR's</u>	<u>Environ- mental Test</u>	<u>Field Test</u>	<u>Application Centers</u>
V	I		5		1	4
	II	6	7			7
	III		8	8		
W	I	4				
Y	II	2	2	2		
Z	I		3			3
	III		11	10	1	
R			13	13		
U		7	9	9		
Task 4		10	13	10	3	
Task 5			9	9		
PRDA		51		51

SECTION III

PROCEEDINGS OF THE 12TH PROJECT INTEGRATION MEETING

The 12th LSA Project Integration Meeting (PIM) was held April 4-5, 1979, on the campus of the California Institute of Technology. Invitation-controlled attendance included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the Photovoltaic Program.

A. INTRODUCTION

Dr. Marshall E. Alper, Manager of Solar Projects at JPL, opened the 12th PIM by announcing two permanent appointments: Mr. Robert G. Forney as Manager, Photovoltaics Technology Development and Applications (TD&A) Lead Center, and Dr. William T. Callaghan as Manager, Low-cost Solar Array Project.

Announcements were continued by Mr. Paul Maycock, Chief of the Photovoltaics Systems Branch of the Department of Energy, regarding the upcoming DOE Semi-Annual meeting to be held May 15-17, 1979, at Gatlinburg, Tennessee, and the importance of the TD&A Lead Center role at JPL. In addition, budgetary prospects for FY80 were also discussed briefly. Dr. Leonard Magid, Senior Program Manager, also of DOE, reported briefly on the status of the Photovoltaics Standards work currently underway and the recent American Physical Society report on photovoltaic energy conversion.

Welcoming comments to attendees of the PIM were continued by Dr. Callaghan. He noted that the 12th PIM was being held jointly with the 3rd Sandia Laboratory Concentrator Technology PIM, managed by Dr. Donald J. Schueler.

The main theme of the LSA Project PIM was presented as consisting of two major thrusts: ingot growth and slicing, and automated process equipment. The status of ingot growth and slicing was chosen as an important theme because of the general advances made over the past two-year period. Specific advances in recent months give strong support for the achievement of \$0.50/Wp (1975 dollars) by the ingot technologies. Presentations detailing these advances, to be given by Dr. James Liu and JPL contractors in the Large Area Sheet Task, were announced.

Likewise, automated process equipment was chosen as a timely and important theme because of recent advances by JPL contractors. Presentations by Mr. Donald Bickler and contractors in the Production Process and Equipment Area were announced to present both narrative and graphic (motion picture and slides) development of notable achievements. Technologies thus covered included cell junction formation, metallization, surface preparation and module fabrication.

After summarizing the importance of the two themes with respect to the demonstration of LSA Project Technical Readiness by FY82, the opening announcements were concluded and the 12th PIM proceeded.

B. THEME TOPICS

1. Ingot technology

The morning plenary session focused on both ingot growth the ingot slicing efforts.

Crystal Systems reported on developments of the heat exchange method and casting of shaped ingots by the HEM process. Current status and Project goals were outlined. Data on solar cell performance with AM1 efficiencies of 13.4% to 15% were presented. Economic analysis was given to show an add-on cost of \$4.46/m² for the ingot growth.

Hamco (Kayex) reported on its advanced Czochralski approach. Crystal growth equipment design data were presented, and goals were compared with status to show that almost all goals in the present effort were achieved. 100 kg ingot growth particulars were given. Solar cell analysis and economic analysis of the process with four alternatives were presented. The effect of number of crystals per crucible as well as recharge and ingot growth times on cost were discussed. Future effort and primary areas of concern were outlined.

Siltec Corp. reported on the continuous liquid-feed Czochralski approach. Furnace-design aspects were illustrated and discussed showing the transfer tube, the furnace hardware, the melt level monitor, etc. Current progress and economic analysis was presented. An add-on cost of \$21.3/m² for ingot growth at the present state of operation was shown, which can be reduced to \$9.92/m² by 1986. Data on the effect of run size on crystal add-on cost was also presented both for the batch recharge as well as continuous recharge.

Crystal Systems, Inc., reported on multiwire slicing by the fixed abrasive slicing technique. Machine hardware and achievements were shown. Economic analysis was presented to show an add-on cost of \$4.63/m² by 1986.

Varian Associates described its progress on the multi-blade slurry sawing effort. An economic summary, as well as technical summaries, was presented to show an add-on cost of \$8.53/m² for the slicing operation by 1986.

Siltec Corp. described enhanced ID slicing, emphasizing the three key elements: a) ingot rotation, with minimum exposed blade area; b) dynamic cutting edge control; and c) use of prefabricated insert blades. Goals were presented and the approach was outlined. Economic analysis showed a slice add-on cost \$6.97/m². Schematics and process hardware were shown.

During the subsequent intertask meeting, progress on refractory material studies, material characterization studies and shaped sheet technology was reviewed.

2. Refractory Materials Studies

Battelle Columbus Labs reported development efforts on die and container materials. Silicon aluminum oxynitride (Sialon) and silicon beryllium oxynitride (Sibeon) were two materials found to be resistant to molten Si attack. Comparative impurity analysis of Si_3N_4 and Sibeon as well as thermodynamic data were presented.

Coors Porcelain Co. is developing mullite substrates (compatible with Si coating of ceramic) and molten Si containers. Extensive data on oxide composition and thermal properties of slotted substrates were presented. Sessile drop test data were also displayed. "K" modification mullite matches the average expansion of Si and is being used by Honeywell for silicon-on-ceramic coating.

Eagle Picher's effort for die and container material development is shared by Miami Research Labs (MRL), University of Missouri-Rolla (UMR) and Chemetal Corp., Pacoima, CA. Their presentation was directed toward study of thermal properties of ceramic substrates and effect of oxygen pressure upon silicon/ceramic contact angle and reactivity. Sessile drop-test setup and results were presented for varying oxygen partial pressures. Three CNTD Si_3N_4 -coated hot-pressed crucibles were delivered to JPL.

RCA's development program of die materials for use in its inverted ribbon-growth process was reported. Various types of die materials have been evaluated, and resulting Si samples grown using those dies were shown to yield up to 8% solar cell efficiency (without AR coating). Oxygen and carbon content, sheet resistance, diffusion length and solar cell data were presented. Problems of substrate thermal mismatch, edge effects and slag formation were highlighted. Tylan Corp. reported on the study of processing parameters of Vitre-Graf (a glass-like carbon glaze) for application to mullite and graphite. Failure mechanisms of silicon-graphite were discussed. The baseline process was described and Series 1 through 8 test plans with results were shown.

3. Material Characterization

OCLI reported on its effort in solar cell fabrication and evaluation of various JPL-supplied low-cost Si sheets. Data on CSI's HEM material, Mobil Tyco's EFG ribbon and Honeywell's SOC material was presented.

Spectrolab similarly presented data on Wacker polycrystalline material, Mobil Tyco's EFG ribbons and Westinghouse's web material. It also described the baseline cell fabrication process.

4. Shaped-Sheet Technology

Progress of the various sheet-growth options was presented. ARCO Solar outlined the vacuum die-casting effort that is just starting. Honeywell, in its silicon-on-ceramic process, outlined the goals for 1979 and the present status. A steady-state vertical growth model for SOC was presented and a film thickness-growth speed relation was discussed. It was shown that production yields for dip-coated substrates have improved to 85% and cell efficiencies around 8% to 10% have been obtained. In the continuous coating machine, however, meniscus instability problems still remain to be solved.

Mobil Tyco presented its EFG Si growth experiments with unsymmetrical dies to show that high meniscus side ribbon was virtually clear of SiC particles. Extensive spreading resistance data and details of die design were presented. Some selected solar cells showed efficiencies from 12.9% to 14.1% for ribbons grown in JPL machines 12 and 13.

Motorola reviewed its progress on RTR silicon. Cell efficiency improvement from 6% to 9% has been achieved by Mo removal by etching and a PH_3 gettering step. Purgeable furnace experiments have not given consistent results. Some solar cell data and the purge furnace design was presented. Polyribbon formation was described. The technique of rigid-edge RTR growth was also highlighted; it allows better material efficiencies, relaxes polyribbon formation requirements and reduces ribbon breakage. Motorola's program plan for high area growth and cell fabrication was also presented.

Westinghouse presented the progress of web dendritic Si growth. Area throughput of $19.8 \text{ cm}^2/\text{min}$, melt replenishment and highest cell efficiency of 15.5% AM1 was their technology status. Analysis of thermal stress vs dislocations was presented. Growth data, cell data, furnace hardware and web solar cell module were illustrated. Program plans for 1986 goals were outlined.

C. PRESENTATIONS

1. Project Analysis and Integration Area

POTENTIAL LSA MODULE PRICES

TOPICS COVERED:

- IMPORTANCE OF THE YEAR 2000
- INGOT TECHNOLOGY POTENTIAL
- NON-INGOT TECHNOLOGY POTENTIAL

**R. W. ASTER
LSA PROJECT PA & I
APRIL 4, 1979**

THE YEAR 2000

- THE YEAR 2000 HAS BEEN TREATED AS AN "IMPORTANT" YEAR IN SOME RECENT STUDIES
 - THIS IS A YEAR WHEN PV COULD BE PRODUCING A "SIGNIFICANT" AMOUNT OF ELECTRICITY IN THE U. S.
 - BY 2000, THE MORE ADVANCED PV CONCEPTS OF TODAY MIGHT HAVE ACHIEVED COMMERCIAL READINESS
- THE LONG TERM PROSPECTS OF FLAT PLATE SILICON ARRAYS ARE SOMETIMES EQUATED WITH INTERMEDIATE (1986) LSA PROJECT GOALS. THIS IS NOT A GOOD WAY TO COMPARE SILICON WITH ALTERNATIVE TECHNOLOGIES IN THE YEAR 2000

INGOT TECHNOLOGY (LATE 1980's)

PROCESS	YIELD	REQUIRED PRICE (VALUE ADDED)	YIELDED PRICE PER UNIT MODULE AREA	REQUIRED PRICE PER PEAK WATT
SILICON	-	10 \$/kg	11.6 $\$/m^2$	0.091 $\$/W$
INGOT	0.85	12 \$/kg	11.8	0.093
SLICE	0.95	10 $\$/m^2$	9.3	0.073
CELL	0.93	15 $\$/m^2$	13.0	0.102
MODULE	0.98	18 $\$/m^2$	18.0	0.141
			64.0 $\$/m^2$	0.50 $\$/W$

BASED ON THESE ASSUMPTIONS:

- ENCAPSULATED CELL EFFICIENCY = 15%
- PACKING EFFICIENCY = 85%
- INGOTS YIELD 1 m^2 WAFER PER kg OF INGOT

INGOT TECHNOLOGY (LATE 1990's)

PROCESS	YIELD	REQUIRED PRICE (VALUE ADDED)	YIELDED PRICE PER UNIT MODULE AREA	REQUIRED PRICE PER PEAK WATT
SILICON	-	8 \$/kg	8.9 $\$/m^2$	0.062 $\$/W_p$
INGOT	0.85	10 \$/kg	9.4	0.065
SLICE	0.95	5 $\$/m^2$	4.5	0.031
CELL	0.96	15 $\$/m^2$	12.9	0.089
MODULE	0.99	18 $\$/m^2$	18.0	0.125
			54.0 $\$/m^2$	0.37 $\$/W_p$

BASED ON THESE ASSUMPTIONS:

- ENCAPSULATED CELL EFFICIENCY = 17%
- PACKING EFFICIENCY = 85%
- INGOTS YIELD 1 m^2 WAFER PER kg OF INGOT

NON-INGOT TECHNOLOGY (LATE 1980's)

PROCESS	YIELD	REQUIRED PRICE (VALUE ADDED)	YIELDED PRICE PER UNIT MODULE AREA	REQUIRED PRICE PER PEAK WATT
SILICON	-	10 \$/kg	5.3 \$/m ²	0.044 \$/W _p
RIBBON	0.80	16 \$/m ²	16.2	0.135
CELL	0.93	15 \$/m ²	14.1	0.118
<u>MODULE</u>	0.98	18 \$/m ²	<u>18.0</u>	<u>0.151</u>
			54.0 \$/m ²	0.45 \$/W _p

BASED ON THESE ASSUMPTIONS:

ENCAPSULATED CELL EFFICIENCY = 13%

PACKING EFFICIENCY = 92%

2.4 m² RIBBON IS PRODUCED FROM 1 kg SILICON

NON-INGOT TECHNOLOGY (LATE 1990's)

PROCESS	YIELD	REQUIRED PRICE (VALUE ADDED)	YIELDED PRICE PER UNIT MODULE AREA	REQUIRED PRICE PER PEAK WATT
SILICON	-	8 \$/kg	2.1 \$/m ²	0.014
RIBBON	0.90	15 \$/m ²	15.0	0.102
CELL	0.96	15 \$/m ²	14.4	0.098
<u>MODULE</u>	0.99	18 \$/m ²	<u>18.0</u>	<u>0.122</u>
			50.0 \$/m ²	0.34

BASED ON THESE ASSUMPTIONS:

ENCAPSULATED CELL EFFICIENCY = 15.5%

PACKING EFFICIENCY = 95%

4.25 m² RIBBON IS PRODUCED FROM 1 kg SILICON

DEFINITIONS AND RELATIONSHIPS

REQUIRED PRICE - THE VALUE ADDED IN THAT PROCESS AREA, INCLUDING THE CAPITAL AND INDIRECT COSTS. UNITS ARE \$/kg SILICON, \$/m² CELL, ETC. THUS, THE YIELDS OF SUBSEQUENT PROCESS AREAS ARE NOT FACTORED IN. (RP)

YIELDED PRICE PER UNIT MODULE AREA - THE YIELDS OF SUBSEQUENT PROCESS AREAS AND THE PACKING EFFICIENCY IS FACTORED IN HERE. (YP)

YIELD - THE AMOUNT OF INPUT FROM PREVIOUS PROCESS AREAS THAT MAKES IT THROUGH THE NEXT PROCESS AREA (Y)

RELATIONSHIPS:

$$YP = (RP \cdot \eta_p) / Y \text{ (EXCEPT FOR THE MODULE PROCESS)}$$

$$$/W_p = YP / (\eta_e \cdot \eta_p \cdot 1000)$$

IMPACTS ON PROJECT GOALS EQUIVALENT ENERGY PRICES

- THIS WILL IMPACT PRICE GOALS FOR SYSTEMS WITH DIFFERENT MODULE EFFICIENCIES (Higher efficiency modules will have an advantage. The extent of this advantage will depend upon area-related costs.)
- THIS WILL IMPACT PRICE GOALS FOR SYSTEMS WITH DIFFERENT LIFETIMES

IMPACTS ON PROJECT GOALS THREE APPLICATION CLASSES

APPLICATION	YEAR	
	TECHNOLOGY READINESS	COMMERCIAL READINESS
RESIDENTIAL	1982	1986
INTERMEDIATE LOAD CENTERS	1982	1986
CENTRAL STATION	1986	1990

PROJECT PAGs HAVE ADDRESSED COMMERCIAL READINESS TARGETS FOR 1986

IMPACTS ON PROJECT GOALS BASE YEAR CHANGE

	1975 DOLLARS		1980 DOLLARS	
SILICON	10	\$/kg	14	\$/kg
INGOT SHEET	18	\$/m ²	25.2	\$/m ²
NON-INGOT SHEET (12%)	17.4	\$/m ²	24.4	\$/m ²
NON-INGOT SHEET (14%)	11.1	\$/m ²	15.5	\$/m ²
CELLS	22	\$/m ²	30.8	\$/m ²
ENCAPSULATION MATERIALS	8	\$/m ²	11.2	\$/m ²
MODULE	15.5	\$/m ²	21.7	\$/m ²
TOTAL	0.50	\$/W _p	0.70	\$/W _p

SOME PRELIMINARY ASPECTS OF THE PV LEAD CENTER PGA

- 1980 DOLLARS ARE USED (CONVERT 1975 DOLLARS INTO 1980 DOLLARS BY MULTIPLYING BY 1.40)
- THREE APPLICATION CLASSES ARE ADDRESSED:
 - RESIDENTIAL
 - INTERMEDIATE LOAD CENTERS
 - CENTRAL STATION
- DIFFERENT SYSTEMS WITHIN THE SAME APPLICATION CLASS SHOULD PROVIDE APPROXIMATELY EQUIVALENT ENERGY PRICES (¢/kWh)

PRICE ALLOCATION GUIDELINE STATUS

- A SYSTEM-WIDE PRICE GOAL ALLOCATION (PGA) IS BEING PRODUCED BY THE PV LEAD CENTER
- MODULES ARE A COMPONENT OF A SYSTEM WHICH WILL RECEIVE A PGA ALLOCATION
- THE LSA PROJECT WILL CONTINUE TO ALLOCATE SUBGOALS TO PROJECT ELEMENTS IN THE FORM OF PRICE ALLOCATION GUIDELINES (PAG)
- LSA PROJECT PAGs WILL BE CONSISTENT WITH THE PV LEAD CENTER PGA FOR MODULES

SAMIS

TOPICS COVERED:

- RELEASE 2 OF SAMIS III
- FORMAT "A" ASSISTANCE

RELEASE 2 OF SAMIS III

- RELEASE 2 WILL PROVIDE BETTER REPORTS
 - ALL PAST IMPROVEMENTS ARE DOCUMENTED
 - THE REQUIRED PRICE OF A PROCESS IS REPORTED IN MORE WAYS
 - REQUIRED PRICE PER UNIT OF OUTPUT
 - VALUE ADDED IN \$/W_{pk}
 - VALUE LOST DUE TO THE YIELD LOSS OF EACH STEP
 - COST OF PROCESS
 - YIELD SENSITIVITY ANALYSIS
- RELEASE 2 WILL BE EASIER TO OPERATE
- RELEASE 2 WILL CONTAIN SEVERAL MODIFICATIONS OF THE INDIRECT REQUIREMENT RELATIONSHIPS

FORMAT A ASSISTANCE

- FORMAT A's ARE IMPORTANT TO SAMIS AND TO LSA
- THERE IS A NEW VERSION OF 5101-44, SAMIS INPUT DATA PREPARATION
 - THERE IS NOW A FORMAT A CHECKLIST
 - AN ATTACHMENT TO EACH FORMAT A IS REQUESTED, DESCRIBING KEY ASSUMPTIONS THAT LEAD TO FORMAT A DATA

LIFETIME COST AND PERFORMANCE MODEL FOR PHOTOVOLTAIC POWER SYSTEMS

**C. BORDEN
D. SCHWARTZ**

MOTIVATION FOR THE LIFETIME COST AND PERFORMANCE (LCP) MODEL

- TO PROVIDE A "BOTTOM-UP" DESCRIPTION OF ALL THE ACTIVITIES ASSOCIATED WITH INSTALLING, OPERATING, AND MAINTAINING A PHOTOVOLTAIC POWER PLANT IN TERMS OF COSTS AND ELECTRICAL PERFORMANCE OVER ITS LIFETIME
- TO PROVIDE A FRAMEWORK FOR MAKING TRADE-OFFS BETWEEN ALTERNATIVE INITIAL AND RECURRENT POLICY OPTIONS
- TO CREATE A GENERAL MODEL WHICH CAN EVALUATE PARAMETRICALLY A WIDE RANGE OF POWER PLANT DESIGNS AND APPLICATIONS
- TO FILL IN THE ANALYTICAL GAP BETWEEN THE SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION (SAMIS) AND THE UTILITY-OWNED SOLAR ELECTRIC SYSTEMS (USES) ECONOMIC MODEL

THE LIFETIME COST AND PERFORMANCE (LCP) MODEL IS

- A MANAGEMENT TOOL USEFUL TO SYSTEM DESIGNERS AND OPERATORS FOR DECIDING BETWEEN ALTERNATIVE
 - SYSTEM CONFIGURATIONS
 - INSTALLATION ACTIVITIES
 - LEVEL OF EFFORT AND TIMING OF OPERATIONS/MAINTENANCE ACTIONS
 - REPLACEMENT OPTIONS
- STRUCTURED TO CAUSALLY RELATE THE IMPACT OF ALTERNATIVE INITIAL DESIGN AND RECURRENT POLICY DECISIONS ON BOTH COST AND ENERGY OUTPUT OVER THE LIFETIME OF A PHOTOVOLTAIC POWERPLANT
- DESIGNED TO MAKE TRADEOFFS ON THE BASES OF MINIMIZING BUSBAR ENERGY COST AND MAXIMIZING THE NET PRESENT VALUE OF THE INVESTMENT

VALUE OF PHOTOVOLTAICS TO THE UTILITY

- PHOTOVOLTAIC POWER PLANTS ARE GRID-CONNECTED AND THEIR VALUES ARE GRID-SPECIFIC
- HOURLY ELECTRICITY GENERATION CALCULATIONS ARE REQUIRED TO DETERMINE THE TRUE VALUE OF PHOTOVOLTAICS
- LCP INCORPORATES PHOTOVOLTAIC PRODUCTION COST VALUES AND CAPACITY VALUES
- THERE IS NO DEDICATED STORAGE FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

LCP ENERGY OUTPUT OBJECTIVES

- HOURLY PLANT OUTPUT (kWh)
- MODEL THE EFFECTS OF
 - INSOLATION
 - TEMPERATURE
 - MODULE PERFORMANCE DEGRADATION
 - ELECTRICAL MISMATCH
 - MODULE FAILURES
 - DIRT ACCUMULATION/CLEANING
 - MODULE REPLACEMENTS
 - COMPONENT EFFICIENCIES

RESULTS REFLECT PRELIMINARY INPUT DATA FOR TESTING OF LCP MODEL

- SYSTEM DESIGN IS BASED UPON A 184 MW CENTRAL POWER STATION
(TANDEM ARRAY WITHOUT REFLECTORS) DESIGNED BY BECHTEL CORPORATION
- SEVERAL POTENTIAL OPERATING ALTERNATIVES ARE ILLUSTRATED

PRELIMINARY INPUT DATA

POWER PLANT LOCATION — PHOENIX	
YEAR FOR SOLMET INSOLATION/TEMPERATURE	= 1953
PLANT PEAK CAPACITY	= 184 MW
BASE YEAR FOR CONSTANT DOLLARS	= 1975
YEAR OF CAPACITY OPERATION	= 1995
CONSTRUCTION/STARTUP PERIOD	= 5 YEARS
PLANT OPERATING LIFETIME	= 30 YEARS
REAL AFTER-TAX DISCOUNT RATE	= 0.026
NUMBER OF PCU's	= 36
NUMBER OF MODULES PER PCU	= 12960
MODULE EFFICIENCY	= 0.144
BALANCE OF SYSTEM EFFICIENCY	≈ 0.85
NUMBER OF CLEANINGS	= 9 PER YEAR (DURING NON-WINTER MONTHS)
MODULE COST	= \$0.50/WATT (= \$214/MODULE)
MODULE FAILURE RATE	= 0.002/YEAR
MODULE DEGRADATION RATE	= 0.03/YEAR

MONTHLY EFFECTS OF DIRT ACCUMULATION AND CLEANING

LIFETIME COST AND PERFORMANCE MODEL

- ALL COSTS ARE INPUT AND OUTPUT IN BASE YEAR DOLLARS (1975)
- BUSBAR ENERGY COSTS ARE LEVELIZED IN CONSTANT DOLLARS ($BBEC_0$) RATHER THAN IN CURRENT DOLLARS ($BBEC$)
- IN THE FOLLOWING EXAMPLES $\overline{BBEC} \approx 1.8 \cdot BBEC_0$

LIFETIME COST AND PERFORMANCE MODEL

BASELINE CASE WITH ZERO DEGRADATION

$$\overline{BBEC}_0 \approx 4.7¢/\text{kWh}$$

$$\overline{BBEC} \approx 8.5¢/\text{kWh}$$

BASELINE CASE WITH 3% DEGRADATION

$$\overline{BBEC}_0 \approx 7¢/\text{kWh}$$

$$\overline{BBEC} \approx 12.5¢/\text{kWh}$$

SENSITIVITY OF BUSBAR ENERGY COST TO CLEANING POLICY

SENSITIVITY OF SYSTEM COSTS TO MODULE PRICE

MODULE REPLACEMENTS DUE TO DEGRADATION

VARIOUS OPTIONS

FOR THE ASSUMED SYSTEM DESIGN, COMPONENT COST AND OPERATING CONDITIONS

- CLEANINGS ARE SHOWN TO BE COST EFFECTIVE.
- BLOCK REPLACEMENTS ARE NOT ECONOMICALLY ATTRACTIVE EITHER IN A BUSBAR ENERGY COST OR NET PRESENT VALUE SENSE.
- DEGRADATION RATE HAS AN IMPORTANT INFLUENCE ON ENERGY OUTPUT AND BUSBAR ENERGY COST.

CURRENT STATUS/PLANNED ACTIVITIES

- CURRENT STATUS
 - SOFTWARE DESIGN DOCUMENT COMPLETED
 - EXTERNAL REVIEW/CRITIQUE BY THEODORE BARRY AND ASSOCIATES IS COMPLETED
 - INITIAL RUNS OF THE COMPUTER MODEL HAVE BEGUN
- PLANNED ACTIVITIES
 - CONTINUING MODEL AND INPUT VALIDATION BOTH INTERNAL AND EXTERNAL TO JPL
 - IN THE FUTURE, LCP WILL EVALUATE RESIDENTIAL APPLICATIONS AND INTERFACE WITH A UTILITY GRID SIMULATION MODEL

2. Technology Development Area

a. Silicon Material Task

AEROCHEM RESEARCH LABORATORIES, INC.

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

OBJECTIVES

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

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

INITIAL RESULTS

1. SMALL-SCALE DEMONSTRATION OF:
VAPOR-PHASE REAGENT SYSTEMS
SILICON PRODUCTION
PRODUCT PURITY
2. SCALED-UP REACTOR DEMONSTRATION OF:
SILICON PRODUCTION AT 0.5 KG/HR
SEPARATION OF SILICON FROM BYPRODUCT
SALT IN HEATED REACTOR

CURRENT WORK

1. EXTEND RUN TIME AND PRODUCE LARGER QUANTITIES OF SILICON.
2. INVESTIGATE EXTENT OF REACTION, HEAT RELEASE RATE, SILICON COLLECTION EFFICIENCY, AND SKULL WALL DEVELOPMENT IN WELL-STIRRED REACTOR.
3. SEED REAGENTS WITH B AND P AND TEST PRODUCT PURITY
4. DETERMINE EFFECTS OF REAGENTS AND PRODUCTS ON MATERIALS OF CONSTRUCTION

Na/GRAPHITE TEST APPARATUS

Na/GRAPHITE TEST APPARATUS

FLOW TUBE FOR Na/GRAPHITE TESTS

FLOW TUBE FOR Na/GRAPHITE TESTS

Na/GRAPHITE FLOW TUBE TESTS

CONDITIONS:

TEMPERATURE = 1200 K AND 1700 K
 PRESSURE = 0.5 ATM
 FLOW = 3-10 M/S NA VAPOR
 DURATION = 15-30 MIN

SAMPLES: PYROLYTIC GRAPHITE COATED GRAPHITE

A GREAT LAKES CARBON CORP.
 HLM GRADE
 B STACKPOLE
 2020 GRADE
 UNCOATED GRAPHITE
 C AIRCO-SPEER, 580 GRADE

TEST RESULTS

T/HIN	SAMPLE	REMARKS
14	A	EXTENSIVE DAMAGE TO COATING AND SUBSTRATE.
	B	SAME AS A.
	C	EXTENSIVE DAMAGE.
16	A	COATING CRACKED AND PEELING. SUBSTRATE GRAPHITE OK.
	B	SAME AS A.
27	A	COATING CRACKED. SUBSTRATE OK. VERY LITTLE NA ABSORBED INTO SAMPLE.
	B	NO DAMAGE VISIBLE.
	C	NO DAMAGE VISIBLE.

CONCLUSIONS

1. ALL SAMPLES AND COATINGS RAPIDLY DEGRADED AT NA DEW POINT.
2. AT 1700 K NO DAMAGE OBSERVED TO SUBSTRATE GRAPHITES. PYROLYTIC GRAPHITE COATINGS CRACKED.

BATTELLE COLUMBUS LABORATORIES

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

JPL CONTRACT No. 954339
SILICON MATERIAL TASK
LOW-COST SOLAR ARRAY PROJECT

BACKGROUND

- FEASIBILITY - 1975 TO 1976
- MINIPLANT AND ECONOMICS - 1976 TO 1977
- PRELIMINARY EPSDU (50 MT/YEAR) DESIGN, ECONOMICS, AND SUPPORT STUDIES - 1977 TO 1978
- FINALIZATION OF EPSDU DESIGN, CONSTRUCTION, AND SUPPORT - 1978 TO 1979
- DESIGN, CONSTRUCTION AND OPERATION OF PDU -- AT PRESENT

SCHEMATIC DRAWING OF EPSDU FOR PREPARATION OF SILICON BY THE ZINC REDUCTION OF SiCl_4

COST ANALYSIS

\$/KG OF SILICON = 1.19 (MATERIAL COSTS + UTILITY COSTS) + 2.37 (MANPOWER COSTS) + 1.92 (EQUIPMENT COSTS)

- CASE A 1-41-IN REACTOR
1-720,000-AMP ELECTROLYTIC CELL
- CASE B 2-29-IN REACTORS
12-60,000-AMP ELECTROLYTIC CELLS

SUPPORT STUDIES

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

FLOW DIAGRAM FOR EPSDU

6.5 IN. ID FLUIDIZED-BED REACTOR

REACTOR CONDENSER
14 FT 10 IN. HI. x 14 IN. DIAMETER

ELECTROLYTIC CELL **36 IN. x 50 IN. x 33 IN. HI.**

ZINC VAPORIZER

DESIGN PARAMETERS - 50 MT/YEAR EPSDU

• ON-STREAM FACTOR	80 PERCENT
• ZN/SiCL ₄ STOICHIOMETRY	2/1
• CONVERSION OF SiCL ₄	63 PERCENT PER PASS
• PRODUCTION RATE	7.20 KG/HOUR (16.8 G/HOUR/ CM ² CROSS SECTION)
• SEED REQUIREMENT (5 PERCENT)	0.36 KG/HOUR
• FLUIDIZED BED REACTORS (TWO)	16.5 CM DIAMETER
• SiCL ₄ PURIFICATION BY DISTILLATION	92 PERCENT CENTER CUT
• ZINC RECYCLE BY ELECTROLYSIS	SIX 5000-6000 AMP CELLS
• ZINC RECOVERY	95 PERCENT
• CL ₂ DISPOSAL BY CONVERSION TO NaOCL	

WESTINGHOUSE R&D CENTER

- * CHARACTERIZE THE EFFECTS OF IMPURITIES ON SILICON SOLAR CELLS
- * PROVIDE A BASIS FOR EVALUATING THE COST-BENEFIT TRADE-OFFS
BETWEEN SILICON PURITY, CELL FABRICATION TECHNOLOGY AND
CELL PERFORMANCE.

IMPURITY EFFECTS

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

EFFICIENCY VERSUS METAL CONTENT; P-BASE DEVICES MODEL-DERIVED CURVES

OCD LIFETIME MAP, INGOT W-093 $MN = 2.75 \cdot 10^{15} \text{ cm}^{-3}$
(75 MM WAFER, 4 OHM-CM P-TYPE, .030" MESA DIODES)

EFFICIENCY VERSUS METAL CONTENT
SOLID CURVES ARE N-BASE;
DASHED CURVES ARE COMPARABLE P-BASE DATA

POCL₃ GETTERING OF TITANIUM

RECIPROCAL TRAP DENSITY VERSUS MINORITY CARRIER LIFETIME (μ S)

CALCULATED AND MEASURED PERFORMANCE FOR INGOTS USED TO MODEL "SOLAR GRADE" FEEDSTOCK

INGOT	IMPURITY	10^{19} cm^{-3}	C_o ppm	10^{14} cm^{-3}	C_s ppm
W074	Cr	0.73	146	0.8	.0016
	Mn	0.62	124	0.8	.0016
	Ni	1.60	320	5.0	.01
	Ti	0.017	3.4	0.0033	-
	V	0.015	3.0	0.06	-
Total		2.97	596	6.6	.0132

$$\eta/\eta_o \text{ (calc)} = 0.93 \pm 0.02$$

$$\eta/\eta_o \text{ (meas)} = 0.89 \pm .03$$

		10^{19} cm^{-3}	ppma	10^{14} cm^{-3}	ppma
W126	Al	0.0033	0.66	10	.02
	Cr	.18	36	0.2	.0004
	Cu	.10	20	8	.016
	Fe	.31	62	0.2	.0004
	Mn	.15	30	0.2	.0004
	Mo	.33	66	0.0015	-
	Ni	2.50	500	8	.016
	P	.0003	.06	9	.018
	Ti	.02	4	0.004	-
	V	.01	2	0.004	-
	Zr	.46	92	0.004	-
Total		4.0	804	35.6	.071

$$\eta/\eta_o \text{ (calc)} = 0.89 \pm 0.03$$

$$\eta/\eta_o \text{ (meas)} = 0.83 \pm 0.03$$

DEVELOPMENT OF MODELS AND COMPUTER CODES TO DESCRIBE SOLAR GRADE SILICON PRODUCTION PROCESSES

PROGRAM OBJECTIVES

OVERALL:

TO DEVELOP COMPUTATIONAL TOOLS TO
PREDICT PERFORMANCE OF METHODS OF
PRODUCING SILICON FROM GAS PHASE
REACTIONS OF SILICON HALIDES OR
HYDRIDES.

IMMEDIATE:

DESCRIBE SiCl_4/Na PROCESSES

APPROACH

1. TREAT GAS PHASE CHEMISTRY AND PARTICLE
FORMATION AND GROWTH IN DETAIL -
2-PHASE MIXING CODE
2. TREAT TRANSFER OF HEAT AND MATERIAL TO
WALLS - BOUNDARY LAYER CODE

STATUS

1. BOUNDARY LAYER CODE - BEGINNING PRODUCTION
RUNS - VAPOR DEPOSITION
2. 2-PHASE MIXING CODE UNDERGOING FINAL
TESTING

PLANS

1. ADD BOUNDARY LAYER CONDENSATION (PARTICLES) TO BOUNDARY LAYER CODE.
2. PRODUCTION RUNS FOR SiCl_4/Na FLOW REACTORS USING BOUNDARY LAYER CODE.
3. PRODUCTION RUNS USING 2-PHASE MIXING CODE - GET PARTICLE SIZE DISTRIBUTION.
4. COMPARE WALL FLUX PREDICTIONS FOR THE MODELS.

