DEPARTMENT OF ENERGY

LSA
LOW-COST SOLAR ARRAY
PROJECT

Project QUARTERLY REPORT -6
FOR THE PERIOD JULY 1977 - SEPTEMBER 1977

5101-55
The JPL Low-cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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Recipients of Jet Propulsion Laboratory
Publication 78-83

SUBJECT: Erratum

Please note the following correction to JPL Publication 78-83, Project
Quarterly Report - 6 for the Period July 1977 - September 1977:

Page 1-1, first paragraph: Change October through December, 1977 to
July through September, 1977.

Very truly yours,

[Signature]

John Kempton, Assistant Manager
Documentation Section
LSA
LOW-COST SOLAR ARRAY
PROJECT

Project
QUARTERLY
REPORT - 6
FOR THE PERIOD JULY 1977- SEPTEMBER 1977

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
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SECTION I
INTRODUCTION AND PROJECT OVERVIEW

A. INTRODUCTION

This report describes the activities of the Low-Cost Silicon Solar Array Project during the period October through December, 1977. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this, and the progress that was made during the quarter.

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

B. PROJECT OVERVIEW

While progress was significant in all areas of the Project this quarter, the highlight of this reporting period was the analysis of the feasibility of the 1982 $2/watt goal at the 7th Project Integration Meeting. Held at Caltech, the meeting produced a consensus among both JPL and contractor personnel that the goal appears feasible, but only given certain conditions. Briefly, they were 1) that the market must continue to expand at the present rate, 2) that continued or accelerated confidence in market prospects must exist among industry, 3) that present technology and factory design/development must continue to be supported at its present rate, and 4) that continued government support both in technical development and in market expansion will be necessary for achievement of the 1982 goal. The attendees felt that the Project had met its FY77 objectives.

At the PIM, the Project presented the results of an economic analysis considering the implications of life-cycle cost on module lifetime and reliability. During the quarter, economic analysis and integration documents were published (see below) that established uniform costing standards. The Phase I SAMICS support contract was completed, and a Phase II contract executed. A major study was performed of the historical diffusion of new technologies in the semiconductor industry and other industries, and of experience of government attempts to expedite private adoption of new technologies. An important action this quarter was the award of a contract to examine necessary conditions for private investment in photovoltaics manufacturing capacity.

*In 1975 dollars
SiH₄ was routinely produced this quarter from dichlorosilane with a greater than 97% yield. A contractor completed a first phase process design and analysis review as well as a system purity analysis. Production of SiH₄ from SiCl₄ using the non-equilibrium jet process did not appear to be feasible. Experiments demonstrated polymer and homologue conversions. A detailed material and energy flow sheet and an analysis of the design of a 50 MT/yr Process System Development Facility to be located in an existing contractor's building were completed. Low Si yields were obtained from an experimental-size arc furnace; two of the runs showed impurity concentrations below 10 ppmw except for B and P. An economic analysis of the commercial Siemens process was completed which gave product prices ranging from $63.60/kg to $72.70/kg. It was shown that there are significant differences between doped p+/n cells as compared with n+/p cells and that molybdenum causes considerable cell degradation at low concentrations. Mixtures of Si and salt were obtained in halosilane-alkali metal flame chemistry studies; the flames were self-initiating, self-sustaining, and very exothermic.

Analysis of the EFG ribbon growth technique using SAMICS interim price estimation guidelines shows that present technology can produce sheet material at less than the 1986 goal of $20/m². Buckling encountered at higher speeds and large widths may be corrected by design changes in the growth cartridge. Use of the fluid flow phenomenon produced ~10% efficiency solar cells from the central 2.5 cm of a 5-cm-wide ribbon in standard runs. The 10-cm-wide ribbon growth furnace was installed at IBM, and thermal profiling of the graphite die was continued; a 9.4-cm-wide ribbon was grown but shattered upon withdrawal from the furnace. Modification to one of the RTR-technique ribbon machines allowed growth of 2-cm-wide ribbon at 10 cm/min, and RTR growth from a doped polyribbon feedstock obtained from a CVD process was achieved. Analysis of the silicon web process concludes that the growth rate needs to be improved by a factor of two to three to satisfy the 1986 cost goals. An "upside down" wafering technique resulted in 100% yields and the highest wafer accuracy yet achieved. Solar cells fabricated on epitaxial layers of about 25 µm thickness were found to produce efficiencies of 12%.

A literature search through documents pertaining to encapsulation materials and techniques was almost completed at 9500 documents reviewed. An approach was developed for relating accelerated test data for Lexan film yellowing to outdoor exposure data. Simultaneous electrostatic bonding of borosilicate glass to silicon cells was demonstrated, with a 1-mil-thick tantalum metallization screen pressed between the two. An analysis was developed that predicts loss of adhesive bond strength in silicone encapsulants caused by moisture. Glass surfaces that had been cleaned by various techniques were characterized by both degree of cleanliness and substrate chemical composition. Failure analysis was performed on degradation observed in large-scale procurement modules. Work was started to develop experimental techniques for measuring "work of adhesion."
Production processes Phase II, which will define, select and demonstrate manufacturing processes, was begun in September. Phase I results were presented which showed that a contemplated factory could profitably produce silicon solar cell modules for $2/watt in 1982, given Si material at $25/kg. Czochralski crystal growth and sawing was assumed in each of the three studies, and was shown to be the major cost driver. Additionally, it was concluded that in a total market of about 25 Mw in 1982, the share of each competing manufacturer will be marginal in affecting sufficient efficiency of operation to meet the $2/watt goal. Two courses to reduce risk and capital investment -- forward contracting and reduction of capital investment were examined, but both were felt to require considerable government support. It was concluded that if technological development after 1982 is slowed by two years, the factory could be justified economically; but if the technology is accelerated, it is already too late to build the $2/watt factory. Contracts were started on development of a high-efficiency (>12%), high packing density (>80%), square cell module, a roofing shingle type module, and a >13% efficiency module. Xerox experienced performance problems with its center-hole cell and stud design module.

A lack of available data from which to determine proper thickness for glass modules was indicated by a survey of methods for calculating breaking strengths of uniformly loaded glass plates. Conventional theories were therefore judged to be inadequate for predicting the effects of wind loading. Cost effectiveness of module design tradeoffs found that, among other things, transmission enhancement techniques, such as the use of low-iron glass, are presently cost effective; but hexagonal cells will not be cost effective until module price drops well below $2/watt. Computer analyses showed that roughly 50% of annual energy at various locations considered is obtained when the module's angle of incidence is greater than 30°, 25% at angles greater than 45°, and 10% at angles greater than 60°. Explorations into cooling modules with water for higher electrical output and into combined thermal/electric modules showed that these will not be cost effective until module price drops below $1/watt. Hail test activities, including high-speed motion pictures, showed that the key failure mode with soft encapsulants is cell crushing; with glass modules it is glass breakage due to excessive local plate bending.

