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Progress Report 14
for the Period August 1979 to December 1979

and Proceedings of the
14th Project Integration Meeting

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

(JPL PUBLICATION 80-21)
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ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period August through November, 1979. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering, and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of the visual materials presented at, the Project Integration Meeting held December 5-6, 1979.
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<td>A</td>
<td>Angstrom(s)</td>
</tr>
<tr>
<td>Ar</td>
<td>Argon</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminum</td>
</tr>
<tr>
<td>AM</td>
<td>Air Mass (e.g., AM1 = unit air mass)</td>
</tr>
<tr>
<td>AR</td>
<td>Antireflective</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of System (non-array elements of a PV system)</td>
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<tr>
<td>BSF</td>
<td>Back-surface field</td>
</tr>
<tr>
<td>B-T</td>
<td>Bias/temperature</td>
</tr>
<tr>
<td>B-T-H</td>
<td>Bias/temperature/humidity</td>
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<tr>
<td>Ca</td>
<td>Calcium</td>
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<tr>
<td>CFP</td>
<td>Continuous-flow pyrolizer</td>
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<tr>
<td>CLF</td>
<td>Continuous liquid feed</td>
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<tr>
<td>Co</td>
<td>Cobalt</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
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<tr>
<td>CVD</td>
<td>Chemical vapor deposition</td>
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<td>CZ</td>
<td>Czochralski (classical silicon crystal growth method)</td>
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<tr>
<td>DCF</td>
<td>Discounted cash flow</td>
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<tr>
<td>DLTS</td>
<td>Deep-level transient spectroscopy</td>
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<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<tr>
<td>DS/RMS</td>
<td>Directionally solidified/refined metallurgical silicon</td>
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<td>Electron beam</td>
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<td>EPSDU</td>
<td>Experimental Process System Development Unit</td>
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<td>ESB</td>
<td>Electrostatic bonding</td>
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<td>EVA</td>
<td>Ethylene vinyl acetate</td>
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<td>FAST</td>
<td>Fixed Abrasive Slicing Technique</td>
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<td>Fe</td>
<td>Iron</td>
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<td>FPUP</td>
<td>Federal Photovoltaics Utilization Program</td>
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<td>GRC</td>
<td>Glass-reinforced concrete</td>
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<td>H</td>
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<td>Nitric acid</td>
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<td>ID</td>
<td>Inner diameter</td>
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<td>Interim Price Estimation Guidelines</td>
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<td>IPEG 2</td>
<td>Improved Price Estimation Guidelines</td>
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<td>Iₛₜₜ</td>
<td>Short-circuit current</td>
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<td>I-V</td>
<td>Current-voltage</td>
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<td>K</td>
<td>Potassium</td>
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<td>LAR</td>
<td>Low-angle ribbon (silicon growth method)</td>
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<td>LAS</td>
<td>Large-Area Silicon Sheet Task</td>
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<td>LCP</td>
<td>Lifetime cost and performance</td>
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<td>Low-Cost Solar Array</td>
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<td>MBS</td>
<td>Multiblade sawing</td>
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<tr>
<td>Mg</td>
<td>Magnesium</td>
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<td>Mn</td>
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<td>Molybdenum</td>
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<td>MWS</td>
<td>Multiwire sawing</td>
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<td>Na</td>
<td>Sodium</td>
</tr>
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<td>NDE</td>
<td>Nondestructive evaluation</td>
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<td>Abbreviation</td>
<td>Definition</td>
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<td>------------</td>
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<tr>
<td>Nb</td>
<td>Niobium</td>
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<td>NOCT</td>
<td>Nominal operating cell temperature</td>
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<td>O</td>
<td>Oxygen</td>
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<tr>
<td>OTC</td>
<td>Optional test conditions</td>
</tr>
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<td>P</td>
<td>Phosphorus</td>
</tr>
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<td>P</td>
<td>Individual module output power</td>
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<td>PA&amp;I</td>
<td>Project Analysis and Integration Area</td>
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<td>Pavg</td>
<td>Module rated power at SOC, $V_{no}$</td>
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<td>PDU</td>
<td>Process Development Unit</td>
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<tr>
<td>P/FR</td>
<td>Problem/failure report</td>
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<td>PIM</td>
<td>Project Integration Meeting</td>
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<tr>
<td>PMA</td>
<td>Polymethylmethacrylate</td>
</tr>
<tr>
<td>P_max</td>
<td>Maximum power</td>
</tr>
<tr>
<td>PnBA</td>
<td>Poly-n-butyl acrylate</td>
</tr>
<tr>
<td>POC13</td>
<td>Phosphorus oxychloride</td>
</tr>
<tr>
<td>PP&amp;E</td>
<td>Production Process and Equipment Area</td>
</tr>
<tr>
<td>ppba</td>
<td>Parts per billion atomic</td>
</tr>
<tr>
<td>ppma</td>
<td>Parts per million atomic</td>
</tr>
<tr>
<td>PRDA</td>
<td>Program Research and Development Announcement</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PVB</td>
<td>Polyvinyl butyral</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>RFP</td>
<td>Request for proposal</td>
</tr>
<tr>
<td>RFQ</td>
<td>Request for quotation</td>
</tr>
<tr>
<td>RMS</td>
<td>Refined metallurgical-grade silicon</td>
</tr>
<tr>
<td>RTR</td>
<td>Ribbon-to-ribbon (silicon crystal growth method)</td>
</tr>
<tr>
<td>S</td>
<td>Sulfur</td>
</tr>
<tr>
<td>SAMICS</td>
<td>Solar Array Manufacturing Industry Costing Standards</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
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<tr>
<td>SAMIS</td>
<td>Solar Array Manufacturing Industry Simulation</td>
</tr>
<tr>
<td>SCIM</td>
<td>Silicon coating by inverted meniscus</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SEMI</td>
<td>Semiconductor Equipment Manufacturers Institute</td>
</tr>
<tr>
<td>SERI</td>
<td>Solar Energy Research Institute</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiCl₄</td>
<td>Silicon tetrachloride</td>
</tr>
<tr>
<td>SiF₄</td>
<td>Silicon tetrafluoride</td>
</tr>
<tr>
<td>SiHC₁₃</td>
<td>Trichlorosilane</td>
</tr>
<tr>
<td>SOC</td>
<td>Silicon on ceramic (crystal growth method)</td>
</tr>
<tr>
<td>SOC</td>
<td>Standard Operating Conditions (module performance)</td>
</tr>
<tr>
<td>SOLMET</td>
<td>Solar-meteorological</td>
</tr>
<tr>
<td>SPG</td>
<td>Silicon particle growth</td>
</tr>
<tr>
<td>SSMS</td>
<td>Spark-source mass spectrometry</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions (cell performance)</td>
</tr>
<tr>
<td>Ta</td>
<td>Tantalum</td>
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<td>TD&amp;A Lead Center</td>
<td>Photovoltaics Program Technology Development and Applications Lead Center</td>
</tr>
<tr>
<td>Ti</td>
<td>Titanium</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet radiation</td>
</tr>
<tr>
<td>V</td>
<td>Vanadium</td>
</tr>
<tr>
<td>Vₙ₀</td>
<td>Nominal operating voltage</td>
</tr>
<tr>
<td>Vₒc</td>
<td>Open-circuit voltage</td>
</tr>
<tr>
<td>W</td>
<td>Tungsten</td>
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<tr>
<td>Xe</td>
<td>Xenon</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td>ZnCl₂</td>
<td>Zinc chloride</td>
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</table>
PROGRESS REPORT

Project Summary

Flat-plate photovoltaic module design and manufacturing technologies have been significantly improved after five years of active cooperation by module manufacturers and JPL/LSA personnel. The four LSA module block buys have provided the stage for a rapid evaluation of module design technologies, module testing (exploratory and qualification), field development and monitoring, and module problem/failure analyses.

Lessons learned were summarized during a plenary session of the 14th Project Integration Meeting with specific design approaches, rationale and recommendations presented in subsequent sessions. Recommendations were made for module design objectives and approaches in the areas of mechanical and electrical configuration, fault tolerance and environmental endurance. Project experience with respect to environmental reliability and durability was described. Progress by the manufacturers in improving production yields by reduction in workmanship defects was described on the basis of Quality Assurance inspection records.

Block IV module manufacturers displayed their brand-new prototype modules and gave presentations on design features and rationale. Numerous design and production technology innovations based upon both LSA and private R&D activities have been incorporated, resulting in improvements in module price, performance, and reliability. A key point stressed was the need for continuing field-data acquisition, array-performance evaluation, and corrective design action for problem/failures experienced.

The Battelle polysilicon Process Development Unit, consisting of the four critical components (full-size) for their 50 MT/yr EPSDU, has started operation.

Hamco has repeatedly grown 105 kg of silicon ingots from a single crucible by periodic melt replenishment. Crystal systems has cast nearly single-crystal ingots using upgraded metallurgical silicon with their heat-exchanger method (HEM). Impurities segregated at the top and sides.

Average wafer-cutting speeds of Crystal Systems multi-wire saw are about 40% higher than required for meeting 1986 goals. Siltec has cut 250-μm-thick wafers with kerfs of 200 μm-thick using their rotating-ingot ID slicing technique.
Mobil Tyco has grown 7.5 cm-wide edge-defined film-fed growth (EFG) ribbons at 5.0 cm/min. Westinghouse has exceeded their throughput goal (27 cm²/min) with their dendritic-web growth. Five-hour growth has been achieved with melt replenishment. Honeywell has grown 200 μm-thick silicon films at 12 cm/min pull rates with their silicon-coating-by-inverted-meniscus (SCIM) unit. Energy Materials Corp. has grown horizontal ribbons (1.5 cm wide) at rates up to 60 cm/min (average 20 to 30 cm/min).

Several 1986 candidate encapsulation systems are now undergoing intensive evaluation of module life, fabrication, and performance. The major unknown for the lowest-cost systems is the 20-year-life requirement. The encapsulation materials now being incorporated into the newest designs should permit 20-year-life module designs in the $2 to $5/W price range. An encapsulation materials status summary is included in this report.

Some highlights in production processing are: spray-on junction technique is successful; nickel is a barrier to copper migration; copper sinters well using a lead frit; thick-film metal systems have been successfully doped with AlSi and AlGe eutectics; induction soldering of ribbon contacts to cell have been successful.

Tony Carey presented HUD's Urban Development Action Grant Problem and its potential for monies to help build plants in areas of high unemployment.

A JPL lead team assured the present and near-term availability of polysilicon, single-crystal ingots and wafers and needs for same. Between 1981 and 1983 there will be a strong sellers' market for polysilicon with a shortage developing in the latter part of that period. This shortage will not be relieved until the new polysilicon production plants are operating (1985 to 1986). Ingot and wafer demand and supply will balance. Lead time for new manufacturing hardware is less than a year.

A summary of the Federal Photovoltaic Utilization Program status was presented.

Prof. A. Weinstein of Carnegie-Mellon University presented a capsule summary of the product liability situation from a manufacturer's viewpoint: safety considerations must be integrated into the design and manufacture of photovoltaic systems as we strive for performance and cost optimization.
Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

PLANNING AND INTEGRATION

The Technical Readiness 1982 document was published October 31 as JPL Document 5101-114.

The SERI PVPO/JPL LSA interface has been established for evaluating the transition of technologies between the various stages of technical development. SAMICS information has been forwarded to SERI on one technology and plans have been formulated for analysis of another candidate material.

In the effort to develop project planning aids, the theory has been developed for combining the cumulative distribution functions for parameters of parallel technology development efforts. An HP-97 calculator program was written for testing the theory. It revealed some problems with the approach used, but an alternative approach has been devised and has apparently overcome the previous difficulties.

ARRAY TECHNOLOGY COST ANALYSIS

The review of the updated Price Allocation Guidelines has been completed. The new guidelines are apportioned by sheet-material type accounting for specific sheet properties such as efficiency and silicon utilization.

The Project Analysis and Integration Area is participating in the evaluation of the Near-Term-Cost-Reduction contracts. Using contractor supplied data plus JFL estimates, SAMIS runs have been completed for five of the contracts. Most runs to date show reasonably good agreement with predicted cost data; however, the technical success of some contracts remains to be seen.

The development of the Improved Price Estimation Guidelines (IPEG2) was completed and presented at the Fourteenth Project Integration Meeting and is shown in the Proceedings (Section III of this document). IPEG2 will permit more flexibility in price estimation and should be in closer agreement with SAMIS results.

ECONOMICS AND INDUSTRIALIZATION

A number of studies were conducted to examine the long-term relationship of the LSA Project and industry and to examine the effects of PV market elasticity on the obsolescence of technology.
TECHNOLOGY DEVELOPMENT AREA
SILICON MATERIAL TASK

INTRODUCTION

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

TECHNICAL GOALS, ORGANIZATION AND COORDINATION

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

SUMMARY OF PROGRESS

Development of Processes for Producing Semiconductor-Grade Silicon

Four processes for producing Si equal to or approaching semiconductor-grade silicon in composition or performance are under development by Battelle Columbus Laboratories, Energy Materials Corporation, Hemlock Semiconductor Corporation, and Union Carbide Corporation. Progress in these four efforts is described below.

Battelle Columbus Laboratories (BCL) is conducting a Process Development Unit (PDU) program for the experimental investigation of four major items of process equipment for a projected 50 MT/yr
Experimental Process System Development Unit (EPSDU). The BCL process is based on the reduction of silicon tetrachloride by zinc; the four items are a zinc feed system, a fluidized bed reactor, a reactor effluent condenser, and a zinc chloride electrolysis cell. Completion of fabrication and assembly of the PDU had been scheduled for October 1, 1979, but now is expected in late January 1980, having been set back by numerous procurement delays and fabrication errors.

The only major item yet to be installed is the zinc feed system. In this period a succession of failures was experienced with it, but remedies have been applied to the known problems, and the system is being assembled.

Energy Materials Corporation, under a near-term cost-reduction contract, is developing and demonstrating a Si melt-replenishment system for continuous Czochralski (Cz) crystal growth. The system consists of a novel reactor for Si production and melting at a rate of 0.5 kg/h by hydrogen reduction of trichlorosilane, and a delivery system to transfer the molten Si to a Cz crystal puller.

The design, fabrication, and installation of a prototype system neared completion. This particular activity is lagging three months behind schedule, primarily because of problems in procurement of the reactor vessel and enclosure.

The Union Carbide Corporation is developing a process based on producing silane and pyrolyzing it in either a free-space reactor or a fluidized bed reactor. In this period, contract negotiations were completed for the Experimental Process System Development Unit (EPSDU) program to be completed in December 1982. The EPSDU will have a capacity of 100 MT of Si per year.

The preliminary piping and instrumentation diagrams were completed, as well as all the layout drawings required to prepare the detailed EPSDU cost estimate. Preparation of requests for purchase was initiated and equipment long-lead items are being identified. Four proposals for Si powder melting and consolidation R&D work by a subcontract were evaluated, and a recommendation was made regarding a subcontractor. Negotiations are under way between this subcontractor and Union Carbide.

A technical workshop on fluidized-bed Si production and free-space reactor technologies, attended by the Oregon State University consultants and personnel from Union Carbide and JPL, was held at Corvallis, Oregon. The major result of the workshop is the assessment that fluidized bed reactors are feasible devices for production of Si from silane.

Installation of the free-space reactor process development unit neared completion. Work on modeling the free-space reactor as an axisymmetric confined jet started. Tests continued in capacitive heating and particle separation in a fluidized bed. The bed was heated to 500°C with a Si-coated electrode for 23 hours. During
these tests a minimal amount of sintering was observed. Particle separation tests conducted with a wide range of particle sizes revealed that large particles can be separated using a boot. More tests are required, however, to optimize the boot design.

A contract was started on October 2, 1979, with Hemlock Semiconductor Corporation for a 15-month R&D effort on a process for making Si by a modification of the Siemens process. The process is based on the use of dichlorosilane and/or mixtures of dichlorosilane and trichlorosilane. Reactor tests were made with trichlorosilane and dichlorosilane to shake down the system and to characterize the reactor. An analysis of reactor parameters was initiated to permit definition of requirements for intermediate-size and LPSDU-size reactors. Three PDU designs were considered for redistribution of trichlorosilane to dichlorosilane. A mixed-feed (trichlorosilane-dichlorosilane) system was chosen as the most cost-effective approach to meeting program requirements, and detailed design with equipment specification was initiated. A preliminary mass balance for the PDU was completed using vent gas composition obtained from experimental reactor runs.

**Development of Processes for Producing Solar-Cell-Grade Silicon**

**SRI International:** An 18-cm-dia reactor made of Inconel (erroneously reported in Progress Report No. 13 as having a diameter of 15 cm) capable of making 1-kg batches of Si, as compared to the 0.5-kg capacity of the previous 13-cm-dia Pyrex reactor, was put into operation. Sodium reaction was relatively complete even when reactants were added at a rate equivalent to 0.5 kg of Si/h. Analyses of Si obtained by melt separation of the product from the sodium/silicon tetrafluoride reaction are presented below in the Proceedings of the 14th Project Integration Meeting.

An economic analysis performed by the contractor indicates a product price of $11.93/kg Si (1980$ 25% ROI), assuming that only 80% of the melted Si is acceptable as solar-grade, and that the balance of the silicon and the by-product sodium fluoride are sold for credit.

**Westinghouse:** Assembly and installation of the process demonstration system and shakedown of the reactant subsystems (sodium and silicon tetrachloride) were completed. Arc heater/reactor tests without reactants were conducted over ranges of arc-heater power and gas flow. Based on the results, a modification was made to the arc heaters to obtain higher gas enthalpy and thereby establish more favorable conditions for the Si condensation process. Another test was conducted without reactants, and then on December 8 a test with reactants was made. The test was terminated early because a thermocouple in the burnoff stack indicated a low burner temperature, apparently erroneously, but 31 min of operation at 100% reactant flows were obtained. Partial disassembly of the system after the test revealed that the only damage sustained appears to be the loss of a portion of the sodium spray nozzle. Earlier tests with the nozzle had indicated that only moderate degradation of the spray characteristics should result from this damage.
A skull of reaction product, appearing to be a mixture of sodium chloride and finely divided Si, covered the inside surfaces of the reactor and cyclone separator. Some small pieces of material having the typical silvery luster of Si were found. The collector was filled with reaction product appearing to be a mixture of sodium chloride and finely divided silicon. A number of samples were taken from various regions in the apparatus and are being analyzed.

Impurity Studies

Aerospace Corporation: This effort, the purpose of which was to assess the applicability of the photon catalysis technique for metal impurity analysis in silicon, was concluded in this period. In this technique, metal atoms from a vaporized sample are excited by active nitrogen, and the atomic emission spectrum is analyzed to give the metal vapor pressure. In the program, direct evidence was obtained that when a silicon sample is evaporated into a stream of active nitrogen, the composition of the vapor is representative of the sample composition. The experimental results also suggest that the excitation process occurs independently for each species present in the vapor, and that the technique is sensitive to silicon impurities at the ppm level. The high signal-to-noise level obtained in the work portends well for achieving the goal of 10-ppb sensitivity by further development of the technique.

C.T. Sah Associates: Thermal-capture and emission-rate measurements were made using the voltage-stimulated capacitance (VSCAP) transients for titanium, zinc, and gold. These measurements are used to make a more accurate assessment of the effects of these elements on Si solar-cell performance.

Solarex Corporation: Twenty-two experimental lots (containing intentionally incorporated impurities) of solar cells were fabricated and measured. Two additional lots were fabricated but are not yet completely electrically characterized. The experimental test cells appear to be clustered into two distinct resistivity ranges, one around 0.2 Ω-cm and the second around 3 to 4 Ω-cm. As is to be expected, the lower-resistivity-range cells generally give higher voltages and lower currents than the higher-resistivity cells.

Where performance degradation occurs due to the incorporated impurities, the current parameter is usually much more drastically affected than the voltage parameter, although both can be severely degraded by titanium. All seven titanium-containing lots thus far tested were severely degraded in maximum power output, even when titanium was present in combination with copper.

Through analysis of the control and monitor cells it has been determined that there are no observable effects that might be attributed to cross-contamination. Also several lots of experimental cells with similar levels of incorporated manganese yielded similar degradations, indicating reasonable consistency. It should be noted that a significant number of cell lots have exhibited marked lifting of grid line metallization that might compound subsequent analysis.
Westinghouse R&D Center: The objective of this program is to define the effects of impurities, various thermochemical processes, and impurity-process interactions on the performance of terrestrial Si solar cells. The results of the study form a basis for Si producers, wafer manufacturers, and cell fabricators to develop appropriate cost-benefit relationships for the use of less pure, less costly solar-grade Si. The Phase III technical effort was completed November 30, 1979.

As part of the assessment of impurity effects for Czochralski (Cs) growth and for silicon web growth (a ribbon crystal production process), the effective distribution coefficients were measured for a variety of potentially harmful impurities. Spark-source mass spectroscopy was used to determine C_s, the Si crystal impurity content, while atomic absorption was used to obtain C_i, the impurity concentration in the liquid from which the crystal grew.

Gettering of titanium-based silicon wafers (4 Ω-cm) improves cell performance by 1% to 2% (absolute) for the highest temperatures and longest times. HCl is somewhat more effective than POCl_3, and HCl produces essentially identical results for molybdenum (Mo) or iron (Fe). The performance improvement is due to a reduction in impurity trap center density which for titanium, and probably the other impurities, is not uniform but varies with distance from the wafer surface. For example, it has been shown by deep-level spectroscopy that a concentration gradient, or profile, forms in titanium-doped silicon wafers during 1100°C gettering treatments. At this temperature the titanium-depleted region extends from the surface to more than 2 mils deep in the wafer; at 850°C, the cell fabrication temperature, the profile extended only about 12 μm. In contrast, molybdenum-doped wafers exhibit abrupt profiles; after 1200°C treatment the molybdenum concentration returns to the bulk value within 6 μm of the surface. This probably explains the rather small response of cell performance to gettering in molybdenum-doped Si.

Gettering of low-resistivity (0.2 Ω-cm) Si produces some improvement of the performance of titanium- and molybdenum-doped cells. However, the cells made on the gettered low-resistivity material exhibit considerable performance variation that tends to negate the benefits due to gettering itself. This behavior, especially evident when Mo-doped material is treated in POCl_3, is due to excessive junction currents in the device. These results are ascribed to precipitate formation near the high-field region of the cell during the high-temperature treatment.

A cell performance-impurity effects model, verified for both n- and p-base cells, is now available to project the efficiency of devices made of Si contaminated with various kinds and amounts of impurities.
Supporting Studies

A contract was initiated with AeroChem Research Laboratories on October 3, 1979, to investigate processes involved in the production of solar-cell-grade Si from silicon halides and alkali metals. The specific objectives of the contract are: 1) to determine the reaction kinetics, extent of reaction, and rates of heat release for a range of operating conditions in a jet-stirred reactor, 2) determine the suitability of various reactor materials for a range of operating conditions of jet-stirred reactor, 3) to determine the Si collection efficiency and purity of Si product for impaction collection devices, and 4) prepare preliminary engineering and economic analysis of a Si production process using the jet-stirred reactor.

Since the beginning of the contract, the jet-stirred reactor test facility has been made operational and some experiments have been run. AeroChem has provided JPL a small sample of Si product for impurity measurements.

The contract with AeroChem for developing a model and computer code for description of Si production processes employing silicon hydrides or halides expired on October 20, 1979. The draft final report was written.

As a result of executing the contract, AeroChem developed two computer programs, CHEMPART and GENMIX, to simulate the Si production process in an arc-heater reaction. The overall reaction of the process is reduction of silicon tetrachloride by sodium in a hydrogen-argon plasma. The computer code CHEMPART simulates the reaction between sodium and silicon tetrachloride, nucleation of silicon, and growth of Si nuclei in the core of the reactor. The computer code GENMIX calculates the rates of heat and mass transfer to the reactor walls from the core of the reactor. Thus GENMIX calculates the transfer and hence condensation of Si vapor and droplets to the reactor wall as a function of reactor length.

Using these two reactor codes, AeroChem simulated the arc-heater process of Westinghouse for Si production for two different enthalpy conditions. The lower enthalpy conditions (0.3 to 0.4 MW of arc-heater power) resulted in the formation of Si droplets in the core of the reactor, thus reducing the collection efficiency for Si condensation on the reactor wall. The higher enthalpy condition (1.8 MW of arc-heater power) resulted in high gas velocities (100 m/s) in the reactor, limiting the collection efficiency of Si condensation to 20% in 8 m of reactor length.

It is, therefore, apparent that the optimal conditions for the operation of the arc-heater reactor lie somewhere between the two power levels. AeroChem is supplying the complete details of the computer codes and their usage in a supplement to the final report. The computer codes CHEMPART and GENMIX can therefore be used by JPL or Westinghouse.
Lamar University: Analyses of process system properties of chemical materials important in the production of Si were continued. Primary activities were initiated for physical, transport, and thermodynamic property data of Si.

Process design results for BCL process--Case A (two deposition reactors and six electrolysis cells) were presented previously. During this reporting period, major chemical engineering efforts were initiated on preliminary process design of the BCL process--Case B (one deposition reactor and two electrolysis cells). Chemical engineering design results are reported for Case B including raw materials, utilities, major process equipment, and production labor requirements for a Si plant of 1,000 MT/yr capacity.

For economic analysis, major efforts centered on cost sensitivity analysis for the BCL process--Case A for producing Si. Cost-sensitivity results are presented for the influence of primary cost parameters. For both 1975 and 1980 time periods, the results indicate that the cost-parameter influence on product cost is: plant investment (most), raw materials (intermediate), utilities (intermediate) and labor (least). For profitability, the results indicate a sales price of $14/kg (1980 $), at a 7.5% DCF rate of return on investment after taxes. These results suggest good potential of the BCL process for meeting the LSA cost goal of $14/kg (1980 $).

Massachusetts Institute of Technology: A contract review was conducted by JPL at the contractor's site on October 26, 1979. It was found that all the contractual activities were on schedule; technical results to date indicated that significant improvement in terms of lowering the operating temperature or pressure could be achieved for the hydrogenation of silicon tetrachloride and metallurgical-grade Si in the Union Carbide contract.

Extensive experiments were carried out on the hydrogenation of silicon tetrachloride to trichlorosilane. Reaction kinetic data were collected as functions of reactor temperatures, pressures, and hydrogen-to-silicon tetrachloride molar ratios. As expected, the reaction rate increases rapidly with increasing reactor temperatures. At higher hydrogen-to-silicon tetrachloride ratio, the conversion of trichlorosilane per pass increases. The effect of reactor pressure on the rate of the hydrogenation reaction was also obtained. The rate of approaching equilibrium at higher reaction pressure (500 psig) is somewhat slower than those at lower reactor pressure (300 psig).

JPL In-house Studies: Silane pyrolysis experiments with high throughput rate were conducted in the continuous-flow pyrolyzer system at reactor temperatures of 600 to 700°C. Si product appears to be of a different texture, higher bulk density, and larger particle size in comparison with the Si particle product obtained in previous CFP experiments. Further experiments are under way to investigate the effectiveness of the current direction.
The 2-in.-dia stainless-steel fluidized-bed reactor was run for 51 minutes with 10% silane in the feed and with gas velocity 10 times minimum fluidization velocity. No agglomeration occurred and the conversion was greater than 95%. The deposition rate was about 2.6 g/min. The Si growth layer appeared to be dense and 15 to 25 μm thick.

The apparatus for conducting Si CVD experiments has become fully operational. Several experiments were made in a 1-in.-dia reactor to study critical concentration phenomena and homogeneous kinetics of silane pyrolysis. A special substrate for heterogeneous pyrolysis of silane was designed and fabricated.

Fifteen contracts now in progress are listed in Table 1.
<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>TECHNOLOGY AREA</th>
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<tr>
<td><strong>SEMICONDUCTOR- GRADE SILICON PROCESSES</strong></td>
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<tr>
<td>Battelle Columbus Laboratories Columbus OH</td>
<td>Reduction of $\text{SiCl}_4$ by $\text{Zn}$ in fluidized bed reactor</td>
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<td>JPL Contract No. 954339</td>
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<tr>
<td>Energy Materials Corporation Harvard MA</td>
<td>Gaseous melt replenishment system</td>
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<td>JPL Contract No. 955269</td>
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<tr>
<td>Hemlock Semiconductor Corporation Hemlock MI</td>
<td>Modified Siemens process using $\text{SiH}_2\text{Cl}_2$</td>
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<td>JPL Contract No. 955533</td>
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<td>Union Carbide Corporation Tonawanda NY</td>
<td>Silane/Si process</td>
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<td>JPL Contract No. 954334</td>
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<tr>
<td><strong>SOLAR-CELL- GRADE SILICON PROCESSES</strong></td>
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<tr>
<td>SRI International Menlo Park CA</td>
<td>$\text{Na}$ reduction of $\text{SiF}_4$</td>
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<td>JPL Contract No. 954771</td>
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<tr>
<td>Westinghouse Electric Corporation Trafford PA</td>
<td>Reduction of $\text{SiCl}_4$ by $\text{Na}$ in arc-heater reactor</td>
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<td>JPL Contract No. 954589</td>
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<td><strong>IMPURITY STUDIES</strong></td>
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<tr>
<td>Aerospace Corporation El Segundo CA</td>
<td>Impurity concentration measurements by analytical photon catalysis</td>
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<tr>
<td>JPL Contract No. 955201</td>
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<tr>
<td>Lawrence Livermore Lab Livermore CA</td>
<td>Impurity concentration measurements by neutron activation analysis</td>
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<td>NASA Defense Purchase Request No. WO-8626</td>
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<td><strong>IMPURITY STUDIES</strong></td>
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<tr>
<td>Sah, C.T., Associates</td>
<td>Effects of impurities on solar cell performance</td>
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<tr>
<td>Urbana IL</td>
<td>JPL Contract No. 954685</td>
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<tr>
<td>Solarex Corporation</td>
<td>Effects of impurities on solar cell performance</td>
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<td>Rockville MD</td>
<td>JPL Contract No. 955307</td>
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<tr>
<td>Westinghouse R&amp;D Center</td>
<td>Definition of purity requirements</td>
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<td>Pittsburgh PA</td>
<td>JPL Contract No. 954331</td>
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<tr>
<td><strong>SUPPORTING STUDIES</strong></td>
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<tr>
<td>AeroChem Research Labs</td>
<td>Investigation of silicon halide/alkali metal flames</td>
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<tr>
<td>Princeton NJ</td>
<td>JPL Contract No. 954777</td>
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<tr>
<td>AeroChem Research Labs</td>
<td>Development of model and computer code for description of silicon production processes employing silicon hydrides or halides</td>
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<td>Princeton, NJ</td>
<td>JPL Contract No. 954862</td>
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<td>Lamar University</td>
<td>Technology and economic analyses</td>
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<tr>
<td>Beaumont TX</td>
<td>JPL Contract No. 954343</td>
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<tr>
<td>Massachusetts Institute of Technology</td>
<td>Hydrochlorination of metallurgical-grade silicon</td>
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<tr>
<td>Cambridge MA</td>
<td>JPL Contract No. 955382</td>
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LARGE-AREA SILICON SHEET TASK

INTRODUCTION

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

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

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

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

ORGANIZATION AND COORDINATION

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

Large-Area Silicon Sheet Contracts

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

Table 2. Large-Area Silicon Sheet Task Contractors

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>TECHNOLOGY AREA</th>
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<tbody>
<tr>
<td><strong>SHAPED RIBBON TECHNOLOGY</strong></td>
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<tr>
<td>Arco Solar, Inc.</td>
<td>Vacuum die casting</td>
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<td>Chatsworth CA</td>
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<td>JPL Contract No. 955325</td>
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<tr>
<td>Energy Materials Corporation</td>
<td>Low-angle Si sheet</td>
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<td>Harvard MA</td>
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<td>JPL Contract No. 955378</td>
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<tr>
<td>Mobil Tyco Solar Energy</td>
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<td>Waltham MA</td>
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<td>JPL Contract No. 954355</td>
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<tr>
<td>Westinghouse Research</td>
<td>Dendritic web process</td>
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<td>JPL Contract No. 954654</td>
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<tr>
<td><strong>SUPPORTED FILM TECHNOLOGY</strong></td>
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<td>Honeywell Corporation</td>
<td>Silicon-on-ceramic substrate</td>
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<td>Bloomington MN</td>
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<td>JPL Contract No. 954356</td>
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<tr>
<td><strong>INGOT TECHNOLOGY</strong></td>
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<tr>
<td>Crystal Systems, Inc.</td>
<td>Heat exchanger method (HEM)</td>
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<td>Salem MA</td>
<td>cast ingot, and multiwire fixed</td>
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<td>JPL Contract No. 954373</td>
<td>abrasive slicing</td>
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<td>CONTRACTOR</td>
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<td><strong>INGOT TECHNOLOGY</strong></td>
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<td>Hamco Corporation</td>
<td>Advanced Cz growth</td>
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<td>Rochester NY</td>
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<td>Silicon Technology Corporation</td>
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<tr>
<td>Oakland NJ</td>
<td>JPL Contract No. 955131</td>
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<td>Siltec Corporation</td>
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<td><strong>DIE AND CONTAINER MATERIALS STUDIES</strong></td>
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<td>University of Missouri Rolla</td>
<td>Partial pressures of reactant gases</td>
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<td>Columbia MO</td>
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<td><strong>MATERIAL EVALUATION</strong></td>
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<tr>
<td>Applied Solar Energy Corp.</td>
<td>Cell fabrication and evaluation</td>
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<td>(Formerly Optical Coating Laboratory)</td>
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<td>City of Industry CA</td>
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<td>Characterization--Si properties</td>
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<td>Ithaca NY</td>
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<td>Charles Evans and Associates</td>
<td>Technique for impurity and surface analysis</td>
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<td>San Mateo, CA</td>
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<td>Spectrolab</td>
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<td>Sylmar CA</td>
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Table 2. Large-Area Silicon Task Contractors (Continued)

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<td>Materials Research, Inc.</td>
<td>Centerville UT</td>
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<td>JPL Contract No. 957977</td>
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TECHNICAL BACKGROUND

Shaped-Ribbon Technology: Vacuum Die Casting
Method—ArcoSolar. This technique to produce a shaped-ribbon material involves lowering a die into a crucible of molten silicon under vacuum. The liquid silicon is forced by argon or some other inert gas into the die where it remains until it has cooled and is then removed from the die. Single-crystal growth may be achieved by slowly solidifying the material from the apex of the die downward. SRI International has been subcontracted by Arco Solar to investigate various die materials. Phase I of the Project is a feasibility study requiring the demonstration of 25 cm²/min throughput rate. The material must be capable of making 12% efficient 2 x 2 cm solar cells at AM1. Phase II is the scale-up phase requiring 7.9 m²/h throughput rate on 12% efficient material.

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

Shaped-Ribbon Technology: EFG Method—Mobil-Tyco Solar Energy Corp. The EFG technique is based on feeding molten silicon through a slotted die. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material that is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width of 7.5 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.
Shaped-Ribbon Technology: Westinghouse. Dendritic web is a thin, wide ribbon form of single-crystal silicon. "Dendritic" refers to the two wirelike dendrites on each side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film supported by the bounding dendrites. Dendritic web is particularly suited for fabrication into photovoltaic converters for a number of reasons, including the high efficiency of the cells in arrays, and the cost-effective conversion of raw silicon into substrates.

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

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

The overall goal of this program is to determine if the heat-exchange ingot casting method can be applied to the growth of large shaped silicon crystals (>8-in.-cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

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

Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Hamco will demonstrate the growth of 100 kg of single-crystal material using only one crucible by periodic melt replenishment.
Ingot Technology: Fixed Abrasive Sawing Technique (FAST) -- Crystal Systems; Inner Diameter (ID) Sawing -- Silicon Technology and Siltec. Today most silicon is sliced into wafers with an inside-diameter saw, one wafer at a time being cut from the crystal. Advanced efforts in this area are continuing. The multiwire slicing operation employs reciprocating blade head motion with a fixed workpiece. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheet, which is impregnated with diamond as an abrasive.

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

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

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

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

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

SUMMARY OF PROGRESS

Shaped-Ribbon Technology: Arco Solar (Vacuum Casting). SRI, subcontractor to Arco Solar, has selected coated graphite as their die material. The fused-salt liquid-barrier coating consists of a sodium silicate-sodium fluoride mixture and is used to prevent any silicon-graphite reaction. Using these dies, several silicon discs are being cast for solar cell fabrication at Arco Solar. Energy Materials (Low-Angle Ribbon): During the current feasibility study,
EMC has grown ribbons up to 34 cm in length at rates up to 85 cm/min.

Mobil Tyco (EFG): Mobil Tyco has reduced operation of the 10-cm growth cartridges to routine operation with 65 m of material having been grown during this period in the multiple machine and in the fully instrumented machine. The multiple machine has been operated in single-cartridge mode with melt replenishment. It is now being prepared for the three-cartridge multiple demonstration of 10-cm material by the end of the year. Studies of material quality and purity have continued, but only minor improvements have been made with efficiencies on a routine basis running from 9% to 10% AM1. Non-routine studies have produced 11% to 12% cells.

Westinghouse (WEB): A 5-hour run using continuous melt replenishment has been demonstrated. The material quality from this run has been shown to be equal to or better than runs without melt replenishment.

Supported Film Technology: Honeywell (SOC). Honeywell has modified the skin coater to improve substrate manipulation and to avoid slipping of the substrates on the transport mechanism. Variations in the angle of skimming indicate little effect of this variation over a range of approximately 5° to 25°. Evaluation of the quality of skin-coated material has been hampered by the lack of large slotted substrates. These have been ordered and shipped, but have not yet been evaluated. Performance of diodes of skin-coated material has been 8% to 9%, which is considered encouraging since no special purification efforts were made during the setup for these runs.

Ingot Technology: Crystal Systems (HEM). Several large ingots, over 10 kg in mass, have been grown. The largest ingot cast to date was 15.3 kg, with dimensions 21 x 21 x 16 cm and no crucible attachment. Several ingots have been cast using upgraded metallurgical-grade silicon as the starting material. Nearly single-crystal ingots were produced, indicating that HEM may be a viable process for using low-purity material directly. Crystal Systems (FAST): Emphasis during this period has been on wire development, especially on the in-house impregnated wires. Several wire packs have been produced and are currently being tested.

Hamco (Cz): Two 100-kg ingots were grown from 100% chunk polysilicon feedstock material at a throughput rate greater than 1.0 kg/h. Wafers taken at a random sampling from the first to the last ingot of the runs have consistently produced 15% to 16% efficient solar cells at AM1. Silicon Technology (ID Wafering): 10-cm ingots have been sliced using crystal rotation and automated recovery to transport and load sliced wafers into a cassette. Kerf thickness of 9 mils has been achieved. Slicing speeds of up to 1 in./min using rotation have been demonstrated with minimal edge chipping. Siltec (Cz): Two 150-kg demonstration runs are scheduled for the end of February, 1980. The program is running behind schedule. Siltec (ID Wafering): Runs producing slices 100 mm in diameter, 250 μm thick, and 200 μm kerfs have been demonstrated. Cutting feed rates were in the range of 12 to 13 mm/min. The test runs were performed with 12-in. blades and 76 μm core thicknesses.
Die and Container Materials: University of Missouri Rolla (UMR). Investigations of the effect of partial pressures of oxygen on devitrification of silica in contact with molten silicon have been completed. The results indicate a trend toward a greater degree of devitrification at lower oxygen partial pressures. Measurements of the effects of oxygen partial pressure upon silicon ribbon were conducted at Mobil Tyco.

Material Evaluation: Applied Solar Energy. Figure 1 summarizes the average efficiencies of various silicon-sheet materials processed by ASEC. Cornell University: No impurity precipitates were found in EFG material that was investigated using the transmission electron microscope (TEM). The electron-beam-induced current (EBIC) studies showed that the twin boundaries contain both electrically active and inactive sections. Grain-boundary passivation using hydrogen was only partially successful. The spatial distribution of dopants and impurities were studied with the SIMS technique. Undoped ribbons indicated an undetectable level of molybdenum, aluminum and boron while doped ribbons indicated a boron content of $2 \times 10^{17}/cm^3$. Spectrolab: Table 3 summarizes the results obtained for various sheet materials. UCLA: The development of a new technique to measure minority carrier diffusion lengths has continued during this period. Materials Research, Inc.: Several hundred cm² of various silicon-sheet materials have been quantitatively characterized for a variety of structural defects.

Procurement Status: Add-on contracts are being negotiated for the following contractors: Energy Materials Corp., Crystal Systems, Honeywell, Materials Research, and Mobil Tyco Solar Energy Corp. UCLA: A four month, no-cost extension has been granted. Varian: The final report has been received by JPL.

JPL In-House Activities: Laboratory facilities for cell processing are nearly complete. The only required items lacking are a vacuum pump for the yellow room and a recirculating water supply for the vacuum evaporators. Baseline cell processing has begun and 13% AMO cells (280°C) have been fabricated (2 x 2 cm). Problems with AR coating are being investigated. HEM cast material is being processed. Initial oxide growth studies indicate this material yields poor cell efficiencies.
Figure 1. Applied Solar Energy's Material Evaluation
Table 3: Spectrolab's Material Evaluation

I-V DATA FOR HIGHEST EFFICIENCY
CELLS IN EACH MATERIAL

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ENCAPSULATION TASK

INTRODUCTION

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

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

The encapsulation system also serves other functions in addition to providing the essential environmental protection: e.g., structural integrity, electrical resistance to high voltage, and dissipation of thermal energy.
The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. These efforts can be divided into two technical areas:

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

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

SUMMARY OF PROGRESS

Materials and Process Development

A baseline ethylene/propylene rubber (EPR) pottant was developed by Springborn Laboratories. EPR is an alternative to EVA, also requiring vacuum lamination. The cost of EPR at a production level of 10 million pounds per year is approximately $1.09 per pound or $0.10 per square foot for a 20-mil-thick sheet versus $0.95 and $0.095 for EVA. EPR is considered ready and is now available for industrial evaluation.

Dow Corning developed a family of low-cost silicone/acrylic films incorporating a flexible UV screening agent. The techniques and details of producing these films are being transferred to Springborn Laboratories for continued development and subsequent production scale-up.

Dr. Edwin P. Plueddemann of Dow Corning has developed a "self-priming" coupling agent for EVA that is incorporated directly in the EVA formulation. He is developing a similar coupling agent (primer) for EPR. Dr. Plueddemann's first annual report on chemical bonding technology has been published (Reference 1).
Fifteen full-size (4x8 ft) glass-fiber-reinforced concrete (GRC) substrate panels were manufactured by MB Associates using semi-automated equipment and procedures. One of these was tested and passed JPL static loading requirements. The other 14 were delivered to JPL. Two of these (one covered with encapsulated cells) were displayed at the JPL 14th Project Integration Meeting (PIM). The estimated cost to produce such panels with encapsulated cells including total field installation cost (but not including the cost of cells and interconnects), at a rate of 15 mW/yr is $6/ft².

Abrasion resistance and transmission tests have been completed on two types of anti-reflection coatings for soda-lime glass at Motorola: acid etching and etched silicate coatings. Acid etching produces AR coatings on glass with 99% transmission but with marginal abrasion resistance. Glass samples produced by the etched silicate coating method show lower transmissions, approximately 96%, but have excellent abrasion resistance. Cost effectiveness of the two competing methods is being evaluated.

Spire has completed semi-automation of the electrostatic bonding (ESB) process to the point where production of 6 x 6-inch, 4- and 6-cell minimodules, with cells electrostatically bonded to Type 7070 glass, is routine. Yield is approximately 90%. Future work will be concentrated on the development of mesh contacts and the development of low-temperature electrostatic bonding using interdigitated back contact cells.

Contracts with Illinois Tool Works, to develop ion plating methods, and with Spectrolab, to design and optimize one or more encapsulation systems, have been initiated.

Life Prediction and Material Degradation

Mini-modules (12 x 16 in.) incorporating six different encapsulation designs were received from two manufacturers. Samples of the six designs are being assembled for placing in outdoor exposure at three Southern California sites: Point Vicente, Goldstone, and JPL. Outdoor weathering racks have been installed at JPL and installations are being completed at the other two sites. Samples of the designs are being subjected to the JPL qualification tests (temperature cycling and high humidity exposure). In addition, NOCT is being determined for each design. All designs are encapsulated with ethylene/vinyl acetate (EVA) pottant, with various combinations of superstrate, substrate, film/foil/film back covers, Mylar back covers, and Korad acrylic film front covers. Electrical output will be determined as a function of site, time of weathering, and soiling over a period of approximately two years.

Rockwell Science Center installed two corrosion monitors at the Meat, Nebraska site. One is covered with Sylgard 184 encapsulant while the other is unprotected. Their comparison will show the protective behavior of the encapsulant. An improved corrosion model
was developed and will be applied to the Solarex and Sensor technology modules at the site.

Construction has begun on a laboratory test simulator for the Mead NE site to control atmosphere (including corrosive gases), temperature, moisture, and insolation. The simulator will be used to simulate or accelerate Mead climate conditions to complement field data from modules previously deployed with special corrosion monitors.

The first phase of a modeling effort to demonstrate the feasibility of a finite element approach to predicting stress distributions in solar cell modules has been successfully completed and reported (Reference 2). The second phase to develop an automated input program was begun. An interactive graphic program, Unitstruc II, written by Control Data Company, was chosen and various sample problems are being run to develop techniques.

The Battelle final report on the development of an accelerated test design for predicting service life of the array at Mead has been published (Reference 3).

A report has been released describing a UV reactor that was designed and constructed at JPL (Reference 4).

References


PRODUCTION PROCESS & EQUIPMENT AREA

AREA OBJECTIVES

As can be seen by Figures 2, 3, and 4, the first two major categories of objectives of the PP&E Area are being successfully completed.

It is appropriate to point out that Phase I, Process Assessment, although completed in its major effort, is not a closed subject. Due to the nature of the industry, it is entirely possible that processes will be developed in the near future that will replace those selected. This is also true of Phase II, Part 1. Both of these areas are considered dynamic and subject to being reopened on an if-needed basis.

Phase III has been started by outlining the requirements of the proposal. Some of those requirements are stated in the Documentation section of the Summary of Progress.

SUMMARY OF PROGRESS

Some of the contracts listed in Table 4 were scheduled to have ended within this reporting period but for a variety of reasons have been extended. In some cases this was caused by logistical problems in some funding and, in at least one, additional work was required. In all cases, except those in which additional work was requested, the extensions were on a no-cost basis.

Process Sequence Development

Westinghouse has completed fabrication of panels made using dendritic web cells. These have been submitted to NASA Lewis for preliminary electrical testing. They will then be sent to JPL for test verification and environmental testing.

At Westinghouse the use of an arc-spray technique for forming aluminum back-surface fields has proven as successful as has evaporating, sputtering or screen printing of the aluminum. This is potentially more cost-effective than the others and will be costed out in the final form of the required SAMIS data.

SAMIS costing-sensitivity analysis by Westinghouse has given the following results:

(1) For $10 \times 10^6 +10\%$ capital expenditure, each $10^6$ of capital adds $0.03/Wp to the selling price.

(2) In the 20\% to 90\% yield range, each 10\% increase in yield decreases the selling price by $0.07/Wp.

27
(3) When web width is decreased from 5.0 cm to 2.5 cm, the selling price is increased by $0.07/dp (assuming equal yields and efficiencies).

(4) In the range of 10 to 15% panel efficiency, for each 1% increase in efficiency the selling price is decreased by $0.06/Wp (assuming equal yields).

Table 4. Production Process and Equipment Contractors

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Figure 2. Production Process and Equipment Area Phase Schedule

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Figure 3. Production Process and Equipment Area Major Milestones

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<td>PHASE I: TECHNOLOGY ASSESSMENT</td>
<td>PHASE III: DEFINE, SELECT, AND DEMONSTRATE MANUFACTURING PROCESSES</td>
<td>PHASE IV: EXPERIMENTAL PLANT IN OPERATION</td>
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<td>PART II SEQUENCE DEVELOPMENT</td>
<td>PHASE V: MASS PRODUCTION PLANT READY FOR OPERATION</td>
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<td>• DETERMINE PRIORITY FOR PROCESS DEVELOPMENT</td>
<td>• COMBINE MOST COST EFFECTIVE PROCESS</td>
<td>• REVIEW REG FOR MASS-PRODUCTION AND IDENTIFY EQUIP REG</td>
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<td>• IDENTIFY AREAS WHERE NEW TECHNOLOGY MUST BE DEVELOPED</td>
<td>• IDENTIFY THE MANUFACTURING EQUIPMENT AND FACILITIES REQUIRED</td>
<td>• PERFORM DETAILED STUDY OF EXISTING EQUIP</td>
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<td>• DEVELOP PROCESSES AND DEMONSTRATE READINESS</td>
<td>• DEMONSTRATE MANUFACTURING TECHNOLOGY READINESS</td>
<td>• MODIFY STANDARD AVAILABLE EQUIP AS REQ</td>
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<td>• DESIGN ADDITIONAL EQUIP AS REQ</td>
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<td></td>
<td>• ESTABLISH MANUFACTURING PROCEDURES, MATERIAL FLOW AND HANDLING</td>
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<td>• ESTABLISH TECHNOLOGY READINESS/COST/PRODUCTION CAPABILITY</td>
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RCA has received a partial shipment of dendritic web material from Westinghouse. They are outlining a process sequence which will include their screen printed metallization.

**Surface Preparation**

Photowatt International reports a uniform 38% output enhancement using spray-on titanium isopropoxide as developed by RCA under another PP&E contract. This is in line with the results reported by RCA on non-texture-etched cells.

The enhancement of texture-etched cells is 8%. Previous reports have reported problems in this area when an investigation was made by Photowatt and Spectrolab together. The change has been due to an intermediate step of spray-on, or dip in, n-butyl acetate.

Photowatt International has submitted the SAMICS Format A's covering the four surface-texturing processes to the formal review board. Work is being completed on the draft final report.

Motorola has investigated Apiezon W, Multiwax and glycol phthalate waxes with methylene chloride, mineral spirits and acetone as solvents for formulation of inks. The only conclusion reached so far is that methylene chloride is the best solvent; mineral spirits left too many residuals and acetone was too volatile.
Spectrolab has continued their investigation of plasma etching on front surfaces. They have found that inclusion of small amounts of oxygen in the Freon 14 enhances its ability to remove diffusion oxides. There is still surface pitting with Freon 14, however. By substituting sulfur hexafluoride the pitting is greatly reduced or eliminated.

The effects of the etching gas used when a small amount of the surface layer is removed are markedly different.

When Freon 14 is used the increase in short circuit current is in the 9% range. Spectral analysis shows this to be a fairly uniform enhancement over the major portion of the range. When sulfur hexafluoride is the etchant gas, however, the predominant response is in the shorter wavelengths and is still in the 9% range.

One possible explanation of this is in the pitting found with the Freon. If the pits are acting the same as textured surfaces it would be expected that this would be true over the entire range since all wavelengths would be similarly treated. The effect from sulfur hexafluoride etching, which takes four times as long but does not produce the pits, is the same as that which could be expected from removal of the dead band.

When tests were run using Freon 23 to remove the diffusion oxide, two problems occurred: the plasma did not completely remove the oxide, and the removal that did occur was not uniform. Fair uniformity occurred in an area about 2 in. in dia at the center. After that there was a sharp fall-off. This is difficult to explain since Freon 23 is standardly used for this purpose. Further evaluations will be made.

Junction Formation

Photowatt International, Inc. has tested the first sprayed-on metallic-aluminum back-surface field cells. On base material in the 3 to 8 Ω-cm range, the $V_{oc}$ is clustered around 580 mV. When 10 to 15 Ω-cm material is used the $V_{oc}$ climbs to between 605 and 610 mV. The previously authorized aluminum spray-on modification to the existing machine has been designed and is currently being fabricated by Advanced Concepts.

Concurrent with the spraying of aluminum, an experiment to verify the reduction of bowing on printed back-surface fields by use of the Spectrolab gridded pattern was conducted. The experiment confirmed that bow was reduced on 4-in. wafers from 0.015 in. average to 0.004 in. average. It was noted, however, that the wafers that had a sprayed-on BSF had no bow. This is being investigated.

Photowatt International, Inc. has produced highly uniform cells using Borofilm to produce back-surface fields. The concentration used was $5 \times 10^{20}$. Over a 50-cell lot the $V_{oc}$ was 60 mV ±2mV. The average curve fill factor was 0.76.
In companion experiment, the back-surface field was screened on using the Spectrolab formulation for aluminum paste. There was an inconsistency in $V_{oc}$ with readings from 570 to 620 mV.

Work has been completed on the Spire contract for pulsed-electron-beam annealing. A final report is being drafted. The cells and the analytical data have been shipped to JPL for analysis.

Metallization

Motorola has successfully plated nickel directly onto silicon electrolytically without an intermediate electroless palladium step. In addition, they have plated a layer of copper over the nickel and heat-soaked the entire system at 300°C for 30 min with no ill effects.

This technique has been used to fabricate several solar cells utilizing Motorola's silicon nitride AR-coating/masking method to define the metallization pattern. The cells produced were comparable in performance to those made with the standard electroless palladium metallization method, which indicates that the nickel does provide an adequate barrier against copper migration into the silicon.

The spray-on copper metallization being done by Photowatt International, Inc., in cooperation with Advanced Concepts, has been accomplished. Although they have been fabricated, the cells have not yet been evaluated.

Applied Solar Energy Corporation has ascertained that nickel is the most practical, most cost-effective barrier to copper migration.

ASEC has constructed a test matrix to test this premise. The basic chromium/palladium/copper plating system will have nickel inserted just before the copper. The cells produced will be soaked at various temperatures and then tested for all parameters.

They are also continuing to develop and test the print-on mask using HB Printing Plating Resist. Promising results have been produced repeatedly, using a 200-mesh screen. Copper lines of less than 0.005 in. width have been produced using HB mask.

Sol/Los, in conjunction with Dr. Goldman, an assistant to Dr. Wolf of the University of Pennsylvania, determined that silver metallization would cost $0.40/W on a megawatt production basis whereas the molybdenum system would cost approximately $0.015/W.

Sol/Los has delivered five ounces of their molybdenum/tin ink formulation and one ounce of their powder (without the binder) to JPL. The plans are to use the screenable ink to produce cells and verify the reported mechanical and electrical properties. Part of the powder will be used in analytical studies and a part of it will be delivered to the Ferro Corporation for studies to see if there is any
incompatibility between it and their Midfilm technique. Testing will occur after the previously reported sheet-resistance problem has been straightened out.

The mechanical and electrical tests scheduled for this period by Sol/Los have been completed. Mechanical contact of the ink to silicon is reported as being equal to the best nickel contact and superior to screened silver. Electrical tests indicate consistently low levels of junction leakage and contact resistance.

The entire system was demonstrated to JPL during this report period.

Sol/Los reports encountering a problem when their molybdenum/tin formulation was applied to live cells which had had an aluminum back-surface field incorporated.