SRI INTERNATIONAL

GAS REACTOR

STEP

1 SiF_4 PREPARATION

2 REACTION

REACTION PRODUCTS — Si, NaF, Na_2SiF_6

3 SILICON RECOVERY FROM REACTION PRODUCTS

FUSION AT TEMP $> 1410^\circ\text{C}$

SILICON (MELT)

NaF (MELT)

GAS REACTOR SILICON ANALYSIS

SPARK SOURCE MASS SPECTROMETRIC AND EMISSION SPECTROGRAPHIC

ELEMENT	PPM Wt.	ELEMENT	PPM Wt.	ELEMENT	PPM Wt.	ELEMENT	PPM Wt.
B	0.1	V	0.04	F	0.1	Mn	0.1
Al	0.8	Cr	<3.5	Na	1.0	Ni	2.0
Ga	0.06	Ti	2.0	Nb	0.02	Co	0.5
*P	0.2	Zr	2.0	Ta	0.4	Fe	< 7
As	Not Obs.			Mo	0.3	Cu	< 4
				W	0.2	Zn	0.01

*Chem. Analysis — 0.09 PPM

ESTIMATION OF PRODUCT COST (LAMAR UNIVERSITY FACTORS)

Dollars Per Kilogram Si			
	SRI (Leach)	SRI (Melt)	SRI/Thermite (Melt)
1. Direct Manufacturing Cost (Direct Cost)			
1. Raw materials	5.725	4.876	4.784
2. Direct operating labor	.674	.674	.674
3. Utilities	.714	1.021	1.021
4. Supervision and clerical	.101	.101	.101
5. Maintenance and repairs	.901	.699	.663
6. Operating supplies	.180	.140	.133
7. Laboratory charge	.101	.101	.101
2. Indirect Manufacturing Cost (Fixed Cost)			
1. Depreciation	.901	.699	.663
2. Local taxes	.180	.140	.133
3. Insurance	.090	.070	.066
3. Plant Overhead	.735	.675	.664
4. By-Product Credit	(4.910)	(4.987)	(5.051)
4a. Total Manufacturing Cost, 1 + 2 + 3 + 4	5.393	4.209	3.952
5. General Expenses			
1. Administration	.324	.253	.237
2. Distribution and Sales	.324	.253	.237
3. Research and Development	.162	.126	.119
6. Product Cost Without Profit, 4a + 5	<u>6.202</u>	<u>4.841</u>	<u>4.545</u>
7. 25% ROI (Profit)	2.251	1.748	1.657
8. Cost + 25% ROI (Profit), 6 + 7	8.454	6.589	6.202

SRI INTERNATIONAL/LSA-JPL

GAS REACTOR

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

STEP 2 REACTION

STEP 2 REACTION

REACTION CONDITIONS

- SOLID SODIUM DROPPED INTO A HOT REACTOR CONTAINING SiF_4 GAS
- AVERAGE REACTION TEMP $\sim 500^\circ\text{C}$
- $P_{\text{SiF}_4} = 0.7\text{-}1.0 \text{ ATM}$
- NICKEL LINER MATERIAL
- INNER LINER GRAFOIL

REACTION PRODUCTS

- SILICON ABOUT 11% WEIGHT
~80% OF MAXIMUM POSSIBLE
- Na_2SiF_6 5-40% WEIGHT
- UNREACTED SODIUM 1-10% WEIGHT
- SILICON PARTICLE SIZE 150 μm

GAS REACTOR

STEP 3 SILICON RECOVERY BY FUSION

- REACTION PRODUCTS MELTED AT $T > 1410^{\circ}\text{C}$
- GRAPHITE CRUCIBLES, ARGON ATMOSPHERE
- SEPARATION OF PHASES
MOLTEN NaF ABOVE MOLTEN SILICON
- NaF WETS GRAPHITE, PREVENTS Si CONTACT

EFFECT OF SURFACE TO VOLUME RATIO OF CYLINDRICAL (6 CM DIAMETER) Na SLICES ON AMOUNT OF Na UNREACTED

<u>SLICE THICKNESS CM.</u>	<u>SURFACE VOLUME CM²/CM³</u>	<u>WEIGHT PERCENT Na IN REACTION PRODUCTS</u>
0.3	5.7	2-4,3-5,2-8
0.6	3.5	5-7,3-5,2-18,9-20,5-11
1.3	1.9	>20

EFFECT OF SURFACE TO VOLUME RATIO OF QUADRANT SHAPED Na SLICES (3 CM EDGE) ON AMOUNT OF Na UNREACTED

<u>SLICE THICKNESS CM.</u>	<u>SURFACE VOLUME CM²/CM³</u>	<u>WEIGHT PERCENT Na IN REACTION PRODUCTS</u>
0.6	3.9	3-9
1.3	2.9	1-10,~5
1.8	2.1	≥20

LAWRENCE LIVERMORE LABORATORIES

MEASUREMENT OF IMPURITY CONCENTRATIONS IN SILICON

IRRADIATION FACILITIES

LIVERMORE POOL TYPE REACTOR IS A RESEARCH REACTOR.

THREE OF THE ACCESS TUBES ARE USED FOR ACTIVATION ANALYSIS.

POSITION	THERMAL FLUX	EPITHERMAL THERMAL	IRRADIATION L.V. (CM)	CONTAINER L. HT. (CM)
S-2	$.5 \times 10^{13}$	.022	(POLY) 6.35	13.03
E-1	2.5×10^{13}	.042	(AL) 1.88	4.27
A-4 (RABBIT)	2.0×10^{13}	.045	(POLY) 2.38	6.99

JPL NUCLIDE LIST BY HALF-LIFE

ELEMENT	NUCLIDE	RATE	HALF-LIFE	E_{γ}	P_{γ}
AL	^{28}AL	3.2×10^6	2.3M	1778.85	1.000
V	^{52}V	3.5×10^7	3.8M	1434.19	1.000
CU	^{66}CU	4.1×10^6	5.1M	1039.00	.090
TI	^{51}TI	7.4×10^4	5.8M	320.10	.950
MG	^{27}MG	6.5×10^4	9.5M	843.76	.720
MO	^{101}MO	1.2×10^5	14.6M	598.91	.200
NI	^{65}NI	1.1×10^5	2.56H	1481.90	.257
MN	^{56}MN	9.6×10^7	2.5CH	846.60	.990
SI	^{31}SI	5.2×10^4	2.62H	1266.20	.0007
CU	^{64}CU	1.8×10^7	12.8H	1345.76	.0048
ZN	^{69}ZN	8.2×10^4	13.8H	439.00	.957
ZR	^{97}ZR	2.6×10^4	17.0H	743.37	.940
W	^{187}W	3.0×10^7	23.9H	685.70	.320
MO	^{99}MO	4.2×10^5	66.7H	140.51	.805
CR	^{51}CR	5.2×10^6	27.8D	320.10	.098
FE	^{59}FE	2.5×10^4	45D	1099.32	.562
ZR	^{95}ZR	4.7×10^4	65D	756.72	.546
(G, P) NI	^{58}CO	8.0×10^4 (9.9×10^3)	71.3D	810.79	.995
ZN	^{65}ZN	2.2×10^6	245D	1115.52	.490

³¹SI ACTIVITY – 2.62 HOUR HALF-LIFE

COOLING TIME (HOURS)	DPH/GM
0	4×10^{10}
24	7×10^7
36	3×10^6
48	1×10^5
60	5300
72	220

GROUP 1 ELEMENTS: REQUIRE PRE-IRRADIATION SEPARATION
FROM SILICON

GROUP 2 ELEMENTS:

	IRRADIATE	COOL	COUNT
E-1	72 MIN	64 HOURS	400 MIN
S-2	6 HOURS	64 HOURS	400 MIN

*DPH = DISINTEGRATIONS PER MINUTE

DETECTION LIMITS – GROUP 1 ELEMENTS

10M IRRADIATION, 10M COOL, 10M COUNT

	REPROD.*	REPROD/GRAM	DET. LIM. NANOGRAMS
²⁸ AL	5.1	47	.05
²⁷ Hg	10.0	11	.45
⁵¹ Tl	3.5	9	.19
⁵² V	4.9	2180	.001
⁵⁶ Mn	4.3	3930	.0005
⁶⁵ HI	16.0	4	1.8
⁶⁶ CU	51.9	430	.051

*DPH(BG) = DISINTEGRATIONS PER MINUTE (BACKGROUND)

UNION CARBIDE CORPORATION

UNION CARBIDE SILANE PROCESS

ECONOMIC PERFORMANCE OF COMMERCIAL UCC SILANE/SILICON PLANTS

	1975 Dollars			
	1000 MT/Yr Size Facility		120 MT/Yr Size Facility	
	Public Financing @ 9% Interest	Private Financing @ 20% DCF	Public Financing @ 9% Interest	Private Financing @ 20% DCF
Total Investment, \$M	6697	6697	3763	3763
Annual Operating Cost W/O deprec. & capital charges), \$M	4658	4838	1645	1739
Molten Silicon Product Price, \$/kg	5.76	7.56	18.61	26.42

Price Breakdown (1975 Dollars/kg)

Raw Materials	\$ 1.80	\$ 1.99
Utilities	.65	.89
Manpower	.97	6.67
Maintenance Materials	.21	.61
Analytical Charges	.03	.29
Consumables	.26	.42
Property Tax and Insurance	.08	.37
Period Costs	.07	.59
Home Office Charges	.58	1.86
Manufacturing Cost, ex. depreciation	4.66	\$ 13.69
Depreciation	.47	2.09
Capital Charges	.63	2.83
Total Product Price	\$ 5.76	\$ 18.61

FLUID BED SILANE PYROLYSIS SCHEMATIC DIAGRAM

FLUID BED PYROLYSIS OF SILANE CRITICAL MOLE FRACTION OF SILANE AS A FUNCTION OF TEMPERATURE

HETEROGENEOUS SILANE DECOMPOSITION, SURFACE REACTION RATE VS T^{-1} (K^{-1})

CHEMICAL REACTIONS UCC SILANE/SILICON PROCESS

STC Hydrogenation

Chlorosilanes Redistribution

Silane Pyrolysis

EFFLUENT PRODUCT COMPOSITION FROM TCS REDISTRIBUTION REACTOR AT 81°C CONTAINING A-21 RESIN CATALYST

BED DIAMETER = 0.43 INCHES

<u>Velocity, ft/hr</u>	<u>K_3</u>	<u>k_3</u>
1	.0210	.01370
2	.0210	.02162
4	.0210	.03041

EFFLUENT PRODUCT COMPOSITION FROM LIQUID DCS REDISTRIBUTION REACTOR AT 56°C CONTAINING A-21 RESIN CATALYST

BED DIAMETER = 0.43 INCHES

PROCESS FEASIBILITY STUDY IN SUPPORT OF SILICON TASK 1

. CHEMICAL ENGINEERING ANALYSIS
. ECONOMIC ANALYSIS

PRELIMINARY PROCESS DESIGN ACTIVITIES FOR SILANE PROCESS-CASE C (UNION CARBIDE)

<u>Prel. Process Design Activity</u>		<u>Status</u>	<u>Prel. Process Design Activity</u>		<u>Status</u>
1.	1. Specify Base Case Conditions	•	7. Equipment Design Calculations		•
	1. Plant Size	•	1. Storage Vessels		•
	2. Product Specifics	•	2. Unit Operations Equipment		•
	3. Additional Conditions	•	3. Process Data (P, T, rate, etc.)		•
			4. Additional		•
	2. Define Reaction Chemistry	•	8. List of Major Process Equipment		•
	1. Reactants, Products	•	1. Size		•
	2. Equilibrium	•	2. Type		•
			3. Materials of Construction		•
	3. Process Flow Diagram	•	8a. Major Technical Factors		•
2.	1. Flow Sequence, Unit Operations	•	(Potential Problem Areas)		•
	2. Process Conditions (T, P, etc.)	•	1. Materials Compatibility		•
	3. Environmental	•	2. Process Conditions Limitations		•
	4. Company Interaction	•	3. Additional		•
	(Technology Exchange)		9. Production Labor Requirements		•
	4. Material Balance Calculations	•	1. Process Technology		•
	1. Raw Materials	•	2. Production Volume		•
	2. Products	•	10. Forward for Economic Analysis		•
	3. By-Products	•			
	5. Energy Balance Calculations	•			
3.	1. Heating	•	0 Plan		
	2. Cooling	•	• In Progress		
	3. Additional	•	• Complete		
	6. Property Data	•			
	1. Physical	•			
	2. Thermodynamic	•			
	3. Additional	•			

BASE CASE CONDITIONS FOR SILANE PROCESS-CASE C (UNION CARBIDE)

STEP 1

1. Plant Size
 - Silicon produced from silane
 - 1000 metric tons/year of silicon
2. Hydrogenation Reaction
 - Metallurgical grade silicon, hydrogen, and recycle silicon tetrachloride (TET) used to produce trichlorosilane (TCS)
 - Copper catalyzed
 - Fluidized bed
 - 500°C, 514.7 psia
 - 20% to 22.5% conversion of SiCl_4 (example)
3. TCS Redistribution Reaction
 - TCS from hydrogenation produces dichlorosilane (DCS)
 - Catalytic redistribution of TCS with tertiary amine ion exchange resin
 - Liquid phase 85 psia, 140°F
 - Conversion a function of inlet concentration (Union Carbide equilibrium)
 - Conversion from pure TCS feed is about 9.5% to DCS (example)
4. DCS Redistribution Reaction
 - DCS produces SiH_4 (silane)
 - Catalytic redistribution of DCS with tertiary amine exchange resin
 - Liquid phase 510 psia, 140°F
 - Conversion a function of inlet concentration (Union Carbide equilibrium)
 - Conversion from pure DCS feed is about 14% to Silane (example)
5. Recycles
 - Unreacted chlorosilanes separated by distillation and recycled
6. Silane Purification
 - Final purification by distillation
 - Designed to remove trace impurities (B_2H_6 , example)
7. Operating Ratio
 - Approximately 85% utilization (on stream time)
 - Approximately 7445 hour/year production
8. Storage Consideration
 - Feed materials (several week supply, approx. 1 month)
 - Product (two shifts storage)
 - Process (several hours to 1 shift)

STEP 1 BASE CASE CONDITIONS MAJOR ITEMS SUMMARY

INTEGRATED PLANT

- HYDROGENATION (CHLOROSILANES)
- DISTILLATION (SEPARATION)
- REDISTRIBUTION REACTION (SILANE)
- SILANE PURIFICATION
- PYROLYSIS
- CONSOLIDATION
- SILICON PRODUCT

MAJOR FEED MATERIALS

- M.G. SILICON
- MAKE-UP SILICON TETRACHLORIDE
- MAKE UP HYDROGEN

RECYCLE OF HYDROGEN OFF-GAS

- SILANE FEED TO PYROLYSIS
- HYDROGEN OFF-GAS IS RECYCLED

STEP 2 REACTION CHEMISTRY FOR SILANE PROCESS – CASE C (REVISED PROCESS)

1. Hydrogenation Reaction

2. Trichlorosilane Redistribution Reaction

3. Dichlorosilane Redistribution Reaction

4. Waste Treatment (representative)

5. Silane Pyrolysis Reaction

Note

1. Reaction 1 product contains H_2 , HCl , SiCl_4 , SiHCl_3 , SiH_2Cl_2 (trace), other trace chlorides
2. Reaction 2 Product contains SiHCl_3 , SiCl_4 , SiH_2Cl_2 , SiH_3Cl
3. Reaction 3 Product contains SiH_2Cl_2 , SiHCl_3 , SiCl_4 , SiH_3Cl , SiH_4

STEP 3 PROCESS FLOW SHEET FOR SILANE PROCESS – CASE C (REVISED PROCESS)

CASE C ECONOMIC ANALYSES: PRELIMINARY ECONOMIC ANALYSIS ACTIVITIES FOR SILANE PROCESS CASE C (UNION CARBIDE)

Prel. Process Economic Activity	Status	Prel. Process Economic Activity	Status
1. Process Design Inputs	•	6. Production Labor Costs	•
1. Raw Material Requirements	•	1. Base Cost Per Man Hour	•
2. Utility Requirements	•	2. Cost/Kg Silicon Per Area	•
3. Equipment List	•	3. Total Cost/Kg Silicon	•
4. Labor Requirements	•		
2. Specify Base Case Conditions	•	7. Estimation of Plant Investment	•
1. Base Year for Costs	•	1. Battery Limits Direct Costs	•
2. Appropriate Indices for Costs	•	2. Other Direct Costs	•
3. Additional	•	3. Indirect Costs	•
		4. Contingency	•
3. Raw Material Costs	•	5. Total Plant Investment (Fixed Capital)	•
1. Base Cost/Lb. of Material	•		
2. Material Cost/Kg of Silicon	•	8. Estimation of Total Product Cost	•
3. Total Cost/Kg of Silicon	•	1. Direct Manufacturing Cost	•
		2. Indirect Manufacturing Cost	•
4. Utility Costs	•	3. Plant Overhead	•
1. Base Cost for Each Utility	•	4. By-Product Credit	•
2. Utility Cost/Kg of Silicon	•	5. General Expenses	•
3. Total Cost/Kg of Silicon	•	6. Total Cost of Product	•
5. Major Process Equipment Costs	•		
1. Individual Equipment Cost	•		
2. Cost Index Adjustment	•		

0 Plan
 • In Progress
 • Complete

STEP 2

CASE C BASE CASE CONDITIONS FOR SILANE PROCESS – CASE C (UNION CARBIDE)

1. Capital Equipment

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

2. Utilities

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

3. Raw Material Cost

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

4. Labor Cost

- Average for Chemical Petroleum, Coal and Allied Industries (1975)
- Skilled \$6.90/hr
- Semiskilled \$4.90/hr

CASE C
STEP 7 ESTIMATION OF PLANT INVESTMENT FOR SILANE PROCESS
CASE C (UNION CARBIDE)

	<u>Investment</u> <u>\$1000</u>
1. DIRECT PLANT INVESTMENT COSTS	
1. Major Process Equipment Cost	1,481.9
2. Installation of Major Process Equipment	637.2
3. Process Piping, Installed	1,096.6
4. Instrumentation, Installed	281.6
5. Electrical, Installed	148.2
6. Process Buildings, Installed	148.2
1a. SUBTOTAL FOR DIRECT PLANT INVESTMENT COSTS (PRIMARILY BATTERY LIMIT FACILITIES)	3,793.7
2. OTHER DIRECT PLANT INVESTMENT COSTS	
1. Utilities, Installed	711.3
2. General Services, Site Development, Fire Protection, etc.	177.6
3. General Buildings, Offices, Shops, etc.	207.5
4. Receiving, Shipping Facilities	311.2
2a. SUBTOTAL FOR OTHER DIRECT PLANT INVESTMENT COSTS (PRIMARILY OFFSITE FACILITIES OUTSIDE BATTERY LIMITS)	1,407.8
3. TOTAL DIRECT PLANT INVESTMENT COST, 1a + 2a	5,201.5
4. INDIRECT PLANT INVESTMENT COSTS	
1. Engineering, Overhead, etc.	815.0
2. Normal Cont. for Floods, Strikes, etc.	1,052.1
4a. TOTAL INDIRECT PLANT INVESTMENT COST	1,867.1
5. TOTAL DIRECT AND INDIRECT PLANT INVESTMENT COST, 3 + 4a	7,068.6
6. OVERALL CONTINGENCY, 10% of 5	2,120.6
7. FIXED CAPITAL INVESTMENT FOR PLANT, 5 + 6	9,189.2
8. WORKING CAPITAL INVESTMENT FOR PLANT	
9. TOTAL PLANT INVESTMENT, 7 + 8	

Note:
Costs are 1975 Dollars.

STEP 8

CASE C ESTIMATION OF TOTAL PRODUCT COST FOR SILANE PROCESS – CASE C (UNION CARBIDE)

	<u>\$/KG of Si</u>
1. Direct Manufacturing Cost (Direct Charges)	
1. Raw Materials	1.906
2. Direct Operating Labor	0.550
3. Utilities	0.427
4. Supervision and Clerical	0.083
5. Maintenance and Repairs	0.919
6. Operating Supplies	0.184
7. Laboratory Charge	0.083
2. Indirect Manufacturing Cost (Fixed Charges)	
1. Depreciation	0.919
2. Local Taxes	0.184
3. Insurance	0.092
3. Plant Overhead	0.656
4. By-Product Credit	-----
4a. Total Manufacturing Cost, 1 + 2 + 3 + 4	6.003
5. General Expenses	
1. Administration	0.360
2. Distribution and Sales	0.360
3. Research and Development	0.180
6. Total Cost of Product, 4a + 5	6.903

Note:

Costs are 1975 Dollars

UCC SILANE PROCESS

- PRELIMINARY COST SENSITIVITY ANALYSIS INITIATED
 - PROFIT CONSIDERATIONS
 - RETURN ON INVESTMENT (% RO), % DCF)
- ADDITIONAL CASES CONSIDERED
 - PLANT INVESTMENT
 - RAW MATERIALS
 - LABOR
 - UTILITIES

STEP 1 COST AND PROFITABILITY ANALYSIS

1. Process.....UCC Silane Process
2. Plant Size.....1,000 Metric Tons/year
3. Plant Product.....Semiconductor-Grade Silicon
4. Product Form.....Liquid Phase Silicon
5. Plant Investment.....\$10,570,000
(1975 dollars)

Fixed Capital	\$9.19 Mega
Working Capital	\$1.38 Mega
(15%) Total	\$10.57 Mega
	(1975 dollars)

6. Return on Original Investment, after taxes (%ROI)

	Sales Price \$/Kg of Silicon (1975 dollars)
0% ROI.....	6.90
5% ROI.....	7.92
10% ROI.....	8.93
15% ROI.....	9.95
20% ROI.....	10.96
25% ROI.....	11.98
30% ROI.....	13.00
40% ROI.....	15.03

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

	Sales Price \$/Kg of Silicon (1975 dollars)
0% DCF.....	6.90
5% DCF.....	7.55
10% DCF.....	8.27
15% DCF.....	9.05
20% DCF.....	9.88
25% DCF.....	10.74
30% DCF.....	11.64
40% DCF.....	13.51

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

**STEP 1 PRODUCT COST VS. RETURN ON INVESTMENT
UCC SILANE PROCESS**

NOTE

COSTS ARE 1975 DOLLARS

STEP 2 PRODUCT COST VS. PARAMETER VARIATION

COST AND PROFITABILITY ANALYSIS SUMMARY

1. Process.....UCC Silane Process
2. Plant Size.....1,000 Metric Tons/year
3. Plant Product.....Silicon
4. Product Form.....Liquid Phase Silicon
5. Plant Investment.....\$10,570,000
(1975 Dollars)

Fixed Capital	\$9.19 Mega
Working Capital	\$1.38 Mega
(15%) Total	\$10.57 Mega
	(1975 Dollars)

6. Product Cost Without Profit.....6.90 \$/kg of Silicon
7. Sales Price With Profit.....9.88 \$/kg of Silicon
at 20% DCF

CONVENTIONAL POLYSILICON PROCESS

STEP 1 BASE CASE CONDITIONS MAJOR ITEMS SUMMARY

- INTEGRATED PLANT
 - TCS PRODUCTION
 - TCS PURIFICATION
 - S.C. GRADE SILICON VIA ROD REACTORS
- PROVEN COMMERCIAL TECHNOLOGY
 - FLUIDIZED BED REACTOR TO PRODUCE TCS
 - DISTILLATION OF TCS FOR PURIFICATION
 - POLYSILICON PRODUCED BY DEPOSITION ON HOT RODS
- RECYCLE OF ROD REACTOR OFF-GAS
 - TCS REUSED IN REACTOR
 - TET BY-PRODUCT FOR SALES

STEP 2 REACTION CHEMISTRY FOR CONVENTIONAL POLYSILICON PROCESS

1. TCS Reactor

2. Rod Reactor

3. Waste Treatment

STEP 3: PRELIMINARY PROCESS FLOWSHEET FOR CONVENTIONAL POLYSILICON PROCESS

STEP 4 ESTIMATION OF PRODUCT COST FOR CONVENTIONAL POLYSILICON PROCESS: CASE B

PRODUCT COST, \$/KG SI

	LOW 1.5¢/KW.HR	HIGH 3¢/KW.HR	INTERMED. 2.25¢/KW.HR
1. Direct Manufacturing Cost (Direct Cost)			
1. Raw Materials	15.34	15.34	15.34
2. Direct Operating Labor	3.65	3.65	3.65
3. Utilities	8.49	14.26	11.37
4. Supervision and Clerical	.55	.55	.55
5. Maintenance and Repairs	2.16	2.16	2.16
6. Operating Supplies	.43	.43	.43
7. Laboratory Charge	.55	.55	.55
2. Indirect Manufacturing Cost (Fixed Cost)			
1. Depreciation	--	--	--
2. Local Taxes	.92	.92	.92
3. Insurance	.46	.46	.46
3. Plant Overhead	3.82	3.82	3.82
4. By-Product Credit	(6.23)	(6.23)	(6.23)
4a. Total Manufacturing Cost, 1 + 2 + 3 + 4	30.14	35.91	33.02
5. General Expenses			
1. Administration	1.81	2.15	1.98
2. Distribution and Sales	1.81	2.15	1.98
3. Research and Development	.90	1.08	.99
6. Product Cost Without Profit, 4a + 5	34.66	41.29	37.97
7. Profit For Product (After Taxes)			
8. Product Cost With Profit, 6 + 7			

Basis: Case B is based on 1975 costs for plant constructed in 1960's. Most plants producing polysilicon in U.S.A. were constructed in 1960's or earlier. Range reflects low and high electrical costs (1.5-3¢/KW.HR). Intermediate reflects intermediate electrical cost (2.25¢/KW.HR).

STEP 5 PRODUCT COST VS. PARAMETER VARIATION
COST SENSITIVITY FOR CONVENTIONAL POLYSILICON
PROCESS: CASE B

STEP 6 : PRODUCT COST VARIATION (SALES PRICE) WITH RETURN ON INVESTMENT (ROI): CASE B

. Process-----Conventional Polysilicon Process
 . Plant Size-----1,000 Metric Tons/Year
 . Plant Product-----Semiconductor Grade Polysilicon
 . Plant Investment-----\$52,900,000

PRODUCT COST WITH PROFIT: $\frac{1}{L}$
SALES PRICE, \$/KG Si

RETURN ON INVESTMENT AFTER TAXES %ROI	LOW 1.5¢/KW.HR	HIGH 3¢/KW.HR	INTERMED. 2.25¢/KW.HR
0	34.66	41.29	37.97
5%	39.95	46.58	43.26
10%	45.24	51.87	48.55
15%	50.53	57.16	53.84
20%	55.76	62.45	59.13
25%	61.05	67.74	64.42
30%	66.34	73.03	69.71
40%	76.92	83.61	80.29
50%	87.5	94.19	90.87
60%	98.08	104.77	101.45

NOTE: 1975 DOLLARS

CASE B STEP 7 CONVENTIONAL POLYSILICON PROCESS: SALES PRICE VS. YEAR

. Process-----Conventional Polysilicon Process
 . Plant Size-----1,000 Metric Tons/Year
 . Plant Product-----Semiconductor Grade Polysilicon
 . Profit After Taxes-----15% ROI

Year	Sales Price \$/KG OF Silicon
1975	54.77
1976	57.64
1977	60.71
1978	64.96*
1979	69.51*
1980	74.37*
1981	79.58*

*Estimated at 7% inflation

**STEP 8 SALES PRICE VS. YEAR (CONVENTIONAL POLYSILICON PROCESS,
CASE B, 15% ROI)**

STEP 9 COST SENSITIVITY FOR CONVENTIONAL POLYSILICON PROCESS: CASE B

C. BCL PROCESS

STEP 1 BCL PROCESS: INITIAL ECONOMIC ANALYSIS RESULTS REPORTED IN 1977

1. Process.....BCL Process
2. Plant Size.....1,000 Metric Tons/year
3. Plant Product.....~~Solar Cell Grade~~ Silicon
4. Product Form.....Solid Phase Silicon (Granules)
5. Plant Investment.....\$10,510,000
(Fixed Capital) (1975 Dollars)
6. Product Cost Without Profit.....8.79 \$/kg of Silicon
7. Product Cost With 8% Interest...9.63 \$/kg of Silicon

STEP 2 BCL PROCESS (BATTELLE COLUMBUS LABORATORIES)

.INITIAL CHEMICAL ENGINEERING - ECONOMIC ANALYSIS RESULTS

- REPORTED IN 1977
- BASED ON INITIAL LABORATORY DATA
- INVOLVED INITIAL PROCESS FLOWSHEET

.PROGRESS SINCE 1977 PROVIDED

- ADDITIONAL LABORATORY DATA
- MORE DETAILED PROCESS FLOWSHEET

.CHEMICAL ENGINEERING ANALYSIS RECENTLY INITIATED

- ADDITIONAL DATA
- PROCESS FLOWSHEET
- WORK ACTIVITIES IN PROGRESS

STEP 3 BCL PROCESS (BATTELLE COLUMBUS LABORATORIES): STATUS

1. Base Case Conditions	95%
2. Reaction Chemistry	95%
3. Process Flow Diagram	90%
4. Material Balance	90%
5. Energy Balance	90%
6. Property Data	90%
7.-8. Equipment Design	90%
9. Production Labor	80%

STEP 4 BCL PROCESS (BATTELLE COLUMBUS LABORATORIES): PLANS

1. Chemical Engineering Analysis

Continue preliminary process desing of the BCL process based on additional laboratory data and more detailed process flowsheet.

2. Economic Analysis

Perform cost analysis of BCL process as results issue from chemical engineering analysis.

CHEMICAL ENGINEERING AND ECONOMIC ANALYSIS: SUMMARY

PROCESS	<u>\$/KG. OF SILICON</u>	<u>COMMENTS</u>
1. BCL PROCESS-CASE A (Zn/SiCl ₄)	8.79	SHOWS PROMISE
2. BCL PROCESS-CASE B (SiI ₄ DECOMP.)	42.0	TOO EXPENSIVE (NEW PLANT)
3. CONVENTIONAL POLYSILICON PROCESS-CASE A	48.43	TOO EXPENSIVE (EXIST. PLANT)
4. CONVENTIONAL POLYSILICON PROCESS-CASE B	37.97	TOO EXPENSIVE (EXIST. PLANT)
5. CONVENTIONAL POLYSILICON PROCESS-CASE C	42.30	TOO EXPENSIVE (NEW PLANT)
6. UCC SILANE PROCESS- CASE A	12.21\$/KG OF SiH ₄	TOO EXPENSIVE-SILANE COST ONLY
7. UCC SILANE PROCESS- CASE B	10.12\$/KG OF SiH ₄	TOO EXPENSIVE-SILANE COST ONLY
8. UCC SILANE PROCESS- CASE C	6.90	SHOWS PROMISE

b. Large Area Silicon Sheet Task

CRYSTAL SYSTEM, INC.