Module deliveries totaled 33.4 kW, off 14.9 kW from the preceding quarter; the decrease resulted from one manufacturer completing its deliveries in the preceding quarter, and from completion of deliveries to the Nebraska agricultural pumping project. Production observations, much as were reported last quarter, were 1) scheduling remained an uncertain venture, 2) module deliveries fluctuated from week to week, and 3) modules were still subjected to 100% source inspection. In testing of the large-scale production modules, temperature cycling tests were discontinued on one manufacturer's modules pending design changes after serious cell cracking developed. Three of the five suppliers' developmental module types completed qualification testing; all passed the test functionally, although some cell cracking and delamination occurred. The installation of the final 18 of 33 stands at the JPL Field Test Site marked the completion of stand installation at the three test sites (JPL, Table Mountain, and Goldstone). The Coast Guard's
facility at Point Vincente approved placement of a site there; it was anticipated that the stands would be installed in November. The data acquisition system, in particular the dynamic load, was still not working properly at the end of the quarter, but the problem was isolated and expected to be corrected shortly. Erratic cell output performance caused by the "photon effect" was studied; it was concluded that the problem is caused by silicon instability, and may be remedied by a change of silicon wafer suppliers.

The Project published the following documents during this quarter:

<table>
<thead>
<tr>
<th>Title</th>
<th>Document Number</th>
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</thead>
<tbody>
<tr>
<td>Interim Price Estimation Guidelines</td>
<td>5101-33 (an internal document)</td>
</tr>
<tr>
<td>SAMICS Workbook</td>
<td>5101-15 (an internal document)</td>
</tr>
<tr>
<td>SAMICS Input Data Preparation</td>
<td>5101-44 (an internal document)</td>
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<tr>
<td>Modeling of Fluidized Bed Silicon Deposition Process</td>
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<td>Chemical Vapor Deposition of Silicon from Silane Pyrolysis</td>
<td>5101-51 (JPL Publication 77-38)</td>
</tr>
<tr>
<td>Humidity and Temperature Cycling Tests of Spectrolab Solar Cells</td>
<td>5101-42 (an internal document)</td>
</tr>
<tr>
<td>Silane to Silicon Chemical Vapor Deposition</td>
<td>Paper accepted by Electrochemical Society for 6th International Conference on CVD</td>
</tr>
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</table>
SECTION II
PROJECT ANALYSIS AND INTEGRATION AREA

A. ARRAY TECHNOLOGY COST ANALYSIS

The need for a simplified calculation procedure led to creation of the "Interim Price Estimation Guidelines" (JPL Internal Document 5101-33, September 10, 1977); a revised "SAMICS Workbook - Version One" (JPL Internal Document 5101-15) for application of the interim guidelines; and "SAMICS Input Data Preparation" (JPL Internal Document 5101-44) to explain how to describe processes for use in SAMICS. By the end of September, uniform costing standards were available for use by the LSSA Project. Printing of the two supplemental documents (5101-15 and 5101-44) was lagging.

The TB&A (Phase One) SAMICS support contract was completed, resulting in a detailed critique of the methodology and a 3-volume final report containing a standardized cost account catalog, indirect requirements, recommendations on the values of financial parameters, facilities capital cost estimating relationships, start-up and construction lead-time estimates, one-time cost submodel information, and three conceptual plant designs (to be used, in part, for validation). A Phase Two contract was let to establish submodels for variable operating schedules, sales and marketing costs, and warehousing and distribution, as well as augmentation of the cost account catalog and indirect requirements.

An in-depth seminar and critique of the SAMIS/SAMICS methodology was held on July 6. As a result, two new algorithms for capturing the economies of scale were developed. One provides a much faster solution, but does not guarantee convergence if some indirect requirements are near a discontinuity in their determining non-linear functions. The other new algorithm will require about as much computation as the algorithm being replaced, but it does guarantee convergence, while the original algorithm did not. Many detailed suggestions made by TB&A were incorporated into the methodology.

Preparation of the SAMIS III computer program continued. With the realization that the program was more difficult than originally anticipated, additional programmers were applied to the task and the targeted release date for the first release was changed to February, 1978. (The September 30, 1977, milestone for release in support of SAMICS was met by the publication of IPEG - the Interim Price Estimation Guidelines.) By the end of September, design and coding (not including the output reports) were 95% complete; compilation and testing were about 20% complete; report design was underway.

B. ARRAY LIFE-CYCLE ANALYSIS

Bechtel is under contract to JPL in support of the life-cycle analysis effort by providing detailed costing relationships in support of the life-cycle cost modeling effort undertaken by the Array Life-Cycle Analysis Task. The cost relationships shall be made for five conceptual
array design approaches to include three fixed array designs, one sea­sonally adjusted design and one single-axis tracking design. The respon­sibilities of the contractor shall include, but are not necessarily limited to the following tasks:

a. Array Concepts: select five conceptual array design approaches.

b. Array Conceptual Designs: develop the selected five array design approaches to enable major life-cycle cost implications to be determined.

c. Cost Estimates: determine detailed cost relationships for each of the five array design approaches and module designs.

d. Cost Dependencies: perform trade-off among design features with respect to cost elements.

e. Utility Practices: contact at least five electric utilities to determine utility practices with respect to photovoltaics.

The implications of life-cycle cost on module life time and reliability was presented to the 7th Project Integration Meeting on August 11, in the intra-/inter-task sessions on Life Prediction Methodology/Reliability. Life time and reliability determination need to be made in conjunction with the life-cycle cost elements of the systems, as a long-life and high-reliability array design may have higher total life-cycle cost than a shorter life and a less reliable array design.

C. ECONOMICS AND INDUSTRIALIZATION ANALYSIS

The major product of the Task in this quarter was a comprehensive evaluation of the Project's approach to industrializing technologies for photovoltaics manufacture. The research for this evaluation was conducted in two parts. First, an analysis of the historical diffusion of technical improvements through the semiconductor and other industries was performed. The results indicate that the lag between the establishment of feasibility (both technical and economic) for a new technique, and its first commercial implementation is likely to be short, ranging from six months to two years. This result strongly implies that cost-effective innovation has not been slowed by noneconomic barriers, or conversely, that establishing the technical and economic superiority of a technique is sufficient to induce its adoption.

The second part of the study focused on previous experience with government attempts to expedite private adoption of new technologies. The major results of this part are:

1. The basic requirements for private adoption of new technology are a demonstrated market for the product and a well-understood technology delivery system extending from raw materials inputs to delivered product.
2. Conduct of a manufacturing demonstration (by itself) contributes to reduction of uncertainty in only a part of the technology delivery system. Such demonstrations cannot compensate for absence of the basic requirements above.

3. Pilot plants make poor demonstrations, in that they are often shut down in pursuit of their primary goal — the production of technical information on design and operation of equipment.

These results contain corresponding implications for the LSSA Project:

1. Production technologies for photovoltaics must be compatible with commercially viable distribution, marketing, installation, and servicing systems.

2. Supply-side demonstrations must be synchronized with the demand-side activities of the Program — industrial receptivity to production demonstrations depends as much on perceived demand as on efficient supply.