After a firing cycle at 700°C was used, cells metallized on the insolated side were shorted. A speckled appearance on both sides of the wafer led them to suspect that aluminum had adhered to the surfaces and this had subsequently been diffused through the junction at 700°C. Processing of a lot of 10 with a maximum of 525°C exposure produced no shorting and the I-V curves were good. The cells were mechanically weaker, however.

Bernd Ross Associates has successfully produced a copper metallization using lead as a frit. Excellent adhesion to the silicon surface was demonstrated by the fact that approximately 20% of the metallized surface pulled a significant quantity of silicon with it when pull tests were performed.

The pull test results allayed initial concerns that soldering would leach the lead out of the copper-lead intergranular alloy that occurs at the copper particle interfaces.

After metallization, firing in hydrogen reduces the oxidized copper surface to a bright elemental one providing an easily soldered connection using tin-lead eutectic solder.

The controlled atmosphere firing furnace is operational at Bernd Ross Associates. Silver fluoride-fluxed silver inks were fired containing GeAlGa (p-type) and GeSb (n-type) additions (5%). These experiments resulted in poor surface bonding to the silicon.

A variety of nickel-based inks containing 5, 10, 20% lead or 5, 10, 20% tin was fired in nitrogen, hydrogen and 10% hydrogen/90% nitrogen. Experiments were performed up to 700°C and no sintering was evidenced. These inks also had silver fluoride added as a fluxing agent.

The RCA-developed thick-film screen-printed metallization appears to be less compatible with ion-implanted cell junctions than with diffused junctions. Average efficiencies of small cell lots was
11.7% AM1 (12% based on exposed silicon) for cells with diffused junctions, compared with 6.7% AM1 (7.3% based on exposed silicon) for cells with ion implanted junctions.

A contract has been executed with Solarex Corporation to optimize and environmentally test the product of a nickel-plating bath. The Program and Process Plan, recently submitted to JPL, appears to need only minor modifications and, as a result, work is proceeding on the initial phases.

Spectrolab has encountered a series resistance problem on their work with Ferro Corporation.

Using Ferro's patented Midfilm process, cells have been produced having silver metallization; unfortunately, voids have shown up and series resistances have been in the 300 $\,\Omega$/unit range vs the expected 100 $\,\Omega$/unit. One possible reason is that the powder was applied at Ferro in Cleveland, OH and the firing occurred at Spectrolab in Sylmar, CA; there could have been in-transit damage. To counter this problem in the future, Spectrolab is sending an engineer to Ferro for technique training.

In spite of these problems the overall yield showed >20% to be in the $\geq 15\%$ efficiency category.

Non-noble metal systems of copper/tin, nickel/tin and molybdenum/tin with Thick Film Systems frit are being formulated for Phase 2 analysis.

The new infrared furnace has been installed at Spectrolab. Initial tests show that firing of the screened-silver front contacts in this furnace produced units with efficiencies of approximately 15%, which is as good as or better than those produced in a tube furnace. When the same thing was tried on aluminum paste, however, the open-circuit voltages were too low. If the drying occurred in an air-circulating oven and firing in the IR oven, the results were good. Spectrolab believes that further work must be done on the IR-drying cycle and that this technique is a viable one, once the proper cycle is evolved. The front contact screen mask has been redesigned to produce a wider ohmic bus to reduce series resistance in a modified cell at Spectrolab.

Assembly and Test

RCA has fabricated two 4 x 4 ft solar modules, and several smaller units, with the double-glass PVB laminate auto-windshield technique using an autoclave. These modules will be exposed to a standard battery of environmental tests at JPL.

Applied Solar Energy Corporation is continuing to make progress toward development of a 3-in. dia, p on n$^+$ high-efficiency cell. Results of a most recent lot of development cells include: 20 wafers; 19 finished cells; 15 cells with good performance $\eta_{\text{max}} = > 15.6\%$, $\eta_{\text{min}} = 15.1\%$, $\eta_{\text{low}} = 14.7\%$. 

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A contract extension has been released for signatures at Applied Solar Energy Corporation. The modification provides $30,500 of added funds to cover further cell development on their 14% module contract. The completion date will be extended to April, 1980.

Module Development

During this period Texas Instruments reported a probable cost overrun of $52K to satisfy all delivery requirements on this contract for development of large-area Tandem-Junction Cells (TJC) and Tandem-Junction Modules (TJM). No fully assembled modules will be delivered unless the overrun is funded. TI has attributed the overrun to their original underestimate of material costs plus current cell-process problems (an entire production lot of 100 large-area TJC was recently lost). A final report, describing all progress made under the contract, will be published.

RCA has completed three double-glass modules. They will be submitted to JPL for evaluation and life testing.

Advanced Equipment Design

Advanced Concepts has notified Photowatt International, Inc. that the metallic-aluminum spraying machine will be delivered in late January. The delays have been caused by their suppliers not keeping to schedule.

Cober Electronics, through a subcontract with Photowatt International, Inc., has made considerable progress on the hardware associated with their microwave process. A horn has been developed and is functional. It has been applied to continuous energy only. A tentative design of a full-scale system has been completed as has a design for a cylindrical wave-guide that has the potential for more uniform wave delivery.

In another phase of the effort, work is being performed on an interference fringe technique of depth-of-penetration control of pulsed microwaves. A variable power supply and the material required for the balance of the system have all been ordered. This is to be a prototype of the final system.

Cober Electronics has reported that heating with microwaves appears to be uniform across the surface of the 3-in. wafer. The shape of the horn has been established and they are now working on a power/frequency matrix to produce the required skin effect. Samples of sprayed-on dopant and printed aluminum have been sent to them for testing.
A low-temperature (900°C) version of the microwave system for alloying and sintering of metallization has been constructed by Cober Electronics. The penetration depth and uniformity are good at 2.45 GHz. Further testing is now being done.

A computer simulation of a cooling jacket arrangement for one side of the wafer holder shows this system to be feasible. This remains to be proven in actual tests, however.

MBAssociates reports that they are nearing completion on their cell-preparation station. All component parts have been purchased or manufactured and tested. One of the components, the solder paste dispenser, has been found to give very uniform results over a wide range of dispensing rates.

Bonding methods for the robot end effectors are being investigated. Good solder bonds have been obtained with resistance-heated electrodes. These require precision placement, however; therefore, investigation is being made into induction-type heating electrodes. These are showing promise.

During early October an internal design review was completed at ARCO Solar's Albuquerque Laboratory. Significant progress has been made on the design of the automated soldering machine. Detail layouts have been completed on the conveyor/transport system that presents wafers to the soldering station. The ribbon-feed mechanism and ultrasonic cleaning equipment have been ordered.

ARCO Solar, Chatsworth, committed to delivery of several thousand final-configuration production cells by 19 October. These are being used for final machine development work at Albuquerque Laboratory. The cell back is an interim design but the contact/interconnect point geometry will be the same as the final one.

The target date for delivery of the completed soldering machine to ARCO in Camarillo has slipped to 18 January 1980. A contract modification that will insure contract completion without additional JPL funds being required and without future scope deletions is in process.

Albuquerque Laboratory of ARCO Solar has successfully completed several minidesign demonstration tests relating to the automated soldering machine. These included: (a) cell cassette unloading; (b) cell alignment; and (c) interconnect ribbon guiding. Norbell, Daytona Beach, Florida, has been selected to supply the ribbon supply and cut-off mechanism.

ARCO Solar, Chatsworth, is continuing soldering development. Twenty cell/interconnect samples were fabricated using the RF induction coil/roller contact method. All samples showed peel strength in the range of 300 to 350 grams.
The full RCA megasonic system is now functional and is being optimized. Preliminary tests indicate that a mechanism is needed for deflecting the wafers while they are progressing through the drying tunnel to promote the removal of water drops from the slots in the carriers. A pair of deflectors was installed and found effective.

Cleaning and drying wafers in 3/16 in. spaced carriers at a speed of 12 cm/min have been tested successfully in ambient conditions with an equivalent rate of 1100 wafers/h. To achieve the projected 2500 wafers/h rate would require either a second drying module or halving the spacing between wafers and increasing the speed to 14/cm/min. Quartz carriers with 3/32 in. spacing are to be delivered soon.

Fluoroware Corporation is now offering these units (in various configurations) for sale to the industry.

Another contract with RCA has been extended for three months to the end of March, 1980. This was done at no additional cost to permit further development of their mass module/interconnect soldering technique using IR lamps. In addition, they will attempt to develop a plasma-etch technique for junction (edge) cleaning.

Module fabrication has been reduced from 20 to 10 because of the lack of availability of silicon sheet materials from a supplier.

Kulicke & Soffa Industries has completed both the theta orientation and flux application station and the vacuum pick-up and lance assembly. The string conveyer and the first interconnect station are in final stages of completion.

Kulicke & Soffa reports having been contacted by two companies with inquiries about the potential procurement of sub-systems developed on their contract. The areas of interest are the vacuum pickup lance subsystem and the tabbing (interconnection) section. Work on the balance of the system and integration of the subsystems continues without serious problems; the previously reported problem with induction-heating soldering combined with the cell-supply problem have caused a delay in the scheduled progress, however. This has resulted in an approved request for a no-charge, three-month extension of the contract. The supplier is Applied Solar Energy Corporation.

Documentation

Theodore Barry and Associates have received the corrections to the handbook draft. A review was conducted with the JPL Technical Manager and the proper corrections will be made.

A new contract for continued consultation is in the mail to the University of Pennsylvania.
Westinghouse has submitted their first-draft final report on their process-sequence development contract.

Phase III general conditions have been outlined:
- Technical readiness to be demonstrated by the end of FY82
- Entire process sequences to be automated (if cost effective)
- Proposers are to select starting silicon sheet material of their choice and use values in SAMIS cost account catalogue (or derive in extensive detail if not in catalogue)
- More than one contract award may be requested
- Cost-sharing proposals are appropriate.

Miscellaneous

The draft form of the final report from Applied Solar Energy Corporation on their efforts to produce cast silicon has been submitted. The report's final conclusions include the statement that casting silicon sheet appears to be feasible in spite of the fact that functional solar cells have not been produced using this material. It further states that more work must be done on the mold materials and on improvement of the casting equipment.

Spectrolab has run comparisons among cells made from three different sources of silicon. Wacker material produced cells that were consistently 20% higher in short-circuit and power-point currents when compared with cells produced from Texas Instruments material. When Smiel material was used, the cells were about 10% better than TI's.

Spectrolab has made an analysis of diffusion lengths vs short-circuit current. For diffusion lengths of less than 60 um there appears to be a marked reduction in Isc.

As a result of this investigation, they attempted to incorporate a diffusion-length requirement in their procurement specification. They found, however, that vendors will not accept such a specification for resistivities less than 15Ω-cm.

Motorola has concluded that cells of 0.004 and 0.008 in thickness can be processed under the same conditions as the 0.013-inch cells.
ENGINEERING AREA

INTRODUCTION

During this reporting period work has been focused on array design and engineering, reliability and durability requirement development and standards. Detailed status of the engineering area contracts (listed in Table 5) was reported in the 14th PIM handout.

SUMMARY OF PROGRESS

Array Design and Engineering

Series/parallel analysis for multi-cell failures in intermediate load applications, which was initiated during the last reporting period, continued. Progress was made on development of a diffuse spectrum model to be incorporated in the spectral analysis computer program. These efforts were directed toward preparation of an in-depth presentation for the 14th IEEE PV Specialists Conference. In conjunction with these presentations, the results of the series/parallel investigations were distilled into preliminary guidelines applicable to circuit design of modules and array subsystems for presentation at the 14th PIM.

Work was initiated on development of test methods and devices to measure the performance of the foundations, structures and panel frames for low-cost utility application array structures. The design and fabrication of a full-scale prototype (8 x 16 ft) array panel structure was completed. The panel successfully withstood a 50 PSF uniform pressure loading test. The panel was displayed at the 14th PIM. Kaiser Steel Co. provided mass-production cost estimates for this panel structure and an alternative version based on this concept but using potentially cheaper-to-produce sections. A quarter-scale model of the panel, including foundations, also was fabricated.

Work was begun on the flat-plate PV thermal-collector design task. During this period activities were concentrated on investigating optimal temperatures of PV/T collectors for heat-pump applications and on the effect of cover glass on PV/T-collector performance.

Reliability and Durability

The IR camera recently acquired by the Engineering Area was successfully used to map the hot-spot problem at Mt. Laguna; it provided useful data on numbers of hot cells and their temperatures. Field mapping and controlled laboratory experiments are being continued to understand further the hot-spot heating problem and to aid in the development of a new module qualification test to eliminate the problem in future module designs.

Engineering Area personnel actively participated in the evaluation and analysis of module design/performance for the
Mt. Laguna array installation and for the planned PRDA 36
applications. Support included series/parallel analyses of
module/array circuitry, performance degradation prediction, cracked-
cell probability studies, I-V curve translation and analysis, and
design of performance degradation exploratory tests.

In the area of module testing, planning for a long-duration
module temperature soak test was initiated. The purpose of this
effort is to develop low-cost testing methods for detecting module
design deficiencies and degradation mechanisms that may not be
revealed during current qualification testing. An outdoor "hotbox"
concept is being pursued.

Work continued on the Phase II module-soiling investigations.
Efforts centered on comparing the differences between the relative
normal hemispherical transmittance (RNHT) and the integrated
hemispherical transmittance (measured at Battelle Pacific Northwest
Laboratories). The values measured at Battelle show, in most cases, a
greater loss in hemispherical transmittance than expected. Also
during this reporting period, material samples from four of the seven
outdoor exposure sites were returned to the materials laboratory for
transmittance measurements. The task report documenting the Phase I
soiling investigations is in final review.

A fracture mechanics, cell testing and analysis program for
determination of cell crack strength characteristics has been
initiated with several of the module manufacturers. A series of
detailed fracture mechanics tests is planned and a large quantity of
samples have been received. The samples include specimens in varying
stages of completion (from wafer to completed cell) taken off the
production line at selected points in the cell-processing cycle.
Tests will be conducted using a modified version of the four-point
flexure jig which has been described previously.

Array Standards

Interactions with consensus standards organizations continued
during the reporting period with participation in ASTM and IEEE
meetings. During the September ASTM solar subcommittee meetings at
Lake Tahoe, Engineering Area personnel presented recent work examining
the appropriateness of the Air Mass 1.5 reference spectrum and
reference temperature and intensity levels. The preliminary results
indicate that the AM1.5 spectrum may overpredict the annual energy
production of flat-plate arrays by 10% or so. This is caused by the
fact that the diffuse component of isolation contributes heavily to
flat-plate-array output and is much bluer (less efficient at
generating cell output) than the reference spectrum. Work has been
initiated at both JPL and DSET better to characterize the diffuse
radiation spectrum to understand the problem. A contract was
negotiated with DSET Labs to perform periodic (monthly) complete
spectral measurements of the natural sunlight over a two-year period
for purposes of supporting the photovoltaic performance measurement
standards effort.
The Array Subsystem Task Group, which is led by Engineering Area personnel, held its sixth meeting at Sandia in conjunction with the concentrator PIM, and its seventh meeting at JPL in conjunction with the LSA 14th PIM. Performance criteria and test methods have been drafted for the following attributes: electrical, mechanical, structural, safety, durability and reliability, installation, operation, and maintenance. A package of all completed documentation is being prepared for submittal to SERI as part of the January 1980 Interim Performance Criteria Release.

Table 5. Engineering Area Contractors

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OPERATIONS AREA
LARGE-SCALE PRODUCTION TASK

Block III Production

During this reporting period the contracts with Sensor Technology, Inc., were modified to allow a change in the design of the Block III module that would provide both an improved module and an improved delivery rate. In four months, August through November, Sensor Tech shipped 4.7 kW, 4.1 kW during the last two months. The Sensor Tech contract is now 81% completed.

The contract with Solarex for high-density modules is again being modified to enable Solarex to deliver a glass-faced high-density module. Completion of this contract is expected during the next reporting period.

Block IV Design and Qualification

All preliminary design reviews have been completed and each contractor has completed a prototype module of the proposed design. These were displayed at the 14th Project Integration Meeting. Motorola has delivered modules to JPL for the qualification test program, but the other contractors are two to three months behind the initial schedule. The delays are the result of unanticipated design problems, internal conflicts for facilities, and optimistic scheduling. JPL has received cells from all contractors and has mounted them in prescribed fixtures, calibrated the cells and returned them to the contractors for use in measuring the power output of the modules.

At this writing, the RFQ for the production part of this block is ready for issuance.

MODULE TEST AND EVALUATION

Environmental Testing

Four sets of Block III modules were subjected to environmental qualification tests during the reporting period, with generally satisfactory results. Humidity-heat and humidity-freezing exploratory tests were completed on sample Block III modules. Degradation from these tests was more severe than for the standard environmental test sequence, and the degradation more closely resembled that induced by field exposure. A comparison of results is given in Table 5.
### Table 6. Block III Environmental Testing: Qualification vs Exploratory Tests

<table>
<thead>
<tr>
<th>VENDORS</th>
<th>NO. MDLS. TESTED</th>
<th>QUALIFICATION TESTS</th>
<th>EXPLORATORY TESTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TEST MDLS.</td>
<td>NO. AFFECTED</td>
<td>RESULTS</td>
</tr>
<tr>
<td>R cells</td>
<td>4</td>
<td>T- 4</td>
<td>Air bubbles</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>T- 4</td>
<td>Air bubbles decreased</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Encap leak</td>
<td>MI-10K 1</td>
</tr>
<tr>
<td>R cells</td>
<td>4</td>
<td>M-2</td>
<td>Bubbles</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>M-2</td>
<td>Bubbles decreased</td>
</tr>
<tr>
<td>U cells</td>
<td>5</td>
<td>T- 5</td>
<td>End channels shrinking, lifting</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>H- 1</td>
<td>El. degrad. 4%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>H- 1</td>
<td>Cell crack</td>
</tr>
<tr>
<td>V cells</td>
<td>8</td>
<td>H- 8</td>
<td>Term corrosion</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>H- 8</td>
<td>Encap leak</td>
</tr>
<tr>
<td>Y cells</td>
<td>4</td>
<td>T- 4</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>Z cells</td>
<td>3</td>
<td>T- 3</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>M-3</td>
<td>Intercon delam.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>H- 2</td>
<td>Frame seal delam.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>1 cell crack</td>
</tr>
</tbody>
</table>

T- --- Temperature Cycling  
H- --- Humidity Cycling  
M- --- Mechanical Integrity  
HR --- Heat - Rain  
HH --- Humidity - Heat  
HI --- Humidity - Freeze

Three developmental module types and two commercial module types were tested. None of these designs was able to pass the tests; severe physical and/or electrical degradation was observed for all types. Cracked cells were a common cause of degradation. Two previously unobserved problems occurred on a glass-PVB laminated design: wrinkling of an aluminum-foil back-side vapor barrier during temperature cycling, and cracking of cells behind an intact glass superstrate during a 0.75 in.-dia hailstone impact test. Another of the developmental module designs tested incorporated cadmium sulfide...
cells. This exploratory test series was intended mainly to develop test techniques for this cell type, since the modules used were rejects from an experimental production run. As expected, pulsed solar simulators cannot be used to measure the output of such modules because of the relatively slow response time of the cells.

A nominal operating cell temperature test on a late-arrival PRDA-38 concentrator assembly was aborted because of moisture accumulation within the enclosure. The linear compound parabolic collector enclosure apparently gathered moisture by diurnal "breathing" and condensation.

In view of the cell fractures observed at Mount Laguna (see Failure Analysis below), two PRDA-38 manufacturer modules were subjected to an exploratory humidity-freeze test. Two Block III modules from the same manufacturer were included in the test for comparison. No electrical degradation was observed on any of the modules. Physical degradation was minor, but the PRDA-38 modules weathered the test better than the Block III modules. A more complete test series is planned, using new modules of each type.

Block III testing has been reported in document 5101-134, "Environmental Testing of Block III Solar Cell Modules, Part 1: Qualification Testing of Standard Production Modules".

Performance Measurements

Calibration and delivery of the Block IV reference cells has been completed with the exception of the ARCO cells. The ARCO cells will be completed after delivery of a new set of 2 x 2 cm solar cells for reference cell fabrication. The new LAPSS facility is nearing completion and is expected to be operating by the end of the year.

A review of field test data from the Pasadena site indicates that the data is statistically very good, exhibiting standard deviations in the 1% range. A problem area has been observed, however, in that the field data indicate a short-circuit degradation of 3% to 8% that is not supported by indoor LAPSS measurements. Investigation into the cause of this anomalous behavior is continuing.

Field Tests

The principal activity this period was preparation of the annual report. In this process a thorough review of data from the over 600 modules at the 16 sites was made. Evaluation indicates that the modules are enduring well both electrically and physically, and most important, there is nothing to suggest that the 20-year lifetime goal cannot be reached. The results from the JPL site to date show that electrical degradation is not a slowly increasing phenomenon, as first believed; it occurs abruptly as the result of an event such as a cell cracking. Therefore, a change in the testing strategy is being
introduced. Instead of placing emphasis on determining degradation rates and failure statistics, the emphasis is being shifted to investigating and isolating degradation mechanisms. A complete summary of the data and a presentation of future plans is included in the annual report.

At the request of the TD&A Lead Center, an on-site survey of a PV array powering a water-well pump was made. The facility is located near Sweetwater AZ and is operated by the Indian Health Service. Results of the array assessment have been forwarded to the Lead Center.

The on-site survey of the LeRC-installed endurance test sites has been completed. Results are given in the Annual Field Test Report. Continuation of testing at these sites is being recommended.

Failure Analysis

The major activity during this reporting period was an investigation of the cause of numerous cell fractures on one module type at the Mount Laguna Air Force Radar Tracking Station, and additional evaluation of the PRDA-38 glass/silicone/Mylar encapsulated module from the same manufacturer.

The analysis accomplished in the laboratory and at the array site of the Block III modules leads to a failure model as shown in the life-cycle diagram:

![Failure Analysis Diagram]

The trigger appears to be cell mismatch in short-circuit characteristics, which leads to reverse bias and subsequent heating because of the high shunt resistance inherent in the cells. Such mismatch can arise from manufacturing, handling, shadowing, or induced environmental effects.
The use of bypass diodes can reduce the amount of power that can be dissipated in a back-biased cell. A series of laboratory tests were performed for the above module type in which short-circuit current (2.0 amps) was dissipated at varying voltages across a single back-biased cell. Figure 5 shows the result of these tests. Note that cell cracking occurred at 14 volts reverse bias, well within the nominal rating for this 40-cell module. A second bypass diode (i.e., one diode per 20 cells) would apparently have prevented the cracking of the cell, at least over the short term.

A similar test was performed on a 36-cell PRDA-38 type module from the same manufacturer. The results are shown in Figure 6. The temperature rise was similar to that of the Block III module, but no cell cracking was observed. This module is of different configuration from Block III, which employed a polyester substrate, prone to outgassing at elevated temperatures. The PRDA-38 module features a glass superstrate, silicone rubber encapsulant, and Mylar film back.

Additional work is in progress to investigate the mechanics of cell heating and cracking.

![Graph showing temperature rise and cell cracking](image)

Figure 5. Block III Module 7801-1377
Figure 6. PRDA Module ZEFH-1104
PROCEEDINGS

of the 14th Low-Cost Solar Array Project Integration Meeting
held at the California Institute of Technology on December 5
and 6, 1979

Note: In a departure from the format of previous PIM Proceedings, we are endeavoring
to present the graphic material given at the meeting in a sequence that more nearly
approaches the order in which the presentations themselves were actually
given. Since many sessions were held simultaneously and others were split, that order can only be approximated.

AGENDA

WEDNESDAY, December 5

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>7:30</td>
<td>Registration</td>
</tr>
<tr>
<td>8:30</td>
<td>Welcome; LSA Announcements W. Callaghan</td>
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<tr>
<td>8:40</td>
<td>DOE &amp; PV Lead Center Announcements L. Magid, R. Forney</td>
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<td>9:00</td>
<td>HUD Announcements A. Carey</td>
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<tr>
<td>9:20</td>
<td>Silicon Material Summary R. Ferber</td>
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<td>9:40</td>
<td>FPUP Status E. Smith, A. Lawson</td>
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<td>10:00</td>
<td>Introduction of Module Mfrs. D. Runkle</td>
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<tr>
<td>11:10</td>
<td>Lessons Learned That Affect Module Design R. Ross, L. Dumas (pp. 3-15)</td>
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<tr>
<td>12:10</td>
<td>Discussion</td>
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<tr>
<td>12:15</td>
<td>Lunch</td>
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<td>Technology Sessions (simultaneous)</td>
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<td>Silicon Material R. Lutwack (pp. 16-46)</td>
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<tr>
<td></td>
<td>Large-Area Sheet J. Liu (pp. 47-176)</td>
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<td></td>
<td>Block IV Module Designs and Design Rationale: Presentations D. Runkle (pp. 177-235)</td>
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<td>Technology Sessions (simultaneous)</td>
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<td>Encapsulation C. Coulbert (pp. 236-244)</td>
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<td>PP&amp;E: Copper Metallization D. Bickler (pp. 296-337)</td>
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<td>PA&amp;I, Engineering &amp; Operations J. Arnett (pp. 354-382)</td>
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**THURSDAY, December 6**

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<tr>
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</tr>
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<td>Large-Area Sheet</td>
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<td></td>
<td>J. Liu (pp. 47-176)</td>
</tr>
<tr>
<td></td>
<td>Module Design</td>
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<td></td>
<td>R. Ross (pp. 383-454)</td>
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<td>1:30</td>
<td>Parallel Sessions</td>
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<td></td>
<td>Automated Module Assembly Studies</td>
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<tr>
<td></td>
<td>D. Bickler (pp. 338-351)</td>
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<td></td>
<td>Modu^/Cell Life Prediction and Modeling (Includes EVA Studies)</td>
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<td></td>
<td>C. Coulbert (pp. 244-247)</td>
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<tr>
<td></td>
<td>Test and Applications</td>
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<tr>
<td></td>
<td>L. Dumas (pp. 455-462)</td>
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<td>Product Reliability and Liability</td>
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<td>A. Weinstein, Carnegie Mellon U. (pp. 463-465)</td>
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<td>LSA</td>
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<td>DOE, Lead Center</td>
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ENGINEERING AND OPERATIONS AREAS

LESSONS LEARNED THAT AFFECT MODULE DESIGN

JET PROPULSION LABORATORY

R. Ross and L. Dumas

The LSA Project has been actively interfacing with, and procuring modules from, photovoltaic manufacturers for five years. Valuable experience and design knowledge has been gained by LSA from rapid evolution of design technologies and from qualification and exploratory testing, field deployment and failure analysis of modules during this time.

A joint presentation at the Wednesday morning plenary session by Ron Ross, Engineering Area Manager, and Larry Dumas, Operations Area Manager, summarized the lessons learned that most significantly influence module design. The module design process, a closed-loop approach, was described by emphasizing from a historical perspective how design problems have been identified in successive block procurements and how appropriate design solutions were found.

In many cases work began as potential design problems were perceived earlier than actual field occurrence was observed. Recommendations were made for module design objectives and approaches in the areas of mechanical and electrical configuration, fault tolerance and environmental endurance. Project experience with environmental reliability and durability was described both from the aspect of understanding and predicting degradation mechanisms and from the results of qualification testing, and field endurance performance.

Progress by manufacturers in improving production yields by reduction in workmanship defects was described on the basis of Quality Assurance inspection records. The need to allow adequate lead time for design, development and qualification of new designs and to plan for and learn from field endurance performance, as part of the iterative module design process, was emphasized.

The details of this overview of module design factors appear in the following graphic material.
In a subsequent four-hour Module Design session (Thursday, 8:00 a.m.) LSA Engineering, Encapsulation and Quality Assurance personnel expanded these Lessons Learned to cover specific design approaches, rationale, and recommendations. Additional sessions covering other aspects of module design, fabrication, and field performance are identified in the meeting agenda. In particular the session in which individual module manufacturers described their Block IV designs will be of interest.

INTER-TECHNOLOGY SESSION

Lessons Learned in Module Engineering

- DESIGN PROCESS OVERVIEW
- MODULE HISTORICAL SUMMARY
- LESSON HIGHLIGHTS
  - MECHANICAL CONFIGURATION
    - EFFICIENCY
    - STRUCTURAL SIZING
    - THERMAL
  - ELECTRICAL CONFIGURATION
    - SAFETY
    - RELIABILITY
  - ENVIRONMENTAL ENDURANCE
    - ENGINEERING
    - ENVIRONMENTAL TEST
    - FIELD TESTS
    - APPLICATIONS
  - PRODUCTION EXPERIENCE
- RECOMMENDATIONS
Module Design Process (Closed Loop)

- SPECIFY REQUIREMENTS
- SYNTHESIZE DESIGNS
- SCREEN DESIGNS USING QUAL TESTS
- ACQUIRE AND FEED BACK PERFORMANCE DATA
- PERFORM FUNDAMENTAL RESEARCH AS REQUIRED
- USE FEEDBACK AND RESEARCH TO IMPROVE DESIGNS

Module Historical Overview

<table>
<thead>
<tr>
<th>YEAR</th>
<th>PROBLEMS</th>
<th>SOLUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>DELAMINATION</td>
<td>FIRST QUAL TESTS</td>
</tr>
<tr>
<td>(BLOCK I)</td>
<td>INTERCONNECT BREAKAGE</td>
<td>(HUMIDITY, TEMP. CYCLE)</td>
</tr>
<tr>
<td>1976</td>
<td>POOR INTERCHANGEABILITY</td>
<td>STANDARD 4'x4' PANEL</td>
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<tr>
<td>(BLOCK II)</td>
<td>EXCESSIVE STRUCTURE</td>
<td>50 lb/ft² TEST</td>
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<tr>
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<td>EXCESSIVE TEMPERATURES</td>
<td>NOCT RESEARCH</td>
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<td>LOW-EFFICIENCY</td>
<td>EFFICIENCY STUDIES</td>
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<td></td>
<td>FIELD WIRING COMPLEXITY</td>
<td>CONNECTOR STUDIES</td>
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<td></td>
<td>VOLTAGE BREAKDOWN</td>
<td>HI-POT QUAL TEST</td>
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<td></td>
<td>WORKMANSHIP PROBLEMS</td>
<td>QA INSPECTION PLAN</td>
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<td></td>
<td>CONTINUED DELAMINATION</td>
<td>UV-RESEARCH</td>
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<td>1977</td>
<td>EXCESSIVE SOILING</td>
<td>SOILING RESEARCH</td>
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<td>(BLOCK III)</td>
<td>CELL CRACKING</td>
<td>SERIES-PARALLEL RESEARCH</td>
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<td>BIAS-HUMIDITY RESEARCH</td>
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<td>DELAMINATION</td>
<td>HAIL RESEARCH</td>
</tr>
<tr>
<td></td>
<td>WORKMANSHIP</td>
<td></td>
</tr>
</tbody>
</table>

YEAR | PROBLEM | SOLUTIONS
1975 (BLOCK I) DElamination, Interconnect breakage
1976 (BLOCK II) Poor interchangeability, Excessive structure, Excessive temperatures, Low-efficiency, Field wiring complexity, Voltage breakdown, Workmanship problems, Continued delamination
1977 (BLOCK III) Excessive soiling, Cell cracking, Continued delamination, Workmanship
<table>
<thead>
<tr>
<th>YEAR</th>
<th>PROBLEMS</th>
<th>SOLUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>• HAIL DAMAGE</td>
<td>• HAIL QUAL TEST</td>
</tr>
<tr>
<td></td>
<td>• CONTINUED</td>
<td>• CONTINUED RESEARCH</td>
</tr>
<tr>
<td></td>
<td>• SOILING</td>
<td>• UV</td>
</tr>
<tr>
<td></td>
<td>• CELL CRACKING</td>
<td>• SERIES-PARALLEL</td>
</tr>
<tr>
<td></td>
<td>• DELAMINATION</td>
<td>• SOILING</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• CELL FRACTURE MECHANICS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• INSULATION RESEARCH</td>
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<tr>
<td>1979</td>
<td>• HOT-SPOT HEATING</td>
<td>• HOT-SPOT QUAL TEST</td>
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<td>• CONTINUED RESEARCH</td>
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<td>• CELL CRACKING</td>
<td>• SERIES/PARALLEL</td>
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<td>• DELAMINATION</td>
<td>• UV, SOILING</td>
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<td>• FRACTURE MECHANICS</td>
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<td>• HAIL DAMAGE</td>
<td>• INSULATION</td>
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<tr>
<td></td>
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<td>• SAFETY RESEARCH</td>
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**Module Lesson Highlights**

- **MECHANICAL CONFIGURATION**
  - EFFICIENCY
  - STRUCTURAL SIZING
  - FIELD ASSEMBLY LABOR

- **ELECTRICAL CONFIGURATION**
  - VOLTAGE LEVEL
  - SAFETY
  - RELIABILITY

- **ENVIRONMENTAL ENDURANCE**
  - ENGINEERING
  - ENVIRONMENTAL TEST EXPERIENCE
  - FIELD TEST EXPERIENCE
  - APPLICATIONS EXPERIENCE

- **PRODUCTION EXPERIENCE**
Mechanical Configuration Lessons

- **MAXIMIZE MODULE EFFICIENCY**
  - Encapsulated vs Unencapsulated Cell Efficiency
  - Cell Operating Temperature (°C \cdot \$/$Watt)
  - Unused Border Area (Large Modules Have Less)
  - Cell Nesting (Shaped Cells)

- **MINIMIZE STRUCTURE COSTS**
  - Array Surface Area Without Cells Costs
    - $60 $/m² in 1986 (1980 $)
  - Costs Increase Linearly with Wind Loading Level.

- **MINIMIZE FIELD ASSEMBLY LABOR**
  - Integrated Structures
  - Minimum Labor Cabling
  - Need for Better Actual Cost Data

Flat-Plate Array Cost Breakdown (1980 $)

<table>
<thead>
<tr>
<th>COST ($/WATT)</th>
<th>FIELD FAILURES (12% PER YEAR)</th>
<th>SOILING (10% LOSSES)</th>
<th>FOUNDATIONS</th>
<th>ARRAY STRUCTURE</th>
<th>PANEL STRUCTURE</th>
<th>CONNECTOR &amp; DIODES</th>
<th>MODULE ASSEMBLY</th>
<th>ENCAPSULATION MATERIALS</th>
<th>CELL PROCESSING</th>
<th>SHEET FABRICATION</th>
<th>SILICON MATERIAL</th>
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<tr>
<td>140-</td>
<td>11.5</td>
<td>11.5</td>
<td>8.0</td>
<td>16.2</td>
<td>20.6</td>
<td>1.4</td>
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<td>22.0</td>
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<td>70-</td>
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</tbody>
</table>

Total Cost: 139.2
Electrical Configuration Lessons

- MAXIMIZE SAFETY
  - MODULE $V_{oc} \leq 30 \text{ VOLTS @ } -20^\circ C$
  - CELL STRING ISOLATED $\Omega \times V_{sys} + 1000 \text{ VDC}$
  - EXTERIOR SURFACES GROUNDED
  - TERMINALS PROTECTED
  - MUST BE COMPATIBLE WITH OVERALL SAFETY SYSTEM

- MAXIMIZE RELIABILITY
  - FACTORY YIELD LOSSES
  - FIELD FAILURE LOSSES
  - FIELD FAILURE RUNAWAY

* INSENSITIVITY TO AND CONTAINMENT OF LOW PROBABILITY CIRCUIT FAILURES.

Reliability Lessons

KEY FAILURE MECHANISMS:
- CRACKED CELLS (OPEN/REDUCED OUTPUT)
- OPEN INTERCONNECTS
- SHORTED CELLS
- SHADOWED CELLS

LESSON:
- RANDOM FAILURES AND ASSOCIATED HOT-SPOT HEATING MUST BE EXPECTED AT LEVELS OF 1 PER 100 CELLS AND MUST BE NEUTRALIZED.

SOLUTIONS:
- BY-PASS DIODES
- MULTIPLE CELL CONTACTS
- SERIES/PARALLELING
### Array Power Degradation vs Circuit Redundancy

![Graph showing array power degradation over time](image)

### Environmental Endurance

<table>
<thead>
<tr>
<th>Degradation Mode</th>
<th>Effect Predictable</th>
<th>Solution Known</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnect Fractures</td>
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<td>Unsoldered Interconnects</td>
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<td>Wire &amp; Terminal Corrosion</td>
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<tr>
<td>Cell Metallization Corrosion</td>
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<tr>
<td>Cracked Cells</td>
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<tr>
<td>Hail Damage</td>
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<tr>
<td>Hot-Spot Heating</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Insulation Breakdown</td>
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<tr>
<td>Encapsulant Delamination</td>
<td>Ø</td>
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<tr>
<td>Encapsulant Cracking/Breakdown</td>
<td>Ø</td>
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<tr>
<td>Encapsulant/Cell Discoloration</td>
<td>Ø</td>
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<tr>
<td>Soiling</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Structural Failure</td>
<td>•</td>
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</tr>
<tr>
<td>Handling/Shipping/Inst. Damage</td>
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</table>

- • • YES
- Ø • PARTIALLY
- Ø • NO
Degradation modes include:

- Interconnect fractures
- Unsoldered interconnects
- Wire & terminal corrosion
- Cell metallization corrosion
- Cracked cells
- Hail damage
- Hot-spot heating
- Insulation breakdown
- Encapsulant delamination
- Encapsulant cracking/breakdown
- Encapsulant/Cell discoloration
- Soiling
- Structural failure
- Handling/shipping/inst. damage

<table>
<thead>
<tr>
<th>Degradation Mode</th>
<th>Importance</th>
<th>Past Designs</th>
<th>Current Designs</th>
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<tr>
<td>Interconnect fractures</td>
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<tr>
<td>Wire &amp; terminal corrosion</td>
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<td>○</td>
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<tr>
<td>Cell metallization corrosion</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cracked cells</td>
<td>●</td>
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<td>●</td>
</tr>
<tr>
<td>Hail damage</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Hot-spot heating</td>
<td>○</td>
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</tr>
<tr>
<td>Insulation breakdown</td>
<td>○</td>
<td>○</td>
<td>●</td>
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<tr>
<td>Encapsulant delamination</td>
<td>●</td>
<td>○</td>
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<tr>
<td>Encapsulant cracking/breakdown</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Encapsulant/Cell discoloration</td>
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<tr>
<td>Soiling</td>
<td>●</td>
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<tr>
<td>Structural failure</td>
<td>○</td>
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<td>Handling/shipping/inst. damage</td>
<td>○</td>
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</tr>
</tbody>
</table>

Importance:
- ● Critical and widespread
- ○ Intermediate concern or uncertain effect
- ○ Occasional problem

Environmental Endurance Lessons

Engineering Lessons

- Environmental stresses and failure mechanisms are very complex and application specific.
- Poor prediction capability places high reliance on qual tests together with real-time system experiments for calibration.
- Large statistical sample sizes (large arrays) are required to quantify failures.
- Reliance on field-failure data places requirements on system experiments:
  - To obtain quantitative data on failures
  - To have failure containment features
  - To have failure contingency plans
Environmental Test Experience

- NEW DESIGNS SELDOM PASS ON FIRST TRY
- TEMPERATURE CYCLING MOST DAMAGING, FOLLOWED BY COMBINED TEMPERATURE AND HUMIDITY CYCLING
- COMMON FAILURE MODES ARE CRACKED CELLS, ENCAPSULANT DAMAGE, AND RESISTIVE SHORTS TO FRAME
- PRESENT QUAL TEST SERIES DOES NOT SCREEN FOR:
  - DIRT EFFECTS
  - UV EFFECTS
  - LONG-TERM CORROSION
  - BACK-BIAS HEATING EFFECTS

Box Score: PRDA Module Test Criteria

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>NUMBER OF PROBLEMS</th>
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<td>TOTAL (%)</td>
<td>49 (43%)</td>
<td>42 (37%)</td>
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</table>
Module Field Test Experience

- **BLOCK II AND III FAILURE RATES LOW**
- DIFFICULTIES IN DETECTING AND MEASURING ELECTRICAL DEGRADATION CAN LEAD TO OVERLY OPTIMISTIC CONCLUSIONS ABOUT FIELD PERFORMANCE
- MOST COMMON CAUSES OF ELECTRICAL DEGRADATION FOR RECENT DESIGNS ARE CRACKED CELLS AND SOILING
- MOST COMMON FORMS OF PHYSICAL DEGRADATION ARE CRACKED CELLS, ENCAPSULANT DELAMINATION, CORROSION, AND VARIOUS TYPES OF DISCOLORATION
- NATURE AND DEGREE OF DEGRADATION ARE GREATLY INFLUENCED BY TYPE OF ENVIRONMENTAL EXPOSURE

Failure Rates for Blocks I and II Modules At JPL & Lewis Test Sites

![Chart showing failure rates for Blocks I and II modules.](chart.png)
Status of JPL/Lewis Endurance Test Sites: Summary of Field Data

<table>
<thead>
<tr>
<th>MODULES INSPECTED 180</th>
<th>CANAV ZONE</th>
<th>KEY WEST</th>
<th>NEW ORLEANS</th>
<th>COOGIN</th>
<th>KNOX HOLLOW</th>
<th>BISHOP PEAK</th>
<th>DUGWAY</th>
<th>WASHINGTON</th>
<th>ALBUQUERQUE</th>
<th>SANTA CRUZ PUE.</th>
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<tr>
<td>METALLIZATION DISCOLORED/CORRODED</td>
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<tr>
<td>FRAME/HARDWARE CORROSION</td>
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<tr>
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</tr>
</tbody>
</table>

- MODERATE AMOUNT
- SUBSTANTIAL AMOUNT
* ENCAPSULANT DAMAGED BEFORE INSTALLATION

Applications Experience

- MODULES OFTEN JUDGED OF THE BASIS OF SUBJECTIVE EFFECTS OF VISUAL OBSERVATIONS
  - ENCAPSULANT DELAMINATION
  - DISCOLORATION
  - CORROSION
- HANDLING, SHIPPING, INSTALLATION, AND MAINTENANCE PROBLEMS BEGINNING TO SURFACE
- OPERATIONAL INTERACTION OF SYSTEM AND MODULE ARE IMPORTANT SOURCE OF MODULE STRESS
  - NOTABLY, STRING SHORTING
- RELIABILITY A KEY CONCERN

13
Production Experience

- Module rejection rates unacceptably high
  - Silicone encapsulant defects and cracked cells main problems
- Production typically low-volume, non-automated, non-equilibrium
- Elapsed time from contract execution to delivery of first production modules:
  - Block I: 2-5 months
  - Block II: 7-13 months
  - Block III: 2-6 months
  - Block IV: ≈ 10-12 months

Block III Inspection Summary

17,580 modules inspected
14,234 modules (81%) accepted
3,347 modules (19%) rejected

Defects (4505)

- Encapsulant: 38%
- Cells: 27%
- Mechanical: 17%
- Interconnects: 9.1%
- Documentation: 6.1%
- Solder: 2%
- 100%
Recommendations

• PROVIDE FOR ADEQUATE QUALIFICATION AND DEBUGGING OF NEW MODULE DESIGNS
  • TEST PROGRAM
  • TIME

• PLAN FOR AND LEARN FROM FIELD FAILURES
  • MONITORING, CONTINGENCY, MAINTENANCE PLANS
  • ACQUIRE DATA — ANALYZE PROBLEMS — IMPROVE DESIGNS

• DESIGN MODULES AND SYSTEMS FOR FAULT - TOLERANCE

• DESIGN MODULES AND SYSTEMS FOR SAFETY

• INTEGRATE SYSTEM AND SUBSYSTEM DESIGN PROCESSES
TECHNOLOGY DEVELOPMENT AREA

Silicon Material Task

Presentations on silicon (Si) production processes and supporting technology were made by 11 contractors and JPL personnel.

In the area of Si production process development, Union Carbide Corp. reported that work proceeded on design of equipment and the facility for the 100-MT/yr EPSDU (Experimental Process System Development Unit) based on their silane-to-Si process. In the supporting R&D program, efforts continued on the two concepts for making Si by decomposing silane: the free-space reactor (FSR) and the fluidized-bed reactor (FBR). The FSR process development unit was installed and checked out and is ready for shakedown testing. In support of the UCC program, the Massachusetts Institute of Technology reported on their experimental and theoretical work on the conversion of metallurgical-grade silicon and silicon tetrachloride to trichlorosilane, the feedstock of the UCC process. The Battelle Columbus Laboratories (BCL) reported that their Process Development Unit (PDU), consisting of the four critical components (full-size) of BCL's 50-MT/yr EPSDU design, was brought to a state of completion that permitted operations to start. The BCL process is based on the reduction of silicon tetrachloride by zinc. The initial operations consist of coating the inside of the fluidized bed reactor with Si formed by decomposing trichlorosilane. Battelle also presented results from their experimental support program, in particular on removal of residual zinc from silicon product. SRI International reported on progress in scaling up their process, based on reducing silicon tetrafluoride by sodium, and presented information on analyses of product silicon. Energy Materials Corporation described their process for producing silicon by gaseous melt replenishment; construction and installation of the prototype system is nearing completion. Hemlock Semiconductor Corporation described a recently started program for developing a modified Siemens process for making Si, using dichlorosilane as feedstock.

In the area of silicon impurity studies, the Westinghouse R&D Center and C.T. Sah Associates reported on their studies of the effects of impurities on Si properties and solar-cell performance. Solarex Corporation described their program for determining the effects on solar-cell efficiency of impurities intentionally incorporated into the Si.

Supporting studies were described by Lamar University (preliminary process design and preliminary cost analysis of the Battelle process), AeroChem Research Laboratories (investigation of the high-temperature reactions of alkali metals and silicon halides), and JPL (studies on the fluidized bed reactor and the continuous-flow pyrolyzer).
The material presented by contractors and JPL is summarized in the following pages.

TECHNOLOGY SESSION
Ralph Lutwack, Chairman

PROCESS FEASIBILITY (TASK I):
BCL PROCESS, CASE B
LAMAR UNIVERSITY

13th PIM: BCL Process - Case A
- Total Product Cost 12.1 $/kg
  (1980 Dollars)
- Case A Based on
  - Two Deposition Reactors
  - Six Electrolysis Cells

14th PIM: BCL Process - Case B
- Results Will be Reported at This Meeting
- Case B Based on
  - One Deposition Reactor
  - Two Electrolysis Cells
Cost Sensitivity Analysis

STEP 1-7  CASE B

Summary of Cost and Profitability (1980 $)

<table>
<thead>
<tr>
<th>PLANT SIZE</th>
<th>1000 MT SI/YR</th>
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<tr>
<td>PRODUCT</td>
<td>SILICON GRANULES</td>
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<tr>
<td>PLANT INVESTMENT</td>
<td>$16,500,000.</td>
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<tr>
<td>FIXED CAPITAL</td>
<td>$14,350,000.</td>
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<tr>
<td>WORKING CAPITAL</td>
<td>$2,150,000.</td>
</tr>
<tr>
<td>PRODUCT COST</td>
<td>$11.08/KG</td>
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<tr>
<td>PRODUCT PRICE</td>
<td>$18.72/KG (25% ROI)</td>
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</table>
Reasons for Considering Chlorosilane Technology

• ONLY MAJOR PRODUCTION PROCESS
• PROVEN MATERIAL QUALITY
• IN-PLACE CAPACITY FORMS BASE FOR MEETING EXPANDED DEMAND
• SIGNIFICANT COST REDUCTION POSSIBLE TO MEET INTERMEDIATE AND LONG RANGE PHOTOVOLTAIC OBJECTIVES

Conclusions

SOLAR CELL REQUIREMENTS

• LOW COST DOE PHOTOVOLTAIC OBJECTIVES WILL ONLY BE MET WITH HIGH EFFICIENCY SOLAR CELLS.

• IT IS COST EFFECTIVE TO USE HIGHER COST POLYSILICON IF HIGHER CELL EFFICIENCY IS ACHIEVED.

Limitations of Existing Siemens Process

• LOW DEPOSITION RATE

• HIGH POWER CONSUMPTION

• LARGE BYPRODUCT STREAM (SiCl₄)

Characteristics of Low-Cost CVD Process

• DICHLOROSILANE FEEDSTOCK
• ADVANCED REACTOR DESIGN
• SiCl₄ RECYCLE

Phase I Objectives

• CHARACTERIZE EXPERIMENTAL REACTOR OPERATION WITH DICHLOROSILANE FEED
• DESIGN AND CONSTRUCT INTERMEDIATE SIZE REACTOR TO DEMONstrate SCALE-UP
• EVALUATE TCS - DCS REDISTRIBUTION PROCESS/PRODUCT
• PRELIMINARY EPSDU DESIGN
HYDROGENATION OF SiCl₄

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

\[ 3 \text{SiCl}_4 + 2 \text{H}_2 + \text{Si} \rightleftharpoons 4 \text{SiHCl}_3 \]

I. REACTION KINETICS

- TEMPERATURE \hspace{1.5cm} 400° - 550°C
- PRESSURE \hspace{1.5cm} \text{to 500 PSIG}
- CONCENTRATION \hspace{1.5cm} \text{H}_2, \text{SiCl}_4
- CATALYST \hspace{1.5cm} COPPER
- PARTICLE SIZE
- SURFACE AREA
- IMPURITIES \hspace{1.5cm} M. G. SILICON
- FLUIDIZATION

II. THEORETICAL STUDIES

- REACTION MECHANISM
- ROLE OF CATALYST
- SURFACE ANALYSIS
Summary

I EXPERIMENTAL RESULTS

• 500 PSIG DATA GENERALLY CONFIRMS PREVIOUS ESTIMATES EXTRAPOLATED FROM LOW PRESSURE DATA

• REACTION RATE INCREASES RAPIDLY WITH TEMPERATURE

• SiHCl₃ CONVERSION INCREASES AT HIGHER H₂: SiCl₄ RATIO

• SiHC₃ CONVERSION INCREASES AT HIGHER REACTOR PRESSURE

• REACTION APPROACHES EQUILIBRIUM SOMewhat SLOWER AT HIGHER REACTOR PRESSURE

• HIGHER REACTOR TEMPERATURE AND PRESSURE GIVE MOST BENEFITS

II PLANS FOR NEXT QUARTER

• COLLECT EQUILIBRIUM DATA

• COMPLETE RATE MEASUREMENTS

• THEORETICAL STUDIES

• COPPER CATALYST
GASEOUS MELT REPLENISHMENT

ENERGY MATERIALS CORP.

Process Description

1. Bring the reactor to temperature under an argon atmosphere.

2. Melt silicon in the U-tube to form a positive gas seal.

3. Introduce $H_2$ and $^{29}SiCl_3$ into the chamber to provide optimum mass deposition of silicon until the desired amount of silicon has been deposited.

4. Raise the reactor temperature to 1450 to melt down the silicon keeping the U-tube solidified.

5. Equilibrate the gas pressure between the reactor and the delivery tube.

6. Raise the temperature of the U-tube above the silicon melting point. The silicon will drain out of the reactor into the crystal growth crucible.

7. The silicon in the U-tube will be solidified and the reactor returned to the initial reaction conditions.
JPL IN-HOUSE STUDIES

Objective

• TO CONDUCT JPL IN-HOUSE COMPLEMENTARY STUDIES IN SILICON PROCESSING AREAS TO SUPPORT CONTRACTUAL ACTIVITIES AND TECHNICAL MANAGEMENT IN THE DOE/LSA SILICON MATERIAL TASK

In-House Si Production Activities

• FLUIDIZED BED REACTOR AREA
  • Si FINE FORMATION EXPERIMENTS
  • FLUID BED Si DEPOSITION EXPERIMENTS

• SILANE PYROLYSIS AREA
  • CONTINUOUS FLOW PYROLYZER
  • SILANE TO MOLTEN Si INVESTIGATION
  • FUNDAMENTAL CVD AND RATE STUDIES

• REACTOR MODELING AREA
  • MODELING OF PYROLYZER OPERATION
  • MODELING OF FLUID BED Si DEPOSITION

FBR Development Needs

DETERMINE RANGES OF TEMPERATURE, FLOW AND SILANE CONCENTRATION THAT MAY CONTINUOUSLY PRODUCE DENSE GROWTH WITH ACCEPTABLE DUST PRODUCTION
Dust Production

LOW LEVELS OF DUST FOR UP TO 15% SILANE WHEN CONVERSION IN BED IS COMPLETE

SIGNIFICANT DUST LEVELS SEEN WHEN CONVERSION IN BED IS INCOMPLETE

Bed Agglomeration

AGGLOMERATION OCCURS RAPIDLY AT >630 °C AND >3% SILANE FOR BUBBLING BEDS

STRONG BONDS SIMILAR TO SINTERING

POSSIBLE CAUSES

HOT SPOTS DUE TO EXOTHERMIC REACTION CAUSE SINTERING
PRESENCE OF LIQUID PHASE AT BULK BED TEMP. DUE TO IMPURITY EUTECTIC

Possible Solutions

HIGH FLOW RATES (>8*MFV)
MULTIPLE INJECTION
USE VERY PURE SILICON

2-in. S.S. FBR Tests

DEPOSITED SILICON AT A RATE OF 2.65 GRAMS/MIN
FOR 51 MIN AT 700°C WITH 10% SILANE IN HYDROGEN FEED AT A SUP VEL OF 8-10*MFV
DEPOSIT APPEARED DENSE; 15-25 MICRONS THICK DUST AMOUNTED TO <0.1% OF SI PRODUCED
NO EVIDENCE OF BED AGGLOMERATION
IN-HOUSE LSA PROGRAM
CONTINUOUS-FLOW PYROLYZER,
SECOND GENERATION: CFP-II

Purposes

- PARAMETRIC STUDIES, e.g., EFFECTS OF T, P, C AND V ON SILICON PARTICLE SIZE AND BULK DENSITY
- REACTOR MATERIAL STUDIES
- REACTOR PURITY STUDIES
- REACTOR CLOGGING STUDIES
- IN GENERAL, COOPERATION WITH AND TECHNICAL SUPPORT FOR THE UC EPSDU

Experimental Runs in Development of CFP-II

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<th>RUN NUMBER</th>
<th>RUN TIME min</th>
<th>AVE TEMP °C</th>
<th>PRESSURE psig</th>
<th>RATE OF Si PROD lb/hr</th>
<th>SEED</th>
<th>% YIELD</th>
<th>BULK DENSITY g/cc</th>
<th>DIAM μm</th>
<th>PRODUCT COLOR</th>
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<td>8</td>
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EFFECTS OF IMPURITIES ON CELL PERFORMANCE

C. T. SAH

This program is conducted for a study of the effects of impurities on the properties of silicon material and performance of silicon solar cell. It includes theoretical and experimental studies to determine the effects of impurities on the properties of silicon doped with specific impurity elements as well as the effects of these impurities on the impurity related energy levels, on the concentration of these energy levels, and on the recombination properties of electrons and holes at these energy levels.

A mathematical model is developed to predict the effects of impurities on solar cell performance. Numerical solutions are obtained from the six coupled nonlinear Shockley Equations on a high speed computer using the equivalent-circuit-model method of solution.