DEVELOPMENTS OF HEAT EXCHANGER METHOD (HEM)

- HISTORICAL INGOT CRACKING PROBLEM SOLVED
- IT IS NOW POSSIBLE TO PROCESS SILICON IN VACUUM
- HEM IS ONLY METHOD WHICH PRODUCES SINGLE CRYSTAL IN SQUARE SHAPE

SQUARE INGOTS CAST BY HEM

HEM INGOT PROGRAM

HEM CURRENT STATUS AND GOALS

	1978	1979	1986
SIZE	10x10x12.5cm	20x20x20cm	30x30x30cm
CRYSTALLINITY,%	95	90	90
GROWTH RATE, KG/HR	1.2	1.0	2.5
EFFICIENCY,%	15	12	15

SOLAR CELL PERFORMANCE OF 2 CM X 2 CM CELLS HEM CAST SILICON (RUN 2-049-C)

Cell No.	AMO I_{sc} (mA)	AMO V_{oc} (mV)	AMO η	CFF	AM1 η
1	148	583	12.2	0.77	14.2
2	156	591	12.8	0.75	15.0
3	156	587	11.6	0.69	13.5
4	156	587	12.5	0.74	14.6
5	157	591	12.4	0.72	14.5
6	148	577	11.5	0.73	13.4
7	149	583	12.0	0.75	14.0

SOLAR CELL DATA ON 2 CM X 2 CM HEM CAST SILICON

HEAT EXCHANGER METHOD (HEM)

ECONOMIC ANALYSIS

- EQUIPMENT COST, \$30,000
- FLOOR SPACE, 60 SQ. FT.
- LABOR, 10 UNITS PER OPERATOR
- EXPENDABLES, \$95/KUN
- BOULE SIZE, 30 CM X 30 CM X 30 CM
- CYCLE TIME, 48 HOURS

VALUE ADDED PRICE, \$/M²

- EQPT, 1.77
- SQ. FT., 1.12
- SLAB, 1.14
- MATS + UTIL, 0.43
- TOTAL, 4.46

KAYEX CORP. (HAMCO)

EQUIPMENT DESIGN AND CONSTRUCTION

GOALS	STATUS
1. RECHARGEABLE CHAMBERS WITH VACUUM-TIGHT ISOLATION VALVE	1. COMPLETE 11/77
2. POLY WEIGHT/RECHARGE SYSTEM	2. COMPLETE 6/78
3. POLY-ROD FEEDSTOCK RECHARGE DEVICE	3. COMPLETE 12/77
4. LUMP POLYSILICON RECHARGE DEVICE	4. COMPLETE 1/79
5. CRYSTAL/POLY TRANSFER EQUIPMENT	5. COMPLETE 3/78
6. DOPANT FIXTURE	6. COMPLETE 1/78
7. 35 KG HOT ZONE (14" DIA CRUCIBLE)	7. COMPLETE 11/78
8. MELT LEVEL CONTROL VIA WEIGHT	8. INCOMPLETE

PROCESS DEVELOPMENT

GOALS	STATUS
1. HOT-FILL METHOD WITH POLY ROD	1. COMPLETE 2/78
2. HOT FILL WITH LUMP SILICON	2. COMPLETE 1/79
3. 100 KILOGRAMS FROM ONE 12-INCH CRUCIBLE	3. COMPLETE 2/79
4. 100 MM DIAMETER OR GREATER	4. 130 MM ACHIEVED
5. 10 CM/HR GROWTH RATE	5. 9.1 CM/HR ON CONTINUOUS RUNS 10 CM/HR FOR 2-3 HOURS
6. 35 KG HOT ZONE (14-INCH)	6. 28 KG INGOT PRODUCED FROM HOT ZONE
7. 14% EFFICIENCY AM-1	7. 9.3 - 10.4% AM-0 = 13 - 14.6% AM-1
8. 1.2 KG/HR THROUGHPUT	8. 1.2 KG/HR

SAMPLES FROM RUN NO. 11 SELECTED FOR SOLAR CELL AND IMPURITY ANALYSES

SAMPLE NUMBER	DESCRIPTION	SOLAR CELL EFFICIENCY (%) AT AM-0
101	First Ingot, top section All single crystal	10.4
103	Second Ingot, top section All single crystal	9.7
104	Second Ingot, bottom section All single crystal	10.1
105	Third Ingot, top section All single crystal	10.2
106	Fourth Ingot, top section All single crystal	9.3
107	Fourth Ingot, bottom section Dislocated material	9.3

SUMMARY OF RUN NO. 30

CRYSTAL INGOT DIAMETER	13.3 cm
AVERAGE GROWTH RATE	8.7 cm/HR
RUN TIME	79 HRS
THROUGHPUT	1.2 KG/HR
PULLED YIELD	99%
ZERO DISLOCATION	27%
TOTAL INGOT PULLED	99.1 KG

SAMICS ANALYSIS OF FOUR METHODS OF CONTINUOUS CZ

CONDITIONS	CZ #1	CZ #2	CZ #3	CZ #4
CRUCIBLE SIZE, DIA. x HT. (in)	12 x 9	14 x 10.5	14 x 11.5	15 x 12
CRYSTAL DIAMETER (cm)	10	12.5	15.2	17.8
GROWTH RATE (cm/hr)	10	10	10	11
NO. CRYSTALS/CRUCIBLE	5	4	4	5
TOTAL POLY MELTED (kg)	105	144	170	260
TOTAL INGOT PULLED (kg)	100	134	160	250
PULLED YIELD (%)	95	93	94	96
USABLE AFTER GRINDING (kg)	87	117	140	219
USABLE INGOT YIELD (%)	83	81	82	84
TOTAL CYCLE TIME (hr)	75	73	75	80
THROUGHPUT (kg/hr), (m ² /hr)	1.2	1.6	1.86	2.74
ADD-ON COST, 1975 \$/m ²	19.24	14.63	12.97	8.56

IPEG PRICE EQUATION INPUT DATA

	CZ 1	CZ 2	CZ 3	CZ 4
EQUIPMENT COST (\$)	124,700	124,700	124,700	128,000
FLOOR SPACE (sq ft)	100	100	100	100
LABOR (\$)	13,353	13,353	13,353	13,373
MATERIALS (\$)	43,110	49,000	49,000	45,000
UTILITIES (\$)	10,848	10,848	10,848	13,350
QUANT (kg/yr)	8,602	11,932	13,423	20,357

(ALL COSTS IN 1975 \$)

EFFECT OF MULTIPLE USE OF CRUCIBLES ON CZ ADD-ON COST

RECHARGE AND INGOT GROWTH TIME (RUN 30)

MELT NO.	RECHARGE TIME (HR) ⁽¹⁾	COMMENTS	CRYSTAL GROWTH ⁽³⁾ TIME (HR)
1	3.5 ⁽²⁾	6.5 KG LUMP HOT FILLED	5.5
2	4.0	ROD MATERIAL, ONLY 12.1 KG	7.5
3	3.0	5.0 KG LUMP PLUS 11.7 KG ROD	7.0
4	3.4	5.0 KG LUMP PLUS 11.0 KG ROD	7.0
5	3.0	6.2 KG LUMP PLUS 10.4 KG ROD	6.5
6	2.0	15.8 KG LUMP	5.7
TOTAL 18.9 HR			39.2 HR

(1) RECHARGE TIME INCLUDES: REMOVAL OF GROWN CRYSTAL

INSERTION OF POLY

HOT FILL

MELT DOWN

SEED PREPARATION UP TO SEEDING THE MELT

(2) INCLUDES COLD FILL AND HOT FILL TIME ON FIRST MELT

(3) AT 125 MM DIAMETER

CONCLUSIONS

1. 100 KG RUN HAS BEEN DEMONSTRATED.
2. SOLAR EFFICIENCY GOAL HAS BEEN MET WITH A FOUR-MELT RUN.
3. MAJOR COST REDUCTION IN FUTURE WILL BE AS A RESULT OF INCREASED THROUGHPUT.
4. FUTURE PROGRAMS WILL EMPHASIZE FASTER RECHARGING.
5. PRIMARY AREA OF CONCERN IS INGOT QUALITY AND ITS EFFECT ON SOLAR EFFICIENCY.

SILTEC CORP (ADVANCED CZ.)

CONTINUOUS CZOCHRALSKI PROCESS

. CURRENT CONTRACT GOALS

DESIGN, FABRICATE, AND DEVELOP EQUIPMENT AND PROCESSES TO DEMONSTRATE CONTINUOUS CZ GROWTH, DEFINED AS 100 KG OF SINGLE SILICON CRYSTAL, 10 CM IN DIAMETER GROWN FROM ONE CONTAINER.

. APPROACH TO ACHIEVE THOSE GOALS

DEVELOP A DUAL CHAMBER FURNACE WITH CONTINUOUS LIQUID REPLENISHMENT OF THE GROWTH CRUCIBLE, ACCOMPLISHED BY A MELT-DOWN AND MELT TRANSFER SYSTEM WITH ASSOCIATED FEEDBACK CONTROLS.

. PRESENT STATUS RELATIVE TO GOALS

FURNACE WAS DESIGNED AND FABRICATED; SEVERAL 100 KG THROUGHPUT RUNS WERE ATTEMPTED. TO DATE THE BEST EFFORT WAS 71 KG THROUGHPUT IN ONE CONTINUOUS RUN.

. ECONOMICS OF SYSTEM AT PRESENT STATE

CRYSTAL ADD-ON COST \$21.30/m ² IN 1975 DOLLARS
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KEY ASSUMPTIONS

25 SLICES/CM 100 MM DIAMETER CRYSTALS 100 MM/HOUR GROWTH VELOCITY
BATCH RECHARGING

CONTINUOUS CZOCHRALSKI PROCESS

ACHIEVABLE ECONOMIC GOAL FOR 1986

CRYSTAL ADD-ON COST \$9.92/m² IN 1975 DOLLARS

KEY ASSUMPTIONS

FURNACE RUNSIZE	150 KG
CRYSTAL DIAMETER	150 MM
CRYSTAL GROWTH VELOCITY	100 MM/HR.
INGOTS PER RUN	3
CRYSTAL YIELD	85%
RUN CYCLE TIME	52 HOURS
PULLERS PER OPERATOR	3
DIRECT LABOR COST	\$6.20/HR.
OPERATING SUPPLIES COST	\$567.00/RUN
EQUIPMENT COST	\$140,000
EQUIPMENT FLOOR SPACE	150 SQ. FT.
EQUIPMENT UTILIZATION	90%
ENERGY REQUIREMENTS	3552 KWH/RUN
ENERGY COST	\$0.04/KWH
SILICON/Slice CONVERSION	25 SLICES/CM

Effect of run size on continuous Czochralski Add-on cost

Effect of run size on continuous Czochralski Add-on cost

$$(1) \quad \frac{V_1^2}{2g} + \frac{P_1}{\gamma} + h_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + h_2 + \xi \frac{V_2^2}{2g}$$

$$V_1 = V_2$$

$$P_1 = P_2 \text{ for CLT}$$

$$(2) \quad \text{If } \frac{Q}{d} \leq 5.6 \times 10^{-4} \frac{\text{m}^3}{\text{s}} \Rightarrow \Delta h = \frac{128L \cdot \nu \cdot Q}{d^4 g \cdot \pi}$$

Δh	head differential	{m}
L	tube length	{m}
ν	kinematic viscosity	{ $\frac{\text{m}^2}{\text{s}}$ }
Q	replenishment rate	{ $\frac{\text{m}^3}{\text{s}}$ }
d	I.D. of transfer tube	{m}

MELT-LEVEL MONITORING

CRYSTAL SYSTEMS, INC. (FAST)

ESSENTIAL REQUIREMENTS FOR SLICING

1. LOW-COST PROCESS
2. HIGH MATERIAL UTILIZATION
3. LOW EXPENDABLE MATERIAL COSTS

FIXED ABRASIVE SLICING TECHNIQUE (FAST)

ACHIEVEMENTS:

- 64 WAFERS PER INCH, 25 WAFERS PER CM
- CONVERSION RATIO: $1.08 \text{ m}^2/\text{KG}$
- SLICE + KERF: 15.6 MILS, 0.40 MM
- LOW KERF: 6.2 MILS, 0.16 MM
- THIN WAFERS: 4 MILS, 0.10 MM
- LOW SURFACE DAMAGE: 3-5 μM

FAST CURRENT STATUS AND GOALS

	1978	1979	1986
WAFER SIZE	10CM DIAMETER	10x10 CM	10 x 10 CM
NO. OF SLICES	120	300	750
SLICING RATE,MM/MIN.	0.06	0.1	0.1
YIELD,%	97	95	95
WAFERS/CM	20	25	25
CONVERSION RATIO, m^2/KG	0.86	1	1

FIXED ABRASIVE SLICING TECHNIQUE (FAST)

ECONOMIC ANALYSIS

- EQUIPMENT COSTS, \$25,000
- FLOOR SPACE, 80 SQ. FT.
- LABOR, 10 UNITS PER OPERATOR
- 25 WAFERS/CM
- $30 \times 10 \times 10 \text{ CM}^3$ WORKPIECE
- YIELD, 95%

VALUE ADDED PRICE, $\$/\text{M}^2$

- EQPT, 1.32
- SQFT, 0.52
- SLAB, 0.76
- MATS + UTIL, 2.04
- TOTAL, 4.63

VARIAN ASSOCIATES (MBS)

MULTIBLADE SLURRY SLICING OF SILICON

ECONOMIC SUMMARY (1975 \$)

YEAR	COST GOAL ($\$/\text{M}^2$) *	KEY ASSUMPTIONS**	PROJECTED COST ($\$/\text{M}^2$)
1978	190.5	NONE***	81.8
1980	122.5	IN-PLANT BLADE PACKS *** 0.30 M^2/KG *** LOWER COST SLURRY VEHICLE (\$0.31/KG/RUN)	49.8
1982	64	LARGE CAPACITY SAW (1000 SLICES/RUN) 0.89 M^2/KG PARTIAL (35%) ABRASIVE RECLAMATION	30.1
1984	19	LOW-COST BLADES (\$4.25/KG) 1.0 M^2/KG LOWEST COST SLURRY VEHICLE (0.09/L/RUN) EXTENDED ABRASIVE RECLAMATION (66%)	19.3
1986	9.1	0.5 WAFER/MIN 15 CM DIAMETER	8.53

* 1/2 OF INGOT AND SLICING ADD-ON

** NOTE ASSUMPTIONS ACCUMULATE FROM YEAR TO YEAR

*** ROUTINE WITH CURRENT TECHNOLOGY

MULTIBLADE SLURRY SLICING OF SILICON

TECHNICAL SUMMARY

<u>GOAL</u>	<u>CURRENT BEST</u>	<u>IMPROVEMENT STATUS</u>
25 WAFERS/CM	22 WAFERS/CM	CUTTING TESTS CARRIED OUT YIELDS LOW EXPECT SUCCESS IN 1 MONTH
LOW COST BLADES (\$4.25 PER KG)	\$4.25 PER KG	ESSENTIALLY COMPLETE FURTHER WORK ON PACKAGING POSSIBLE FOR EVEN LOWER COST
LOW COST SLURRY VEHICLE (\$0.09 PER L PER RUN)	\$0.66/L/RUN	GOALS AND PROBLEMS DEFINED FOR TWO SYSTEMS: OIL: ADDITIVES ARE BEING INVESTIGATED (POTENTIAL \$0.056) WATER: CORROSION INHIBITORS BEING INVESTIGATED (POTENTIAL UNSURE)
LOW COST (RECYCLED) ABRASIVE (65% RECLAMATION AT \$3.60 PER KG)	- - -	COST GOAL WILL BE BEATEN SEPARATION FROM USED SLURRY ACHIEVED CUTTING TEST SHORTLY
1 WAFER/MIN (100 MM)	.43 WAFER/MIN	EQUIPMENT DESIGNED AND FABRICATED TEST SHORTLY

**SILTEC CORP.
(ADVANCED ID SLICING)**

**ENHANCED I.D. SLICING TECHNOLOGY
CURRENT CONTRACT GOALS**

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

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

APPROACH TO ACHIEVE THESE GOALS

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

PRESENT STATUS RELATING TO GOALS

PROGRAM ONLY TWO MONTHS IN EFFECT, PRESENTLY IN DESIGN PHASE

SILTEC/4-4-79

ENHANCED I.D. SLICING TECHNOLOGY

ACHIEVABLE ECONOMIC GOAL FOR 1986

SLICE ADD-ON COST \$6.97/m² IN 1975 DOLLARS

KEY ASSUMPTIONS

EQUIPMENT COST	\$38,000
SPACE REQUIREMENT	30.00 SQ. FT.
EQUIPMENT UTILIZATION	90%
POWER REQUIREMENTS	1.5 KW
LABOR RATE	\$4.80
SLICING YIELD	95%
CRYSTAL DIAMETER	150 MM
ENERGY COST	\$0.04/KWH
CUTS/BLADE	2000
PRODUCTIVITY/MACHINE/24 HR.	900
BLADE COST	\$ 35

BLADE HEAD CONFIGURATION

BLADE DRESSING PROCEDURE (SIDES)

BLADE DRESSING PROCEDURE (SIDES)

CLOSED LOOP BLADE POSITION CONTROL SYSTEM

CONVENTIONAL ID BLADES

PERSPECTIVE VIEW: PREFABRICATED INSERT BLADE

BLADE CROSS-SECTION AFTER BONDING

BATTELLE'S COLUMBUS LABORATORIES

PROGRAM PLAN	1978												1979					
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
SOLUTION THERMODYNAMICS																		
FABRICATION OF SILICON METAL OXYNITRIDE CERAMICS																		
EVALUATION OF SILICON METAL OXYNITRIDE CERAMICS																		
FABRICATION OF DIE SAND CONTAINERS																		
MANUFACTURING PROCESS SPECIFICATION AND COST PROJECTION FOR 10 ⁵ UNITS PER YEAR																		

SUMMARY OF ACCOMPLISHMENTS

- (1) DEVELOPMENT OF WELL CONTROLLED PROCESSING SCHEDULES
FOR FABRICATING HIGH QUALITY MATERIALS
- (2) DEVELOPMENT OF PROMISING MATERIALS
- (3) FABRICATION OF SHAPING DIE
- (4) THERMODYNAMICS DATA

SPARK SOURCE MASS SPECTROSCOPIC ANALYSIS (PPMW) OF Si_3N_4 AND X = 0.35 SIBEON

Element	SN502 Si_3N_4	Hot Pressed X=0.35 Sibeon
Li	0.1	0.005
Be	0.003	High
B	0.2	0.2
F	0.1	0.5
Na	5	3
Mg	5	10
Al	60	100
Si	Major	Major
P	0.2	0.5
S	0.6	1
Cl	500	7
K	0.6	1
Ca	12	3
Sc	0.3	0.2
Ti	7	1
V	0.2	0.3
Cr	10	1
Mn	0.2	0.1
Fe	10	5
Co	0.4	0.3
Ni	0.2	1
Cu	0.7	5
Zn	0.5	0.1
Ga	0.4	0.5
Ge	0.1	0.3
As	0.02	0.03
Se	2	0.5
Br	0.2	0.1
Rb	0.2	0.3
Sr	0.3	0.1
Y	3	1
Zr	60	10
Nb	0.2	0.05
Mo	400	30

THERMODYNAMICS DATA

- (1) DEVELOPMENT OF WELL CONTROLLED PROCESSING SCHEDULES
FOR FABRICATING HIGH QUALITY MATERIALS
- (2) DEVELOPMENT OF PROMISING MATERIALS
- (3) FABRICATION OF SHAPING DIE
- (4) THERMODYNAMICS DATA

MATERIALS PERFORMANCE

- (1) SIALON AND SIBEON MORE RESISTANT TO MOLTEN SILICON ATTACK THAN ANY OTHER METAL CATION CONTAINING MATERIALS
- (2) SIBEON MORE STABLE THAN SIALON
- (3) LOW WETTING ANGLES

ORIGINAL ONE-PIECE DIE DESIGN SUPPLIED BY JPL

COORS PORCELAIN

INTRODUCTION

1. MULLITE FOR CONTAINERS AND SILICON-ON-CERAMIC
2. FINAL REPORT
3. SESSILE DROP
4. CONTAINERS
5. SUBSTRATES

SESSILE DROP

1. CARBON RESISTANCE VACUUM FURNACE
2. 1450°C 10 MIN, 20 MIN, 10 HOUR
3. 10, 20 MIN REACTION MINIMAL
4. 10 HOUR - REACTION VERY PRONOUNCED
5. POROUS PARTS REACTED THE MOST
6. CONCLUSION - NOT USEABLE MATERIAL IN CONTACT WITH MOLTEN SILICON

SUBSTRATES

1. MANUFACTURE
 - A. DRY PRESS
 - B. ROLL COMPACTION
 - C. SLOTTED SUBSTRATES - SAWING
 - D. SLOTTED SUBSTRATES - PUNCHING
 - E. 1.75 x 3 x .040 INCHES, 2 x 20 x .040 INCHES, 4 x 40 x .040 INCHES
2. THERMAL EXPANSION
 - A. DECREASE Al_2O_3/SiO_2 RATIO DECREASES THERMAL EXPANSION
 - B. "K" MODIFICATION MATCHES SILICON THERMAL EXPANSION
 - C. "K" MODIFICATION CAN BE MADE IN ALL SHAPES

TABLE II

TASK	BODY	APPROXIMATE % OXIDE COMPOSITION									Th. Ex. 800°C
		Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	Al ₂ O ₃ /SiO ₂	
A	Std S-1-SI Coors Composition	57.6	38.9	0.62	0.13	0.25	0.92	0.25	1.12	1.48	0.375
C	996 HPM High Silica	52.2	44.7	0.56	0.13	0.22	0.83	0.22	1.01	1.17	0.35
	117 HPM S-1-SI + 10% SiO ₂	52.3	44.7	0.56	0.14	0.23	0.83	0.22	1.02	1.17	0.37
	118 HPM S-1-SI + 12.5% SiO ₂	51.1	46.0	0.55	0.14	0.22	0.81	0.22	0.99	1.11	0.36
	119 HPM S-1-SI + 15% SiO ₂	49.9	47.2	0.54	0.14	0.22	0.80	0.21	0.97	1.07	0.38
1st	120 HPM S-1-SI + 17.5% SiO ₂	48.8	48.3	0.53	0.14	0.21	0.78	0.21	0.85	1.01	0.37
J	121 HPM S-1-SI + 20% SiO ₂	47.8	49.4	0.52	0.14	0.21	0.76	0.20	0.93	0.97	0.33
1st	134 HPM S-1-SI + 27.2% SiO ₂	45.0	52.4	0.49	0.14	0.20	0.72	0.19	0.87	0.86	0.32
K	183 HPM 80% S-1-SI + 20% SiO ₂	45.8	51.5	0.50	0.14	0.20	0.73	0.19	0.89	0.89	
2nd	184 HPM 72.5% S-1-SI + 27.5% SiO ₂	41.4	56.2	0.45	0.14	0.18	0.66	0.18	0.81	0.74	0.292
L	71.43% S-1-SI 28.57% SiO ₂	40.7	56.9	0.45	0.14	0.18	0.66	0.18	0.79	0.715	0.287
M	69% S-1-SI 218 HPM 31% SiO ₂	39.2	58.4	0.43	0.14	0.17	0.64	0.17	0.77	0.67	0.315
MA	By Chem Lab Analysis	44.6	54.2	NA	NA	NA	NA	NA	NA	0.82	0.315
MR	69% S-1-SI 304 HPM 31% SiO ₂	39.2	58.4	0.43	0.14	0.17	0.64	0.17	0.77	0.67	0.290
	66.8% S-1-SI 307 M 33.2% SiO ₂	38.1	59.7	0.42	0.14	0.17	0.61	0.16	0.74	0.64	0.285
	63.65% S-1-SI 308 M 36.35% SiO ₂	36.2	61.6	0.40	0.14	0.16	0.58	0.15	0.76	0.59	0.277
	56.7% S-1-SI 309M 43.3% SiO ₂	32.2	65.9	0.36	0.14	0.14	0.51	0.14	0.63	0.49	0.330

56.7% S-1-SI + 43.3% SiO₂

EAGLE-PICHER, INC.

1. MATERIALS W/O PRESSING ADDITIVES AS COATINGS
2. COMPATIBLE SUBSTRATES - LIKE CERAMIC
 - A. COEFFICIENT OF THERMAL EXPANSION
 - B. P_{O_2} NOT FIXED BY SUBSTRATE
3. P_{O_2} EFFECTS UPON CONTACT ANGLE AND REACTIVITY
4. CHARACTERIZATION - BEFORE AND AFTER SESSILE DROP TESTS
5. HARDWARE DELIVERY TO JPL

MAIN ASPECTS OF EAGLE-PICHER/UMR/CHEMETAL EFFORT

Schematic Illustration of Sessile Drop Experiment Under Precisely Defined Oxygen Partial Pressure
 (A) Hydrogen gas, (B) Platinized asbestos, (C) Al_2O_3 separator, (D) Titanium powder, (E) Heating element, (F) Cold-trap-chiller, (G) Camera, (H) Sessile drop test furnace, (I) Optical pyrometer, (K) Oxide cell

RELATIONSHIP BETWEEN LOG P_{O_2} AND GALVANIC EMF OUTPUT AT
1000°C AND 1100°C

**TIME AND P_{O_2} DEPENDENCE OF MOLTEN SILICON CONTACT
ANGLE ON CNTD Si_3N_4 AT 1420°C**

**DECREASING OXIDATION EFFECTS WITH DECREASING OXYGEN
PARTIAL PRESSURE, 1420°C, CNTD Si_3N_4**

RCA CORP.

Sample	Approximate Content		Treatment
	α -Si ₃ N ₄	β -Si ₃ N ₄	
(SDE)Si/SiO _x N _y /RS-Si ₃ N ₄ (etched)	28%	72%	4 hr in He at 1450°C
(SDC)Si/SiO _x N _y /RS-Si ₃ N ₄ (etched)	22%	78%	4 hr in He at 1450°C
(SDC)Si/SiO _x N _y /RS-Si ₃ N ₄ (etched)	10%	90%	20 hr in He at 1450°C

	Oxygen (ppma)	Carbon (ppma)
Seed	~35	~30-40
Ribbon	< 5	< 25

Sample	Sheet Resistance ($\Omega/\square$)
R 2-1-78	60
R 2-1-78	57
R 2-10-78	48
R 2-10-78	49
Control	48

Sample	Lifetime τ (μ s)	Diffusion Length ($L = \sqrt{D\tau}$) (μ m)
R 2-1-78	0.6	39
R 2-10-78	0.9	48
Control	3.6	95

	Sample R 2-10-78	
	No AR	AR
J _{sc} (mA/cm ²)	18.5	27.0
V _{oc} (mV)	550	562
η (%)	8.0	11.8
F. F.	0.767	0.769

CAPILLARY DIE

EFG DIE FABRICATION – PROBLEM AREAS

EFG DIE FABRICATION - PROBLEM AREAS

● SUBSTRATE MATERIALS

- a) Thermal Expansion Mismatch
- b) Thermal Stability
- c) Purity

● SUBSTRATE EDGE EFFECTS ON CVD

- a) Enhanced CVD Rate at Edges
- b) CVD Layer Cracking at Edges

● CAPILLARY RISE IN CVD COATED DIES

- a) Oxygen Content in System
- b) Transport Reactions - Slag Formation

DIES FABRICATED AND FILLED WITH SILICON

CVD Si_3N_4 /H.P. Si_3N_4

CVD SiO_xNy /H.P. Si_3N_4

CVD Si_3N_4 / $\text{Si}_2\text{N}_2\text{O}$

CVD SiO_xNy / $\text{Si}_2\text{N}_2\text{O}$

IMPURITY CONTENT (PPM) OF MATERIALS IN SILICON SESSILE DROP EXPERIMENT

<u>Element</u>	<u>Si₃N₄ (Powder)</u>	<u>Si₃N₄ (Hot-Pressed)</u>	<u>Si₃N₄ (Under Silicon Sessile Drop)</u>	<u>Si (Sessile Drop)</u>	<u>Si (Source)</u>
Al	600-6000	600-6000	600-6000	30-300	3-30
Ba	10-100	10-100	10-100		
B	30-300	100-1000	100-1000	60-600	50-500
Ca	30-300	30-300	100-1000		3-30
Cu	5-50	6-60	3-30	3-30	
Fe	10-100	15-150	20-200	10-100	0.6-6
Hg	15-150	(S)	(S)	3-30	1-10
Mn	5-50	10-100	10-100	1-10	10-100
Na	20-200				
Ni		3-30	6-60		
Sr		0.3-3	1-10		
Ti	10-100	30-200	50-500		3-30
Zr		1-10	3-30		

RESULTS OF X-RAY ANALYSIS ON "Si₂N₂O" BOTH BEFORE AND AFTER IMMERSION IN MOLTEN SILICON

<u>Sample Region</u>	<u>Treatment</u>	<u>Approximate Content</u>		
		<u>Si₂N₂O</u>	<u>α-Si₃N₄</u>	<u>β-Si₃N₄</u>
Bulk	As received	90%	5%	5%
Surface	After immersion in molten silicon for 1 h at ~1440°C in Ar	25%	30%	45%
Subsurface	After immersion as stated	70%	10%	20%

TYLAN CORP.

OBJECTIVE: DETERMINE PROCESSING PARAMETERS OF VITRE-GRAF

(a glass-like carbon glaze) FOR OPTIMAL PER-

FORMANCE AND ECONOMY WHEN APPLIED TO (a) MUL-

LITE AND (b) GRAPHITE.

TEST PLAN:

SERIES 1. - EVALUATE PREPARATION OF SUBSTRATE

SERIES 2. - EVALUATE APPLICATION METHODS

SERIES 3. - EVALUATE COATING THICKNESS

SERIES 4. - EVALUATE CURE TEMPERATURE

SERIES 5. - EVALUATE HEATING RATE

SERIES 6. - EVALUATE ALTERNATE GAS ATMOSPHERES

SERIES 7. - DISCRETIONARY

SERIES 8. - DISCRETIONARY

FAILURE MECHANISMS BETWEEN MOLTEN SILICON AND GRAPHITE/GLASSY CARBON

IN BULK GRAPHITE

- (1) SILICON PENETRATES AND INVADES OPEN PORES.
- (2) SILICON CARBIDE REACTION AT ALL INTERFACES BY:
 - DIFFUSION OF SILICON INTO BINDER PHASE
 - DIFFUSION OF CARBON FROM FILLER PARTICLES INTO SILICON.
- (3) GROWTH OF SILICON CARBIDE REACTION PHASE WITHIN PORES.
- (4) GROWTH OF SILICON CARBIDE ALONG MACROSCOPIC INTERFACE.
- (5) CONTINUED DIFFUSION OF CARBON THROUGH SiC INTO SILICON.
- (6) SATURATION OF CARBON AT SiC - Si INTERFACE CREATING WELL FORMED SiC CRYSTALS THAT FLOAT AWAY.

IN GLASSY CARBON GLAZE

- (1) SILICON CARBIDE FORMS BY DIFFUSION OF SILICON INTO GLASSY CARBON GLAZE FORMING SiC "BARRIER".
- (2) CARBON DIFFUSES THROUGH SiC "BARRIER".
- (3) CARBON SATURATION AT SiC - Si INTERFACE CREATES SiC CRYSTALS THAT FLOAT AWAY.
- (4) "BARRIER" BECOMES BREACHED AND Si INVADES GRAPHITE STRUCTURE.

BASELINE PROCESS

- A SOLUTION OF DECOMPOSED POLYMERIC RESIN IN AN ORGANIC SOLVENT IS PREPARED HAVING CHARACTERISTICS OF LACQUER.
- THE SOLUTION IS APPLIED TO POROUS GRAPHITE BY USING TYPICAL PAINT TECHNIQUES AND CURED AT ELEVATED TEMPERATURE.
- THE COATING MATERIAL FILLS AND SEALS SURFACE PORES TO RENDER THE SUBSTRATE IMPERVIOUS TO GAS OR LIQUID PENETRATION.
- COATING THICKNESSES (5 layers) ARE TYPICALLY 5-10 μm AND CLOSELY MATCHES THE THERMAL EXPANSION OF GRAPHITE.

OCLI

OBJECTIVE

The objective of this program is to investigate, develop and utilize technologies appropriate and necessary for improving the performance of solar cells made from various unconventional silicon sheets.

SCOPE

1. Material Evaluated
 - o Cast Silicon by HEM (Crystal System)
 - o EFG RH (Mobil Tyco)
 - o SOC (Honeywell)
2. Performance Characterization
 - o Illumination Characteristics (AM0)
 - o Dark I-V Characteristics
 - o Spectral Response
 - o Minority Carrier Diffusion Length
 - o Small Light Spot Scanning Across Cell
3. Problem Areas Related to Process and Performance

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM CAST SILICON BY HEM; STANDARD PROCESS

		CAST SILICON "A"	CAST SILICON "B"	CONTROL
V_{OC} (mV)	Average	568	571	591
	Standard Deviation	4	18	3
	Range	557-574	535-588	588-595
J_{SC} (mA/cm ²)	Average	30.8	28.4	33.4
	Standard Deviation	0.6	0.8	0.2
	Range	29.5-31.5	27.2-28.9	33-33.6
CFF (%)	Average	73	61	75
	Standard Deviation	2	11	2
	Range	67-75	46-75	73-77
η (%)	Average	9.5	7.4	10.9
	Standard Deviation	0.4	1.4	0.2
	Range	8.4-9.9	5.3-9.2	10.7-11.2

- NOTE: 1. Measured at 25°C under AMO conditons (with SiO AR)
2. Cast Silicon "A": 3 ohm-cm
Cast Silicon "B": 0.5 ohm-cm
3. Number of Samples: Cast Silicon "A" - 18
Cast Silicon "B" - 12
Control Cells - 6

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM EFG RH RIBBON; STANDARD PROCESS

		EFG "A"	EFG "B"	EFG "C"	CONTROL
V_{OC} (mV)	Average	517 (492)	515 (502)	508 (500)	580
	Standard Deviation	9 (19)	2 (2)	-	-
	Range	490-526 (464-510)	510-508 (498-506)	480-527 (492-514)	576-588
J_{SC} (mA/cm ²)	Average	25.2 (17.9)	24.9 (17.6)	25 (18)	33.5
	Standard Deviation	0.6 (0.3)	0.7 (0.6)	-	-
	Range	24.8-26.1 (17.5-18.4)	23.5-25.5 (16.5-18.2)	24-25.5 (17.2-18.6)	33-33.8
CFF (%)	Average	64 (60)	73 (72)	56 (60)	73
	Standard Deviation	12 (14)	1 (2)	-	-
	Range	47-74 (42-73)	71-74 (69-74)	34-75 (49-72)	67-73
η (%)	Average	6.2 (4.0)	6.9 (4.8)	5.4 (4)	10.5
	Standard Deviation	1.4 (1.1)	0.2 (0.2)	-	-
	Range	4.3-7.5 (2.6-5.1)	6.6-7.2 (4.5-5.0)	2.9-7.4 (3.0-4.9)	9.7-11.2

NOTE:

- Measured at 25°C under AMO Conditions (cells with SiO AR). Parenthesis Numbers are for the Parameters Before AR Coating.
- Identification and Sample Numbers of EFG RH Ribbon Cells:
 - "A": 5-866 - 5 Cells
 - "B": 5-868 - 7 Cells
 - "C": 5-870 Uncontrolled SiC - 3 Cells
 - Control: 1-3 ohm-cm Czochralski - 3 Cells

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM SOC; STANDARD PROCESS

		SOC	CONTROL
V_{OC} (mV)	Average	547	589
	Standard Deviation	3.7	4
	Range	541-553	581-592
J_{SC} (mA/cm ²)	Average	24.1	33.8
	Standard Deviation	1.4	0.8
	Range	22-26.3	32.4-34.8
CFF (%)	Average	60	72
	Standard Deviation	6	3
	Range	52-69	67-77
η (%)	Average	5.9	10.6
	Standard Deviation	0.6	0.5
	Range	5.1-6.8	10-11.3

NOTE: 1. Measured Under AMO Condition.

2. SOC Solar Cells:

Average Cell Size: 15.1 cm²

Number of Cells Evaluated: 7

Active Area: 80-85%

AR Coating: SiO

PROBLEM AREAS RELATED TO PROCESS AND PERFORMANCE

SHEETS	PROCESS	CELL PERFORMANCE
EFG (RF AND RH)	Metallization & Measurement; Non-Flat and Non-Uniform Thickness	Shunting (Low Fill Factor); Surface Inclusion (SiC)
RTR	Metallization & Measurement; Wavy Surface	Low Lifetime Low Fill Factor
DENDRITIC WEB	Removal of Surface Deposit (SiO) Handling; Fragile (Thin Web)	No Major Problem
SILSO (WACKER) WAFER	No Major Problem	Shunting; Inclusion
CAST SILICON BY HEM	No Major Problem	Shunting; Microcrack
SOC	Metallization & Measurement; Warping and Back Slot	Shunting; Surface Inclusion Series Resistance; Small Area Back Slot Contact (?)

CONCLUSION

- o Back up measurements confirm the solar cell performance (efficiency) and minority carrier diffusion length will be the ultimate limiting factor.
- o Inclusion caused shunting problem.
- o Non-flat and non-uniform surface introduced process and measurement problems.
- o Need close interaction between cell processor and sheet producer.