3. Decisions to construct pilot plants should depend on their potential contributions to the technology development process — not on a desire to demonstrate technology or to secure a steady source of product.

Another important development in this quarter was the award to Gnostic Concepts, Inc. of a support contract in the Investment Decision subtask. The contractor's expertise in venture analysis in the semiconductor industry is expected to considerably improve Project understanding of the necessary conditions for private investment in photovoltaics manufacturing capacity. Results from this effort will appear in later quarterlies and as a Project document.
SECTION III
TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to establish by 1986, an installed plant capability for producing Si suitable for solar cells at a rate equivalent to 500 megawatts (peak) of solar arrays per year at a price of less than $10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal cannot be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade Si. Consequently, it is necessary that either a different process be developed for producing semiconductor-grade Si or a less pure and less costly Si material (i.e., a solar-cell-grade Si) be shown to be utilizable.

1. Technical Goals

Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about $65 per kilogram. A drastic reduction in price of material is necessary to meet the economic objectives of the LSSA Project. One means for meeting this requirement is to devise a process for producing a Si material which is significantly less pure than semiconductor-grade Si; the price goal for this material is less than $10 per kilogram. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSSA is dependent on optimization trade-offs, which concomitantly treat the effects of the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume and low-cost processes for producing different impurity-grades of Si.

2. Organization and Coordination of the Silicon Material Task Effort

The Silicon Material Task effort is organized into five phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing processes (in Part III) for the production of solar-cell-grade Si. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies and the most promising processes will have been selected.
Phase II will be initiated to obtain scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of a large-scale production plant.

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

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

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

3. Silicon Material Task Contracts

Nine contracts are in progress: three for Part I, one for Part II, four for Part III, and one for Part IV. These contracts were negotiated after careful evaluations of responses to a Request for Proposal (RFP) and of unsolicited proposals. The contracts are listed in Table 3-2. Additional contractors for subsequent phases will be selected from unsolicited proposals and from future RFPs.

4. Silicon Material Task Technical Background

The objectives of Phase I of the Silicon Material Task are as follows:

(1) Part I - Establish the practicality of a process capable of the high-volume production of semiconductor-grade Si at a markedly reduced cost.

(2) Part II - Investigate the effects of impurities and process-steps on the properties of single-crystal Si material and the performance characteristics of solar cells.
Table 3-1. Organization of the Silicon Material Task Effort

<table>
<thead>
<tr>
<th>Phase/Part</th>
<th>Objective</th>
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<tr>
<td>Phase I</td>
<td>Demonstrate the technical feasibility and practicality of processes for producing Si.</td>
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<tr>
<td>Part I</td>
<td>Establish the practicality of a process capable of high-volume production of semiconductor-grade Si at a markedly reduced cost.</td>
</tr>
<tr>
<td>Part II</td>
<td>Investigate the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells.</td>
</tr>
<tr>
<td>Part III</td>
<td>Establish the practicality of a process capable of high-volume production of solar-cell-grade Si at a price of less than $10 per kilogram.</td>
</tr>
<tr>
<td>Part IV</td>
<td>Evaluate the relative commercial potential of the Si-production processes developed under Phase I.</td>
</tr>
<tr>
<td>Phase II</td>
<td>Obtain process scale-up information.</td>
</tr>
<tr>
<td>Phase III</td>
<td>Conduct experimental plant operations to obtain technical and economic evidence of large-scale production potential.</td>
</tr>
<tr>
<td>Phase IV</td>
<td>Design, install, and operate a full-scale commercial plant capable of meeting the production objective.</td>
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(3) Part III - Establish the practicality of a process capable of the high-volume production of solar-cell-grade Si at a price of less than $10 per kilogram.

(4) Part IV - Evaluate the relative commercial practicality of the Si-production processes developed under Phase I of the Silicon Material Task.

a. Processes for Producing Semiconductor-Grade Silicon.

1) Production of Si by Zn Reduction of SiCl₄ - Battelle Memorial Institute. The contract with Battelle Memorial Institute is for development of the reaction for the Zn reduction of SiCl₄ using a fluidized bed reactor as an economical means for producing Si. Based on calculations by
Battelle and Lamar University, this process has the potential for a total product cost between $9.12 and $9.68/kg Si for a 1000 metric ton/year plant.

2) Production of Si From SiH₄ Prepared by Redistribution of Chlorosilanes – Union Carbide Corporation. The Union Carbide contract is for the development of processes for the production of SiH₄ and for the deposition of Si from SiH₄. The SiH₄ process includes systems for the redistribution of chlorosilanes and the hydrogenation of the by-product SiCl₄ to SiHCl₃, which can be used as a feed for redistribution. The free space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

3) Production of Si by SiF₄/SiF₂ Transport – Motorola Corporation. The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using the SiF₂ transport purification reaction steps.

b. Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells – Westinghouse Electric Corporation. Phase II of this contract consists of five tasks: (1) The effects of processing-steps, such as heat treatment, gettering, and crystal growth parameters, will be determined in conjunction with the impurity effects. (2) The combined effects of impurities and high B concentrations on solar cell performance will be examined. (3) The effects of impurities on n-type, P-doped Si will be determined; these data will be compared with those for p-type, B-doped Si material. (4) The impurity matrix for n-type Si will be expanded, especially in two areas: measurement and modeling for material containing two or more impurities and study of impurities which may contaminate the Si during the Si production process. (5) The effects of oxygen and C interactions with the impurities will be studied.

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Processes – Dow Corning Corporation. The Dow Corning contract is for the development of a process for improving the purity of Si produced in the arc furnace by using purer raw materials and for the further purification of the Si product by unidirectional solidification, arc furnace studies, and unidirectional solidification, and Si analysis.

2) Production of Si from Na₂SiF₆ Source Material Using Na Reduction of SiF₄ and SiF₄ Transport Processes – Stanford Research Institute. The contract with Stanford Research Institute is for the development of a two-step process for the production of Si. The steps are (1) the reduction of SiF₄ by Na to produce high purity Si and (2) the further purification of this product by reaction with SiF₄ to form SiF₂ followed by the disproportionation of the SiF₂ to yield Si with the regeneration of the SiF₄. The work to date has dealt entirely with the first reaction.