Theoretical and numerical analyses are performed on the effects of specific impurities and fabrication processes on the properties of silicon materials and silicon solar cell performance using experimental data.

In this presentation, a summary of the findings will be discussed. The physics of the mathematical model will first be reviewed. Results of the effect of several impurity related recombination levels on silicon solar cell performance will be presented.
Computation Procedure

1. SYNTHESIZE THE 6 SHOCKLEY EQUATIONS INTO 2 TRANSMISSION LINE EQUIVALENT CIRCUITS.
   * D.C. STEADY-STATE EQUIVALENT CIRCUIT
   * SMALL-SIGNAL ERROR CORRECTION EQUIVALENT CIRCUIT

2. IMPOSE BOUNDARY CONDITIONS
   * PUT IN APPROPRIATE VALUES OF RECOMBINATION CONDUCTANCES FOR INTERFACE RECOMBINATION AT THE FRONT AND BACK SURFACES

3. INPUT PARAMETERS
   * AM1 SOLAR SPECTRAL DENSITY TABLE
   * MOBILITIES VS IMPURITY CONCENTRATION
   * RECOMBINATION PARAMETERS: c_n, c_p, e_n, e_p, E_T
   * INTRINSIC CARRIER CONCENTRATION: n_i(T, N_{DD}, N_{AA})
   * DIFFUSION PROFILE: N_{DD}(x), N_{AA}(x)
   * DEVICE THICKNESS
   * DEVICE TEMPERATURE

4. COMPUTER MODEL SELECTION
   * 4 REGIONS (EMITTER, JUNCTION SPACE CHARGE, QUASI-NEUTRAL BASE, BACK SURFACE FIELD.)
   * Δx VARIATIONS IN EACH REGION.

5. NUMERICAL ITERATION FOR ILLUMINATED I-V
   * BEGINS AT 0 VOLTS AND DARK
   * INCREASES LIGHT INTENSITY TO AM1
   * INCREASES APPLIED VOLTAGE TO V_{OC} OR J > 0.

6. COMPUTE J_{MAX}, V_{MAX}, P_{MAX}, EFF, FF, V_{OC}
   * USE POLYNOMIAL FIT TO I-V

28
Computation Results

(High-Efficiency Cells)

1. HEAVY DOPING EFFECTS
   IN DIFFUSED EMITTER AND BACK SURFACE FIELD LAYERS FOR
   HIGH BASE RESISTIVITY CELLS.
   • INTERBAND AUGER RECOMBINATION.
   • ENHANCED SOLUBILITY OF RECOMBINATION CENTER.
   • NONIDEAL DIFFUSION PROFILES.

2. STEADY-STATE LIFETIMES
   • POSITION DEPENDENCES
   • CARRIER DENSITY DEPENDENCES
     ** FORWARD VOLTAGE DEPENDENCE
     ** ILLUMINATION LEVEL DEPENDENCE
   • RECOMBINATION LEVEL DENSITY DEPENDENCE
     ** ELECTRON LIFETIME ≠ HOLE LIFETIME
     (2 STEADY-STATE LIFETIMES)

3. INTERFACE RECOMBINATION
   • BACK SURFACE - SHIELDED BY BACK SURFACE FIELD
   • FRONT SURFACE - IMPORTANCE DIMINISHED BY BULK EMITTER
     RECOMBINATION

CONCLUSION

BASE RECOMBINATION AT IMPURITY OR DEFECT RECOMBINATION
CENTERS DOMINATES SOLAR CELL PERFORMANCE.
(Impurity-Doped Cells)

1. TITANIUM DOPED CELLS
   * P+/N/N+ CELL BETTER THAN N+/P/P+ CELL.
   * For EFF(AM1) > 16% (P+/N/N+) (N+/P/P+)
     \[ N_{TT} < 6 \times 10^{12} \text{ Ti/cm}^3 \] \[ N_{TT} < 4 \times 10^{11} \text{ Ti/cm}^3 \]
     \[ V_{OC} = 576 \text{ mV} \]
     \[ J_{SC} = 30.2 \text{ mA/cm}^2 \]
     \[ FF = 0.82 \]
     \[ N_{DD} = 5 \times 10^{16} \text{ p/cm}^3 \]
     \[ L = 250 \mu \text{m} \]
     \[ X_E = 0.25 \mu \text{m} \]
     \[ \tau_n = \tau_p = 6.5 \mu \text{s} \]

2. ZINC DOPED CELLS
   * N+/P/P+ CELL BETTER THAN P+/N/N+ CELL.
   * For EFF(AM1) > 16%
     \[ N_{TT} < 8 \times 10^{12} \text{ Zn/cm}^3 \] \[ N_{TT} < 2 \times 10^{12} \text{ Zn/cm}^3 \] \[ (N+/P/P+) \] \[ (P+/N/N+) \]
CHEMICAL PROCESS EVALUATION

BATTELLE'S COLUMBUS LABORATORIES

OBJECTIVE - $14/kg (1980 DOLLARS)
$10/kg 1975 DOLLARS) SILICON FOR
PHOTOVOLTAIC APPLICATION
CURRENT PHASE - ZINC REDUCTION OF SILICON
TETRACHLORIDE IN A FLUIDIZED BED TO
PRODUCE SILICON GRANULES

Experimental Operation of the PDU

- DEMONSTRATE OPERABILITY
  - NOMINAL OPERATING CONDITIONS

- REACTOR OPERATION VARIABLES
  - REACTANT COMPOSITION
  - REACTANT THROUGHPUT
  - PRODUCT PARTICLE SIZE

- CONDENSER OPERATION
  - HEAT TRANSFER

- ELECTROLYTIC CELL OPERATION
  - ZINC PRODUCT PURITY
  - CURRENT EFFICIENCY
  - POWER EFFICIENCY
  - CONVERSION OF SUSPENDED SILICON

- ZINC VAPORIZER OPERATION
  - LEVEL CONTROL SYSTEM
  - VAPORIZATION RATE CONTROL
  - ALTERNATIVE HEAT SOURCE

- PRODUCT QUALITY
- ENERGY CONSUMPTION
Experimental Support Program

- RESIDUAL ZINC REMOVAL
- REACTOR LINER OPTIMIZATION
- ALTERNATIVE ZINC VAPORIZER DESIGNS

Residual Zinc Distribution

(PRELIMINARY ELECTRON MICROBE RESULTS, SCANS OF ONLY FIVE PARTICLES TOTAL FROM MINIMUM RUN: 93, 95, 97, AND 99)

Zinc Highly Segregated

- Peaks as high as 2.4% (2400ppm) above ± 400ppm background. (Neutron activation = 1480ppm (Run 97), 1520ppm (Run 99) for average analysis)

- Correlation with deposition band sequence questionable

- Some multiple peaks of up to 20-30μm net width (thickness of deposition band)

- Suggests occluded zinc mist as origin

- If so, correctable with no need for post-deposition heat treatment to remove zinc

- Further study planned
Si PROCESS BASED ON REDUCTION OF SiF₄ by Na

SRI INTERNATIONAL

Impurity Analysis, ppm, Sample 30-4

<table>
<thead>
<tr>
<th>ELEMENTS</th>
<th>EMIS. SPEC.</th>
<th>SPARK SOURCE SPEC.</th>
<th>PLASMA EMIS. SPEC.</th>
<th>PLASMA SPEC.</th>
<th>NEUT. ACT.</th>
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*Balazs Vet Chem.*
### Impurity Analysis, ppm, Sample 30-7

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*Balazs Vet Chem.*
COMBUSTION PROCESS

AEROCHEM RESEARCH LABORATORIES

Objectives

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.
2. EVALUATE PRODUCT SEPARATION AND COLLECTION PROCESSES.
3. DETERMINE EFFECTS OF REACTANTS AND/OR PRODUCTS ON MATERIALS OF CONSTRUCTION.

Process Vessel
Status

EFFORT TO PRODUCE 0.2-0.5 KG SAMPLES. RUNS OF 0.5-1 HR.

PROBLEMS WITH REACTANT INLET AND REACTOR CLOGGING DUE TO INSUFFICIENT START-UP TEMPERATURES.

LARGER POWER SUPPLIES ARE BEING INSTALLED.

VERY SMALL SAMPLES OF FUSED SILICON HAVE BEEN PRODUCED.

Plans

PRODUCE 0.1-0.5 KG SAMPLES

CHECK:

1. SAMPLE COLLECTION EFFICIENCY
2. REACTION EFFICIENCY
3. SAMPLE PURITY

INCREASE RUN TIME--LARGER SAMPLES. CHECK RELIABILITY
EFFECTS OF IMPURITIES

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
POCl$_3$ Gettering of Ti-Contaminated Silicon

- Starting Water
- 825°C/50 min POCl$_3$ Diffusion
- 1100°C/1 hr POCl$_3$ Gettering
- 1100°C/5 hr POCl$_3$ Gettering

Electrically Active Ti Concentration (cm$^{-3}$) vs. Distance From the n$^+$ p Interface
Chromium $a_x = 0.23$
Vanadium $a_x = 0.28$
Titanium $a_x = 0.40$
Molybdenum $a_x = 1.0$
Web Grown From Battelle Silicon

Polysilicon Characteristics  Battelle Lot 33645-38-97 (Supplied by JPL)
Pretreated 6 hrs at 1290°C in Argon to Emit Zn

Web Growth Behavior  Same as Observed for Semiconductor Grade Silicon

Solar Cell Characteristics  Cell Efficiency: Uncoated Avg. 9.0 ± 0.2% (η_{AR} ~ 12.8% est.)
Range Uncoated 8.6 to 9.2% (η_{AR} 12.3% to 13.2% est.)

Test Conditions: n^+ pp^+ Cell, 91.6 mW/cm^2 Illumination
SOLAREX CORP.

PURPOSE OF THE PROGRAM:

TO CONDUCT A SOLAR CELL FABRICATION AND ANALYSIS PROGRAM TO DETERMINE THE EFFECTS ON THE RESULTANT SOLAR CELL EFFICIENCY OF IMPURITIES INTENTIONALLY INCORPORATED INTO SILICON.

METHOD:

EMPLOY "FLIGHT-QUALITY" TECHNOLOGIES AND QUALITY ASSURANCE TO ASSURE THAT VARIATIONS IN CELL PERFORMANCE ARE DUE TO THE IMPURITIES INCORPORATED IN THE SILICON.

SAMPLES:

PROVIDED BY JPL FROM WESTINGHOUSE-DOW CORNING PROGRAM.

PROGRAM ORGANIZATION:

DESIGNED TO INSURE THAT:

• SAMPLES ARE ALWAYS POSITIVELY IDENTIFIED.

• ALL PROCESSES ARE WELL CONTROLLED AND DOCUMENTED TO ASSURE THAT THE RESULTS ARE NOT PROCESS DEPENDENT.

• THERE IS NO CROSS-CONTAMINATION FROM LOT TO LOT.

• FINISHED CELLS ARE SUBJECTED TO SUFFICIENT MEASUREMENTS AND ANALYSIS SO THAT THE MECHANISMS OF IMPURITY EFFECTS ON CELL BEHAVIOR CAN BE IDENTIFIED.

CONTROL SILICON:

VERIFICATION CELLS - DONE BEFORE STARTING TEST PROGRAM TO SERVE AS A TRAINING TOOL FOR THE PROCESS SEQUENCE AND TO SERVE AS A DATA BASE.

CONTROL CELLS - PROCESSED WITH THE TEST CELL SILICON TO ASSURE THAT THE RESULTS ARE NOT PROCESS DEPENDENT.

MONITOR CELLS - PROCESSED AFTER CLEANING OF EQUIPMENT TO ASSURE THAT ALL IMPURITIES ARE REMOVED FROM THE EQUIPMENT AND WILL NOT CONTAMINATE SUBSEQUENT LOTS.
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<th>Parameter</th>
<th>Value</th>
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<td>( V_{OC} )</td>
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<td>( P_{MAX} )</td>
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<td>( I_{MP} )</td>
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</tr>
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<td>( I_{SC\ BLUE} )</td>
<td>38.8 mA CORNING #9788</td>
</tr>
<tr>
<td>( I_{SC\ RED} )</td>
<td>84.0 mA CORNING #2408</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>78.3%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>12.9% AM0 AT 25°C</td>
</tr>
<tr>
<td></td>
<td>15% AM1 AT 25°C</td>
</tr>
</tbody>
</table>
## Impurity Content vs Performance

<table>
<thead>
<tr>
<th>EXPERIMENTAL LOT #</th>
<th>IMPURITY</th>
<th>CONCENTRATION 10^15 ATOMS/CC</th>
<th>P/P₀</th>
<th>ISC/ISC₀</th>
<th>VOC/VOC₀</th>
<th>FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>200-400</td>
<td>0.87</td>
<td>0.95</td>
<td>0.96</td>
<td>74</td>
</tr>
<tr>
<td>2</td>
<td>Ca</td>
<td>?</td>
<td>0.93</td>
<td>0.96</td>
<td>0.97</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>Cr</td>
<td>0.5</td>
<td>0.85</td>
<td>0.89</td>
<td>1.03</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>Cu</td>
<td>2.0</td>
<td>0.92</td>
<td>0.92</td>
<td>1.02</td>
<td>76</td>
</tr>
<tr>
<td>5</td>
<td>Mn</td>
<td>0.63</td>
<td>0.83</td>
<td>0.89</td>
<td>0.94</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>Mn</td>
<td>1.0</td>
<td>0.77</td>
<td>0.87</td>
<td>0.92</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>Mn</td>
<td>0.66</td>
<td>0.83</td>
<td>0.88</td>
<td>0.94</td>
<td>78</td>
</tr>
<tr>
<td>8</td>
<td>P</td>
<td>28</td>
<td>0.95</td>
<td>0.95</td>
<td>1.00</td>
<td>78</td>
</tr>
<tr>
<td>9</td>
<td>Cr-Mn</td>
<td>0.5/0.3</td>
<td>0.58</td>
<td>0.72</td>
<td>0.87</td>
<td>73</td>
</tr>
<tr>
<td>10</td>
<td>Mn</td>
<td>0.7</td>
<td>0.87</td>
<td>0.90</td>
<td>1.02</td>
<td>74</td>
</tr>
<tr>
<td>11</td>
<td>Mn</td>
<td>0.63</td>
<td>0.86</td>
<td>0.92</td>
<td>0.95</td>
<td>77</td>
</tr>
<tr>
<td>12</td>
<td>Mo</td>
<td>0.00092</td>
<td>0.81</td>
<td>0.88</td>
<td>0.92</td>
<td>79</td>
</tr>
<tr>
<td>13</td>
<td>Cu/Ti</td>
<td>1.0/0.033</td>
<td>0.53</td>
<td>0.62</td>
<td>0.87</td>
<td>76</td>
</tr>
<tr>
<td>14</td>
<td>Ti</td>
<td>0.11</td>
<td>0.38</td>
<td>0.55</td>
<td>0.80</td>
<td>66</td>
</tr>
<tr>
<td>15</td>
<td>Ti</td>
<td>0.167</td>
<td>0.31</td>
<td>0.44</td>
<td>0.90</td>
<td>60</td>
</tr>
<tr>
<td>16</td>
<td>Ta</td>
<td>&lt;0.0008</td>
<td>0.79</td>
<td>0.90</td>
<td>0.95</td>
<td>72</td>
</tr>
<tr>
<td>17</td>
<td>Cr/Ti</td>
<td>1.0/0.011</td>
<td>0.60</td>
<td>0.69</td>
<td>0.87</td>
<td>78</td>
</tr>
<tr>
<td>18</td>
<td>Ti</td>
<td>0.033</td>
<td>0.56</td>
<td>0.65</td>
<td>0.87</td>
<td>76</td>
</tr>
<tr>
<td>19</td>
<td>Cr/Mn/Ti</td>
<td>0.4/0.5/0.0033</td>
<td>0.73</td>
<td>0.82</td>
<td>0.91</td>
<td>77</td>
</tr>
</tbody>
</table>

Lots E-3, 4, & 10 are 0.2 to 0.25 n-CM.
Remainder between 3.0 & 6.0 n-CM.
Control Silic<sup>**</sup> 1.0 to 3.0 n-CM.
Materials Effects

SINGLE DOPANTS

1. CARBON - BLUE CURRENT NORMAL
   200-400 VOLTAGE NORMAL
   RED OR BULK CURRENT MAJOR DEGRADATION
   SOME EVIDENCE OF SHUNTING

2. CALCIUM - BLUE CURRENT NORMAL
   VOLTAGE NORMAL
   RED OR BULK CURRENT MAJOR DEGRADATION
   FILL FACTOR NORMAL

3. CHROME - BLUE CURRENT SLIGHTLY LOWER
   0.5 VOLTAGE NORMAL
   RED OR BULK CURRENT NORMAL
   SHUNTING MAJOR DEGRADATION

4. COPPER - AFTER EFFECTS OF RESISTIVITY AND
   2.0 PROCESSING ARE FACTORED OUT, THERE
   IS NO STATISTICAL DIFFERENCE BETWEEN
   THIS LOT AND THE CONTROLS. (REQUIRES
   RUNS ON 0.2 Ω-CM CONTROL SI TO
   VERIFY.)

5. MANGANESE

SUMMARY OF Mn RUNS

<table>
<thead>
<tr>
<th>LOT #</th>
<th>10^15 ATOMS/CC</th>
<th>P/PO</th>
<th>ISC</th>
<th>VOC</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.63</td>
<td>0.83</td>
<td>0.85</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>0.77</td>
<td>0.87</td>
<td>0.92</td>
<td>POLYCRYSTALLINE</td>
</tr>
<tr>
<td>7</td>
<td>0.66</td>
<td>0.83</td>
<td>0.88</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>0.87</td>
<td>0.90</td>
<td>1.02</td>
<td>LOWER RESISTIVITY</td>
</tr>
<tr>
<td>11</td>
<td>0.63</td>
<td>0.86</td>
<td>0.92</td>
<td>0.95</td>
<td>SLOW GROWTH</td>
</tr>
</tbody>
</table>

BLUE CURRENT NORMAL
VOLTAGE NORMAL
RED OR BULK CURRENT MAJOR DEGRADATION
MANY CELLS EXHIBIT NORMAL FILL FACTORS
SOME CELLS IN EACH LOT EXHIBIT SHUNTING
POLYCRYSTALLINE CELLS EXHIBIT MUCH MORE
SEVERE SHUNTING PROBLEM.
8. PHOSPHOROUS - MINOR DEGRADATION IN POWER LOSS DUE TO DECREASE IN BLUE CURRENT ALL OTHER COMPONENTS NORMAL

12. MOLYBDENUM - VOLTAGE SOMEWHAT REDUCED BLUE CURRENT NORMAL FILL FACTOR NORMAL RED OR BULK CURRENT MAJOR DEGRADATION

14. TITANIUM

<table>
<thead>
<tr>
<th>LOT #</th>
<th>CONCENTRATION $10^{15}$ ATOMS/CC</th>
<th>P/Po</th>
<th>Isc/Io</th>
<th>Voc/VoCC</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.11</td>
<td>0.38</td>
<td>0.55</td>
<td>0.8</td>
<td>(3-6 a-CM)</td>
</tr>
<tr>
<td>15</td>
<td>0.167</td>
<td>0.31</td>
<td>0.44</td>
<td>0.9</td>
<td>(0.2 a-CM)</td>
</tr>
<tr>
<td>18</td>
<td>0.033</td>
<td>0.56</td>
<td>0.65</td>
<td>0.87</td>
<td>(4-6 a-CM)</td>
</tr>
</tbody>
</table>

LARGE CONCENTRATIONS OF Ti (14 & 15) CAUSE DEGRADATION OF ALL COMPONENTS INCLUDING SEVERE SHUNTING.

SMALL CONCENTRATIONS OF Ti (18) CAUSE MAJOR DEGRADATION OF BULK CURRENT, MINOR DEGRADATION OF BLUE CURRENT BUT NO SHUNTING.

16. TANTALUM - VOLTAGE NORMAL BLUE CURRENT NORMAL RED OR BULK CURRENT MAJOR DEGRADATION LOWER FF DUE TO SHUNTING

MULTIPLE DOPANTS

9. CR - INI - BLUE CURRENT NORMAL VOLTAGE SOMEWHAT REDUCED RED OR BULK CURRENT MAJOR DEGRADATION SEVERAL CELLS SHUNTED REMAINDER HAVE NORMAL FILLS

APPEAR TO BE SYNERGISTIC EFFECT WITH MULTIPLE DOPING CAUSING MORE DEGRADATION THAN SUM OF INDIVIDUAL.
13. **Cu - Ti** - Blue current normal
   
   1.9/0.033  Fill factor normal
   Voltage degraded
   Red or bulk current major degradation

   Degraded slightly more than lot E-18 with the same amount of Ti but no copper.

17. **Cr - Ti** - Blue current normal
   
   1.0/0.011  Fill factor normal
   Voltage degraded
   Red or bulk current major degradation

   Sufficient data not available to compare multiple dopants with each individual dopant.

19. **Cr Mo-Ti** - Blue current normal
   
   0.4/0.5/0.0033  Voltage slightly degraded
   Red or bulk current major degradation
   Several cells shunted
   Remainder exhibit normal fill
Large-Area Silicon Sheet Task

INGOT TECHNOLOGY

Crystal Systems, Inc., reported on ingots cast from upgraded metallurgical silicon using the Heat Exchanger Method (HEM). Nearly single-crystal ingots have been cast due to impurity segregation to the top of the ingot and the walls of the crucible. High-purity meltstock has produced single-crystal shaped ingots of 22 x 22 x 18 cm dimensions weighing 16.3 kg.

Hamco (Kayex Corporation) reported on repeated demonstrations of growth of 105 kg of silicon ingots from one crucible by periodic melt replenishment. A total of five 100-kg runs have been accomplished on this contract, with two of them completed in this reporting period. Efficiencies of solar cells fabricated on silicon from an earlier run ranged from 11% to 13.5% AM1. Also, impurity analyses on earlier runs are being used to determine sources of growth contamination. Under another contract for Near-Term Cost Reduction, Hamco also reported on the modification of a CC2000 Hamco Crystal Puller to demonstrate growth of up to 150 kg of 6-in.-dia single-crystal silicon from one crucible. Modification of the crystal puller is nearly complete and the microprocessor control is being tested. Three preliminary runs have been completed using the puller in the standard resistance mode.

Siltec Corporation reported on a continuous liquid-feed Czochralski approach to growing 150 kg of monocrystalline silicon ingots, 150 mm in dia, from one crucible. Fifteen runs with 12-kg charges were performed and solidification rates of 2.7 to 3.5 kg/h were achieved. Of the total material grown, 96% was monocrystalline. Manufacturing of parts and installation of the polyrod feed mechanism for continuous recharging of the meltdown chamber was completed, together with the feedback control system which uses the melt level sensor of the growth crucible as input. Short melt replenishment runs with 5 to 8 kg of continuous melt transfer were performed.

WAFFERING TECHNOLOGY

Crystal Systems, Inc., reported on wire improvements for the multi-wire Fixed Abrasive Slicing Technique (FAST). Average cutting rates of 0.143 and 0.122 mm/min were attained; these rates are about 40% higher than those required to meet the 1986 goals. The performance of 45 μm diamonds used in the diamond-impregnated wires has been seen to be superior to the 35 μm diamonds.

Siltec Corporation performed demonstration runs of ingot cutting with ingot rotation and minimum exposed blade area in their program to develop and demonstrate enhanced ID slicing technology. Slices with 100 mm dia were produced with 250 μm thickness and kerfs of 200 μm. Applied cutting feed rates were in the range of 12 to 13 mm/min.
A characterization of the slices from the test series was performed to analyze taper, bow, thickness variation and depth of saw damage.

Silicon Technology Corporation reported results of ID sawing of 100-mm dia ingots with 9-10 mils kerf loss. Optimal programmed feeds (in./min) and rotation (rpm) vs slice thickness was detailed.

SHAPED-SHEET TECHNOLOGY

Arco Solar: Stanford Research Institute (SRI) reported on their die material research for Arco Solar. Boron nitride, low-density graphite, high-density graphite and silicon nitride were found to be unacceptable. A graphite die coated with boron nitride and sodium silicate-sodium fluoride was found to keep the silicon from wetting the coating. Preliminary casting experiments were carried out in boron nitride dies with some success. A standard process has been developed at Arco Solar for polycrystalline cells using Wacker Silso material.

Mobil-Tyco Solar Energy Corporation is developing a multiple-growth furnace to grow three 10-cm-wide edge defined film fed growth (EDF) ribbons with continuous melt replenishment. Rates of 3 to 3.8 cm/min and ribbon thicknesses of 7 to 15 mils have been achieved. Diffusion length measurements have revealed a real inhomogeneity with averages of 10 to 20 μm. High-speed growth runs have resulted in growth of 7.5-cm-wide ribbons at 5.0 cm/min with active helium gas cooling of cartridges and 4.5 cm/min without. Installation of instrumentation for automatic control of meniscus height for the 10-cm system is completed.

Westinghouse has exceeded the area throughput rate goal (27 cm²/min) and the solar cell conversion efficiency goal (15.5%) set for their silicon web growth process. Process acceptance of solar grade (Battelle) polysilicon has been demonstrated and short-term (5 h) growth has been achieved with melt replenishment.

Energy Materials Corporation reports growth speeds of up to 60 cm/min for their horizontal-ribbon-growth method, with the rate typically being 20 to 30 cm/min. The length of the ribbon grown has been limited by the stroke of the puller to about 66 cm. The ribbons, 1.5 cm wide and 0.03 to 0.12 cm thick, are of a large-grain polycrystalline structure.

SUPPORTED-FILM TECHNOLOGY

Honeywell has grown 200-μm thick silicon films at 0.2 cm/sec with helium cooling in their silicon-coating-by-inverted-meniscus (SCIM) effort. Cell efficiencies of 9.9% on a 10 cm² cell and 10.04% on a 4 cm² cell have been achieved. Another new SCIM coater design is complete and construction is underway.
MATERIAL CHARACTERIZATION

The University of Missouri Rolla has studied the effects of varying partial pressures of reactant gases, primarily oxygen and nitrogen, in a furnace where molten silicon is in contact with die and container materials. A new portable thoria-7 wt% yttria polycrystalline ceramic solid electrolyte cell, designed to be used in measuring the oxygen partial pressure above silicon melts at the sheet and ribbon production facilities of other Task II contractors, has been constructed. Calibration procedures and initial results were described.

Cornell University reported on the microstructure of EFG and RTR ribbons. The EFG ribbon showed coherent twins, bundles of microtwins and, less frequently, incoherent twins on the (112) planes and high-angle grain boundaries. RTR ribbons showed twin boundaries perpendicular to the silicon surface.

Applied Solar Energy Corporation presented data on further evaluation of EFC ribbon (Rh process), dendritic web and continuous Czochralski. A cell efficiency of almost 13% (AM0) was achieved on dendritic web with best state-of-the-art cell processing. The evaluation groups are exploring the optimum process for each sheet and to identify possible areas for improvement in terms of controllable sheet properties.

Spectrolab presented data on processing of HEM, continuous Cz, EFG, RTR, Wacker Silso and dendritic web materials including overall cell conversion efficiency and relative spectral response. The program will continue to try to optimize processing for each sheet to achieve 12% AM1 efficiency at 280°C.

JPL IN-HOUSE PROGRAM

Two additional laboratories are now available for direct support of contractor activities. The Photovoltaic Materials and Device Testing Laboratory has facilities for dicing, lapping and polishing wafers and electronically testing wafers and completed solar cells. The Solar Cell Prototype Fabrication Laboratory has facilities for total processing of solar cells from unpolished wafer to finished, AR-coated cells.
TECHNOLOGY SESSION

J. Liu, Chairman

CRYSTAL CASTING – HEM

CRYSTAL SYSTEMS, INC.

C. P. Khattak and F. Schmid

It has been demonstrated that silicon produced by the Heat Exchanger Method (HEM) is comparable to that produced by the Czochralski process for photovoltaic application. In addition, it has been shown that the process can be easily scaled up to produce large-size ingots. The projected costs of this directional solidification process is low. Significant advancements have been made to show that low-cost polycrystalline silicon can be used as a starting material with HEM for sheet production. This has been demonstrated with upgraded metallurgical silicon. Nearly single-crystal ingots were cast with a single HEM solidification using this starting material. The impurities were rejected to the last material to freeze—near the wall of the crucible. The upgraded metallurgical silicon is contaminated with silica and silicon carbide. Macroscopic precipitates, presumably SiC, did not break down the solid-liquid interface and, in some cases, caused only localized twin formation. The resistivity of the silicon produced after HEM solidification was 0.1 - 0.2 $\Omega$-cm. With this silicon, the material cost could be reduced below the cost goal and the projected silicon shortfall would be avoided. The initial experiment with upgraded metallurgical silicon showed the entrapment of SiC particles in the silicon. In the second experiment, by using a slagging operation during solidification, the SiC particles were considerably minimized. In this experiment single crystallinity was maintained all the way to the top of the ingot and the sides of the crucible. This slagging step eliminates a polycrystalline silicon charge preparation step, thereby reducing the costs further.

In the scale-up of the process, square ingots of 22 cm x 22 cm x 18 cm weighing 16.3 kg have been solidified out of high-purity melt stock. The ingots were almost entirely single-crystalline. The crucible attachment problem has been eliminated and good reproducibility has been achieved.
22 × 22 × 18 cm Crystal Solidified by HEM

Polished and Etched Section of 22 × 22 cm Cross Section Crystal
Crystallinity of Ingots After Single Directional Solidification by HEM Using Upgraded Metallurgical Si

(a) Without Slagging

(b) With Slagging During Solidification
Significant developments have been made using the multi-wire Fixed Abrasive Slicing Technique (FAST).

High throughput of the slicer and extended life of the wires has been demonstrated. Cutting rates of about 40% more than the projected estimates used in the economic analysis to meet 1986 goals have been achieved. This has been accomplished through the combination of higher surface speeds of the wires and improvement in the wire. Figure 1 shows a plot of the depth of cut with time for runs 328-SX and 329-SX using the same bladepack. At a surface speed of 400 ft/min, the average cutting rates for these two runs were 0.143 and 0.122 mm/min, respectively. Also shown is the data for run 2-002-SX at a surface speed of 200 ft/min. The average cutting rate was 0.059 mm/min for this run.

Figure 2 shows the slicing performance achieved during runs 344-SX, 345-SX and 346-SX. These runs were sliced with the same set of electroplated wires and the average slicing rate was 0.120, 0.105 and 0.095 mm/min, respectively. These data show that the wires can be used to slice three silicon ingots with little degradation in performance. This set of wires was electroplated using 30 μm natural diamonds. The performance of 45 μm diamonds has been seen to be superior as compared to 30 μm size, hence still longer life is expected.

Commercially available impregnated wires used have shown poor quality control. Impregnation equipment has been fabricated to impregnate diamonds in the cutting edge only. Very high diamond concentrations with good uniformity have been achieved. Slicing tests have shown that the absence of diamonds on the top of the wires allows the wires to seat well in the grooved rollers and thereby achieve better accuracy and lower kerf.
Impregnated Wire with Diamonds in Cutting Edge Only
ADVANCED CZ CONTINUOUS GROWTH

HAMCO DIVISION OF KAYEX CORP.

Introduction

CONTINUOUS CZ INGOT GROWTH

The approach to this project is to use periodic melt replenishment between successive ingot growth cycles using rod or lump polysilicon to grow 100 kilograms of silicon crystal from one crucible.

Status of Continuous CZ Ingot Growth

<table>
<thead>
<tr>
<th>GOAL</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Grow 100 kg from one crucible.</td>
<td>Complete</td>
</tr>
<tr>
<td>2. Achieve 14% solar cell efficiency (AM-1).</td>
<td>Achieved</td>
</tr>
<tr>
<td>3. Replenish melt using rod or lump.</td>
<td>Demonstrated</td>
</tr>
<tr>
<td>4. Maintain high quality crystal growth throughout run.</td>
<td>Demonstrated</td>
</tr>
<tr>
<td>5. Perform six 100 kg runs.</td>
<td>Four completed</td>
</tr>
<tr>
<td>6. Reduce procedures for continuous CZ growth to routine technology.</td>
<td>Ongoing (process specification being written)</td>
</tr>
<tr>
<td>7. Improve add-on cost.</td>
<td>Goals can be achieved or possibly surpassed by growing fewer crystals.</td>
</tr>
</tbody>
</table>

Run No. 55 and No. 2* represent the third and fourth 100 kg continuous runs of the six required under the project extension. Run No. 55 was performed on the original crystal grower built for the 954888 project, while Run No. 2* was performed on a new crystal grower to be used for the "FSGAS" project (contract No. 955270). Run No. 55 was performed using a 35.5 cm (14 inch) crucible and hot zone, while Run No. 2* was performed using a 30.5 cm (12 inch) crucible and hot zone.
The crystal diameter varied from 12.7 cm to 16.0 cm during Run No. 55 due to an early problem with the diameter control, which was corrected after the third crystal was grown. 100.6 kg was grown from a total melt of 106.1 kg, yielding 95.1 kg of final crystalline ingot. 10 ingots were grown. During the growing of the eighth crystal, a pin hole water leak developed in a viewport weld. This problem was readily visible during the following recharge cycle. From that point on, it was impossible to grow high quality crystals. This condition increased the yield of high quality crystal from 92.5% after the eighth crystal was grown to 74.6% when the run was completed following the tenth crystal.

Run No. 2* was performed on a new standard crystal grower that will be used in conjunction with the 755270 project. A presentation relating to that project will be given by Mr. Roberts following my presentation. This grower was delivered and set up with a 12 inch hot zone. The first crystal we grew in this grower was very successful and resulted in a previously unscheduled continuous run being attempted with this new grower.

At the request of the JPL Mentor, we attempted a continuous run on this machine with the results shown in the vibrogram. Even though the first one-crystal run performed in this grower was very successful, we were plagued with several mechanical problems during the continuous run, which resulted in nine crystals being grown over an exceptionally long time period of 108 hours. This resulted in a disappointing throughput of 0.93 kg/hr and a correspondingly low yield of high quality crystal (65.7%). However, we were able to cast 100.5 kg of ingot from 104.5 kg total melt.

The number of crystals cast during these two runs was greater than planned. Therefore, the run time was also longer than planned, resulting in low efficiencies.
### Summary of Run No. 55 and Run No. 2*

<table>
<thead>
<tr>
<th></th>
<th>Run No. 55</th>
<th>Run No. 2*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRYSTAL INSERTED</td>
<td>12.7 - 16.0 cm</td>
<td>12.7 cm</td>
</tr>
<tr>
<td>INITIAL MELT CHARGE</td>
<td>30 kg</td>
<td>18 kg</td>
</tr>
<tr>
<td>CRUCIBLE DIAMETER</td>
<td>35.5 cm (14 in)</td>
<td>50.5 cm (19.9 in)</td>
</tr>
<tr>
<td>TOTAL SILICON METAL</td>
<td>106.1 kg</td>
<td>104.5 kg</td>
</tr>
<tr>
<td>TOTAL INPUT METAL</td>
<td>100.0 kg</td>
<td>100.3 kg</td>
</tr>
<tr>
<td>PULLED YIELD</td>
<td>99.8%</td>
<td>98%</td>
</tr>
<tr>
<td>TOTAL PULL CRYSTAL</td>
<td>25.1 kg (9.4 lb)</td>
<td>16.0 kg (5.6 lb)</td>
</tr>
<tr>
<td>NUMBER OF INGOTS</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>THROUGHPUT</td>
<td>1.11 lb/hr</td>
<td>1.3 lb/hr</td>
</tr>
<tr>
<td>TOTAL RUN TIME</td>
<td>18.6 hrs</td>
<td>18.6 hrs</td>
</tr>
<tr>
<td>CRYSTAL MATERIAL</td>
<td>19.2 kg</td>
<td>19.2 kg</td>
</tr>
</tbody>
</table>

Several individual process runs were attempted between Run No. 49 - the 118 kg continuous run - and the first continuous run (Run No. 55). Two of these runs resulted in 15 cm (5.9 inch diameter) crystals being grown. This slide from the crystal grown during Run No. 51. This crystal is twenty five (25) inches long and weighs 25.9 kg. The time necessary to grow this crystal was 15-1/2 hours from power on to power off. If four high quality crystals like this could be grown, we would exceed our goals for Cell 2. If you add 3 hours to resume after each growth cycle, the throughput would be 1.4 kg/hr.

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* This page is of poor quality.
Run No. 51

This picture shows the second crystal grown during Run No. 55. It has been cut and polished, and is 6 inches in diameter. This crystal was grown when we were having trouble with dendritic growth. However, it does show that high-quality crystals can be grown at this diameter.

Crystal No. 2, Run No. 55
During the last nine months, much emphasis has been placed on solving the problem of structure loss during continuous rechange runs.

Impurity analysis of crystal ingots, virgin feed stock poly silicon, residual melt and crucibles has been stressed.

Based upon preliminary impurity analysis results and data compiled from continuous runs, it is felt that the ability to maintain a leak-free furnace system is vital to the production of a large percentage of high quality crystal. An air leak or microscopic water vapor contamination due to weld degradation appears to drastically reduce the capability to grow high quality crystal. It is also felt that volatile contaminants within the furnace system may cause the loss of high quality crystal structure.

This table shows a chart of impurity analysis results for Run No. 47 and Run No. 49. Only the elements felt to be significant to this discussion are listed here.

This preliminary data tends to indicate that impurity concentrations are much higher in the crucible than in the grown crystal ingots or the residual melt. The chart shows impurity concentrations in the crucible from 6 to 4 x $10^3$ times greater than in the last ingot grown.

However, it is possible that some impurities might be introduced into the melt when recrystallizing new silicon.

**Impurities**

(Concentration in ppm weight)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Sodium</th>
<th>Magnesium</th>
<th>Calcium</th>
<th>Potassium</th>
<th>Fluorine</th>
<th>Chlorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>47-1 Top</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>47-3 Bottom</td>
<td>0.8</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>47 Melt</td>
<td>1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>47-Crucible</td>
<td>66</td>
<td>6</td>
<td>35</td>
<td>35</td>
<td>20</td>
<td>29</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Sodium</th>
<th>Magnesium</th>
<th>Calcium</th>
<th>Potassium</th>
<th>Fluorine</th>
<th>Chlorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>49-1 Top</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>49-5 Top</td>
<td>4</td>
<td></td>
<td>0.1</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49-9 Top</td>
<td>7</td>
<td>0.5</td>
<td>0.1</td>
<td>0.6</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>49-9 Bottom</td>
<td>1</td>
<td>0.5</td>
<td>0.1</td>
<td>(</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>49-Crucible</td>
<td>41</td>
<td>7</td>
<td>410</td>
<td>80</td>
<td>11</td>
<td>41</td>
</tr>
</tbody>
</table>

---

61
The next table lists typical impurity concentrations of fused quartz crucibles— as supplied by the crucible manufacturers. Comparisons of impurity concentrations of this chart with the test results of the previous table indicate the high impurity concentrations were not present in the crucibles before the run was started.

Published test results show that alkalies and halides increase the rate of devitrification of silica glass. Therefore, it is felt that this type of furnace contamination will increase the rate of crucible devitrification during continuous runs. It is also felt that devitrification of the crucible may be the main cause of structure loss during continuous crystal growth. Microscopic silica particles from the crucible may migrate to the growth interface, causing structure loss.

### Crucible Impurities

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Overall</th>
<th>Quartz Products</th>
<th>General Electric</th>
<th>Corning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>12</td>
<td>70</td>
<td>78</td>
<td>5</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>NR</td>
<td>41</td>
<td>0.5</td>
</tr>
<tr>
<td>Ca</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Sr</td>
<td>4</td>
<td>NR</td>
<td>41</td>
<td>0.05</td>
</tr>
<tr>
<td>Fe</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Li</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>NR</td>
</tr>
<tr>
<td>Mg</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>NR</td>
</tr>
<tr>
<td>Na</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Ti</td>
<td>41</td>
<td>2</td>
<td>2</td>
<td>NR</td>
</tr>
<tr>
<td>Cr</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Zn</td>
<td>NR</td>
<td>NR</td>
<td>2</td>
<td>NR</td>
</tr>
<tr>
<td>Mn</td>
<td>NR</td>
<td>NR</td>
<td>2</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR: Not Reported

*Volcanic impurities in fused quartz (Ultra, 510A) crucibles provided by vendors, expressed in parts per million by weight.*
Run No. 47

This slide shows devitrification of the crucible used for Run No. 47. The inner surface of the crucible, which is in contact with the melt, is completely covered with a thick layer of crystallized silica glass. Some of this layer has been broken away on the right to reveal the glassy state underneath the layer.

The degree of devitrification can be seen from the cutaway portion shown on the left. The greatest degree of devitrification normally occurs on the outside surface of the crucible.

Run No. 47

This next slide shows devitrification of the crucible used for Run No. 47. The degree of devitrification is much less than the crucible used during Run No. 49. Our results show that, although both runs produced a high percentage of single crystal, the percentage of zero dislocation material produced during Run No. 47 was more than double the amount produced during Run No. 49.

Run No. 47
The solar cell efficiency data from Run No. 49 has been received and tabulated on the graph shown.

NOTES: RESIST. 1.8 - 2.7 ohm-cm
EFF. OF 4 CONTROL CELLS 16.0 - 16.7%
AVG. EFF. 16.35%

Four cells from each wafer were fabricated and tested. The top line represents the average of the four cells. The range of results for each wafer is indicated by each vertical line.

The cells from the top of the first crystal, taken after approximately four (4) kg had been grown, had an average efficiency of 16.3%. The cells from the bottom of the first crystal at the 10 kg mark averaged 16.1%. The cells from the sixth crystal grown at the 50 kg mark yielded an average efficiency of 16.2%. The last crystal grown yielded average efficiencies of 16.1% at the top (30 kg) and 15.8% towards the bottom after 100 kg had been grown.

The heavy dark line represents the 14% project goal.

As you can see, efficiency results have exceeded the 14% AM1 goal of this project on all cells tested. Moreover, there does not appear to be any significant decrease in efficiency throughout the run.

Four control cells yielded efficiencies from 16.0% to 16.7%, which is similar to the samples tested.
This videograph presents an updated projection of the time cycles and add-on costs for the Cz-2 process when four 25 kg ingots are grown from a 35.5 cm diameter crucible.

This updated projection was formulated using data from Run No. 49 and Run No. 55. Based on the actual Run data, we have decreased the initial melt down time for 30 kg from 4 hours to 2 hours. We have increased the amount of time needed for growing preparation to take into account the possibility of structure loss during grown growth or the re-melting over procedure. Therefore, the steps involving growth preparation can significantly improve the total run time when favorable results are achieved in this area. Ingot growth time remains the same as earlier projections based on a growth rate of 10 cm/hr. Finally, the re-charge cycle time has been decreased from 22% of the run time as previously projected to 16%, due to improvements brought about by the lump re-charging method.

The resultant add-on cost for this updated projection in 1980 dollars is $23.25 per kilogram. This add-on cost is slightly less than the previously projected add on cost of $25.76 per kilogram.

### Cost Update for Cz No. 2

<table>
<thead>
<tr>
<th>Operation</th>
<th>Updated Projection (HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Down</td>
<td>2 (36%)</td>
</tr>
<tr>
<td>Growing Preparation</td>
<td></td>
</tr>
<tr>
<td>1) Standard Temperature</td>
<td>14.6 (86%)</td>
</tr>
<tr>
<td>2) Growing Solid</td>
<td>(4 inches)</td>
</tr>
<tr>
<td>3) Crystal Growth</td>
<td></td>
</tr>
<tr>
<td>4) Melt Ends</td>
<td></td>
</tr>
<tr>
<td>Ingot Graining</td>
<td>30.4 (54%)</td>
</tr>
<tr>
<td>(Sectional Section)</td>
<td>(10 cm/hr)</td>
</tr>
<tr>
<td>Recovery Cycle (Lump Only)</td>
<td>9.0 (16%)</td>
</tr>
<tr>
<td>1) Removal of Crystal</td>
<td>(5 times)</td>
</tr>
<tr>
<td>2) Fuel Burner</td>
<td></td>
</tr>
<tr>
<td>3) Fuel Fill</td>
<td></td>
</tr>
<tr>
<td>4) Melt Down</td>
<td></td>
</tr>
<tr>
<td>Total Time</td>
<td>56.0</td>
</tr>
</tbody>
</table>

Add on Cost Cz (1980 dollars/kg) $23.25

<table>
<thead>
<tr>
<th>Cz No. 2: 25&quot; crystal base</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kg</td>
</tr>
<tr>
<td>13.5 cm diameter</td>
</tr>
<tr>
<td>10 cm/hr</td>
</tr>
</tbody>
</table>
Program Plan - Continuous CZ Development

<table>
<thead>
<tr>
<th>Project Goals</th>
<th>1979</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APR</td>
</tr>
<tr>
<td>A. 100 kg Continuous Runs</td>
<td></td>
</tr>
<tr>
<td>1. Schedule of Runs</td>
<td></td>
</tr>
<tr>
<td>2. Sample Preparation &amp; Analysis (All Runs)</td>
<td></td>
</tr>
<tr>
<td>3. Solar Cell Analysis (All Runs)</td>
<td></td>
</tr>
<tr>
<td>4. Economic Model, Update</td>
<td></td>
</tr>
<tr>
<td>B. Process Development Runs (10 Total)</td>
<td></td>
</tr>
<tr>
<td>1. Run Schedule</td>
<td></td>
</tr>
<tr>
<td>2. Crucible Comparison, Analysis</td>
<td></td>
</tr>
<tr>
<td>3. Graphite Purification, Analysis</td>
<td></td>
</tr>
<tr>
<td>4. High Purity Runs</td>
<td></td>
</tr>
<tr>
<td>C. Reports</td>
<td></td>
</tr>
</tbody>
</table>

Summary and Conclusions

1. 100 kilograms of silicon crystals can be grown from one crucible with acceptable yields.
2. At least 5.9 inch diameter crystals can be grown in the crystal grower used for this project.
3. 100 kilograms of silicon crystals has been grown from one crucible using a standard production grower and continuous run techniques.
4. Crucible devitrification may be the primary cause of structure loss during continuous crystal growth.
5. Accelerated crucible devitrification can be caused by the combined effect of contamination and high temperatures.
6. Cost objectives - as projected - can be realized by decreasing the number of crystals grown during a 100 kg continuous run.
7. Solar cell efficiencies do not appear to deteriorate through the 100 kg continuous run.
LOW-COST CONTINUOUS-GROWTH TECHNOLOGY

HAMCO DIVISION OF KAYEX CORP.

Program Introduction

The program requires process improvement concepts aimed at:
1. Lowering the costs of the melt-down and growth processes. (Faster melt-down and increased growth rate).
2. Reducing labor costs and improving yields by process automation. (1 production operator per 6 growers).

A combination of the above will reduce the continuous CZ add-on costs to:

- Low Cost CZ (Rod Feed) = $15.36/kg
- Low Cost CZ (Poly Chunk Feed) = $14.95/kg

Both in 1980 $

*Approximately 27.2% cost reduction compared to "Cold Fill" process.

Cz Growth Methods

<table>
<thead>
<tr>
<th>CONDITIONS</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crucible Size (inches)</td>
<td>14&quot; x 11-1/2&quot;</td>
<td>14&quot; x 11-1/2&quot;</td>
</tr>
<tr>
<td>Crystal Diameter (cm)</td>
<td>15.25</td>
<td>15.25</td>
</tr>
<tr>
<td>Growth Rate (cm/hr)</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Total Poly Melted (kg)</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Total Crystal Pulled (kg)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Pulled Yield (%)</td>
<td>93.75</td>
<td>93.75</td>
</tr>
<tr>
<td>Yield After CG (%)</td>
<td>85.0</td>
<td>85.0</td>
</tr>
<tr>
<td>No. Crystals/Crucible</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cycle Time (hrs)</td>
<td>59.8</td>
<td>59.1</td>
</tr>
<tr>
<td>Throughput (kg/hr)</td>
<td>2.25</td>
<td>2.28</td>
</tr>
</tbody>
</table>

67
### SAMICS/IPEG Input Data and Cost Calculation

**Input Data (1980 $)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Equipment Cost (ESPT)</td>
<td>$219,000</td>
<td>$209,000</td>
</tr>
<tr>
<td>Manufacturing Floor Space (SQFT)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Annual Direct Labor Salaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prod. Operator (0.05 persons/yr)</td>
<td>$8,100</td>
<td>$8,100</td>
</tr>
<tr>
<td>Elect. Tech. (0.3 persons/yr)</td>
<td>$1,425</td>
<td>$1,425</td>
</tr>
<tr>
<td>Inspector (0.1 persons/yr)</td>
<td>$1,068</td>
<td>$1,068</td>
</tr>
<tr>
<td><strong>Total DIAB</strong></td>
<td>$10,593</td>
<td>$10,593</td>
</tr>
</tbody>
</table>

**Conditions (per Cycle)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Si Melted (kg)</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Crystall Weight</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>No. of Crystals/Crucible</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Diameter of Crystal (cm)</td>
<td>15.25</td>
<td>15.25</td>
</tr>
<tr>
<td>Growth Rate (cm/hr)</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Cycle Time (hrs)</td>
<td>9.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Crucible Size</td>
<td>14&quot; x 11-1/2&quot;</td>
<td>14&quot; x 11-1/2&quot;</td>
</tr>
<tr>
<td>% Yield (Total in Spec.)</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Thru-Put (kg/hr)</strong></td>
<td>2.25</td>
<td>2.28</td>
</tr>
</tbody>
</table>

**Add-On Cost ($/kg or $/m²)**

- **Assume 1 Kg = 1 m²**
  - $15.36 (1980)
  - $14.95 (1980)

**SAMICS/IPEG Input Data and Cost Calculation**

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Cost CZ (Rod Feed)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Low Cost CZ (Poly Lump Feed)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SAMICS/IPEG Input Data and Cost Calculation**

<table>
<thead>
<tr>
<th>Price</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 ESPT = 80.49$/yr - 80/ft²</td>
<td>$107,310</td>
<td>$102,410</td>
</tr>
<tr>
<td>C2 SQFT = 97$/yr - 97SQFT</td>
<td>9,700</td>
<td>9,700</td>
</tr>
<tr>
<td>C3 DIAB = 82.1$/yr - 40LAB</td>
<td>22,245</td>
<td>22,245</td>
</tr>
<tr>
<td>C4 MATS = 81.3$/yr - 40MATS</td>
<td>101,037</td>
<td>101,818</td>
</tr>
<tr>
<td>C5 UTIL = 81.3$/yr - 40UTIL</td>
<td>19,533</td>
<td>19,811</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$259,825</td>
<td>$255,384</td>
</tr>
<tr>
<td><strong>Quan. (Total Charge x % Yield)</strong> (Kg)</td>
<td>16,918</td>
<td>17,122</td>
</tr>
<tr>
<td><strong>Throughput</strong></td>
<td>2.25</td>
<td>2.28</td>
</tr>
</tbody>
</table>

**SAMICS/IPEG Input Data and Cost Calculation**

<table>
<thead>
<tr>
<th>Data</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Add-On Cost ($/kg or $/m²)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Assume 1 Kg = 1 m²)</td>
<td>$15.36 (1980)</td>
<td>$14.95 (1980)</td>
</tr>
</tbody>
</table>

**SAMICS/IPEG Input Data and Cost Calculation**

<table>
<thead>
<tr>
<th>Price</th>
<th>Low Cost CZ (Rod Feed)</th>
<th>Low Cost CZ (Poly Lump Feed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Cost CZ (Rod Feed)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Low Cost CZ (Poly Lump Feed)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Low Cost CZ (Rod Feed)  |  Low Cost CZ (Poly Lump Feed)  
---|---

**Direct Used Materials & Supplies:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Rod Feed</th>
<th>Poly Lump Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles/yr Hrs/Cycle</td>
<td>124.4/59.8</td>
<td>125.9/59.1</td>
</tr>
<tr>
<td>Poly-Kg/yr (charged)</td>
<td>19,904</td>
<td>20,144</td>
</tr>
<tr>
<td>Seed ($5.82)</td>
<td>$722</td>
<td>$733</td>
</tr>
<tr>
<td>Dopant (not costed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon (100 ft³/Cycle-1hr @ 0.002 ft³)</td>
<td>$14,878</td>
<td>$14,881</td>
</tr>
<tr>
<td>Crucibles (14&quot; = $291)</td>
<td>36,084</td>
<td>36,666</td>
</tr>
<tr>
<td>Miscellaneous (including graphite: $3.5/Cycle)</td>
<td>26,092</td>
<td>26,042</td>
</tr>
<tr>
<td>Materials Total (MATS)</td>
<td>$77,721</td>
<td>$78,322</td>
</tr>
</tbody>
</table>

**Utilities (Process):**

- **Electricity**
  - (65kw x 0.035/kw) (Cycle Time-3 hrs) (U Cycles) $16,075 $16,354
- **Cooling Water**
  - (65kw) (0.0074) (Cycle Time-2 hrs) (U Cycles) 3,468 3,467

Utilities Total (UTIL) $19,543 $19,811

**Overall Process Program**

<table>
<thead>
<tr>
<th>Program</th>
<th>Program Goal</th>
</tr>
</thead>
</table>
| 1. Accelerated Melt | (a) Decrease Crucible Devitrification  
| | (b) Achieve Faster Melt-Dark Rates, i.e. up to 40 kg/hr |
| 2. Accelerated Growth | Increase Growth Rate to 15 cm/hr for 15.25 cm Diameter Crystal Growth |
| 3. Cold Crucible | (a) Maintain Melt Purity Level into Crucible  
| | (b) Prevent Crucible Devitrification |
| 4. Microprocessor Control | (a) Reduce Labor Costs  
| | (b) Improve Yield |

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Program Discussion

GOALS:

1. Demonstration of the growth of 150 kg of 6" diameter single crystal silicon from one crucible.

2. Modification of a CG 2000 Hanco Crystal Puller to allow periodic melt replenishment of either 5" diameter polysilicon rods or polycrystalline silicon chunk.

3. Demonstration of a melt rate of 25 kg to 40 kg/hr.

4. Demonstration of a growth rate of 15 cm/hr, utilizing a heat sink.

5. Install a microprocessor control system to reduce costs and to improve yields.

GENERAL:

An important consideration associated with growth of >100 kg of silicon from one quartz crucible is that of crucible devitrification.

Devitrification is known to take place during conventional "top loading" melting procedures when temperatures approximately 200°C above the melting point of silicon are required to melt the crucible polysilicon.

Also, maintenance of crystal structure can be a problem when devitrification occurs.

By substituting conventional melting of "top loaded" cold silicon with an RF induction heated work coil, poly rods can be melted directly into a crucible or poly chains can be melted using a "cold crucible" premelter. Devitrification will then be minimized.