SPECTROLAB

SOLAR CELL FABRICATION

CONTROL FLOW CHART

CURRENT - VOLTAGE CURVE WACKER SILSO AND CONTROL CELL

SOLAR CELLS, WACKER SILSO, SINGLE SHEET

9.0 1 .73	2	3	9.0 4 .73	5
8.8 6 .70	9.8 7 .74	9.8 8 .75	9	10
9.0 11 .73	10.0 12 .74	10.0 13 .75	9.9 14 .75	15
9.0 16 .74	9.4 17 .74	10.0 18 .75	9.6 19 .74	20
8.5 21 .74	9.0 22 .72	9.0 23 .75	24	7.6 25 .73

	η %	$\bar{V}_{OC}$	$\bar{I}_{SC}$
ZONE 1	8.7%	539 mV	120 mA
ZONE 2	9.3	549	129
ZONE 3	10.0	554	131
ALL	9.3	544	125

☐	CONVERSION EFFICIENCY
☐	LOCATION
☐	CURVE FILL FACTOR

SOLAR CELLS, WACKER SILSO

BASELINE PROCESS					
	N	I_{sc} mA	V_{oc} mV	FF	η %
POLY	4	133	554	.76	10.4
CONTROL	8	142	597	.78	12.2
POLY	23	130	546	.74	9.7
CONTROL	7	139	598	.75	11.6
POLY	16	123	546	.74	9.2
CONTROL	5	133	599	.76	11.2
POLY	16	125	545	.74	9.4
CONTROL	8	137	595	.73	11.2
POLY	59	127	546	.74	9.5
CONTROL	20	139	598	.76	11.6

EFG SOLAR CELLS – 1" X 1"

PRELIMINARY

S/N	I_{sc}	V_{oc}	CFF	η
3	177	535	.57	6.2
6	159	529	.64	6.1
7	174	539	.69	7.4
8	154	534	.48	4.6
9	159	535	.66	6.4
13	179	541	.59	6.4
15	174	528	.65	6.3

I-V DATA MEASURED AT AMO, 28°C

CURRENT – VOLTAGE WEB MATERIAL 2 CM X 2 CM

(VERY PRELIMINARY)

S/N	V _{OC} mV	I _{SC} mA	CFF	%
B	494	131	.73	8.7
C	485	131	.72	8.4
D	475	132	.72	8.3
E	490	132	.71	8.4
F	514	144	.71	9.7
H	501	131	.72	8.8
J	513	129	.72	8.8
CONT.	601	141	.76	11.9

~ AMO, 25°C

ARCO SOLAR

VACUUM DIE CASTING

The vacuum die casting program is a joint effort between ARCO Solar and SRI International to cast thin sheet silicon and fabricate that material into 12% efficient solar cells. The program was just funded two weeks ago.

In the casting process liquid silicon is forced by argon or another inert gas to enter an evacuated die consisting of rigid parallel flat plates forming slots sandwiched between the plates.

SILICON-ON-CERAMIC PROCESS

HONEYWELL MATERIAL SCIENCES CENTER

1979 GOALS

- DETERMINE MAXIMUM DIP-COATING GROWTH SPEED
- DEMONSTRATE 11% SOC SOLAR CELLS

STATUS

- 10.1% ON 4CM²
 - 9.2% ON 10CM²
 - THICK DENDRITIC GROWTH AT .2-.3 CM/SEC.
- @ 0.06 CM/SEC.

INVESTIGATORS:

D. ZOOK, B. GRUNG, D. HEAPS, S. SCHULTZ, B. KOEPKE

Cross-Section View of SOC Growth. The meniscus shape is based on hydrostatic equilibrium. Radiative background temperatures T_0 and T_1 are seen above and below the liquid - solid interface, respectively.

MENISCUS INSTABILITY

- TEMPERATURE DEPENDENT SURFACE TENSION
- GRAVITATIONAL EFFECTS

COATER MODIFICATIONS

- INCLINED SUBSTRATE
- TOP COATING

DIP-COATING PROGRESS

- PRODUCTION YIELD IMPROVED
 - UP TO 85% IN RECENT RUNS
- COOLING SHOES WITH X-Y MOTION
IN EXPERIMENTAL SYSTEM

CHARACTERISTICS OF RECENT SOC CELLS

		TOTAL-AREA				
	CELL NUMBER	I _{sc} (mA)	V _{oc} (V)	FILL FACTOR	J _{sc} 2 (mA/cm ²)	EFF (%)
1	148 -16-102-0	64.60	.53	.65	15.8	5.4
	148 -16-102-1	88.50	.54	.69	21.7	8.1(AR)
2	148 -16-201-0	66.50	.54	.72	16.3	6.4
	148 -16-201-1	89.60	.54	.65	22.0	7.7(AR)
3	150 -14-102-0	70.60	.54	.74	17.3	6.9
	150 -14-102-1	88.80	.55	.75	21.8	9.0(AR)
4	156 -06-103-0 } (10 cm ²)	163.00	.54	.74	16.3	6.6
	156 -06-103-1	236.00	.54	.72	23.6	9.2(AR)
5	160 -02-102-0	73.00	.55	.74	17.9	7.3
	160 -02-102-1	102.20	.56	.72	25.1	10.1(AR)
6	160 -02-201-0	68.00	.54	.72	16.7	6.5
	160 -02-201-1	98.00	.55	.71	24.0	9.4(AR)
7	160 -05-102-0	68.20	.54	.74	16.7	6.7
	160 -05-102-1	95.70	.55	.71	23.5	9.2(AR)
8	160 -05-201-0	68.00	.54	.72	16.7	6.5
	160 -05-201-1	96.70	.55	.70	23.7	9.1(AR)
9	160 -09-103-0 } (10 cm ²)	164.90	.54	.70	16.9	6.3
	160 -09-103-1	224.00	.55	.71	23.0	8.9(AR)
10	164 -01-103-0 } (10 cm ²)	174.30	.55	.69	17.4	6.6
	164 -01-103-1	244.00	.55	.68	24.4	9.1(AR)
11	165 -01-101-0	69.00	.52	.62	16.9	5.4
12	165 -01-202-0	69.70	.53	.61	17.1	5.5
13	165 -14-103-0 } (10 cm ²)	162.10	.53	.63	16.2	5.4
14	168 -08-101-0	71.10	.54	.69	17.4	6.5
15	168 -08-202-0	67.00	.52	.61	16.4	5.2
16	Q62A -00-102-0	85.60	.55	.75	21.0	8.7
	Q62A -00-102-1	123.70	.54	.70	30.3	11.6(AR)
17	Q62A -00-201-0	87.20	.55	.76	21.4	9.0
	Q62A -00-201-1	123.60	.56	.70	30.3	11.9(AR)
18	Q62B -00-102-0	89.30	.55	.76	21.9	9.2
	Q62B -00-102-1	123.80	.55	.73	30.3	12.3(AR)
19	Q64A -00-102-0	89.60	.57	.68	22.0	8.5
20	Q64B -00-103-0	214.00	.57	.63	21.4	7.7
21	Q69A -00-101-0	88.70	.56	.76	21.7	9.2
22	Q69A -00-202-0	87.80	.56	.75	21.5	9.0

Single
Crystal
Cells

SLOTTED SOC CELL

(# 160-2-102-1, 2/16/79)
 TOTAL AREA = 4.08 cm²
 METAL COVERAGE = 10%

SUMMARY OF PROGRESS

THERMAL ANALYSIS	- EFFECT OF CERAMIC ON GROWTH - SHAPE OF LIQUID-SOLID INTERFACE - THICKNESS VS. VELOCITY TRADE-OFF
CONTINUOUS COATING	- GOOD STRUCTURE - MENISCUS INSTABILITY PROBLEM - PROPOSED SOLUTIONS
DIP-COATING	- INCREASED YIELD - UP TO 85% - COOLING SHOES IN EXPERIMENTAL DIPPER
MATERIAL EVALUATION	- $L_H = 25-50\mu m$ - AVG. WITHIN GRAINS - SCATTERED LASER LIGHT COUNTS GB
CELL PERFORMANCE	- REPRODUCIBLE RESULTS: LOW VARIABILITY - NEW JPL STANDARD CELL - 10.1% ON 4 cm² - 9.2% ON 10 cm²

MTSEC (EFG)

Solar Cell Data for Ribbon Material Grown from
Kun-18-103. Cells are $2.5 \times 7.5 \text{ cm}^2$, cut across
the ribbon width.

100 mW/cm², ELH light, 28°C, AR coated

Cell No.	I_{sc} (mA/cm ²)	V_{oc} (V)	FF	P (mW/cm ²)
1031	25.78	0.539	0.663	9.22
1032	25.30	0.544	0.668	9.20
1033	24.45	0.532	0.672	8.74
1034	24.89	0.535	0.656	8.73
1035	24.50	0.532	0.670	8.73
1036	24.88	0.541	0.671	9.03
1037	25.13	0.538	0.636	8.60
1038	26.64	0.546	0.653	9.50
1039	26.57	0.550	0.685	10.02
10310	24.66	0.544	0.697	9.36
Mean Value	25.28	0.540	0.667	9.11
Standard Error	0.254	0.0019	0.0054	0.132

1. LOW MENISCUS SIDE HAS USUAL SiC PARTICLE DENSITY 1 - 10 PARTICLES 1 CM².
2. HIGH MENISCUS SIDE IS VIRTUALLY CLEAR OF SiC PARTICLES AND EXCEPTIONALLY SMOOTH.
3. GROWTH STABILITY EXCELLENT FOR 0.005" DISPLACEMENT ON 0.020" TOP SLOT FOR SPEEDS 2 - 3.5 CM/MIN.
4. HIGHER SPEEDS, GREATER DISPLACEMENTS ALLOW NARROW RIBBON GROWTH ONLY.

PERFORMANCE OF SELECTED SOLAR CELLS FROM RIBBON GROWN IN MACHINES 12 AND 13. GROWN AT 2.5 CM/MIN, 2.5 CM WIDE, RF HEATING.

AREA (CM ²)	V _{OC} (MV)	I _{SC} (MA/CM ²)	FF	η (%)
4.20	564	29.8	.730	13.0
4.26	567	29.1	.737	12.9
4.06	580	29.6	.774	14.1
4.25	574	29.9	.742	13.5
4.13	562	30.0	.736	13.6

LIGHT INTENSITY 94.5 MW/CM². CALIBRATION BASED ON JPL, TERRESTRIAL SECONDARY STANDARD 004.

PERFORMANCE OF SELECTED SOLAR CELLS MADE FROM RIBBON
GROWN IN MACHINE #1. GROWN AT 3.5 CM/MIN, 7.5 CM
WIDE, RESISTANCE HEATING.

AREA (CM ²)	V _{OC} (mV)	I _{SC} (mA/CM ²)	FF	n (%)
4.76	553	27.1	.714	11.3
4.86	553	26.3	.761	11.7
7.23	547	25.2	.751	11.0
10.29	550	25.8	.749	11.2
10.92	552	24.8	.754	10.9

LIGHT INTENSITY 94.5 MW/CM². CALIBRATION BASED ON JPL, TERRESTRIAL SECONDARY STANDARD 004.

DISTANCE ACROSS RIBBON WIDTH (cm) →

Spreading resistance data from displaced die run 18-90. Traces are taken on a beveled surface within the cross-section of the ribbon at locations indicated in Fig. 7. The traces go from the low meniscus surface on the left to the high meniscus surface on the right.

MOTOROLA, INC.

PROGRESS HIGHLIGHTS

PROGRESS HAS BEEN DEMONSTRATED ON ALL ASPECTS OF THE RTR DEVELOPMENT EFFORT:

CELL EFFICIENCY

- CELLS FABRICATED ON RTR SUBSTRATES GROWN FROM CVD FEEDSTOCK HAVE DEMONSTRATED AN AVERAGE EFFICIENCY OF OVER 9% WITH A 'BEST' CELL EFFICIENCY OF 11.3%.

POLYRIBBON FORMATION

- SEQUENTIAL SEPARATION OF LARGE (2" x 24") POLYRIBBON SUBSTRATES HAS BEEN ACHIEVED IN A SEMI-CONTINUOUS MANNER, WITH A TOTAL OF ALMOST 10' IN A SINGLE RUN.

RTR GROWTH

- AN ALTERNATIVE GROWTH MODE HAS BEEN DEMONSTRATED WHICH WILL ALLOW MATERIAL-EFFICIENT RTR GROWTH UTILIZING SHORT SUBSTRATES, THUS ELIMINATING THE NEED FOR NEAR-CONTINUOUS SHEETS OF POLYSILICON FEEDSTOCK.

EFFICIENCY AND CONTAMINATION PROBLEMS

CELL EFFICIENCY IMPROVEMENTS

- CELL EFFICIENCY IMPROVEMENTS FROM $\eta \leq 6\%$ TO $\eta \geq 9\%$ ATTRIBUTED TO:
- ETCH REMOVAL OF Mo CONTAMINATED SURFACE ($\sim 15 \mu\text{m}$ REMOVED).
 - EFFECTIVE GETTERING OCCURRING DURING PH_3 DIFFUSION.
 - GROWTH WITHOUT A FURNACE.

PURGEABLE FURNACE EXPERIMENTS

GROWTH EXPERIMENTS WITH PURGEABLE FURNACE HAVE NOT GIVEN REPEATABLE RESULTS. GOOD QUALITY RIBBONS HAVE BEEN GROWN, BUT NOT CONSISTENT.

- Pt ELIMINATED FROM VICINITY OF MELT.
- STRAY BEAM VAPORIZATION DOES NOT APPEAR TO BE A PROBLEM IN THESE EXPERIMENTS.

CVD SOLAR CELLS

η	L	VOC	JSC	FF	RIBBON #	LOT #	COMMENTS
*			26.5 *		967J-1	6113	SHADING METAL FILM ON FRONT
*			26.3 *		967J-2	6113	" " "
		.515	26.2		967P-1	6114	BROKEN; BAD METAL
9.4		.52	27.	67	967P-2	6114	
6.8		.50	24.8		967P-3	6114	
8.9		.522	27.8	62	967U-2	6114	
8.9		.52	26.8	64	967U-3	6114	
10.1*		.517	28. *	70	967R-1	6114	
11.3*		.533	29.4 *	72	967R-2	6114	
10.7*		.53	27.8 *	72	967R-3	6114	
8.5*		.51	26.3 *	63	967O-2	6114	
7.0*		.486	21. *	69	967O-3	6114	
9.07% AVG.			26.54 AVG.				

PURGED FURNACE DESIGN

POLYRIBBON FORMATION

- PROBLEMS WITH END SEALS HAVE BEEN RESOLVED.
- GOOD QUALITY SILICON DEPOSITS ARE OBTAINED BUT DO NOT ALWAYS SEPARATE.
- TEMPERATURE AND TEMPERATURE GRADIENT CONTROL APPEAR CRUCIAL. HIGH YIELD IN BATCH OPERATION HAS NOT CARRIED OVER TO SEMI-CONTINUOUS MODE.
- SUCCESSFUL DEPOSITION AND SEPARATION HAS BEEN DEMONSTRATED IN A SEMI-CONTINUOUS MANNER BUT CONDITIONS NEED TO BE OPTIMIZED.

MULTILAYER SUBSTRATES

- Si_3N_4 COATED Mo SUBSTRATES PROVIDE GOOD NUCLEATION AND RESULT IN POLYRIBBON FEEDSTOCK WITH AN ORDER-OF-MAGNITUDE REDUCTION IN Mo CONTENT AS MEASURED BY NEUTRON ACTIVATION ANALYSIS.
- OXIDE COATED Mo SUBSTRATES PROVIDE GOOD ISOLATION BETWEEN Si AND Mo SUBSTRATE BUT NUCLEATION IS POOR, AND SEPARATION WILL NOT OCCUR. ADDITION OF A THIN (5000Å) COATING OF Mo PROVIDES GOOD NUCLEATION, GOOD SEPARATION, AND GOOD ISOLATION.

HIGH THROUGHPUT RTR GROWTH

- MULTIPLE RIBBON GROWTH HAS ALREADY BEEN DEMONSTRATED BY GROWTH OF 4 RIBBONS SIMULTANEOUSLY. AREA GROWTH RATE IS LIMITED BY FURNACE ZONE WIDTH.
- FABRICATION IS NEARLY COMPLETE ON A FURNACE WHICH WILL ALLOW 15 CM WIDE GROWTH (TWO 7.5 CM OR THREE 5 CM WIDE RIBBONS). AN AREA GROWTH RATE OF $100 \text{ cm}^2/\text{MIN}$ SHOULD BE ATTAINABLE.

RTR GROWTH

A TECHNIQUE HAS BEEN DEMONSTRATED WHICH ALLOWS USE OF SHORT SUBSTRATES FOR RTR GROWTH. THIS TECHNIQUE, BASED ON RIGID EDGE RTR GROWTH, WILL:

- ALLOW MATERIAL EFFICIENCIES IN EXCESS OF 90% EVEN IN A 5 CM X 25 CM SAMPLE SIZE.
- RELAX REQUIREMENTS ON POLYRIBBON FORMATION.
- REDUCE THE IMPACT OF POLYRIBBON BREAKAGE DURING RTR GROWTH.

PROGRAM PLANS

1. CONTINUE EFFORTS TO RESOLVE FURNACE CONTAMINATION PROBLEM.
2. PERFORM HIGH AREA GROWTH RATE EXPERIMENTS WITH NEW FURNACE.
3. COMPLETE FABRICATION OF LARGE AREA CELLS.

WESTINGHOUSE (WEB)

SILICON WEB

TECHNOLOGY STATUS

AREA THROUGHPUT	MAXIMUM DEMONSTRATED 19.8 CM ² /MIN
MELT REPLENISHMENT	POLYSILICON FED SIMULTANEOUSLY WITH GROWTH OF HIGH QUALITY WEB
CELL EFFICIENCY	AVERAGE ~ 13% AM1 MAXIMUM 15.5% AM1

Curve 713010-A

SILICON WEB

PROGRESS ATTAINED DURING PHASE II

	START	PRESENT
<u>DEMONSTRATED AREA THROUGHPUT RATE</u>	8 cm ² /MIN	19.8 cm ² /MIN
<u>MELT REPLENISHMENT</u>	FEASIBILITY SHOWN	SIMULTANEOUS MELT REPLENISHMENT AND GROWTH OF HIGH QUALITY WEB.
<u>CELL EFFICIENCY</u>	AVERAGE ~ 12% AM1 MAXIMUM 14.5% AM1	AVERAGE ~ 13% AM1 MAXIMUM 15.5% AM1

REGIONS OF THERMALLY GENERATED STRESS

RELATIONSHIP BETWEEN ETCH PIT (DISLOCATION) DENSITY AND RESIDUAL STRESS

R. Seidensticker
c. m. - l. r. 2-15-79

COLD AFTERTRIMMER FOR CONTROL OF THERMALLY GENERATED STRESS

RECENT THROUGHPUT RESULTS

RUN NO.	THROUGHPUT RATE cm ² /min	WIDTH mm	GROWTH VELOCITY cm/min
J-95	12.3	23.0	5.35
J-123	11.4 8.8	22.4 30.8	5.1 2.9
J-125	14.7	25.0	5.9
J-126	12.2	14.7	8.3
RE-98	11.2 12.7	26.2 25.5	4.3 5.0
J-129	12.3	24.2	5.1
RE-99	12.7 14.8	23.2 27.9	5.5 5.3
RE-100	12.8	21.3	6.0
J-131	12.7 13.7 14.3 12.3	26.5 29.3 26.0 24.2	4.8 4.7 5.5 5.1
RE-101	10.4	27.5	3.8
RE-102	11.9 13.4	23.9 26.7	5.0 5.0
J-133	15.7 13.9	29.1 32.3	5.4 4.3
J-135	12.2	24.0	5.1
RE-105	19.8	33.0	6.0
RE-107	15.1	35.5	4.25
RE-108	16.4	31.6	5.2
RE-113	14.3	30.4	4.7

SILICON WEB

CONTINUOUS MELT REPLENISHMENT IS A CRITICAL REQUIREMENT

- PROVIDES LONG PERIODS OF UNINTERRUPTED GROWTH.
- PROVIDES SUSTAINED GROWTH AT MINIMUM THERMAL STRESS -- PERMITS INCREASED WIDTH.
- PROVIDES SUSTAINED GROWTH AT MAXIMUM SPEED.

SIMPLIFIED SCHEMATIC OF MECHANIZED MELT REPLENISHMENT SYSTEM

WEBQUAL 20 = DATA SUMMARY

A = 1.039 cm², AM1 @ 91.6 mW/cm²

CRYSTAL	NO. CELLS	I _{SC} mA	V _{OC} VOLT	FF	η ₀ %	η _{AR} %	τ _{OC} μsec	NOTES
RE12-3.2	4	22.18	.548	.737	9.47	13.5	11.4	STD.
RE102-2.2	4	20.18	.520	.734	8.15	11.7	3.8	
J131-2.2	4	20.98	.537	.746	8.88	12.7	6.3	
J131-3.4	4	19.40	.513	.733	7.73	11.1	2.8	
J134-2.2	4	21.70	.536	.749	9.21	13.2	6.7	
W141-1.2	4	21.90	.569	.738	9.73	13.9	6.3	
W151-1.2	4	22.18	.543	.738	9.35	13.4	8.6	FEED EXPT.
W154-1.4	4	21.58	.542	.722	8.92	12.8	7.5	FEED EXPT.
W154-2.3	4	21.35	.531	.734	8.79	12.6	5.4	FEED EXPT.

SOLAR PANEL MADE WITH SILICON WEB SOLAR CELLS

SILICON WEB

MAJOR TECHNICAL REQUIREMENTS FOR 1986 GOAL
HAVE NOW BEEN DEMONSTRATED.

- $\sim 20 \text{ cm}^2/\text{MINUTE}$ WEB THROUGHPUT RATE.
- SIMULTANEOUS MELT REPLENISHMENT WITH
WEB GROWTH OF HIGH QUALITY (η WITH
REPLENISHMENT = η W/O REPLENISHMENT).
- CELL EFFICIENCY $\geq 15\%$ AM1.

NECESSARY DEVELOPMENTS TO REACH 1986 SHEET GOALS

- SUSTAINED MELT REPLENISHED HIGH
THROUGHPUT GROWTH (TO $25 \text{ cm}^2/\text{MIN}$).
- MEAN CELL EFFICIENCY $\geq 15\%$.
- AUTOMATED GROWTH.

c. Encapsulation Task

OBJECTIVES:

1. DEFINE, DEVELOP, DEMONSTRATE ENCAPSULATION SYSTEMS, MATERIALS, AND PROCESSES TO MEET THE LSA PROJECT LIFE, COST, AND PERFORMANCE GOALS
2. DEVELOP AND VALIDATE A MODULE LIFE PREDICTION METHODOLOGY BASED ON MODELING LIFE-LIMITING FAILURE MODES AND ON CONDUCTING AND ANALYZING ACCELERATED AGING TESTS

1982 TECHNOLOGY READINESS

1. NARROW LIST OF CANDIDATE ENCAPSULATION SYSTEMS, MATERIALS, AND PROCESSES CAPABLE OF MEETING 1986 COST AND PERFORMANCE GOALS
2. DOCUMENTED CHARACTERIZATION OF ABOVE LIST RELATIVE TO PHYSICAL PROPERTIES, PROCESSING METHODS, MODULE PERFORMANCE, AND LONG-TERM DEGRADATION MECHANISMS AND RATES
3. TECHNOLOGY TRANSFER TO INDUSTRY VIA REPORTS, PIMS, AND DIRECT PARTICIPATION IN DESIGN, ANALYSES, AND TESTING

FLAT-PLATE PHOTOVOLTAIC ENCAPSULATION SYSTEM DESIGN

SUPERSTRATE BONDED

SUBSTRATE BONDED

LAMINATED

**COST COMPARISON FOR SUPERSTRATE AND SUBSTRATE MATERIALS
(APPROXIMATELY 1978 DOLLARS)**

<u>Materials</u>	<u>Bulk Cost \$/kg</u>	<u>Panel Thickness cm</u>	<u>Panel Cost \$/m²</u>
<u>Transparent Superstrates</u>			
Soda Lime Glass	0.51	0.25	3.15
Low-iron Tempered Glass	---	0.32	7.50
Borosilicate Glass	---	0.32	5.00-15.00
Acrylic (PMMA)	3.12	0.80	19.00
Polycarbonate	4.00	0.80	37.00
<u>Structural Substrates</u>			
Epoxy/Fiberglass	6.17	0.35	44.00
Kraft paper honeycomb	---	2.5	1.00
Plywood	---	0.54	1.64
Hardboard	---	0.58	1.44
Mild Steel	0.34	0.17	4.53
Aluminum	1.88	0.25	12.44
Stainless Steel	2.50	0.17	34.00
Glass Reinforced Concrete	0.18	0.64	3.00

**COST COMPARISON FOR TRANSPARENT POTTANT MATERIALS
(APPROXIMATELY 1978 DOLLARS)**

Material Candidate	Bulk Cost \$/kg	Module Cost (cents/m ² per 0.025mm thickness)
<u>Weatherable</u>		
Acrylics	3.30	10.7
Silicone gels	8.25	21.5
Silicone elastomers	19.80	53.8
Fluorocarbons and Halocarbons	14.85 tn >44.00	>53.8
<u>Requires UV protection</u>		
Ethylene propylene rubber	1.10	2.4
Ethylene vinyl acetate	1.10	2.6
Polyvinyl chloride plastisol	1.32	4.0
Polyvinyl Butyral	---	12.3

BATTELLE MEMORIAL INSTITUTE

SUMMARY OF MODULE R_s MEASUREMENTS: R_s IN OHMS

Module	W/R Method	F/B Slope (dark)	Two-Diode Model (dark)
ST 1506	0.74	≥ 0.77	0.66
ST 1914	1.40	≥ 0.83	0.70
ST 1952	≈ 0.3	≥ 0.75	0.87
ST 1986(a)	0.38	≥ 0.90	0.53
SLX 2355	2.06 ^(b)	≥ 0.60	
SLX 3149	1.75	≥ 0.64	
SLX 3170	2.77	≥ 0.60	
SLX 3856	2.46	≥ 0.63	

a. No field exposure

b. Non-uniform illumination effects to some degree

MBASSOCIATES

PHYSICAL PROPERTIES GLASS FIBER REINFORCED CONCRETE

Ultimate flexural strength	3,000 - 4,500 psi
Ultimate tensile strength	1,000 - 1,600 psi
Compressive strength	7,000 - 12,000 psi
Impact strength (Charpy)	70-140 inch - lbs./in ²
Youngs Modulus	1.5×10^6 psi - 3×10^6 psi
Density	105 lbs./ft. ³ - 130 lbs./ft. ³
Modulus of Rupture	3,000 - 4,600 psi
Thermal Conductivity	7.0 BTU in/ft ² Hr ° F.
Coefficient of Thermal Expansion	6×10^{-6} - $9 \times 10^{-6}/^{\circ}F$

A POSSIBLE FIELD ARRAY CONCEPT INDICATING
POSTS AND BRACKETS SUPPORTS

SPIRE

INTEGRAL GLASS ENCAPSULATION FOR SOLAR ARRAYS PHASE III PROGRAM OBJECTIVES

- LOW LEVEL PRODUCTION OF STANDARD ESB MODULES
 - DEMONSTRATE PRODUCTION RATE AND YIELD OF ESB MODULES
 - INSURE READINESS FOR PROCESS SCALE UP
- INCORPORATION OF ESB MODULES INTO JPL MINIMODULES CONFIGURATION
- DEVELOPMENT AND PRODUCTION OF ADVANCED MODULES
 - PREFORMED WIRE MESH CONTACTS
 - HIGH EFFICIENCY CELLS
- DEVELOP ENGINEERING CONCEPTS FOR LARGE AREA BONDER

SPRINGBORN LABORATORIES

ETHYLENE – VINYL ACETATE COPOLYMER SURVEY

EVA Compound	Total Integrated Transmission (Visible) T%	Average (g/10 min) Equivalent Melt Index	Cost (\$/lb.)
EY 901-25	86	7.5	\$0.64
UE 654-35	84	48.0	\$0.645
UE 638-35	86	24.0	\$0.635
UE 646-04	85	25.0	\$0.615
Elvax 150 ^(a)	91	43	\$0.575
Elvax 240	89	43	\$0.545
Elvax 250	91	25	\$0.545
Elvax 260	86	6	\$0.545
Elvax 420	82	151	\$0.545
Elvax 350	87	19	\$0.505
Elvax 4260 ^(b)	87	6.0	\$0.675
Elvax 4320 ^(b)	91	150	\$0.635
Elvax 4355 ^(b)	91	6.0	\$0.665

(a) Presently used compound.

(b) Acid Terpolymer.

CURRENT EVA PIGMENTED FORMULATION⁽¹⁾

<u>MATERIAL</u>	<u>DESCRIPTION</u>	<u>PARTS</u>
ELVAX 150		100.0
LUPERSOL 101	- †	1.5
KADOX 15	ZINC OXIDE	4.0
TITANOX RF-3	TITANIUM DIOXIDE	1.5
FERRO AM-105	UV ABSORBER	0.25

(1) 8320B

EVA REFORMULATION

ELIMINATION OF SR-350 CROSSLINKING AGENT

ADVANTAGES:

- . BETTER CURE - HIGHER GEL CONTENT
- . ELIMINATION OF A VOLATILE COMPONENT
- . COST REDUCTION IN TOTAL FORMULATION
- . ONE LESS VARIABLE

DISADVANTAGES:

- . HIGHER EXTRUSION TEMPERATURES DEVELOPED
- . POOR PIGMENT DISPERSION IN WHITE COMPOUND

PIGMENT DISPERSION MAY BE SOLVED BY PRECOMPOUNDING SMALL VOLUMES OF RESIN WITH HIGH PIGMENT LOADINGS AND BLENDING PRIOR TO EXTRUSION.

VACUUM BAG PROCESS

1. ASSEMBLE MATERIALS AND SEAL EDGES.
2. PLACE MATERIAL ASSEMBLY BETWEEN PLATE-AND-FRAME/DIAPHRAGM.
3. PLACE FRAME/DIAPHRAGM ON SUPPORT PLATE.
4. APPLY VACUUM: REMOVE AIR AND COMPRESS ASSEMBLY.
5. POSITION VACUUM BAG BETWEEN HEATED PLATENS OF HYDRAULIC PRESS.
6. CURE FOR 20 MINUTES, ABOVE 140°C.