3) Production of Si Using Arc Heater Process for Reduction of SiCl₄ by Na, Mg, or H₂ – Westinghouse Electric Corporation. This contract with Westinghouse is for the development of an electric arc heater for the production of Si using reactions for the reduction of SiCl₄ by either Na,
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<th>Contractor</th>
<th>Technology Area</th>
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<tr>
<td><strong>SEMICONDUCTOR-GRADE PRODUCTION PROCESSES</strong></td>
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<tr>
<td>(Part I of Phase I)</td>
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<tr>
<td>AeroChem Research Laboratories Princeton, New Jersey (JPL Contract No. 954560)</td>
<td>Si halide-alkali metal flames</td>
</tr>
<tr>
<td>Battelle Memorial Institute, Columbus, Ohio (JPL Contract No. 954339)</td>
<td>Si from SiCl₄ reduction by Zn</td>
</tr>
<tr>
<td>Union Carbide, Sistersville, W. Virginia (JPL Contract No. 954334)</td>
<td>Si from SiH₄ derived by redistribution process</td>
</tr>
<tr>
<td>Motorola, Phoenix, Arizona (JPL Contract No. 954442)</td>
<td>Si using SiF₄ reaction with metallurgical grade Si and SiF₂ transfer</td>
</tr>
<tr>
<td><strong>SOLAR-CELL-GRADE SPECIFICATIONS</strong></td>
<td></td>
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<tr>
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</tr>
<tr>
<td>Northrop Research Hawthorne, California (JPL Contract No. 954614)</td>
<td>Lifetime and diffusion length measurements</td>
</tr>
<tr>
<td>Spectrolab, Inc. Sylmar, California (JPL Contract No. 954471)</td>
<td>Solar cell fabrication and analysis - Si slices</td>
</tr>
<tr>
<td>Westinghouse Electric, Pittsburgh, Pennsylvania (JPL Contract No. 954331)</td>
<td>Investigation of effects of impurities on solar cell performance</td>
</tr>
</tbody>
</table>
### SOLAR-CELL-GRADE PRODUCTION PROCESSES

**Part III of Phase I**

<table>
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<tr>
<th>Contractor</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AeroChem Research Laboratories, Princeton, New Jersey (JPL Contract No. 954560)</td>
<td>Si by use of a nonequilibrium plasma jet</td>
</tr>
<tr>
<td>Dow Corning, Hemlock, Michigan (JPL Contract No. 954559)</td>
<td>Si from purer source materials using arc furnace processing</td>
</tr>
<tr>
<td>Monsanto Research Corp., St. Louis, Missouri (JPL Contract No. 954338)</td>
<td>Solar Cell Grade Si Process</td>
</tr>
<tr>
<td>Stanford Research Institute, Menlo Park, California (JPL Contract No. 954471)</td>
<td>Si by Na reduction of SiF₄</td>
</tr>
<tr>
<td>Texas Instruments, Dallas, Texas (JPL Contract No. 954412)</td>
<td>Plasma Process for Production of Solar-Cell-Grade Si</td>
</tr>
<tr>
<td>Westinghouse Electric, Pittsburgh, Pennsylvania (JPL Contract No. 954589)</td>
<td>Si by plasma-arc-heater reduction of SiCl₄ with H₂ and alkali metals as reducing agents</td>
</tr>
</tbody>
</table>

### COMMERCIAL POTENTIAL OF PROCESSES

**Part IV of Phase I**

<table>
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<tr>
<th>Contractor</th>
<th>Task Description</th>
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<tbody>
<tr>
<td>Lamar University, Beaumont, Texas (JPL Contract No. 954343)</td>
<td>Evaluate relative commercial potentials of Si-production processes developed under the Silicon Material Task</td>
</tr>
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</table>

Mg, H or Zn. The first phase consists of a review of the chemical and engineering feasibility and the designing of a system for experimental verification; it includes four subtasks: reaction analysis, plasma reactor, reactor storage and injection, and product collection and effluent disposal.

4) Production of SiH₄ or Si Using a Nonequilibrium Plasma Jet for the Reduction of SiCl₄ - AeroChem Research Corporation. The objective of this program is to determine the feasibility of high volume,
low-cost production of high purity SiH$_4$ or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes (added either to the discharge or to the hydrogen atom stream) are being studied.

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

5. Summary of Progress

a. Union Carbide

SiH$_4$ produced via the steps of redistribution of dichlorosilane and purified by distillation and adsorption of residual chlorosilane on activated C was found during this quarter to yield 50 ohm-cm n-type Si in epitaxial deposition. Extended operation of a small process-development unit routinely produced high-quality SiH$_4$ in 97% yield from dichlorosilane. The production rate was consistent with design loadings for the fractionating column and for the redistribution reactor. Laboratory and process-development reactor systems were built to study the hydrogenation of co-product.

A glass fluid-bed reactor for Si deposition was constructed for room-temperature operation. The behavior of a bed of Si particles was observed as a function of various feedstocks, component configurations, and operating conditions. For operating modes other than spouting, the bed behaved in an erratic and unstable manner. A second reactor with a modified gas-feed system for increased bed stability is being constructed.

In some free-space reactor experiments for SiH$_4$ pyrolysis, friable clusters of Si particles formed on the tip of the gas injector and on the reactor wall. The temperature at the growth sites was the major parameter controlling the extent of the reaction. The results can be modified by controlling the temperatures of the reactor and of the injected SiH$_4$.

Modifications of the free-space reactor are in progress for minimizing free-space reactor powder contamination. The analysis of powder showed that Ni and graphite reactor liners were impurity sources. A quartz reactor liner was installed, and the powder produced is being analyzed.

A method was developed for melting and casting molten Si powder into crack-free solid pellets for process evaluation. The Si powder was melted and cast into thin-walled quartz tubes that broke on cooling. The samples are intended for resistivity and spark-source mass spectroscopic analyses. More activities are planned in this area to further improve product purity and to obtain data for engineering analyses.
b. Westinghouse

This contract is for the development of an electric arc heater process for the production of Si using reactions for the reduction of SiCl₄ by Na. The first phase consisted of a review of the chemical and engineering feasibility and the design of a system for experimental verification; it included four subtasks: reaction analyses, plasma reactor subsystem design, design of the reactant storage and injection subsystems, and design of the product collection and effluent disposal subsystems. Phase I was completed at the end of April, 1977. The Phase II effort started in early October, 1977. The major emphasis in a task for process analysis and design review was placed on designing process units and obtaining price data on, the equipment required for a plant producing 1000 MT/yr of Si. This was based on a complete process which includes recycling of by-products. System-component information and cost data were assembled for the SiCl₄ feed system, sodium feed system, plasma reactor/separator system, and the Si collection system. The cost data are being factored into an economic analysis.

Analysis and design continued on the effluent separation system using a salt cyclone technique. The cyclone employs injection of solid NaCl into the effluent gas stream, which contains NaCl vapor, argon, and hydrogen from the reduction reaction. The injected NaCl cools and quenches the NaCl vapor to aid nucleation and separation of the salt from the gases.

A computer program for the system purity analysis, which will predict the maximum allowable impurities in the SiCl₄ and Na feedstocks based on the desired impurity levels in the Si product, was modified, and the activity coefficients of Fe, Cr, Mn, and Al in liquid Si at several temperatures have been obtained. These, along with Ti, V, Na, B, P, Mo, Zr, and Cu, are the impurities which are being considered for the impurity analysis.

c. Aerochem - Non-Equilibrium Plasma Jet

Results obtained earlier from the work being done by AeroChem Research Laboratories in using a non-equilibrium plasma jet for the reduction of Si chlorides were further evaluated. One conclusion reached is that an original objective of the effort, production of SiH₄ from SiCl₄, does not appear feasible because the main reactions, occurring on surfaces, do not yield SiH₄. More recent experiments indicate that SiH₄ may be produced in the gas phase when SiHCl₃ is a reactant.