Also, the use of high purity graphite is considered essential in reducing devitrification of the outer crucible wall.
Equipment Status for Accelerated Melt and Growth Programs

GOAL

1. CG2000 RC CRYSTAL PULLER INSTALLATION & COMMISSIONING
2. R.F. GENERATOR INSTALLATION
3. R.F. REMOTE STATION INSTALLATION FOR ACCELERATED MELT PROGRAM
4. INSTALLATION OF R.F. FEED-THRU & WORK COIL
5. R.F. GENERATOR COMMISSIONING
6. SUB-CONTRACT DELIVERY OF POLY ROD RECHARGE MECHANISM
7. DELIVERY OF PURIFIED GRAPHITE PIECE-PARTS

STATUS

Complete
Complete
Complete
Complete
Ongoing (Commenced 12/3/79)
Ongoing
Complete

CG2000 RC Puller
RF Work Coil Assembly

R.F. Heating Generator, Coil Design and Heat Sink

A 50 kW output thyristor controlled R.F. generator operating at a frequency of 450 kHz has been purchased. System incorporates two remote stations, i.e., one station feeds a low voltage, single turn work coil fabricated from machined copper. This coil will be used as the heat sink in the accelerated growth program and used to melt the 5" polysilicon feedstock for the accelerated melt program. The second remote station feeds a high voltage multi-turn coil for the silicon cold crucible premelter system.

CG2000 RC Crystal Puller Run Summary

Total of 3 crystal growth runs have been completed utilizing the puller in standard resistance mode. 7 kg charged to check-out mechanical/electronic functions.

Run 1 18 kg charged - 28.4 inches of 4-inch 2.D. quality material pulled = 16.7 kg.
A growth rate of up to 4.9 inches/hr obtained.
Grown yield = 92.8%.

Run 2 Grown as part of JPL Contract #554888 at the request of Technical Project Monitor.
Summary of Run No. 2

*This run was completed using 12" piece-parts as part of Contract #54-888.

Crystal Ingot Diameter: 12.7 cm
Initial Melt Charge: 18 kg
Crucible Diameter: 30.5 cm
Total Wt. of Silicon Melted: 104.5 kg
Total Ingot Pulled: 100.3 kg
Pulled Yield: 95%
Total Yttria Crystal: 63.9 kg (63.7%)
Number of Ingot: 9
Throughput: 0.93 kg/hr*
Total Run Time: 108 hrs
Recharge Material: 100% Lump

Cold-Crucible Silicon Premelter Program

<table>
<thead>
<tr>
<th>GOAL</th>
<th>STATUS</th>
<th>COMPLETION DATE</th>
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<tr>
<td>1. Design of Cold Crucible</td>
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<td>12/7/79</td>
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<td>2. Sub-Contractor Design Discussions</td>
<td>Ongoing</td>
<td>12/14/79</td>
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<td>3. Cold Crucible Boat/Coil Delivery</td>
<td>Ongoing</td>
<td>1/25/80</td>
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<tr>
<td>4. Cold Crucible/Melt Transfer and</td>
<td>Ongoing</td>
<td>2/20/80</td>
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<tr>
<td>Ancillary Feed-Thru Design</td>
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<td></td>
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<tr>
<td>5. Furnace Cover Modification/Crucible Interface</td>
<td>Ongoing</td>
<td>4/25/80</td>
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</table>
Schematic of a Cold Crucible With Hopper Mechanism

Cold Crucible

Feed Hopper 100 KG.

Vibration Mech.

Isolation Valve

Retraction Mech.

Pre-Melt Chamber
(20 micron)
Argon Back Fill
# Microprocessor Control Program Status

<table>
<thead>
<tr>
<th>GOAL</th>
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<td>1. Software Programming</td>
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<td>2. Data Storage</td>
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<td>6. De-Bug/Test Control Sequences</td>
<td>Ongoing</td>
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# Program Plan, Low-Cost Cz Crystal Growth

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<th>ELAPSED TIME IN MONTHS</th>
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<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18</td>
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<td>1. PROGRAM #1 MODIFICATION TO CO 2000 CRYSTAL GROWER</td>
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<td>a) 1A OVERALL CONCEPTUAL DESIGN</td>
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<td>b) 1B MICROPROCESSOR CONTROLS</td>
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<tr>
<td>c) 1C HEAT SINK AND HEAT SINK</td>
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<td>d) 1D MODIFIED GROWTH CHAMBER</td>
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<td>e) 1E CRUCELLE DEVELOPMENT</td>
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<td>2. PROGRAM #2 DEFINITION OF PROCESS AND VARIABLES</td>
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<td>a) 2A ACCELERATED MELT BACK</td>
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<td>b) 2B GROWTH CRYSTAL CONCEPT</td>
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<td>c) 2C ACCELERATED GROWTH</td>
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<td>d) 2D CRUCELLE DEVELOPMENT</td>
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<td>3. PROGRAM #3 DESIGN IMPROVEMENTS</td>
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<td>a) 3A DESIGN REVISION</td>
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<td>b) 3B PERIODIC REVIEW AND REPORTS</td>
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<td>4. PROGRAM #4 PROCESS EVALUATION</td>
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<td>a) 4A ECONOMIC MODEL UPDATE</td>
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<td>5. PROGRAM #5 DOCUMENTATION</td>
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<td>a) 5A DESIGN REPORT</td>
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TOTAL MAIN MONTHS: 60.75

START: DESIGN APPL COMPLETED: COMPLETED
# CONTINUOUS LIQUID FEED Cz GROWTH

**SILTEC CORP.**

## Program Plan

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<tr>
<th>Task Description</th>
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<th>3</th>
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<td>Develop particle feed system</td>
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<td>Provide support personnel</td>
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<td>Provide design and performance analysis</td>
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<td>Provide documentation</td>
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<td>Provide parts, materials, and services as required</td>
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</table>

**Legend**
- A = As late as 7/31
- B = As required
- C = As late as 1/31
- D = As late as 2/28

## CLF Furnace Diagram
Polyrod Feeding Mechanism for CLF Furnace

Particle Feed Mechanism for CLF Furnace
Simultaneous Polyrod Feed and Crystal Growth

Rigid Graphite Heater

- Heating Element
- Quartz Tube
- Silicon Carbide Coated Graphite Shell
- Electrical Insulation
Quartz Transfer Tube
Transfer Tube Heating Element
Transfer Tube Graphite Jacket

CLF Furnace in Operation
Saw With Cover Off Showing Heat With 15" Dia Blade in Place

Blade Head Configuration

**Current Practice**

**Proposed Machine**

Reduced Diameter Head with Minimum Exposed Blade Area
Conventional ID Blades

- .004 - .005 Inches
- .08 - .20 Inches
- Core
- .011 - .015 Inch Kerf

(Not to Scale)

Average Diamond Diameter = 1.8 - 3.0 Mils.

Prefabricated Insert Blade

- PREFABRICATED INSERT
- SAW BLADE

Insert, I.D. Blade Pre-Fab

- DIAMONDS: GRIT 5/88, 40 µm
- 80 CONCENTRATION

Blade Cross-Section After Bonding (Scale 50:1)

- .003 - .004 BOND
- .08
- .006
Blade Dressing

Before Dressing

![Image of blade before dressing]

 Remaining Blade Life

After Dressing

![Image of blade after dressing]

 Remaining Blade Life

Truing Blade With Rotary Grinding

![Diagram of truing process]
Wafer Sliced With Reduced Feed Rate

0.15 CM/REV

NO ROTATION
1.20 cm of Feed per Ingot Revolution

CUTTING

FEED

INGOT ROTATION
Wafer Sliced With Accelerated Feed Rate

Blade Deflection Control by Position Monitor

Relative Flows Altered to Dynamically Position Blade

Closed Loop Blade Position Control System

[Diagram of closed loop blade position control system]
ID SLICING

SILICON TECHNOLOGY CORP.

Development of Methods of Producing Large Areas of Silicon Sheet by the Slicing of Silicon Ingots using Inside Diameter Saws.

Contract Goals:

- Ingot Diameter: 10cm
- Wafer Thickness: .24mm
- Kerf: .24mm
- Slicing Speed: 2.5 cm/min.
- Yield: >90%

Equipment

- 16-inch STC I.D. Saw
- Vacuum Wafer Recovery System
- Crystal Rotating System
- Programmable Electric Feed
- Dyna-Track Blade Monitoring System
Critical Factors in Rotational Slicing

- Orientation of Crystal Axis
- Initial Feed Rate
- Wafer Thickness
- Initial Rotation Rate
- Blade Condition

Program Cam Shapes

Programmed Feed

\[ \text{1/2 Inch} \]

\[ \text{1/2 Crystal Diameter} \]

Programmed Rotation
Siltec ID R&D Saw
Slicing Tests

CRYSTAL DIAMETER - 100 mm
KERF LOSS 9 - 10 MILS

Optimal Programmed Feeds and Rotations

<table>
<thead>
<tr>
<th>SLICE THICKNESS</th>
<th>FEEDS (IN/Min)</th>
<th>ROTATION</th>
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</thead>
<tbody>
<tr>
<td>15 MILS</td>
<td>.3</td>
<td>1.0</td>
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<tr>
<td>12 MILS</td>
<td>.1</td>
<td>.5</td>
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<tr>
<td>10 MILS</td>
<td>.07</td>
<td>.3-.5</td>
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<tr>
<td>8 MILS</td>
<td>.05</td>
<td>.3</td>
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</table>

Rotational Slicing

CYCLE TIME VS WAFER THICKNESS

![Graph showing cycle time vs wafer thickness]
Recommended Work

**New Saw Capabilities:**

1. **32-inch Blade Capacity**
   - 3 - 10cm crystals
   - 2 - 15cm crystals

2. **10-inch Linear Stroke - JAM Accuracy**

3. **Increased Mass - Reduction of Vibration by a factor of 10.**

4. **μ-Processor Controls, Programmed Feed**

5. **Unlimited Crystal Length**

6. **Hollow Spindle - Auto Wafer Recovery Reduced Turbulence.**

**Blade Development**

**Possible New Core Materials**
- Special 302 Stainless Steel
- H11 Tool Steel
- Beryllium Copper
- Full Work Hardened 201 Stainless Steel

**Diamond Matrix Metals**
- Present Matrix - Soft Nickel Plate
- New Metals: - Rhodium
  - Chromium

**Objectives**
- Thinner Blade
- Longer Life
- Less Dressing
VACUUM DIE CASTING OF SILICON SHEET

ARCO SOLAR, INC.

D. Sacoli

Basic Approach

CASTING EXPERIMENTS

DEMONSTRATE PRINCIPLE

SIMPLE SPLIT DIES

SOLIDIFICATION RATE

GRAIN SIZE

PURITY

4 x 1 x 0.012 IN SILICON SHEET

DIE MATERIAL SELECTION

SHEET RECOVERY

CONTAMINATION

REACTIVITY EXPERIMENTS

MONOLITHIC MATERIALS

SURFACE FINISH

COATINGS BARRIERS

HEAT TRANSFER

FABRICATION

DIE DESIGN
Die Casting of Liquid Silicon
Silicon Sheet Cast in BN Die

(a) Cross Section
(b) Plane Section
Detail of Microstructure: Silicon Sheet Cast in BN Die

(a) Cross Section
(b) Plane Section
Die for Pressing Sheets from Liquid Silicon

DIE SURFACES COATED WITH NaF/Na$_2$SiO$_3$
Die Arrangement for Forming Thin Sheets from Liquid Silicon
Silicon Melted in Graphite Crucible With Liquid Barrier Coating
Solidified Silicon Drops on Various Ceramics

(a) CVD Si$_3$N$_4$
(b) NC350
(c) NC312
(d) NCX34

(e) CVD SiC
(f) Oxidized NC350
(g) Oxidized NC132
(h) Oxidized NCX34
Silicon Disc Pressed From a Sessile Drop

(a) Disc
(b) Microstructure
(c) Microstructure
LARGE AREA SI SHEET BY EFG

MOBIL TYCO SOLAR ENERGY CORP.

JPL Furnace 18, Separate Probes; ELH; 100 mW/cm²; 28°C

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Area (cm²)</th>
<th>$I_{\text{rv}}$ (mA/cm²)</th>
<th>$V_{\text{oc}}$ (V)</th>
<th>IP (mA)</th>
<th>$I_{\text{sc}}$ (mA/cm²)</th>
<th>FF</th>
<th>$P$ (mW/cm²)</th>
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RIBBON NUMBER: 17-062
DIFFUSION NUMBER: HYBRID
DATA TAKEN BY: JDM
DATE: 12/3/79
NUMBER OF CELLS: 8
COMMENTS: CELLS FROM 4" WIDE RIBBON
ELA. 100 mW/cm², 28°C, AR COATED

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<td>&quot;CENTRAL REGION&quot; AVG.:</td>
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Distribution of Minority Carrier Diffusion Length (SPV) Values Over the Width of a 10 cm LFG Ribbon (Sample No. 17-063-1).
JPL Multiple Furnace — 10-cm-Wide Ribbon

GOALS THROUGH OCTOBER 1979

- DEVELOP SINGLE CARTRIDGE GROWTH TO EQUAL 5 cm SYSTEM WITH RESPECT TO RATE, STABILITY, THICKNESS, STRESS AND FLATNESS.

PRESENT STATUS

- ALL GROWTH IS WITH CONTINUOUS MELT REPLENISHMENT.
- RATES OF 3 to 3.8 cm/min HAVE BEEN ACHIEVED.
- STABILITY DEMONSTRATED IN FULL-WIDTH GROWTH OVER TWO HOURS ON SIX OCCASIONS.
- THICKNESS RANGE: 7 to 15 MILS.
- FLATNESS AND STRESS AT ACCEPTABLE LEVELS.

GROWTH STATISTICS

- EIGHT OF 11 RUNS YIELDED FULL-WIDTH RIBBON.
- TOTAL LENGTH GROWN: 67 m (220 FT).
- PERCENT FULL WIDTH: 70%.
- AVERAGE SPV DIFFUSION LENGTH: 10 to 20 μm. VERY INHOMOGENEOUS.
- SiC PARTICLE DENSITY STILL ERRATIC. EXPERIMENTS WITH PROPER DIE DESIGN CHANGES IN PROGRESS.

GOAL FOR DECEMBER 31, 1979

* RUN THREE 10 cm CARTRIDGES CONTINUOUSLY FOR SEVERAL HOURS.

PRESENT STATUS

* ALL PARTS HAVE BEEN ORDERED, MANY RECEIVED. INSTALLATION OF TWO MORE CARTRIDGES IS IMMINENT.
JPL Furnace 17 – High-Speed and Automatic Controls

PROGRESS IN 7.5 cm WIDE GROWTH

• ACHIEVED FLAT, STRESS-FREE RIBBON GROWTH AT HIGH SPEEDS:
  
  (a) 5.0 cm/min WITH CARTRIDGE HELIUM.
  
  (b) 4.5 cm/min WITHOUT CARTRIDGE HELIUM

PROGRESS IN 10 cm WIDE GROWTH

• INSTALLATION AND TESTING OF 10 cm WIDE CARTRIDGE SYSTEM COMPLETED.

• ACHIEVED REASONABLY FLAT, STRESS-FREE, FULL-WIDTH RIBBON GROWTH AT 4.0 cm/min WITHOUT CARTRIDGE GAS.

• INITIAL EXPERIMENTS UNDER "CLEAN" CONDITIONS ENCOURAGING.

AUTOMATIC CONTROLS

• INSTALLATION OF INSTRUMENTATION FOR AUTOMATIC CONTROL OF MENISCUS HEIGHT FOR 10 cm SYSTEM IS COMPLETED. TESTS ARE IMMINENT.

Materials Characterization Effort

I. ROUTINE SPV DIFFUSION LENGTH MEASUREMENT

II. ROUTINE CELL EVALUATION

   (i) FURNACE NO. 3A: 10 CM WIDE GROWN RIBBONS

   (ii) FURNACE 17: 10 CM WIDE GROWN RIBBONS
III. CELL OPTIMIZATION

(i) CELL PERFORMANCE: DIFFUSION A VS. DIFFUSION B

(ii) BULK DIFFUSION LENGTH ENHANCEMENT: DIFFUSION A VS. DIFFUSION B

(iii) 2 x 2 CM CELLS

Distribution of Minority Carrier Diffusion Length (SPV)
Values Over the Width of a 10 cm EFG Ribbon
(Sample No. 14-198-41)
Solar Cell Data for Material Grown from Run 16-198.
ELH Light Source at 100 mW/cm², 28°C. AR Coated.

10 cm wide ribbon: -3 cm/min

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Area (cm²)</th>
<th>( J_{sc} ) (mA/cm²)</th>
<th>( V_{oc} ) (Volt)</th>
<th>FF</th>
<th>n (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>198-1-2</td>
<td>54.9</td>
<td>17.23</td>
<td>.530</td>
<td>.585</td>
<td>5.35</td>
<td>Cell Length Parallel to Ribbon Width</td>
</tr>
<tr>
<td>-3</td>
<td>18.3</td>
<td>24.46</td>
<td>.559</td>
<td>.721</td>
<td>9.86</td>
<td>Cell Length Perpendicular to Ribbon Width</td>
</tr>
</tbody>
</table>

Comparison of Solar Cell Data for Ribbons Grown from Run 16-187 and Fabricated by Two Different Diffusion Runs, A and B.

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Diffusion Runs</th>
<th>( J_{sc} ) (mA/cm²)</th>
<th>( V_{oc} ) (Volt)</th>
<th>FF</th>
<th>n (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>Run A:</td>
<td>16.11</td>
<td>.520</td>
<td>.694</td>
<td>5.82</td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td>Temperature: 1025°C</td>
<td>15.77</td>
<td>.522</td>
<td>.690</td>
<td>5.68</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>Time: 50 minutes</td>
<td>15.89</td>
<td>.522</td>
<td>.657</td>
<td>5.44</td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td>Source: Phosphorous-doped oxide</td>
<td>16.14</td>
<td>.528</td>
<td>.687</td>
<td>5.85</td>
<td></td>
</tr>
<tr>
<td>-5</td>
<td></td>
<td>16.91</td>
<td>.537</td>
<td>.723</td>
<td>6.56</td>
<td>No AR</td>
</tr>
<tr>
<td>-6</td>
<td></td>
<td>15.82</td>
<td>.525</td>
<td>.727</td>
<td>6.04</td>
<td></td>
</tr>
<tr>
<td>-7</td>
<td></td>
<td>15.96</td>
<td>.531</td>
<td>.727</td>
<td>6.16</td>
<td></td>
</tr>
<tr>
<td>-8</td>
<td></td>
<td>16.17</td>
<td>.522</td>
<td>.635</td>
<td>5.39</td>
<td></td>
</tr>
<tr>
<td>-9</td>
<td></td>
<td>15.92</td>
<td>.523</td>
<td>.701</td>
<td>5.84</td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>Run B:</td>
<td>11.58</td>
<td>.508</td>
<td>.735</td>
<td>4.33</td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td>Temperature: 900°C</td>
<td>11.24</td>
<td>.490</td>
<td>.679</td>
<td>3.74</td>
<td>No AR</td>
</tr>
<tr>
<td>-3</td>
<td>Time: 30 minutes</td>
<td>11.37</td>
<td>.492</td>
<td>.667</td>
<td>3.73</td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td>Source: PH₃ gas</td>
<td>12.07</td>
<td>.503</td>
<td>.720</td>
<td>4.37</td>
<td>No AR</td>
</tr>
<tr>
<td>-5</td>
<td></td>
<td>12.68</td>
<td>.512</td>
<td>.730</td>
<td>4.74</td>
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<tr>
<td>-6</td>
<td></td>
<td>11.71</td>
<td>.496</td>
<td>.716</td>
<td>4.16</td>
<td></td>
</tr>
<tr>
<td>-7</td>
<td></td>
<td>11.67</td>
<td>.504</td>
<td>.784</td>
<td>4.61</td>
<td></td>
</tr>
</tbody>
</table>
Summary of Annealing Experiments in N$_2$
Ambient. Furnace 18 Ribbons Grown
with Graphite Crucible.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Annealing Condition</th>
<th>Position</th>
<th>$I_D$ ($\mu$)</th>
<th>Deviation ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-176-1C</td>
<td>As-grown</td>
<td>A1</td>
<td>19.6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2</td>
<td>26.7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3</td>
<td>24.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4</td>
<td>16.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A5</td>
<td>23.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>22.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000°C, 1 hr, N$_2$</td>
<td>B1</td>
<td>15.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>19.8</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3</td>
<td>19.5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>14.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>12.1</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>16.0 (-28%)</td>
<td></td>
</tr>
<tr>
<td>18-176-1J</td>
<td>As-grown</td>
<td>A1</td>
<td>25.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2</td>
<td>28.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3</td>
<td>23.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4</td>
<td>24.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A5</td>
<td>24.9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>25.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000°C, 1 hr, N$_2$</td>
<td>B1</td>
<td>14.6</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>7.7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3</td>
<td>21.5</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>20.9</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>6.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>14.3 (-44%)</td>
<td></td>
</tr>
</tbody>
</table>
Summary of Annealing Experiment in O\(_2\) Ambient. Furnace 18 Ribbons Grown with Graphite Crucible.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Annealing Condition</th>
<th>Position</th>
<th>(L_D) ((\mu))</th>
<th>Deviation ((\mu))</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-176-2H</td>
<td>As-grown</td>
<td>A1</td>
<td>19.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2</td>
<td>35.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3</td>
<td>36.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4</td>
<td>25.9</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A5</td>
<td>36.6</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>30.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000°C, 1 hr, O(_2)</td>
<td>B1</td>
<td>15.5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>21.4</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3</td>
<td>34.4</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>26.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>12.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>21.9 (-29%)</td>
<td></td>
</tr>
<tr>
<td>18-176-3H</td>
<td>As-grown</td>
<td>A1</td>
<td>14.5</td>
<td>0.5</td>
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<tr>
<td></td>
<td></td>
<td>A2</td>
<td>28.1</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A3</td>
<td>40.8</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4</td>
<td>32.4</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A5</td>
<td>12.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000°C, 1 hr, O(_2)</td>
<td>B1</td>
<td>4.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>31.4</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3</td>
<td>25.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>18.8</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>9.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average:</td>
<td>10.6 (-59%)</td>
<td></td>
</tr>
</tbody>
</table>
Effects of Diffusion Temperature and Conditions on the Bulk Diffusion Length of Graphite-Grown RH-EFG Ribbon.

Ribbon No. 18-167

\[ L_n (\mu m) \]

\[ T_A (^\circ C) \]

Doped Oxide Source

PH₃/O₂ Source
Bulk diffusion length enhancement characteristics of solar cells fabricated from two diffusion runs, A and B. The cell samples were taken from the multiple grown ribbon, No. 16-187.
Diffusion Lengths in Solar Cells as a Function of Light Intensity in 1" Wide EFG Ribbon Grown in an Induction-Heated System Using a Quartz Crucible.

"QUARTZ" CRUCIBLE RUN #13-1047.
Technology Status:

- Area Throughput Rate Goal Exceeded (27 cm²/min)
- Solar Cell Conversion Efficiency Goal Exceeded (15.5%)
- Process Acceptance of Solar Grade (Battelle) Polysilicon Demonstrated
- Melt Replenished Growth Demonstrated (5 hrs)

Development Underway:

- Long Term Melt Replenishment (1 to 3 Days)
Simplified Sketch of Melt Replenishment System

- Pellet Reservoir and Mechanism for Dropping Pellets into Melt
- Growth Chamber Envelope
- Pellet Feed Tube
- Susceptor Lid and Shields
- Induction Heating Work Coil
- Susceptor
- Growth Compartment of Melt and Crucible
- Melt Replenishment Compartment of Melt and Crucible
Susceptor System

Showing Location of Vertically Adjustable Heat Shield, Melt Temperature Profile Measurement and Thermocouple Probe Holes

Susceptor With Adjustable Thermal Shield
Optical Pyrometer Mounted on Web Furnace
Schematic of Melt Level Sensor

Susceptor for Melt Level Sensing
Top of Web Furnace Showing Laser and Detector

SILICON WEB
Status of Hardware Modifications for Long-Term Melt Replenished Growth

Thermal Trimming
- Adjustable Shield System Built and Installed
- Characterization Near Completion

Melt Level Sensing
- Laser Sensor System Built and Installed
- Optical Alignment of Components Completed
Webqual 20: Data Summary

$A = 1.039 \text{ cm}^2$, AM1 $= 91.6 \text{ mW/cm}^2$

<table>
<thead>
<tr>
<th>CRYSTAL</th>
<th>NO. CELLS</th>
<th>$I_{SC}$ mA</th>
<th>$V_{OC}$ V</th>
<th>FF</th>
<th>$R_0$</th>
<th>$\eta_{AR}$</th>
<th>$\eta_{ODC}$</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE13-3.2</td>
<td>4</td>
<td>22.18</td>
<td>.548</td>
<td>.737</td>
<td>9.47</td>
<td>13.5</td>
<td>11.4</td>
<td>STD.</td>
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<td>RE102-2.2</td>
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<td>20.18</td>
<td>.520</td>
<td>.734</td>
<td>9.15</td>
<td>11.7</td>
<td>3.8</td>
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</tr>
<tr>
<td>J131-2.2</td>
<td>4</td>
<td>20.90</td>
<td>.537</td>
<td>.746</td>
<td>8.80</td>
<td>12.7</td>
<td>6.3</td>
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<td>J131-3.4</td>
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<td>20.40</td>
<td>.513</td>
<td>.733</td>
<td>9.73</td>
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<td>21.70</td>
<td>.526</td>
<td>.749</td>
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<tr>
<td>M141-1.2</td>
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<td>21.90</td>
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<td>.738</td>
<td>9.73</td>
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<tr>
<td>M151-1.2</td>
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<td>22.18</td>
<td>.543</td>
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<td>9.55</td>
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<td>.722</td>
<td>9.62</td>
<td>12.8</td>
<td>7.5</td>
<td>FEED EXPT.</td>
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<td>9.79</td>
<td>12.6</td>
<td>5.4</td>
<td>FEED EXPT.</td>
</tr>
</tbody>
</table>

Web Grown from Battelle Silicon

Polysilicon Characteristics
Battelle Lot 33645-38-97 (Supplied by JPL)
Pretreated 6 hrs at 1290°C in Argon to Emit Zn

Web Growth Behavior
Same as Observed for Semiconductor Grade Silicon

Solar Cell Characteristics
Cell Efficiency: Uncoated Ave. 9.0 ± 0.2% ($\eta_{AR} \approx 12.8\%$ est.)
Range Uncoated 8.6 to 9.2% ($\eta_{AR} \approx 12.3\%$ to 13.2% est.)

Test Conditions: $n^+pp^+$ Cell, 91.6 mW/cm$^2$ Illumination

Preliminary Comparison of Cells Fabricated From Silicon
Web Grown at Various Throughput Rates

<table>
<thead>
<tr>
<th>Wafer Identity</th>
<th>Conversion Efficiency* (AM1)</th>
<th>Uncoated</th>
<th>AR Coated (Est.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZ Baseline</td>
<td>8.5</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>Si Web @ 4 cm$^2$/min</td>
<td>9.2</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Si Web @ 15 cm$^2$/min</td>
<td>8.0</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>Si Web @ 25 cm$^2$/min</td>
<td>9.0</td>
<td>12.9</td>
<td></td>
</tr>
</tbody>
</table>

*Average of Several Cells Fabricated in a Single Run
Summary

- Area Throughput Goal Exceeded
- Solar Cell Conversion Efficiency Goal Exceeded
- Solar Grade Polysilicon Acceptable
- Melt Replenished Growth Demonstrated With Good Cell Efficiency
- Preliminary Data Show Good Cell Efficiency With High Throughput Rate Web
- Hardware Modifications for Long Term Melt Replenished Growth Completed—Characterization and Operation Begun.
LOW-ANGLE SHEET GROWTH

ENERGY MATERIALS CORP.

Schematic of Horizontal Ribbon Growth

Schematic of Low-Angle Ribbon Growth
LEADING EDGE GROWTH ZONE
GROWTH RATE - UP TO 60 CM/MIN
GROWTH DIRECTION - HORIZONTAL ON MELT SURFACE
HEAT LOSS - VERTICAL RADIATION & CONVECTION

MAIN CRYSTAL GROWTH ZONE
GROWTH RATE 10 CM/HR
GROWTH DIRECTION - DOWN
HEAT LOSS - UP RADIATION & CONVECTION
Comparison of Horizontal and Low-Angle Si Sheet Growth (Longitudinal Sections)

Horizontal Growth - Schematic Diagram

- Silicon Ribbon
- Convective Stirring
- Overgrowth
- Silicon Melt

Low Angle Silicon Sheet Growth - Schematic Diagram

- Shallow Trough - No Convection
- Raised Meniscus
- Silicon Ribbon
- Pull Direction
- Hot
- Advancing Edge Stabilizer
- Thermal Impedance
- Scraper
Results to Date

LOW ANGLE GROWTH OF SILICON RIBBON FROM FUSED SILICA TROUGHS

LENGTH - Several ribbons have been grown which were limited by the stroke of the puller - about 66 cm. Maximum pulled was 71 cm.

GROWTH SPEED - Typically 20 to 30 cm/min but speeds up to 60 cm/min are easily achieved.

WIDTH - Typically 1.5 cm

THICKNESS - Typically .06 cm ranging from .03 cm to .12 cm

QUALITY - The leading edge is producing a dendritic top surface, resulting in large grained polycrystalline structure. Efforts to grow single crystal material are waiting for melt level control and continuous pulling.

There has been no attempt to grow clean material or to evaluate the semiconductor characteristics.

EMC 11/28/79
SILICON-ON-CERAMIC PROCESS

HONEYWELL CORP.

1979 Program Objectives

- Demonstrate growth speeds of 0.3 cm/sec
  produce material at 0.2 cm/sec for cell fabrication

- Demonstrate 11% conversion efficiency on 10 cm^2 cells

- Demonstrate continuous coating of large-area substrates
  (Honeywell funded from 2/79 - 12/79)

- Determine relative importance of impurities vs. structure on SOC cell performance.

[Diagram of the silicon-on-ceramic process]

AFTER HEATER
COOLING SHOE

SUBSTRATE
CRUCIBLE
CRUCIBLE HOLDER
HEATER
HEAT SHIELD

LIQUID SOLID INTERFACE
SILICON MELT

20°

GAS FLOW
Meniscus Shape at Various Coating Angles

- **Liq-Solid Interface**
- **Fused Silica Trough**
- **Substrate Travel**

- **Optimum Melt Temp?**

Legend:
- **O** NO GAS
- **x** ARGON
- **△** HELIUM

Graph:
- **Silicon Thickness (Å)**
- **Growth Speed (cm/sec)**

Data from Monthly Zook, Grung
SLOTTED SOG CELL
(SC, 141-3-891)
(9/30/71)
- TOTAL AREA: 4.89 cm²
- METAL COVERAGE: 10%

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<td>EFF.</td>
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CURRENT (mA) vs. VOLTAGE (V)
GROWTH SPEED (cm/sec)

- Silicon thickness (um)
- Open-circuit voltage (V)
- Fill factor
- Active-area short-circuit current density (A/cm²)
- Conversion efficiency (%)

\( y^2.91_t = 0.0586 \)
Figure 8. Performance of Slotted SOC Cells as a Function of Base Doping Concentration, for Cells with AR Coating.
\[ I = I_0 \left[ \frac{e^{\frac{V - I R_n}{A T}}}{e^{\frac{V - I R_n}{A T}} - 1} \right] - I_{0n} \left[ \frac{e^{\frac{V - I R_n}{A T}}}{e^{\frac{V - I R_n}{A T}} - 1} \right] - \frac{V - I R_n}{R_{th}} + I_{sc} \]

**Graph:**

- FF = 0.88
- FF = 0.78
- FF = 0.75

**Parameters:**

- \( R_{th} = 10 \, \text{K ohms} \)
- \( n = 2 \)
- \( R_s = 1 \, \text{ohm cm}^2 \)
- \( J_{sc} = 1 \, \text{mA cm}^{-2} \)
- \( A = 1.25 \times 10^{-2} \, \text{cm}^2 \)
- \( A = 5 \, \text{cm}^2 \)

**Axes:**

- Current (mA)
- Voltage (V)
Comparison of Diffusion Lengths Before & After Cell Fabrication

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<th>CELL NO.</th>
<th>BEFORE PROCESSING</th>
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<td>INTEGRATED SCAN (µm)</td>
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## Summary

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<td>0.2-0.3 cm/sec growth speed</td>
<td>200 μm thick at 0.2 cm/sec with helium cooling</td>
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<tr>
<td>11% cell efficiency</td>
<td>9.91% on 10 cm² cell</td>
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<tr>
<td></td>
<td>10.04% on n cm² cells</td>
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<tr>
<td>Continuous coating</td>
<td>SCIM principle demonstrated</td>
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<td>new coater design complete</td>
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<td>- construction underway</td>
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During the reporting period, the Quantimet 720 Image Analyzer (QTM 720) was upgraded to enhance its capability for the automated defect analysis of silicon sheet samples. Also, during this period sixty silicon samples were analyzed using the upgraded QTM 720 System.

The previous QTM 720 System made use of a Hewlett-Packard Model 9810 Programmable Calculator interfaced to the system by means of a special QTM module, the Field Data Interface. The data was printed on a conventional teletype. In the present configuration, the H-P 9810 Calculator has been replaced by a PDP-11/03 Computer and the teletype replaced with a Digital Equipment Corporation Deckwriter III high speed printer. A dual floppy disk drive has also been added to the QTM 720 System. These new additions have substantially improved the data acquisition and analysis capability of the QTM, as well as increasing the speed with which the silicon samples may be analyzed.

A computer program was written for the PDP 11/03 computer to provide for software control of many of the QTM functions and automated analysis of silicon samples.

After chemical polishing and etching, sixty silicon sheet samples were analyzed for twin boundaries and dislocation pits on the upgraded QTM 720 System. Thirtytwo of these samples were manufactured by Motorola, twentyseven by Mobil-Tyco, and one by Tylan. The twin boundary and dislocation pit densities for these samples are listed as computer printouts in the technical reports: MRI - 272, - 273, and - 274. Grainboundary length measurements were made on these samples by optical microscopy technique. These data and a preliminary analysis of data are also included in the aforementioned reports. All samples have been returned to JPL for solar-cell fabrication. Conversion efficiencies will be measured on these samples and attempt will be made to correlate efficiencies with defect densities in these samples.
EFFECTS OF VARYING PARTIAL PRESSURES OF REACTANT GASES

UNIVERSITY OF MISSOURI ROLLA
Figure 1. With alumina end cap.

Figure 3. End flange.

Figure 4. Copper tubing permits water flow to cool o-rings in thoria tube assembly.
Figure 5. Furnace leads are taken through ports at end opposite thoria tube assembly.

Figure 6. Thoria 7 wt% yttria tube and assembly. Note platinum wire-paste leads (painted along a helix) and alumina heat shield.
Figure 7. Thoria tube assembly in place. Small alumina tube exhausts reference gas and brings out central platinum wire lead.

Figure 8. View of completed O₂ cell.
Figure 9. View of completed O₂ cell.

Figure 1. Silicon on fused silica at about 1400°, in CO/CO₂ buffer at P₀₂ = 10⁻¹⁴ atm. Silica has already become deformed, indicative of devitrification (t=0).
Figure 2. Silicon begins reacting (presumably with oxygen content of CO/CO₂ buffer gas) to produce a mist of particles (t=16 minutes).

Figure 3. Silicon reaction continues. Silicon surface becomes pitted (t=22 minutes).
Figure 4. Well above silicon melting point (about \(1430^\circ\)C). Silicon surface shows pronounced pitting and build-up of oxides has begun. Tendrils of particulates being carried in the buffer gas can be seen by the furnace wall (t=53 minutes).

Figure 5. Much build-up of oxide on surfaces of silicon and fused silica. Particulates in gas stream still visible (t=90 minutes).
Figure 6. Silicon reaction has terminated (t=105 minutes).

Figure 7. Side view of sample after annealing.
Figure 8. Top view of sample after annealing.

Figure 9. Bottom view of sample after annealing.
Figure 10. Bottom view of sample, together with white powdery deposit and Dee tube showing glaze.

Figure 11. Fused silica in air at 1430° in situ. No warping observable.
Figure 12. Fused silica after annealing in air at 1430°C for 1 hour. Surface devitrification only.

Figure 13. "Before" and "After" annealing fused silica at 1430°C for 1 hour.
Figure 14. Fused silica in helium at $1430^\circ C$ in situ. No warping observable.

Figure 15. Fused silica after annealing in helium for one hour at $1430^\circ C$. 


COMPARISON OF \( P_{O_2} \) MEASUREMENTS OVER MOLTEN SILICON BETWEEN EQUILIBRATED SESSILE DROP AND NON-EQUILIBRATED EFG RIBBON ATMOSPHERES.

**Summary**

I. **Silicon sessile drop experiments at UMR are generally carried out at oxygen partial pressures below** \( 10^{-18} \) **atm. (below the equilibrium pressure for formation of SiO\(_2\)). Oxygen partial pressure in the Mobil-Tyco silicon ribbon pulling furnace was measured by the UMR oxygen cell to be between** \( 10^{-6} \) **and** \( 10^{-8} \) **atm., yet no gross oxidation of the silicon is observed.**

II. **As an illustration of what occurs under equilibrium conditions above** \( 10^{-18} \) **atm., a silicon sessile drop experiment was performed at** \( P_{O_2} \) **of** \( 1.5 \times 10^{-12} \) **atm. using a CO/CO\(_2\) buffer gas. The extreme reaction with the silicon was documented.**

III. **It was concluded that the atmosphere in the Mobil-Tyco furnace was not in equilibrium with the molten silicon, and that the high oxygen content was due to the high amounts of oxygen in the argon purge gas and to air leakage into the furnace.**

IV. **Devitrification of fused silica observed in all experiments in the sessile drop furnace increased at lower** \( P_{O_2} \)'s. **The slow heating rates characteristic of this furnace preclude obtaining meaningful contact angle data on fused silica.**

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**EVALUATION OF LAS MATERIAL**

**CORNELL UNIVERSITY**

D. Ast

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<th>Techniques</th>
<th>Structural:</th>
<th>Chemical:</th>
<th>Electrical:</th>
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<td>1) Optical Microscopy + Etching</td>
<td>1) SIMS</td>
<td>1) Photovoltaic scanning</td>
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<td>2) X-ray, all conventional techniques + synchrotron radiation</td>
<td>2) Neutron Activation</td>
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<td>3) SEM</td>
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<td>5) TEM a) Conventional b) High resolution c) High voltage</td>
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Available Fall 80: Ion back sputtering (J. Mayer)

**Materials analyzed so far**

- EFG: Mobil Tyco
- Large grain EFG: Mobil Tyco
- RTR: Motorola

(In addition non JPL sponsored fundamental research on grain boundaries (see Phil. Mag. A, 40 (1979) 589)).
A) EFG, regular and large grain.

Predominant defects: Coherent twins
High resolution shows that optical twin boundaries consists of bundles of microtwins, some of which are only a few (say 4) (111) planes thick.

Less frequent: Incoherent twins on (112) planes
High angle grain boundaries.

No visible precipitates in either regular or large grain EFG. Incoherent twins show translations both parallel and perpendicular to boundary plane, possibly due to local incorporation of carbon. Coherent twins may be electrically unactive, partially active in sections only, or fully active. Possible reasons include: a) Termination of microtwins, b) Interactions with lattice dislocations, c) Twin boundary dislocations, d) Impurities. Passivation with atomic hydrogen tentatively indicates that most (but not all) electrical activity is impurity controlled.

B) RTR

Surface orientations: 110, 113, 135, 012, 001

Essentially twin boundaries perpendicular to surface. Twinned regions vary in size from long microtwins only a few (111) planes thick to large twinned areas. High density (1...1.2x10^{13}/cm^3) small precipitates, platelet shape, habit plane generally 100 with edges parallel to 110, typical dimensions 50...100 Å. So far indications for amorphous structure (diffraction, high resolution). Tentatively: Si-nitrides, possibly associated with heavy metals. In addition, low density of nondecorated stacking faults, frequently located close to twin boundaries, of average size of \sim 1.5 \mu m.
Since the last PIM, further evaluation has proceeded on
- EFG Ribbon (RH Process) - Mobil-Tyco
- Dendritic Web - Westinghouse
- Continuous Czochralski - Hamco

The photovoltaic performance after standard processing, and the other measured properties, agreed with earlier tests on these materials, and continued to show good internal consistency.

We have extended efforts to increase cell efficiency by using advanced processing with various sheet materials. Process modifications were chosen to offset material limitations identified after standard processing. The advanced processing led to significant increase in output for the ribbon-forms, from the measured properties of the continuous Czochralski slices we can predict advanced process performance approaching that of conventional Czochralski silicon.

We have begun to increase $\frac{A_{\text{H}}}{A_{\text{MD}}}$ ratios for various sheets. We are also investigating unexpected problems for low resistivity (2 ohm cm) Czochralski silicon when processed with the aluminum paste BSF method. Severe shunting with decreased cell output was observed. We are studying the effects of background impurities, orientation and deposition of aluminum on the front surface, even through protective masks. Preliminary SIMS analysis showed Al penetration at the front surface. The analysis also confirmed the Al depth profile on the back surface.
Efficiency & $I_{sc}$ Density vs Minority Carrier Diffusion Length of Unconventional Si Sheets

![Graph showing Efficiency and Short Circuit Current Density vs Minority Carrier Diffusion Length](image-url)
Average AMO Efficiency of Cells
From Various Sheet Silicon

- ○ BASELINE PROCESS
- △ BSF PROCESS
- □ SHALLOW JUNCTION PROCESS
- X BEST STATE-OF-THE-ART PROCESS
Processed Data: Depth Profile

SLOW SPUTTERING #2 CLEAN AREA

- 31 (P)
- 14 (Si)
- 27 (A1)
- 11 (B)

SPUTTERING TIME (sec)
General Comments

Overall, the work so far has shown good correlation between standard-processed cell performance and the diffusion length, and good agreement for separate samples of various sheets. Also, all the backup measurements (dark diode characteristics, spectral response, fine light spot scanning) confirmed the PV results.

The array of measurements used was chosen to verify the PV results, and to increase the confidence level of the sheet suppliers. These confidence levels are now well established, and it has been stimulating to observe first-hand the technical progress achieved for all the sheet forms. The evaluation groups have tried to explore the best potential for all sheets, and to identify possible areas for improvement, in terms of controllable sheet properties.

JPL has extended the evaluation programs in two directions to reduce the dollar-per-watt ratio. Efforts are included to increase output (without equivalent cost increase), and also lower cost processes are being tested for their applicability. Understanding of the interaction of the sheet Si properties and various cell process methods is essential to combination in a mechanized operation to meet the 1982 cost goals. (This is the last PIM for the '70's, only 3 years away from the 1982 target date).

Thus the program appears to be moving steadily towards the goals. Recently our complacency was shaken slightly, forcing re-evaluation of several factors which we had been glossing-over, and we thought discussion of these would interest this group. We realized that the management of solar cell companies in their future planning must already begin to select the most promising sheet form(s). This selection involves the sequence of licensing, technical transfer, and equipment purchase, accompanied by planning for a detailed process sequence (partly mechanized) suited to the sheet chosen. It is clear that correct selection may be critical to a company's future, because acquisition of one sheet growth and processing equipment may not ensure easy transfer to other sheets and processes should these latter prove superior.
Therefore, groups familiar with sheet evaluation are already being challenged to consolidate their experience into definite recommendations. One obvious option is to follow the current JPL "Strawman sequence. However, we thought this integration meeting would be appropriate to share a prejudiced list of some of the factors we found important.

1. **Consistency of Performance and Properties**
   For manufacturing this must be rated high. As the volume of production rises, an inconsistent process can prevent anticipated cost-reduction, and can generate large quantities of scrap. There is decreasing chance of adjusting to changing properties when operating under cost restraints. Inconsistency of ribbons can reduce advantages such as the chance of continuous processing or of regular size samples.

2. **Efficiency**
   For routine processing with reasonable costs, higher efficiency is preferable to reduce cost of handling, of support structures or land use, and to reduce the energy payback period. Any increase in process costs needed to increase efficiency must be carefully evaluated. Some enhancement methods (e.g., surface treatment, pulse heating, GB passivation, gettering, BSF, texturing) may not be applicable to all sheets. As the sheets become thinner, present technology requires an effective BSF to maintain efficiency.

3. **Adaptability to Low Cost Processing and Methods**
   a.) Squares (cast) or rectangles have ~15% advantage over round slices in arrays, for considerations like output area, land usage, support, etc., and also have some process advantages from increased packing factor. However, this must be balanced against their efficiency and by the fact that the major silicon industry will continue to develop equipment suited to round slices.
b.) Mechanical strength will be most important for cell and array formation, and in testing, and in ability to accommodate low cost contact processes such as screen printing or plating. The interaction with the contact method will be particularly important, because contacts will remain a major problem for cost and reliability, the latter essential to build-up user-confidence on large scale PV applications.

c.) Improved slicing methods will be applicable to all grown and cast Si. As the costs of starting Si, and of slicing are reduced, ribbon methods lose some of their present advantage in Si usage, and must have comparable all-round properties to remain competitive.

d.) The ready availability of low cost starting Si may not mean that all sheet methods can maintain performance already achieved (depends on the growth conditions).

e.) Support substrates for ribbons may introduce handling problems, additional weight and difficulties in reducing series resistance and in providing good heat transfer.

In conclusion, we cannot present any firm conclusions, but hope we have provided some areas worth remembering. We think that present Czochralski technology can sustain any effort required for high efficiency concentrator cells. We are sure that some novel approaches will be developed in the future, although often, business decisions must be made only on available evidence.
## SPECTROLAB

### HEM-4, Baseline, AR Film, AMO 28°C

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Spectral Response Data:
Selected Cells, Run HEM-4

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CONTROLS

#858 (8)

#859 (3)

#854 (56)

WAVELENGTH, NM
Run HEMEX-2, AR Film, AMQ 28°C

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Hemex-2

![Diagram of Hemex-2 data]
Run HAMB-2-3; Baseline Processing, AR Film, AM0 28°C

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*INDICATES POLYCRYSTALLINE MATERIAL  
**CONTROL CELL IN RUN HAVING MAXIMUM EFFICIENCY
Spectral Response Data: Continuous-Cz Cells

From Top & Middle Sections,

Crystal No. 1, Run HAMB-1

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Spectral Response Data: Continuous-Cz Cells
From Top Sections of Crystals
No. 1 Through No. 6

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[Graph showing relative response vs. wavelength (nm)]
Run HAMO-1, AR Film, AMO 28°C

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* Textured
** Polycrystalline
Spectral Response, HAMO-1

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Graph showing spectral response with markers for 5T16A, 5T16B, 6T3A, and 6T4B.
Run HAMO-2, AR Film, AM0 28°C

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Run EFGO-1, EFG(RH), AR Film, AM0 28°C

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* BACK SURFACE FIELD

I-V Data for Highest Efficiency Cells in Each Material

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* - Textured
** - BSF
Maximum conversion efficiency, AM0-28°C, for solar cells in Phase I for each material studied. Column notes processing method and gives average value for processing by that same method. ☐ - Maximum ☐ - Average

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Outline of Phase II

Goal: 12% conversion efficiency at 28°C
Continue optimization program
Utilize low-cost processes
A) Replace acid etches, where possible, with base etches.
B) Replace evaporated contacts with screen-printed contacts.
C) Replace evaporated AR coating with spray-on spin-on AR coating.
Continue Phase I measurements + AM1 I-V on percentage of cells.
Specific tabulation of breakage during processing and testing.
EFG-1, EFG(RH), AR Film, Phase II, AMO 28°C

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Breakage - Some blade breakage because of wavy surface
4 ribbon cells broken at V/I probing
2 ribbon cells broken at edge etch 35% yield (EFG)
1 control cell broken at edge etch 87.5% control yield

* Maximum ribbon cell efficiency
** Maximum control cell efficiency
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WAVELENGTH, wM
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1 CELL, (B), BROKE WHILE LOADING INTO EVAPORATION MASKS
1 CELL, (B), BROKE DURING INK AND BAKE OPERATION
3 OF STRIP RE 161-1.7, (A), BROKEN DURING SCRIBING
6 OF STRIP J203-2.6, (B), BROKEN DURING SCRIBING
A CELLS FROM STRIP RE 161-1.7 (340 um) 8 a-cm
B CELLS FROM STRIP J203-2.6 (220 um) 11.9 a-cm
WEB B-1 Phase II, AM0 25°C

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WAVELENGTH, nm

175
I-V Data for EFGO-1, Screen-Printed BSF
- And Contacts, AR Film, AM0 28°C, Phase II

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*MAXIMUM EFFICIENCY
**BASELINE PROCESSING

BREAKAGE OCCURRED ON LARGE RIBBON SECTIONS DURING SCREEN PRINTING.
ONE CONTROL CELL WAS BROKEN DURING EDGE ETCH.
OPERATIONS AREA

Large-Scale Production Task

BLOCK IV MODULE DESIGNS
AND RATIONALES

One of the parallel technology sessions on Wednesday afternoon comprised presentations by the Block IV module manufacturers on design features and rationale. These presentations were a milestone for the Project, marking the first in-depth exposition of current design practices by the Production Task contractors. In this latest step toward the simultaneous improvement of module price, performance, and reliability, the manufacturers have incorporated a number of design and production technology innovations based on their own R&D and that of other Project participants.

An Operations Area presentation on Test and Applications experience will be found on pp. 456-462 and a joint Project Analysis and Integration Area, Engineering Area and Operations Area presentation appears on pp. 354-382.

TECHNOLOGY SESSION

L. D. Runkle, Chairman

APPLIED SOLAR ENERGY CORP.

View of Completed Module
Introduction

THE OBJECTIVE OF THIS PROGRAM IS TO DESIGN, FABRICATE, ACCEPTANCE TEST, AND EVALUATE TEN (10) PRE-PRODUCTION MODULES COMPLYING WITH THE REQUIREMENTS OF JPL DOCUMENT NO. 5101-16, REVISION A, ENTITLED "BLOCK IV SOLAR CELL MODULE DESIGN AND TEST SPECIFICATION FOR INTERMEDIATE LOAD CENTER APPLICATIONS", DATED 1 NOVEMBER 1978. THE TOTAL OUTPUT OF THE TEN (10) MODULES SHALL BE IN EXCESS OF 900 WATTS OF PEAK POWER AT AM1.5 AND NOCT. IN ADDITION, ASEC IS TO PREPARE A STANDARDIZED PRICE ESTIMATE USING SAMICS FOR 10, 100, AND 1000 KILOWATTS OF SOLAR MODULES.
High-Efficiency Solar Cell

SIZE: 3.05 INCH DIAMETER
      47.137 SQ.CM.

TYPE: P-TYPE CZOCHRALSKI GROWN
      10 OHM-CM
      BORON DOPED

CONTACTS: EVAPORATED AND SINTERED
          TITANIUM-PALLADIUM-SILVER
          ALUMINUM ALLOYED BACK SURFACE
          FIELD

COATING: DUAL LAYER ANTIREFLECTIVE COATING

Cell
I-V Curve

CURRENT (AMPS)

VOLTAGE (mV)

TEST CONDITIONS: AM1 28°C
Cell Flow Chart

1. GROW INGOT
2. GRIND INGOT
3. SLICE INTO WAFERS
4. CLEAN AND CHEMICALLY POLISH WAFERS
5. DEPOSIT DIFFUSION MASK
6. DIFFUSE WAFER TO FORM JUNCTION
7. REMOVE DIFFUSION OXIDE AND MASK
8. APPLY ALUMINUM TO P-SIDE
9. ALLOY ALUMINUM TO FORM BACK SURFACE FIELD
10. CLEAN WAFERS FOR CONTACT APPLICATION
11. DEPOSIT P-CONTACT MATERIALS (AL, TI-PD-AG)
12. GENERATION OF N-CONTACT AND GRIDLINES USING PHOTORESIST TECHNIQUE
13. DEPOSIT ANTIREFLECTIVE COATING
14. SINTER CONTACTS AND AR COATING
15. INSPECT FOR MECHANICAL DEFECTS
16. TEST FOR ELECTRICAL OUTPUT

Encapsulated Assembly

- SUNADEA DEEP EMBOSSED PATTERN GLASS
- POLYVINYL BUTYRAL
- SOLDERED CELL ARRAY
- POLYVINYL BUTYRAL
- TEDLAR
Section View Through Frame and Junction Box

Soldering Machine
Cells Grouped and Stored in Box

Cell Laydown
Soldering Process

Frame Assembly

- ALUMINUM ESTRUSION - ALLOY COC3-T5
- FOUR PIECE CONSTRUCTION
- PRESS FIT MECHANICAL CORNER FASTENERS
- ANODIZED FINISH
- LIGHTWEIGHT
- STRONG
- REINFORCED MOUNTING HOLES
Assembled Frame

Junction Box
Corner Lock Brace and Spring Clips

Corner Lock Brace With Springs Installed
Frame With Corner Brace

Inserting Corner Brace
Section View of Frame

- Aluminum Extrusion
- Silicone Sealant Reservoir
- Encapsulation Assembly
- Reinforced Mounting Hole
- Receptacle for Corner Look Brace
**Module Efficiency**

*Estimated: at 46° (NOCT) and AM1.5*

Current at 15V and NOCT = 6.63 Amps

Module Efficiency at NOCT = 11.5%

Packing Factor = 76.8%

**Actual Data on First Module:**

<table>
<thead>
<tr>
<th></th>
<th>JPL FIRST TEST</th>
<th>ASEC* ( \text{SUNLIGHT} )</th>
<th>JPL SECOND TEST</th>
<th>TABLE MT.**</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATE</td>
<td>10-12-79</td>
<td>10-22-79</td>
<td>10-22-79</td>
<td>11-5-79</td>
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<tr>
<td>Temp. Corrected</td>
<td>48</td>
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</tr>
<tr>
<td>to °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{NO} ), VOLTS</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>I, AMP</td>
<td>5.35</td>
<td>5.932</td>
<td>5.44</td>
<td>5.72</td>
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<tr>
<td>( P_{NOCT} ), WATTS</td>
<td>80.3</td>
<td>89</td>
<td>81.6</td>
<td>85.8</td>
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<td>( V_{DC} ), VOLTS</td>
<td>18.4</td>
<td>18.9</td>
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<td>( I_{SC} ), AMPS</td>
<td>6.7</td>
<td>6.04</td>
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<td>( V_{MAX} ), VOLTS</td>
<td>13.5</td>
<td>15</td>
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<tr>
<td>( I_{MAX} ), AMP</td>
<td>6.3</td>
<td>5.932</td>
<td>6.21</td>
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<td>( P_{MAX} ), WATTS</td>
<td>85</td>
<td>89</td>
<td>85.7</td>
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<tr>
<td>CFF, Max</td>
<td>.08C</td>
<td>.709</td>
<td>.692</td>
<td>.712</td>
</tr>
</tbody>
</table>

* 51.6 MW/cm²

** 166 MW/cm² (Scattering)
MOTOROLA, INC.

Solar Module MSF43C
MSP43C Characteristics

- **ELECTRICAL:**
  - 33 SERIES CELLS  NOMINAL POWER @ STC:40W
    NOMINAL POWER @ SOC: 36W

- **DIMENSIONS:**
  - LENGTH: 1200 mm (47.24")
  - WIDTH: 340 mm (13.3")
  - HEIGHT: 38mm (1.5")

- **CONSTRUCTION:**
  - COVER GLASS: .125 THK TEMPERED (SOLATEX)
  - POTANT: POLYVINYL BUTRYAL (SAFLEX)
  - BACK SKIN: AL-POLYVINYL FLUORIDE (TEDLAR) LAMINANT
  - EDGE SEALANT: HOT MELT COPOLYMER
  - FRAME: 304 SS
  - J-BOX: PVC II GLASS FILLED POLYCARBONATE
  - BINDING POSTS: NICKEL PLATED STL
  - INTERCONNECT (CELL): THREE COPPER RIBBONS, CONTINUOUSLY
    BONDED ACROSS TOP AND BOTTOM OF CELLS.