KORAD 201R UV STABILIZED ACRYLIC OUTER COVER

Tensile strength, psi	4400
Yield strength, psi	4200
Elongation, %	130
Light transmission, %	92
Haze, %	1.3
Gloss at 60°	92
Glass transition (T _g)	88°C

SCRIM MATERIAL SURVEY

Manufacturer	Cell Size (Mils x Mils)	Scrim Thickness (Mil)	Cost \$/ft ²
Burlington Glass Fabrics (Glass Fiber)	50 x 100	5	\$.038
	33 x 63	4.5	\$.027
	50 x 50	4	\$.017
	33 x 71	6.2	\$.025
	50 x 100	4	\$.013
	50 x 100	4.7	\$.014
Bay Mills (Bayex) (Polyester)	500 x 1000	~10	\$.005
	125 x 125	~10	\$.022
	2000 x 1000	~6	\$.003
Apex Mills Corp. (Nylon)	50 x 50	~5	\$.028
	125 x 125	~12	\$.042
	63 x 63	~8	\$.041
	438 x 438	~14	\$.047
	34 x 34	~5	\$.04

MODULE NUMBER 5 SUBSTRATE DESIGN – SUPER DORLUX

MATERIAL ASSEMBLY

- .. KORAD 201-R OUTER COVER
- . CLEAR EVA POTTANT
- . SOLAR CELLS (FACE UP)
- . SCRIM SPACER
- . WHITE EVA
- . SUPER DORLUX SUBSTRATE
- . WHITE EVA
- .. GLASS FIBER CLOTH-HEAT RADIATION

CORROSION TESTING

	SALT SPRAY 24 HRS	SALT SPRAY 450 HRS	HIGH HUMIDITY 450 HRS
<u>COMPLETELY ENCAPSULATED</u>			
ALUMINUM-EVA			
COPPER - EVA			
GALVANIZED - EVA		UNAFFECTED	
CELL - EVA			
<u>WITH EDGE EXPOSED</u>			
ALUMINUM - EVA		C	
COPPER - EVA		C	
GALVANIZED - EVA	C	C	
<u>CONTROLS</u>			
ALUMINUM		C	
COPPER	C	C	
GALVANIZED	C	C	
CELL		C	

ABRASION (AND DIRT?) RESISTANT COATINGS

	<u>COST</u> <u>¢/FT (2)</u>	<u>MATERIAL</u> <u>COMMERCIALY</u> <u>AVAILABLE</u>
<u>SILICATES</u>		
DOW CORNING		YES
GENERAL ELECTRIC	9 (0.2 MILS) (1)	YES
E. I. DUPONT		NO
BERG INDUSTRIES		YES
AMERICAN OPTICAL		NO
3M		NO
OWENS ILLINOIS	2.3 (0.3 MILS)	YES
ROHM & HAAS		NO & YES
<u>URETHANES</u>		
DEXTER MIDLAND		YES
HUGHSON	4.8	YES
BEE CHEMICAL	3.5 (MIL)	YES
<u>ACRYLIC</u>		
BEE CHEMICAL	2.26 (MIL)	YES
<u>ORGANIC</u>		
ROHM & HAAS		YES
<u>FLUOROCARBON FILM</u>		
DUPONT (TEDLAR)	9 (MIL) (2)	YES
PENNWALT (KYNAR)		YES

(1) INCLUDES PRIMER AND UV ABSORBER

(2) TEDLAR UT

**ADHESION TESTING
SODA - LIME GLASS
AVERAGE BOND STRENGTH (PSI)**

SIDE A IS AIR SIDE
SIDE B IS TIN SIDE OF FLOAT GLASS

		<u>CONTROL</u>	<u>2 HOURS BOILING WATER</u>	<u>24 HOURS BOILING WATER</u>
EVA	SIDE A	2	-	-
	SIDE B	4	-	-
EVA, SS4179 PRIMER	SIDE A	21 (c)	2.2	13
	SIDE B	18 (c)	2.5	-
*EVA, A8330B PRIMER	SIDE A	22 (c)	30 (c)	17 (c)
	SIDE B	20 (c)	25 (c)	9.6
EVA, SS 4179 PRIMER BLENDED INTO POLYMER				
	SIDE A	9.9	2.3	2.2
	SIDE B	30 (c)	25 (c)	10 (c)
EVA, A89212 PRIMER BLENDED INTO POLYMER				
	SIDE A	32 (c)	10	10
	SIDE B	23 (c)	30 (c)	11 (c)

*BEST PERFORMANCE FOUND IN THESE SPECIMENS

(c) COHESIVE FAILURE IN POLYMER

SS4179 - proprietary formula, General Electric Co.
A8330-B- hydrolyzed Dow Corning Z-6030 primer
A8921-2- mixture of 90% Z-6030 and 10% Z-6020

POTTANTS CHOSEN FOR FURTHER STUDY

<u>POTTANT</u>	<u>DEGREE OF:</u>	
	<u>COST</u>	<u>UV PRO- TECTION NEEDED</u>
ETHYLENE/VINYL ACETATE COPOLYMER (EVA)	LOW	HIGH
ETHYLENE/PROPYLENE ELASTOMER (EPR)	LOW	HIGH
POLYVINYL CHLORIDE PLASTISOL (PVC)	LOW	HIGH
ACRYLIC HOT MELT	MODER- ATE	LOWER
ALIPHATIC URETHANE	MODER- ATE	MEDIUM

DOW CORNING

ADHESION OF KRATON 1102 TO PRIMED GLASS

(PRESSED 1 MIN. AT 150°C)

<u>SILANE (10%) ADDED TO RESIN IN PRIMER</u>	<u>PICCOTEX LC</u>		<u>PICCO LTP-135</u>	
	<u>DRY</u>	<u>WET</u>	<u>DRY</u>	<u>WET</u>
NONE	1	—	1	—
$\text{CH}_2=\text{CHSi}(\text{OCH}_3)_3$	1	—	1	—
$\text{HSCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_2$	1	—	1	—
$\text{ClCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$	1	—	1	—
$\text{C}_6\text{H}_5\text{Si}(\text{OCH}_3)_3$	1	—	1	—
$(\text{CH}_3)_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$	1	—	2	1
$\text{CH}_3\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$	3	1	3	3
$\text{H}_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$	4	3	4	2
$\text{H}_2\text{NCH}_2\text{CH}_2\text{NH}(\text{CH}_2)_3\text{Si}(\text{OCH}_3)_3$	4	3	4	4

ORGANOFUNCTIONAL SILANE COUPLING AGENTS

ORGANOFUNCTIONAL GROUP	DOW CORNING PRODUCT	STRUCTURE OF ORGANOFUNCTIONAL GROUP
AMINE	LAB	$-\text{CH}_2\text{CH}_2\text{CH}_2\text{NH}_2$
DIAMINE	Z-6020	$-\text{CH}_2\text{CH}_2\text{CH}_2\text{NHCH}_2\text{CH}_2\text{NH}_2$
POLYAMINO	Z-6050	DOW POLYETHYLENEIMINE
EPOXY	Z-6040	$-(\text{CH}_2)_3\text{OCH}_2\overset{\text{O}}{\underset{\text{O}}{\text{C}}}\text{CH}_2-$
MERCAPTAN	Z-6062	$-\text{CH}_2\text{CH}_2\text{CH}_2\text{SH}$
CATIONIC STYRYL	QZ8-5069	$-\text{CH}_2\text{CH}_2\text{CH}_2\text{NH}-\text{CH}_2\text{CH}_2$ V.B. $\cdot\text{HCl}^1$
METHACRYLATE ESTER	LAB	$-\text{CH}_2\text{CH}_2\text{CH}_2$ M.A. ²
METHACRYLATE QUAT. ESTER	A-6031	$-(\text{CH}_2)_3\overset{\oplus}{\text{N}}(\text{CH}_3)_2-\text{CH}_2\text{CH}_2$ M.A. ² Cl^-
SATURATED QUAT. ALCOHOL	XZ8-5061	$-(\text{CH}_2)_3\overset{\oplus}{\text{N}}(\text{CH}_3)_2-\text{CH}_2\text{CH}_2\text{OH}$ Cl^-

¹ V.B. = VINYL BENZYL

² M.A. = METHACRYLATE

OUTDOOR VS ATLAS SUNSHINE CARBON ARC WEATHER-OMETER (WOM) STRESSING: EFFECTS ON PROPERTIES

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
1. DOW CORNING® 808 Resin	3-4 mil coating on aluminum panels	6 years Florida, 45° south	36% loss 60° gloss, no checking or dirt retention
		4,234 hours filtered WOM	33% loss 60° gloss, 7 check rating, no dirt retention
2. DOW CORNING® 901 Resin	6 mil coating on fine weave fiberglass	4 years Arizona, 45° south	99% of original 350-2400 NM transmission
		40 Langley's - Emmagua 3,524 hours filtered WOM	94% of original 350-2400 NM transmission Resin flaked off of substrate.
3. B66 Acrylic/DC® 840 Blend	3-4 mil coating on aluminum and steel panels	13 years Texas	Slight dirt retention, no loss gloss or checking
		7 years Florida, 45° south 3,750 hours filtered WOM	High corrosion protection 100% coating off. No measurement
4. DOW CORNING® 996 Resin	2 mil coating on aluminum panel	10 years Midland	No loss gloss, no color change, checking rating 6
		4,234 hours filtered WOM	69% loss 20° gloss (spots from water spray), 37% loss of 60° gloss, checking 2, no dirt retention.
5. LS 53 Rubber	1/8" thick strips-folded, stretched 20%, unstressed	20 years Florida	Slight dirt & mildew, no cracking or checking
		4,234 hours filtered WOM	No change

OUTDOOR VS ATLAS SUNSHINE CARBON ARC WEATHER-OMETER (WOM) STRESSING: EFFECTS ON PROPERTIES

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
6. RTV 132U Elastomer	1/8" thick strips-folded, stretched 20%, unstressed	20 years Florida	Some loss of tensile and Elongation, Same as LS 53
		4,234 hours filtered WOM	Slight trace dirt
7. RTV 501 Elastomer	1/8" thick strips-folded, stretched 20%, unstressed	16 years Florida	Slight dirt retention and mildew
		4,019 hours filtered WOM	No checking
8. 55U Silastic® Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight dirt retention and mildew
		4,234 hours filtered WOM	No change
9. Silastic® 675 Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight decrease in durometer, tensile and elongation, some surface cracking
		4,234 hours filtered WOM	No change
10. RIV /HI	6 mil coating on aluminum panel	20 years Wisconsin	Dirt pick up, slight lowering in durometer
Building Sealant	6 mil coating on aluminum panel	3,679 hours filtered WOM	No loss 20° gloss, some blisters

132U EXPOSED IN WOM (FILTERED III)

UV EXPOSURE	TENSILE	Δ	ELONGATION	Δ
0	517 PSI		580 %	
290 HR.	503 PSI	- 2.7%	540 %	- 6.9%
641 HR.	454 PSI	-12.2%	500 %	-13.8%
900 HR.	437 PSI	-15.5%	470 %	-19.0%
1200 HR.	485 PSI	- 6.2%	590 %	- 1.7%
1500 HR.	402 PSI	-22.2%	480 %	-17.2%
2000 HR.	475 PSI	- 8.1%	570 %	- 1.7%
2510 HR.	471 PSI	- 8.9%	570 %	- 1.7%
3009 HR.	438 PSI	-15.2%	520 %	-10.3%
3260 HR.	395 PSI	-23.6%	495 %	-14.6%
3481 HR.	461 PSI	-10.8%	560 %	- 3.4%
3786 HR.	362 PSI	-30.0%	450 %	-22.0%

PULL RATE 2"/MIN.

OUTDOOR EXPOSURE PANELS (DC 184)

SUBSTRATE DISPLAY MODULE

Twenty-four holes were countersunk to a depth of 15 mils in a 12" x 16" panel of tempered Masonite®* using a 2-1/8" drill bit. Grooves for interconnects were cut between the recessed openings. Holes were drilled and countersunk for the terminals. The front, back and edges of the panel were then sprayed with DOW CORNING® Q1-2577 Conformal Coating pigmented with 30% titanium dioxide and allowed to air dry.

The 24-cell circuit string was bonded to the panel with Q1-2577 and the leads soldered to two flathead bolts which serve as terminals.

The front of the panel and cells were then sprayed with a thin coating of clear Q1-2577 and the module allowed to air dry.

Cost of this mini-module (in 1978 dollars):

Super Dorlux® Masonite

Thickness - 0.125 inches (1/8") \$0.11/ft²

DOW CORNING® Q1-2577 Conformal Coating

Pigmented with TiO₂

Front and back .002 inches (2 mils). \$0.19/ft²

DOW CORNING® Q1-2577 Conformal Coating

Clear adhesive .002 inches (2 mils) \$0.09/ft²
(Assuming 100% cell coverage)

DOW CORNING® Q1-2577 Clear Conformal Coating

(4 mils). \$0.19/ft²

TOTAL \$0.58/ft²

*Tempered Masonite was used to simulate Super Dorlux®.

NEW ENCAPSULATION CONCEPT

This novel encapsulation concept was prepared in the following manner:

A flat surface is first covered with polyethylene coated paper which serves as a release coating.

A thin coating of DOW CORNING® Q1-2577 Conformal Coating is applied to the polyethylene coated paper and a 24-cell circuit string is placed front side up on this coating. A sheet of woven glass cloth is placed over the cells and additional Q1-2577 is flow coated over the glass cloth and the excess removed with a straight edge.

The resin is allowed to air dry and removed from the polyethylene release paper.

Alternatively, the 24-cell circuit string can be placed front side down and the woven glass cloth placed on the back of the cells.

Both of these concepts provide only encapsulation protection and additional superstrate or substrate mechanical support is required.

Cost:

Woven glass cloth	\$.03-.05/ft ²
DOW CORNING® Q1-2577 Conformal Coating	\$.05/mil/ft ²
10 mils =	\$.50/ft ²
TOTAL COST	<hr/> \$.55/ft ²

3. Production Process and Equipment Area

AUTOMATED PROCESSING EQUIPMENT CURRENT PERFORMANCE

<u>SPEAKER</u>	<u>COMPANY</u>	<u>SUBJECT</u>
W. KERN	RCA	SPRAY ANTIREFLECTION COATING
R. V. D'AIELLO	RCA	THICK FILM METALLIZATION
S. CHITRE	SENSOR TECH	LASER SCRIBER
S. CHITRE	SENSOR TECH	SPRAY-ON JUNCTION
R. D. CAMPDELL	WESTINGHOUSE	DIP ANTIREFLECTION COATING

PLANS

- HOLLOW-CATHODE PARAMETRIC STUDY
 - NEW CATHODES ARRIVING SOON
- RETROFIT SPIRE-LIKE SOURCE WITH HOLLOW CATHODE
- NON-MASS-ANALYZED IMPLANT WITH SOLID SOURCE

CALTECH & JPL IN-HOUSE

- CALTECH STUDY: EFFECTS OF NON-MASS-ANALYZED ION IMPLANTATION (SOLID PHOSPHORUS SOURCE)
 - MOLECULAR PHOSPHORUS (P_4 , P_3 , P_2)
 - IMPURITIES (O, N, H, ETC)
- JPL IN-HOUSE
 - HOLLOW-CATHODE TESTING
 - SOLID PHOSPHORUS SOURCE DEVELOPMENT
- FUTURE WORK

JPL IN-HOUSE

- HOLLOW-CATHODE TEST SET-UP IN OPERATION
 - TEST FLOW CHARACTERISTICS
 - OPTIMIZE DISCHARGE PARAMETERS
- TENTATIVE HOLLOW-CATHODE RESULTS
 - OPERATES AT LOW FLOW (< 20 mA EQUIVALENT)^a
 - HYDROGEN APPEARS TO DEGRADE CATHODES
 - DISCHARGE OPERATES AT LOWER VOLTAGE, HIGHER CURRENT
- SOLID PHOSPHORUS SOURCE DEVELOPMENT
 - CAN PRODUCE ~ 8 mA AT 10 keV
 - DISCHARGE 35V, 3A
 - SAMPLE CAROUSEL READY FOR NON-MASS ANALYZED IMPLANT
- PROBLEMS
 - CONSUMPTION OF SOLID PHOSPHORUS TOO HIGH
 - BETTER UNDERSTANDING OF CONTROL PARAMETERS NEEDED

OBJECTIVES

- DEVELOP CELL HANDLING END EFFECTORS FOR PLACEMENT AND INTERCONNECTION OF CELLS
- DEVELOP TECHNIQUES FOR AUTOMATED INTERCONNECTION OF CELLS USING ROBOTICS
- DETERMINE TOLERANCE REQUIREMENTS FOR PLACEMENT OF CELLS
- STUDY METALIZATION PATTERN RECOGNITION FOR ORIENTATION
- ASSESS PROCESS SEQUENCE FOR FURTHER APPLICATION OF ROBOTICS

MODULE FRAMING OPERATION

- (A) PNEUMATIC RAM KEYED TO LOCATION OF EXTRUSION HEAD, INITIATED BY TRAVELING BEAM.
- (B) TRAVELING BEAM WITH SUCTION GRIP POSITIONS PANEL (EXTRUSION HEAD POSSIBLY MOUNTED HERE TO APPLY ADHESIVE TO FRAME).
- (C) PNEUMATIC RAM KEYED BY RETRACTION OF FRAME POSITIONING RAM LOWERS TABLE, ALLOWING THE PANEL TO SLIDE ONTO THE NEXT CONVEYOR.

MODULE EDGE SEALING STATION

MATERIAL PROPERTIES

	<u>Mo</u>	<u>Si</u>	<u>MoO₃</u>
MELTING POINT (°C)	2622	1420	795
BOILING POINT (°C)	4510		SUBLIME
DENSITY (G/CM ³)	10.2	2.33	4.5
COEF. OF THERMAL EXP. (CM/CM/°C) 10 ⁻⁶	3.1	4.2	
ELECTRICAL RESISTIVITY (MICRO OHM-CM)	5.17		

CONVERSION OF M_2O_3 TO M_0 (TEMPERATURE - TIME - ATMOSPHERE CYCLE)

RCA LABORATORIES

SPRAY-ON ANTIREFLECTION COATINGS FOR SILICON SOLAR CELLS

WERNER KERN

WORK PERFORMED AS PART OF "AUTOMATED ARRAY ASSEMBLY" FOR JET
PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, UNDER
NASA CONTRACT NAS 7-100 DOE/JPL-954868.

OBJECTIVE

TO DEVELOP A LOW-COST, HIGH-SPEED MASS PRODUCTION
PROCESS FOR DEPOSITING SINGLE-LAYER THIN FILM
ANTIREFLECTION (AR) COATINGS ON METALLIZED SINGLE-
CRYSTAL SILICON SOLAR CELLS FOR TERRESTRIAL
APPLICATIONS.

MATERIALS FOR THIN FILM AR COATINGS ON SILICON

COMPOUND	REFRACTIVE INDEX (n) ^a	ABSORPTION BELOW (λ ~ μm)
Ta ₂ O ₅	2.4 - 2.8	310
TiO ₂	2.2 - 2.7	380
Si _x N _y H _z	2.1 - 2.4	380
ZrO ₂	1.7 - 2.2	340
HfO ₂	2.0	220
SnO ₂	1.9 - 2.3	350
In ₂ O ₃	1.7 - 2.4	420
Si ₃ N ₄	1.9 - 2.1	300
SiO	2.0	380
Al ₂ O ₃	1.6 - 1.8	340
SiO ₂	1.4 - 1.5	205

^a Depending on method of formation and crystallographic form.

OPTICAL CONSIDERATIONS

REFLECTANCE	= R
TRANSMITTANCE	= T
REFRACTIVE INDEX	= N
N _{air}	= 1.0
N _{cover}	= 1.5
N _{Si} AT λ = 6000 Å	= 3.9

$$R = \left[(N_{Si} - N_{air}) / (N_{Si} + N_{air}) \right]^2 = 0.35$$

- T OF SUNLIGHT INTO CELL WITHOUT AR COATING IS THUS 65%.
- A 100% - EFFECTIVE AR COATING (R=0, T=100%) SHOULD RESULT IN A 54% GAIN IN ELECTRICAL OUTPUT.
- OPTIMAL N_{Si} AT QUARTER WAVELENGTH THICKNESS FOR R_{min} AT 6000 Å IS 2.0 IN AIR AND 2.4 UNDER COVER.

SUMMARY OF PROCESS AND COST COMPARISON FOR PRODUCING AR COATINGS ON SILICON SOLAR CELLS

(per 100 x 10⁶ cells per year)

<u>PROCESS</u>	<u>SPRAYING</u>	<u>LP - CVD</u>	<u>PE - CVD</u>
• FILM TYPE	SiO ₂ -TiO ₂	Si ₃ N ₄	Si _x N _y H _z
• THICKNESS, Å	700	700	700
• REACTANTS	Ti-Si "C"	SiCl ₂ H ₂ + NH ₃	1.5%SiH ₄ -Ar,N ₂
• CONDITIONS	NTP	750°C 0.25 TORR	250°C, 1.0 TORR
• MACHINE	ZICON RECIPRO- CATING SPRAYER	HORIZONTAL TUBE FURNACE	GLOW DISCHARGE CONTINUOUS REACTOR
• THROUGHPUT, CELLS/MACHINE	33.5 x 10 ⁶ /YEAR	7.1 x 10 ⁶ /YEAR	2.0 x 10 ⁶ /YEAR
• SYSTEMS NEEDED	3	15	50
• SYSTEM COST, \$/UNIT	110,000	134,000	78,000
• \$/TOTAL UNITS	330,000	2,016,000	3,900,000
• POWER REQUIRE- MENTS, KW TOTAL	75	80	250
• MATERIAL COST, \$/TOTAL	268,000	34,000	612,000
• MANPOWER COST, \$/TOTAL	36,000	90,000	210,000
• TOTAL COST, \$/TOTAL	634,000	2,134,000	4,722,000
<u>COST RATIO</u>	<u>1.0</u>	<u>3.4</u>	<u>7.5</u>

SUMMARY OF RESULTS FROM ZICON SPRAY TESTS FOR AR COATING⁽¹⁾

Solution System	Constituents: (2) 1 vol Concentrate (3) +	Physical Film Qualities, Grading (4)					Quality Index	Remarks	Best Overall Systems
		Flow Prop- erties	Micro Tex- ture	Gel, Parti- cles	Thickness Unifor- mity				
A	1 vol iso-amyl alcohol + 2 vol cellosolve acetate	2	3	2	3	10	useless for spraying applications		
B	1 vol 2-ethyl-1-hexanol + 1 vol methyl isobutyl ketone	2	2	3	1	8	particle density increases with spray time		
C	1 vol 2-ethyl-1-hexanol + 1 vol butyl acetate	2	2	3	1	8			
D	2 vol 2-ethyl-1-hexanol	1-	1	3	1	6-			
E	1 vol 2-ethyl-1-hexanol + 1 vol sec-butanol	2	2	2	1	7		X	
F	1 vol 2-ethyl-1-hexanol + 1 vol ethyl acetate	1	2	3	1	7	particle density decreases with spray time		
G	0.5 vol ethanol + 1.5 vol 2-ethyl-1-hexanol	2	2	2	1	7		X	
I	2 vol diacetone alcohol	2	2	3	2	9	useless for spraying applications		
J	0.2 vol ethanol + 1 vol 2-ethyl-1-hexanol + 1 vol methyl ethyl ketone	2	2	3	1	7			
K	1 vol ethanol + 1 vol 2-ethyl-1-hexanol	2	2	3	1	8	small-grain particulates only		
L	1 vol isopropanol + 1 vol 2-ethyl-1-hexanol	2	1	2	1	6	small-grain particulates only	X	
M	1 vol ethanol, spin-on (5) for comparison	2	1	2	2	7	spun-on (6); particles, cause comets		

- (1) Standard Model, Zicon Series 11000 Autocoater. Substrates were Si wafers and 7.5-cm diam. metallized solar cell structures.
- (2) In the sequence of addition.
- (3) Titania-Silica Film "C", special concentrate (Organometallic Composite) by Emulsitone Co.
- (4) Grading as follows: 1-good, 2-fair, 3-poor. Evaluation after standard, immediate post-deposition heat treatments in room air (60s drying in IR oven at 200°C, 60s curing at 200°C and 60s densification at 400°C on hot plates).
- (5) Titania-Silica Film "C", formulation for spin-on applications by Emulsitone Co.
- (6) Spun on at 3300r/min, 30s; (for comparison with spray-on deposits).

EFFECTIVENESS OF AR FILMS FROM THREE SOURCE SOLUTIONS

Source Solution	Vol. Ratio	Vol. %	Film Thickness, Å	Performance Effectiveness*	
				I_{sc} AR coated/ I_{sc} uncoated	Increase %
Emulsitone					
Titania-Silica "C" concentrate	1	33.3	833	1.32	32
butylacetate	0	0			
2-ethyl-1-hexanol	1	33.3			
isopropanol	1	33.3			
RCA I					
titanium isopropoxide	1	8.3	824	1.35	35
butyl acetate	3	25.0			
2-ethyl-1-hexanol	4	33.3			
isopropanol	4	33.3			
RCA II					
titanium ethoxide	1	8.3	848	1.36	36
butyl acetate	3	25.0			
2-ethyl-1-hexanol	4	33.3			
isopropanol	4	33.3			

* These ratios indicate the increase in short circuit current of the cells after AR coating; they can be considered essentially equivalent of the increase in efficiency, since V_{oc} remains unchanged after coating.

COMPOSITION AND COST OF AR COATING SPRAY SOURCE SOLUTION FOR RCA I TiO_2

COMPONENT	VOL	VOL%	FUNCTION
TITANIUM (IV) ISOPROPOXIDE, $Ti[OCH(CH_3)_2]_4$	1	8.3	TiO_2 SOURCE
n-BUTYL ACETATE, $CH_3CO_2(CH_2)_3CH_3$	~ 3	~25	DILUENT SOLVENT
2-ETHYL-1-HEXANOL, $CH_3(CH_2)_3CH(C_2H_5)CH_2OH$	> 4	>33	SPRAYABILITY AGENT
ISOPROPANOL, ANHYDROUS, $(CH_3)_2CHOH$	< 4	<33	LEVELING AGENT
COMPOSITE	~ 12	~100	

MATERIALS COST

\$414 PER 100 L MIXTURE

0.04¢ PER 0.1 mL NEEDED PER 3" DIAMETER CELL

CONCLUSIONS

1. A HIGH-SPEED AUTOMATED SPRAYING PROCESS HAS BEEN DEVELOPED FOR DEPOSITING A LOW-COST AR COATING ON SILICON SOLAR CELLS.
2. THE OPTIMIZED SPRAY SOLUTION CONSISTS OF TITANIUM (IV) ISOPROPOXIDE, n-BUTYL ACETATE, 2-ETHYL-1-HEXANOL, AND ISOPROPANOL.
3. OXIDATIVE HYDROLYSIS AND HEAT TREATMENTS OF THE SPRAY FILM YIELDS A STABLE AR COATING OF CRYSTALLINE TiO_2 (ANASTASE) OF $n = 2.2$.
4. AR COATING THICKNESS IN THE RANGE OF 600-750 Å IS NON-CRITICAL.
5. THE INCREASE OF ELECTRICAL OUTPUT EFFICIENCY ACHIEVED BY OUR AR COATING APPROACHES THE THEORETICAL MAXIMUM.

SPECTROLAB, INC.

ARRAY AUTOMATED ASSEMBLY PHASE 2

WILLIAM E. TAYLOR

PROCESS SEQUENCE
REVISED AS OF DECEMBER 1
(CONT.)

PRINTED ALUMINUM P⁺

PROBLEM SOURCES:

- SPIKE FIRING REQUIRED
- EDGE AND FRONT SURFACE CONTAMINATION
- INCOMPLETE COVERAGE (WETTING) OF BACK SURFACE
- ALUMINUM POWDER
- SENSITIVITY OF FIRING CYCLE TO THERMAL MASS
- INTERACTIONS WITH DIFFUSION PROCESS

EFFECT OF THERMAL MASS ON OPTIMUM FIRING CYCLE

	ROUND 2.125 INCH	SQUARE 2.125 INCH
TEMPERATURE	825°C	850°C
TIME	40 SEC	80 SEC

DIFFERENT FIRING FIXTURES

SPRAY ON DIFFUSION

TEXTURIZED → SMOOTH

N250 OBSERVED TO GIVE ERRATIC
SHEET RESISTIVITY:

- RUN TO RUN
- WAFER TO WAFER?
- WITHIN WAFERS

SPRAY ON DIFFUSION

TEXTURIZED → SMOOTH

N250

- OPERATOR DEPENDENT
- DILUTED → FULL STRENGTH
- REQUIRES SHEET RESISTANCE OF 15 OHMS/SQUARE VS. 30-35 FOR PHOSPHINE

PX-10

- MORE CONSISTENT RESULTS
- 30-35 OHMS/SQUARE SUITABLE

CELL PERFORMANCE RUN 3.18.9-C

BARE				AR COATED				
Voc mV	Isc mA	I500 mA	Rsh OHMS	Voc mV	Isc mA	I500 mA	7 %	
604	723	607	12.9	614	982	819	14.2	
603	721	618	15.4					
605	723	634	23.6	610	967	822	14.2	
606	722	629	23.9					
603	723	622	14.7					
603	728	621	17.7					
604	735	632	17.7					
604	732	630	18.8	614	994	836	14.4	
602	730	630	22.4					
606	707	622	21.5	612	966	829	14.3	
603	747	630	22.9	611	999	812	14.0	
604	736	628	20.3					
606	713	628	24.2	614	952	820	14.1	
606	713	618	17.8					
604	707	617	18.4	613	956	817	14.1	
$\bar{x}$	604.2	724.0	624.4	19.49	612.5	973.7	822.1	14.19
σ	1.3	11.2	7.3	3.56	1.6	18.3	7.99	0.13

SENSOR TECHNOLOGY, INC.

**AUTOMATED ARRAY ASSEMBLY TASK
DEVELOPMENT OF LOW-COST POLYSILICON SOLAR CELLS**

AIM AND OBJECTIVES

1. POLYSILICON SOLAR CELL PROCESS SEQUENCE.
2. FRONT SURFACE GRID PATTERN OPTIMIZATION.
3. SURFACE MACROSTRUCTURE PROCESS.
4. JUNCTION FORMATION.
5. ANTI-REFLECTION COATINGS.
6. OTHER PROCESSES.

PROJECT STATUS

POLYSILICON MATERIAL HAS BEEN ORDERED FROM THE FOLLOWING COMPANIES:

- 1) WACKER
- 2) CRYSTAL SYSTEMS
- 3) EXOTIC MATERIALS

OTHER COMPANIES ALL BEING SOUGHT FOR POLYSILICON MATERIAL.

PHASE 2

ARRAY AUTOMATED ASSEMBLY TASK

GREGORY T. JONES
SANG S. RHEE
KIMBERLY ALLISON

DESCRIPTION OF INDUSTRY

- 1) WAFERCO SUPPLIES WAFERS TO CELLCO AT THE PRICE OF 22 CENTS/WATT IN 1975 CENTS.
- 2) CELLCO AND MODULCO ARE VERTICALLY INTEGRATED COMPANIES.
- 3) CELLCO AND MODULCO REQUIRE 4.7 SHIFTS PER DAY, 24 HOURS PER DAY, 7 DAYS A WEEK, 345 OPERATING DAYS.
- 4) CELLCO AND MODULCO WILL SHARE 40% OF THE 500 MW MARKET IN 1986.

CELLCO

1) PRODUCT

90 mm DIAMETER HEXAGONAL SOLAR CELLS

CELL EFFICIENCY: 14.7%

PEAK POWER: 0.76 WATTS/CELL

USABLE SILICON PER WAFER: 81%

2) PRODUCTION YIELD

COMPANY YIELD IS 96.31%

3) PRODUCTION SIZE

278 X 10⁶ CELLS/YEAR OR 210.3 X 10⁶ WATT/YEAR

4) PROCESS STEPS

9 PROCESS STEPS

CELLCO PRODUCTION LINE

40 MEGAWATT PER YEAR CAPACITY

7200 WAFERS PER HOUR

CELLCO NEEDS SIX LINES FOR 200 MEGAWATT PER YEAR PLANT

MODULCO

1) PRODUCT

MODULE SIZE: 2' X 4' NOMINAL

NUMBER OF SOLAR CELLS: 119 FULL HEXAGONAL SOLAR CELLS

PACKING RATIO: 87%

ENCAPSULANT MATERIALS: GLASS/PVB/CELLS/PVB/MYLAR

PEAK POWER: 90 WATT/MODULE AT NOTC, 100 MW/CM²

2) PRODUCTION YIELD

COMPANY YIELD IS 95.13%

3) PRODUCTION SIZE

2.222 X 10⁶ MODULES/YEAR

-OR-

200 X 10⁶ WATTS/YEAR

4) PROCESS STEPS

7 PROCESS STEPS

CELLCO PROCESS COST SUMMARY

(COST PER PEAK WATT IN 1975 CENTS)

PROC. NO.	PROCESS REFERENT	EQUIP.	FL. SPACE	LABOR	MAT. & BY. PROP.	UTIL.	TOTAL
C-1	WFSURPR	.200	.072	.440	.780	.190	1.602
C-2	JUNF	.660	.174	.570	1.200	.641	3.135
C-3	FSPP	.128	.110	.270	.424	.050	.982
C-4	ELNIPL	.084	.038	.430	3.810*	.138	4.500*
C-5	RESREM	.027	.017	.220	1.636	.109	2.009
C-6	HEXLS	.270	.030	.350	.004	.123	.777
C-7	SDPLW	.050	.021	.210	1.900	.213	2.394
C-8	ARCT	1.861*	.124	.940	.800	.274	3.999*
C-9	CELLTEST	.100	.018	.185	0	.010	.321
TOTAL		3.270	.604	3.615	10.554	1.756	19.800

* HIGHEST COST ELEMENT

MODULCO PROCESS COST SUMMARY (PLAN A)

(COST PER PEAK WATT IN 1975 CENTS)

PROC. NO.	PROCESS REFERENT	EQUIP.	FL. SPACE	LABOR	MAT. & BY. PROP.	UTIL.	TOTAL
M-1	INTCON	0.118	0.370	0.240	85.35*	1.766	87.84*
M-2	MDLAYUP	0.081	0.113	0.235	18.31*	0.004	18.743*
M-3	DEGAS	0.089	0.038	0.313	0	0.067	.507
M-4	AUTOCLAV	0.228	0.073	0.083	0	0.380	.764
M-5	FRMASEM	0.007	0.110	0.055	7.581*	0.002	7.755*
M-6	MDLTEST	0.074	0.016	0.189	0	0.003	.282
M-7	PICDMDL	0.010	0.017	0.348	0.536	0	.911
TOTAL		0.607	0.737	1.463	111.777*	2.222	116.806

* HIGHEST COST ELEMENT

MODULE SELLING PRICE (PLAN A)

(1975 CENTS PER PEAK WATT)

WAFERCO	22. ¢
CELLCO	19.8¢
<u>MODULCO</u>	<u>116.8¢</u>
MODULE SELLING PRICE	158.6¢/WATT

MODULCO COST REDUCTION RECOMMENDATIONS FROM PLAN A TO PLAN B

- 1) FLEXIBLE PRINTED CIRCUIT SHEET IS REPLACED BY A STAMPED COPPER STRIP ON KAPTON.
PRICE CHANGE: \$5/FT² TO \$0.25/FT²
- 2) LAMINATION MATERIAL PVB IS REPLACED BY EVA.
PRICE CHANGE: \$.34/FT² TO \$0.086/FT²
- 3) ALUMINUM FRAME IS MODIFIED BY CHANGING THE SPECIFICATIONS AS FOLLOWS:
3 INCH HEIGHT AND 1/8 INCH THICKNESS CHANGED TO 2 INCH HEIGHT and 3/32 INCH THICKNESS.
PRICE CHANGE: \$0.38/FT TO \$0.19/FT

MODULCO PROCESS COST SUMMARY (PLAN B) POTENTIAL FUTURE MODULE

(COST PER PEAK WATT IN 1975 CENTS)

PROC. NO.	PROCESS REFERENT	EQUIP.	FL. SPACE	LABOR	MAT.	UTIL.	TOTAL
M-1	INTCON	0.118	0.370	0.240	4.268	1.766	6.762
M-2	MDLAYUP	0.081	0.113	0.235	14.08	0.004	14.513
M-3	DEGAS	0.089	0.038	0.313	0	0.067	.507
M-4	AUTOCLAV	0.228	0.073	0.083	0	0.380	.764
M-5	FRMASEM	0.007	0.110	0.055	4.23	0.002	4.404
M-6	MDLTEST	0.074	0.016	0.189	0	0.003	.282
M-7	PKDMDL	0.01	0.017	0.348	0.536	0	.911
TOTAL		0.607	0.737	1.463	23.114	2.222	28.143

MODULE SELLING PRICE (PLAN B)

MODULE SELLING PRICE (PLAN B)

(1975 CENTS PER PEAK WATT)

WAFERCO	22.00¢
CELLCO	19.80¢
<u>MODULCO</u>	<u>28.14¢</u>
MODULE SELLING PRICE	69.94¢

CONCLUSIONS

- 1) THE SOLAR CELL AND MODULE PROCESS COSTS ARE FEASIBLE AND WILL MEET THE 1986 LSA COST GOALS.
- 2) THE MODULE FABRICATION MATERIAL COSTS ARE HIGH. FOUR MAJOR PROBLEM AREAS ARE:
 - LAMINATION MATERIAL
 - FRAME MATERIAL
 - SEALANTS
 - TERMINALS

AUTOMATED ARRAY ASSEMBLY TASK INDEPTH STUDY OF SILICON WAFER SURFACE TEXTURIZING

AIM AND OBJECTIVES

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

PROJECT STATUS

1. EFFECT OF GETTERING AND TEXTURIZING ON POOR TO FAIR QUALITY 1.406 INCH, SQUARE SILICON MATERIAL.
2. EFFECT OF GETTERING AND TEXTURIZING ON FAIR TO GOOD QUALITY 3 INCH DIAMETER ROUND SILICON MATERIAL.