Theoretical estimates indicate that the H-atom concentration decays to less than 20% of its initial value by the time the gas stream reaches the liquid nitrogen traps. Hence, improved yields of SiHCl₃ can be obtained by moving the traps closer to the point where the SiCl₄ is mixed with the H/H₂ jet, since the conversion to SiHCl₃ appears to take place in the traps and not in the gas stream. The conversion efficiency for this reaction is presently about 15%. It is planned
to substantiate the observation that SiHCl₃, product formation occurs on the cooled surfaces and not in the gas stream.

Several series of experiments were made in which the nature of the film deposited on the reactor walls was observed as a function of different chlorosilane reactants, the deposition time and equivalence ratio, and heating the films to as high as 1200°K in an inert gas atmosphere. Both amorphous and polycrystalline films (sometimes simultaneously) of Si, which adhere very tightly to Pyrex or Vycor surfaces, were laid down from SiCl₄ or SiHCl₃; SiH₄ did not produce a strongly adhering film. The maximum conversion efficiency of 17% was for SiHCl₃. The films are stable at temperatures up to 1200°K except for cracking and a change to a more metallic appearance.

d. Motorola, Inc.

This contract is for the investigation of the conversion of metallurgical-grade Si (mg-Si) into higher quality semiconductor-grade Si (sg-Si) via a three step process in which SiF₄ reacts with mg-Si to form SiF₂, which is then condensed to a solid polymer. The polymer is then thermally disproportionated into sg-Si and SiF₄ for recycle in the process.

A series of experiments was undertaken to investigate the conversion of (SiF₂)ₓ polymer. Mass spectral analyses were used to compare the compositions of products liberated during the course of polymer conversion with the products liberated from the SiₓF₂ₙ homologues over identical temperature ranges of about 275°C to 400°C.

The conclusion was that the homologue byproducts are capable of conversion into desirable products when thermally disproportionated at temperatures over 400°C. Apparently, insufficient residence time at elevated temperatures resulted in only partial disproportionation and a resulting low product yield.

In the batch-type apparatus the polymer conversion efficiency averaged 59% over 12 runs, ranging between 52% to 59%. The wide range was surmised as being due to varied residence times at elevated temperature. Mass balance over 3 runs ranges between 76% to 93%.

The purity of the Si product from the batch-type apparatus was not known.

Seven runs were made in a semi-continuous operation apparatus having a capacity of 25 gm/hr. An average rate of 17.6 gm/hr of Si was attained over a 165-minute period. Although the operating parameters were not optimized, an overall process efficiency of 78% was obtained.

An economic analysis of the process was made based on preliminary considerations of material and energy balances, and assuming a fixed capital investment of $10 million. The estimated manufacturing cost was $8.96/kg of Si for a 1000 MT/yr facility.
During the next quarter, the near-continuous apparatus will be run for longer times (2 hr) on a daily basis, and Si samples will be produced for analysis. Additional experimental studies will be carried out to investigate Si deposition and harvesting techniques, and secure data for the optimization of the process. The economic analysis for this process will be updated.

e. Battelle Memorial Institute

The objective is the development of a process for the preparation of semiconductor-grade Si by the Zn reduction of SiCl₄ using a fluidized-bed reactor.

A detailed material and energy flow sheet for a 50 MT/yr was prepared. A plant layout was developed for locating the experimental facility within an available structure at Battelle.

A step-by-step analysis of the design and operation of the 50 MT/yr facility was performed. This is to be used as an aid in reviewing and revising concepts and in uncovering problems and items requiring more information.

A fluidized bed reactor is to be constructed of graphite-lined stainless steel. Either a coaxial or external Zn vaporizer will be used. The dispersion support plate will have 12 holes for SiCl₄ gas injection aligned on a ring about 0.25 the distance from the outer wall to the center. Zinc vapor was to be introduced on an inner ring located 0.6 the distance from the outer wall and contain 0.8 inlet ports. It is anticipated that an SiC coating would be needed on the graphite liner to minimize C contamination. The concept of using an SiC-coated graphite felt sleeve liner is being considered because of the mismatch in thermal expansions between SiC and graphite.

The design of the Zn vaporizer as a "flash vaporizer" concept requires as high a ΔT as possible. However, the reactor design places limitations on the available ΔT because of the intended use of a stainless steel containment shell which must operate below 980°C. Since the boiling point of Zn is 925°C at 1.2 atm, a ΔT of only 55°C is available. A tray-type vaporizer requiring a low inventory of Zn was being developed. Differential heat-transfer calculations were being made for use in enhancing the tray-type design.

The experimental Zn electrolysis cell was modified to conform to the Bureau of Mines electrode configuration by providing the cell with horizontal electrodes having slanted chlorine vent channels on the underside of the anode. In the intended process, the Zn produced in this cell by electrolysis of Zn/ZnCl₂ mixture (byproducts from the fluidized-bed reactor) is recycled as a reactant raw material. The operation of the experimental cell revealed the need for several design changes. These involve the liquid level indicator system and the need for a greater freeboard above the salt mixture level to prevent loss of the mixture due to foaming and blowover.
The miniplant was operated to supply JPL with Si product for evaluation and LSSA Project use. The deposition on the seed material has been about 50% of the total Si product. The shipments to JPL have totalled 2.2 kg. It is believed that the operation of the 50 MT/yr facility will result in yields of greater than 95% deposited on the seed material.

f. Dow Corning Corporation

The objective is the development of a process which improves the purity of arc-furnace-produced Si by smelting higher-than-normal-purity raw materials and further refining the Si product by unidirectional solidification techniques. The impurity elements of particular interest are boron (B) and phosphorous (P). Adequate sources of high-purity quartz (SiO₂) were established in earlier work of the contract. High-purity C-containing materials suitable for arc furnace use were not available from commercial sources. Hence, experimental studies for development of a C reductant were in progress.

Charcoal was selected over other C because of its relative high purity. Earlier work had demonstrated that the charcoal can be purified to levels below the detection limits of emission spectroscopy, i.e., about 10 parts per million by weight (ppmw). However, difficulties were encountered in smelting with purified charcoal. Apparently, the charcoal structure had undergone a structural change during the elevated temperature (1700 to 2000°C) purification with halogen gases. In addition, the purification treatments did not significantly reduce the inherent B and P levels of the charcoal to the required levels. An in-depth study was initiated to identify high-purity C reductants which are low-cost and chemically reactive in an arc-furnace environment.

A development-size arc furnace located at the Elkem facility in Norway was used to evaluate the smelting of higher-than-normal-purity raw materials. There were four experimental runs made during this quarter. A summary of the parameters and results are given in Table 3-3.