- **OPERATIONAL CONDITIONS**
  - TEMPERATURE: -40C TO 60C
  - WIND: Constant velocity: 160 Km/Hr (100 MPH)
    GUST VELOCITY: 200 Km/Hr (125 MPH)

- **MECHANICAL:**
  - SNOW LOADING: 290 Kg/m² (60 PSF)
  - SHOCK: .4M (15 IN) DROP PER MIL-STD-810B
  - VIBRATION: VARIABLE FREQUENCY PER MIL-STD-310B
  - FLEXURE: ± 1/4"/ft. PER JPL 5101-16
Development Philosophy

PROJECT STATEMENT

Provide a design solution to:
- High present module mat’l and labor cost/matt
- Major industry reliability problems
- Early 1980’s user profile

STRATEGY

- Few, simple piece parts
- Few, simple assembly steps
- Increased packaging density
- Provide inherent solutions to reliability problems
- Utilize a combination of analytical & experimental approaches.

OBSTACLES

- Material properties vs. cost
- Design function vs. cost
- Interface incompatibilities
- Code requirements

CORRECTIONS

- Provide materials sheltering from harmful aspects of environment
- Search out compatible material combinations
- Provide design compromises to minimize negative effects
- Feedback test results
### Desired Manufacturing Aspects

<table>
<thead>
<tr>
<th>ASPECT</th>
<th>BENEFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMPLE PIECE PARTS</td>
<td>LOW VENDOR TOOLING COSTS</td>
</tr>
<tr>
<td></td>
<td>SHORT LEAD TIMES</td>
</tr>
<tr>
<td></td>
<td>LOW PIECE PARTS COSTS</td>
</tr>
<tr>
<td></td>
<td>MECHANIZABLE AT LOW VOLUME</td>
</tr>
<tr>
<td></td>
<td>WIDE CHOICE OF POTENTIAL VENDORS</td>
</tr>
<tr>
<td></td>
<td>EARLY SECOND SOURCING</td>
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<tr>
<td>FEW ASSEMBLY STEPS</td>
<td>LOW LABOR CONTENT</td>
</tr>
<tr>
<td></td>
<td>MINIMUM TRAINING REQUIREMENTS</td>
</tr>
<tr>
<td></td>
<td>LOW FLOOR SPACE REQUIREMENTS</td>
</tr>
<tr>
<td></td>
<td>LOW CAPITALIZATION REQUIREMENTS</td>
</tr>
<tr>
<td>MECHANIZABLE ASSEMBLY PROCESSES</td>
<td>RAPID GROWTH RATE POTENTIAL</td>
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<tr>
<td></td>
<td>HIGH EXPERIENCE CURVE SLOPES</td>
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<tr>
<td>NO SOLVENTS UTILIZED</td>
<td>REDUCED IPO COST</td>
</tr>
<tr>
<td>KNOWN MANUFACTURING TECHNOLOGIES</td>
<td>MINIMUM MANUFACTURING - TECHNICAL RISKS</td>
</tr>
</tbody>
</table>
**Desired Customer Features**

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>BENEFIT</th>
</tr>
</thead>
</table>
| HIGH PACKAGING DENSITY (80%) | MIN. D/C COST  
MIN. INSTALLATION TIME |
| HIGH RELIABILITY | LOW $/KW-HR, INSTALLED  
LOW OPERATING COST  
LOW 3P/3T  
IMMUNE TO CELL CRACKS |
| REDUNDANT MODULE CONNECTIONS |  |
| REDUNDANT CELL INTERCONNECTIONS |  |
| ACROSS-THE-CELL CONTACTS |  |
| COMBINATION OF PROVEN WEATHERABLE MATERIALS |  |
| OPTIMIZED FOR 12 VOLT SYSTEMS | MAXIMUM CHARGING CURRENT PER PURCHASED MATT FOR 12 VOLT SYSTEMS  
LOW OPERATING COST |
| 33 SERIES CELLS |  |
| LOW CELL TEMPERATURE |  |
| MAINTENANCE FREE CONSTRUCTION |  |
| TEMPERED GLASS |  |
| 304 ss |  |
| MEETS/EXCEEDS APPLICABLE CODES & STANDARDS | SAFETY  
DESIGN INTEGRITY  
INTERCHANGABILITY |
| NATIONAL ELECTRICAL CODE |  |
| JPL BK IV SPEC. 5101-16 |  |
I-V Curve

39 WATTS (STC)

36W @ NOCT, 15V

MSP43C

.8 OHMS SERIES RESISTANCE
PHOTOWATT INTERNATIONAL, INC.

Sang S. Rhee

Agenda

1. DESCRIPTION OF PRE-PRODUCTION MODULE
   1.1 PHYSICAL DATA
   1.2 ELECTRICAL DATA
   1.3 THERMAL & ENVIRONMENTAL DATA

2. DESIGN RATIONAL
   2.1 ELECTRIC PERFORMANCE
   2.2 ELECTRICAL DESIGN
   2.3 MECHANICAL DESIGN
   2.4 ENVIRONMENTAL DESIGN
   2.5 COST CONSIDERATION

3. DESIGN INNOVATIONS AND ADVANTAGES

Physical Data

(1) MODULE DIMENSIONS & RELATED DATA

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>LENGTH</td>
<td>1198 MM</td>
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<tr>
<td>WIDTH</td>
<td>395.5 MM</td>
</tr>
<tr>
<td>HEIGHT</td>
<td>63.5 MM</td>
</tr>
<tr>
<td>AREA</td>
<td>4737.3 CM²</td>
</tr>
<tr>
<td>PACKING EFFICIENCY</td>
<td>80.7%</td>
</tr>
</tbody>
</table>

(2) MODULE ENCAPSULATIONS

GLASS/PVB/CELL/PVB/MYLAR

(3) CELL INTER-CONNECTIONS

8 CELL IN SERIES — A SUBSTRING
3 SUBSTRINGS IN PARALLEL — A SUBSTRING ASSEMBLY
5 SUBSTRING ASSEMBLY IN SERIES — A MODULE STRING
TOTAL 120 CELLS
(4) **CELL SIZE & SHAPE**
A HALF HEXAGONAL CELL
CELL AREA = 31.86 cm²
POINT-TO-POINT DIA. = 99 mm

(5) **CELL CONFIGURATION**
N⁺ - P - P⁺ TYPE CELL
NICKEL / SOLDER METALLIZATION
"RAIL ROAD TRACK" PATTERN

(6) **ELECTRIC TERMINATIONS**
A PAIR OF TERMINALS AT EACH END.
A GROUND CONNECTION STUD AT EACH END.
A BUILT-IN BY-PASS DIODE.
BLOCKING DIODE AS AN OPTION.
"QUICK-CONNECT" CONNECTORS.

**Module Configurations**
Cell Interconnect Diagram

SUNDEX TEMPERED GLASS
0.125 IN. (3.28MM) THK.

PVB FILM. 15 MILS (0.38MM) THK.
BOTH SIDES OF CELLS

CELL INTERCONNECT RIBBON WIRE
0.16 IN. WIDE. 0.004 IN. THK.

POLYESTER FILM 5 MILS THK.

TYPICAL HALF HEXAGONAL CELL
Electrical & Related Data

(A) CELL ELECTRICAL PERFORMANCE AT OTC = 28°C

- $V_P = 0.42$ V
- $I_{sc} = 1.05$ A
- $I_P = 0.90$ A
- $V_{oc} = 0.535$ V
- $P_P = 0.378$ W
- $F_F = 0.673$
- $Y\text{ CELL} = 11.86$
- $\Delta P/P = \pm 8\%$

(b) CELL TEMPERATURE COEFFICIENTS

- $\Delta V/\Delta T = -2.55$ mV / CELL /°C
- $\Delta I/\Delta T = 0.382$ mA / CELL /°C

* BASED ON REF. CELL NO. V8-417 & V8-419
(c) MODULE ELECTRICAL PERFORMANCES

<table>
<thead>
<tr>
<th>AT OTC = 28°C, PEAK POWER POINT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>43.09W</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>9.10%</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>16.8V</td>
</tr>
<tr>
<td>CURRENT</td>
<td>2.57A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AT NOCT = 45°C, PEAK POWER POINT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>38.92W</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>8.21%</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>15.07V</td>
</tr>
<tr>
<td>CURRENT</td>
<td>2.58A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AT SOC, (NOCT = 45°C, V = 15 Volt)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>37.90W</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>8.00%</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>15V</td>
</tr>
<tr>
<td>CURRENT</td>
<td>2.53A</td>
</tr>
</tbody>
</table>

* TRANSMISSION LOSS OF SUPERFACCE = 5%. MODULE PACKING EFFICIENCY = 80.7%
Cell Electrical Performance

AT OTC = 28°C, SAMPLE SIZE = 15 CELLS
Environmental Data

NO ENVIRONMENTAL TEST HAS BEEN PERFORMED AT PRESENT TIME.

FOLLOWING TESTS ARE TO BE PERFORMED:

- NOCT MEASUREMENT AT STE
- WIND LOAD TEST AT PHOTO M & T
- TWIST TEST
- THERMAL LOAD AT OUTS. C. LAB.
- HUMIDITY LOAD
- HAIL STORM TEST AT JPL

*TEST WILL CONDUCT ACCORDING TO THE SPECIFICATIONS IN JPL DOC. NO. 5101-16A.

Electrical Performance

1. AVERAGE OUTPUT POWER AT SOC

   More than ten modules will be tested to determine the rated average power output. The expected average power output is estimated to be 58 watts.

2. MINIMUM MODULE POWER OUTPUT AT SOC

   90% of average module power output will be used for acceptable minimum module power. Predicted minimum power is 54 watts.

3. NOMINAL OPERATING VOLTAGE

   Nominal operating voltage is 1.5 VDC. The predicted peak power voltage at NOCT of 45°C is 15.07 VDC.

4. NOCT UNDER STANDARD THERMAL ENVIRONMENT (STE)

   Prediction of NOCT at STE is 45°C.
Electrical Design Requirements

(1) ELECTRIC VOLTAGE ISOLATION

The insulation for each component is designed to meet 500 VDC system voltage, and will withstand 2000 VDC.

(2) ELECTRICAL GROUNDING

The entire module is laminated with non-conductive materials, excluding the aluminum frame. Therefore, only the aluminum frame requires safety grounding studs. This is provided at the center of both ends of the aluminum frame.

(3) MODULE ELECTRIC INTERFACE

Two parts of terminal blocks are used for redundant terminations of module output. These terminals are also used for the by-pass diode (shunt diode). The designed rates of these terminal blocks are 5 AMP and 750 VDC.

(4) CELL STRING CIRCUIT RELIABILITY

All cells are interconnected by two ribbon wires to improve reliability. 8 cells are connected in series. Three of these string assemblies are connected in parallel to improve redundancy. An integral by-pass diode will be provided at the terminal block to improve the array reliability.

Mechanical Design Requirements

(1) MODULE GEOMETRY

A. Maximum envelope dimensions all satisfy design specifications.
B. Polarity of output terminals are clearly marked.
C. Mounting hole spacings and clearances satisfy design specifications.
D. Constrain of view angle is less than 30 degrees from illumination surface.
E. Maximum weight is 13 lbs.

(2) INTER-CHANGEABILITY

Dimensions and tolerances are chosen so that no problem will occur in view of module inter-changeability.

(3) OPTICAL SURFACE SOILING

Tempered glass is used as a superstrate. No soiling problem is expected due to self-cleaning by wind and rain.

(4) MODULE LABELING OF MANUFACTURER'S I.D.

The following information is provided on the manufacturer's label:

- Model No.: 10-20-1949
- Serial No.: XXXX
- Date of Mfg.: XX-XX
- Max. System Voltage: 500 VDC
- Nominal Voltage: 15 VDC
- Nominal Power: 38W
Environmental Design Requirements

(1) THERMAL LOAD

The thermal load design is -40°C to 90°C. The critical areas which must be considered due to this thermal load are as follows:

A. BETWEEN GLASS AND CELL

The thermal coefficient of glass is three times larger than the thermal coefficient of the silicon solar cell. The thermal expansion due to this thermal coefficient mismatch can be absorbed if the PVB film thickness is larger than 15 mils for 4 in. silicon solar cell.

B. BETWEEN GLASS AND ALUMINUM FRAME

The thermal coefficient of aluminum is two and one-half times larger than the thermal coefficient of glass. This mismatch of thermal expansion can be absorbed if the bearing strip at the edge sealing has a thickness of 00 mils or more. The required mismatch displacement at each edge is 20 mils.

C. ALUMINUM FRAME AND STEEL ARRAY MOUNTING FRAME

The thermal mismatch and module tolerances should be accounted for in the mounting hole design. The minimum tolerance of the hole and bolt must be larger than 0.5 mm to absorb this mismatch thermal expansion and module tolerances.

(2) HUMIDITY

Module should withstand 95% RH; for a prolonged time period

A. The entire aluminum frame is made of corrosion resistant 6063-T6 aluminum, and it is anodized. All bolts and nuts are made of stainless steel.

B. The edge of the laminated module is sealed with silicon rubber gasket and the back side is protected by polyester film.

(3) MECHANICAL CYCLIC LOAD (WIND LOAD)

A. Design requirement is 50 lbs/sq.ft. load for 1000 cycles.

B. Prediction of glass stress is 4059 PSI which is less than the allowable stress of 8100 PSI.

C. Maximum deflection of glass is 0.156 in. which is satisfactory.

D. Critical stress of aluminum frame is calculated to be 3228 PSI which is less than allowable stress of 25000 PSI.

E. Maximum deflection of aluminum frame is 0.06 in.

(4) TWIST TEST REQUIREMENT

No theoretical prediction has been made. The critical area will be the corner joint and cells.

(5) HAIL IMPACT TEST

According to JPL Dec. 9101-47, the predicted limit of hail size will be 1.25 in. diameter.

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Cost Considerations

In order to reduce the module cost to meet LSA 1PEG goal of $4/watt in 1975 dollars, the following improvements have been made.

1) Increase of packing efficiency from 67% to 80.7%

Trade-off cost calculation shows that the module cost will remain the same.

2) New encapsulation method

Replacement of expensive RTV and aluminum extrusion with glass superstrate module reduces the cost significantly.

3) Change to lower cost solar cell fabrication processes

A. POCL3 diffusion is replaced by spray on dopant junction formation.
B. Aluminum back surface is replaced by spray on back surface field.
C. Spray-on AR coating is used instead of the silicon monoxide evaporation process.

The initial Sarics analysis shows the pre-production module will achieve the LSA 1PEG goal.

Cost Summary, Type A Module, 1980 Price in 1975 $/Wp

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>ELEMENT COST</th>
<th>SUB-TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Wafer price (1980 1pg goal)</td>
<td></td>
<td>1.43</td>
</tr>
<tr>
<td>2) Cell process cost</td>
<td></td>
<td>0.91</td>
</tr>
<tr>
<td>A. Surface texturizing</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>B. Junction formation</td>
<td>0.055</td>
<td></td>
</tr>
<tr>
<td>C. Metallization</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td>D. Laser scribing</td>
<td>0.280</td>
<td></td>
</tr>
<tr>
<td>E. Solder dipping</td>
<td>0.140</td>
<td></td>
</tr>
<tr>
<td>F. Anti-reflective coating</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>G. Cell test</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>3) Module encapsulant material</td>
<td></td>
<td>0.345</td>
</tr>
<tr>
<td>A. Glass (0.125 in. thick)</td>
<td>0.095</td>
<td></td>
</tr>
<tr>
<td>B. P.V.B. film (two 15 mils)</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>C. Mylar film type A (5-mil)</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>D. Other frame, seal 2 terminals</td>
<td>0.175</td>
<td></td>
</tr>
<tr>
<td>4) Module assembly</td>
<td></td>
<td>0.81</td>
</tr>
<tr>
<td>Grand total</td>
<td></td>
<td>$3.495/watt</td>
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</table>
Fractional cost increment of silicon with minimum cost line and cost savings of an optimized modified hexagonal solar cell module.
Design Innovations and Advantages

(1) HIGHER MODULE EFFICIENCY

- IMPROVED PACKING EFFICIENCY FROM 67% TO 80%.
- USE OF TEXTURIZING PROCESS.
- NEW AR COATING.
- ADDING BACK SURFACE FIELD

(2) LOWER COST MATERIALS AND PROCESS METHOD

- LOWER COST ENCAPSULATION MATERIAL
- LOWER COST SOLAR CELL PROCESSING METHODS
- HIGHER PACKING EFFICIENCY
- IMPROVEMENT OF MODULE EFFICIENCY

(3) IMPROVED ELECTRICAL PERFORMANCE RELIABILITY

- REDUNDANT CELL CONNECTION: TWO WIRE INTER-CONN.
- REDUNDANT STRING CONNECTION: THREE PARALLEL STRINGS
- REDUNDANT TERMINAL OUTPUT: TWO PAIRS OF TERMINAL BLOCKS

(4) OTHER IMPROVEMENTS

- BETTER WEATHERABILITY: RELIABLE EDGE SEALING
- LIGHT WEIGHT: REDUCED FROM 4.2 LBS/SQ.FT. TO 2.4 LBS/SQ.FT.
- REDUCED SOILING: SELF CLEANING GLASS TOP
- SAFE UNDER HAIL STORM: TEMPERED GLASS SUPERSTRATE.
Module Design Considerations

- Match thermal expansion coefficients (cells & encapsulant package)
- Maximize optical transmission to cells
- Choose materials least subject to attack by environment
- Choose materials & construction techniques consistent with automation
- Emphasize reliability over cost but
- Choose low cost materials to achieve performance goals
- Test individual components and prototype assemblies to determine failure mechanisms & their likelihood
- Conceive of module as part of an array, not stand alone item
Subsystem Design Tradeoffs

- SUBSTRATE
- SUPERSTRATE
- OTHER

- STRUCTURAL
- MECHANICAL
- STRENGTH
- MANUFACTURABILITY
- PACKING FACTOR
- WEATHERABLE

- SUPERSTRATE
- SILICONE RUBBER
- PVB
- EVA
- OTHERS

- ENCAPSULATION
- LOW MODULUS
- $/LB.
- PROCESSABLE
- OPTICAL QUALITY
- CHEMICAL STABILITY

- POWER GENERATION
- CIRCULAR CELLS
- RECTANGULAR
- RECTANGULAR SHINGLED
- RECTANGULAR WRAP A.

- POWER GENERATION
- MA/cm² - CELL
- Wb/kft² - MOD.
- AMENABLE TO AUTOMATION

Primary Module Design

- SUBSTRATE SUBSYSTEM
- SOLAR CELL SUBSYSTEM
- ENCAPSULATION SUBSYSTEM
**SUBSYSTEM**

<table>
<thead>
<tr>
<th>PARTS</th>
<th>PRIMARY FUNCTION</th>
</tr>
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<tbody>
<tr>
<td>SUBSTRATE LOW CARBON STEEL</td>
<td>STRUCTURAL</td>
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<tr>
<td>2 COAT PORCELAIN ENAMEL (BLACK)</td>
<td></td>
</tr>
<tr>
<td>SOLAR CELL</td>
<td>POWER</td>
</tr>
<tr>
<td>SINGLE CRYSTAL SILICON</td>
<td>GENERATOR</td>
</tr>
<tr>
<td>5CUB,125 MESH INTER.</td>
<td></td>
</tr>
<tr>
<td>BRASS TERMINALS</td>
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<tr>
<td>HT. NYLON INSULATORS</td>
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</tr>
<tr>
<td>ENCAPSULATION</td>
<td>CELL STRING PROTECTION</td>
</tr>
<tr>
<td>5 MIL ACRYLIC TOP FILM</td>
<td>&amp; OPTICAL</td>
</tr>
<tr>
<td>.054&quot; EVA (CLEAR)</td>
<td></td>
</tr>
<tr>
<td>.005&quot; FIBER GLASS SCRIM</td>
<td></td>
</tr>
</tbody>
</table>

**Substrate Subsystem**

**MATERIALS**

- .042" C.R. LOW CARBON STEEL PAN, RIBS & GUSSETS
- .072" C.R. LOW CARBON STEEL STIFFENERS
- .687" DIA, C.R. LOW CARBON STEEL MOUNTING LUGS
- .010" THICK ACID RESISTANT PORCELAIN ENAMEL COATING PER SIDE

**CONSTRUCTION**

- STAMPED & FORMED RIBS, GUSSETS & STIFFENERS
- SPOT WELDED TO PAN
- STAMPED OR DRAWN PAN
- STUD WELDED TERMINAL LUGS
- DIPPED & FIRED PORCELAIN ENAMEL (2 COATS)

**STRUCTURAL DATA**

- DEFLECTION: .105" @ 50 PSF
- FATIGUE STRENGTH: STIFFENERS & LUGS STRESSED BELOW ENDURANCE LIMIT
- BUCKLING: STIFFENERS WILL WITHSTAND ≥ 120 PSF MOUNTING LUG TORSIONAL STRENGTH: 35 FT-LBS ASSEMBLED
- THERMAL EMISSIVITY: .92 @ 72°F

210
Solar Cell Subsystem

MATERIALS
- Wraparound contact cells (288)
- 5Cu8.125 expanded mesh solder plated 4" wide
- 3/4" dia x 1 1/8" lg brass terminals (4)
- Ht. nylon insulators (4)

CONSTRUCTION
- 36 cells in series x 8 rows parallel
- Solder reflow of mesh to rear of cells
- Mesh placed across 8 rows
- Terminals soldered to last row of mesh on either end of string

ORIGINAL PAGE IS OF POOR QUALITY
Encapsulation Subsystem

MATERIALS

- .005" ACRYLIC TOP SHEET
- .05" FIBERGLASS SCRIM
- .054 EVA

CONSTRUCTION

1 LAYER OF .018 THICK EVA
1 LAYER OF .005 THICK FIBERGLASS SCRIM
2 LAYERS OF .018 THICK EVA
1 LAYER OF .005 THICK ACRYLIC TOP SHEET

DEARATION OF ENTIRE SYSTEM
SCHEDULE OF HEAT AND PRESSURE
UNTIL EVA CURES & LAMINATE IS COMPLETE

DATA FOR PACKAGE

- % TRANSMISSION: 93.8%
- IMPACT STRENGTH - SHOULD SURVIVE 3/4" HAIL @ 45 MPH
- UV STABILITY: 3000 HRS RS4 ≤ 2%
- ADHESIVE STRENGTH: EXCELLENT (COHESIVE FAILURE ONLY)
- LOSS IN TRANSMISSION
- THERMAL STIFFNESS: STRESS LEVELS < CELL STRENGTH AT INTERFACE

Fabrication Technique

- Heat Source
- Vacuum Pump
- Upper Chamber
- Diaphragm
- Lamination
- Module
- Lower Chamber
Fabrication Cycle

(a) BOTH CHAMBERS EVACUATED AT R.T.
(b) ONSET OF HEAT CYCLE
(c) UPPER CHAMBER AERATED
(d) 10 MIN. AT 140°C

TIME, MINUTES

Temperature Levels:
- R.T.
- 50°C
- 100°C
- 120°C
- 140°C
Module I-V Curve

NOCT @ 46°C
Isc = 5.35A
Voc = 19.30V
Pp = 73.30 WATTS
FF = .71
DENSITY = 10.6 mW/cm² @ 46°C
Design Features

- NEW MATERIAL EXPERIENCE
  - PORCELAINIZED STEEL
  - EVA
  - ACRYLIC COVER
  - SCARF
  - MESH INTERCONNECT
  - WRAP AROUND CELL

- NEW FABRICATION METHODS

- LARGER & HIGHER WATT MODULE

Module Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isc</td>
<td>5.35 AMPS</td>
</tr>
<tr>
<td>Vno @ SOC</td>
<td>15.0 Vdc</td>
</tr>
<tr>
<td>Peak Power at SOC</td>
<td>73.3 Watts</td>
</tr>
<tr>
<td>Series - Parallel Cell Connection</td>
<td>36 x 8</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1.2M x .6M</td>
</tr>
<tr>
<td>Envelope Area</td>
<td>7200 cm²</td>
</tr>
<tr>
<td>Cell Area</td>
<td>6912 cm²</td>
</tr>
<tr>
<td>P&lt;sub&gt;n&lt;/sub&gt;</td>
<td>.96</td>
</tr>
</tbody>
</table>

DESIGNED TO MEET JPL DOC. 5101-16 REV A.
Module Features

- 40 x 120 CM (16 x 48 IN.)
- 152 CLOSELY PACKED RECTANGULAR CELLS
- REDUNDANT INTERCONNECTIONS
- 50 WATTS @ SOC
- SUNADFX GLASS COVER
- EVA ENCAPSULANT
- STAINLESS STEEL FRAME

Module Interconnections

- CELL CONFIGURATION
  - 152 RECTANGULAR CELLS
  - 4 PARALLEL X 38 SERIES
- INTERCONNECTIONS
  - 3 POINTS EACH CELL FRONT
  - 4 POINTS EACH CELL BACK
  - MATERIAL - EXPANDED COPPER MESH
  - CONNECTION - SOLDERING
- PARALLEL CROSS TIES
  - AT EVERY SERIES CONNECTION
Cell Features

- $N^+P^+P^+P^+$ SILICON
- ION IMPLANTED JUNCTION AND BSF
- HIGH EFFICIENCY TO 15% (AM 1.5/25°C/POWER POINT)
- RECTANGULAR SHAPE FOR HIGH PACKING DENSITY
- 4.6 X 6.0 CM
- OPTIMIZED CONTACT PATTERN

Solar Module Cell

ORIGINAL PAGE IS OF POOR QUALITY
AMO I-V Curve of Spire Solar Module Cell

![Graph showing AMO I-V curve with voltage (mV) on the x-axis and current (A) on the y-axis. The curve peaks at 0.464 WATT, 12.4% AMO and 12.6% AMI.]

Performance Distribution, 400 Block IV Module Cells

![Histogram showing current distribution at 450 mV with bars representing percentage. The average current is 947.142 mA, with a standard deviation of 57.387.]

Average: 947.142
Std. Dev.: 57.387
Encapsulation System Components

- SUNADEX GLASS
- CLEAR EVA
- CELLS
- POLYESTER RIP STOP
- MYLAR/ALUMINUM BACKING
- HIGH EMISSIVITY COATING ON BACK

Major Components

EVA Curing System

...
Block IV Module
Characteristics

SPIRE SOLAR MODULE

- 4 CELLS IN PARALLEL
- 38 CELLS IN SERIES
- DIMENSIONS 120 X 40 CM
- $P_{\text{max}} = 60.3$ WATTS
- PANEL EFFICIENCY 12.6% (28°C)

Performance Data

- PROGRAM GOAL
  - DELIVER 20 MODULES
  - 45 WATTS PER MODULE
    - AT SOC
    - $V_{\text{no}} = 15$ VOLTS

- PROTOTYPE MODULE PERFORMANCE
  - AT 28°C
    - $P_{\text{max}} = 60.3$ WATTS
    - PANEL EFFICIENCY 12.6%
  - AT SOC, $V_{\text{no}}$
    - $P_{15V} = 53.6$ WATTS
    - PANEL EFFICIENCY 11.2%
Program Status and Summary

- Prototype Module Fabricated
  - All Design Elements Verified
  - All Fabrication Processes Demonstrated
  - Performance Goal Exceeded

- Module Fabrication
  - Qualification Modules Being Made
GENERAL ELECTRIC CO.

Neal Shepherd

First-Generation Shingle Module
Array of First-Generation Shingle Modules
Second-Generation Shingle Module
Array of Second-Generation Shingle Modules
Comparison of Shingle Module Designs

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>First-Generation (JPL 954607)</th>
<th>Second-Generation (PRDA-38)</th>
<th>Third-Generation (JPL 955401)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cell Diameter (mm)</td>
<td>53</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Solar Cell Supplier</td>
<td>Spectrolab</td>
<td>Solarax</td>
<td>Arco-Solar</td>
</tr>
<tr>
<td>Number of Solar Cells</td>
<td>19</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>Total Solar Cell Area (m²)</td>
<td>0.0419</td>
<td>0.0550</td>
<td>0.1481</td>
</tr>
<tr>
<td>Exposed Module Area (m²)</td>
<td>0.0507</td>
<td>0.0743</td>
<td>0.1955</td>
</tr>
<tr>
<td>Module Packing Factor</td>
<td>0.826</td>
<td>0.740</td>
<td>0.758</td>
</tr>
<tr>
<td>NOCT (°C)</td>
<td>61 (1)</td>
<td>57 (1)</td>
<td>64 (2)</td>
</tr>
<tr>
<td>Maximum Power Output at SOC (watts)</td>
<td>4.93 (1)</td>
<td>5.88 (1)</td>
<td>17.14 (2)</td>
</tr>
<tr>
<td>Areal Specific Output (W/m² module area)</td>
<td>97.2</td>
<td>79.1</td>
<td>87.7</td>
</tr>
<tr>
<td>Module Weight (kg)</td>
<td>1.00</td>
<td>1.45</td>
<td>3.85</td>
</tr>
<tr>
<td>Areal Specific Weight (kg/m² module area)</td>
<td>19.7</td>
<td>19.5</td>
<td>19.7</td>
</tr>
<tr>
<td>Power-to-Weight Ratio (W/kg)</td>
<td>4.93</td>
<td>4.06</td>
<td>4.45</td>
</tr>
</tbody>
</table>

(1) NOCT at 80 mW/cm² insolation
(2) NOCT at 100 mW/cm² insolation

Shingle Module Construction

[Diagram of Shingle Module Construction]
### Shingle Materials

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>COVERPLATE</td>
<td>SUNADEX GLASS, THERMALLY-TEMPERED, .188 IN. THICK</td>
</tr>
<tr>
<td>OUTER SUBSTRATE SKIN</td>
<td>FLEXSEAL WHITE SUPPORTED HYPALON WITH 6 X 6 POLYESTER SCRIM</td>
</tr>
<tr>
<td>FOAM CORE</td>
<td>L-200 MINICELL POLYETHYLENE FOAM, .188 IN THICK</td>
</tr>
<tr>
<td>REAR COVER</td>
<td>PAN-L BOARD, .056 IN. THICK</td>
</tr>
<tr>
<td>CELL BONDING ADHESIVE</td>
<td>GE 534-044 SILICONE</td>
</tr>
<tr>
<td>MODULE ENCAPSULANT</td>
<td>GE 1202 SILICONE CONSTRUCTION SEALANT</td>
</tr>
<tr>
<td>SUBSTRATE ADHESIVE</td>
<td>M6338 SILAPRENE</td>
</tr>
</tbody>
</table>

### Module Interconnection Electrical Schematic

---

*Module-to-Module Interconnector*
Module-to-Module Interconnection

Shingle Arrangement on a Rectangular Roof

\[ W = 32.4N_p + 17.2 \]

\[ S = 9.35(N_S + 17.75) \]

\[ N_S = \text{number of series-connected modules} \]

\[ N_P = \text{number of parallel-connected modules} \]
## Typical Residential System Performance

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>PHOENIX</th>
<th>ALBUQUERQUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF MODULES (25 SERIES x 19 PARALLEL)</td>
<td>475</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL SOLAR CELL AREA (m²)</td>
<td>70.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL EXPOSED MODULE AREA (m²)</td>
<td>92.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL GROSS ROOF AREA (m²)</td>
<td>104.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARRAY OUTPUT AT SOC (kW PEAK) NOCT = 64°C</td>
<td>8.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANNUAL DC ENERGY INPUT TO INVERTER (kWh)</td>
<td>19763</td>
<td>20682</td>
<td></td>
</tr>
<tr>
<td>ANNUAL AC ELECTRICAL ENERGY OUTPUT (kWh)</td>
<td>17455</td>
<td>18336</td>
<td></td>
</tr>
<tr>
<td>ANNUAL INSOLATION ON ARRAY SURFACE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANNUAL INSOLATION ON ARRAY SURFACE (kWh/m²)</td>
<td>2348</td>
<td>2350</td>
<td></td>
</tr>
<tr>
<td>OVERALL SYSTEM EFFICIENCY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SYSTEM AC OUTPUT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INSOLATION X MODULE AREA 8.0%</td>
<td>8.4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SOLAREX CORP.

Contract Scope

18 INTERMEDIATE LOAD MODULES
18 RESIDENTIAL LOAD MODULES
FIVE OF EACH TYPE TO JPL ENVIRONMENTAL TEST
SAMIS/SAMICS PARTICIPATION
36 2 x 2cm REFERENCE CELLS
Design Characteristics

- 63.5 cm x 120 cm outside dimension
- 9.5 cm x 9.5 cm semicrystalline cells
- Array configuration - 6 wide x 12 long
- 3/16" tempered glass
- EVA pottant
- White TEDLAR moisture barrier

Electrical Design, Intermediate Load

- Two 36 cell strings
- Each cell connected in parallel with one other

- 2 P x 36 S x 36 SEB Configuration
  AT: NOCT (51°C)
  1000W/cm²

  \[ V_{DC} = 18.9 \text{ volts} \]
  \[ I_{SC} = 5.08 \text{ amps} \]
  \[ V_{PP} = 14.6 \text{ volts} \]

Power (15 volts) = 65.4 watts
Electrical Design, Residential

- Six 12 cell strings
- Every six cells connected in parallel
- 6 P x 12 S x 12 SEB configuration

At: NOCT (51°C)
100 MW/cm²

\[
\begin{align*}
V_{OC} &= 6.3 \text{ volts} \\
I_{SC} &= 15.24 \text{ amps} \\
V_{PP} &= 4.9 \text{ volts} \\
\text{Power (5 volts)} &= 66.0 \text{ watts}
\end{align*}
\]
Cell-Interconnect Design

Six pads per cell

After tabbing - all interconnects from back

Interconnect material - copper clad fluoro-glass
Frame Design, Intermediate Load

**ONE PIECE**

**ANODIZED ALUMINUM**

**MODIFIED CHANNEL**

Frame, Intermediate Load

1/8" MODIFIED CHANNEL - ALUMINUM

CHOSEN BECAUSE OF:

- Simplicity
- Ease of Manufacture
- Economy
- Mounting Simplicity
- Rigidity

FEATURES:

- One Piece
- Mechanical supports in corners and near "split"
- Drain holes
- Grounding provision
TECHNOLOGY DEVELOPMENT AREA

Encapsulation Task

During the PIM Module Design session a presentation outlined the design and performance criteria developed for each of the functional elements making up a complete solar module encapsulation system. The functional elements reviewed were the module front surface, front cover, pottant, spacers, structural panels, back cover, and edge frame support and seal. Within the LSA 1986 price goal allocation guidelines for the encapsulation materials of $14/m² (1980 $) or 10¢ to 14¢/Wpk, several candidate material systems have been developed. These material systems are now undergoing intensive evaluation by industry and by JPL relative to potential module service life, preferred fabrication methods and effects on module performance. A summary of the status of these candidate materials is given in a following chart.

The major unknown in the selection of the lowest-cost candidate encapsulation system is the potential of achieving a 20-year service life. However, available data and current research on individual module degradation mechanisms (such as polymer degradation, metal corrosion or module structural damage) indicate that a 20-year life is reasonable for one or more of the candidate material systems.

The emphasis of the LSA-supported effort has been on developing new and very low-cost encapsulation material systems and process for meeting the 1986 price goals and beyond. The near-term solar module applications that are cost-effective at $2.00 to $5.00/Wpk can consider more rugged designs costing 15¢ to 30¢/Wpk or more than $30/m² for materials. This larger allocation justifies the use of low-iron tempered-glass superstrates with glass or metal backside panels. Silicones or polyvinyl butyral are currently used as pottants in commercial solar modules. In properly sealed packages, solar arrays should certainly last 20 years or more. For the extreme stresses experienced by navigational aids subject to tropical or arctic marine environments, an all-borosilicate-glass sealed envelope filled with silicone rubber is state-of-the-art.

An advanced concept developed by Spire Inc. and under evaluation is the electrostatic bonding (ESB) of solar cells directly to glass with a backside panel of shaped glass bonded at the module periphery forming a complete hermetic envelope for the solar cells.

The LSA approach to developing the lowest-costing encapsulation system has been to define the minimum performance requirements for each functional element and then surveying all possible low-cost materials or material combinations that could meet the performance criteria with appropriate designs and have the potential of a 20-year service life.
This effort has resulted in identifying several materials, including ethylene vinyl acetate (EVA), as low-cost pottant candidates. A curable laminating sheet product of EVA that was developed has been selected by a number of firms for industrial evaluation.

The lowest-costing structural panel materials identified were the reconstituted wood-fiber boards (e.g. hardboard or strandboard). Problems associated with dimensional stability and long life appear solvable. An initial approach is to encapsulate the hardboard along with the solar cells using the EVA polymer.

A full report on the development and status of these low-cost-material concepts will be published as an LSA report early in 1980.

As these materials are characterized and sufficient environmental test experience is compiled, the module manufacturers are expected to undertake their own evaluations and develop marketable module designs. Polyvinyl butyral has been thus adopted and EVA has been incorporated into several Block IV module designs.

A demonstration of the development by MBAssociates of glass-fiber-reinforced concrete (GRC) as a solar array structural panel and substrate was provided by an MBAssociates display at the PIM. An active 4 x 8 ft GRC solar panel mounted on wood posts was set up with a variety of electrical loads in operation.

Increasing effort of the Encapsulation Task is given to developing test and analysis methodologies to establish module power degradation rate predictions for a 20-year service life. These rate predictions will be based on degradation mechanism models and experimental data from carefully designed accelerated stress testing of modules, components, and individual material systems. These module degradation-rate predictions can then be supplied to existing LSA life-cycle cost-analysis programs to optimize material selection and module designs.

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

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

Encapsulation material degradation data for low-cost advanced encapsulant systems is being gathered using various test hardware such as mini-modules (12 x 16 in.), one- and two-cell modules and individual material samples. Exposure facilities include JPL laboratory reactors and selected field test sites such as Point Vicente, JPL, and Goldstone.
A thermomechanical computer model of a photovoltaic module has been formulated and is being refined and used to study failure modes associated with temperature and moisture expansion stresses within the module encapsulation system. The Mead NB array hardware has been used in this initial analytical study.

A long-term accelerated module life test is being implemented to evaluate the validity of a life testing plan developed by Battelle. A closely controlled and monitored module degradation-rate experiment with accelerated temperature cycling, high humidity and applied current flow will be conducted with 10 prototype modules simultaneously over a 4-to-6 month test period.

ENCAPSULATION MATERIALS SUMMARY

<table>
<thead>
<tr>
<th>MODULE ELEMENT</th>
<th>CANDIDATES</th>
<th>STATUS</th>
<th>CONTINUING DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOP SURFACE</td>
<td>Antireflective coating</td>
<td>• High transmission demonstrated by Motorola process</td>
<td>• Scale-up of process plus environmental testing</td>
</tr>
<tr>
<td></td>
<td>Abrasion-resistant hard coats</td>
<td>• Effectiveness on polymer covers demonstrated on several types</td>
<td>• Life and soiling characteristics known</td>
</tr>
<tr>
<td></td>
<td>Soil-resist treatments for polymers</td>
<td>• Glass cleans with rain; polymers not self cleaning</td>
<td>• R&amp;D on surface treatments including surface modification and ion-plating</td>
</tr>
</tbody>
</table>

| COVERS           | Glasses                        | • Current commercial use                         | • Selection for optimum cost/performance               |
|                  | Soda lime                      | • Structurally analyzed                          |                                                       |
|                  | Low-iron tempered Borosilicate | • Bonding criteria available                     |                                                       |
|                  |                                | • Electrostatic bond directly to cells           | • Scale-up of electrostatic bond process               |
## ENCAPSULATION MATERIALS SUMMARY (Continued)

<table>
<thead>
<tr>
<th>MODULE ELEMENT</th>
<th>CANDIDATES</th>
<th>STATUS</th>
<th>CONTINUING DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Sheet (with UV screen)</td>
<td>Acrylics</td>
<td>• Korad UV-screen</td>
<td>• Stabilized UV screen film synthesis for cost/life/spectral cut-off optimization</td>
</tr>
<tr>
<td></td>
<td>Fluorocarbons</td>
<td>• Fluorocarbon films available have cost and processing limits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silicone/Acrylic</td>
<td>• Silicone/acrylic films under development (Dow Corning/Springborn)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copolymers</td>
<td>• UV screen candidates synthesized for copolymer films</td>
<td></td>
</tr>
<tr>
<td>POTTANTS</td>
<td>Silicones</td>
<td>• Current commercial use</td>
<td>• Lower cost silicones and designs using less material</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High cost, soil adheres, good weatherability, some delamination problems</td>
<td>• Suitable cover film and surface treatment</td>
</tr>
<tr>
<td></td>
<td>Polyvinyl butyral</td>
<td>• Current commercial use</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Subject to weathering if not sealed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Intermediate cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Process &amp; storage constraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ethylene vinylacetate</td>
<td>• Undergoing industrial evaluation in commercial modules</td>
<td>• Scale-up of sheet production Improved handling and storage qualities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Processes for high volume available</td>
<td>• Develop and demonstrate best adhesion methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Extensive life modeling started</td>
<td>• Large area module designs and processes</td>
</tr>
</tbody>
</table>
ENCAPSULATION MATERIALS SUMMARY (Continued)

<table>
<thead>
<tr>
<th>MODULE ELEMENT</th>
<th>CANDIDATES</th>
<th>STATUS</th>
<th>CONTINUING DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>POTTANTS</td>
<td>Acrylic elastomer poly-n-butyl-acrylate (PnBA)</td>
<td>- Polymer specimens formulated</td>
<td>- Improve and scale-up formulation methods</td>
</tr>
<tr>
<td>(continued)</td>
<td></td>
<td>- Mini-module built and tested</td>
<td>- Module design, fabricate, and test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Photodegradation studies started</td>
<td>- Develop compatible cover film</td>
</tr>
<tr>
<td></td>
<td>Ethylene propylene rubber (EPR)</td>
<td>- Photodegradation studies started</td>
<td>- Develop best application method (cast, direct extrusion, etc.)</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPACER (scrim)</td>
<td>Non-woven glass mat</td>
<td>- Lowest-cost scrim and separator sheet</td>
<td>- Selection of thickness and fabrication sequence</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Aids lamination process to avoid bubbles</td>
<td>- Evaluate as transparent top cover filler to enhance ruggedness and safety</td>
</tr>
<tr>
<td>SUBSTRATE</td>
<td>Aluminum</td>
<td>- Current commercial use</td>
<td></td>
</tr>
<tr>
<td>PANEL</td>
<td></td>
<td>- High cost, high thermal expansion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiberglass reinforced polymers (epoxy, polyester)</td>
<td>- Higher cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Subject to outgassing and delamination</td>
<td></td>
</tr>
</tbody>
</table>
### Encapsulation Materials Summary (Continued)

<table>
<thead>
<tr>
<th>MODULE ELEMENT</th>
<th>CANDIDATES</th>
<th>STATUS</th>
<th>CONTINUING DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBSTRATE PANEL (continued)</strong></td>
<td>Steel - Porcelainized - Galvanized - Polymer coat</td>
<td>• Under industrial evaluation • Subject to distortion in flat panels • Intermediate cost • Demonstrated good corrosion resistance and thermal performance</td>
<td>• Optimize panel design for structural efficiency and fabricability • Improve coating systems for cost/thermal/life/fabricability trade-offs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>• Commercial panels have shown 20 year weatherability • Cost study shows this to be the lowest cost structural panel • JPL mini-modules have passed temperature/humidity cycle</td>
<td>Design modules and panels for stability in outdoor environment using coatings and films</td>
<td>Scale-up designs for large panels with integral ribs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>• 4' x 8' prototype panels and array structure under field test • Automated panel lay-up fabrication method demonstrated • Cost effective integration of PV module and field array structure shown</td>
<td>Improved encapsulation system design to mount PV cells on concrete surface</td>
<td>Determine environmental effects on encapsulants and concrete (electrical, thermal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK COVER</td>
<td>Polymer films</td>
<td>• Current commercial use of Teldar and Mylar • Films are weatherable and bonded to pottant but are not a full moisture barrier</td>
<td>Determination of module life limits due to film permeability and types of solar cell and interconnects used</td>
</tr>
</tbody>
</table>
ENCAPSULATION MATERIALS SUMMARY (Continued)

<table>
<thead>
<tr>
<th>MODULE ELEMENT</th>
<th>CANDIDATES</th>
<th>STATUS</th>
<th>CONTINUING DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACK COVER</td>
<td>Flexible metal foil laminates</td>
<td>• Aluminum foil/polyester film laminates under industrial evaluation</td>
<td>• Determination of electrical isolation</td>
</tr>
<tr>
<td>(continued)</td>
<td></td>
<td>• Steel foil/polyester film under industrial evaluation</td>
<td>• Development of edge seal design criteria and determination of failure mode and life limits</td>
</tr>
<tr>
<td></td>
<td>Glass mat/EVA film</td>
<td>• Used as weather barrier for hardboard and steel substrates</td>
<td>• Evaluation of weathering and life limits of encased hardboard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Evaluation of dimensional stability of encased hardboard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Evaluation of electrical isolation and corrosion resistance of encased steel substrates</td>
</tr>
</tbody>
</table>
Potential Failure and Degradation Rates

Material Systems Development

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>MATERIAL TECHNOLOGY</th>
<th>ACCOMPLISHMENTS IN 1979</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPRINGBORN</td>
<td>LOW-COST ENCAPSULANTS</td>
<td>• COMPLETE CANDIDATE SYSTEMS DESIGNED, FABRICATED &amp; PROCESSES DEFINED.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• SUPERSTRATE &amp; SUBSTRATE DESIGNS, DEMONSTRATED AT LESS THAN $6.00/M²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• MATERIALS UNDER INDUSTRIAL EVALUATION</td>
</tr>
<tr>
<td>DOW CORNING</td>
<td>SILICONE/ACRYLICS</td>
<td>• SILICONE-ACRYLIC COVER FILM WITH UV SCREEN FORMULATED AND EVALUATED.</td>
</tr>
<tr>
<td>MB ASSOCIATES</td>
<td>GLASS-REINFORCED CONCRETE</td>
<td>• FULL-SCALE GRC SUBSTRATE PANELS PLUS ACTIVE MINIMODULES FABRICATED FOR EVALUATION.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PANELS MEET COST &amp; STRUCTURAL GOALS.</td>
</tr>
<tr>
<td>UNIV. OF MASS</td>
<td>UV SCREENS</td>
<td>• UV SCREEN (VINYL TINOVIN) SYNTHESIZED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• DEMONSTRATED STABILIZED COPOLYMER FILMS</td>
</tr>
<tr>
<td>E. PLUEDDEMANN</td>
<td>ADHESIVES &amp; PRIMERS</td>
<td>• MATERIALS &amp; CRITERIA FOR BONDING 1986 MATERIAL SYSTEMS IDENTIFIED</td>
</tr>
<tr>
<td>(CONSULTANT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPL (IN-HOUSE)</td>
<td>POLY-ß BUTYL ACRYLATE</td>
<td>• FORMULATION &amp; PROCESSING STEPS FOR P-ßBA DEVELOPED</td>
</tr>
</tbody>
</table>
**Process and Design Studies**

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>TECHNOLOGY AREA</th>
<th>ACCOMPLISHMENTS IN 1979</th>
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<tbody>
<tr>
<td>SPIRE</td>
<td>ELECTROSTATIC BONDING (ESB)</td>
<td>• ROUTINE PRODUCTION OF ESB CLOSE-PACKED RECTANGULAR CELLS ACHIEVED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• TRAPPED WIRE MESH CELLS WITH GOOD I-V DEMONSTRATED</td>
</tr>
<tr>
<td>MOTOROLA</td>
<td>AR COATED GLASS SHEET</td>
<td>• HIGH TRANSMISSION DEMONSTRATED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PROCESS FOR LARGE GLASS SHEET COATING DEMONSTRATED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ABRASION-RESISTANCE EVALUATED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• OPTIMIZATION STUDIES UNDER WAY</td>
</tr>
<tr>
<td>ILLINOIS TOOL WORKS</td>
<td>ION-PLATING</td>
<td>• NEW CONTRACT STARTED ON CORROSION-RESISTANT AND HIGH-TEMPERATURE METALLIZATION AND COATING CONCEPTS</td>
</tr>
<tr>
<td>SPECTROLAB</td>
<td>DESIGN, ANALYSIS, TEST VERIFICATION OF ADVANCED (1986) ENCAPSULATION SYSTEMS</td>
<td>• NEW CONTRACT TO INTEGRATE AND OPTIMIZE ENCAPSULATION SYSTEM TECHNOLOGY</td>
</tr>
</tbody>
</table>

**Life Prediction Methodology**

<table>
<thead>
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<th>CONTRACTOR</th>
<th>TECHNOLOGY AREA</th>
<th>ACCOMPLISHMENTS IN 1979</th>
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<tr>
<td>ROCKWELL SCI. CTR.</td>
<td>ENCAPSULATION INTERFACE PHENOMENA (CORROSION)</td>
<td>• ATOMIC PHASE CORROSION MODEL DEVELOPED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ATOMIC PHASE CORROSION SIMULATOR DESIGNED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• DIAGNOSTIC INSTRUMENTS AND TECHNIQUES EVALUATED</td>
</tr>
<tr>
<td>CASE WESTERN</td>
<td>AGING AND DIFFUSION MECHANISMS</td>
<td>• STARTED AGING-RATE MEASUREMENT AND MODELING FOR P-nBA</td>
</tr>
<tr>
<td>UNIV. OF TORONTO</td>
<td>PHOTODEGRADATION MODEL FOR EVA</td>
<td>• NEW CONTRACT</td>
</tr>
<tr>
<td>CALTECH</td>
<td>FRACTURE AT INTERFACES</td>
<td>• EXPANSION STRAINS VERSUS TIME, TEMPERATURE, AND MOISTURE MEASURED AND CORRELATED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• EXPERIMENTAL MODEL FOR DEBOND EXTENSION DEVELOPED</td>
</tr>
<tr>
<td>BATTellei</td>
<td>LIFE TEST PLAN</td>
<td>• EXPERIMENTAL PLAN FOR ACCELERATED TEST DEFINED AND FEASIBILITY TESTING INITIATED</td>
</tr>
</tbody>
</table>
In-House Studies

<table>
<thead>
<tr>
<th>TECHNOLOGY AREA</th>
<th>ACCOMPLISHMENTS IN 1979</th>
</tr>
</thead>
</table>
| UV DEGRADATION  | • UV TEST REACTOR FOR ENCAPSULATED CELLS COMPLETED AND OPERATING  
|                 | • CRITERIA FOR ACCELERATED UV AGING OF DIFFERENT POLYMERS |
| FIELD MEASUREMENT OF INTEGRATED UV | • DEVELOPED AND CALIBRATED UV ACTINOMETERS FOR FIELD DEPLOYMENT IN 1980 |
| THERMOECHANICAL MODEL | • FINITE ELEMENT MODEL DEVELOPED AND USED TO PREDICT STRESSES AND STRAINS IN MODULE ENCAPSULATION SYSTEM. |
| ADVANCED ENCAPSULANT FIELD TESTING | • MINIMODULES FABRICATED AND TEST SITES PREPARED AT JPL, SAN VICTENTE, GOLDSTONE |

EVA Photodegradation Studies

• TRANSPARENT EVA (REVISED BATCH) PROCURED FROM SPRINGBORN

• ROLE OF RESIDUAL CROSS LINKING AGENT IN INITIATING PHOTODEGRADATION

• NATURE OF PHOTODEGRADATION  
  FT-IR, EXTRACTION / GPC, UV-VISIBLE SPECTROSCOPIC DATA

• LONG TERM RATES (UNDER MEASUREMENT)

• EFFECT OF PHOTODEGRADATION ON MODULUS, STRESS / STRAIN RESPONSE
Suitability of Use of PnBA as Pottant

- **HIGH TRANSPARENCY**
- **EXCELLENT ADHESION TO GLASS, WOOD, METALS, SOLAR CELLS, CLOTH**
- **CAN BE THERMALLY CYCLED (-50° TO +90°) WITHOUT FRACTURE**
- **POTENTIAL LONG LIFE → MAY NOT NEED HIGH LEVEL OF UV SCREENING**
- **CAN BE PROCESSED BY SOLVENT FREE CASTING METHOD → CURE CONDITIONS DETERMINED AT JPL**
- **LOWEST COST ACRYLIC → MONOMER AT 45¢/lb FOR TANK CAR QUANTITIES**

**DISADVANTAGE**

- **NO MATERIAL AVAILABLE FOR INDUSTRIAL EVALUATION YET**

**What Is PnBA?**

\[
[-\text{CH}_2 - \text{C} -]_n
\]

\[
\text{O} - \text{O}-\text{CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_3
\]

IT IS USED AS A CROSS-LINKED, ELASTOMERIC POTTANT AND APPLIED BY A SOLVENT FREE CASTING TECHNIQUE

- **\( T_g \):** -55°C APPROX
- **TRANSMISSION (20 MIL):** > 94%
- **DENSITY:** 1.09 ± 0.01
- **MODULUS (10% STRAIN):** 3 x 10^6 N/m² APPROX

**Results**

PHOTO DEGRADATION STUDIES ON PNBA PHOTOLYSIS AT 2537 Å

\[
\text{H}
\]

\[
\text{O}^\text{+} \quad \text{O}^\text{-} \quad \text{CH}_2\text{-CH}_2\text{-CH}_2\text{-CH}_3
\]

SCISSON MODE A \( n\text{-bu}\cdot\text{C}-\text{O} \cdot \rightarrow \text{CO}_2 \cdot n\text{-bu} \cdot \rightarrow \text{BUTENE} \)

SCISSON MODE B \( n\text{-hu}\cdot\text{C}-\text{O} \cdot \rightarrow n\text{-bu} \cdot \text{OH}, \text{CH}_2\text{O} \cdot \text{PROPENE} \)

SCISSON MODE C \( n\text{-hu} \cdot \text{P} \cdot \text{CO}_2 \cdot \rightarrow \text{BUTENE} + \text{CO}_2 \)

IN ALL CASES THERE WILL BE SIMULTANEOUS CHAIN SCISSION AND CROSS LINKING
Plan for Further Work on PnBA

• PROCESSING STUDIES
  • DIPPING AND CURING
  • TWO STAGE ENCAPSULATION
DELIBERABLE MAKE 6 ONE CELL/TWO CELL MODULES (JUNE 80)

• CURING / FORMULATION STUDIES
  • ADD POLYMERIZABLE UV STABILIZERS IN SYRUP
  • STUDY CURING AT 90°C / IN AIR
DELIBERABLE REPORT ON SYRUP COMPOSITION / CURE (AUGUST 80)

• DEGRADATION / PHOTODEGRADATION STUDIES
  • ASSESS NEED FOR UV SCREENING / BACK COVER PROTECTION
DELIBERABLE REPORT ON PHOTODEGRADATION MODEL (NOVEMBER 80)
On Tuesday, December 4th, 1979, the PP&E Area held a contractor's summary meeting in the new PP&E Laboratory. All contractors except those who were working on copper metallization and automation studies presented summaries of their efforts at this time.