COST OF POC1₃ JUNCTION FORMATION IN CENTS PER PEAK WATT

BATH	I _{sc} (a)	V _{oc} (v)	I _{pp} (a)	V _{pp} (v)	η (%)	FF	$\frac{\Delta\eta}{\eta}$ (%)	$\frac{\Delta FF}{FF}$ (%)
1. Solar Cells: 1.406 inch square, texturized (10% NaOH), texturized (1% NaOH), spray-on doped (both sides), nickel plated, no A.R. coating.								
High	.300	.550	.235	.45	8.30	.64	+47.2	+16.4
Low	.200	.520	.105	.45	3.70	.45	-34.4	-18.2
Wt. Ave.	.245	.535	.160	.45	5.64	.55	--	--
2. Solar Cells: 1.406 inch square, texturized (10% NaOH) texturized (1% NaOH) spray-on doped (both sides, nickel plated, SiO ₂ glass removed								
High	.290	.550	.28	.45	9.87	.79	+74.4	+41.1
Low	.235	.515	.10	.40	3.14	.33	-44.5	-41.1
Wt. Ave.	.240	.535	.17	.425	5.66	.56	--	--
3. Solar Cells: 1.406 inch square, gettered, texturized (10% NaOH), texturized (1% NaOH), spray-on doped (both sides) Nickel plated, no A.R. coating.								
High	.285	.560	.235	.455	8.38	.67	+18.9	+13.6
Low	.267	.535	.155	.40	4.85	.43	-31.2	-27.1
Wt. Ave.	.280	.545	.20	.45	7.05	.59	--	--
4. Solar Cells: 1.406 inch square, texturized (10% NaOH), gettered, texturized (1% NaOH), spray-on doped (both sides), nickel plated, no A.R. coating.								
High	.260	.565	.23	.465	8.38	.73	+8.0	+2.8
Low	.235	.555	.195	.45	6.90	.68	-11.1	-4.2
Wt. Ave.	.250	.560	.22	.45	7.76	.71	--	--

COST OF SPRAY ON DOPANT JUNCTION FORMATION IN CENTS PER PEAK WATT

Batch	I_{sc} (A)	V_{oc} (v)	I_{pp} (a)	V_{pp} (v)	η (%)	FF	$\Delta\eta$ (%)	ΔFF (%)
B-1. Controlled Cell, Std. Two Step Tex., Std. $POCl_3$ Diff. with Al Back								
High	1.40	0.580	1.22	0.435	12.82	0.654	16.55	15.14
Low	1.30	0.565	0.99	0.365	8.73	0.492	-20.64	-13.38
Wt. Ave.	1.38	0.582	1.20	0.38	11.00	0.568	--	--
B-2. Intermediate Gettering								
High	1.43	0.575	1.26	0.44	13.40	0.680	8.94	5.43
Low	1.43	0.555	1.20	0.37	10.71	0.559	12.93	13.33
Wt. Ave.	1.40	0.565	1.24	0.41	12.30	0.645	--	--
B-3 Pre-Gettering								
High	1.42	0.575	1.25	0.420	12.68	0.643	8.10	4.72
Low	1.37	0.560	1.10	0.370	9.83	0.531	-16.20	-13.52
Wt. Ave.	1.40	0.565	1.20	0.405	11.73	0.614	--	--
B-4 Intermediate Gettering with SiO AR Coating								
High	1.45	0.573	1.30	0.455	14.29	0.712	7.61	3.79
Low	1.40	0.555	1.20	0.43	12.46	0.664	-6.17	-3.21
Wt. Ave.	1.42	0.565	1.28	0.43	13.28	0.686	--	--

COST OF $POCl_3$ JUNCTION FORMATION IN CENTS PER PEAK WATT

Equipment Cost	2.15
Labor Cost	0.80
Material	9.73
Utility	0.01

TOTAL 13.39

COST OF SPRAY ON DOPANT JUNCTION FORMATION IN CENTS PER PEAK WATT

Equipment	0.296
Floor Space	0.065
Labor	0.296
Material	0.781
Utility	0.0887

TOTAL	1.5267 cents/peak watt
-------	------------------------

SPRAY ON DOPANT PROCESS

TYPE OF CELL

N⁺-P-P⁺

Solution for N⁺ junction - water base phosphor

Film N = 10¹⁹ /cm³ viscosity = 5-9 centipoise
@28°C

Solution for p⁺ junction - water base Boron Film

N = 10¹⁸ / cm³ viscosity 5-9 centipoise
@28°C

Infra Red Oven Temperature = 400°F

<u>PARAMETERS</u>	<u>PRESENT</u>	<u>FUTURE</u>
AVG. CELL EFFICIENCY	13%	14.5%
CONVEYOR SPEED	2'/Minute	2'/minute
RECIPROCATOR SPEED	90 osc/min.	90 osc/min.
SOLVENT CONSUMPTION/GUN	7cc/min.	7cc/min.
ATOMIZATION PRESSURE	20 PSI	25 PSI
COATING THICKNESS	2 ⁺ 0.5 U	2 ⁺ 0.5 U
COST OF EQUIPMENT	18,000.00	78,790.00
THROUGHPUT/HOUR	450	2800
DRIVE-IN	Furnace Temp 925°	Investigating new techniques

COMPARISON OF PROCESS COSTS FOR A FULLY AUTOMATED
 SPRAY-ON-DOPANT PROCESS AND A MANUAL POCl_3 JUNCTION
 FORMATION PROCESS IN TERMS OF 1975 CENTS PER PEAK WATT

SAMICS RESULTS FOR SPRAY-ON
 DOPANT PROCESS IN 1975 CENTS PER
 PEAK WATT

EQUIPMENT	0.550
FLOOR SPACE	0.174
LABOR	0.570
MATERIAL	1.200
<u>UTILITY</u>	<u>0.641</u>
TOTAL	3.135

SAMICS RESULTS FOR POCl_3 JUNCTION
 FORMATION PROCESS IN 1975 CENTS
 PER PEAK WATT

EQUIPMENT	2.644
FLOOR SPACE	3.969
LABOR	38.330
MATERIAL	39.207
<u>UTILITY</u>	<u>16.810</u>
TOTAL	100.960

SPRAY-ON DOPANT PROCESS

1. SPRAY-ON
2. DRIVE-IN
3. EXCESS DOPANT REMOVAL

POCl_3 JUNCTION FORMATION PROCESS

1. PREDIFFUSION CLEANING
2. POCl_3 DIFFUSION
3. FRONT SURFACE PRINTING
4. BACK SURFACE ETCHING
5. ALUMINUM EVAPORATION
6. ALUMINUM FIRE-IN

PROCESS COSTS FOR PARALLEL FLOW LASERSCRIBE SYSTEM IN CENTS PER PEAK WATT

	1986 cents		1975 cents	
	Old Value	Corrected Value	Old Value	Corrected Value
Equipment	0.5850	0.5850	0.3049	0.3049
Floor space	0.0612	0.0612	0.0319	0.0319
Labor	0.8449	0.8449	0.4400	0.4400
Materials	0.0192	0.0192	0.0100	0.0100
Utilities	11.0986	0.2783	5.7869	0.1451
TOTAL	12.6089	1.788	6.5737	0.932

**PROCESS COSTS FOR SERIAL FLOW LASERSCRIBE SYSTEM
IN CENTS PER PEAK WATT**

	1986 cents		1975 cents	
	Old Value	Corrected Value	Old Value	Corrected Value
Equipment	0.5219	0.5219	0.2721	0.2721
Floor Space	0.0564	0.0564	0.0294	0.0294
Labor	0.5612	0.5612	0.2926	0.2926
Materials	0.0247	0.0247	0.0129	0.0129
Utilities	9.1261	0.2319	4.7580	0.1209
TOTAL	10.2903	1.3961	5.3650	0.7279

COST OF SERIAL FLOW LASERSCRIBE SYSTEM

(1975 CENTS PER PEAK WATT)

EQUIPMENT	.270
FLOOR SPACE	.030
LABOR	.350
MATERIAL	.004
UTILITY	.123
TOTAL	.777*

*TOTAL COST INCLUDES SCRIBING A MODIFIED
HEXAGONAL SOLAR CELL WITH CENTRAL HOLE.

LASERSCRIBING PROCESS

Laser Parameters	Existing	Serial	Parallel Flow
Mode	TEM ₀₀	TEM ₀₀	TEM ₀₀
Beam Size	0.6 mil	1 mil	1 mil
Power/Beam	10 watts	32 watts	32 watts
Pulse Rate	10 KHZ	10 KHZ	10 KHZ
Time Cycle	45 sec.	19 sec.	31 sec.
Velocity	2.5 in/sec.	10 in/sec.	10 in/sec.
Throughput/hour	120	7200	4800
Wafer Resident time	25 sec.	19 sec.	31 sec.
Cost of Equipment	\$85,000.00	\$520,000.00	\$387,000.00

JUNCTION FORMATION ADD-ON PRICES

CALTECH STUDY (OCLI)

- PRODUCED ~12% AM1 CELLS WITH P_4^+ (BASELINE)
 - WITHIN 10% OF DIFFUSED CONTROL SAMPLES
 - RELATIVELY INSENSITIVE TO BEAM PARAMETERS
- PRODUCED P^+ & P_2^+ IMPLANTED CELLS FOR COMPARISON
 - SLIGHTLY LOWER THAN P_4^+ IMPLANTED SAMPLES
 - STILL UNDER STUDY
- IMPLANTED SAMPLES WITH BEAM IMPURITIES
 - SUBMITTED TO OCLI FOR PROCESSING
- PRELIMINARY RESULTS
 - MOLECULAR PHOSPHORUS PROMISING
 - P_4^+ IMPLANT MAY INCREASE THROUGHPUT

PRINCIPLES OF ION IMPLANTER DESIGN

PROCESS ENERGIES FOR JUNCTION FORMATION PROCESSES (kWh/M²)

PROCESS	YIELD (%)	ENERGY OF LOST SILICON		MAT. ENERGY (TH)	DIRECT ENERGY (EL)	EQUIP. ENERGY (TH)	FACIL. ENERGY (TH)	TOTAL ENERGY		TOTAL (EL)
		TH	EL					TH	EL	
SPECTROLAR PH ₃ DIFFUSION (1978)	99.9	0.97	1.28	0.61	2.39	5.90	18.22	25.90	3.67	11.44
VARIAN-EXTRION P ION IMPLANTA- TION (1978)	99	9.68	12.79	1.72	18.28	33.10	28.89	73.39	53.09	75.11
MOTOROLA PH ₃ DIFFUSION (1986)	99	0.94	1.41	0.073	6.19	0.74	4.07	5.823	7.60	9.35
MOTOROLA ACTIVATION ANNEALING (1986)	99.4	0.57	0.85	0.09	3.1	0.34	1.91	2.91	3.95	4.52
RCA 2-SIDE ION IMPLANTATION (1986)	99	0.94	1.41	2.43	4.39	10.38	16.51	30.26	5.80	14.28
MOTOROLA UNANALYZED P BEAM IMPLANTATION (1986)	99.8	0.19	0.28	0.073	6.19	0.74	4.07	5.07	6.47	7.99
SPIRE HIGH THRUPUT P IMPLANTATION (1986)	99.9	0.095	0.14	0.017	1.95	3.56	0.93	4.60	2.09	3.47

0.3 kWh (EL) = 1 kWh (TH)

ENERGIES OF STARTING MATERIAL

	TH	EL
1978	967.89	1279.12
1986	94.94	141.29

TECHNICAL AND ECONOMIC COMPARISON OF PRESENT AND PROPOSED JUNCTION FORMATION PROCESSES

ORGANIZATION	Varian-Extrion 200-1000 W (Spire)	Spectrolab PH ₃ dif- fusion	Motorola PH ₃ dif- fusion	Motorola 5-step diffusion process	RCA 2-side ion implanta- tion w/an- nealing (1986)	Motorola Activation annealing (1986)	Motorola Unanalyzed beam im- planter (1986)	Spire High thruput ion implan- ter (1986)
	(1978)	(1978)	(1986)	(1986)	(1986)	(1986)	(1986)	(1986)
Throughput/rate (no.h ⁻¹ /dia. (cm))	240/7.6-cm	129/7.6-cm	1000/12-cm	1000/12-cm	2000/7.6-cm	2000/12-cm	4800/12-cm	18,000/10-cm
1. Direct Materials	0.01	0.02	0.29	2.26	6.25	--	0.03	0.07
2. Indirect Materials	0.75	0.19	0.18	0.25	0.69	0.03	0.07	0.02
3. Expendible tooling	2.63	0.28	0.07	0.16	0.27	0.05	0.00	0.06
4. Electrical Energy	0.73	0.08	0.20	0.44	0.22	0.10	0.02	0.08
5. Total Materials (1.0526 * (1.+2.+3.+4.))	4.34	0.59	0.78	3.27	1.51	0.18	0.13	0.24
6. Direct Labor	5.50	4.65	0.52	1.68	0.42	0.24	0.12	0.07
7. Maintenance Labor	0.70	--	0.08	0.37	0.14	--	0.02	0.02
8. Indirect Labor (0.23 * (6. + 7.))	1.55	1.17	0.15	0.51	0.14	0.06	0.03	0.02
9. Total Labor (1.3158 * (6. + 7.))	8.16	6.12	0.78	2.72	0.73	0.32	0.18	0.11
10. Equipment	7.54	1.61	0.17	0.79	2.45	0.07	0.05	0.40
11. Facility	0.39	0.37	0.05	0.19	0.26	0.03	0.02	0.01
12. Capital (10. + 11.)	7.93	1.98	0.22	0.98	2.71	0.10	0.07	0.41
13. Overhead	0.48	0.13	0.02	0.05	0.17	0.01	0.005	0.03
14. Return-on-equity	13.45	5.69	0.76	2.96	4.68	0.31	0.21	0.62
15. Add-on price of process	34.45	14.51	2.56	9.98	9.90	0.93	0.58	1.42
16. Yield (%)	99	99.9	99	--	--	99.4	99.8	99.9
17. Yield add-on process price	34.83	14.52	2.59	9.98	9.90	0.93	0.58	1.42
18. Cost of silicon lost-in-process	3.53	0.35	0.42	1.78	0.84	0.25	0.08	0.04
19. Add-on price	38.36	14.87	3.01	11.76	10.74	1.18	0.66	1.46

DEVELOPMENT OF ECONOMICAL IMPROVED THICK FILM SOLAR CELL CONTACT

OBJECTIVES:

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

ACCOMPLISHMENTS

1. A LOW TEMPERATURE DEPOLYMERIZING PASTE BINDER HAS BEEN IDENTIFIED.
2. THREE SCREENABLE OXIDE SCAVENGERS HAVE BEEN FOUND.
3. LOW TEMPERATURE SINTERING OF AN ALL-METAL PASTE HAS BEEN ACCOMPLISHED IN A SILVER SYSTEM.
4. ELECTRODES HAVE EXCELLENT METALLURGICAL AND ENVIRONMENTAL PROPERTIES.
5. TO DATE 61 PASTE FORMULATIONS HAVE BEEN PREPARED AND CHARACTERIZED.

AVERAGE GRAIN DIAMETER VARIATION VERSUS RECIPROCAL TEMPERATURE FOR SEVERAL ALL METAL INKS

Average Grain Diameter
(μm)

AUGER SURFACE SPECTRA VERSUS ETCH DEPTH OF DECOMPOSED $AgF - Si$ INTERFACE

PROBLEM AREAS AND FUTURE PLANS

1. ELECTRICAL PROPERTIES OF INKS TO DATE ARE INADEQUATE. CONTACT RESISTANCE OF EARLY SCREENED ALL-METAL CONTACTS WAS IN THE MEGOHM RANGE. USE OF DOPANTS, EUTECTICS AND LOW ENERGY GAP INTERMEDIARY HAS RESULTED IN MARKED IMPROVEMENT.
2. ADDITIONAL EUTECTIC-DOPANT ALLOYS WILL BE TRIED TO REDUCE CONTACT RESISTANCE FURTHER.
3. ONCE CONTACT RESISTANCE IS ACCEPTABLE, BASE METAL SYSTEM DEVELOPMENT WILL BEGIN.

AUTOMATED ARRAY ASSEMBLY TANDEM JUNCTION MODULE

- DESIGN LARGE AREA TJC
- VERIFY TJC PROCESS
- DESIGN TANDEM JUNCTION MODULE
- FABRICATE TEST MODULES

LARGE AREA TJC DESIGN

DESIGN CONSIDERATIONS

SERIES RESISTANCE

- BASE RESISTANCE
- METAL FINGER RESISTANCE (P+)
- CONTACT RESISTIVITY (P+)

SURFACE RECOMBINATION

- P+ REGION

MODULE ASSEMBLY

- SERIES OR PARALLEL INTERCONNECT
- P+ AND N+ CONTACTS ON OPPOSITE EDGES

TANDEM JUNCTION MODULE

LARGE AREA TJC DESIGN

LOSSES

$$F_f = \frac{J_m d m l^2}{24 V_{oc} T_1} + \frac{J_m d m l^2}{24 V_{oc} T_2} \sim 1.7\%$$

$$F_b = \frac{J_m p_s d^2}{12 V_{oc}} \sim 2.6\%$$

OPTIMIZATION

$$I_{sc} = \alpha_n I_{\lambda e} + I_{\lambda c}$$

$$V_{oc} = \frac{KT}{q} \ln \frac{I_{sc}}{I_{cbo}}$$

$$I_{cbo} = I_{cs} (1 - \alpha_n \alpha_1)$$

TRANSISTOR MODEL OF TANDEM JUNCTION CELL

(a) TJC CROSS SECTION

(b) EQUIVALENT CIRCUIT

TJC METAL PATTERN

TANDEM JUNCTION MODULE

PROCESS VERIFICATION

P+ CONTACT RESISTIVITY

AI THICKNESS	AI ALLOY	TEMPERATURE
2000Å	650°C	850°C
4000Å	$2 \times 10^{-3} \Omega\text{-cm}^2$	$4 \times 10^{-3} \Omega\text{-cm}^2$

CELL THICKNESS

- KEY FACTOR IS LIFETIME AFTER PROCESSING
- TARGET THICKNESS 125 - 140 m

TANDEM JUNCTION MODULE

PROCESS VERIFICATION

EFFECT OF BORON IMPLANT ON TJC

CALCULATED VS MEASURED J_{SC} VS THICKNESS AS A FUNCTION OF LIFETIME

TANDEM JUNCTION MODULE

MODULE DESIGN

- SINGLE N+ AND P+ CONTACT
- PARALLEL - SERIES INTERCONNECT
- PORCELAINIZED STEEL - GLASS
- COPPER CLAD INVAR INTERCONNECTS
- 30 CELL SAMPLE MODULES

OPTICAL COATING LABORATORY, INC.

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

OBJECTIVE

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

THE SECOND PHASE OF THIS PROGRAM IS TO DESIGN AND FABRICATE PRODUCTION TOOLING FOR THE MANUFACTURE OF THE HIGH EFFICIENCY CELLS AND MODULES. TWENTY (20) VERIFICATION MODULES ARE TO BE FABRICATED AND DELIVERED TO JPL.

AP		SOLDER JOINT ALLOY 60/40	10
4		TEFLON HEAT SHRINK INSUL. 3/16x1" 8 MIL	9
2		#8-32 HEX. NUT (SST)	8
1		#8-32 F.I.A. R.H. MACH. SCR (SST)	7
2		#8 STAR LOCK WASHER	6
2		STRAIN RELIEF-HEYCO #SP-1	5
2		1/4 AWG. TEFLON INSUL. HOOK-UP WIRE #48 (WHITE)	4
2		1/4 AWG. TEFLON INSUL. HOOK-UP WIRE #48 (BLACK)	3
1	C202391	JUNCTION BOX	2
1	D202373	LAMINATED CELL ASSEMBLY	1
QSB	PART NUMBER	DESCRIPTION	ITEM

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		DRAWN BY E. J. WHITE DATE 1/18/72	OCL OPTICAL COATING LABORATORY, INC. PHOTOELECTRONICS GROUP 11251 Dan Johnson Rd. • City of Industry, Calif. 91746	
TOLERANCES		PROD	JUNCTION BOX	
DECIMALS .01		QA	TERMINAL WIRING	
FRACTIONS 1/16		MATERIAL	SIZE C	CODE IDENT NO C202392
ANGLES			SCALE NONE	REV N/C
DO NOT SCALE DRAWING			SHEET 1 OF 1	
APPLICATION

SECTION A-A

1	MYLAR INSULATING TAPE 2 MIL THK = 8 1/2" (3M)	17
4	REFLECTIVE INSULATING TAPE 8 MIL THK = 1 1/2" (MORGAN)	16
1	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	12
1	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	19
2	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	18
2	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	13
2	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	11
4	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	10
30	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	9
116	INTERCONDUCTIVE SOLDER PASTE 70% CU 30% SN 10% AG	8
AR	ACTIVATING DOSE WHITE SEMI-CONDUCTOR PASTE 50% SN	7
1	MYLAR CLAMP 3 MIL = 22 x 47% (CARCO)	6
AR	PARALLEL AMMETER PAPER 16" x 12"	5
1	PVD DE 20 MIL = 22 x 47% (MORGAN)	4
1	PVD SRU 15 MIL = 22 x 47% (MORGAN)	3
1	VINYL 12 x 97% SUNSHADE GLASS 1/8" THK (MORGAN)	2
120	AZ02337 3" DIA SOLAR CELL	1

DATE: 10/10/73 DRAWN: 10/10/73 CHECKED: 10/10/73 APPROVED: 10/10/73		OCU OFFICIAL ORIGINATOR: LAMAR TERRY, INC. PROJECT: 120 CELL ENCAPSULATION	
PART NUMBER: 120 DESCRIPTION: 120 CELL ENCAPSULATION		D202373	
NEXT ASSY: USED ON: APPLICATION:		SCALE: 1/2" = 1" SHEET 1 OF 1	

FLOW CHART FOR HIGH EFFICIENCY P + N N+ CELLS

1. GROW INGOT, N-TYPE, 7-14 OHM-CM.
2. PREPARE WAFERS.
3. APPLY DIFFUSION MASK TO FRONT.
4. DIFFUSE N+ ON BACK TO FORM BACK SURFACE FIELD.
5. HF CLEAN.
6. APPLY DIFFUSION MASK TO BACK.
7. DIFFUSE P+ TO FORM JUNCTION.
8. HF CLEAN.
9. EVAPORATE BACK CONTACT (Al, Ti-Pd-Ag).
10. APPLY FRONT CONTACT MASK (PHOTORESIST).
11. EVAPORATE FRONT CONTACT (Ti-Pd-Ag).
12. EVAPORATE AR COATING.
13. SINTER.
14. MECHANICAL INSPECTION.
15. ELECTRICAL TEST.

PROBLEM AREAS

ONLY ONE MAJOR PROBLEM IS ANTICIPATED; THAT IS THE DEVELOPMENT OF A LARGE AREA, HIGH EFFICIENCY, P/N SOLAR CELL. TO ACHIEVE AN AVERAGE CELL EFFICIENCY OF 16.5% AT AM1 AND 28°C, A GOOD PROCEDURE TO PROVIDE AN EFFECTIVE BACK SURFACE FIELD MUST BE DEVELOPED. PRESENTLY, PHOSPHORUS DIFFUSION WITH PHOSPHORUS OXYCHLORIDE AS THE SOURCE MATERIAL IS BEING INVESTIGATED. ALL OTHER PROCESSING STEPS ARE WELL IN HAND.

SPIRE CORPORATION

PULSE PROCESSING FOR SOLAR CELLS

SPIRE CORPORATION
BEDFORD, MA

LSA PRODUCTION PROCESSES
JPL APRIL 4, 1979

SOLAR CELL PROCESS SEQUENCE

MATERIAL - 10 OHM-CM (100) CZ FLASH ETCHED
5 OHM-CM CAST POLY FLASH ETCHED

IMPLANT - BACK $5 \times 10^{15} \text{ B}^+$ 25 keV
FRONT $2 \times 5^{15} \text{ P}^+$ 10 keV

ANNEAL - 850°C - 15 MIN
 550°C - 30 MIN OR PULSED ELECTRON BEAM

CLEAN - HF

CONTACTS - TiPdAg FRONT AND BACK

AR - TiO_2

PERFORMANCE DISTRIBUTION FOR ION IMPLANTED SOLAR CELLS DELIVERED TO JPL

ANNEAL MATRIX SUMMARY

ANNEAL TYPE	P _{max} (W)	V _{oc} (V)	I _{sc} (A)	FF
Standard	.766 (3.8%)	.587 (0.2%)	1.760 (1.5%)	.74 (3.1%)
1	.761 (2.4)	.585 (0.3)	1.753 (1.3)	.74 (1.4)
2	.767 (1.8)	.586 (0.3)	1.744 (1.4)	.75 (1.3)
3	.682 (19.4)	.579 (0.8)	1.703 (8.2)	.69 (14.6)
4	.699 (12.7)	.567 (0.2)	1.710 (2.5)	.72 (10.8)
5	.738 (2.1)	.581 (0.4)	1.709 (1.0)	.74 (1.4)
6	.720 (4.3)	.506 (0.4)	1.732 (1.9)	.71 (2.8)
7	.743 (2.4)	.585 (0.7)	1.741 (0.7)	.73 (1.5)

- 7.6 CM n⁺ p p⁺ ION IMPLANTED CELLS
- 10 μ -CM CZ FLASH ETCHED SILICON
- PERCENT STD. DEVIATION IS IN PARENTHESIS (%)

TIME AT TEMPERATURE FOR IMPLANT ANNEAL TESTS

PERFORMANCE DISTRIBUTION: POLYCRYSTALLINE SILICON

SPECTRAL RESPONSE FOR SINGLE AND POLYCRYSTALLINE ION IMPLANTED CELLS

SHEET RESISTANCE MAP FOR 2" ELECTRON BEAM

SHEET RESISTANCE MAP FOR 3" ELECTRON BEAM

PULSED ELECTRON BEAM CHARACTERISTICS

POST PULSE ANNEAL
MEASURED V_{cc} (AM0-25°C) FOR POST PULSE FURNACE ANNEALING

SAMIS III COST ELEMENTS (JUNCTION AND BSF FORMATION)

PROCESS ELEMENT	COST (1975 \$/WATT)					TOTAL VALUE ADDED
	CAPITAL COSTS	DIRECT LABOR	MAT'L'S	UTILITIES	INDIRECT (incl. taxes)	
Phosphorus Implant Junction	0.0053	0.0004	0.0012	0.0003	0.0027	0.0101
Aluminum Implant BSF	0.0061	0.0008	0.0015	0.0006	0.0012	0.0102
Furnace Anneal	0.0009	0.0004	--	--	0.0009	0.0022
Plasma Etch	0.0027	0.0002	--	0.0001	0.0035	0.0065
TOTAL						\$0.0290

- 100 MW/YR IMPLANTER
- 7.5 X 10 CM SHEET, 11% AM1 CELLS

MOTOROLA, INC.

THE DEVELOPMENT OF A METHOD OF PRODUCING ETCH RESISTANT WAX PATTERNS ON SOLAR CELLS

PATTERNED WAX MASKING

- A. ATTEMPT TO REPLACE PHOTORESIST PROCESSING WITH A PATTERN PRINTING TECHNIQUE.
- B. PHOTORESIST DISADVANTAGES
 - 1. HIGH COST
 - 2. SPECIAL FACILITIES AND EQUIPMENT
 - 3. SOLVENT FUMES
 - 4. LIMITED SHELF LIFE
 - 5. TIME-CONSUMING EXPOSE-DEVELOP-BAKE CYCLE.
- C. REPLACEMENT TECHNIQUE
 - 1. REPLACE PHOTORESIST WITH INERT WAX.
 - 2. APPLY WAX WITH A PRINTING PLATE.
- D. ADVANTAGES
 - 1. LOW COST
 - 2. NO SPECIAL SAFETY ILLUMINATION, HUMIDITY CONTROL, ETC.
 - 3. NO SOLVENT FUMES
 - 4. INDEFINITE SHELF LIFE
 - 5. SIMPLE AND QUICK PROCESSING
- E. PRINTING TECHNIQUES
 - 1. LETTERPRESS - RAISED PLATE AREAS BEAR WAX AND TRANSFER ON CONTACT WITH WAFER.
 - 2. INTAGLIO - WAX IS BORNE BY DEPRESSIONS IN PLATE. SURFACE TENSION CAUSES BEADING OF WAX. TRANSFER OCCURS ON CONTACT.
 - 3. LITHOGRAPHY - WAX SELECTIVELY WETS DEFINED PLATE AREAS. NO PLATE CONTOUR.
- F. DISADVANTAGES
 - 1. INTAGLIO PRINTING REQUIRES A WAX SURFACE TENSION NOT EASILY OBTAINED.
 - 2. LITHOGRAPHIC PLATE PREPARATION IS TIME CONSUMING. PLATES ARE DIFFICULT TO REPLACE.

PRINTING TECHNIQUES

PRODUCE PRINTING PLATES IN QUANTITY FROM DURABLE MASTERS

PRINT BY LETTERPRESS TECHNIQUE

G. AREAS OF RESEARCH

1. PRINTING PLATE MATERIAL
2. TYPE OF MASKING WAX
3. PRINTING DEVICE CONFIGURATION
4. PATTERN DEFINITION
5. COST

H. PROJECT TASKS

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

THE PROCESS SEQUENCE

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

*MAY BE COMBINED

PROCESS SPECIFICATIONS

1. PLASMA SILICON ETCHING TO REMOVE SAW DAMAGE.
2. WAX MASKING.
3. ION IMPLANTATION
4. VACUUM SILICON NITRIDE DEPOSITION.
5. PLASMA METAL PATTERN DEFINITION.
6. METALLIZATION

PLASMA PATTERNING: A MAJOR TECHNOLOGY ADVANCEMENT

1. ALL DRY PROCESS.
2. MECHANICALLY MASKED.
3. REPLACES PHOTORESIST PATTERNING.
 - REDUCES MATERIALS CONSUMPTION
 - REDUCES FLOOR SPACE REQUIREMENTS
 - REDUCES CAPITAL COSTS
 - REDUCES ENVIRONMENTAL CONTROL REQUIREMENTS

PHOTORESIST VS PLASMA COMPARISON

PHOTORESIST

1. APPLY PHOTORESIST*
2. BAKE
3. EXPOSE
4. BAKE
5. DEVELOP*
6. ETCH*
7. REMOVE PHOTORESIST*

PLASMA PATTERN

1. ALIGN TO MASK
2. LOAD IN CHAMBER
3. PLASMA ETCH*
4. UNLOAD

*MATERIALS CONSUMED

EXTENSION PROGRAM

1. OPTIMIZATION OF PLASMA SILICON ETCHING.
2. FEASIBILITY OF PLASMA TEXTURE ETCHING.
3. ADVANCED ION IMPLANTATION AND ANNEALING ANALYSIS.
4. OPTIMIZATION OF PLASMA ETCHING OF SILICON NITRIDE.
5. METALLIZATION COST REDUCTION.
6. COST ANALYSIS.
7. PROCESS VERIFICATION.

METALLIZATION COST REDUCTION

1. ELIMINATE ELECTROLESS PALLADIUM LAYER.
2. REPLACE SOLDER CONDUCTOR LAYER.

COMPARISON OF METAL CONDUCTOR LAYERS

	SOLDER (60 ₃ N-40 ₀ PB)	COPPER	SILVER
COST PER POUND* (\$ ON 3-29-79)	4.67	1.00	104.22
RESISTIVITY (MICRO OHM-CM)	14.5	1.673	1.59
DENSITY (GM/CM ³)	8.53	8.96	10.49
RELATIVE WEIGHT PER UNIT CONDUCTIVITY	8.26	1.0	1.11

* BASED ON PURE METAL COMPONENT COSTS

RESULT: TO ACHIEVE IDENTICAL CONDUCTIVITY, FROM A MATERIALS COST STANDPOINT ONLY,

1. SOLDER IS ABOUT 40 X AS EXPENSIVE AS COPPER.
2. SILVER IS ABOUT 115 X AS EXPENSIVE AS COPPER.

THE ESTABLISHMENT OF A PRODUCTION-READY MANUFACTURING PROCESS UTILIZING THIN SILICON SUBSTRATES FOR SOLAR CELLS

PRINCIPAL INVESTIGATOR: R.A. PRYOR

TECHNICAL OBJECTIVES

1. INVESTIGATE, DEVELOP, AND CHARACTERIZE METHODS TO ESTABLISH A MANUFACTURING PROCESS WHICH UTILIZES THIN SILICON SUBSTRATES FOR SOLAR CELLS.
2. BY PROCESS VERIFICATION TESTS AND ANALYSES, DEMONSTRATE THAT AT ANNUAL PRODUCTION VOLUME OF 15 MEGAWATTS AND A 5 YEAR FACTORY LIFE THE FOLLOWING COSTS CAN BE ACHIEVED:

WAFER THICKNESS AS-SAWED	KERF	COST PER CAPITAL	PEAK WATT LABOR
15 MILS	12 MILS	\$ 0.35	\$ 0.135
8 MILS	7.5 MILS	\$ 0.20	\$ 0.080
5 MILS	7.5 MILS	\$ 0.16	\$ 0.065

TECHNICAL APPROACH

1. STANDARD (15 MIL) AND THIN (8 MIL AND 5 MIL) AS-SAWED SUBSTRATES WILL BE CHEMICALLY ETCHED TO REMOVE SAW DAMAGE.
2. THESE SUBSTRATES WILL BE USED TO FABRICATE SOLAR CELLS BY STANDARD PROCESSING TECHNIQUES.
3. PARTICULAR PROCESSING PROBLEMS WILL BE DIAGNOSED AND PROCESSES WILL BE MODIFIED TO ACCOMMODATE THIN SUBSTRATES.
4. OPTIMUM SAW DAMAGE REMOVAL WILL BE DETERMINED THROUGH PROCESSING EXPERIMENTAL SUBSTRATES.
5. OPTIMUM SUBSTRATE THINNESS WILL BE EVALUATED.
6. VARIOUS PROCESS SEQUENCES WILL BE CONSIDERED.

CONTRACT TASKS

- TASK 1. FABRICATION AND EVALUATION OF SOLAR CELLS ON 8 MIL WIRE-SAWED WAFERS ETCHED TO 7 MILS.
- TASK 2. FABRICATION AND EVALUATION OF SOLAR CELLS ON 5 MIL WIRE-SAWED WAFERS ETCHED TO 4 MILS.
- TASK 3. EVALUATE POSSIBILITY OF THINNER CELLS.
- TASK 4. DETERMINE OPTIMUM THICKNESS OF SAW DAMAGE REMOVAL.
- TASK 5. SPECIFY A PILOT LINE PROCESS.
- TASK 6. DEMONSTRATE PILOT LINE CAPABILITY.
- TASK 7. PREPARE PROCESS SPECIFICATION SHEETS.
- TASK 8. COST ANALYSIS.
- TASK 9. SPECIFY PRODUCTION PROCESS.

A BASELINE PROCESS (NO BSF)

START WITH SAWED AND ETCHED WAFER

1. TEXTURE ETCH - BOTH SIDES.
2. PH_3 DIFFUSE, 900°C - BOTH SIDES.
3. ETCH BACK, MESA ETCH FRONT.
4. SILICON NITRIDE AR COAT.
5. ETCH BACK, PATTERN FRONT.
6. METALLIZE.