The charcoal purified at 1700°C was used in Experiments No. 8 and 9. In Experiment No. 8, the average C content was 80% of the change. The furnace operated easily, but inefficiently, and produced small quantities of Si. Apparently, large quantities of SiC accumulated in the furnace without further reaction. A higher fixed-C ratio was used in Experiment No. 9 that averaged 93% C. Again, large quantities of SiC were formed. The two experimental runs gave data which led to the conclusion that charcoal purified at 1700°C is not a good arc-furnace reductant.

Arc-furnace Experiments No. 10 and 11 used charcoal purified at 2000°C and 1900°C. A higher C ratio of 94.2% was used in No. 10 to prevent attack of the hearth lining that occurred in the two previous experiments. The charcoal reductant was once again converted largely to SiC and little Si product was made, and led to the conclusion that the 2000°C purified charcoal was not a good reductant. In No. 11, the
Table 3-3. Experimental Parameters and Results
For Arc-Furnace Tests

<table>
<thead>
<tr>
<th>Expmt. No.</th>
<th>Raw Matl Type</th>
<th>Source of Quartz</th>
<th>Charcoal</th>
<th>Run Time (h)</th>
<th>% SI Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Arkansas</td>
<td>1700°C</td>
<td></td>
<td>26</td>
<td>1.3</td>
</tr>
<tr>
<td>9</td>
<td>British Columbia</td>
<td>1700°C</td>
<td></td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>British Columbia</td>
<td>2000°C</td>
<td></td>
<td>17</td>
<td>1.4</td>
</tr>
<tr>
<td>11</td>
<td>British Columbia</td>
<td>*1900°C</td>
<td></td>
<td>29</td>
<td>?</td>
</tr>
</tbody>
</table>

*under vacuum conditions

charcoal purified at 1900°C (under vacuum) was varied between 80% to 85% for the run and operated for a total of 29 hours. Once more, excessive quantities of SiC were formed. Low yields of Si were obtained in these experiments.

The Si product from runs No. 9 and 11 was further purified by undirectional solidification using a Czochralski apparatus. A 25- to 30-mm-diameter ingot was pulled, leaving 30% of the Si remaining in the crucible. Emission spectrographic analyses of the seed and tang ends of the ingots from No. 9 and 11 showed all elements except B and P to be below the 10 ppmw detection limits.

A cost analysis of the envisioned overall process was performed. A 3000 MT/yr arc-furnace facility was estimated to require $10 million in capital and have a manufacturing cost of $7.99/kg of Si product.

g. Lamar University

Major efforts were continued for process system properties of Si source materials under consideration for solar-cell-grade Si including data collection, analysis estimation and correlation. The initial correlation efforts focused on vapor pressure data of pure source materials, since these data are very important in phase equilibria of chemical processes and the engineering design of some equipment depends on accurate information.

The vapor pressure of Si tetrachloride was correlated as a function of temperature using the following equation:
Values for the correlation constants $A$, $B$, $C$, $D$, and $E$ were obtained. The versatile correlation covered both low and high pressure regions with good agreement of calculated and experimental data. Average absolute deviation was only 0.7% for 58 data points tested.

Heat capacity data for the gas phase were correlated by a series expansion in temperature:

$$C_p = A + BT + CT^2 + DT^3$$

The correlation constants were determined from a least-squares fit of the available data from American, Russian, German and Japanese sources. The average absolute deviation was about 0.7% for 52 data points. These results were to be used in the chemical engineering analyses.

The calibration of the apparatus for measuring thermal conductivity of gases from 25°C to 400°C was completed. The accuracy of data to be obtained from this instrument was evaluated by making thermal conductivity measurements for argon. The thermal conductivity values obtained in this study were in excellent agreement with recommended values from the literature. Deviations were only $\pm 2\%$ up to 300°C and $\pm 4\%$ up to 400°C.

Chemical engineering analysis of the Union Carbide SiH$_4$ process was continued using the revised flowsheet from Union Carbide. Material balance is about 95% complete for the preliminary design. Energy balance, property data and equipment design are about 60% complete.

The review and modification of the conventional polysilicon process preliminary process design was completed. Major items modified include the rod reactor area, waste treatment area, and labor requirements. Key items were HCl and metallurgical grade Si consumption, electrical requirements for the rod reactors, and the rod reactor areas.

Economic analysis activities for the production of (Siemens) semiconductor-grade polysilicon via the conventional hairpin process technology were continued, including completion of the preliminary review in the areas of major process equipment, utilities and production labor costs.

Three cases for the conventional polysilicon process were considered. Case A is based on 1975 costs of raw materials, labor, utilities, etc. for a plant constructed in 1975. Case B is based on 1975 costs for a plant constructed in the 1960s. (Most of the U.S. polysilicon plants were constructed during or before the 1960s.) Case C is based on 1977 costs for a plant constructed in the 1960s. In each case the ranges reflect low and high electricity costs (1.5-3.0¢/kW hr). The results are summarized below:
1. Case A

   Product Cost (Sales Price)......63.6-70.3$/KG Si @ 10% ROI*

2. Case B

   Product Cost (Sales Price)......61.1-67.7$/KG Si @ 25% ROI*

3. Case C

   Product Cost (Sales Price)......64.8-72.7$/KG Si @ 25% ROI*

Case C probably best represents the current situation for polysilicon production of semiconductor grade.

h. Westinghouse Research Laboratory

The objective of Phase II of this program was to investigate the effects of various processes, metal contaminants, and contaminant-process interactions on the performance of terrestrial Si solar cells so that purity requirements for a solar grade Si can be delineated. The specific elements of the Phase II program are:

(1) The effect of heat treatment and gettering on the properties of Si containing deep-level impurities like Ti and Cr.

(2) The combined effects of metal contaminants and low base resistivity on solar cell performance.

(3) The relative performance of p-base and n-base solar cells containing similar levels of metal impurities.

(4) The role of multiple contaminants on solar cell behavior.

(5) The effect of grain boundaries on metal-contaminated solar cells.


(7) Improved techniques for the analysis of impurity effects in Si and Si solar cells.

The program approach consisted of (1) the growth of doubly and multiply-doped Si single crystals containing a baseline B or P dopant and specific impurities which produce deep levels in the forbidden band gap, (2) assessment of these crystals by a battery of chemical, microstructural, electrical and solar cell tests, (3) correlation of the impurity kind and level with crystal quality and device performance,

*Return on Investment
(4) delineation of the role of impurities and processing on subsequent Si solar cell performance, and (5) determination of the combined effects of impurities and growth rate on the crystal quality and cell performance of Si produced by both the dendritic web and Czochralski methods. The central effort for this quarter was in three areas: the crystal growth of impurity-bearing ingots with different base doping types and concentrations; evaluation of the solar cell performance of n-base and p-base devices; and refinement of techniques for the analysis of solar cells subjected to various contaminants and process variations.