On Wednesday afternoon those contractors involved with copper metallization summarized their efforts and on Thursday afternoon the "Automated Module Assembly Studies" session covered this subject.

Salient points of the meeting and plans for the next period follow:

REPORTED PROGRESS SINCE LAST PIM

Surface Preparation:
- Gettering must be evaluated on specific materials
- NH₄OH - H₂O₂ cleaning solution is replenishable
- Spray-on AR coating being perfected
- Texture/polish option still open.

Junction Formation Processes:
- Technique is important in forming Al BSF
- Carbonaceous layer formed during ion implanation
- Investigating current increase after plasma etching outermost surface
- Spray-on junctions successful
- Ion implanted cells using non-mass-analyzed source.

Metallization Processes:
- Nickel is a barrier to copper migration
- Thick-film metal systems have been successfully doped with AlSi and AlGe eutectics
- Copper sinters well using Pb frit
- Progress is being made in Ni plating directly on Si.
Assembly:

- Laminating chamber developed
- Induction soldering of ribbon to cell successful
- Single-pass IR soldering of multiple strings
- Automated soldering is dependent upon cell metallurgy.

Plans For Next Period

- Receive Phase III proposals and begin evaluation
- Establish control-cell capability in PP&E Lab
- Begin development of pulsed electron beam anneal (PEBA) machine
- Continue development of low-cost metallization system.

TECHNOLOGY SESSION

D.B. Bickler, Chairman

PRODUCTION PROCESSES AND EQUIPMENT, PHASE II

MOTOROLA, INC.

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
11. CELL TEST AND INTERCONNECT
12. ENCAPSULATE

*ELIMINATED IF PLASMA TEXTURE ETCHING IS CHOSEN
**MAY BE COMBINED
Texture Etching

Silicon ribbons with multiple orientations are readily textured,
- Strong preferred orientation of grains
- Far less than 5% is oriented near (111)

Has major impact on ion implanter design.

Texture-Etched RTR Surface
Ion Implantation

1. FORMATION OF CARBONACEOUS LAYER OBSERVED
   - WAFER NOT HYDROPHOBIC IN HF
   - OXIDATION PLUS HF RETURNS HYDROPHOBIC FEATURE
   - RELATED TO VACUUM PUMP OIL

2. PERFORMING SIMULATED NON-MASS-ANALYZED IMPLANT
   - GASEOUS SOURCES OF PH₃, ASH₃, BF₃
   - IMPLANT PROPORTIONATELY FOR EACH MAJOR MASS COMPONENT IN
     SPECTRUM.
   - IMPLANTED CELLS ARE INDIFFERENT FROM MASS-ANALYZED
     IMPLANTED CELLS

3. TRUE UNANALYZED BEAM IMPLANT
   A. UTILIZED ION MILLING MACHINE
   - PH₃ SOURCE
   - IMPLANT AT ~2 KEV
   - BEAM CURRENT ~200 MILLIAMS (UNCALIBRATED)
   - NON-TEXTURED WAFER

Typical BF₃ Spectrum
Typical PH$_3$ Spectrum

Typical AsH$_3$ Spectrum
Ion Implantation (Continued)

B. TIME OF IMPLANT EXCESSIVE
   - NEAR 20 SECONDS
   - PROBABLE DOSE GREATER THAN $10^{16}$

C. ANNEALED 30 MINUTES (900°C), SILICON NITRITE (780°C-45 MINUTES),
   550°C-2 HOURS.

D. $V_{OC} = 593$ MILLIVOLTS
   $I_{SC} = 1450$ MILLIAMPS

Plasma Patterning

1. DEMONSTRATED SIMULTANEOUS FRONT AND BACK PATTERNING OF SILICON
   NITRIDED
   - REACTIVE ION ETCHING MODE
   - SPACINGS ALLOWED BETWEEN MASK AND CELL WHILE STILL
     ACHIEVING MASK REPLICATION
   - ALLOWS TEXTURED AND/OR NON-PLANAR SUBSTRATES

2. PROCESS IS MASK MATERIAL DEPENDENT
   - NICKEL AND POLYCYDRENUM MASKS QUENCH PLASMA REACTION
   - ALUMINUM MASKS ARE SUITABLE

Mechanically Masked Plasma Patterning

![Mechanically Masked Plasma Patterning Diagram]
Plated Metallization

1. BASELINE PROCESS CONTAINED:
   - IMMERSION PALLADIUM (DISPLACEMENT)
   - ELECTROLESS PALLADIUM (AUTOCATALYTIC)
   - ELECTROLESS NICKEL
   - SOLDER

2. ELIMINATED NEED FOR ELECTROLESS PALLADIUM
   - WAS THE MAJOR METAL MATERIAL COST FACTOR
   - ELECTROPLATE NICKEL CONTACT
   - JIGGING DIFFICULT, BUT FEASIBLE

3. RE-EVALUATING ELECTROLESS NICKEL
   - DIFFERENT FORMULATIONS
   - ELIMINATE (OR EFFECTIVELY MINIMIZE) SILICON OXIDATION
   - MOST SUCCESSFUL WITH IMMERSION PALLADIUM LAYER

4. COPPER PLATING HAS BEEN DEMONSTRATED FOR REPLACING SOLDER
SILICON WAFER TEXTURIZING

PHOTOWATT INTERNATIONAL, INC.

Gregory T. Jones

Aim and Objectives

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

Specific Goals

THE SPECIFIC GOALS FOR THIS STUDY OF WAFER SURFACE TEXTURIZING FOR NEAR TERM IMPLEMENTATION OF FLAT PLAT COST REDUCTIONS ARE:

(1) REDUCE THE CLEANING MATERIALS COST FROM 3.7 CENTS PER PEAK WATT TO LESS THAN 0.7 CENTS PER PEAK WATT.

(2) PRODUCE CONSISTENT SOLAR CELL EFFICIENCIES GREATER THAN 10% IN PRODUCTION OVER A SIMILAR BATCH OF SOLAR CELLS WITHOUT TEXTURIZATION.

Project Status

PROJECT COMPLETED IN AUGUST 1973. FINAL REPORT IS BEING SUBMITTED TO JPL FOR FINAL REVIEW PRIOR TO PUBLICATION.
Project Results

LOW-COST WAFER CLEANING
(1) Low-cost cleaning method was found to be suitable to large scale production.
(2) Cleaning method uses recycled Freon TMS in an ultrasonic vapor degreaser.
(3) Cost goal achieved. Costs for wafer cleaning is less than 0.7 cents per peak watt.

LOW-COST WAFER DRYING
(1) Low-cost clean air system is suitable for large scale production.
(2) Clean air can replace nitrogen.
(3) Air convection drying is not cost effective due to long drying time.
(4) Force air dry tunnel system is cost effective at an initial wafer drying temperature of 80°C.

TWO-STAGE TEXTURIZING PROCESS
(1) Under laboratory controlled conditions, process time per TFT in the two-stage texturizing process (10% TMAH) is five minutes.
(2) Current conditions in large scale production where wafer surface characteristics are not controlled, processing time was variable and required more than five minutes.

GETTERING PROCESS
(1) Large improvement in average solar cell efficiency can be achieved by utilizing a low temperature gettering treatment in combination with a two stage texturizing process sequence.
(2) Intermediate gettering produced the highest batch efficiency, 13.5% (with 510°C) in production.
(3) Highest efficiency achieved in production was 14.3%.
(4) Optimum intermediate gettering temperature is 875°C, 35 minutes.
(5) Low temperature intermediate gettering minimized efficiency and fill factor dispersions.
(6) Gettering improved the quality of silicon material. Quality of silicon material is defined in terms of the characteristic I-V curves for a batch of solar cells.
Recycled gettering is feasible and cost effective.

The average efficiency 12.3% (without A.R. coating) of the texturized/gettered batch of solar cells was found to be 18.3% higher than the average efficiency, 10.4% of the isotropic surface etched/gettered solar cells.

The efficiency goal was achieved for the wafer surface texturizing study for the near term implementation of flat plate photovoltaic cost reduction.

Process Equipment Cost Analysis

(1) Texturizing process cost including cleaning, drying and texturizing amounted to 1.26 cents per peak watt (1975 cents).

(2) Gettering cost was 0.97 cents per peak watt.

(3) The wafer surface preparation cost including the texturization process and gettering process steps was found to be in line with the 1986 JPL low-cost solar array project goal (in 1975 cents) of 50 cents per peak watt.

Comparison of Characteristic I-V Curves Of the Texturizing-Gettering Process

(1) Initial experiments -- gettering placement and temperature.

(2) Gettering (POCl₃, 875 C, 35 minutes).

(3) Gettering temperature.

(4) Gettering surface etched wafers.
Texturizing-Gettering Batch Test Results

Texturizing Gettering Batch Tests

P1 - Control cells, Texturized, 54.9 cm² active areas.
P2 - Intermediate gettered (1000 C).
P3 - Presettered (875 C).
P4 - Intermediate gettered (875 C)

B1 - Control cells - Texturized, 41.4 cm² active areas.
B2 - Intermediate gettered (875 C).
B3 - Presettered (875 C).
B4 - Intermediate gettered (875 C) with 510.

C1 - Intermediate gettered (1050 C), 41.4 cm² active area.
C2 - Intermediate gettered (975 C).
C3 - Intermediate gettered (990 C).

D1 - Control cells - Surface etched, 42.6 cm² active area.
D2 - Intermediate gettered (925 C).
D3 - Intermediate gettered (875 C).

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Objective of the Current Program

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

Outline

I. PROGRESS IN THE STUDY OF THREE MANUFACTURING SEQUENCES
   A. MATERIAL AND PROCESS COMPATIBILITY PROBLEMS
      a. SOLAR-GRADE WAFERS AND ION-IMPLANTATION
      b. SCREEN-PRINTED THICK-FILM METALIZATION
      c. SPRAY-ON AR COATING
   B. EVALUATION OF SEQUENCE I, II AND III PROCESSING
      a. OVERALL COMPARISONS
      b. "GETTERING" — EFFECT ON EFFICIENCY AND COST

II. INTERCONNECT AND PANEL ASSEMBLY PROCESSES
   A. REFLOW SOLDER INTERCONNECT PROCESS
   B. DOUBLE-GLASS LAMINATION PROCESS

III. CONCLUSIONS AND PLANS
Fill Factor as Function of Sheet Resistance
Incl. Avg. Values For Lots 106, 107, 910, 115m

<table>
<thead>
<tr>
<th>Lot No.</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (mV)</th>
<th>$FF$</th>
<th>$\eta^0$</th>
<th>$R_D$ (Ω/□)</th>
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</thead>
<tbody>
<tr>
<td>107P</td>
<td>21.7</td>
<td>552</td>
<td>0.659</td>
<td>7.9</td>
<td>58</td>
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<tr>
<td>106P</td>
<td>20.7</td>
<td>557</td>
<td>0.710</td>
<td>8.2</td>
<td>34</td>
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<tr>
<td>910P</td>
<td>20.5</td>
<td>560</td>
<td>0.700</td>
<td>8.0</td>
<td>52</td>
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<tr>
<td>950 - 952</td>
<td>19.5</td>
<td>499</td>
<td>0.518</td>
<td>5.1</td>
<td>75-150</td>
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*No AR Coating*
**Average Cell Parameters: Sequences I, II and III**

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<thead>
<tr>
<th>MANUFACTURING SEQUENCE</th>
<th>MEASURED — NO AR</th>
<th>ESTIMATED — WITH AR</th>
<th>BEST MEASURED WITH AR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Structure</td>
<td>( I_c ) mA</td>
<td>( V_{op} ) mV</td>
</tr>
<tr>
<td>I</td>
<td>( n^+ / p^+ )</td>
<td>670 667</td>
<td>0.701 0.1</td>
</tr>
<tr>
<td>II</td>
<td>( n^+ / p^+ )</td>
<td>670 674</td>
<td>0.705 0.0</td>
</tr>
<tr>
<td>III</td>
<td>( p^+ / n^+ )</td>
<td>1020 666</td>
<td>0.866 0.7</td>
</tr>
<tr>
<td>PDCO₂</td>
<td>( n^+ / p^+ )</td>
<td>687 684</td>
<td>0.756 0.3</td>
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</tbody>
</table>

(a) Cell area = 42 cm².
(b) Measured values.

**Cell Interconnect Process**

1. **SCREEN PRINT SOLDER PASTE — FRONT AND BACK.**
2. **SOLDER PREFORMED TABS TO CELL — RADIANT HEAT.**
3. **CLEAN CELLS TO REMOVE FLUX.**
4. **LAYOUT CELL ARRAY AND TRANSFER TO REFLOW TABLE.**
5. **INTERCONNECT ARRAY BY RADIANT-HEAT MASS REFLOW.**
SPECTROLAB

William E. Taylor

Comparison of IR and Tube Furnace Firing of Printed Contacts

<table>
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<th>$V_{OC}$ (mV)</th>
<th>$I_{SC}$ (mA)</th>
<th>$I_{500}$ (mA)</th>
<th>$R_{sh}$</th>
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SETS 1 AND 2: Ag FRONT CONTACTS
SET 3: AL BACK CONTACT
EFFECT OF MINORITY CARRIER DIFFUSION LENGTH OF STARTING WAFERS ON SOLAR CELL OUTPUT 12/79

CURRENT DENSITY - mA/cm²

MINORITY CARRIER DIFFUSION LENGTH - μm
Cell After 24 sec Plasma Etch

SOLAR CONVERTER E I CURVE

SPECTROLAB 0 C FORM 101
SYLMAR CALIFORNIA DATE 2-8-72

PROJECT C 5-4

SERIAL NO 7-3

CELL MODULE PANEL DESIGNATION:

SOURCE SUN TUNGSTEN XENON

COLLIMATED UNCOLLIMATED

TEST TEMP 70 °C

TEST R.O. PROC I/O

VOLTS 0.1 0.2 0.3 0.4 0.5 0.6 0.7

CURRENT (mA) X ^ 100

VOLTAGE (VOLTS X /)
EFFECT OF PLASMA ETCHING CELL FRONT SURFACE WITH FREON 14 + 8% O₂

ETCH TIME - SECONDS

CHANGE OF CURRENT - PERCENT

1500

ISC

12/79
SOLAR CELL SPECTRAL RESPONSE BEFORE AND AFTER 18 SECONDS PLASMA ETCHING IN FREON 14 + 8% O₂

12/79

REL. RESPONSE - mA/m²/cm²

WAVELENGTH - MICRONS

AFTER

BEFORE
Increase of $I_{SC}$

DUE TO AR COATING SOLAR CELLS AFTER PLASMA ETCHING THE FRONT SURFACE WITH FREON 14 + 8% $O_2$

\[ \begin{array}{|c|c|}
\hline
& 12/79 \\
\hline
40 & - \\
30 & - \\
20 & - \\
10 & - \\
0 & - \\
\hline
\end{array} \]

\[ \begin{array}{|c|c|c|c|c|c|}
\hline
\text{PLASMA ETCH TIME - SEC.} & 5 & 10 & 15 & 20 & 25 \\
\hline
\text{\$I_{SC}$ - \$I_{SC}$} & - & - & - & - & - \\
\hline
\end{array} \]
COMBINED ISC ENHANCEMENT FROM PLASMA ETCHING WITH FREON 14 + 8% O₂ FOLLOWED BY AR COATING

12/79

ETCH TIME - SEC.

EXPECTED ISC ENHANCEMENT FROM AR COAT
Phosphorus-Diffused (Ps-35 ?/□) Plasma Etched

10 Min. SE, 4000X

MAC/TSD SEM 18 4000X

MAC/TSD SEM 26 4000X

ORIGINAL PAGE IS OF POOR QUALITY
CHANGE OF SHORT CIRCUIT AND LOAD POINT CURRENT WITH PLASMA ETCHING IN SULFUR HEXAFLUORIDE

12/79

ETCH TIME - SECONDS

CHANGE OF CURRENT - PERCENT

0 15 30 45 60 75 90

0 10 -10

+10

271
SOLAR CELL SPECTRAL RESPONSE BEFORE AND AFTER 60 SECONDS ETCHING IN SULFUR HEXAFLUORIDE 12/79

REL. RESPONSE - MA/m²/cm²

WAVELENGTH - MICRONS

○ BEFORE
x AFTER
HIGH-RESOLUTION, LOW-COST SOLAR CELL CONTACT DEVELOPMENT (MIDFILM)

SPECTRCLAB
Nick Mardesich

Standard Cell Processing

SURFACE PREPARATION - 30% NaOH
JUNCTION FORMATION - SPIN-ON DIFFUSION SOURCE
ALUMINUM BACK SURFACE FIELD - SCREEN PRINTED ALUMINUM PASTE
CLEAN RESIDUAL ALUMINUM AND DIFFUSION OXIDE - HF AND BRUSH
JUNCTION CLEAN - LASER SCRIBE
*FRONT CONTACT - MIDFILM
AR COAT - EVAPORATED SiO_x

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

Ferro E-100 Midfilm Process
Program Task

1. EXPLORATORY DEVELOPMENT

II. ENVIRONMENTAL EVALUATION

III. INVESTIGATION OF ALTERNATE METALS

Silver Powder Evaluated

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<th>POWDER COMPOSITIONS</th>
<th>EVALUATION</th>
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<td>GRIDLINE THICKNESS (μ)</td>
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<td>1. 98% FINE FLAKE SILVER POWDER; 2% DRAKENFELD FRITZ METZ “C” (80)PbO(10)B2O3 - (10)SiO2 (Wt%)</td>
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<td>2. 98% FERRO SILVER POWDER; 2% DRAKENFELD FRIT</td>
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<tr>
<td>3. TFS 3347 COMPOSITION WITHOUT SCREENING MEDIUM</td>
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<td>4. 98% FERRO SILVER POWDER; 2% SPECTROLAB FRIT #2-</td>
<td>7</td>
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<td>5. 98% FERRO SILVER; 2% FERRO BISMUTH FRIT #3</td>
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<tr>
<td>6. 95% FERRO SILVER POWDER; 5% TFS 3347 FRIT</td>
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Photomicrographs of Midfilm Metallization

Good Metallization of Composition
No. 2 250X Mag.

Poor Metallization of Composition
No. 3 250X Mag.
Surface of Applied and Fired Silver-Frit Powders

Composition 2, 2000X Magnification

Composition 3, 2000X Magnification
Cross Section of Gridline and Substrate

Composition 2, 2000X Magnification

Composition 3, 2000X Magnification
Surface of Cell After Silver Was Etched Away Leaving Only Frit

Composition 2, 2000X Magnification

Composition 3, 2000X Magnification
Distribution of Midfilm Contact

**IR FIRED CELLS, POWDER COMPOSITION #2**

NO AR COATING

BELT SPEED 46 INCHES/MIN., ZONE 1, 2, 3, 4: 0, 900, 700, 700

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<th>I&lt;sub&gt;sc&lt;/sub&gt; (mA)</th>
<th>I&lt;sub&gt;500&lt;/sub&gt; (mA)</th>
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*Not taken into average.

**500 increased by 34% to account for AR coating.
### Midfilm Metallization Process

#### Environmental Evaluation - Humidity Test

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<th>$R_{shunt}$ (ohm)</th>
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Environmental Evaluation - Thermal Shock

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Environmental Evaluation - 5 min. baking

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### Midfilm Problems

**PROBLEMS**

1. **HIGH SERIES RESISTANCE**

2. **LOW SHUNT RESISTANCE**

3. **SILVER - SOLDER INTERACTION**

**SOLUTIONS**

1. OPTIMUM POWDER COMPOSITION

2. OPTIMUM APPLICATION PROCEDURE

3. MINIMUM HANDLING OF WATERS

**SOLDER THAT DOES NOT LEACH OUT SILVER**
Cost Effectiveness

\[ PR = (0.49 \cdot EQPT + 97 \cdot SOFT + 2.1 \cdot DLAB + 1.3 \cdot MATS + 1.3 \cdot UTIL) / QUAN. \]

\[ EQPT = 210,000 + 6,000 - 10,009 \times 206,000 \]

\[ SOFT = 1,500 \]

\[ DLAB = 1.0 \text{ PRSN.YRS./SHIFT} \times 4.7 \times 8,100 + 0.4 \text{ PRSN.YRS./SHIFT} \times 4.7 \times 11,000 = 58,750/\text{YR} \]

\[ MATS = (0.025 \text{ GM AG POWDER} \times 0.58/\text{GM} + 0.205 \text{ ML RESIN} \times 0.0171/\text{ML}) \times 55,890,000 \text{ CELLS/YR} \]

\[ UTIL = 0.0055 \text{ kWh/CELL} \times 55,890,000 \text{ CELLS/YR} \times 0.0452/\text{kWh} \]

\[ QUAN = 7500 \text{ CELLS/HR} \times 0.90 \times 8280 \text{ HR/YR} \times 55,890,000 \text{ CELLS/YR} \]

\[ Pr = (100,940 + 145,500 + 123,375 + 1,309,268 + 18,962) / 55,890,000 \]

\[ = 0.0304/\text{CELL} \]

\[ IF n = 0.13 \]

\[ \text{POWER/CELL} = 10.16^2 \text{ cm}^2 \times 0.1 \times 0.13 \]

\[ = 1.342 \text{ WATTS/CELL} \]

\[ Pr = 0.0226/\text{WATT} \]

Assuming no yield loss.
PULSE PROCESSING OF SOLAR CELLS

SPIRE CORP.

Contract Summary

DEVICE TECHNOLOGY

- OPTIMIZED IMPLANT PARAMETERS
  -- Low Energy (10-50 keV)
  -- Junctions and BSF

- FABRICATED REPRODUCIBLE 16.5% AM1 CELLS
  -- 3" Diameter
  -- Implant Compatible Metallization

- PROCESS CONFIRMED BY JPL CONTRACTORS

EQUIPMENT TECHNOLOGY

- INSTALLED FIRST SOLAR CELL IMPLANTER
  -- 300 Wafers/Hour
  -- Low Energy (10-50 keV)

- DESIGNED 100 MW/YR IMPLANTER
  -- 180 M²/Hour for 1986

Advantages of Ion Implantation

- MAXIMUM CELL EFFICIENCIES
  -- Reproducible
  -- High Yield
  -- Operator Independent

- CONTINUOUS MODE OPERATION
  -- High Throughputs
  -- Unlimited Scale-up

- MINIMUM ADDITIONAL PROCESSING
  -- No Wet Chemistry
  -- Line of Sight Process
  -- No Edge Etching
Ion-Implanted Furnace-Annealed Solar Cells

500 CELL PROCESS LOT
10.5 cm CZ
76 cm Ø

<table>
<thead>
<tr>
<th>$I_{sc}$ (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 1.2 1.3 1.4 1.5 1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voc (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>580 585 590 595 600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fill Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 13 14 15 16</td>
</tr>
</tbody>
</table>
Ion-Implanted Furnace-Annealed Silso Solar Cells

100 CELL PROCESS LOT
5Ω-cm SILSO
5 x 5 cm

Voc (V)

0.50 0.51 0.52 0.53 0.54 0.55 0.56

Isc (A)

0.56 0.58 0.60 0.62 0.64 0.66 0.68

AMI EFFICIENCY (%)
$2 \times 2$ cm Cells AMO $\pm 5^\circ C$

Diagram showing different annealing methods:
- Step Furnace Anneal
- Beam Pulse Anneal
- Nd:YAG Laser Pulse Anneal

-71 mW, 13.1% AMO
-66 mW, 12.6% AMO
-64 mW, 11.8% AMO

Note: AMO illumination $\pm 5^\circ C$
Pulsed Electron Beam Energy

7-6 cm BEAM
\( \bar{E} = 25 \text{ keV} \)

5-0 cm BEAM
\( \bar{E} = 12 \text{ keV} \)
Implanted/Pulse EB Annealed Cell 2138-2
AM0 25°C, 7.6 cm ø Cell n⁺pp⁺
Ion-Implanted Pulse-Annealed Solar Cells

500 CELL
PROCESS LOT
ION-ct cm CZ

[Ampere (amps)]

[Voltage (mV)]

[Efficiency (%)]

289
Annual Production Rates

ION BEAM CURRENT (milliamperes)

PRODUCTI N RATE (MW/yr)

0.9
0.8
0.7 duty cycle

8 10 12 14 16 18 20 22 24

8 10 12 14 16 18 20 22 24
Conceptual Drawing of a 100 mA Automated Production Implanter
Commercial Solar Ion Implanter for 1982 Goals

20 MWp/Yr Output
Cost in Production, 250K (1980s)
Wafer Processing Cost, 3.5¢/Watt (1980s)
Ion Implant Cost

Ion Implant Cost

- Basic Solar Implanter (1980) 1200K
- 100 MW/yr Machine (250K)
- 20 MW/yr Machine (250K)

20 MW/yr Machine

100 MW/yr Machine

1982 Goal

1986 Goal

Production Per Year (MWp)
SAMIS Cost Estimates

Price ($1980/Watt) vs Production QTY (MW/YR)

- (7.87 OHD RATE)
- (5.13 OHD RATE)
- TOTAL (4.4 OHD RATE)
- IMPLANT BSF
- ANNEAL & ETCH
- IMPLANT JUNCTION

294
LOT 2277
AMO - 25°C
2 x 2 cm (PEBA)
n"pp"104 cm S.

VOLTAGE (mV)

CURRENT (mA)

PEBA CELL UNIFORMITY
CONTACT DEVELOPMENT
APPLIED SOLAR ENERGY CORP.

Diffusion Data

- $\Delta$ Cu-Ag
- $\bigcirc$ Cu-Au
- $\bigoplus$ Cu-BE
- $\bigcirc$ Cr-Cu
- $\bigtriangleup$ Cu-Fe
- $\diamond$ Cu-Ni
- $\bigodot$ Pd-Cu
- $\times$ Cu-Pt
- $\circ$ Cu-Zr

* Only data found

$D(\text{cm}^2/\text{sec})$

$10^{-8}$

$10^{-9}$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^4 \left( \frac{0}{k^{-1}} \right)$

5 6 7 8 9 10 11 12

296
2000A Pd—Thick Ag

Change of $V_{oc}$ (mV)

Temperature (°C)

- Control
- 5m
- 15m
- 5m Pd-An
- 15m Pd-An
2000A Cr—Thick Ag

Change in ISC (mA)

Temperature (°C)

O: 5m Control
•: 15m Cr-Ag
+: 15m
□: 15m
1000A Pd—Thick Cu

Change in $V_{0C}$ (mV)

Temperature ($^\circ$C)

- Controls
- 5m Pd-Cu
- 15m Pd-Cu

301
1000A Pd - Thick Cu

- Controls
- Pd-Cu

Change in ISC (mA)

Temperature (°C)
Chromium-Copper Contacts:
Result of 5-min Heat Treatment

% CHANGE OF CFF

HEAT TREATMENT TEMPERATURE °C

-60 -50 -40 -30 -20 -10 0 +10 +20
300 400 500 600

x: 1000 Å
Δ: 2000 Å
o: 3000 Å
Chromium-Copper Contacts:
Result of 15-min Heat Treatment

HEAT TREATMENT TEMPERATURE °C

Δ CFF

x: 1000Å
Δ: 2000Å
o: 3000Å
Chromium-Nickel-Copper Contacts:
Result of 5-min Heat Treatment

°C

Heat Treatment Temperature

CHROMIUM 1000Å - NICKEL 1000Å
CHROMIUM 1000Å - NICKEL 2000Å
CONTROLS
Chromium-Nickel-Copper Contacts: Result of 15-min Heat Treatment

- CHROMIUM 1000Å - NICKEL 1000Å
- CHROMIUM 1000Å - NICKEL 2000Å
- CONTROLS

HEAT TREATMENT TEMPERATURE °C
\[ \Delta: \text{CHROMIUM } 1000\text{Å - NICKEL } 1000\text{Å} \]

\[ \odot: \text{CHROMIUM } 1000\text{Å - NICKEL } 2000\text{Å} \]

\[ \nabla: \text{CONTROLS} \]
\( \Delta \): CHROMIUM 1000Å - NICKEL 1000Å
\( \circ \): CHROMIUM 100Å - NICKEL 2000Å
\( \nabla \): CONTROLS

HEAT TREATMENT TEMPERATURE °C

FACTOR ÷ DARK CURRENT AT .3V

INCREASE

DECREASE
Plated Pd-Cr-Cu Cell With Print-on Plating Mask

2 1/4" Diameter Cell

$V_{OC} = 586$ mV

$I_{SC} = 620$ mA

CFF = 75%

$\eta_{AM1} = 10.3\%$ (no AR)

Temp = $25^\circ$C
2.25-in. Dia Contact Pattern

Contact Coverage: 12%
Grid Line Thickness: .5 mil
Cr-Ni-Cu Contacts: 15 min Heating

 CHANGE OF VOC (mV)

 SINTERING TEMPERATURE (°C)

 TI-PD-AG CONTROLS
 + 1000A-CR- 1000A-NI
 Q 1000A-CR- 2000A-NI
Cr-Cu Contacts: 15 min Heating

![Graph showing change of VOCC with sintering temperature](image)
The Following are SEM Photomicrographs of Copper Ink S079 Containing 5% AgF 5% Al-S; Eutectic and 5% Pb as a Function of Temperature. The Fifth Photo Shows Similar Ink with 5% Al-Ge Eutectic Instead of Silicon (Compare with First Photo)

(a) 975X

(b) 975X; N760°C, H760°C
(c) 975X; N760°C, H860°C

(d) 4800X; N760°C, H658°C
(e) 975X; N760°C, H658°C
SEM Photomicrograph of Doped Cu Ink S079
Containing 5% Si Al Eutectic,
5% Pb and 5% AgF, 480X

X-Ray Fluorescence Scan on Above. Log
Intensity vs X-Ray Energy in keV.
(a) 975X; 596°C N₂, 596°C H₂

(b) 4800X; 596°C N₂, 596°C H₂
(c) 975X; 658°C N₂, 658°C H₂

(d) 4800X, 658°C N₂, 658°C H₂
SEM Photomicrographs of S071 Copper Paste, Containing 5% AgF and 5% Pb, as a Function of Temperature
Corrected* Vapor Pressure Over Silver Fluoride

\[
\text{Vapor over liquid: } \log P(\text{atm}) = -1.023 \cdot 10^4 / T_{\text{K}} + 5.99
\]

\[
\text{Vapor over solid: } \log P(\text{atm}) = -0.937 \cdot 10^4 / T_{\text{K}} + 4.78
\]

* H. Goldman, Private comm. (Sep 1979)
<table>
<thead>
<tr>
<th>Sample</th>
<th>$V_m$</th>
<th>$I_m$</th>
<th>$P_m$</th>
<th>eff*</th>
</tr>
</thead>
<tbody>
<tr>
<td>79 (STEPED)</td>
<td>475</td>
<td>0.51</td>
<td>.242</td>
<td>9.4</td>
</tr>
<tr>
<td>79</td>
<td>0.485</td>
<td>.230</td>
<td>.230</td>
<td>9</td>
</tr>
<tr>
<td>CONTROL</td>
<td>0.445</td>
<td>.211</td>
<td>.211</td>
<td>8.2</td>
</tr>
<tr>
<td>80 (STEPED)</td>
<td>0.425</td>
<td>.202</td>
<td>.202</td>
<td>7.9</td>
</tr>
<tr>
<td>80</td>
<td>0.425</td>
<td>.202</td>
<td>.202</td>
<td>7.9</td>
</tr>
</tbody>
</table>

550°C
AM1, 28°C

*without AR coating
The diagram shows the current-voltage characteristics of a solar cell under different conditions. The graph plots current (in milliamperes) against voltage (in millivolts) for three different temperature ranges:

- **80-550°C**
- **79-550°C**
- **80-750°C**

For the 80-550°C range:

- Current at 0.5 A
- Voltage range from 0 to 600 mV

For the 79-550°C range:

- Current at 0.42 A
- Voltage range from 0 to 600 mV

For the 80-750°C range:

- Current at 0.46 A
- Voltage range from 0 to 600 mV

The power output is calculated as follows:

- For 80-550°C: $P_m = 4.75 \text{ mV} \times 0.5 \text{ A} = 2.37 \text{ mW}$, efficiency (eff) = 9.3%
- For 79-550°C: $P_m = 0.460 \text{ mV} \times 0.42 \text{ A} = 0.193 \text{ mW}$, efficiency (eff) = 7.5%

The graph also indicates an AM1, 28°C condition.
Initial Test Results From Cu Pastes (AM1)

<table>
<thead>
<tr>
<th>Paste</th>
<th>Cell</th>
<th>Short Circuit Current (A)</th>
<th>Open Circuit Voltage (V)</th>
<th>Maximum Power Point Voltage (V)</th>
<th>Maximum Power Point Current (A)</th>
<th>Maximum Power Point Power (W)</th>
<th>Fill Factor (F)</th>
<th>Bare Efficiency (%)</th>
<th>Coated Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S079</td>
<td>(1)</td>
<td>0.553</td>
<td>0.592</td>
<td>0.475</td>
<td>0.510</td>
<td>0.242</td>
<td>0.740</td>
<td>9.4</td>
<td>13.1</td>
</tr>
<tr>
<td>S079</td>
<td>(2)</td>
<td>0.542</td>
<td>0.588</td>
<td>0.475</td>
<td>0.485</td>
<td>0.310</td>
<td>0.723</td>
<td>9.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Control</td>
<td>(2)</td>
<td>0.531</td>
<td>0.585</td>
<td>0.475</td>
<td>0.445</td>
<td>0.211</td>
<td>0.653</td>
<td>8.2</td>
<td>11.5</td>
</tr>
<tr>
<td>S080</td>
<td>(1)</td>
<td>0.552</td>
<td>0.585</td>
<td>0.475</td>
<td>0.425</td>
<td>0.202</td>
<td>0.625</td>
<td>7.9</td>
<td>11.0</td>
</tr>
<tr>
<td>S080</td>
<td>(2)</td>
<td>0.498</td>
<td>0.585</td>
<td>0.475</td>
<td>0.425</td>
<td>0.202</td>
<td>0.694</td>
<td>7.9</td>
<td>11.0</td>
</tr>
<tr>
<td>S079</td>
<td>(3)</td>
<td>0.545</td>
<td>0.583</td>
<td>0.475</td>
<td>0.500</td>
<td>0.238</td>
<td>0.749</td>
<td>9.3</td>
<td>13.0</td>
</tr>
<tr>
<td>S080</td>
<td>(3)</td>
<td>0.545</td>
<td>0.583</td>
<td>0.475</td>
<td>0.490</td>
<td>0.233</td>
<td>0.733</td>
<td>9.1</td>
<td>12.7</td>
</tr>
</tbody>
</table>

S079 COPPER PASTE CONTAINING 5% AgF 5% Pb 5% Al-Si EUTECTIC
S080 " " " 5% AlGe EUTECTIC

(1) ASEC 2.25 IN OD SOLAR CELL APPROX 2 OHM-CM N/P MEDIUM JUNCTION DEPTH, STEPPED COLLECTOR
(2) ASEC 2.25 IN OD SOLAR CELL APPROX 2 OHM-CM N/P MEDIUM JUNCTION DEPTH, STRAIGHT COLLECTOR
(3) FRONT CONTACT APPLIED AFTER BACK CONTACT WAS FIRED

No BSF, FRONT CONTACT Ti-Y'D-AG, BACK CONTACT PASTE
ALL PASTE CONTACTS SHOWN, FIRED AT 550°C

Conclusions

1. The allmetal paste system has been metallurgically demonstrated.
2. Silver-lead, nickel-lead, and copper-lead adherent structures have been fabricated.
3. A two step system of firing has been devised allowing AgF activation in nitrogen, and base metal sintering in hydrogen.
4. For solar cell back contacts, the copper paste using eutectic Al-Si doping has given good results yielding 13% AM1 efficiencies and fill factors of 0.74%.
5. While all systems are solderable and seem stable metallurgically, more environmental tests are required.
COPPER CONDUCTOR LAYER FOR Si SOLAR CELLS

MOTOROLA, INC.

M. G. Coleman, R. A. Pryor and T. G. Sparks

Comparison of Metal Conductor Layers

<table>
<thead>
<tr>
<th></th>
<th>SOLDER (60Sn-40Pb)</th>
<th>COPPER</th>
<th>SILVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST PER POUND*</td>
<td>14.5</td>
<td>1.00</td>
<td>104.22</td>
</tr>
<tr>
<td>(ON 5-29-79)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESISTIVITY</td>
<td>14.5</td>
<td>1.673</td>
<td>1.59</td>
</tr>
<tr>
<td>(MICRO OHM-CM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DENSITY</td>
<td>8.53</td>
<td>8.96</td>
<td>10.49</td>
</tr>
<tr>
<td>(GM/CM³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RELATIVE WEIGHT</td>
<td>8.26</td>
<td>1.0</td>
<td>1.11</td>
</tr>
<tr>
<td>PER UNIT CONDUCTIVITY</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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.
Cost of Metal Conductors ($/lb)
(Based on Pure Metal Prices)

<table>
<thead>
<tr>
<th>DATE</th>
<th>SOLDER (60 Sn-40 Pb)</th>
<th>COPPER</th>
<th>SILVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-6-77</td>
<td>3.77</td>
<td>0.60</td>
<td>64.50</td>
</tr>
<tr>
<td>10-6-78</td>
<td>4.32</td>
<td>0.685</td>
<td>80.62</td>
</tr>
<tr>
<td>3-29-79</td>
<td>4.67</td>
<td>1.00</td>
<td>104.22</td>
</tr>
<tr>
<td>11-29-79</td>
<td>5.18</td>
<td>1.005</td>
<td>254.65</td>
</tr>
</tbody>
</table>

REGARDLESS OF THE TIMEFRAME,
COPPER HAS A SIGNIFICANT COST ADVANTAGE!

Diffusion Kinetics

1. \[ D = D_0 e^{-\frac{Q}{RT}} \]
   - \( D \) = Diffusion Coefficient
   - \( D_0 \) = Frequency Factor
   - \( Q \) = Activation Energy
   - \( R \) = Gas Constant
   - \( T \) = Absolute Temperature

2. \[ C = C_0 \text{erf}\left(\frac{X}{\sqrt{4DT}}\right) \]
   - \( C_0 \) = Surface concentration or initial concentration
   - \( N \) = Geometry Factor
   - \( T \) = Time of Diffusion
   - \( D \) = Diffusion Coefficient

The quantity \( \sqrt{DT} \) is a distance.
- Common measure of impurity penetration
- At a distance from the source of \( 10 \sqrt{DT} \), the amount of impurity is vanishingly small
- A suitable barrier for diffusion must have a thickness of at least \( 10 \sqrt{DT} \)
Cost of Metal Conductors ($/lb)  
(Based on Pure Metal Prices)

<table>
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<td>4.32</td>
<td>0.685</td>
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</tr>
<tr>
<td>11-29-79</td>
<td>5.18</td>
<td>1.005</td>
<td>254.65</td>
</tr>
</tbody>
</table>

Regardless of the timeframe, copper has a significant cost advantage!

Diffusion Kinetics

1. \[ D = D_0 \, e^{\frac{-E}{R T}} \]

   - \( D \): Diffusion Coefficient
   - \( D_0 \): Frequency Factor
   - \( E \): Activation Energy
   - \( R \): Gas Constant
   - \( T \): Absolute Temperature

2. \[ C = C_0 \, \text{erf} \left( \frac{x}{\sqrt{4D T}} \right) \]  
   (Limited Source)

   \[ C = C_0 \, \text{erf} \left( \frac{x}{\sqrt{4D T}} \right) \]  
   (Infinite Source)

   - \( C \): Concentration at distance \( x \) from surface
   - \( C_0 \): Surface concentration or initial concentration
   - \( N \): Geometry Factor
   - \( T \): Time of Diffusion
   - \( D \): Diffusion Coefficient

The quantity \( \sqrt{DT} \) is a distance:

- **Common measure of impurity penetration**
- **At a distance from the source of** \( 10\sqrt{DT} \), the amount of impurity is vanishingly small
- **A suitable barrier for diffusion must have a thickness of at least** \( 10\sqrt{DT} \)

\[ C = \frac{5}{327} \]
Copper Diffusion in Silicon

1. EXTRAPOLATE DATA* FROM NEAR 400°C

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>D (cm²/sec)</th>
<th>Dt (cm) (T = 20 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.0 x 10⁻¹⁰</td>
<td>0.44</td>
</tr>
<tr>
<td>80</td>
<td>1.35 x 10⁻⁹</td>
<td>0.92</td>
</tr>
<tr>
<td>100</td>
<td>3.15 x 10⁻⁹</td>
<td>1.4</td>
</tr>
<tr>
<td>120</td>
<td>6.7 x 10⁻⁹</td>
<td>2.1</td>
</tr>
</tbody>
</table>

2. QUALITATIVELY VERIFIED AT MOTOROLA

*R.M. HALL, ET. AL. (REFERENCE IN JULY QUARTERLY)

COPPER DIFFUSES RAPIDLY INTO SILICON
AND DEGRADES THE P-N JUNCTION
MUST, THEREFORE, HAVE A COPPER BARRIER

Nickel

1. PROMISING DIFFUSION BARRIER FOR COPPER.
2. NICKEL AND COPPER FORM COMPLETE SOLID SOLUTIONS.
3. NUMEROUS STUDIES OF INTERDIFFUSION OF COPPER AND NICKEL.
   - ALL AT HIGH TEMPERATURES
   - SHOW SIMILAR DIFFUSION PARAMETERS
4. EXTRAPOLATION OF DIFFUSION DATA IN FACE-CENTERED-CUBIC METALS IS A GOOD APPROXIMATION.
Diffusion of Copper in Nickel

EXTRAPOLATION FROM DATA** USING TYPICAL VALUES OF

\[ Q = 60 \text{ Kcal/g. Atom} \]
\[ D_0 = 1.5 \text{ cm}^2/\text{sec} \]

\( T = 20 \text{ YEARS} \)

<table>
<thead>
<tr>
<th>( T (\degree \text{C}) )</th>
<th>( D (\text{cm}^2/\text{sec}) )</th>
<th>( D_T (\text{cm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>7.8 \times 10^{-36}</td>
<td>7 \times 10^{-14}</td>
</tr>
<tr>
<td>200</td>
<td>2.2 \times 10^{-28}</td>
<td>3.7 \times 10^{-14}</td>
</tr>
<tr>
<td>300</td>
<td>1.6 \times 10^{-23}</td>
<td>1 \times 10^{-7}</td>
</tr>
</tbody>
</table>

\( T = 30 \text{ MINUTES} \)

<table>
<thead>
<tr>
<th>( T (\degree \text{C}) )</th>
<th>( D (\text{cm}^2/\text{sec}) )</th>
<th>( D_T (\text{cm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.6 \times 10^{-23}</td>
<td>1.7 \times 10^{-10}</td>
</tr>
</tbody>
</table>

**JOHN ASKILL, TRACER DIFFUSION DATA FOR METALS, AND SIMPLE OXIDES, IFI/PLENUM DATA CORP. NEW YORK, 1970.

A PROMISING METALLIZATION SYSTEM, THUS, IS (PALLADIUM) - NICKEL - COPPER.

Metallization Process Sequence

1. IMMERSION PALLADIUM PLATE
2. HEAT TREATMENT: 15 MINUTE AT 250\degree \text{C}
3. ELECTROLESS NICKEL PLATE
4. CONTACT FORMATION: 30 MINUTE AT 250\degree \text{C}.
5. ELECTROLYTIC COPPER PLATE
COPPER METALLIZATION

WESTINGHOUSE RESEARCH

ADVANTAGES
- Copper Less Expensive than Silver
- Copper Has Nearly the Same Electrical Conductivity as Silver
- Electroplating of Copper is Industrial Practice

APPROACH
- Evaluate Following Systems on Silicon:
  - Cu
  - Pd Cu
  - Ti Pd Cu
  - Ti Cu
- Determine Requirements for Barrier Metal

Electroless Copper Plating Solution

The electroless copper plating solutions have been obtained from Shipley Co., In., Newton, MA. The system consists of three solutions CP 70A, CP 70M and Cuposilt Z. The proportions used are as follows:

1. Add 1 part CP 70A and 2 parts CP 70M to 16 parts of delonized water.
2. Add 1 part Cuposilt Z to the mixture just before plating.
3. Maintain bath temperature at 49°C ± 2°C.
4. Time 20 seconds.
5. Rinse in running delonized water for 10 minutes.
6. Dry with N₂.

Electrolytic Copper Plating Solution

1. Dissolve 200 grams of CuSO₄ - 5H₂O in 1 liter of delonized water.
2. Add carefully, 30 ml of H₂SO₄.
3. Plating temperature 20 - 40°C
4. Current density 20 - 40 mA/cm².
5. Ratio of cathode to anode 1:1
6. Anode - copper.
Evaporated or Plated Cu on Silicon

- Yield - 30 - 40%
- Survived Samples - n - 10 - 11%
  \( R_s = 0.5 \Omega \)
  \( R_{sh} = 2 - 5 \Omega \)

- Yield losses associated with low shunt resistance and large excess junction current. Presumably due to copper diffusing to junction and precipitating during cell processing.
  \((T_{MAX} = 150^\circ C)\)

Screened Ag on Silicon

- Samples heated at 250°C for 18 hrs.
- Excess junction current increased by factor of 10; efficiency decreased by 1.5%

Evaporated Pd-Plated Cu Contacts

<table>
<thead>
<tr>
<th></th>
<th>800Å Pd + 4 µm Cu</th>
<th>3000Å Pd + 4 µm Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unsintered  Sintered</td>
<td>Unsintered  Sintered</td>
</tr>
<tr>
<td>( n(%) )</td>
<td>12.7  6.63</td>
<td>13.0  4.25</td>
</tr>
<tr>
<td>( I_{SC}(mA) )</td>
<td>30.5  29.7</td>
<td>29.8  29.8</td>
</tr>
<tr>
<td>( V_{OC} (V) )</td>
<td>0.542  0.501</td>
<td>0.552  0.350</td>
</tr>
<tr>
<td>FF</td>
<td>0.727  0.426</td>
<td>0.746  0.4</td>
</tr>
<tr>
<td>( R_s(\Omega) )</td>
<td>0.8  0.4</td>
<td>0.6  0.3</td>
</tr>
<tr>
<td>( R_{shL,V} (Ku) )</td>
<td>46  40</td>
<td>33  30</td>
</tr>
<tr>
<td>( I_{j}</td>
<td>_{an}(mA) )</td>
<td>0.01  5.67</td>
</tr>
</tbody>
</table>

- Sintering was done at 300°C for 15 min. in \( N_2 \).
- Sintering severely degrades the junction response.
- Unsintered Pd is unable to form a barrier for Cu diffusion regardless of Pd thickness.
- AM-1, AR-coated
Sintered Pd-Plated Cu Contacts

800 Å Pd (Sintered at 300°C) + 4 μm Plated Cu

<table>
<thead>
<tr>
<th>System</th>
<th>Unsintered</th>
<th>Sintered (150°C)</th>
<th>System</th>
<th>Unsintered</th>
<th>Sintered (300°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (%)</td>
<td>12.5</td>
<td>6.6</td>
<td></td>
<td>12.4</td>
<td>3.5</td>
</tr>
<tr>
<td>ISC (mA)</td>
<td>29.9</td>
<td>29.9</td>
<td></td>
<td>29.7</td>
<td>26.3</td>
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<tr>
<td>V OC (V)</td>
<td>0.538</td>
<td>0.488</td>
<td></td>
<td>0.513</td>
<td>0.298</td>
</tr>
<tr>
<td>FF</td>
<td>0.755</td>
<td>0.458</td>
<td></td>
<td>0.725</td>
<td>0.420</td>
</tr>
<tr>
<td>RS (Ω)</td>
<td>1.5</td>
<td>0.46</td>
<td></td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>RS at -1V (Ω)</td>
<td>100</td>
<td>60</td>
<td></td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Jg at 0.3V (mA)</td>
<td>0.019</td>
<td>4.5</td>
<td></td>
<td>0.038</td>
<td>11</td>
</tr>
</tbody>
</table>

- **Heat Treatment of System (Sintered Pd + Plated Cu) Severely Degraded Junction**
- **Pd Sintered at 300°C Does Not Serve as a Barrier for Cu Diffusion**
- **AM-1 - AR Coated**

Ti-Pd-Cu System

(Evaporated Ti-Pd-Ag) Vs (Evaporated Ti-Pd-Plated Cu)

<table>
<thead>
<tr>
<th>Ti-Pd-Ag</th>
<th>Ti-Pd-Cu 300°C Sinter</th>
<th>Ti-Pd-Cu 400°C Sinter</th>
<th>Ti-Pd-Cu 500°C SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (%)</td>
<td>14.0</td>
<td>14.2</td>
<td>13.2</td>
</tr>
<tr>
<td>ISC (mA)</td>
<td>30.7</td>
<td>30.5</td>
<td>30.6</td>
</tr>
<tr>
<td>V OC (V)</td>
<td>0.572</td>
<td>0.580</td>
<td>0.580</td>
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<tr>
<td>FF</td>
<td>0.74</td>
<td>0.754</td>
<td>0.76</td>
</tr>
<tr>
<td>PS (Ω)</td>
<td>0.6</td>
<td>0.45</td>
<td>0.5</td>
</tr>
<tr>
<td>P_sh (kΩ)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>J_0/3V (mA)</td>
<td>0.044</td>
<td>0.044</td>
<td>0.040</td>
</tr>
<tr>
<td>t_ocd (μsec)</td>
<td>11</td>
<td>11.5</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Dendritic web cells
AR coated; AM-1
Test for Stability of Ti-Pd-Cu System

<table>
<thead>
<tr>
<th>Test Cond.</th>
<th>$I_{sc}$ (mA)</th>
<th>$V_{oc}$ (V)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Fabricated</td>
<td>30.4</td>
<td>29.8</td>
<td>.512</td>
</tr>
<tr>
<td>75 hrs./225 C in $N_2$</td>
<td>30.4</td>
<td>29.8</td>
<td>.520</td>
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<tr>
<td>23 hrs./225 C in $N_2$</td>
<td>30.0</td>
<td>29.5</td>
<td>.520</td>
</tr>
<tr>
<td>375 hrs./225 C in $N_2$</td>
<td>30.0</td>
<td>29.5</td>
<td>.522</td>
</tr>
<tr>
<td>600 hrs./225 C in $N_2$</td>
<td>30.0</td>
<td>29.7</td>
<td>.521</td>
</tr>
</tbody>
</table>

- Cells AR coated
- Measured at AM-1, 91.6 mW/cm²
- TiPdCu is as stable as baseline TiAg

Ti-Cu System

**FORMATION OF TiSi₂**

- Silicide formed at 700°C in $N_2$ as determined by resistivity measurements
- In Ti contact systems, Ti - not TiSi₂ - is acting as a barrier material
Comparison of Costs (Based on SAMICS)

Cu vs. Ag Electroplating

(1980 $ per peak watt)

- Cost of Ag electroplating process .................. $0.034
- Position of process cost applicable to Ag metal .................. $0.018
- Cost of Cu metal plus Cu flash and wet cleaning before plating .................. $0.017
- Cost saving using Cu plating .................. $0.011

$0.018 - $0.017 = $0.011

(Does not take into account any yield differences)

Conclusions

- Best adhesion achieved only when electroless copper flash used before copper electroplating
- Ti required as a barrier metal
- TiPdCu is equal to TiPdAg
AUTOMATED SOLAR MODULE ASSEMBLY

KULICKE & SOFFA INDUSTRIES

Max Bycer

Automated Solar Module Assembly Machine

PROPOSED MACHINE SYSTEM

MACHINE TO:
- INTERCONNECT CELLS IN STRINGS UP TO 4- FEET LONG
- HANDLE 3-INCH DIAMETER SOLAR CELLS (ADAPTABLE TO 100 mm DIAMETER CELLS)
- ELECTRICALLY TEST CELL INTERCONNECTS

TARGET MACHINE CYCLE:
- 5 SECONDS/CELL AT 95% MINIMUM YIELD
Bonding Without Inversion of Cell

SECOND INTERCONNECT STATION

FEED

COLLECTOR SIDE UP - BOND TAKES PLACE ON UNDERSIDE OF SECOND CELL

Bonding With Inversion of Cell

SECOND INTERCONNECT STATION

FEED

COLLECTOR SIDE DOWN - BOND TAKES PLACE ON TOP SIDE OF FIRST CELL

Advantages of Inverting Cell at Bonding Step

1. It minimizes contact on the sun (collector) side of the cell.
2. Inverting the cells allows bonding of second interconnect from the top side.
3. Inverting the cells facilitates making string interconnections in the module array.
Tabs Formed and Placed Before Bonding
Tabs Bonded on Collector Side
Vacuum Pickup Lance of Bonded String
AUTOMATED PROCESS DEVELOPMENT

PROCESSING STEPS:

PREPARATION AND FEED STATION

1. FEED CELL FROM CASSETTE
2. VACUUM CLAMP CELL
3. OPTICALLY ORIENT CELL
4. DISPENSE SOLDER PASTE TO CELL
5. FEED INTERCONNECT RIBBON AND FORM STRAIN RELIEF CRIMP
6. FEED INTERCONNECT RIBBON ONTO CELL AND APPLY SOLDER PASTE TO TRAILING LEADS
7. CUT INTERCONNECT RIBBON

ROBOT

1. VACUUM PICKUP PREPARED CELL
2. MOVE AWAY FROM PREPARATION AND FEED STATION AND BEGIN INDUCTION HEATING
3. PLACE CELL ON TOP OF PREVIOUS CELL CONTACTS
4. INDUCTION HEAT UNTIL SOLDERED
5. ROBOT LEAVES CELL TO CONTINUE CYCLE
Feed Cell From Cassette
Vacuum Clamp Cell
Optically Orient Cell
Dispense Solder Paste to Cell
Feed Interconnect Ribbon and Form
Strain Relief Crimp

Feed Interconnect Ribbon Onto Cell
and Apply Solder Paste to Trailing Leads
Cut Interconnect Ribbon
Vacuum Pickup Prepared Cell
Move Away From Preparation and Feed Station and Begin Induction Heating
Place Cell on Top of Previous Cell Contacts
Induction Heat Until Soldered
Robot Leaves Cell to Continue Cycle
ENGINEERING AREA

In keeping with the theme of this PIM, Module Design, presentations by Engineering Area in-house personnel and contractors (see below) concentrated on Module Design Technology. Two of these presentations, "Lessons Learned that Affect Module Design" and "Module/Array Design," are described in detail (pp. 3-15 and 383-455, respectively). The remaining presentations are described below along with their supporting graphic material. A number of major Engineering Area in-house activities and contracts were not reported on at this PIM, but are listed for reference on Page 353. Descriptions of the unreported Engineering Area contractor activities appeared in the PIM handout (5101-140).