EVALUATE

WIRE SAW PARAMETERS

PRIMARY

PITCH (WIRE SPACING) - 0.3, 0.4, 0.6 MM

ABRASIVE - 5, 10, 15, 20, 30 μM

WIRE DIAMETER - .075, .10, .15, .20 MM

SECONDARY

WIRE FEED RATE

WIRE SPEED

WIRE LOADING

YASUNAGA WAFERING SYSTEM (YASUNAGA PHOTO)

PITCH

- WIRE SPACING
- COMPLETELY DETERMINES WAFERS/KG
- 0.3, 0.4, 0.6 MM AVAILABLE

PITCH	TOTAL VOLUME	WEIGHT	SILICON COST
0.3 MM	1.37 CM ³	3.19 G	\$.573
0.4 MM	1.82 CM ³	4.25 G	.764
0.6 MM	2.74 CM ³	6.37 G	1.147

ABRASIVE

- 5, 10, 15, 20, 30 μm USED
- KERF LOSS APPROXIMATELY THREE-FOUR TIMES ABRASIVE DIAMETER
- SAW TIME INVERSELY PROPORTIONAL TO ABRASIVE SIZE
- SURFACE DAMAGE PROPORTIONAL TO ABRASIVE SIZE

10 μ m ABRASIVE

WIRE DIAMETER

- MAJOR CONTRIBUTOR TO KERF LOSS
- YASUNAGA ADVERTISES 3 MIL (0.075 MM) MAY BE USED
- 0.075, 0.10, 0.15, 0.20 MM DIAMETER TRIED

WAFERING COST ESTIMATE

ASSUMPTIONS:

- ONE OPERATOR FOR THREE MACHINES
- 0.3 MM PITCH
- 0.15 MM WIRE
- 0.005 μm ABRASIVE
- 3 INCH INGOT

COSTS:	SILICON	\$0.573/WAFER
	LABOR	0.179/WAFER
	MATERIAL	0.177/WAFER
	EQUIPMENT	0.041/WAFER
TOTAL		\$0.970/WAFER
		\$213/METER ²
		\$1.907/WATT

TECHNICAL PROBLEM AREAS

- WIRE SPOOL BREAKAGE
- WEAK RESPOOLER MOTOR
- UNSYNCHRONIZED TRAVERSING MOTOR
- NON-UNIFORM CUTTING RATE
- LOADING VARIATIONS
- EXCESSIVE AIR USAGE
- SLURRY HOSE RUPTURE
- ABRASIVE SETTLES OUT OF SLURRY
- THIN WIRES ARE NOT ECONOMICALLY USABLE
- UNEVEN SILICON SURFACE

OPTICAL COATING LABORATORY, INC. (PCA)

DEVELOPMENT OF LOW COST CONTACTS TO SILICON SOLAR CELLS

(4 December 1978 - 4 April 1979)

The goal of the contract is to test the technical feasibility and effective cost of a copper plating system for the manufacture of solar cells for high volume production of low cost solar array modules.

A sequence has been developed to plate electrolessly, chromium-copper contacts onto the very thin palladium layer formed by the Motorola Pd-immersion bath. Contacts to both P+ and N+ surfaces of slices were formed by simultaneous deposition. These plated Cr-Cu contacts were compared to Cr-Cu contacts formed by vacuum evaporation.

For both systems, the contact thickness was built up using electrolytic copper deposition. Good adhesion and good cell performance was obtained for both systems. However, there was cell degradation after repeated heat treatments. Attempts were made to decrease the degradation by using more effective masking methods during plating.

In addition cells have been made by depositing copper (electrolessly) directly onto Pd formed by the Motorola immersion method and electroless bath. These cells also had contact build up by electrolytic Cu plating. Preliminary results show that the overall cell properties resemble those made using the Pd-Cr-Cu sequence.

March 19, 1979

D. P. Tanner

PLATED PALLADIUM-PALLADIUM-COPPER

PLATED PALLADIUM-CHROMIUM-COPPER

EVAPORATED CONTACT TEST

GROUP NO.	CONTACT TYPE
1	Cr-Cu (1000Å Cr - 5000Å Cu)
2	Cr-Cu-Plated Cu (4-6 microns)
3	Ti-Pd-Ag (only 2000Å Ag)
4	Ti-Pd-Ag-Plated Ag (4-6 microns)

Sets from each group were heated at 400°C, 450°C, and 500°C for 5 minutes in Nitrogen. Groups 1 and 3 plated-up after heat treatments for proper comparison:

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Chromium-Copper Evaporated Heat Treat Tests

TEST CONDITION:

AM0

TEMPERATURE:

28°C

DATE: 23 March 1979

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
GROUP 1										
400°C	594	143	51	91	130	.5	65	.76	12	4
500°C	554	141.7	50	92	104	.385	40	.51	7.4	4
GROUP 2										
400°C	597	144	51.6	93	133	.495	65.8	.77	12.2	4
500°C	302	141	50	90	103	.16	16.5	.39	3	4
GROUP 3										
400°C	594	146	50	96.8	135	.495	66.8	.77	12.4	4
500°C	597	148	51	97.6	136	.5	58.4	.77	12.7	4
GROUP 4										
400°C	596	147.8	50	97.5	134	.495	66.3	.75	12.3	4
500°C	595	146	53	93	132.5	.49	64.9	.75	12	4

CONTACT ADHESION

CONTACT TYPE	MODE	AREA	PULL STRENGTH	
			FRONT	BACK
Ti-Pd-Ag	Evaporated	.02 cm ²	200 gm*	236 gm [†]
Cr-Cu	Evaporated	.02 cm ²	117 gm*	250 gm [†]
Pd-Cr-Cu	Plated	.02 cm ²	83 gm*	220 gm [†]
Pd-Pd-Cu	Plated	.02 cm ²	170 gm*	280 gm [†]

*Pulled Some Silicon

[†]Cell Broke

Cell Substrate: 7-14 ohm-cm P-Type - Chemically Polished Front -
Al Alloyed Back

ARCO SOLAR, INC.

AUTOMATED SOLAR PANEL ASSEMBLY LINE

OBJECTIVES

1. ESTABLISH MODULE DESIGN COMPATIBLE WITH AUTOMATED MODULE FABRICATION TECHNIQUES.
2. DESIGN AND FABRICATE AUTOMATED SOLAR CELL SOLDERING MACHINE CAPABLE OF ASSEMBLING 12 CELLS/MINUTE.
3. DESIGN AND FABRICATE AUTOMATED MODULE LAMINATING MACHINE CAPABLE OF 12 MODULES/HOUR.
4. INSTALL EQUIPMENT INTO PRODUCTION LINE AND OPERATE AUTOMATED PILOT LINE.

APPROACH

MODULE DESIGN

100 MM SOLAR CELL WITH FULLY REDUNDANT INTERCONNECTS COMPATIBLE WITH AUTOMATION. FIELD PROVEN ENCAPSULATION SYSTEM.

SOLDERING MACHINE

DEVELOP SIMPLE, RELIABLE MECHANISMS. SIMULTANEOUS SOLDERING OF TOP AND BOTTOM CELL INTERCONNECTS.

LAMINATION SYSTEM

VACUUM LAMINATION CHAMBER USING INFRARED HEATING, DIAPHRAGM SEALING AND FORCED COOLING.

CELL STRINGER

STATUS

MODULE DESIGN AND TESTING

DESIGN COMPLETE; DESIGN LIMIT THERMAL CYCLING COMMENCED

SOLDERING MACHINE

1. SOLDERING HEAD DESIGNED AND MECHANICALLY TESTED
2. a. CELL ALIGNMENT AND TRANSPORT IN DESIGN
b. RIBBON FEED AND ADVANCE IN DESIGN
3. CELL CLEANING SYSTEM DESIGNED
4. MYLAR STRIP ATTACHMENT DESIGN NEAR COMPLETION

LAMINATION SYSTEM

5. PRODUCTION LAMINATION CHAMBER DESIGNED
6. INSTRUMENTATION AND CONTROL IN DESIGN
7. LAMINATION ROTARY IN DESIGN

OPEN ISSUES

1. SOLDERING PROOF OF DESIGN TO BE DEMONSTRATED
2. THINNER LAMINATION PROCESS TO BE DEVELOPED

AR COATING BY WITHDRAWAL FROM SOLUTION

- 88% TiO_2 - 12% SiO_2
- RESULTS DEPENDENT ON - VISCOSITY
 - CONCENTRATION
 - RATE OF WITHDRAWAL
- EFFICIENCY ENHANCEMENT UP TO 48%
- COST EFFECTIVE

Coating thickness as a function of solution concentration and withdrawal rate in dipping application.

Spectral reflectivity of a AR coating on a web silicon solar cell (composition 88% TiO_2 - 12% SiO_2 , heat treated at 450°C)

Change in index of refraction and coating thickness during heat treatment

EFFECT OF METAL-ORGANIC DERIVED AR COATINGS ON SOLAR CELL PERFORMANCE

CELL	COATING	EFFICIENCY (%)		ENHANCEMENT
		UNCOATED	COATED	
1009B3	TaO ₂ (BASELINE)	8.95	12.70	42%
1012B3	TiO ₂ + SiO ₂	8.65	12.82	48%

ANTIREFLECTION FILM THICKNESS VS ENHANCEMENT FACTOR

PRESENT PROCESS FOR DIP COATING AR

CONDITIONS: 1 WEB WITHDRAWN AT A TIME

30 CM/MIN = 0.5 WATTS

YEARLY OUTPUT - 0.25×10^6 WATTS

COSTS: 4 TECHNICIANS + SUPERVISION - 65K\$

UTILITIES \$ 125

MATERIALS \$ 750

LAB SPACE \$2500

CAPITAL \$2000

COST/WATT -- .28/WATT PEAK (1986\$)

LABOR INTENSIVE

AR COATING BY DIPPING COST INPUTS

2.01	BUFFER (HOLDING AREA FOR MATERIAL FROM JUNCTION FORMATION PROCESS)	LABOR - 0.1 PY CAPITAL - 10K\$ FLOOR SPACE - 97 FT ² - UTILITIES 0.5 KW
2.02	AR - DIP & DRAIN (WEB - HELD IN FRAMES DIPPED IN VAT OF SOLUTION)	LABOR - 0.25 PY CAPITAL - 60K\$ FLOOR SPACE 17 FT ² - UTILITIES 0.5 KW COMMODITIES: AR SOL'N 1.33×10^{-5} L/MIN ISOPROPYL 6.3×10^{-3} L/MIN ALCOHOL
2.03	BAKE AND COOL (WEB BAKED AT 400°C FOR 5 MIN. AND COOLED FOR 10 MIN.)	LABOR - 0.25 PY CAPITAL - 20K\$ FLOOR SPACE 48 FT ² UTILITIES - 4.5 KW

BASIC PROCESS STEPS

(P ON N CELL - BORON IMPLANTED JUNCTION)

- 1.) APPLY FRONT (10-12 μ Al) AND BACK (.1-.3 μ OF As DOPED Ag + 2 - 3 μ Ni) CONTACTS THROUGH APPROPRIATE MECHANICAL MASKS.
- 2.) APPLY COMBINED COATING (AR, HERMETIC SEAL, IMPLANTATION OXIDE) OF Al_2O_3 OVER FRONT SURFACE AND EDGE.
- 3.) ION-IMPLANT FRONT JUNCTION USING MECHANICAL EDGE MASK TO PROVIDE PASSIVATED STRUCTURE.
- 4.) HEAT TREAT TO SIMULTANEOUSLY ELECTRICALLY ACTIVATE IMPLANTED IONS AND ALLOY CONTACTS.

MANUFACTURING PROCESS SEQUENCE

MANUFACTURING ADVANTAGES

- 1) EXTREME SIMPLICITY - ONLY 4 MAJOR MANUFACTURING STEPS INCLUDING ENCAPSULATION - SIMPLE CELL CONFIGURATION.
- 2) COMPLETELY INTEGRAL CELL - NO SURFACE BONDED INTERFACES - WELDABLE CONTACTS.
- 3) FOOLPROOF PROCESSING - HIGH YIELD
- 4) COMPLETELY AUTOMATABLE AND CAPABLE OF VERY LARGE SCALE PRODUCTION.
- 5) ALL CONVENTIONAL SILICON STARTING MATERIALS USEABLE(Cz, FLOAT-ZONED, DENDRITIC, EFG ETC. - COULD BE PREFERRED METHOD FOR THIN FILM MATERIALS).
- 6) ALL MATERIALS USED READILY AVAILABLE AND CONSISTENT WITH LOW COST PROCESSING.
- 7) CELL CONFIGURATION FOR LINEAR MATERIALS CONSISTENT WITH LOW COST ARRAY FABRICATION.

FRONT CONTACT SHEET RESISTIVITY

Al Thickness (μ)	Measuring Condition	Heat Treatment	Sheet Resistivity ($m\Omega/\square$)	Effective Metal Resistivity ($\times 10^{-6}\Omega\text{-cm}$)
8.6	Al-Al	No H. T.	9.1	7.8
	Al-Al	870°C	16.9	14.5
	Al-Al ₂ O ₃	870°C	16.6	14.3
	Al-Al	2nd 870°C	17.8	15.3
	Al-Al ₂ O ₃	2nd 870°C	17.8	15.3
16.8	Al-Al	no H. T.	5.6	9.4
	Al ₂ O ₃ - Al ₂ O ₃	870°C	9.5	16.0
25.4	Al-Al	no H. T.	4.6	11.7
	Al ₂ O ₃ - Al ₂ O ₃	870°C	7.5	19.1

FRONT CONTACT RESISTANCE

Front Contact Al Thickness (μ)	Heat Treatment	Resistance One Contact Tab ($m\Omega$)	Resistance Two Contact Tabs ($m\Omega$)
9	no H.T.	1.67 (Ω)	1.56 (Ω)
	870°C	63.5	30.1
	970°C	65.4	31.0
17	no H.T.	1.72 (Ω)	1.64 (Ω)
	870°C	54.2	25.2
	970°C	55.9	26.1
23	no H.T.	1.64 (Ω)	1.57 (Ω)
	870°C	48.1	23.0
	970°C	50.0	23.7

LARGE AREA ALLOYED DIODE CHARACTERISTICS

200 mA/div. -vertical
0.5 V/div. -horizontal

1(a) 0.9 x 1.6 cm Diode

KINETIC COATINGS, INC.

200 mA/div. -vertical
0.5 V/div. -horizontal

1(b) 2'' x 2'' Diode

KULICKE & SOFFA

SECTION I – INTRODUCTION

K & S TO DESIGN, BUILD, & DELIVER AN AUTOMATED ASSEMBLY LINE WITH THE FOLLOWING GOALS:

1. FLEXIBLE DESIGN - ADAPTABLE TO VARIETY OF APPLICATIONS
 - ASSEMBLE UP TO A 6 STRING MODULE
 - PERMIT STRINGS TO BE ASSEMBLED IN SERIES OR SERIES/PARALLEL RELATIONSHIP
2. MACHINE TO BE BUILT -
 - TO ASSEMBLE A TYPICAL SOLAR CELL AND MODULE
 - MACHINE CYCLE TIME - 5 SECONDS
 - INDEX TIME - 1 - 1.5 SECONDS
 - OPERATION TIME - 3.5 - 4 SECONDS
 - YIELD - 95% OR BETTER

SECTION III – MACHINE CONSIDERATIONS AND DESIGN APPROACH

SECTION III STRING TESTING STATION

FORWARD BIAS TEST - AFTER EACH 2ND INTERCONNECT IS MADE

STATION 11 - VACUUM TRANSFER

PRODUCTION PROCESS AND EQUIPMENT AREA

AUTOMATED PROCESSING EQUIPMENT CURRENT PERFORMANCE

<u>SPFAKFR</u>	<u>COMPANY</u>	<u>SUBJECT</u>
W. KERN	RCA	SPRAY ANTIREFLECTION COATING
R. V. D'AIELLO	RCA	THICK FILM METALLIZATION
S. CHITRE	SENSOR TECH	LASER SCRIBER
S. CHITRE	SENSOR TECH	SPRAY-ON JUNCTION
R. B. CAMPBELL	WESTINGHOUSE	DIP ANTIREFLECTION COATING

SURFACE PREPARATION

GOALS

- COST CONTRIBUTIONS OF LESS THAN 2¢/W
- REDUCE REFLECTION LOSS TO LESS THAN 5%
- REMOVE SURFACE DAMAGE/IMPURITIES
- COMPATIBLE WITH OTHER PROCESSING

CURRENT STATUS

- COST CONTRIBUTIONS
 - ETCHING 2.1¢ TO 8.5¢/W
 - AR COATING
 - VACUUM $\approx$ 62¢/W
 - SPIN-ON $\approx$ 3¢/W
- REFLECTION LOSS
 - VACUUM COATED $\approx$ 5%
 - SPUN ON $\approx$ 16%
- DAMAGE REMOVED WITH $\approx$ 0.0015 IN
- TENDENCY FOR PEELING

JUNCTION FORMATION

GOALS

- COST CONTRIBUTION OF LESS THAN 2¢/W
- COMPATIBLE WITH 16% CELL EFFICIENCY
- COMPATIBLE WITH METALLIZATION
- INCLUDE BSF TRADEOFFS
- INCLUDE MATERIAL THICKNESS & RESISTIVITY

CURRENT STATUS

- COST CONTRIBUTIONS
 - GASEOUS DIFFUSION 7¢ TO 14¢/W
 - SPIN-ON $\approx$ 5¢/W
 - ALUMINIUM P⁺ BSF $\approx$ 4¢/W
- SPIN-ON EFFICIENCIES $\leq$ 13%
- ALUMINIUM-SILVER COMBINATION TENDS TO CORRODE

METALLIZATION

GOALS

- COST CONTRIBUTION OF LESS THAN 4¢/W
- GOOD METALLURGICAL BOND
- CONTACT RESISTANCE LESS THAN 10 m Ω /cm²
- SHEET RESISTANCE LESS THAN 10 m Ω /square
- GOOD SOLDERABILITY
- YIELD OF 99.95%
- 20 YEAR LIFE

CURRENT STATUS

- COST CONTRIBUTIONS
 - THICK FILM SILVER 22¢ TO 29¢/W
 - NICKEL PLATE WITH SOLDER 43¢ TO 75¢/W
- ADEQUATE BOND, CONDUCTIVITY, AND SOLDERABILITY
- YIELD INCONSISTENT
- RELIABILITY UNPROVEN

ASSEMBLY

GOALS

- COST CONTRIBUTION OF LESS THAN 17¢/W
- YIELD GREATER THAN 99.9%
- 20-YEAR LIFE
- COMPATIBILITY WITH VARIOUS SHEET FORMS

CURRENT STATUS

- COST CONTRIBUTION OF \$1 TO \$4.60/W
- YIELD HIGH WITH REWORK
- LIFE NOT KNOWN

4. Engineering Area

ENGINEERING DEVELOPMENTS POTPOURRI

R. ROSS

5 APRIL 1979

MAJOR UNREPORTED ENGINEERING ACTIVITIES

- CELL RELIABILITY TESTING (CLEMSON)
- ELECTRICAL TERMINATION STUDY (MOTOROLA)
- ELECTRICAL SAFETY REQUIREMENTS (UL)
- ARRAY STRUCTURAL ANALYSIS (BECHTEL/JPL)
- ENVIRONMENTAL TEST DEVELOPMENT (JPL)
 - SOILING
 - INSULATION DURABILITY

ENGINEERING AREA PRESENTATIONS

- CENTRAL STATION WIND LOADS (BOEING)
- RESIDENTIAL MODULE REQUIREMENTS (BURT HILL)
- MODULE ELECTRICAL INSULATION REQ. (BECHTEL)
- SOLAR CELL FRACTURE STRENGTH (JPL)
- IR CAMERA HOT-SPOT TEST RESULTS (JPL)
- SERIES-PARALLEL ANALYSIS UPDATE (JPL)
- MISMATCH LOSS FIELD EXPERIENCE (MIT/LL)
- ARRAY STANDARDS UPDATE (JPL)

PHOTOVOLTAIC ENERGY CALCULATION CONSIDERATIONS

OBJECTIVE: DERIVE MEASUREMENT REFERENCE CONDITIONS REQUIRED FOR ACCURATE ENERGY OUTPUT CALCULATIONS

GIVEN:

$$\text{ANNUAL ENERGY OUTPUT / m}^2 = \int_{\text{YEAR}} \int_{\lambda} S_{\lambda}(t) \eta_{\lambda}(T) d\lambda dt$$

WHERE:

S_{λ} = SPECTRAL INSOLATION AT TIME (t), ($\text{W/m}^2/\lambda$)

η_{λ} = ARRAY SPECTRAL ELECTRICAL EFFICIENCY, $\left(\frac{\text{W/m}^2}{\text{W/m}^2/\lambda} \right)$

T = CELL TEMPERATURE AT TIME (t), °C

CALCULATION SIMPLIFICATION IMPLICATIONS

SIMPLIFICATION: IGNORE TIME VARYING SPECTRUM

$$\int_{\text{YEAR}} \int_{\lambda} S_{\lambda}(t) \eta_{\lambda}(T) d\lambda dt \approx \int_{\text{YEAR}} S(t) \eta(T) dt$$

WHERE:

S = PYRANOMETER INSOLATION AT TIME (t), W/m^2

η = ARRAY EFFICIENCY FOR REFERENCE SPECTRUM

T = CELL TEMPERATURE AT TIME (t), °C

REQUIREMENT:

REFERENCE SPECTRUM SHOULD BE CHOSEN FOR BEST APPROXIMATION WITH:

- VARIOUS CELL SPECTRAL RESPONSES
- VARIOUS SITE INSOLATION SPECTRUMS

SIMPLIFICATION: IGNORE TIME VARYING EFFICIENCY

$$\int_{\text{YEAR}} S(t) \eta(t) dt \approx \eta(T_{\text{NOCT}}) \int_{\text{YEAR}} S(t) dt$$

WHERE:

T_{NOCT} = NOMINAL OPERATING CELL TEMPERATURE, °C

• CELL TEMPERATURE FOR REFERENCE
AIR TEMPERATURE, INSOLATION AND WIND

REQUIREMENT:

REFERENCE AMBIENT CONDITIONS SHOULD BE CHOSEN FOR BEST APPROXIMATION WITH:

- VARIOUS ARRAY THERMAL DESIGNS
- VARIOUS SITE AMBIENT CONDITIONS

ENERGY OUTPUT VS CELL TEMPERATURE

ENERGY OUTPUT VS INSOLATION LEVEL

CELL EFFECTIVE OPERATING TEMPERATURE VS EFFECTIVE INSOLATION LEVEL

(ALBUQUERQUE, N.M.)

CELL EFFECTIVE OPERATING TEMPERATURE

(FOR 100 mW/cm² EFFECTIVE INSOLATION LEVEL)

CELL EFFECTIVE OPERATING TEMPERATURE (FOR 80 mW/cm² EFFECTIVE INSOLATION LEVEL)

SIMPLIFIED ENERGY CALCULATION SUMMARY

ARRAY TYPE	SITE LOCATION	TOTAL INSOL. KW-Hrs m ² -YR	ACTUAL ARRAY OUTPUT KW-Hrs m ² -YR	$\eta_{NOCT} \int S dt / YR$ / ACTUAL ARRAY OUTPUT			
				S:80 T:80, 20	S:100 T:80, 20	S:100 T:100, 20	S:100 T:100, 15
AVG. FLAT PLATE	ALBUQ.	2316	248	1.00	1.01	0.98	1.00
	CAP. HAT.	1832	196	0.99	1.01	0.98	1.01
	OMAHA	1853	201	0.99	1.00	0.97	0.99
	MIAMI	1895	196	1.03	1.04	1.02	1.04
AVG. 2-AXIS CON.	ALBUQ.	2552	274	0.99	1.01	0.98	1.00
	CAP. HAT.	1512	162	0.99	1.01	0.98	1.01
	OMAHA	1638	177	0.99	1.00	0.97	0.99
	MIAMI	1372	142	1.03	1.05	1.01	1.04
HOT 2-AXIS CON.	ALBUQ.	2552	252	1.00	1.01	0.96	0.98
	CAP. HAT.	1512	152	0.97	1.00	0.94	0.97
	OMAHA	1638	166	0.97	0.98	0.93	0.95
	MIAMI	1372	134	1.01	1.02	0.96	0.99

S: INSOLATION (mW/cm²), T: INSOL. (mW/cm²), AIR TEMP. (°C)

PHOTOVOLTAIC ARRAY SERIES/PARALLEL STUDIES

CHARLES GONZALEZ

SERIES-PARALLEL STUDIES

- OBJECTIVE:

DEVELOP GUIDELINES FOR SOLAR CELL CONFIGURATIONS
WHICH ARE CONSISTENT WITH MINIMUM LIFE-CYCLE
COST

- APPROACH:

- DEFINE CELL/MODULE FAILURE MECHANISMS
- USE COMPUTER PROGRAM TO PERFORM PARAMETRIC ANALYSES
- ANALYZE RESULTS IN ORDER TO DEVELOP GUIDELINES FOR:
 - DETERMINING OPTIMUM SERIES-PARALLEL COMBINATIONS
 - APPROPRIATE USE OF BYPASS DIODES

CURRENT STATUS

- TOPICS PREVIOUSLY COVERED:

- POWER LOSS VS SERIES-PARALLELING
- MISMATCH LOSSES
- "HOT-SPOT" HEATING
- USE OF DIODES
- MANUFACTURING YIELD

- EXPANSION OF ABOVE TOPICS

- MULTI-CELL FAILURES CONSIDERED
- "HOT-SPOT" HEATING UNDER NON-UNIFORM CELL PARAMETERS
- DIODE VS SERIES-PARALLELING TRADE-OFFS
- MANUFACTURING YIELD CONSIDERATIONS FOR DIFFERENT CELL FAILURE RATES

MANUFACTURING YIELD STUDY UPDATE

• PREVIOUS CONCLUSION:

MODULES OF MORE THAN 100 CELLS REQUIRE AT LEAST SIX PARALLEL STRINGS AND TWO SERIES BLOCKS TO IMPROVE YIELD BASED ON CELL FAILURE RATE OF 1 PER 1000

• UPDATED CONCLUSIONS:

IN ADDITION:

- MODULES OF 100 CELLS OR MORE REQUIRE EXTENSIVE SERIES-PARALLELING TO ATTAIN ACCEPTABLE YIELDS FOR CELL FAILURE RATES OF 1 PER 100
- MODULES OF MORE THAN 100 CELLS REQUIRE MINIMAL SERIES-PARALLELING FOR CELL FAILURE RATES OF 1 PER 10,000

BRANCH CIRCUIT POWER LOSS VS CELL FAILURE DENSITY

DIODE VS SERIES-PARALLEL TRADE-OFF

MAXIMUM NUMBER OF
CROSS TIES AND
SERIES BLOCKS

NO CROSS TIES,
ONE SERIES BLOCK,
MAXIMUM NUMBER OF DIODES

MODULE IV CURVE VS NUMBER OF DIODES

BRANCH CIRCUIT POWER LOSS VS NUMBER OF DIODES PER SUB-STRING

"HOT-SPOT" HEATING CELL SHUNT RESISTANCE

"HOT-SPOT" HEATING VS CELL CONFIGURATION

HEATING CONSTANT HISTOGRAM

HEATING CONSTANT VS NUMBER OF CELLS IN A SUB-STRING

CONCLUSIONS

- FOR 4 STRINGS IN PARALLEL MULTI-CELL FAILURES LEAD TO A NON-LINEAR POWER LOSS FOR CELL FAILURE DENSITIES GREATER THAN 0.0001
- TRADE-OFFS BETWEEN USE OF DIODES AND USE OF SERIES-PARALLELING FAVOR DIODES – ALL THINGS BEING EQUAL
- NON-UNIFORM CELL PARAMETERS REQUIRE THAT THE OPTIMUM SERIES-PARALLEL ARRANGEMENTS TO REDUCE "HOT-SPOT" PROBLEMS BE DETERMINED STATISTICALLY

FUTURE WORK

- COMPLETE MULTI-CELL FAILURE ANALYSIS FOR PARALLEL STRINGS GREATER THAN FOUR
- "HOT-SPOT" HEATING
 - EXPAND GUIDELINES DEVELOPMENT FOR NON-UNIFORM HEATING BASED ON GIVEN PARAMETER DISTRIBUTIONS
 - CORRELATE ANALYTICAL RESULTS WITH EMPIRICAL DATA
- DOCUMENT RESULTS OF ANALYSES TO DATE INCLUDING GUIDELINES AND RECOMMENDATIONS

FRACTURE MECHANICS TESTING OF SILICON SOLAR CELLS

by
C. P. Chen

OBJECTIVES

- DETERMINE NATURE AND SOURCE OF FLAW CONTROLLING FRACTURE OF SILICON SOLAR CELLS
- DETERMINE STRENGTH OF SOLAR CELLS AS FUNCTION OF:
 - MANUFACTURING PROCESS STEPS - SAWING, CHEMICAL POLISHED, TEXTURE ETCHED . . . COMPLETED CELL
 - CELL PHYSICAL FACTORS - CELL MATERIAL, SHAPE, SIZE, DESIGN, . . .
 - STRESS CONDITIONS - UNIAXIAL, BIAXIAL, SHEAR
- DETERMINE STANDARD TEST METHOD FOR SILICON SHEET MATERIAL

CYLINDRICAL BENDING OF SOLAR CELL

$$\sigma_f = \frac{3P(L-l)}{2dt^2}$$

BIAXIAL FLEXURE STRENGTH TEST OF SOLAR CELLS

$$\sigma_{r \max} = \sigma_{t \max} = -\frac{3}{4\pi} \frac{P}{t^2} (X - Y)$$

WHERE

$$X = (1 + \nu) \ln \left(\frac{b}{c} \right)^2 + \frac{1}{2} \frac{\nu}{2} \left(\frac{b}{c} \right)^2$$

$$Y = (1 + \nu) \left[1 + \ln \left(\frac{a}{c} \right)^2 \right] + (1 - \nu) \left(\frac{a}{c} \right)^2$$

FOUR-POINT TWISTING OF SOLAR CELL

$$\tau_s = \frac{T}{abt^2}$$

WHERE

$$T = \text{TORSIONAL MOMENT} = \frac{P}{2} s$$

$$b = s$$

$$\alpha = f \left(\frac{b}{t} \right), \text{ FOR } \frac{b}{t} \rightarrow \infty, \alpha \rightarrow \frac{1}{3}$$

WEIBULL DISTRIBUTION (WEAKEST LINK STATISTICS)

$$\text{FRACTURE PROBABILITY } G = 1 - \exp \left[- \int_V \left(\frac{S - S_u}{S_0} \right)^m dV \right]$$

S_u = STRESS BELOW WHICH NONE WILL FAIL

$S_u + S_0$ = STRESS ABOVE WHICH ALL WILL FAIL

S = STRESS OF INTEREST

m = WEIBULL MODULUS (RELATE TO SLOPE OF PLOT)

S_m = S AT 0.5 G , $S_m \approx S_{ave}$

EFFECT OF TEST METHODS ON THE MEASURED STRENGTH OF SILICON WAFERS

FRACTURE PROBABILITY vs MODULUS OF RUPTURE OF AS-CUT AND CHEMICAL POLISHED SILICON WAFERS

$\langle 110 \rangle$

$\langle 100 \rangle$

FRACTURE PROBABILITY vs BIAxIAL STRENGTH OF SILICON WAFERS

AS-CUT

CHEMICAL POLISHED

EFFECT OF CELL PROCESSES ON THE STRENGTH OF WAFERS

Typical Fracture of Silicon Wafers Subjected to Four-point Twisting

SUMMARY

- STRENGTH*, (ksi)/DEFLECTION**, (in.)

CELL PROCESS	UNIAXIAL MOR	BIAXIAL	SHEAR
AS-CUT	16-19 (24-17 μ)/0.05	24-34/0.06	5-15/0.09
CHEM POLISHED	20-48 (18-3 μ)/0.11	28-120/0.13	14-55/0.21
TEXT. ETCHED	-	36-65/0.09	9-28/0.14
COMPLETED CELL	-		17-42/0.14

* STRENGTH RANGE IN WHICH 90% OF FAILURES OCCUR

** MEAN DEFLECTION

() CALCULATED FLAW SIZE RANGE

- SHEAR STRENGTH MEASURED BY FOUR-POINT TWISTING TEST IS RECOMMENDED AS A STANDARD TEST METHOD FOR STRENGTH MEASUREMENT OF SILICON SOLAR CELLS

FUTURE WORK

- CONTINUE AND COMPLETE STRENGTH MEASUREMENT ON CELLS AT SEVERAL CELL MANUFACTURERS AND MANUFACTURING PROCESSES
- PERFORM TESTS OF CELLS WITH OTHER PHYSICAL CHARACTERISTICS - IN TERMS OF NATURE OF SHEET, SHAPE, SIZE, etc.
- CONDUCT FAILURE ANALYSIS TO DETERMINE NATURE AND SOURCE OF FLAW CONTROLLING FRACTURE OF SOLAR CELLS
- PERFORM WEIBULL STATISTICAL ANALYSIS

MODULE/ARRAY INTERFACE STUDY

Research and Engineering Operation
Bechtel National, Inc.
San Francisco, California

The objectives of this study are to: 1) evaluate the technical and economic feasibility of a curved glass-superstrate module configuration and 2) develop voltage isolation requirements for modules.

A previous study, performed by Bechtel, indicated that a clip-supported, slightly curved glass superstrate module would cost substantially less than an equivalent metal-framed module, due to reductions in framing material costs. During the present study a survey of glass manufacturers and fabricators was conducted to determine the cost and practicality of manufacturing the curved superstrate in both test sample and production quantities. Survey results indicate that the design is technically feasible and that prototype curved glass structures are being fabricated for use as mirrors in thermal systems. However, sufficient cost data to permit analysis of large quantity production costs have not been obtained thus far.

In the area of electrical insulation, a literature search was conducted to identify and evaluate existing design practices and test methods applicable to photovoltaic modules. Available data mostly relates to insulation in ac fields and reflects work done by the cable industry. This data indicates that dielectric strength decreases with time and that to ensure acceptable long-term (e.g., 20 years) performance, the maximum stress levels must be kept well below the measured short-time breakdown values. The existing data indicate that short-duration test procedures are useful for quality control purposes, but do not predict long-time performance. Although various types of accelerated aging tests have been proposed, it appears that real-time testing is required to verify insulation system design integrity. This is especially true for novel configurations, such as solar cell encapsulation systems, in which the materials will be stressed by DC and, possibly, inverter ripple-induced AC fields. Also, the long-time effect of voltage stress on extremely thin layers of material (e.g., thin plastic films or primer coats) within the encapsulation system requires further investigation. This is necessary because for insulation systems in DC fields, where the voltage is distributed across a series combination of two or more different insulating materials, the ratio of the field strengths in the materials varies directly with the ratio of their resistivities (as opposed to the materials' permittivities for AC or transient fields). In such multilayer cases, unacceptable stress levels might result.