The comparative study of n- and p-base solar cells doped with metal impurities continued to reveal significant differences in the response of these two types of devices to contaminants. The p+n devices containing V showed substantially better performance than n+p cells doped to the same metal concentration. For example, n-base devices about 70% as efficient as the uncontaminated base devices (n = 10% without AR coating) were readily produced while comparable p-base devices are only about 40% as efficient as the baseline cells. The performance improvement for the V-doped p+n cells paralleled that achieved previously for Ti. For Ni doping the situation is reversed. n+p cells with 4x10^15 atoms/cm^-3 Ni showed little degradation compared to the baseline. However p+n cells containing similar Ni levels were only 54% as efficient as the baseline devices. The performance degradation in the n-base cells seemed to be linked to precipitation effects in the junction rather than base lifetime reductions. Doped with Fe, n- and p-base devices performed in a similar fashion, the p+n cells being somewhat less efficient.

The first solar cell results for Mo-doped p-base material became available during this period. At an estimated 6x10^14 atoms/cm^-3 concentration, Mo, a material often used in furnaces and reactors, depreciates cell performance to about 75% of the baseline efficiency. Although the chemical analysis must be refined, this result suggests that the potential effects of Mo be kept in mind when it is employed as a material of construction. P compensation may be required for some forms of solar grade material; P may also be present as a contaminant in Si. As part of this study P compensation of 4 cm baseline material was being evaluated. For an ingot compensated to about 15% of the B primary doping level (6x10^14 atm/cm^-3) P has little or no effect on cell performance.

During Westinghouse's previous modeling studies it was observed that cells containing the impurities Cu, Ni, and Fe showed a reduction in performance not wholly attributable to a reduction in base lifetime. A method for the quantitative analysis of solar cell I-V data which permits the effects of impurities on junction, base and contact behavior to be separated and accessed had recently been developed and tested. This tool, along with precision lifetime measurements, will soon to be applied to study processing and impurity phenomena in solar cells.

In the in-house Si processing effort, Si particle fluidization experimentation continued in a 2-inch quartz column using metallurgical-grade Si. The purpose of these experiments is to investigate distributor design, fluidization monitoring techniques, and particle size characteristics. The distributor designs under investigation include porous plates and
conical types. Fluidization characteristics are being monitored primarily with electronic pressure transducers.

The construction of a 2" stainless steel fluidized bed reactor system was completed. A minicomputer-based data acquisition system was constructed to monitor the various process conditions. Safety systems were also installed and are awaiting the safety reviews.

In the next quarter, system shakedown tests will be run, and it is expected that the first Si deposition experiments with SiH₄ will be made.

The continuous flow pyrolyzer (CFP) was mounted in place and instrumented for temperature, pressure and gas flow. Safety features, such as Lucite safety shield and alarms for hydrogen gas and moisture accumulations, were installed and a safety review was written.

Two JPL publications, "Modeling of Fluidized Bed Silicon Deposition Process" and "Chemical Vapor Deposition of Silicon from Silane Pyrolysis," were published. A technical paper on "Silane to Silicon Chemical Vapor Deposition (CVD) Study" was accepted by the 6th International Conference on Chemical Vapor Deposition, Electrochemical Society.

i. Stanford Research Institute

Si obtained by the SiF₄-Na reaction was analyzed by spark source mass spectrometry (SSMS). A partial listing of the results is given below. The concentration units in parentheses are ppm wt.

B(0.1), Al(0.8), Ga(0.06), P(0.2), F(0.1), Na(1.0), V(0.04), Mo(0.3), Ti(2.0), Zr(2.0), Mn(0.1), Ni(2.0), Zn(0.01), Cu(20.0), Cr(11.0), Fe(55.0)

The source of the Fe and Cr is suspected to be the stainless steel container for liquid sodium. An independent check for the P content was made by a wet colorimetric method and was found to be 90 parts per billion (ppb), in reasonable agreement with the SSMS result of 200 ppb.

A stainless steel reactor was designed and fabricated to perform the SiF₄-Na reaction under $P_{SiF_4}$ greater than 1 atmosphere. The amount of Si produced was increased from 25 g per batch in the glass reactor to greater than 70 g per batch in the stainless steel reactor.

The study of the effects of reaction variables such as $P_{SiF_4}$ and maximum temperature attained on the particle size of Si powder showed that the Si particle size tends to grow larger with increasing pressure of the SiF₄ gas in the reaction system.

j. AeroChem

This program is designed to test the feasibility of utilizing continuous, high temperature, diffusion flames of gaseous alkali metals and Si halides as an economical source of high purity Si. Thermochemical
analyses of these systems indicate that high temperatures are attained and that Si is the only condensed-phase material in the equilibrium product distribution. The reactions are self-initiating and their highly exothermic nature indicates, by analogy to more conventional combustion systems, that the resulting flames will be self-sustaining and characterized by fast kinetics.

A series of detailed thermochemical calculations was performed to determine comparative flame properties as functions of input composition, temperature and pressure. Vapor generators for both liquid halides and alkali metals were built, tested and installed in a low pressure burner housing. Counterflow diffusion flames of K vapor with SiCl$_4$ were sustained at low pressures with and without Ar diluent. The products, when allowed to condense in the reactor volume or on its walls, comprise a mixture of white and brown powders, which are readily separated by washing with water; the brown material appears to be amorphous Si.

B. LARGE-AREA SILICON SHEET TASK

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

1. Technical Goals

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

Growth of Si crystalline material in a geometry which 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, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections), requiring very little manpower and machinery would also appear plausible. However, 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 and multiple-wire cutting initiated in 1975-1976 is in progress.

2. Organization and Coordination of the Large-Area Silicon Sheet Task Effort

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

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 3-3. This work will continue through the end of FY 1977, by which time it is expected that technical feasibility will have been demonstrated. Selection of "preferred" growth methods for further development during FY 1978-80 is planned for late FY 1977 or early FY 1978. By 1980, both technical and economic feasibility should be demonstrated by individual growth methods.

An economic analysis of the Czochralski ingot growth process was performed to assess its potential to meet near-term and 1986 goals. The study was made with the intention of identifying key features of the process that are making the process costly at the present time. The analysis, conducted at JPL and elsewhere, shows that continuous growth process is the key. It was decided to solicit proposals to develop an advanced Czochralski process, specifically one achieving continuous ingot growth through multiple use of crucibles, and incorporating improved sawing techniques. These techniques, when successfully developed, will reduce costs associated with crucibles, processing, and sawing losses.

4. Large-Area Silicon Sheet Task Technical Background

a. Silicon Ribbon Growth: EFG Method--Mobil-Tyco Solar Energy Corporation. The edge-defined film-fed growth (EFG) technique is based on feeding molten Si through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material which is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG
process to a speed of 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.

b. **Silicon Ribbon Growth: CAST Method - IBM.** The capillary action shaping technique (CAST) is based on the same principle as EFG growth (Figure 3-1); i.e., it utilizes a die constructed from material which is wetted by molten Si. Work under this contract is directed toward evaluation of the technical and economic potential of CAST for the preparation of Si ribbon. The effort concentrates on (1) understanding and extrapolating the effects of growth conditions, (2) characterization of the ribbon, with special emphasis on the correlation of structure and electrical performance, and (3) economic analysis of Si growth by this and other growth techniques.