**Engineering Area Presentations**

- LESSONS LEARNED IN MODULE ENGINEERING
- MODULE/ARRAY DESIGN OPTIMIZATION
  - ELECTRICAL CIRCUIT DESIGN
  - MECHANICAL/STRUCTURAL DESIGN
  - ENVIRONMENTAL REQUIREMENTS
  - ELECTRICAL SAFETY
- MODULE TERMINALS STUDY (MOTOROLA)
- GLASS SIZING STUDY (JPL)
- LOW-COST STRUCTURES DEVELOPMENT (JPL/KAISER)
- PRODUCT LIABILITY (CARNEGIE-MELLON)
Unreported Engineering Activities

- Residential Array O&M Study (Burt Hill)
- Residential Array Industrial Design (T&G)
- Residential Integrated Array Design (RFP)
- PV-Thermal Module Development (JPL/RFP)
- Array Wind Tunnel Testing (Boeing)
- Cell Fracture Mechanics Testing (JPL)
- Environmental Test Development
  - Hot-Spot Endurance (JPL)
  - Emqua (DSET)
  - Soiling (JPL)
  - Insulation Durability (JPL)
- Array Standards (W/SEI)
In the Engineering/Operations/PA&I Intertechnology Session (Wednesday, 3:45 pm) presentations were made covering the status of IPEG 2, module termination requirements, and module/array structural design investigations. R. W. Aster (JPL) described recent changes and updating of IPEG to incorporate the experiences gained from the last two years of working with SAMIS. The new annual revenue input data coefficients were provided and a sample case described to show the comparison between IPEG and IPEG-2. F. Mosna of Motorola described the results of the module termination requirements contract. Selection of criteria and rating methods, typical candidate hardware features and capabilities, life-cycle cost data, and recommendations of promising termination types were provided. Don Moore (JPL) described the results of extensive finite element analyses that have led to development of a recommended design method for thickness sizing of glass superstrate or substrate modules. Both the theory and example problems were described. Details including the necessary deflection versus load nomographs for application of this design method will be the subject of LSA Document 5101-148, scheduled for release in March 1980. In a related presentation A. Wilson (JPL) described in-house activities supporting design, fabrication and test of low-cost array structures for intermediate load applications. Cost estimates for a variety of panel and foundation approaches were provided. A full scale 8 x 16 ft. panel structure that was successfully fabricated and tested to a 50 lb/ft² loading was described. The panel was on display during coffee. The graphic material supporting these four presentations follows.

INTER-TECHNOLOGY SESSION

J.C. Arnett, Chairman

WED. 9:30-5:30

1) IPEG 2 - R. ASTER, JPL
2) MODULE TERMINATIONS - F. MOSNA, MOTOROLA
3) GLASS SIZING - D. MOORE, JPL
4) ARRAY STRUCTURES - A. WILSON, JPL
IPEG 2
IMPROVED PRICE ESTIMATION GUIDELINES

JET PROPULSION LABORATORY

R. W. Aster

• MOTIVATION AND BASIC CHANGES
• NEW EQUATION
• COMPARISONS
• PLANS

Motivation and Basic Changes

• INCORPORATE 2 YEARS OF SAMIS EXPERIENCE INTO IPEG
  • IPEG 2 FACILITIES COSTS NOW MATCH SAMIS
  • IPEG 2 EQUIPMENT RELATED COSTS ARE LARGER, AND NOW MATCH SAMIS
  • IPEG 2 STARTUP COSTS ARE NOW SMALLER
• IPEG 2 ALLOWS SEVERAL EQUIPMENT LIFETIMES
• IPEG 2 WILL GIVE MANUFACTURING PRICE ESTIMATES IN 1980 DOLLARS
The New Equation for Required Annual Revenue

<table>
<thead>
<tr>
<th>INPUT DATA</th>
<th>EQPT (3-20 YEAR LIFETIME)</th>
<th>FT²</th>
<th>DLAB</th>
<th>MATS &amp; UTIL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 5 7 10 15 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COEFFICIENT</td>
<td>.83 .65 .57 .52 .48 .46</td>
<td>109.</td>
<td>2.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

WHERE:

- EQPT is the installed cost of equipment in 1980 dollars
- FT² is the process area required by the equipment and its operators, in square feet
- DLAB is the annual cost of labor (including fringe benefits)
- MATS & UTIL is the annual cost of materials, supplies, and utilities

Comparisons

<table>
<thead>
<tr>
<th></th>
<th>OLD IPEG</th>
<th>NEW IPEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQUIPMENT COEFFICIENT (7 YR)</td>
<td>0.49</td>
<td>0.57</td>
</tr>
<tr>
<td>FT² COEFFICIENT (1980 DOLLARS)</td>
<td>135.8</td>
<td>109.0</td>
</tr>
<tr>
<td>DLAB COEFFICIENT</td>
<td>2.1</td>
<td>2.1*</td>
</tr>
<tr>
<td>MATS &amp; UTIL COEFFICIENT</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>A RECENT SAMIS PRINTOUT (SAMIS PRICE = 0.90 $/Wp)</td>
<td>0.97</td>
<td>0.93</td>
</tr>
</tbody>
</table>

*THIS IS FOR DIRECT LABOR WITH FRINGE BENEFITS. INCREASE THIS COEFFICIENT TO 2.8 IF FRINGE BENEFITS ARE NOT INCLUDED.
Operating Costs and Other Costs

(7-YEAR EQUIPMENT LIFETIME CASE)

OPERATING COST = 6 x FT² + 1.7 x DLAB + 1.0 x (MATS + UTIL)

OTHER COSTS:

- RETURN ON EQUITY
- INTEREST EXPENSE
- ONE-TIME COSTS
- INCOME TAXES (LESS INVESTMENT TAX CREDIT)
- PROPERTY TAXES
- INSURANCE
- REPLACEMENT OF CAPITAL INVESTMENT
- MISCELLANEOUS EXPENSE

FINAL COST = 0.57 x EQPT + 109 x FT² + 2.1 x DLAB + 1.2 x (MATS + UTIL)
PV MODULE ELECTRICAL TERMINATION
DESIGN REQUIREMENTS

MOTOROLA, INC.
F. Mosna

Study Summary

OBJECTIVE:
DEVELOP INFORMATION TO FACILITATE THE SELECTION
AND IMPROVEMENT OF LIFE-CYCLE COST-EFFECTIVE
ELECTRICAL TERMINATION HARDWARE

APPROACH:
DEVELOP REQUIREMENTS
IDENTIFY EXISTING HARDWARE
EVALUATE CANDIDATES

STATUS:
FINAL REPORT TO BE AVAILABLE MID-DECEMBER

TASK 1
DEVELOP MODULE AND ARRAY DESIGN REQUIREMENTS.
A. ANALYSIS AND SURVEY OF MANUFACTURERS,
   USERS, AND CODE GROUPS.
B. DEVELOP ELECTRICAL TERMINATION SELECTION
   CRITERIA.

TASK 2
IDENTIFY EXISTING ELECTRICAL TERMINATION CANDIDATE
HARDWARE.
A. SURVEY MANUFACTURERS, USERS, AND GOVERNMENT
   AGENCIES.
B. RANK CANDIDATE TERMINATION HARDWARE.
C. SUMMARIZE ATTRIBUTE DEPENDENCIES.

TASK 3
EVALUATE CANDIDATES AND POTENTIAL IMPROVEMENTS
A. IDENTIFY PROMISING HARDWARE.
B. IDENTIFY IMPROVEMENTS FOR COST REDUCTION.
C. IDENTIFY COST DRIVERS/REQUIREMENT
   MODIFICATIONS FOR COST REDUCTION.
Selection Criteria

FUNCTIONAL
- Voltage Rating
- Current Rating
- Insulation and Seal Level
- Ground Provision
- Heat Dissipation
- Disconnect Cycles
- Contact Resistance and Pressure
- Reliability (MTBF)

MANUFACTURING
- Preparation Time
- Productivity
- Repairability
- Labor Skill Level
- Special Tools
- Safety

ENVIRONMENTAL DURABILITY
- Moisture
- Temperature Cycling
- Corrosive Atmosphere and Contamination
- Vandalism
- UV Radiation
- Vibration and Strain Relief

UTILITY
- Series and Parallel Connections
- Wire-to-Wire Connections
- Panel-to-Wire Connections

CODE
- NEC

COST

359
Candidate Hardware

I. SPRING CLIP
II. CRIMP
   BUTT SPLICE
   PARALLEL SPLICE
   CLOSED END
III. TWIST-ON
IV. PLUG/RECEPTACLE
V. INSULATION DISPLACEMENT
VI. HAND-SOLDER
VII. SCREW
VIII. WELD
IX. WIRE WRAP
THREE METHODS OF SPLICING WIRES WITH CRIMPING TOOL AND CONNECTORS.
Rating System Method

- Assign values to each termination type for each selection criterion.

- Assign weighting factors to each selection criterion on the basis of application (remote, residential, intermediate, industrial).

- Multiply termination value with application factor for each termination type in each application.

- Termination receiving highest algebraic sum is best-suited electrical termination in each application.
## Termination Attributes

<table>
<thead>
<tr>
<th>TERMINATION TYPE</th>
<th>VOLTAGE RATING</th>
<th>CURRENT RATING</th>
<th>INSUL. LEVEL</th>
<th>SEAL LEVEL</th>
<th>GND PROVS.</th>
<th>HEAT DISSIP.</th>
<th>DISCON. CYCLES</th>
<th>CONTACT RES.</th>
<th>RELIAB. (MTBF)</th>
<th>PREP TIME</th>
<th>PRODUC. ABILITY</th>
<th>REPAIR ABILITY</th>
<th>LABOR SKILL LEVEL</th>
<th>SPEC TOOLS</th>
<th>SAFETY</th>
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<tbody>
<tr>
<td>I SPRING CLIP</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
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<td>4</td>
<td>4</td>
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<tr>
<td>II CRIMP</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
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<td>3</td>
<td>4</td>
<td>3</td>
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<tr>
<td>III TUDIOON</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>3</td>
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<td>IV PLUG RECEPT</td>
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<td>2</td>
<td>3</td>
<td>3</td>
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<tr>
<td>VI HAND SOLDERED</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>4</td>
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<tr>
<td>VII SCREW</td>
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<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
<td>2</td>
<td>4</td>
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<tr>
<td>VIII WELDED</td>
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<td>1</td>
<td>4</td>
<td>1</td>
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<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>IX WIRE-wrap</td>
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<td>2</td>
<td>4</td>
<td>1</td>
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<table>
<thead>
<tr>
<th>TERMINATION TYPE</th>
<th>DURABILITY</th>
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<tr>
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<td>TEMP. CYCLE</td>
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<td>4</td>
</tr>
<tr>
<td>II CRIMP</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>III TWIST-ON</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>IV PLUG/RECEPTACLE</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>V INSUL. DISP.</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>VI HAND-SOLDERED</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>VII SCREW</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>VIII WELDED</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>IX WIRE WRAP</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

* = All termination types considered sealed in some manner

1 = poor, unacceptable; 2 = fair, average; 3 = good, above average; 4 = excellent
### Application Attribute Weighing Factors

<table>
<thead>
<tr>
<th>APPLICATIONS</th>
<th>Attributes</th>
<th>DURABILITY</th>
<th>FUNCTIONAL</th>
<th>MANUFACTURING</th>
<th>UTILITY</th>
<th>CODE</th>
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<tbody>
<tr>
<td></td>
<td>Moisture</td>
<td>TEMP. CYCLING</td>
<td>Compos. Atm.</td>
<td>Contamination</td>
<td>UV Radiation</td>
<td>Vibration</td>
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<td>Remote</td>
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<td>1 4 4 1 2</td>
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<td>Residential</td>
<td>3 2 1 2 2 3 2 2 4 4 4 4 4 4 1 1 1 2 2 2 3 2 2 4 2 3 3 2 4</td>
<td></td>
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<td></td>
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<td>Industrial</td>
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<td></td>
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* These factors to be multiplied by termination attribute ratings (above) for final ranking.
### Ranking by Numerical Order

<table>
<thead>
<tr>
<th>RANK</th>
<th>APPL</th>
<th>REMOTE</th>
<th>RESIDENTIAL</th>
<th>INTERMEDIATE</th>
<th>INDUSTRIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>PLUG/RECEPT (301)</td>
<td>PLUG/RECEPT (254)</td>
<td>PLUG/RECEPT (284)</td>
<td>PLUG/RECEPT (289)</td>
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<tr>
<td>2</td>
<td></td>
<td>CRIMP (293)</td>
<td>CRIMP (239)</td>
<td>SCREW (267)</td>
<td>SCREW (283)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>SCREW (287)</td>
<td>SCREW (238)</td>
<td>CRIMP (260)</td>
<td>CRIMP (272)</td>
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<tr>
<td>4</td>
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<td>INSL. DISP. (271)</td>
<td>INSL. DISP. (213)</td>
<td>INSL. DISP. (244)</td>
<td>INSL. DISP. (256)</td>
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<tr>
<td>5</td>
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<td>WELDED (260)</td>
<td>TWIST-ON (209)</td>
<td>TWIST-ON (231)</td>
<td>TWIST-ON (240)</td>
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<tr>
<td>6</td>
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<td>TWIST-ON (259)</td>
<td>HAND-SOLDER (197)</td>
<td>WELDED (226)</td>
<td>HAND-SOLDER (237)</td>
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<tr>
<td>7</td>
<td></td>
<td>WIRE-WRAP (256)</td>
<td>WELDED' (198)</td>
<td>WIRE-WRAP (224)</td>
<td>WIRE-WRAP (237)</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>HAND-SOLDER (223)</td>
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<td>9</td>
<td></td>
<td>HANd-SOLDER (249)</td>
<td>WIRE-WRAP (195)</td>
<td>SPRING CLIP (209)</td>
<td>SPRING CLIP (222)</td>
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<tr>
<td></td>
<td></td>
<td>SPRING CLIP (242)</td>
<td>SPRING CLIP (180)</td>
<td>SPRING CLIP (209)</td>
<td>SPRING CLIP (222)</td>
</tr>
</tbody>
</table>
Typical Initial Costs of Generic Termination Types
(Wire Size 12AWG, Maximum Current 40 Amps)

(VOLUME)

(TERMINATION COST)

(WIRE SIZE 12AWG; MAXIMUM CURRENT 40 AMPS)
Factors Affecting Cost

- MANUFACTURING MATERIAL, EQUIPMENT, LABOR
- INSTALLATION LABOR, SKILL, EQUIPMENT
- SEALING MATERIAL, LABOR

Cost vs MTBF

<table>
<thead>
<tr>
<th>Component</th>
<th>MTBF (HRS.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCREW</td>
<td>$5.00</td>
</tr>
<tr>
<td>SPRING CLIP</td>
<td>$4.00</td>
</tr>
<tr>
<td>INSULATION DISPLACEMENT</td>
<td>$3.00</td>
</tr>
<tr>
<td>WELD</td>
<td>$2.00</td>
</tr>
<tr>
<td>PLUG/RECEPTACLE</td>
<td>$1.00</td>
</tr>
<tr>
<td>TWIST-ON</td>
<td>$1.00</td>
</tr>
<tr>
<td>CRIMP</td>
<td>$1.00</td>
</tr>
</tbody>
</table>
Factory and Field Assembly Costs
For Termination Types

- SEALING MATERIAL AND LABOR
- FIELD LABOR AT $19.15/HR.
- FACTORY LABOR AT $9.70/HR.
- INITIAL COST

Initial Cost
- SPRING CLIP
- CRIMP-TYPE
- TWIST-ON
- PLUG/RECEPTACLE
- INSULATION DISPLACEMENT
- HAND SOLDER
- SCREW-TYPE
- WELDED
- WIRE WRAP
Field Termination Replacement
Due to Termination Failure

- Field labor rate $19.50/hr,
- Not including: travel time, fault detection time, preparation time.
Suggested Crimp Termination Seal

Existing Electrical Terminations Most Suitable for Use With PV Systems

CRIMP-TYPE (SEALED)

PLUG/RECEPTACLE
GLASS THICKNESS SIZING METHOD

JET PROPULSION LABORATORY

D. Moore

Background

CLASSICAL APPROACH
• LINEAR PLATE THEORY
• TRADITIONAL GLASS STRENGTH = 1500 psi

GLASS DESIGN CONSIDERATIONS
• NON-LINEAR STRESS ANALYSIS
• GLASS FRACTURE CONSIDERATIONS
  • PROBABILISTIC IN NATURE
  • STATIC FATIGUE
  • GLASS AREA DEPENDENT

CURRENT WINDOW DESIGN PRACTICE
• EMPIRICALLY DEVELOPED CURVES
• GLASS THICKNESS vs AREA AND LOAD FOR 8 FAILURE PER 1000

Analysis Method

LOAD
DIMENSIONS
MAT'L PROPS

NON-LINEAR
DESIGN CURVES

APPLIED STRESS

GLASS
AREA
TEMPER
LOAD TIME

FRACTURE
MECHANICS
CONCEPTS

BREAKAGE STRESS

COMPARE

α < α_B
Problem Definition

\[ a = \text{LENGTH OF PLATE} \]
\[ b = \text{WIDTH OF PLATE} \]
\[ t = \text{THICKNESS OF PLATE} \]
\[ E = \text{YOUNG'S MODULUS} \]
\[ v = \text{POISSON'S RATIO} \]
\[ D = \text{FLEXURAL RIGIDITY} \]
\[ D = \frac{Et^2}{12 (1 - v^2)} \]
Dimensionless Parameters

- **LOAD**
  
  \[ \text{LIF} = \text{LOAD INTENSITY FACTOR} = \frac{pD^4}{D} \]

- **DEFLECTION**
  
  \[ \frac{w_{\text{max}}}{t} = \text{CENTER DEFLECTION ÷ PLATE THICKNESS} \]

- **STRESS**
  
  \[ \text{SIF} = \text{STRESS INTENSITY FACTOR} = \frac{\sigma b^2 t}{D} \]

**Finite Element Models**

![Finite Element Models Diagram]
Deflection vs Load

![Deflection vs Load Graph](image)

LEGEND
- **ANALYTICAL LINEAR THEORY**
- **FEMA 356 RESULTS**
- **FEMA 356 PROVISIONS**
- **EXPERIMENTAL RESULTS AND MATHAMATICAL ANALYSIS EXTENDED**
- **PARKER AND EXAMPLE**
Maximum Principal Stress vs Load
Glass Breakage Stress

FUNCTION OF
- LOAD DURATION TIME
- GLASS TYPE
  SHEET, FLOAT, PLATE
- GLASS TEMPER
  ANNEALED, TEMPERED, SEMI-TEMPERED
- PLATE SURFACE AREA

PROPOSED FORMULATION

\[ \sigma_B = f_T \left( \frac{1}{A} \right)^{1/6} \sigma_{11} \]

WHERE
- \( \sigma_{11} \) = GLASS PLATE BREAKAGE STRESS NORMALIZED TO 1 MIN, 1 M\(^2\)
- \( f_T \) = FUNCTION TIME (SEE CURVE)
- \( A \) = PLATE AREA IN M\(^2\)

Design Values:

Design Values for Glass Breakage Stress - KSI

NEW SHEET AND FLOAT GLASS
NEW PLATE GLASS
WEATHERED GLASS

\( \sigma_{11} \) = GLASS BREAKAGE STRENGTH - KSI
1-SQUARE-FT PLATES
1 MIN LOAD DURATION

\( P_f \) = PROBABILITY OF FAILURE - PERCENT
$F_t$ vs Load Duration Time

\[ f_t = \text{Fraction of 1 minute load duration breakage stress of annealed glass} \]

- **ANNEALED**

Graph showing the relationship between load duration time and the fraction of 1-minute load duration breakage stress of annealed glass.
Sample Problem

DESIGN A 1-M-SQUARE, SIMPLY SUPPORTED ANNEALED GLASS PANEL TO SUSTAIN A 50 lb/m² LOAD OF 15 MIN DURATION WITH A PROBABILITY OF FAILURE OF 1%.

CALCULATE THE STRESS

\[ a = 39.4'' \quad b = 39.4'' \quad P = 50 \text{ psf} = 2.372 \text{ psi} \]
\[ E = 10,000,000 \text{ psi} \quad \nu = 0.22 \]
\[ \text{TRY} \quad t = 0.155'' \quad y = 0.22 \]

\[ D = \frac{E t^3}{12 (1 - \nu^2)} = 3261 \]
\[ \text{LIF} = \frac{P t^4}{D} = 1555 \]
\[ \rightarrow \text{SIF} = 230 \text{ (FROM DESIGN CURVE)} \]
\[ \sigma = \frac{D}{b^2 y} \text{SIF} = 3117 \text{ psi} \]

DETERMINE GLASS BREAKAGE STRESS

FOR \( P \) • 1%, \( \sigma_{11} = 3800 \text{ psi} \)
FOR \( \tau \) • 15 MIN, \( t \) • 0.825
\[ \sigma_B = \frac{t}{1 \left( \frac{1}{A} \right)^{1/6}} \quad \sigma_{11} = 3135 \]

COMPARE
\[ 3117 \cdot 3135 :: \text{OK} \]

ADVERTISEMENT

LSA TASK REPORT
PROPOSED METHOD FOR DETERMINING THE GLASS THICKNESS OF RECTANGULAR GLASS SOLAR COLLECTOR PANELS SUBJECTED TO UNIFORM NORMAL PRESSURE LOADS

Donald M. Moore

380
ARRAY STRUCTURE COST REDUCTION STUDY

JET PROPULSION LABORATORY

Abe Wilson

OBJECTIVE

• IDENTIFY MEANS FOR REDUCING THE COST OF FLAT-PLATE ARRAY STRUCTURES FOR LARGE INDUSTRIAL/CENTRAL STATION ARRAYS

• PANEL FRAME (6 x 16 FOOT)
• ARRAY STRUCTURE
• ARRAY FOUNDATION

APPROACH

• DESIGN AND FABRICATE LOW-COST PANEL FRAME AND PROOF TEST TO FAILURE
• DISCUSS DESIGN WITH MASS PRODUCTION VENDORS AND OBTAIN COST ESTIMATES ON EQUIVALENT DESIGN
• FABRICATE EQUIVALENT PANEL AND PROOF TEST
• DESIGN AND FABRICATE LOW-COST FOUNDATION AND STRUCTURE
• TEST DESIGN FOR SEVERAL SOIL CONDITIONS
• DISCUSS DESIGN WITH VENDORS:
  • HOLE DRILLING, PILE DRIVING
  • WOOD TREATING, GALVANIZING
• CONSIDER EFFECT OF NUMBER OF HOLES ON OVERALL COST
• ESTIMATE COST OF ARRAY FOUNDATION AND STRUCTURE
• FABRICATE AND PROOF TEST COMPLETE STRUCTURE WITH FOUNDATION
Panel Frame Cost/Quantity Sensitivity

$50
$40
$30
$20
$10
$0

COST PER PANEL FRAME
1980 $/m²

0 1000 5000 10000 50000 100000
NUMBER OF PANEL FRAMES

*PER QUOTE BY KAISER STEEL

Preliminary Study Results (1980 $/m²)

* SIGNIFICANT COST REDUCTIONS ARE POSSIBLE

<table>
<thead>
<tr>
<th>DATE OF ESTIMATE</th>
<th>PANEL FRAME</th>
<th>PANEL FRAME MATERIAL AND STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG '78</td>
<td>$18.90</td>
<td>CONCRETE</td>
</tr>
<tr>
<td>NOV '79</td>
<td>$13.45</td>
<td>EARTH</td>
</tr>
<tr>
<td></td>
<td>$28.42</td>
<td>$22.97</td>
</tr>
<tr>
<td></td>
<td>$40.32</td>
<td>$7.56</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>TOTAL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$59.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$21.01</td>
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</table>

*BARE PANEL FRAME COST PLUS $9.52 FOR GASKET, GROUND CONNECTORS ASSEMBLY LABOR, FREIGHT AND INSTALLATION LABOR, PER BECHTEL STUDY.
The module design theme of this PIM was addressed in detail during a special four-hour session Thursday morning. LSA Engineering, Encapsulation and Quality Assurance personnel expanded discussion of the specific design parameters, approaches, experience and recommendations that had been summarized by Ross and Dumas in the Wednesday session titled "Lessons Learned that Affect Module Design". Nine presentations were made, as indicated in the session agenda. The graphic material from these presentations appears below.

AGENDA

<table>
<thead>
<tr>
<th>TIME</th>
<th>TOPIC</th>
<th>SPEAKER</th>
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<tbody>
<tr>
<td>8:00</td>
<td>OVERALL DESIGN OPTIMIZATION</td>
<td>R. ROSS</td>
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<tr>
<td>8:20</td>
<td>ELECTRICAL CIRCUIT DESIGN</td>
<td>C. GONZALEZ</td>
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<tr>
<td>9:10</td>
<td>SAFETY DESIGN</td>
<td>A. LEVINS (UL)</td>
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<tr>
<td>9:30</td>
<td>ELECTRICAL TERMINAL DESIGN</td>
<td>R. SUGIMURA</td>
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<td>9:45</td>
<td>COFFEE</td>
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<td>10:00</td>
<td>MECHANICAL CONFIGURATION</td>
<td>J. ARNETT</td>
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<tr>
<td>10:20</td>
<td>STRUCTURAL DESIGN</td>
<td>D. MOORE</td>
</tr>
<tr>
<td>10:40</td>
<td>ENVIRONMENTAL REQUIREMENTS</td>
<td>A. HOFFMAN</td>
</tr>
<tr>
<td>11:00</td>
<td>ENCAPSULATION AND PROCESSING</td>
<td>E. CUDDHY</td>
</tr>
<tr>
<td>11:45</td>
<td>QUALITY ASSURANCE</td>
<td>W. BISHOP</td>
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OVERALL MODULE AND ARRAY DESIGN OPTIMIZATION

Overall Module Requirements

• GENERATE POWER
  • EFFICIENTLY
  • SAFELY
• INTEGRATE INTO ARRAY
  • ELECTRICALLY
  • MECHANICALLY
  • THERMALLY
• PROVIDE LONG LIFE AND LOW MAINTENANCE
  • ELECTRICAL CIRCUIT RELIABILITY
  • STRUCTURAL ENDURANCE
  • ENVIRONMENTAL ENDURANCE
• BE INEXPENSIVE TO MANUFACTURE
• MAINTAIN HIGH QUALITY CONTROL

Overall Module/Array Design Optimization

OBJECTIVE: MINIMIZE ARRAY LIFE-CYCLE ENERGY COST

METHODOLOGY:

\[
\text{LIFE-CYCLE BENEFIT} = \text{LIFE-CYCLE COST} \\
1/\text{\$/kW-h} \times \left( \frac{\text{LIFE-CYCLE ENERGY}}{\text{LIFE-CYCLE COST}} \right) = \text{LIFE-CYCLE COST}
\]

THEREFORE:

OPTIMUM = MINIMUM \( \left( \frac{\text{LIFE-CYCLE COST}}{\text{LIFE-CYCLE ENERGY}} \right) \)
Optimization Algorithm

\[
\text{OPTIMUM} = \text{MINIMUM} \left( \frac{\text{LIFE-CYCLE COST}}{\text{LIFE-CYCLE ENERGY}} \right)
\]

\[
= \text{MINIMUM} \left( \frac{C_0 + \sum_{n=1}^{L} C_n (1+k)^{-n}}{E_0 \sum_{n=1}^{L} e_n (1+k)^{-n}} \right)
\]

THEREFORE:

\[
\text{OPTIMUM} = \text{MINIMUM} \left( \frac{\text{INITIAL COST/m}^2}{\text{L-C O&M COST/m}^2} \right) \left( \frac{\text{INITIAL ARRAY EFFICIENCY (80\text{\,mW/cm}^2,\text{\,NOCT})}}{\text{ANNUAL INSOLATION (kW-h/m}^2\text{\,yr)}} \right) x \left( \frac{\text{L-C ENERGY FRACTION*}}{1/FCR, \text{\,(FOR CONSTANT POWER)}} \right)
\]

*1-C ENERGY FRACTION = \sum_{n=1}^{L} \left( \frac{\text{POWER IN YEAR n}}{\text{INITIAL POWER}} \right) (1+k)^{-n}

Life-Cycle Energy Fraction
No Degradation With Time

![Graph showing life-cycle energy fraction with 6%, 8%, and 10% present value discount rate]

Present Value Discount Rate
0 5 10 15

6% 8% 10%

Life-Cycle Energy Fraction
0 5 10 15

30 25 20 15 10 5

Present Value Discount Rate
0 5 10 15 20 25 30
Example Design Problem

- DETERMINE OPTIMUM MODULE CONFIGURATION FOR LARGE GROUND-MOUNTED ARRAY
- MECHANICAL CONFIGURATION/MODULAR SIZE
- CIRCUIT DESIGN
- MAINTENANCE/REPLACEMENT REQUIREMENTS

- ARRAY CONFIGURATION:

![Array Configuration Diagram]

Nominal Array Costs (1975 $)

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>UNITS</th>
<th>MODULE SIZE (ft x ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 x 4</td>
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<tr>
<td>INITIAL:</td>
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<td></td>
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<tr>
<td>MODULE DIRECT COST</td>
<td>$/m²</td>
<td>60</td>
</tr>
<tr>
<td>MODULE YIELD COST*</td>
<td>$/m²</td>
<td>0.5</td>
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<tr>
<td>MODULE SUBTOTAL</td>
<td>$/m²</td>
<td>60-65</td>
</tr>
<tr>
<td>PANEL FRAME</td>
<td>$/m²</td>
<td>24</td>
</tr>
<tr>
<td>PANEL WIRING</td>
<td>$/m²</td>
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<tr>
<td>PANEL SUBTOTAL</td>
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<td>26-28</td>
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<tr>
<td>PANEL INSTALLATION</td>
<td>$/m²</td>
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<tr>
<td>INSTALLED ARRAY STRUCT</td>
<td>$/m²</td>
<td>22</td>
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<tr>
<td>ARRAY TOTAL</td>
<td>$/m²</td>
<td>109-116</td>
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</table>

PER REPLACEMENT ACTION:

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<tr>
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<th>4 x 8</th>
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<tbody>
<tr>
<td>FAULT IDENTIFICATION</td>
<td>$/PANEL</td>
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<td>PANEL SUBSTITUTION LABOR</td>
<td>$/PANEI</td>
<td>21</td>
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<td>21</td>
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<tr>
<td>MODULE REPLACEMENT LABOR</td>
<td>$/MOD</td>
<td>12</td>
<td>12</td>
<td>12</td>
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<tr>
<td>REPLACEMENT MODULE PARTS (INC 1% INVENTORY COST)</td>
<td>$/m²</td>
<td>61-66</td>
<td>61-69</td>
<td>61-84</td>
</tr>
</tbody>
</table>

* 1 CELL FAILURE PER 1000 DURING ASSEMBLY/SHIPPING/INSTALLATION
### Nominal Performance Parameters

<table>
<thead>
<tr>
<th>MODULE SIZE (ft x ft)</th>
<th>2 x 4</th>
<th>4 x 4</th>
<th>4 x 8</th>
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<tbody>
<tr>
<td>INITIAL ARRAY EFFICIENCY</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
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<tr>
<td>ENCAP. CELL EFFICIENCY</td>
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<td>0.92</td>
<td>0.92</td>
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<tr>
<td>NOCT EFFICIENCY</td>
<td>0.89</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>PACKING EFFICIENCY</td>
<td>0.123</td>
<td>0.126</td>
<td>0.128</td>
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<tr>
<td>ARRAY EFFICIENCY SUBTOTAL</td>
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<td></td>
</tr>
<tr>
<td>BALANCE-OF-PLANT EFFICIENCY</td>
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<tr>
<td>ELECTRICAL EFFICIENCY</td>
<td>0.92</td>
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<td>MODULE SOILING EFFICIENCY</td>
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<td>BALANCE-OF-PLANT SUBTOTAL</td>
<td>0.85</td>
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<tr>
<td>BALANCE-OF-PLANT COSTS (1975$)</td>
<td>150 $/kW</td>
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<tr>
<td>DISCOUNT RATE (OVER INFLATION)</td>
<td>10%</td>
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<tr>
<td>ANNUAL INSOLATION</td>
<td>1825 kW-h/m²/yr</td>
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</tr>
</tbody>
</table>

### Array Power Degradation vs Circuit Redundancy

![Array Power Degradation vs Circuit Redundancy Graph]

- **FRACTION INITIAL POWER** vs **TIME (YEARS)**
- **120 SERIES BLOCKS**
- **1200**
- **15**
- **1**
Life-Cycle Energy Cost vs Circuit Configuration

- Cell Failure Rate: 1 per 10,000 per year
- Branch Circuit: 8 P x 2400 S, no diodes
- Module: 4 x 8 foot (320 cells)

Life-Cycle Energy Cost vs Module Size

- Cell Failure Rate: 1 per 10,000 per year
- BC: 8 x 2400, no diodes
- Cell Fill Factor: 0.7
- Module Size: (ft x ft)
Module/Array Design Optimization

CONCLUSIONS:

- MODULE/ARRAY DESIGN OPTIONS AND COSTS ARE HIGHLY INTERDEPENDENT
  - MODULAR SIZE
  - STRUCTURAL DESIGN
  - MECHANICAL INTERFACES
  - ELECTRICAL CIRCUIT DESIGN
  - MAINTENANCE/REPLACEMENT STRATEGY
- MODULE/ARRAY OPTIMIZATION MUST BE CARRIED OUT SIMULTANEOUSLY
- ALL COST ELEMENTS MUST BE INCLUDED
  - INITIAL COSTS INCLUDING INSTALLATION
  - MAINTENANCE/REPLACEMENT COSTS

MODULE AND ARRAY CIRCUIT GUIDELINES

JET PROPULSION LABORATORY

C. Gonzalez

Statement of Problem

- SELECTION OF APPROPRIATE ELECTRICAL CIRCUIT CONFIGURATION FOR PHOTOVOLTAIC MODULES
Areas of Consideration

- GENERAL DESIGN CONSTRAINTS
  - MODULE SIZE/NUMBER OF CELLS
  - VOLTAGE/CURRENT LEVEL
  - SAFETY CONSIDERATIONS
- MODULE PERFORMANCE CRITERIA
  - MODULE MISMATCH LOSSES
  - MODULE MANUFACTURING YIELD
  - ARRAY FAULT TOLERANCE

General Design Constraints

- MODULE SIZE/NUMBER OF CELLS
- VOLTAGE/CURRENT LEVEL
  - APPLICATION/BATTERY CHARGING, 15 VOLTS @ NOCT
- SAFETY CONSIDERATIONS
  - $V_{OC} < 30$ VOLTS @ $-20^\circ$C

Module Performance Criteria

- MISMATCH LOSSES
- MODULE MANUFACTURING YIELD
- FAULT TOLERANCE
Mismatch Losses

- PROBLEM STATEMENT
  - REDUCE ELECTRICAL LOSSES DUE TO CELL MISMATCH WITHIN MODULES

- APPROACH
  - INTRODUCE CIRCUIT REDUNDANCY TO REDUCE MISMATCH LOSSES TO ACCEPTABLE LEVEL (< 5%)

- ANALYTICAL PROCEDURE
  - DETERMINE $I_{SC}$ DISTRIBUTION
  - USE MONTE CARLO TECHNIQUES TO SELECT $I_{SC}$ IN RANDOM WAY
  - COMBINE CELL IV CURVES TO COMPUTE LOSSES

- SIMULATED BY USING RANDOM DISTRIBUTION OF $I_{SC}$ AND FF

- $I_{SC}$

  ![Diagram](image)

  - MISMATCH EFFECTS MOST SEVERE WHERE COMBINING ALONG CONSTANT CURRENT LINES

- FF

  ![Diagram](image)

  - MISMATCH EFFECTS LESS SEVERE THAN THOSE DUE TO VARIATION IN $I_{SC}$
Module Mismatch vs Cell $I_{sc}$ Distribution
And Module Series/Paralleling

Fractional Decrease in Power, %

Number of Parallel Strings

Series Blocks per Module

Fraction of Total Cells

Series Blocks per Module

Fraction of Total Cells
Mismatch Loss Conclusions

- KEY FACTORS DETERMINING AMOUNT OF MISMATCH
  - $I_{SC}$ DISTRIBUTION SHAPE AND HALF-WIDTH
  - RATIO OF $I_{MAX}$ POWER TO $I_{SC}$
  - CELL SHUNT RESISTANCE

- FOR 0.7 FILL FACTOR
  - A 10% HALF-WIDTH LEADS TO 1% OR LESS MISMATCH LOSSES INDEPENDENT OF SERIES/PARALLELING
  - A 20% HALF-WIDTH LEADS TO MISMATCH LOSSES OF 5% OR MORE, DROPPING TO 2% WITH EXTENSIVE SERIES PARALLELING
Module Manufacturing Yield

- **PROBLEM STATEMENT**
  - Reduce number of module rejects due to failures during module assembly, shipping and installation

- **APPROACH**
  - Introduce circuit redundancy to reduce single-failure power loss below acceptable level (10%)

- **ANALYTICAL PROCEDURE**
  - Determine single-failure degradation as a function of number of parallel strings and series blocks in module
  - Calculate fraction of modules containing failures assuming 1 failed cell per 1000 and given number of cells per module
  - Calculate fraction of modules with power degradation greater than acceptable level (10%)

Module Power Loss vs Module Series/Paralleling

(1 to 3 failed cells per module)
Manufacturing Yield Due to Cell Breakage
Vs Module Series/Paralleling

Manufacturing Yield Conclusions

• FOR MODULES OF 100 CELLS OR LARGER WITH FOUR PARALLEL STRINGS, YIELD IS 90% OR LESS AND IS INDEPENDENT OF NUMBER OF SERIES BLOCKS

• FOR MODULES WITH 6 PARALLEL STRINGS, YIELD CAN BE INCREASED TO 99% BY ADDING UP TO 6 SERIES BLOCKS

• FOR MODULES WITH 8 OR MORE PARALLEL STRINGS YIELD CAN BE INCREASED TO 99% BY ADDING UP TO 3 SERIES BLOCKS

Techniques for Enhancement of Fault Tolerance

• MULTIPLE CELL CONTACTS

• SERIES/PARALLELING

• USE OF BYPASS DIODES
Multiple Cell Contacts

- **PROBLEM STATEMENT**
  - REDUCE CELL AREA LOSS DUE TO CRACKING

- **APPROACH**
  - INTRODUCE REDUNDANT CONTACTS TO REDUCE CELL AREA LOSS TO LESS THAN 10%

- **ANALYTICAL PROCEDURE**
  - DETERMINE AMOUNT OF CELL AREA LOST TO CRACK FOR DEFINED CRACK PATTERNS
  - FOR GIVEN CONTACT CONFIGURATIONS
  - SUM ALL CASES LEADING TO OPEN CELL OR HOT-SPOT FAILURE

- **Fraction of Cracked Cells Leading to Failed Cells**

| PERCENT LOSS OF CELL AREA | 0° | 60° | 90° | -180° | + | +
|---------------------------|----|-----|-----|-------|---|---
| 0-5                       | .36| .42 | .50 | .64   | .36| .91|
| 5-10                      | .09| .15 | .18 | .18   | .14| .09|
| 10-20                     | .06| .12 | .12 | .12   | .12| 0 |
| 20-40                     | .03| .06 | .06 | .06   | .11| 0 |
| 40-70                     | 0  | 0   | 0   | 0     | .04| 0 |
| 100                       | .45| .24 | .14 | 0     | .23| 0 |
| SUM OF > 10               | .54| .42 | .32 | .18   | .50| 0 |
Multiple Cell Contact Conclusions

- **SINGLE CONTACTS LEAD TO A 50% FAILURE RATE AMONG CRACKED CELLS**
- **USE OF DOUBLE TABS REDUCES FAILURE RATE BY 20%-60%, DEPENDING ON ORIENTATION**
- **USE OF TRIPLE TABS LEADS TO NEGLIGIBLE FAILURE RATE**

Series/Paralleling/Diodes

- **PROBLEM STATEMENT**
  - REDUCE SYSTEM POWER DEGRADATION DUE TO CELL AND MODULL FAILURES
- **APPROACH**
  - INCREASE SYSTEM FAULT TOLERANCE BY PROVIDING REDUNDANT CURRENT PATHS
- **ANALYTICAL PROCEDURE**
  - CONDUCT PARAMETRIC ANALYSES TO DETERMINE FIELD POWER DEGRADATION FOR GIVEN LEVELS OF SERIES/PARALLELING/DIODES, PARAMETERS INCLUDE:
    - CELL FILL FACTOR AND SHUNT RESISTANCE
    - NUMBER OF PARALLEL STRINGS AND SERIES BLOCKS
    - NUMBER OF CELLS PER MODULE
    - NUMBER OF BYPASS DIODES
    - CELL FAILURE RATE
  - DETERMINE EXISTENCE OF HOT SPOT PROBLEMS
Series/Parallel Nomenclature

Module:
- 3 Parallel Strings
- 2 Series Blocks
- 2 Cells per Substring
- 2 Diodes per Module

Branch Circuit:
- 3 Parallel Strings
- 6 Series Blocks
- 2 Cells per Substring
- 1 Diode per Series Block

Technique for Determining System Power Degradation

- Compute substring failure density ($F_{SS}$) for given series/parallel configuration, cell failure density ($F_C$), and no. of cells per substring (N) using:
  \[ F_{SS} = 1 - (1 - F_C)^N \]

- Determine fraction of branch circuits with given levels of failed substrings

- Use computer model to calculate branch circuit power loss by combining I-V curves of:
  - Failed elements
  - Unfailed elements

- Combine power degradation of branch circuits to obtain system degradation
Visualization of Hot-Spot Cell Heating

Cell Shunt Resistance

- Number of cells per resistance category:
  - 0 volts: 2, 1, 14, 10, 11, 3, 1
  - 1: 1
  - 3: 1
  - 6: 10
  - 17
  - 2
  - 1

- Cell shunt resistance, ohms:
  - 1.0 to 1.5
  - 2.2
  - 3.3
  - 4.7
  - 6.8
  - 10
  - 15
  - 22
  - 33
  - 47
  - 68
  - 100
  - 150
  - 220
  - 330
  - 470
  - 680
  - 1000
Example Problem

- **Problem Statement** - Determine optimum circuit configuration for array of modules

- **Fixed Module and System Parameters**
  - 40 Cell Module
  - 250 Volt System

- **Module and System Parameter Options**
  - 1, 4, 8 parallel strings per module
  - 0, 1, 2, 3, 4 by-pass diodes per module
  - Single, double, and triple cell contacts
  - 14, 56, 112 modules per branch circuit
  - 1, 4, 8 parallel strings per branch circuit
  - 1, 3 series blocks per module
Array Power Loss

\[ F_{SS} = 1 - (1-F_C)^N \]

- \( F_{SS} \): Substring Failure Density
- \( F_C \): Cell Failure Density
- \( N \): Number of cells per substring

- 4 parallel strings
- FF = 0.76
- No diodes

Array Power Loss Fraction

- Series blocks per branch circuit
- 2400, 1000, 500, 250, 100, 50, 25, 12, 6, 2, 1
$F_{SS} = 1 - (1-F_C)^N$

$F_C = \text{CELL FAILURE DENSITY}$

$N = \text{NUMBER OF CELLS}$

PER SUBSTRING

$F_{SS}, \text{SUBSTRING FAILURE DENSITY}$

$FF = 0.76$

NO DIODES

8 PARALLEL STRINGS

$FSS, \text{SUBSTRING FAILURE DENSITY}$
8 PARALLEL STRINGS
FF = 0.76
1 SERIES BLOCK PER DIODE

ARRAY POWER LOSS FRACTION

F_{SS}, SUBSTRING FAILURE DENSITY
## System Power Loss for Solar-Power Options

<table>
<thead>
<tr>
<th>MODULE 5 x P</th>
<th>CELL CONTACTS</th>
<th>PARALLEL CELLS/BC</th>
<th>SERIES BLOCKS PER BC</th>
<th>DIODES PER MODULE</th>
<th>CELLS PER DIODE</th>
<th>SYSTEM POWER LOSS, %</th>
<th>P/P MAX</th>
<th>MANUFACT YIELD</th>
<th>MIS-MATCH</th>
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<tbody>
<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>560</td>
<td>96</td>
<td>0</td>
<td>0</td>
<td>96%</td>
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<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>96%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 x 1</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>7</td>
<td>0</td>
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<td>17%</td>
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<td>1</td>
<td>40</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>53%</td>
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<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>53%</td>
<td></td>
<td></td>
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<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>53%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 x 1</td>
<td>4</td>
<td>14</td>
<td>0</td>
<td>560</td>
<td>65</td>
<td>16</td>
<td>96%</td>
<td></td>
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</tr>
<tr>
<td>40 x 1</td>
<td>4</td>
<td>14</td>
<td>1</td>
<td>40</td>
<td>35</td>
<td>0</td>
<td>96%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 x 1</td>
<td>8</td>
<td>14</td>
<td>0</td>
<td>560</td>
<td>15</td>
<td>0</td>
<td>53%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 x 1</td>
<td>8</td>
<td>14</td>
<td>1</td>
<td>40</td>
<td>35</td>
<td>0</td>
<td>53%</td>
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<td></td>
</tr>
<tr>
<td>10 x 4</td>
<td>4</td>
<td>56</td>
<td>0</td>
<td>560</td>
<td>35</td>
<td>0</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 x 4</td>
<td>4</td>
<td>56</td>
<td>1</td>
<td>10</td>
<td>22</td>
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<td>560</td>
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<tr>
<td>5 x 8</td>
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<td>112</td>
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<td>5</td>
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<td>0</td>
<td>53%</td>
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<td></td>
</tr>
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<td>5 x 8</td>
<td>8</td>
<td>560</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5.7%</td>
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</tr>
</tbody>
</table>

### Conclusions and Recommendations

- **Multiple cell contacts considerably reduce risk of failure due to cell cracking**
- **Use of bypass diodes best circuit design tool to reduce power loss and hot spot problems**
- **Paralleling of cell strings within modules effective for reducing cell mismatch and module yield loss**
- **Use of increased number of series blocks can exacerbate hot spot problem - should be accompanied by use of bypass diodes**
- **Determination of potential hot spot problems - should be accomplished by testing modules having artificially induced hot spots**
- **Number of parallel cells per module can be chosen to give proper power per branch circuit**
Module and Array Safety Considerations

- National Electrical Code
- Building Codes
- UL Interface with Codes
- Fire Safety
- Polymeric Material Evaluation
- Burn Hazard
- Ground Fault Protection
- Module Voltage/Current Levels
- Grounding

Standard AC Ground-Fault Interrupter
DC Ground-Fault Disabler

CLOSE SIGNAL ON CURRENT DIFFERENTIAL ABOVE A SPECIFIED VALUE

SYNC SIGNAL FROM AC LINE

POWER TO AC LINE

DIFFERENTIAL CIRCUIT

SOLAR CELLS

GROUND DETECTOR

SHUNT

INVERTER
MODULE TERMINATION DESIGN

JET PROPULSION LABORATORY

Russ Sugimura

Constraints on Module Termination Design

(Based on Studies by Motorola, Underwriters Laboratories, and Burt Hill Kosar Rittelmann Assoc.)

- AMPACITY
- PROTECTION
- COST
- NATIONAL ELECTRIC CODE

Code Considerations

- NATIONAL ELECTRIC CODE
  - IMPACT: RESIDENTIAL AND INTERMEDIATE APPLICATION
  - APPROVAL
Protection and Cost Considerations

- PROTECTION OF THE TERMINATION
  - MOUNTING
  - SEALING
  - SAFETY

- COST: TOTAL COST OVER THE LIFE OF THE MODULE

\[
\text{TOTAL COST} = \text{INITIAL COSTS} + \sum_{\text{MODULE LIFE}} \left( \text{DISCOUNTED MAINTENANCE & REPAIR COSTS} \right)
\]

- INITIAL COSTS
  - PARTS
  - FACTORY LABOR
  - FIELD LABOR

- MAINTENANCE & REPAIR COSTS
  - FAILURE DETECTION
  - PARTS, SHIPPING
  - SHOP LABOR
  - FIELD LABOR
  - LOST ENERGY

Ampacity Constraints

- AMPACITY IS CONSTRAINED BY
  - APPLICATION
  - MODULE VOLTAGE
  - INTERCONNECTION OF CELLS
  - MODULE SIZE

<table>
<thead>
<tr>
<th>MODULE SIZE</th>
<th>POWER</th>
<th>MODULE CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 2 FT</td>
<td>22 Wp</td>
<td>1-5A</td>
</tr>
<tr>
<td>2 x 4 FT</td>
<td>86 Wp</td>
<td>5-20A</td>
</tr>
<tr>
<td>4 x 4 FT</td>
<td>173 Wp</td>
<td>10-40A</td>
</tr>
<tr>
<td>4 x 8 FT</td>
<td>345 Wp</td>
<td>20-100A</td>
</tr>
</tbody>
</table>
Termination Choices vs Ampacity

WIRE WRAP
SPRING CLIP
INSULATION DISPLACEMENT
TWIST-ON
HAND SOLDER
WELDED
SCREW
PLUG/RECEPTACLE
CRIMP

CURRENT (AMPS)
Total Termination Cost

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

• MODULE TERMINATION SELECTION MUST CONSIDER:
  • SAFETY: MANUFACTURE / INSTALLATION / OPERATION / MAINTENANCE
  • AMPACITY: CONSTRAINED BY MODULE SIZE
  • TOTAL COST OVER THE LIFE OF THE MODULE

• MODULE TERMINATIONS MUST COMPLY WITH NEC REQUIREMENTS FOR RESIDENTIAL AND, MOST LIKELY, INTERMEDIATE APPLICATIONS

RECOMMENDATION

• MODULE MANUFACTURERS SHOULD BECOME FAMILIAR WITH GENERAL AND SPECIFIC ELECTRICAL REQUIREMENTS CURRENTLY ENFORCED BY THE NEC
MECHANICAL CONFIGURATION
DESIGN GUIDELINES

JET PROPULSION LABORATORY

J.C. Arnett

Mechanical Configuration

- EFFICIENCY CONSIDERATIONS
- STRUCTURAL / SIZING
- THERMAL PERFORMANCE

Factors Influencing Module Configuration

- CELL SIZE/SHAPE
- CIRCUIT ARRANGEMENT (S/P)
- ENCAPSULATION MATERIALS
  - SUPERSTRATE
  - SUBSTRATE
- EFFICIENCY CONSIDERATIONS
- MOUNTING PROVISIONS/RESTRICTIONS
- INTERCHANGEABILITY/REPLACEMENT
- THERMAL PERFORMANCE
  - NOCT
  - HOT-SPOT RESISTANCE
- ENVIRONMENTAL CONSTRAINTS
- APPLICATION (USER) CONSTRAINTS
Cell-Related Factors

• NUMBER/MODULE
• SIZE
• SHAPE
  - CELL-TO-CELL SPACING
  - INTERCONNECT LOCATION
  - PACKING FACTOR
• CIRCUIT ARRANGEMENT
  - SERIES/PARALLEL RESTRICTIONS
  - DIODE PLACEMENT REQUIREMENTS
  - OUTPUT TERMINATION LOCATION
• AR COATINGS

Efficiency Considerations

• ENCAPSULANT MATERIAL INFLUENCE
• CHOICE OF AR COATINGS
• CELL OPERATING TEMPERATURE
• PACKING FACTOR AFFECTED BY:
  • CELLS / SIZE / SHAPE / SPACING
  • CELL NESTING
  • BORDER/MOUNTING AREA
  • SERIES/PARALLEL CIRCUIT ROUTING
  • LOCATION OF OUTPUT TERMINATIONS
• TRANSMISSION LOSSES OF FRONT SURFACE
Cell Operating Temperature Efficiency

-20 0 20 40 60

AMBIENT TEMPERATURE, °C

\[ \eta_{\text{NOCT}} = \frac{P \text{ at NOCT}}{P \text{ at 28°C}} \]

\[ \frac{4P}{\Delta T} \left( \text{NOCT} - 28 \right) \]

where:
- NOCT • NOMINAL OPERATING CELL TEMPERATURE
- CELL TEMPERATURE FOR:
  - 80 mW/cm INSOLATION
  - 20°C AIR TEMPERATURE
  - 1 M/SEC WIND VELOCITY
  - OPEN BACK SIDE

Module Cell Packing Efficiency

PERCENT ACTIVE CELL AREA

NUMBER CELL ROWS/COLUMNS

W/1/2 CELLS

HX

SS

RS
Near-Term Efficiency Goals

ENCAPSULATED CELL 12%
NOMINAL OPERATING CELL TEMP 97%
BORDER 96%
BUS 99%
INTERCONNECT 98%
NESTING 92%

\[
\text{MODULE EFFICIENCY } = \eta_{\text{EC}} \times \eta_{\text{NOCT}} \times \eta_{\text{p}}
\]
\[
= 12\% \times 97\% \times 86\% = 10\% \text{ GOAL}
\]
\[
= 11\% \times 96\% \times 85\% = 9\% \text{ MIN}
\]

Structural and Sizing Considerations

• STANDARDIZED MOUNTING INTERFACES COMPATIBLE WITH VARIETY OF ASSEMBLY / SUPPORT ARRANGEMENTS
• SUBSTRATE / SUPERSTRATE THICKNESS OPTIMIZED FOR LOADING
• LARGER CELLS DICTATE LARGER MODULES TO SATISFY VOLTAGE, SERIES / PARALLEL CONSTRAINTS
• LARGER MODULES MINIMIZE BORDER / BUS AREAS
• INTEGRATED MODULE / ARRAY SUPPORT STRUCTURE
Module Configuration Requirement

- 63.5 mm max.
- 50.8 mm max.
- 35.4 mm min.

Width including allowance for module spacing may not exceed 1.2 m basic.