Viewgraphs detailing this presentation appear on the following pages.

CURVED GLASS MODULE AND MODULE ELECTRICAL INSULATION REQUIREMENTS

DAN ROSEN
BECHTEL NATIONAL, INC.

APRIL 5, 1979

CURVED GLASS MODULE

4x8 FT PANEL TYPE	PANEL STRUCTURAL COSTS-\$/M ² (1975 \$/S)		
	35 PSF	50 PSF	75 PSF
FLAT PLATE "PICTURE FRAME" SUPPORT	18.00	21.70	26.60
CURVED GLASS ⁽¹⁾ CLIP SUPPORT	6.90	6.90	6.90

(1) EXCLUSIVE OF COST FOR CURVING THE GLASS

CURVED GLASS MODULE SUPPORT STRUCTURE CONCEPTS

CURVED GLASS MODULE FUTURE WORK

WORK TO BE ACCOMPLISHED DURING THE NEXT THREE MONTHS WILL INCLUDE :

- EVALUATION OF FABRICATION COSTS FOR CURVING GLASS SHEETS IN COMMERCIAL PRODUCTION QUANTITIES
- DEVELOPMENT OF DESIGNS AND ESTIMATES OF INSTALLED COSTS FOR THE CURVED GLASS MODULE AND THE FOUR SUPPORT STRUCTURE TYPES FOR UNIFORM LOADINGS OF 20, 35 AND 50 PSI
- COMPUTER AIDED FINITE ELEMENT ANALYSES OF STRESS DISTRIBUTIONS IN THE CURVED GLASS SHEET
- DEVELOP A TEST PLAN TO EVALUATE AND VERIFY THE FINALIZED CURVED GLASS DESIGN

ELECTRICAL ISOLATION DESIGN CONCLUSIONS

- EXISTING INFORMATION RELATES PRIMARILY TO INSULATION IN AC FIELDS.
- MAXIMUM STRESS LEVELS MUST BE KEPT WELL BELOW MEASURED SHORT-TIME BREAKDOWN VALUES.
- DESIGN EVALUATION MUST CONSIDER :
 - SHORT TERM MATERIAL CHARACTERISTICS
 - EFFECTS OF AGEING ON MATERIAL CHARACTERISTICS
 - EFFECTS OF CONFIGURATION AND CONSTRUCTION ON THE STRESS DISTRIBUTION WITHIN THE ENCAPSULATING MATERIALS
- SHORT-TIME TESTS DO NOT SUBJECT THE MODULE TO THE EFFECTS OF AGEING ENCOUNTERED IN SERVICE AND ARE OF LIMITED USE IN PREDICTING LONG TIME PERFORMANCE
- REAL TIME TESTING UNDER ACTUAL OPERATING CONDITIONS IS NECESSARY TO VERIFY INSULATION DESIGN INTEGRITY

EFFECT OF TIME ON THE DIELECTRIC STRENGTH OF POLYETHYLENE UNDER AC STRESS

FACTORS AFFECTING THE BREAKDOWN LEVEL INCLUDE:

MODULE VOLTAGE ISOLATION DESIGN LEVELS

● REQUIREMENTS

THE MODULE ENCAPSULATING SYSTEM MUST MAINTAIN ACCEPTABLE ELECTRICAL INSULATING PROPERTIES THROUGHOUT THE MODULES USEFUL LIFE, BOTH TO PREVENT PREMATURE FAILURE AND TO PROTECT PERSONNEL AGAINST SHOCK HAZARDS.

● SOURCES OF ELECTRICAL STRESS

THE MODULE ENCAPSULATING SYSTEM WILL BE STRESSED BY ELECTRIC FIELDS RESULTING FROM:

- (1) DC SYSTEM VOLTAGE
 - (A) MAXIMUM OPEN-CIRCUIT VOLTAGE
 - (B) OPERATING VOLTAGE (VARIES WITH TEMPERATURE)
- (2) TRANSIENT VOLTAGE
 - (A) LIGHTNING INDUCED
 - (B) INVERTER (IF USED) CAUSED
- (3) AC RIPPLE (IF INVERTER IS USED)

THE DIELECTRIC STRENGTH OF AN INSULATING MATERIAL DECREASES WITH INCREASING TIME UNDER STRESS

VOLTAGE DISTRIBUTION VERSUS TIME FOR DIELECTRIC IN SERIES

ELECTRICAL ISOLATION DESIGN CONSIDERATIONS

- EACH DESIGN MUST BE INDIVIDUALLY EVALUATED TO ASSESS ITS LONG TERM ISOLATION CAPABILITIES

- DESIGN EVALUATION MUST CONSIDER:
 - SHORT TIME MATERIAL CHARACTERISTICS
 - EFFECTS OF AGEING ON MATERIAL CHARACTERISTICS
 - EFFECTS OF CONFIGURATION AND CONSTRUCTION ON THE STRESS DISTRIBUTION WITHIN THE ENCAPSULATING MATERIALS

- IF PROPERLY APPLIED, SHORT TIME TESTS SUCH AS THE UL DIELECTRIC WITHSTAND TEST PROCEDURE CAN BE USEFUL IN ASSESSING MANUFACTURING QUALITY

- SHORT TIME TESTS DO NOT SUBJECT THE MODULE TO THE EFFECTS OF AGEING ENCOUNTERED IN SERVICE AND ARE OF LIMITED USE IN PREDICTING LONG TIME PERFORMANCE

RESIDENTIAL PHOTOVOLTAIC MODULE REQUIREMENTS STUDY

Burt Hill Kosar Rittelmann Associates
Butler, Pennsylvania

The objective of this almost-completed study was to investigate the requirements that would be placed upon modules integrated into a residence. The study was divided into four sections. The first section was a review of building codes and their referenced standards. This portion of the task was completed at the end of December.

The second section of the study was the investigation of module size and installation procedures. It was determined that the best approach was to deal with the module as a "black box" and ignore module construction. Four mounting types were identified: rack mount, stand-off mount, direct mount, and integral mount. Cost breakdowns were developed for the identified module sizes for each of these mounting types.

Upon completion of the second section of the study, the contractor began analyzing the effect of the electrical code upon the module design and also upon the associated wiring and terminal requirements.

The final section of the study was the cost analysis of installed arrays for the different mounting configurations, module sizes, and module wiring schemes.

The final report will be developed as a series of studies to show the particular concerns each of the mounting types must face in reference to the building industry. It will also be a preliminary document for the development of appropriate standards and test methods to assist in the penetration of the residential market with photovoltaic modules.

The draft final report is in preparation. The final report is expected to be available in July, 1979.

Viewgraphs detailing this presentation appear on the following pages.

RESIDENTIAL MODULE REQUIREMENTS

P.R. RITTELMANN/J. OSTER
BURT HILL KOSAR RITTELMANN ASSOCIATES
APRIL 5, 1979

CODE DEVELOPMENT AND USAGE

STANDARDS AND TESTING AGENCIES REVIEWED

- . AMERICAN SOCIETY OF TESTING AND MATERIALS (ASTM)
- . AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)
- . NATIONAL BUREAU OF STANDARDS (NBS)
- . FEDERAL STANDARDS AND SPECIFICATIONS
- . NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)
- . UNDERWRITERS LABORATORIES (UL)

BUILDING OFFICIALS AND CODE ADMINISTRATORS INT. INC. (BOCA)

INTERNATIONAL CONFERENCE OF BUILDING OFFICIALS

SOUTHERN BUILDING CODE CONGRESS INTERNATIONAL (SBCC)

PLASTIC LAMINATIONS

BOCA	CLASSIFICATION	MAX. PANEL AREA	TOTAL AREA OF PLASTIC ON ROOF
		(INDIVIDUAL UNIT)	(% OF FLOOR AREA)
	CLASS A	300 S.F.	30%
	CLASS B	200 S.F.	25%
	CLASS C	100 S.F.	20%
SBC	CLASS CC1	300 S.F.	30%
	CLASS CC2	100 S.F.	25%

CODE CONCLUSIONS

- BOCA, UBC, SSBC ALL AGREE THAT RESIDENTIAL PHOTOVOLTAIC MODULES NEED NOT BE INCOMBUSTIBLE.
- CODES PLACE SEVERE RESTRICTIONS ON THE USE OF PLASTICS IN ROOF MATERIALS. THE STATEMENTS ARE SEVERE ENOUGH TO PROHIBIT ITS USE.
- PHOTOVOLTAIC MODULES IN RACK OR STAND-OFF MOUNT WILL MOST LIKELY BE CONSIDERED AS ROOF STRUCTURES BY THE CODE AND SUBJECTED TO ALL THE ASSOCIATED CODE RESTRICTIONS.
- APPLICATIONS WHICH MAY PLACE PV PANELS IN PEDESTRIAL AREAS MUST BE TEMPERED OR WIRED FOR GLASS IF GLASS IS USED.
- PV MODULES WHICH BECOME PART OF THE BUILDING STRUCTURE, I.E., INTEGRAL, MUST COMPLY WITH ALL CODE MANDATED LOADING REQUIREMENTS.

NOTES: CODES ARE WRITTEN ON A NATIONAL LEVEL AND ARE THEORETICALLY UNIFORM THROUGHOUT THE U.S. HOWEVER, EACH CODE MUST BE LOCALLY INTERPRETED. THIS LOCAL INTERPRETATION ALLOWS FOR GREAT DISCREPANCIES. THE MANUFACTURER MUST BE AWARE OF THIS, BUT CANNOT COUNT ON THEM.

NATIONAL ELECTRICAL CODE SUMMARY

GENERAL

THE PURPOSE OF THE CODE IS PRACTICAL SAFEGUARDING OF PERSONS AND PROPERTY.

SAFETY

LIVE PARTS OPERATING AT 50 VOLTS OR MORE SHALL BE GUARDED AGAINST ACCIDENTAL CONTACT DURING INSTALLATION. THIS MAY BE NECESSARY AT ALL VOLTAGE LEVELS.

GROUNDING

METAL FRAMED PANELS WILL REQUIRE GROUNDING UNLESS SPECIAL PROVISIONS FOR ISOLATING LIVE WIRES ARE MADE. METAL FRAMES USED AS CONDUCTOR RACEWAYS REQUIRE GROUNDING.

TERMINALS

QUICK CONNECT TERMINALS, ALTHOUGH NOT SPECIFICALLY MENTIONED IN THE CODE, ARE A RECOGNIZED METHOD FOR MAKING ELECTRICAL CONNECTIONS. SOME MUNICIPALITY CODES DO NOT RECOGNIZE QUICK CONNECT SPLICES WHERE INSTALLATIONS ARE CONSIDERED TO BE PERMANENT.

WIRING

FACTORY INSTALLED INTERNAL WIRING OF EQUIPMENT DOES NOT COME UNDER THE JURISDICTION OF THE CODE, IF THE EQUIPMENT HAS BEEN LISTED BY AN ELECTRICAL TESTING LABORATORY.

ALL CONDUCTORS USED FOR GENERAL WIRING SHALL NOT BE SMALLER THAN #14 COPPER. WIRING USED IN LIGHTING FIXTURES AND SIMILAR EQUIPMENT SHALL NOT BE SMALLER THAN #18 COPPER. PV PANELS MAY BE CONSIDERED TO BE SIMILAR TO LIGHTING FIXTURES.

CONDUCTOR OPERATING TEMPERATURES FOR SPECIFIC MOUNTING TYPES MUST BE DETERMINED SO THAT CONDUCTORS CAN BE PROPERLY SIZED.

MODULE WIRING SYSTEMS, I.E. FACTORY LUBRICATED CABLE/TERMINAL ASSEMBLIES INTENDED TO MINIMIZE FIELD LABOR ARE RECOGNIZED BY THE CODE.

BUILDING MODULE INTEGRATION TYPES

ELEMENTS OF STUDY MATRIX

PANEL SIZE

- . JPL 48"x48"
- . HEATING AND COOLING 32"x96"
- . FIBONNOCI
- . HYBRID OF 2 AND 3

ARRAY ASPECT RATIO

- . 1:1
- . 1:2
- . 1:3
- . 1:4
- . 1:7
- . 1:15

MOUNTING TYPE

- . INTEGRAL
- . DIRECT
- . STANDOFF
- . RACK

MODULE CONSTRUCTION

SUBSTRATE/SUPERSTRATE

- . NONE/GLASS
- . NONE/PLASTIC
- . NONE/SILICON ENCAPSULANT
- . PLASTIC/GLASS
- . PLASTIC/PLASTIC
- . PLASTIC/SILICON ENCAPSULANT
- . ETC.

MODULE SIZE

ARRAYS USING 48" X 48" PANELS

ARRAYS USING 32" X 96" PANELS

48" X 48" PANEL

32" X 96" PANEL

WIRING COSTS

G. E. SHINGLE MODULE

COMPARISON OF PV SHINGLE PROPERTIES VS. FLAT PANEL PROPERTIES

FLAT PANEL

1. LARGER AREA PER PANEL. AWKWARD FOR ONE MAN. MAY NEED A CRANE.
2. LARGER AREA MEANS FEWER JOINTS.
3. PANEL/SKYLIGHT TECHNOLOGY MUST ADAPT TO CONVENTIONAL RESIDENTIAL ROOF-TRUSS TECHNOLOGY.
4. SLICK SURFACE TO SHED RAIN AND SNOW.
5. FEWER ELECTRICAL CONNECTIONS - LESS VULNERABILITY. CONNECTIONS CAN BE PROTECTED BEHIND PANEL IN WEATHER-PROTECTED SPACE.
6. PANELS CAN BE ADAPTED TO DIFFERENT MOUNTING TYPES: INTEGRAL, FLUSH, STANDOFF, VERTICAL OR FLAT.

SHINGLES

1. A SHINGLE CAN BE HANDLED BY ONE MAN.
2. MANY JOINTS, MANY CONNECTIONS.
3. SHINGLES ARE AN ATTEMPT TO MAKE AN EASY TRANSITION INTO HOUSING MARKET.
4. TOOTHED SURFACE OF SHINGLES MAY PROMOTE ICE BUILDUP.
5. MANY ELECTRICAL CONNECTIONS FROM SHINGLE TO SHINGLE - MORE CHANCE OF ELECTRICAL FAILURE. CONNECTIONS ARE ALL ABOVE PLYWOOD SUBSTRATE.
6. SHINGLES GO ON THE ROOF IN ONLY ONE WAY AND WITHIN CERTAIN LIMITS OF PITCH.

RETROFIT GARAGE OPTIONS

PRELIMINARY CONCLUSIONS

- . PV NOT ADDRESSED IN NEC
- . POSSIBLE INCLUSION IN NEC 1984 EDITION. DRAFT REQUIRED BY MID - 1982.
- . PREMANUFACTURED WIRING SYSTEMS ADVENTAGEOUS
- . VOLTAGE LEVEL 110 - 220 V (BASED ON COST OF WIRING)
- . UL TESTING AND APPROVAL NECESSARY
- . FURTHER WORK REQUIRED ON OPTIMUM SIZE
- . NO MAJOR OR INSURMOUNTABLE PROBLEMS
- . DESIGN INVESTIGATION FOR LOWER COST DIRECT AND INTEGRAL MOUNT PV MODULES.
- . STANDARD INVESTIGATION IS ANTICIPATORY AND CURRENTLY UNDERWAY BY SERI AND ANSI.
- . CODE INVESTIGATION REQUIRED FOR EACH APPLICATION.

WIND LOADS ON FLAT PLATE ARRAY FIELDS

Boeing Engineering and Construction Company
Seattle, Washington

The objective of this study is to develop more refined estimates of wind loading on flat-plate photovoltaic modules and array support structures.

A prototype two-dimensional separated flow analysis program was used to calculate front and base pressures on flat plates at large angles of attack and close proximity to the ground. Pressure distributions on photovoltaic modules due to wind can be obtained using this program. The wind loads that the supporting structure is subjected to were determined by integrating the pressures over the area of the module. The pressures generated on the photovoltaic modules and the total force transmitted to the array structure are strongly dependent on the array angles to the wind and ground and the array elevation above the ground. This dependency is partly because the height of the array is a function of the angle at which the array is positioned and that the wind velocity affecting the array decreases near the ground.

Barriers such as fences can effectively reduce the wind velocity behind the barriers and so reduce the wind loading on photovoltaic arrays positioned behind the barriers. The wind velocity profile is affected by the porosity of the barrier and the distance away from the barrier.

Other devices besides fences can be used to decrease the wind loading on a photovoltaic array, but are difficult to analyze theoretically. A wind tunnel study is being planned to validate the theoretical results and to investigate wind load reducing techniques that defy theoretical solutions.

Final documentation of the study is underway.

Viewgraphs detailing this presentation appear on the following pages.

Wind Loads on Flat Plate Array Fields

Objective: Develop more refined estimates of wind loading on flat-plate photovoltaic modules and array support structures

Study plan:

Plate Array Conditions and Environment

Wind environment:

- Steady state — frequency independent
- Unsteady — frequency dependent

Panel Theoretical Aerodynamic Loads (Separated Flow Analysis)

Array Pressure Distribution

Wind Velocity = 90 mph
 Array Chord = 8 ft
 Array Elevation = 2 ft

Press. = qC_p
 where
 q = wind dyn. press.

Two-Dimensional Plate Normal Force Coefficient in Close Ground Proximity

Envelope of Wind Forces on Arrays

Protective Barriers

Zone 1: Zone of unobstructed flow
 Zone 2: Zone of pressure rise
 Zone 3: Standing eddy zone
 Zone 4: Zone of redevelopment
 Zone 5: Zone of redeveloped flow

Zone 3:
 • Zone of reduced steady state flow
 • Zone of increased turbulence
 • $L = 12h - 16h$

Effect of Fence Porosity on Wind Velocity Profile

$X \approx 4 \text{ m}$

CONDITIONS:

- Free stream velocity = 40 m/sec
- Fence height = 2.5m
- Steady state wind

Effect of Fence Porosity on Wind Velocity Profile

$X = 7.5 \text{ m}$

CONDITIONS:

- Free stream velocity = 40 m/sec
- Fence height = 2.5m
- Steady state wind

Wind Tunnel Test Plan

Location: Colorado State University
Timing: Late Summer, Fall
Tunnel Type: Environmental Wind Tunnel
test section 12' x 7' to 9'
Models: 10 flat plate arrays
fences with porosity of
0%, 35%, 50%

Test Requirements

- Measurements
 - Pressures
 - Forces
- Flow visualization
- Array Geometry
 - Vary horizontal spacing
 - Vary array elevation
 - Vary angle of attack
- Load Alleviation Techniques
 - Flow blockage beneath arrays
 - Porosity at module perimeters
 - Array - Fence combination
 - vary horizontal distance from fence
 - vary fence height
 - vary fence porosity

PHOTOVOLTAIC MODULE ELECTRICAL TERMINATION
DESIGN REQUIREMENT STUDY

Motorola Semiconductor Group
Phoenix, Arizona
and
ITT Cannon Electric Division
Santa Ana, California

An important step in meeting LSA Project goals is the selection and improvement, where needed, of life-cycle cost effective electrical termination hardware for modules and arrays. The objective of this study is to develop information to facilitate this selection and improvement.

This study draws upon the information base for the vast quantity of existing outdoor electrical termination hardware. Results will be presented in parametric form to the fullest extent possible and in a form to allow updating as the LSA Project progresses. Results expected from this study include:

1. Termination hardware requirements, including environmental, system interface, design, production, and application requirements.
2. A catalog of existing termination hardware with its attributes.
3. A summary of the attribute cost dependencies and cost-driven sensitivities.
4. A listing of candidate electrical termination hardware.
5. Areas for cost improvement.

Cost is an important selection factor in conducting this study. With an allocation of \$0.50/Wp for the whole module, termination hardware cost should not be a significant fraction of that amount. One emphasis of the study is to seek out and describe the cost dependencies of each attribute or property important to the selection of electrical termination hardware for solar cell modules and arrays. By doing so, it is anticipated that cost drivers can be identified. Life-cycle cost is to be used throughout the study. Included in the life-cycle cost are the costs of installation and maintenance, as well as the first cost of the hardware.

INVESTIGATION OF RELIABILITY ATTRIBUTES AND ACCELERATED STRESS FACTORS ON TERRESTRIAL SOLAR CELLS

Clemson University
Clemson, South Carolina

The objective of this study is to a) develop test methods for evaluation of solar cells, b) perform investigations of factors involved in the reliability of terrestrial solar cells and c) to develop specifications for the accelerated stress testing of solar cells. The overall program approach involves determining the reliability characteristics of currently available commercial cells by accelerated stress testing. In order to do this consideration was given to defining cell failure in terms of changes in a cell's measured parameters (I_{sc} , V_{oc} , FF, etc.). Degradational failures are expected to predominate. One major objective is to identify life-limiting failure mechanisms that occur during accelerated stress testing. The information gained from time-to-failure distributions and failure mechanism identification will be utilized to generate a preliminary cell qualification test schedule.

A cell reliability test facility was established and jigs designed and constructed for testing three different cell sizes. The capability for reproducible measurements of I_{sc} , V_{oc} , I_m , V_m , FF, R_s , R_{sh} was demonstrated. Stress test equipment is in place and operational for temperature-voltage (T-V) stress, temperature-humidity-bias under pressure (T-H-B) stress, pulsed power-temperature stress, temperature-voltage-humidity (atmospheric 85°C-85RH) and thermal cycle.

A cell stress-testing schedule was developed, with two phases. During Phase 1 small quantities were tested for limited times to generate data necessary for proper design of Phase 2, which was the large-scale testing program. A quantity of 200 Si solar cells from each of four manufacturers was made available for the Phase 2 testing requirements.

Results of the first year of testing are now being documented in a final report to be released by the end of April 1979. Meanwhile, the second year's testing effort is getting under way. In the follow-on phase new types of cells. i.e., cells made of polycrystalline material, cells with ion-implanted junctions, and cells made with different metallization systems will be added to the Clemson test program.

ACCELERATED SUNLIGHT ENDURANCE
TESTING OF SOLAR CELL MODULES

DSET Laboratories, Inc.
Phoenix, Arizona

The accelerated aging of Block II mini-modules was continued using DSET's Super-MAQ Fresnel-concentrating accelerated weathering machine. Through March 19, 1979, five of the modules had been subjected to approximately 1,300,000 langley's of radiation, one module to 1,200,000 langley's, and two modules to 500,000 langley's.

Weekly visual inspections have revealed the development of delamination, cracked cells, carbonation, and contact corrosion within some modules. The weekly reports are supplemented by monthly slide photos of all modules.

I-V measurements are made for each module on a monthly basis. Global insolation measurements are made with a WMO Class I pyranometer. Normal incident (direct) measurements are made with a pyrliometer for reference. An A/D buffer has been added to DSET's computer facility and now is employed in obtaining I-V measurements. This permits the computerization of all data and digital plotting of the un-normalized I-V curves. JPL algorithms are being programmed into DSET's computer for plotting normalized I-V curves.

Cooling studies on Super-MAQ aimed at maintaining modules at or near NOCT during exposure are contemplated for the immediate future.

5. Operations Area

FIELD EXPERIENCE UPDATE

LARRY DUMAS
OPERATIONS MANAGER

ANTONIAK'S SECOND LAW

"THERE'S TOO MUCH DATA AND NOT ENOUGH THINKING"

DATA BASE: MODULES BLOCK BUY HISTORY

	<u>BLOCK I</u>	<u>BLOCK II</u>	<u>BLOCK III</u>	<u>BLOCK IV</u>
FROM:	JAN 1976	JUL 1976	DEC 1977	MAY 1979
TO:	UC1 1976	MAR 1978	JUNE 1979	JUL 1980
POWER (kW)	58	110	213	TBD
NUMBER OF CONTRACTORS	4	4	5	8
LARGEST DELIVERY (kW/MO)	10.5	23.4	36.0	-
PRICE 1975 \$/W	21.0	13.7	10.4	-

BLOCK BUY MODULE UTILIZATION (kW)

	<u>BLOCK I</u>	<u>BLOCK II</u>	<u>BLOCK III</u>	<u>DATE FIELD</u>	<u>LEVEL OF SURVEILLANCE</u>
<u>MIT/LL</u>					
MUSEUM	1.6			8/77	MODULE
UNIV OF TEXAS (HYBRID)		8.0		11/78	
MEAD, NEBRASKA		28.2		11/77	
ROOF-TOP ARRAY }	4.7			1/78	
		4.4		5/77-1/78	
LL RESIDENTIAL ARRAY }		7.0	6.0	11/78	
ENVIR. SITES	0.8			FALL 77	
<u>LeRC</u>					
REMOTE WEATHER	0.5			4/77-10/77	ARRAY
STF	13.4			11/76	
INDIAN RESERVATION	0.3	3.5		7/76-12/78	
USFS	0.8			10/76-SUM 78	
OTHER	0.9			4/77-10/77	

BLOCK BUY MODULE UTILIZATION (kW)

	<u>BLOCK I</u>	<u>BLOCK II</u>	<u>BLOCK III</u>	<u>DATE FIELD</u>	<u>LEVEL OF SURVEILLANCE</u>
<u>DOD</u>					
BATTERY CHARGERS	0.6			7/76	ARRAY
REMOTE RADAR	8.1			3/77	
TELEPHONE VAN	2.7			7/76	
WATER PURIFICATION*	10.6			4/77	
RADIO SYSTEMS	0.3			7/76	
<u>JPL FIELD TEST SITES</u>					
PASADENA	0.9	1.4	0.4	SPRING 77	MODULE
				FALL 77	
				1/79	
TABLE MOUNTAIN	0.2			11/76-3/77	
		0.3		1/77-10/77	
GOLDSTONE	0.3			4/76-12/76	
		0.3		4/77-9/77	
POINT VICENTE		0.3		8/78	
<u>JPL/LeRC ENDURANCE TEST SITES</u>					
VARIOUS LOCATIONS		3.9		10/77-5/78	MODULE

TOTAL NUMBER OF
MODULES IN SERVICE ≈ 7000

* DECOMMISSIONED

FORMS OF FIELD DEGRADATION

- ELECTRICAL FAILURE
- PHYSICAL DEGRADATION
- ELECTRICAL DEGRADATION

PROBLEM/FAILURE REPORT (P/FR) FLOW PLAN

PROBLEM/FAILURE REPORT (P/FR) STATUS

PROCUREMENT	NUMBER OF P/FR's	NUMBER OF P/FR's CLOSED	ENVIRONMENTAL TEST	JPL FIELD TEST	FIELD TEST & APPLICATION PROJECTS
BLOCK I	173	159	100	34	39
BLOCK II	145	119	105	3	37
BLOCK III	54	43	54	0	0
DEVELOPMENTAL	46	30	43	3	0
COMMERCIAL	41	25	41	0	0
MISC	38	3	38	0	0
TOTAL	497	379	381	40	76

FIELD TEST & APPLICATION P/FR SUMMARY

	INTERCONNECT FRACTURES	UNSOLDERED INTERCONNECTS	HAIL DAMAGE	CRACKED CELLS	WIRE & TERMINAL CORROSION	GROUNDING CELL STRING	ENCAPSULANT DELAMINATION
BLOCK I	31	7	2	10	3	2	16
BLOCK II	0	8	9	16	0	4	5
TOTAL	31	15	11	26	3	6	21

FAILURE MODE-INTERCONNECT FRACTURES

- NUMBER OF OCCURRENCES 31
- NUMBER OF MANUFACTURERS INVOLVED 4
- EFFECT: OPEN CIRCUIT; ELECTRICAL OUTPUT DEGRADATION; HOT SPOTS AND OVERHEATING
- PROBABLE CAUSE: DESIGN/WORKMANSHIP
- CORRECTIVE ACTION: STRESS RELIEF DESIGN AND PRODUCTION CONTROL

FAILURE MODE-UNSOLDERED INTERCONNECT

- NUMBER OF OCCURRENCES 15
- NUMBER OF MANUFACTURERS 3
- EFFECT: OPEN CIRCUIT
- PROBABLE CAUSE: WORKMANSHIP
- CORRECTIVE ACTION: PROCESS CONTROL

FAILURE MODE-HAIL DAMAGE

- NUMBER OF OCCURRENCES 11
- NUMBER OF MANUFACTURERS 2
- EFFECT: OPEN CIRCUIT; ELECTRICAL DEGRADATION
- PROBABLE CAUSE: DESIGN
- CORRECTIVE ACTION: DESIGN FOR ENVIRONMENT

REFERENCE: ENVIRONMENTAL HAIL MODEL FOR ASSESSING RISK TO SOLAR COLLECTORS, LSA 5101-45

PHOTOVOLTAIIC SOLAR PANEL RESISTANCE TO SIMULATED HAIL, LSA 5101-62

FAILURE MODE-CRACKED CELLS

- NUMBER OF OCCURRENCES 26
- NUMBER OF MANUFACTURERS 4
- EFFECT: OPEN CIRCUIT; ELECTRICAL DEGRADATION; LOCAL OVERHEATING
- PROBABLE CAUSE: DESIGN/WORKMANSHIP
- CORRECTIVE ACTION:
 - (a) DESIGN TO MINIMIZE THERMAL AND MECHANICAL STRESSES ON CELLS
 - (b) IMPROVE INPROCESS INSPECTION AND HANDLING TO AVOID BADLY CHIPPED OR PARTIALLY CRACKED CELLS IN COMPLETED PRODUCT

REFERENCE: REJECTION CRITERIA FOR JPL LSA MODULES, LSA 5101-21 REV A

FAILURE MODE-WIRE AND TERMINAL CORROSION

- NUMBER OF OCCURRENCES 3
- NUMBER OF MANUFACTURERS 1
- EFFECT: ELECTRICAL DEGRADATION
- PROBABLE CAUSE: DESIGN/WORKMANSHIP
- CORRECTIVE ACTION: IMPROVE MATERIAL SELECTION; TORQUE SPECS FOR MECHANICAL CONNECTION

FAILURE MODE-GROUNDED CELL STRING

- NUMBER OF OCCURRENCES 6
- NUMBER OF MANUFACTURERS 3
- EFFECT: SAFETY HAZARD
- PROBABLE CAUSE: WORKMANSHIP
- CORRECTIVE ACTION: IMPROVE ASSEMBLY TECHNIQUES

FAILURE MODE-ENCAPSULANT DELAMINATION

- NUMBER OF OCCURRENCES 21
- NUMBER OF MANUFACTURERS INVOLVED 3
- EFFECT: MOISTURE PENETRATION AND ENTRAPMENT
- PROBABLE CAUSE: DESIGN/WORKMANSHIP
- CORRECTIVE ACTION: MORE EXACTING PREPARATION OF ASSEMBLY SURFACES DURING MANUFACTURE AND SELECTION OF COMPATIBLE MATERIALS

REFERENCE: EXPERIENCE WITH SILICONES IN PHOTOVOLTAIC MODULES,
DOE/JPL -1012-79/8
PHOTODEGRADATION OF POLYMERIC ENCAPSULANTS OF
SOLAR CELL MODULES, LSA 5101-77

FAILURE OBSERVATIONS: PROBLEMS AND RECOMMENDATIONS

PROBLEM	POTENTIAL SOLUTION(S)
• FAILURES DIFFICULT TO DETECT IN AN ARRAY	<ul style="list-style-type: none"> • MODULE LEVEL TESTING • IMPROVED DETECTION METHODS
• FAILURES DIFFICULT TO ISOLATE IN AN ARRAY	<ul style="list-style-type: none"> • IMPROVED DETECTION METHODS • TEST POINT ACCESS
• UNCERTAIN DATA BASE	<ul style="list-style-type: none"> • FOCUS ON WELL INSTRUMENTED AND ATTENDED SITES

PHYSICAL DEGRADATION

- DEPENDENT ON VISUAL OBSERVATIONS
- RESULTS REPORTED IN VARIOUS JPL, LeRC, AND MIT/LL PUBLICATIONS
- TYPICALLY LITTLE CORRELATION WITH FAILURE DATA

PHYSICAL DEGRADATION OBSERVATIONS: PROBLEMS AND RECOMMENDATIONS

PROBLEM	POTENTIAL SOLUTION(S)
• INCONSISTENCIES IN REPORTED VISUAL OBSERVATIONS	<ul style="list-style-type: none"> • DEVELOP UNIFORM INSPECTION METHODOLOGIES AND DEGRADATION CLASSIFICATION
• LACK OF CORRELATION WITH RELIABILITY/ LIFETIME DATA	<ul style="list-style-type: none"> • IMPROVE INSPECTION METHODOLOGY AND DEGRADATION CLASSIFICATION BASED ON FIELD EXPERIENCE AND RELIABILITY/LIFETIME STUDIES • DEVELOP/APPLY NON-VISUAL TECHNIQUES

ELECTRICAL DEGRADATION

- DEPENDS ON DETECTION, ISOLATION, AND QUANTITATIVE MEASUREMENTS
- TYPICALLY UNREPORTED
- COMMON CAUSES:
 - CRACKED CELLS
 - CORRODED CIRCUITRY
 - DIRT
 - AND...?

CORRECTED I_{SC} HISTORY FOR A REPRESENTATIVE BLOCK II MODULE

ELECTRICAL DEGRADATION OBSERVATIONS: PROBLEMS AND RECOMMENDATIONS

PROBLEM	POTENTIAL SOLUTION(S)
<ul style="list-style-type: none"> • LACK OF QUANTITATIVE DATA 	<ul style="list-style-type: none"> • IMPROVED IN-SITU MEASUREMENT TECHNIQUES AND EQUIPMENT • LABORATORY MEASUREMENTS OF SAMPLES • MODULE AND SUB-MODULE FIELD EXPERIMENTATION

OVERALL CONCLUSIONS/RECOMMENDATIONS

- THE BEST FIELD DATA TO DATE HAVE COME FROM A FEW INTENSIVELY MONITORED SITES
- FAILURE RATES ARE LOW!
- CORRELATION WITH ENVIRONMENTAL STRESS LEVELS IS LACKING
- PROBLEM/FAILURE REPORTING AND ANALYSIS SYSTEM HAS PROVEN VALUABLE AND SHOULD BE EXPANDED BEYOND LSA PROCUREMENTS
- FIELD OBSERVATIONS OF PHYSICAL DEGRADATION NEED BETTER UNIFORMITY AND INTEGRATION WITH RELIABILITY/LIFETIME EFFORTS
- BETTER TOOLS ARE NEEDED FOR THE DETECTION AND MEASUREMENT OF FIELD DEGRADATION
- AN OVERALL PLAN FOR DATA ACQUISITION IS NEEDED