3 mm to 6 mm space between modules

7.1 mm dia. mounting hole

20 mm min. dia. clearance around thru mounting holes

VIEW SHOWING THRU-HOLE MOUNTING

1.18 m basic support structure mounting pattern

VIEW SHOWING EDGE MOUNTING AND REAR MOUNTING

SOLAR CELL LAYOUT

Support structure basic hole spacing is an integer multiple of 20 mm increments
NOCT Specification

- **OBJECTIVE:**
  - TO ALLOW THE ELECTRICAL PERFORMANCE OF MODULES OF VARIOUS THERMAL DESIGNS TO BE SPECIFIED AND COMPARED AT AN OPERATING POINT REPRESENTATIVE OF TYPICAL FIELD OPERATING CONDITIONS

- **APPROACH:**
  - SPECIFY ELECTRICAL PERFORMANCE AT A CELL TEMPERATURE (NOCT) WHICH REFLECTS THE MEASURED CELL OPERATING TEMPERATURE IN THE NOMINAL TERRESTRIAL ENVIRONMENT:
    - AIR TEMPERATURE - 20°C
    - WIND VELOCITY - 1 m/s
    - INSOLATION - 80 mW/cm²
    - MOUNTING - OPEN BACK, TILTED

**NOCT Measurement Procedure**

- MEASURE $T_{CELL} - T_{AIR}$ VERSUS INSOLATION LEVEL

- INTERPOLATE $(T_C - T_A^{REF})$ VALUE FOR REFERENCE INSOLATION LEVEL
- CALCULATE NOCT $(T_C - T_A^{REF}) +$ REFERENCE AIR TEMP.
Thermal Test Summary

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>ΔNOCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOF MOUNT</td>
<td>-4°C</td>
</tr>
<tr>
<td>(INSULATED REAR SIDE)</td>
<td></td>
</tr>
<tr>
<td>MAX. POWER OUT</td>
<td>-3°C</td>
</tr>
<tr>
<td>(vs OPEN CIRCUIT)</td>
<td></td>
</tr>
<tr>
<td>DIRTY MODULE</td>
<td>+2°C</td>
</tr>
<tr>
<td>(vs CLEAN)</td>
<td></td>
</tr>
<tr>
<td>FINS</td>
<td>-3°C</td>
</tr>
<tr>
<td>(vs NO FINS)</td>
<td></td>
</tr>
</tbody>
</table>

Typical Values for NOCT

<table>
<thead>
<tr>
<th>MODULE CONSTRUCTION</th>
<th>NOCT (°C)</th>
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</thead>
<tbody>
<tr>
<td>FINNED ALUMINUM SUBSTRATE</td>
<td>40</td>
</tr>
<tr>
<td>CLEAR GLASS SUBSTRATE</td>
<td>41</td>
</tr>
<tr>
<td>ALUMINUM SUBSTRATE (NO FINS)</td>
<td>43</td>
</tr>
<tr>
<td>FIBERGLASS/PLASTIC SUBSTRATE</td>
<td>47</td>
</tr>
<tr>
<td>DOUBLE PANDE WITH AIR GAP</td>
<td>60</td>
</tr>
</tbody>
</table>

\[ T_{\text{CELL}} = T_{\text{AIR}} + \left(\frac{\text{NOCT} - 20}{80}\right) S, \text{ °C} \]

\[ S = \text{INSOLATION, mW/cm}^2 \]
Thermal Performance

- LOWER NOCT LEADS TO:
  - INCREASED MODULE EFFICIENCY
  - EXTENDED ENCAPSULANT MATERIAL LIFETIME
  - REDUCED BACKGROUND TEMP IN HOT SPOTS
  - REDUCED PERSONNEL BURN HAZARD

- NOCT AFFECTED BY:
  - ENCAPSULATION MATERIAL SELECTION
  - SUB/SUPERSTRATE GEOMETRY, THICKNESS
  - MOUNTING PROVISIONS
  - SOILING

Application (User) Constraints

- SPECIALIZED SUPPORT STRUCTURES
- FIELD CABLE ROUTING
- FIELD MAINTENANCE/REPAIR
- MAXIMUM SIZE FOR HANDLING
- INVENTORY/SPARES POLICY
- INTERCHANGEABILITY/REPLACEMENT
Mechanical Design Recommendations

- CLOSE-PACKED, SHAPED CELLS
- END-TO-END CIRCUIT RUNS
- MINIMIZE BORDER AREA
- HIGH-TRANSMISSION OPTICAL SURFACES
- STANDARD MOUNTING INTERFACES
- LONG-LIFE, HIGHER TEMP ENCAPSULANTS
- REDUCE NOCT
- SIMPLE CABLING INTERFACES
- OPTIMIZE STRUCTURE FOR EXPECTED LOADS
- LARGEST MODULES WITHIN MANUFACTURING, ASSEMBLY, YIELD CONSTRAINTS

MODULE STRUCTURAL DESIGN

JET PROPULSION LABORATORY

D. Moore

Module Structural Considerations

UNIFORM NORMAL PRESSURE LOADS
- WIND
- EARTHQUAKE
- SNOW
- ICE
- DEADWEIGHT

ANSI A58.1 - 1972

CONSTRAINT LOADS
- FOUNDATION SETTLEMENT (NON-PLANAR MOUNTING SURFACES)
- THERMAL EXPANSION/CONTRACTION

IMPACT/HANDLING LOADS
- HAIL IMPACT
- TRANSPORTATION
- HANDLING
- INSTALLATION
Uniform Normal Pressure Loads

WIND LOAD
- SHORT TIME DURATION
- HIGH LOCAL PRESSURES
  - ARRAY STRUCTURE  20-30 lb/ft^2
  - MODULE  50 lb/ft^2

GLASS THICKNESS SIZING METHOD

DETERMINE GLASS THICKNESS FOR
- SIMPLY SUPPORTED RECTANGULAR PLATES
- UNIFORM NORMAL PRESSURE LOADS
- GLASS TYPE - ANNEALED, TEMPERED
- PROBABILITY OF FAILURE

SAMPLE PROBLEM
- 1-m SQUARE PLATE
- 50 lb/ft^2 LOADING FOR 15 MIN
- 1% PROBABILITY OF FAILURE
- ANNEALED GLASS
  - REQUIRED THICKNESS - 0.155 in.,
Glass Cost vs Module Area

ANNEALED GLASS
RECTANGULAR
SIMPLY-SUPPORTED
50 lb/ft² LOADING
15 min LOAD DURATION
1% PROBABILITY OF FAILURE

REF: PROPOSED METHOD FOR DETERMINING
THE GLASS THICKNESS OF RECTANGULAR
GLASS SOLAR COLLECTOR PANELS SUBJECTED
TO UNIFORM NORMAL PRESSURE LOADS
Glass Cost Data

REF: MODULE/ARRAY INTERFACE STUDY
BECHTEL FINAL REPORT DOE/JPL 954698-78/1A

0.01% IRON, TEMPERED
0.01% IRON, ANNEALED
0.05% IRON, TEMPERED
0.1% IRON, TEMPERED
0.1% IRON, ANNEALED
0.05% IRON, ANNEALED

GLASS COST ($/m^2)

GLASS THICKNESS (IN)

1 2 3 4 5 6 7 8 MM

0 0.05 0.10 0.15 0.20 0.25 0.30 IN
Glass Thickness vs Module Area

Constraint Loads

MOUNTING INDUCED LOADS
- WARPED MOUNTING SURFACES
- HANDLING LOADS

THERMAL LOADS
- DIFFERENTIAL THERMAL EXPANSION
- INTERCONNECT STRESS
- MODULE STRUCTURAL COMPONENTS
- LOCAL "HOT SPOTS"
- BACK-BIASED CELLS
- STRESS IN GLASS SUPERSTRATE (80 psi/°C)
Impact Criteria

TRANSPORTATION, HANDLING & INSTALLATION
• TO BE CONSIDERED
• PARTLY COVERED BY MINIMUM HAIL REQUIREMENTS

HAIL IMPACT RESISTANCE (LARGER OF)
• 1 in. dia SIMULATED HAILSTONE @ 52 mph
• dia DEPENDENT ON GEOGRAPHIC LOCATION OF PHOTOVOLTAIC MODULE INSTALLATION

\[ \text{dia} = 0.3 \times ( \text{AVERAGE NO. OF HAIL DAYS PER YEAR} \text{ FROM HUD*}) \]

VELOCITY = FREE FALL TERMINAL VELOCITY IN STILL AIR


Hail Impact Resistance

REF: PHOTOVOLTAIC SOLAR PANEL RESISTANCE TO HAIL LSA TASK REPORT 5101-62, DOE/JPL-1012-7816

<table>
<thead>
<tr>
<th>TOP SURFACE MATERIAL</th>
<th>HAILSTONE DIAMETER - in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAR SILICONE POTTING</td>
<td>0.5</td>
</tr>
<tr>
<td>0.10 in. ACRYLIC SHEET</td>
<td>1.0</td>
</tr>
<tr>
<td>0.09 in. ANNEALED GLASS (ALUM SUBSTRATE)</td>
<td>1.5</td>
</tr>
<tr>
<td>0.12 in. ANNEALED GLASS</td>
<td>2.0</td>
</tr>
<tr>
<td>0.12 in. TEMPERED GLASS</td>
<td></td>
</tr>
<tr>
<td>0.19 in. TEMPERED GLASS</td>
<td></td>
</tr>
</tbody>
</table>

FAILURES RANGE
ENVIRONMENTAL REQUIREMENTS

JET PROPULSION LABORATORY

Alan R. Hoffman

Hail-Resistant Design

FAILURE MECHANISM
• LOCAL BENDING AT POINT OF IMPACT
• TENSION FAILURES ON REVERSE SIDE

GLASS SUPERSTRATE
• FAILURES AT EDGES
• EDGES WELL SUPPORTED
• SMOOTH EDGES

POLYMERIC ENCAPSULANT
• CELL FAILURE
• UNIFORM, FIRM SUPPORT
  MINIMUM SOLDER BUILDUP ON CELLS
  SMOOTH SUBSTRATE
  MINIMUM CELL/SUBSTRATE GAP

Environmental Qualification Testing

• OBJECTIVE:
  • DISCOVER POTENTIAL FIELD-FAILURE MODES AND MECHANISMS TO ALLOW FOR THEIR ASSESSMENT AND CORRECTION

• APPROACH:
  • SUBJECT MODULES TO CAREFULLY CHOSEN ENVIRONMENTS WITH KNOWN IMPORTANCE

• PHILOSOPHY:
  • MINIMUM TEST COMPLEXITY TO REDUCE COST
  • MAXIMUM TEST STABILITY ALLOW CORRELATION AND COMPARISON
Module Environmental Testing Categories
For Manufacturers and Users

• MODULE DEVELOPMENT AND CHARACTERIZATION
  • EXPLORATORY
  • DESIGN OPTIMIZATION
  • PRE-QUALIFICATION

• MODULE DESIGN/WORKMANSHIP VERIFICATION
  • QUALIFICATION (+ APPLICATION DEPENDENT)
  • SAFETY (+ APPLICATION DEPENDENT)
  • IN-PROCESS VERIFICATION
  • ACCEPTANCE

• MODULE LIFE PREDICTION
  • FIELD
  • LABORATORY

Key Failure Modes and Mechanisms

• ELECTRICAL INTERCONNECT BREAKAGE
  • THERMAL CYCLING
  • WIND LOADING (CYCLIC PRESSURE LOADING, WIND RESISTANCE)

• SOLAR CELL CRACKING
  • THERMAL CYCLING
  • HAIL IMPACT

• ENCAPSULANT DELAMINATION AND CRACKING
  • THERMAL CYCLING
  • HUMIDITY
  • ULTRAVIOLET

• CORROSION (CELL METALLIZATION, WIRE, TERMINAL)
  • HUMIDITY

• ELECTRICAL INSULATION BREAKDOWN

• OPTICAL SURFACE SOILING
Temperature Cycling Requirement

- **OBJECTIVE:**
  
  TO VERIFY ABILITY OF MODULE TO WITHSTAND THERMAL STRESS CAUSED BY DIURNAL AND CLIMATIC VARIATIONS

- **APPROACH:**
  
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - MODULE MOUNTED IN TEST FRAME SIMULATING FIELD SUPPORT
  - 50 TEMPERATURE CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- **Susceptible Parts:**
  
  - ENCAPSULANT SYSTEM
  - BONDING MATERIALS
  - CELLS
  - INTERCONNECTS

Humidity Cycling Requirement

- **OBJECTIVE:**
  
  TO VERIFY ABILITY OF MODULE TO TOLERATE EXPOSURE TO MOISTURE DURING SERVICE

- **APPROACH:**
  
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - 5 HUMIDITY CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- **Susceptible Parts:**
  
  - ENCAPSULANT SYSTEM
  - BONDING MATERIALS
  - CELL METALLIZATION
  - INTERCONNECTS
Cyclic Pressure Loading Requirement

- **OBJECTIVE:**
  
  TO VERIFY ABILITY OF MODULE TO WITHSTAND PRESSURE LOADS (†) CAUSED BY WIND GUSTING

- **APPROACH:**
  
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - 10,000 PRESSURE CYCLES
  - POST-TEST INSPECTION/PERFORMANCE

- **SUSCEPTIBLE PARTS**
  
  - CELL INTERCONNECTS
  - CELLS
  - ENCAPSULANT SYSTEM

Twisted Mounting Surface Requirement

- **OBJECTIVE:**
  
  TO ASSURE THAT MODULE CAN FUNCTION UNDER SUSTAINED DISTORTION CAUSED BY MOUNTING ON NON-PLANAR STRUCTURE

- **APPROACH:**
  
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - MODULE MOUNTED TO FLAT SURFACE
  - SURFACE TWISTED 20 mm/m

- **SUSCEPTIBLE PARTS:**
  
  - CELLS
  - INTERCONNECTS
  - ENCAPSULANT SYSTEM
Hail Impact Requirement

- **OBJECTIVE:**
  
  TO VERIFY ABILITY OF MODULE TO WITHSTAND HAIL IMPACT FOR EXPECTED ARRAY APPLICATIONS

- **APPROACH:**
  - EXPLORATORY TESTING OF SAMPLE MODULE(s) TO DETERMINE IMPACT-SENSITIVE LOCATIONS
  - 10 IMPACTS
    - 25.4mm (1 in) ICE BALL
    - 23.2m/sec (52 mph)
  - POST-IMPACT INSPECTION/PERFORMANCE

- **SUSCEPTIBLE PARTS:**
  - CELLS (ESPECIALLY EDGES NEAR ELECTRICAL CONTACTS)
  - ENCAPSULANT SYSTEM (CORNERS AND EDGES, POINTS OF SUPERSTRATE SUPPORT, POINTS OF MAXIMUM DISTANCE FROM SUPERSTRATE SUPPORT)

Wind Resistance Requirement

- **OBJECTIVE:**
  
  TO VERIFY ABILITY OF SHINGLE MODULES TO WITHSTAND AERODYNAMIC LIFT CAUSED BY WINDS

- **APPROACH:**
  - MODULE INSTRUMENTED TO DETECT OPEN OR SHORT CIRCUITS
  - LIFT FORCE 1.7 kPa (35 lb/ft²)
  - POST-TEST INSPECTION/PERFORMANCE

- **SUSCEPTIBLE PARTS**
  - CELL INTERCONNECTS
  - CELLS
  - ENCAPSULANT SYSTEM
Salt Fog Requirement

APPLICATION DEPENDENT

• OBJECTIVE:
  TO VERIFY MODULE TOLERANCE OF SALT-LADEN ENVIRONMENT AT MARINE SITES

• APPROACH:
  • 48-h EXPOSURE
  • POST-TEST INSPECTION PERFORMANCE

• SUSCEPTIBLE PARTS:
  • MODULE FRAME
  • WIRING

Module Environmental Test Levels
For 1982 Technical Readiness

• TEMPERATURE CYCLING: -40° TO +90°C, 100°C/h, 50 cycles
• HUMIDITY CYCLING: MIL-STD-810C, 507.1. V
• CYCLIC PRESSURE LOADING: ±2400 pascals (+50 lb/ft²), 10,000 cycles
• TWISTED MOUNTING SURFACE: ±2 cm/m (+0.25 in/ft)
• HAIL IMPACT: 10 HITS ON MODULE, BY 2.54cm (1 in) ICE BALL
• WIND RESISTANCE (SHINGLE MODULES) UNDERWRITERS LAB STANDARD 997
ENCAPSULATION MATERIALS SELECTION
AND PROCESSING

STATUS OF MATERIALS, MATERIALS DEVELOPMENT
AND ENCAPSULATION PROCESSES

JET PROPULSION LABORATORY

E.F. Cuddihy

Encapsulation Requirements

- OUTDOOR LIFE: 20 YEARS
- OPTICAL TRANSMISSION TO SOLAR CELLS: > 90% OF INCIDENT
- MODULE POWER DECREASE AFTER 20 YEARS: > 50% OF INITIAL
- PROCESSING AND FABRICATION: AUTOMATED
- STRUCTURAL PERFORMANCE (INCLUDING HANDLING AND WEATHERING): NO FAILURES

1986 Encapsulation Cost Goals

\[ < \$14.00/m^2 \quad (\$1.40/ft^2) \]

INCLUDING FRAME CONFIGURATION COMPATIBLE WITH
OUTDOOR RACK MOUNTING REQUIREMENTS

(1980 Dollars)
Generalized Flat-Module Design

<table>
<thead>
<tr>
<th>MODULE SUNSIDE</th>
<th>LAYER DESIGNATION</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SURFACE</td>
<td>• LOW SOILING</td>
</tr>
<tr>
<td></td>
<td>1) MATERIAL</td>
<td>• EASY CLEANABILITY</td>
</tr>
<tr>
<td></td>
<td>2) MODIFICATION</td>
<td>• ABRASION RESISTANT</td>
</tr>
<tr>
<td></td>
<td>TOP COVER</td>
<td>• ANTIREFLECTIVE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• UV SCREENING</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• STRUCTURAL SUPERSTRATE</td>
</tr>
<tr>
<td></td>
<td>POTTANT</td>
<td>• SOLAR CELL ENCAPSULATION</td>
</tr>
<tr>
<td></td>
<td>SPACER</td>
<td>• ELECTRICAL ISOLATION</td>
</tr>
<tr>
<td></td>
<td>SUBSTRATE</td>
<td>• MECHANICAL SEPARATION</td>
</tr>
<tr>
<td></td>
<td>BACK COVER</td>
<td>• STRUCTURAL SUPPORT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BACKSIDE MECHANICAL PROTECTION</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BACKSIDE WEATHERING BARRIER</td>
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</tbody>
</table>

Known Weatherable and Transparent Commercial Materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>EXAMPLE</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GLASS</td>
<td>• LOW-IRON GLASS</td>
<td>• TOP COVER/SUPERSTRATE</td>
</tr>
<tr>
<td>• ACRYLICS</td>
<td>• PLEXIGLAS, LUCITE</td>
<td>• TOP COVER/SUPERSTRATE</td>
</tr>
<tr>
<td>• SILICONES</td>
<td>• SYLGARD 184, RTV 615, GEL</td>
<td>• POTTANT (CASTABLE)</td>
</tr>
<tr>
<td>• FLUOROCARBONS</td>
<td>• TEDLAR</td>
<td>• TOP COVER (SPRAY)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• TOP COVER/BACK COVER</td>
</tr>
</tbody>
</table>
### Other Encapsulation Materials Used Industrially

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYVINYL BUTYRAL</td>
<td>LAMINATION POTTANT</td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>SUBSTRATE</td>
</tr>
<tr>
<td>NEMA-G10</td>
<td>SUBSTRATE</td>
</tr>
<tr>
<td>GLASS-REINFORCED POLYESTER</td>
<td>SUBSTRATE</td>
</tr>
<tr>
<td>PORCELAINIZED STEEL</td>
<td>SUBSTRATE</td>
</tr>
<tr>
<td>MYLAR</td>
<td>BACK COVER</td>
</tr>
</tbody>
</table>

### Encapsulation Materials Identified, Developed, Or Under Development by Task III

#### TOP COVERS (WITH UV SCREENING)
- KORAD 212
- TEDLAR 100-BG-30-UT
- SILICONE/ACRYLIC COPOLYMER

#### SPACER
- NON-WOVEN GLASS MATS

#### SUBSTRATE PANELS
- HARDBOARDS
- STRANDBOARDS
- MILD STEEL (INCL. GALV.)
- GLASS REINFORCED CONCRETE

#### POTTANTS
- ETHYLENE VINYL ACETATE (EVA)
- ETHYLENE PROPYLENE RUBBER
- POLY-n-BUTYL ACRYLATE
- POLYVINYLL CHLORIDE PLASTISOL
- POLYURETHANE
- SILICONE ELASTOMER
- QL-2577 SILICONE RESIN
- SILICONE/ACRYLIC COPOLYMER

#### BACK COVERS
- POLYMER FILMS (KORAD)
- METAL FOILS (ALUMINUM)
- WHITE-PIGMENTED EVA
Transparent Polymeric Pottants

• MODES OF OUTDOOR WEATHERING DEGRADATION
  1) THERMAL OXIDATION
  2) HYDROLYSIS
  3) UV PHOTO-OXIDATION
  4) UV PHOTOLYSIS

• COST/WEATHERING RELATIONSHIP

  > $1.50/pound  • GENERALLY WEATHERABLE
  $0.55 TO $1.50/pound  • UV SENSITIVE  • RESISTANT TO THERMAL OXIDATION/ HYDROLYSIS
  < $0.55/pound  • GENERALLY UNWEATHERABLE

REQUIREMENTS

• COMMERCIALLY AVAILABLE BASE POLYMERS OR MONOMERS
• USEFUL AS IS, OR AMENABLE TO LOW-COST MODIFICATION OR POLYMERIZATION
• POTENTIAL FOR AUTOMATED FABRICATION
• SELF-BONDING (DELAMINATION RESISTANCE)
• NON-TOXIC
• CHEMICALLY INERT
# Materials Available for Industrial Evaluation

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>ENCAPSULATION PROCESS</th>
<th>PROJECTED OR COMMERCIAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYVINYL CHLORIDE PLASTISOL</td>
<td>CAST</td>
<td>$0.83/pound</td>
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<tr>
<td>ETHYLENE VINYL ACETATE</td>
<td>LAMINATION</td>
<td>$0.95/pound</td>
</tr>
<tr>
<td>ETHYLENE PROPYLENE RUBBER</td>
<td>LAMINATION</td>
<td>$1.09/pound</td>
</tr>
<tr>
<td>ALIPHATIC POLYETHER URETHANE</td>
<td>CAST</td>
<td>$1.29/pound</td>
</tr>
<tr>
<td>SILICONE ELASTOMER, 534-044</td>
<td>CAST</td>
<td>$3.00/pound</td>
</tr>
<tr>
<td>SILICONE RESIN, QI-2577</td>
<td>SPRAY</td>
<td>$11.26/pound</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>UV SCREENING</th>
<th>SOIL PROTECTION</th>
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</thead>
<tbody>
<tr>
<td>POLYVINYL CHLORIDE PLASTISOL</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>ETHYLENE VINYL ACETATE</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>ETHYLENE PROPYLENE RUBBER</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>ALIPHATIC POLYETHER URETHANE</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>SILICONE ELASTOMER, 534-044</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>SILICONE RESIN, QI-2577</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
Ethylene Vinyl Acetate Compared With Polyvinyl Butyral

COMMENTS FROM INDUSTRIAL EVALUATION

EVA ADVANTAGES

- COST
- APPEARANCE
- CLARITY
- NON-YELLOWING
- LOW-BLOCKING
  - ELIMINATES COLD STORAGE
- DIMENSIONAL STABILITY
- PROCESSING ADVANTAGES
  - REDUCES TIME
  - ELIMINATES PRESSURE AUTOCLAVE
- GOOD FLOW PROPERTIES AND VOLUMETRIC FILL

Ethylene Vinyl Acetate: Directions for Improvements And Questions Resulting From Industrial Evaluation

IMPROVEMENTS

- INCORPORATE PRIMER
- INCREASE WHITING CONTENT
- REDUCE TIME/TEMP. FOR FASTER PROCESSING
- EMBOSSED FOR AIR REMOVAL AND FILM WINDING
- AVOID GASSING ADDITIVES

QUESTIONS

- MAXIMUM STORAGE TIME/HUMIDITY?
- MAXIMUM HANDLING TEMPERATURE (BLOCKING) ?
- REPAIRABILITY?
- LIFE?
### Materials Under Development

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<thead>
<tr>
<th>PROCESS AND PROJECTED COST</th>
<th>PROCESS</th>
<th>COST</th>
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<tbody>
<tr>
<td>POLY-n-Butyl Acrylate</td>
<td>CAST</td>
<td>&lt;$1.50/pound</td>
</tr>
<tr>
<td>Silicone/Acrylic Copolymer</td>
<td>SPRAY</td>
<td>&lt;$3.40/pound</td>
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</table>

#### Top Coverage Requirements

<table>
<thead>
<tr>
<th>POLY-n-Butyl Acrylate</th>
<th>UV</th>
<th>YES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone/Acrylic Copolymer</td>
<td>NO</td>
<td>?</td>
</tr>
</tbody>
</table>

### Polymer Film Top Covers With UV Screening Property

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>STATUS</th>
<th>UV SCREENING PROPERTY</th>
<th>PROJECTED OR COMMERCIAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>KORAD 212</td>
<td>AVAILABLE</td>
<td>TEMPORARY*</td>
<td>1.5¢/ft² mil</td>
</tr>
<tr>
<td>Silicone/Acrylic Copolymer</td>
<td>UNDER DEVELOPMENT</td>
<td>PERMANENT</td>
<td>~3.5¢/ft² mil</td>
</tr>
<tr>
<td>TEDLAR 100-BG-30-UT</td>
<td>AVAILABLE</td>
<td>PERMANENT</td>
<td>5.0¢/ft² mil</td>
</tr>
</tbody>
</table>

* PERMANENCE OF UV SCREENING PROPERTY UNDER DEVELOPMENT
Substrate Panels

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Status</th>
<th>Projected or Commercial Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARDBOARDS</td>
<td>AVAILABLE</td>
<td>1/8-inch THICKNESS; $\approx 12$/ft$^2$</td>
</tr>
<tr>
<td>STRANDBOARDS</td>
<td>UNDER DEV'L</td>
<td>3/8-inch THICKNESS; $\approx 16$/ft$^2$</td>
</tr>
<tr>
<td>METAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILD STEEL</td>
<td>AVAILABLE</td>
<td>0.028-inch THICKNESS; $\approx 24$/ft$^2$</td>
</tr>
<tr>
<td>GALVANIZED STEEL</td>
<td>AVAILABLE</td>
<td>$\approx 15%$ HIGHER THAN MILD STEEL</td>
</tr>
<tr>
<td>ENAMELED STEEL</td>
<td>AVAILABLE</td>
<td>$\gg 15%$ HIGHER THAN MILD STEEL</td>
</tr>
<tr>
<td>CONCRETE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLASS-REINFORCED</td>
<td>UNDER DEV'L</td>
<td>1/4-inch THICKNESS; $\approx 62$/ft$^2$</td>
</tr>
</tbody>
</table>

Wood Substrate Panels

- **MODES OF OUTDOOR WEATHERING DEGRADATION**
  1) WATER ROT
  2) UV PHOTO-OXIDATION
  3) MECHANICAL BREAKDOWN FROM EXTREMES OF HYGROSCOPIC EXPANSION AND CONTRACTION

- **WEATHER-PROOFING APPROACH**
  
  ENCAPSULATION WITHIN A PIGMENTED AND UV STABILIZED CONFORMAL POLYMERIC COATING
Mild Steel Substrate Panels

• PRIMARY MODE OF OUTDOOR DEGRADATION
  CORROSION

• CORROSION PROTECTION APPROACHES
  1) CONFORMAL COATING ENCAPSULATION WITH CHEMICAL COUPLING AGENTS
  2) ION-PLATED CORROSION-RESIST SURFACE COATINGS
  3) ENAMELING

Non-Woven Glass Mats* for Electrical and Mechanical Spacer Application

<table>
<thead>
<tr>
<th>Thickness, mils</th>
<th>Cost $/m²</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 5 7 9 12</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>1.32 1.76</td>
<td>2.2 2.8 3.7</td>
</tr>
<tr>
<td>210</td>
<td>- - 1.56</td>
<td>- -</td>
</tr>
<tr>
<td>200</td>
<td>0.66 0.78</td>
<td>0.97 1.36 1.81</td>
</tr>
</tbody>
</table>

CRANEGLAS, DISTRIBUTED BY
ELECTROLOCK, INC.
CHAGRIN FALLS, OHIO
Back Covers

GLASS SUPERSTRATE DESIGNS

MYLAR
KORAD
TEDLAR
ALUMINUM
ALUMINUM/POLYMER LAMINATES

SUBSTRATE DESIGNS WITH WOOD AND MILD STEEL

PIGMENTED AND UV-STABILIZED POTTANTS AS CONFORMAL COATINGS
(e.g. WHITE-PIGMENTED EVA)

Surface Materials & Modifications to Top-Cover Surfaces

REQUIREMENTS

1) TRANSPARENT
2) LOW-SOILING
3) EASILY CLEANED
4) ABRASION RESISTANT
5) ANTIREFLECTIVE
Soiling Theory

ATMOSPHERIC SOILING MATERIALS

1) ORGANICS
   a) VAPORS
   b) PARTICULATES

2) INORGANICS
   a) WATER SOLUBLE
   b) WATER INSOLUBLE

LOW-SOILING SURFACE REQUIREMENTS

1) HARD
2) HYDROPHOBIC
3) OLEOPHOBIC

NATURAL CLEANING

1) WIND
2) RAIN

Outdoor Soiling Experience of PV Modules With Different Exterior Surfaces

POWER RECOVERY AFTER CLEANING

<table>
<thead>
<tr>
<th>Surface</th>
<th>SOFT SILICONE ELASTOMERS</th>
<th>SILICONE RTV615</th>
<th>SYLG. 184</th>
<th>SILICONE HARD COAT</th>
<th>GLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSET 161 DAYS</td>
<td>+9</td>
<td>+9</td>
<td>+4</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>CARIBBEAN (1 yr.)</td>
<td>+9</td>
<td>+9</td>
<td>0</td>
<td>+2</td>
<td></td>
</tr>
<tr>
<td>MIT</td>
<td>+13 (5 mo.)</td>
<td>+14</td>
<td>+10 (5 mo.)</td>
<td>+6 (5 mo.)</td>
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</tr>
<tr>
<td>NYU</td>
<td>+23 (6)</td>
<td>+29 (5)</td>
<td>+22-26</td>
<td>+11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+33 (12)</td>
<td>+38 (12)</td>
<td></td>
<td></td>
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<tr>
<td>COLUMBIA U.</td>
<td>+21 (6)</td>
<td>+22 (6)</td>
<td>-</td>
<td>+12 (6)</td>
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<tr>
<td></td>
<td>+29 (12)</td>
<td>+33 (12)</td>
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<td></td>
<td></td>
</tr>
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</table>

DECREASING OIL, RH ENVIRONMENT

INCREASING SURFACE HARDNESS

441
Commercial Surfacing Materials

1) FLUOROCARBONS
   TEDLAR (DU PONT)
   KYNAR (PENNWALT)
   HALAR (3M)
   TEFLON (DU PONT)
   ABSITE (DU PONT)

2) GLASS RESINS
   GLASS RESIN 650 (OWENS-ILLINOIS)

3) SILICONE RESINS WITH COLLOIDAL SILICA
   ARC (DOW CORNING)
   SAR (DU PONT)
   SHC-1000 (GENERAL ELECTRIC)

Surface Materials & Modifications Under Investigation

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>FUNCTION</th>
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<tbody>
<tr>
<td>CHEMICAL ETCHING OF GLASS SURFACE</td>
<td>ANTIREFLECTION</td>
</tr>
<tr>
<td>IONIC CROSSLINKING OF KORAD SURFACE</td>
<td>SOILING AND ABRASION RESISTANCE</td>
</tr>
<tr>
<td>ION-PLATED DEPOSITION OF SILANES</td>
<td>1) SOILING AND ABRASION RESISTANCE</td>
</tr>
<tr>
<td></td>
<td>2) ANTIREFLECTION</td>
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442
Adhesives & Primers for Solar Cells
And Encapsulation Materials

<table>
<thead>
<tr>
<th>SOLAR CELLS</th>
<th>GLASS</th>
<th>KORAD</th>
<th>EVA</th>
<th>SILICONE ELASTOMER</th>
<th>HARDBOARD</th>
<th>ETC.</th>
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</tr>
<tr>
<td>GLASS</td>
<td>1, 2, 3, 7</td>
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<tr>
<td>KORAD</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>EVA</td>
<td>5</td>
<td>5, 6</td>
<td>U</td>
<td></td>
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<tr>
<td>GE SILICONE ELASTOMER</td>
<td>4</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HARDBOARD</td>
<td>2</td>
<td>X</td>
<td>X</td>
<td>5, 6</td>
<td></td>
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</table>
List of Primers, Adhesives & Non-Material Bonding Techniques

**ADHESIVES**

1) X1-2561 (DOW CORNING)
2) Q1-2577 (DOW CORNING)
3) Q96-083 (DOW CORNING)

**PRIMERS**

4) 2-6020 (DOW CORNING)
5) 2-6020/2-6030 MIX (DOW CORNING)
6) SS-4179 (GENERAL ELECTRIC)

**NON-MATERIAL**

7) ELECTROSTATIC BONDING (SPIRE)
Encapsulation Processes

1) LAMINATION
2) CAST
3) SPRAY
4) EXTRUSION

Task III & Task III Contractors' Successful Experience With Encapsulation Processes

(PASSES JPL THERMAL CYCLE TEST)

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>MODULE DESIGN</th>
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<tr>
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<tr>
<td></td>
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</tr>
<tr>
<td>LAMINATION</td>
<td>YES</td>
</tr>
<tr>
<td>CAST</td>
<td>YES</td>
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<tr>
<td>SPRAY</td>
<td>YES</td>
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<tr>
<td>EXTRUSION</td>
<td>-</td>
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Fabricated Modules

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<thead>
<tr>
<th>PROCESS</th>
<th>PROCESS WOOD</th>
<th>METAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMINATION</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CAST</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>SPRAY</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>EXTRUSION</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
Vacuum-Bag Lamination

MATERIALS LAYUP

- OPTIONAL SHEET METAL
- RELEASE LAYER
- KORAD
- CLEAR EVA
- CELLS AND EXTERNAL CONNECTORS
- SPACER
- WHITE PIGMENTED EVA
- SUBSTRATE
- SPACER
- WHITE PIGMENTED EVA
- RELEASE LAYER
- OPTIONAL SHEET METAL

ALL DRY FILMS, NO SOLVENTS

Vacuum-Bag Fixture

TOP PLATE

2-mil CAPRAN FILM

VACUUM

BOTTOM PLATE
HEATED IN HYDRAULIC PRESS

TOP PRESS PLATEN

TOP PLATE

TOP FRAME

BOTTOM FRAME

BOTTOM PLATE

BOTTOM PRESS PLATEN

EVA CURE SCHEDULE: 20 minutes AT 140 TO 150°C, UNDER VACUUM

Fabricated Substrate Module With EVA Pottant

SOLAR CELLS

KORAD SURFACE

CLEAR EVA

ENCAPSULATED SUBSTRATE

WHITE PIGMENTED EVA/Glass Mat
Electrical Breakdown of a Glass Superstrate Module With EVA

MODULE MATERIALS

1) SODA-LIME WINDOW GLASS
2) 20 mil CLEAR EVA FILM
3) CELL STRING
4) 5 mil NON-WOVEN GLASS MAT
5) 12 mil WHITE PIGMENTED EVA FILM
6) 1 mil ALUMINUM FOIL

D. C. ELECTRICAL BREAKDOWN VOLTAGE

5.8 kV

Vacuum-Bag Process

CONCERNS

- HANDLING OF LARGE-AREA PREFABRICATED CELL STRINGS
- AIR REMOVAL FROM LARGE AREA LAMINATED MODULES
- PROVISIONS FOR EXTERNAL CONNECTORS AND LEADS
- CELL SHIFTING

Spray Process

POSSIBLE ADVANTAGES

- ELIMINATE HANDLING OF PRE-FABRICATED CELL STRINGS
  1) ADHESIVELY BOND CELLS WITH INTERCONNECT TABS TO SUBSTRATE/SUPERSTRATE
  2) FINISH INTERCONNECTION IN-PLACE
- EXTERNAL LEADS AND CONNECTORS MORE EASILY ACCOMMODATED
- NO CELL SHIFTING
POSSIBLE CONCERNS

• CLEANLINESS
• INCOMPLETE COVERAGE
  a) SHADOWING AND FILLING
• THIN COVERAGE
  a) EXPOSED ELECTRICAL CONDUCTORS
  b) STEPPED CELL EDGES
    i) MECHANICAL DAMAGE
    ii) CRACKING AND FRACTURING OF COATING (THERMAL EXP.)
• MATERIAL WASTE FROM SPRAY LOSSES
  a) HEALTH

The Future

• ACCELERATED/ABBREVIATED LIFE PREDICTION METHOD
• SOILING RESISTANCE AND MAINTENANCE
• EVALUATION OF ALL PROCESSING TECHNIQUES
  • MATERIALS APPROPRIATELY FORMULATED FOR AUTOMATION
• OPTIMAL MODULE DESIGN
  • COST
  • STRUCTURAL
  • OPTICAL
  • ELECTRICAL ISOLATION
  • THERMAL
  • PROTECTION OF CELLS, INTERCONNECTS, WIRES, ETC.
• CONTINUE MATERIALS DEVELOPMENT
  • UV SCREENS, POTTANTS, PRIMERS, SURFACE MATERIALS/MODIFICATION
  • SUBSTRATES
DISCREPANCIES
BLOCK II AND BLOCK III

JET PROPULSION LABORATORY

Walter E. Bishop

Discrepancy Rate: All Defects, All Suppliers

<table>
<thead>
<tr>
<th>BLOCK</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>46.5</td>
</tr>
<tr>
<td>III</td>
<td>38.1</td>
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</table>

TOTAL DEFECTS
CATEGOR Y DISCREPANCY RATES

All Defects, Supplier A (Block III Only)

<table>
<thead>
<tr>
<th>Category</th>
<th>Block III</th>
<th>PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRACKED CELLS</td>
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<td>7.4</td>
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<tr>
<td>ENCAPSULANT</td>
<td></td>
<td>6.5</td>
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<tr>
<td>INTERCONNECTS</td>
<td></td>
<td>47.1</td>
</tr>
<tr>
<td>ASSEMBLY/Mechanical</td>
<td></td>
<td>27.2</td>
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<tr>
<td>ELECTRICAL</td>
<td></td>
<td>6.7</td>
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<tr>
<td>OTHER</td>
<td></td>
<td>5.0</td>
</tr>
</tbody>
</table>

All Defects, Supplier B

<table>
<thead>
<tr>
<th>Category</th>
<th>Block III</th>
<th>PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRACKED CELLS</td>
<td>II</td>
<td>12.1</td>
</tr>
<tr>
<td>ENCAPSULANT</td>
<td>II</td>
<td>4.9</td>
</tr>
<tr>
<td>INTERCONNECTS</td>
<td>II</td>
<td>0.2</td>
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<tr>
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<td>II</td>
<td>7.1</td>
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<tr>
<td>ELECTRICAL</td>
<td>III</td>
<td>1.9</td>
</tr>
<tr>
<td>OTHER</td>
<td>II</td>
<td>18.7</td>
</tr>
</tbody>
</table>

451
All Defects, All Suppliers

Discrepancy Rate
All Defects, All Suppliers

SUPPLIER | BLOCK | PERCENT
---|---|---
A | II | 41.6
 | III | 41.4
B | II | 23
 | III | 12.9
C | II | 33.3
 | III | 26.5
E | II | 4.4
 | III | 57.5
F | II | 31.0
 | III | 31.0

Note: The graph shows the percentage distribution of defects for different components and suppliers.
The Thursday-afternoon session on test and applications was initiated by an overview of T&A experiments status and plans given by Dr. John Hesse of the TD&A Lead Center. Covering those projects underway in stand-alone, intermediate load, residential, and congressionally mandated application sectors, Dr. Hesse made it clear that the Program is on the verge of fielding a great quantity and variety of PV systems. Special attention was given to the potential impact if PV power systems are selected for the Missile-X Program. An expanded version of Dr. Hesse's talk is available in the Proceedings of the DOE Semiannual Review, conducted at Pinehurst, N.C., on November 5-7, 1979.

Dr. Steve Forman updated T&A session participants on experience at MIT/LL test sites. The cumulative module failure total for all sites over the past two years is 3%. A significant problem has occurred at the University of Texas (Arlington) residential test site, where 22% of the Block II modules in use there have failed. The principal failure mode at that site is cracked cells, probably related to back-bias heating when circuit strings were short-circuited. Dr. Forman will present a paper on MIT/LL field experience at the IEEE PV Specialists Conference in San Diego on January 7-10, 1980.

Jim Deyo, Manager of the NASA LeRC PV Project, gave a summary of experience with stand-alone applications. Over the past three and a half years, 6% of the Block I and II modules installed in their applications have failed (a third of these were lost to high waves in a RAMOS installation). Array performance and public acceptance of PV systems have been good, with particular interest in village power systems displayed by the international community. Adequate load data for system sizing and the logistics of maintenance at remote sites were noted as continuing problems.

Ron Baisley of the LSA Project provided an update on the status of the 60 kW Mt. Laguna array. Failures to date stand at 2% of the array, although 18% of one module type there contain cracked cells and 36% of the second module type contain cracked cells. The former effect is believed to have been caused by a hailstorm at the site; the latter effect is a form of progressive cell cracking aggravated by gas generation under these cells, caused by back-bias heating. Design features needed to prevent the recurrence of such problems in future module types are in hand, and a discussion of available options was presented in Engineering Area sessions.
In looking forward, it is expected that the evaluation of the technology innovations of Block IV modules and the performance of the systems being now being fielded at an accelerated pace will provide the basis for a new round of lessons learned, leading to further improvements in module price, performance, and reliability.

TECHNOLOGY SESSION

TEST AND APPLICATIONS EXPERIENCE

L. Dumas, Chairman

STAND-ALONE APPLICATIONS PROJECT

APPLICATION EXPERIENCE

NASA LEWIS RESEARCH CENTER
James L. Deyo

- MODULES
- POWER SYSTEM
- LOADS
- MAINTENANCE
- PUBLIC INTEREST

Power System

- GENERAL OPERATION SATISFACTORY
- PROBLEM AREAS INVOLVED:
  - VOLTAGE REGULATORS/CONTROLS
  - RUN TIME METERS
  - AMP-HOUR METERS
  - ARRAY CONNECTORS
Loads

LOADS HAVE BEEN MAJOR SOURCE OF PROBLEMS

LOAD PROFILES: OPERATION DIFFERS FROM PREDICTED

IMPROPER LOAD DEVICE OPERATION:
  REFRIGERATOR OPEN DOORS/DEFROSTING/LOCATION
  GRINDER PLATE WEAR
  DUST STORM SIGN WINTER USE

REFRIGERATORS:
  COMPRESSOR MOTORS
  REFRIGERANT CHARGE
  INADEQUATE CABINET INSULATION

WEATHER SYSTEM: DATA LINKS, BATTERIES, TRANSMITTER

DUST STORM SIGN: ACTUATOR MECHANISM

USERS SOMETIMES MISTAKENLY PERCEIVE A FAILURE OF THE LOAD DEVICE AS A PV/LOAD SYSTEM FAILURE.

Maintenance

FOR REMOTE SITES, MAJOR PROBLEMS HAVE BEEN:
- DISCOVERING PROBLEM IN A TIMELY WAY
- SHIPPING, AND TRANSPORTATION OF MATERIAL AND PERSONNEL TO SITES SIGNIFICANTLY DELAY MAINTENANCE AND FAULT CORRECTION
- ONLY ROUTINE MAINTENANCE NEEDED CONSISTS OF:
  BATTERY ELECTROLYTE LEVEL CHECK
  ARRAY WASHING (OCCASIONALLY, SOME SYSTEMS)

Public Interest

- GENERAL REACTION POSITIVE
- CONTINUING HIGH LEVEL OF INTEREST IN SCHUCHULI AND UPPER VOLTA ESPECIALLY FROM INTERNATIONAL COMMUNITY
Summary

- Load devices have been a major source of problems
- Modules have not been a problem
- Maintenance problems have been related to remoteness of locations rather than the maintenance required

Module Experience

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>NUMBER</th>
<th>MFGR</th>
<th>JPL BLOCK</th>
<th>FAILURES</th>
<th>CAUSE</th>
<th>INSTALLED</th>
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</thead>
<tbody>
<tr>
<td>Isle Royale Refrig.</td>
<td>24</td>
<td>SX</td>
<td>1</td>
<td>0</td>
<td></td>
<td>5/76</td>
</tr>
<tr>
<td>Sil Naka Refrig.</td>
<td>36</td>
<td>SX</td>
<td>1</td>
<td>2</td>
<td>Cracked cell/open</td>
<td>7/76</td>
</tr>
<tr>
<td>Forest Lookout</td>
<td>64</td>
<td>SX</td>
<td>1</td>
<td>0</td>
<td></td>
<td>10/76</td>
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<tr>
<td>Dust Storm Sign</td>
<td>20</td>
<td>ST</td>
<td>1</td>
<td>1</td>
<td>Vandalism</td>
<td>4/77</td>
</tr>
<tr>
<td>Insect Trap</td>
<td>32</td>
<td>ST</td>
<td>1</td>
<td>1</td>
<td>Open</td>
<td>5/77</td>
</tr>
<tr>
<td>Ramos</td>
<td>64</td>
<td>SX</td>
<td>1</td>
<td>28</td>
<td>12 storm/10 low output</td>
<td>5/77-10/77</td>
</tr>
</tbody>
</table>

| RAMOS               | 1      | ST   | II        | 1        | Vandalism       | 10/77     |
| LONE PINE           | 48     | ST   | II        | 0        |                 | 9/77      |
| Schuchuli           | 192    | SX   | II        | 2        | 1 open/1 hail   | 12/78     |
| Upper Volta         | 100    | SX   | GSA (11)  | 1        | Open?           | 2/79      |

| TOTALS              | 342    | 4    | 581       | 36       |

| Systems Test Facility | 112    | SX   | 1         | 1        | Interconnect   | 4/76      |
|                      | 642    | ST   | 1         | 0        |                 | 9/76      |
|                      | 644    | SP   | 1         | 1        | Interconnect   | 12/76     |
|                      | 1920   | ST   | III       | 0        |                 | 6/79      |
STATUS REPORT: MT. LAGUNA AIR FORCE STATION

JET PROPULSION LABORATORY

Ron Baisley

History

• DEDICATION - AUGUST 15, 1979

• SCOPE OF INVESTIGATION (JULY 21-OCTOBER 30)
  • 11 VISUAL, IR & FUNCTIONAL FIELD AUDITS
  • JPL FIELD TESTS
  • LABORATORY ANALYSIS
  • ANALYTICAL MODELING

• OPERATING CONDITIONS
  • SYSTEM CHECKOUT/LIMITED OPERATION - (JULY-AUG. 15)
  • FULL OPERATIONAL/MAX POWER TRACK (AUG. 15-OCT. 5 AND NOV. 3-PRESENT)
  • FULL OPERATIONAL/REDUCED POWER (OCT. 6-NOV. 2)

Observations

ELECTRICAL PERFORMANCE

• BYPASSED MODULES
  OCT 5 ........................................... 37
  OCT 23 ........................................... 40

• DEGRADATION - DIFFICULT TO DETERMINE WITH PRESENT DATA SYSTEM

Observations—Visual
Cracked Cells/Impact Fractures

• 217 CRACKED CELLS IN 136 MODULES

• 136 OF 756, OR 18% OF SOLAREX MODULES AFFECTED

• TYPICAL OF IMPACT CRACKS

• HAILSTORM 07/22/79
Observations—Visual
Cracked Cells/Burst-Type Fractures

- OCCURRENCE - 790 CELLS (573 MODULES)
- DELAMINATION - 238 CELLS
- HOT CELLS - 240 CELLS (2-70 $c^0\Delta$)
- CORRELATION
  - CRACK/BURST $\rightarrow$ HOT CELL $\cdot$ VARYING WITH AUDIT
- DISTRIBUTION - NON-UNIFORM

Observations—Visual
Cracked Cells/Burst Fracture History
Observations—IR
Cell Temperature Distribution

System Power Loss, Mt. Laguna Array Configuration
(1% Cracked Cells, 560 Series/BC)

<table>
<thead>
<tr>
<th>Module Size x Parallel Cells</th>
<th>Cell Contacts</th>
<th>Parallel Blocks</th>
<th>Series Blocks per bc</th>
<th>Diodes per Module</th>
<th>Cells per Diode</th>
<th>System Power Loss %</th>
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<tbody>
<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>560</td>
<td>96</td>
</tr>
<tr>
<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>32</td>
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<td>40 x 1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>20</td>
<td>16</td>
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<tr>
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<td>1</td>
<td>4</td>
<td>4</td>
<td>10</td>
<td>7</td>
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<tr>
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</tr>
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<td>1</td>
<td>40</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>40 x 1</td>
<td>4</td>
<td>14</td>
<td>0</td>
<td>560</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>40 x 1</td>
<td>4</td>
<td>14</td>
<td>1</td>
<td>40</td>
<td>35</td>
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<td>8</td>
<td>14</td>
<td>0</td>
<td>560</td>
<td>40</td>
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<td>56</td>
<td>0</td>
<td>560</td>
<td>36</td>
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<tr>
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Conclusions

- BURST-CELL PHENOMENON IS CONTINUING
- PROBABLE "TRIGGER"
  - CRACKED CELL - OPERATIONAL AND/OR ENVIRONMENTAL STRESSES
  - CELL MISMATCH - MANUFACTURING AND/OR DEGRADATION
- IMPACT FRACTURES
  - PROBABLE CAUSE - HAILSTORM
- PROSPECT FOR ARRAY SURVIVAL IS UNKNOWN
  - INSUFFICIENT DATA
  - CRACKED CELL FAILURE MODE/LIFE NOT UNDERSTOOD
- VALUABLE SOURCE OF DATA
  - ARRAY DYNAMICS
  - ON-SITE TROUBLESHOOTING TECHNIQUES

Recommendations
Mt. Laguna

- IMPROVE DATA SYSTEM
- CONTINUE ON-SITE AUDITS
- CONTINUE FAILURE ANALYSES

Recommendations
Future Generations

MANUFACTURERS

- PROVIDE MULTIPLE CELL CONTACTS
- CONSIDER INTERNAL SERIES/PARALLELLING AND BYPASS DIODE PROTECTION
- ELIMINATE ENCAPSULANT MATERIALS WITH OUTGASSING TENDENCIES
- IMPROVE CELL MATCHING

JPL

- REVISE MODULE DESIGN AND TEST SPECIFICATIONS TO
  ENCOMPASS WORSE-CASE OPERATIONAL CONDITIONS
Professor A. Weinstein of Carnegie-Mellon University, an expert in the field of product liability, was an invited speaker at the 14th PIM. In his talk, titled "Safety and Product Liability," he alerted the LSA photovoltaic community to possible penalties of introducing unsafe products for commercial use. Highlights of his talk included a discussion of concerns relative to litigations that might result should injury be caused by a defective product.

Of the various legal theories upon which action might be based, three were mentioned: negligence, breach of warranty and strict liability. The area of most concern is that of strict liability; with such cases, no proof of fault is required. In a certain landmark decision by the California state Supreme Court, strict liability was once established when a product was shown to present unreasonable danger to an extent beyond that which an ordinary user or consumer might contemplate. Professor Weinstein further explained that even posting warnings of danger on a product is not sufficient to avoid liability in most instances. It was noted that a product can also be considered defective if excessive preventable danger can be shown to exist.

Professor Weinstein concluded that establishment of safety and product liability guidelines by the photovoltaic community should be initiated now. He emphasized that safety and product liability factors can be introduced as a part of basic design, overall risk-benefit analyses and in the development of standards.

A. Weinstein  
Carnegie-Mellon University

Considerations for Liability

PRODUCT RELIABILITY
SPECIFICATIONS
WARRANTIES
USEFUL LIFE

PRODUCT SAFETY
HAZARDS/RISKS OF INJURY
PROPERTY DAMAGE
Legal Bases for Liability

DESIGNER/ENGINEER
NEGligence

MANUFACTURER/ASSEMBLER/SELLER
NEGligence
EXPRESS WARRANTY/MISREPRESENTATION
STRICT LIABILITY

Basic Legal Principles in Product Liability

1. NEGLIGENCE WHICH TESTS THE CONDUCT OF THE DEFENDANT.

2. EXPRESS WARRANTY AND MISREPRESENTATION WHICH TESTS THE PERFORMANCE OF PRODUCTS AGAINST THE EXPLICIT REPRESENTATIONS MADE ON THEIR BEHALF BY THE MANUFACTURER AND SELLERS; AND

3. STRICT LIABILITY AND IMPLIED WARRANTY WHICH TEST THE QUALITY OF THE PRODUCT.

Indicia for Unreasonably Dangerous Defect

1. THE USEFULNESS AND DESIRABILITY OF THE PRODUCT

2. THE AVAILABILITY OF OTHER AND SAFER PRODUCTS TO MEET THE SAME NEED

3. THE LIKELIHOOD OF INJURY AND ITS PROBABLE SERIOUSNESS

4. THE OBVIOUSNESS OF DANGER

5. COMMON KNOWLEDGE AND NORMAL PUBLIC EXPECTATION OF THE DANGER (PARTICULARLY FOR ESTABLISHED PRODUCTS)

6. THE AVOIDABILITY OF INJURY BY CARE IN USE OF THE PRODUCT (INCLUDING THE EFFECT OF INSTRUCTIONS AND WARNINGS)

7. THE ABILITY TO ELIMINATE THE DANGER WITHOUT SERIOUSLY IMPAIRING THE USEFULNESS OF THE PRODUCT OR MAKING IT UNDULY EXPENSIVE.

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Elements of Design Procedure:
The Reasonably Safe Product

A. DELINEATION OF PRODUCT USES

B. IDENTIFICATION OF ENVIRONMENTS WITHIN WHICH THE PRODUCT WILL BE USED

C. DESCRIPTION OF USER POPULATION

D. POSTULATE ALL POSSIBLE HAZARDS, TOGETHER WITH SOME ESTIMATE AS TO PROBABILITY OF OCCURRENCE AND SERIOUSNESS OF THE RESULTING HARM

E. DELINEATE ALTERNATIVE DESIGN OR PRODUCTION FEATURES INCLUDING WARNINGS AND INSTRUCTIONS, THAT WOULD EFFECTIVELY MITIGATE OR ELIMINATE THE HAZARDS

F. EVALUATE SUCH ALTERNATIVE FEATURES RELATIVE TO THE EXPECTED PERFORMANCE STANDARDS OF THE PRODUCT, INCLUDING
   1. EFFECT ON THE SUBSEQUENT USEFULNESS OF THE PRODUCT
   2. EFFECT ON THE SUBSEQUENT COST OF THE PRODUCT
   3. COMPARISON TO SIMILAR PRODUCTS

G. DECISION AS TO WHICH FEATURES TO INCORPORATE IN FINAL DESIGN TO PROVIDE THE REASONABLY SAFE PRODUCT