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Technology Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobil-Tyco Solar Energy Corp., Waltham, Massachusetts (JPL Contract No. 954355)</td>
<td>Edge-defined, film-fed growth</td>
</tr>
<tr>
<td>IBM, Hopewell Junction, New York (JPL Contract No. 954144)</td>
<td>Edge-defined, film-fed growth</td>
</tr>
<tr>
<td>RCA, Princeton, New Jersey (JPL Contract No. 954465)</td>
<td>Inverted Stepanov growth</td>
</tr>
<tr>
<td>Univ. of So. Carolina, Columbia, So. Carolina (JPL Contract No. 954344)</td>
<td>Web-dendritic growth</td>
</tr>
<tr>
<td>Motorola, Phoenix, Arizona (JPL Contract No. 954376)</td>
<td>Laser zone ribbon growth</td>
</tr>
<tr>
<td>Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)</td>
<td>Dendritic web process</td>
</tr>
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</table>
Table 3-4. Large-Area Silicon Sheet Task Contractors (Continuation 1)

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Technology Area</th>
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</thead>
<tbody>
<tr>
<td><strong>SUPPORTED FILM TECHNOLOGY</strong></td>
<td></td>
</tr>
<tr>
<td>Honeywell, Bloomington, Minnesota (JPL Contract No. 954356)</td>
<td>Dip-coating of low-cost substrates</td>
</tr>
<tr>
<td>Rockwell, Anaheim, California (JPL Contract No. 954372)</td>
<td>Chemical vapor deposition on low-cost substrates</td>
</tr>
<tr>
<td>General Electric, Schenectady, New York (JPL Contract No. 954350)</td>
<td>Chemical vapor deposition on floating Si substrate</td>
</tr>
<tr>
<td>Univ. of Pennsylvania, Philadelphia, Pennsylvania (JPL Contract No. 954506)</td>
<td>Hot-forming of Si sheet</td>
</tr>
<tr>
<td><strong>INGOT TECHNOLOGY</strong></td>
<td></td>
</tr>
<tr>
<td>Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)</td>
<td>Heat-exchanger ingot casting*</td>
</tr>
<tr>
<td>Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)</td>
<td>Multiple wire sawing*</td>
</tr>
<tr>
<td>Varian Associates, Lexington, Massachusetts (JPL Contract No. 954374)</td>
<td>Breadknife sawing</td>
</tr>
</tbody>
</table>

*Single contract provides for both ingot casting and multiple wire sawing.
c. **Silicon Ribbon Growth: Inverted Stepanov Technique - RCA.** In this program emphasis is placed on developing a technique for growing ribbon-shaped Si using a "nonwetted" die (Figure 3-2). The use of the "nonwetted" die provides the possibility of minimizing the reaction between the molten Si and the die material. Reaction between molten Si and wetted dies is one source of degradation in the crystallographic quality of Si grown using a wetted die (i.e., the edge-defined film-fed growth method). The introduction of the feed from above and the growth of the single crystal in a downward direction (the inverted Stepanov technique) in part compensates for the hydrodynamic drag in the slot and for the lack of capillary rise. (The capillary rise feeds the material to the die edge in the EFG method.) The inverted geometry also leads to considerable flexibility in the growth configuration when the feed is introduced from a molten zone at the end of a solid Si rod.

d. **Silicon Ribbon Growth: Web-Dendritic Method - University of South Carolina.** Web-dendritic growth makes its own guides of Si, whereas most other ribbon processes must rely on materials other than Si for the guides (i.e., dies) (Figure 3-3). The guides are thin dendrites that grow ahead of the sheet and support the molten Si between them to form the sheet. The dendrite guides grow in a very precise orientation dictated by their unique growth habit. Thus the

![Figure 3-1. Capillary Die Growth (EFG and CAST) - Mobil-Tyco and IBM](image-url)
orientation of the sheet which grows between them takes on this precise orientation. The twin plane reentrant edge mechanism (TPREM) controls the growth of the edge dendrites, giving them their unique and internally-controlled growth direction, allowing them to grow ahead of the sheet and thus act as guides.

e. Silicon Ribbon Growth: Laser Zone Growth in a Ribbon-to-Ribbon Process - Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 3-4). The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

f. Silicon Sheet Growth: Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International. The purpose of this contract is to explore the chemical vapor deposition (CVD) method for the growth of Si sheet on inexpensive substrate materials (Figure 3-5). As applied to Si sheet growth, the method involves pyrolysis, or reduction, of suitable Si compound at elevated temperature and approximately atmospheric pressure. A laboratory-type CVD reactor system with a flow-through

![Diagram of Inverted Stepanov Technique - RCA](image)

Figure 3-2. Inverted Stepanov Technique - RCA
(open-tube) vertical deposition chamber is used for these investigations. The substrate is mounted on a Si carbide-coated C pedestal heated by an RF coil external to the chamber. The reactor system has been extensively modified by installation of mass flow controllers, automatic process sequence timers, and special bellows-sealed air-operated valves. This system, which has a capacity of 30 cm$^2$, is used as a research vehicle in an attempt to reach the goals of 100 m grains deposited 20 to 100 m thick on inexpensive thick substrates at rates up to 5 cm per minute.

g. Silicon Sheet Growth: Hot-Forming of Silicon – University of Pennsylvania. This contract is designed to determine the feasibility of hot-forming Si in a cost-effective manner. The procedure to be followed is high-strain-rate (>$1$), high-compression deformation of Si. From this information, one can construct the hot-forming diagram for Si and make some extrapolations of the economics of the process. The program also includes evaluations of metallurgical properties such as hot-forming texture, recrystallization texture and grain size, and of electrical properties.

h. Ingot Growth: Heat Exchanger Method – Crystal Systems. The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-6). Heat is removed from

![Diagram of web-dendritic growth](image-url)
the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchanger ingot casting method can grow large Si crystals (6 inches in diameter by 4 inches in height) 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-pound ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for Si.

1. Ingot Cutting: Multiple Wiring Sawing - Crystal Systems. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a big cost factor in producing solar cells. The lesser-used multiblade slicer can be utilized to slice Si. The multiblade slicer has not been developed for the semiconductor industry since this method produces bow and taper unacceptable for integrated-circuit applications.

Figure 3-4. Laser Zone Crystallization - Motorola
The overall goal of the slicing program is to optimize multiblade (wire) Si slicing, investigating the following parameters in particular:

(1) Rate of material removal and kerf removal.
(2) Slice thickness, wire blade dimensions, cutting forces, wire/blade tension, and other machine variables.
(3) Wires versus blades as a cutting tool.
(4) Variation of rocking motion.
(5) Introduction of abrasive during slicing operation.
(6) Effect of surface condition of tool, including consideration of hardness and method of plating.
(7) Effect of diamond abrasive particle size and type.
(8) Effect of cutting fluid composition.

Figure 3-5. Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International
The slicing operation employs a rocking motion and utilizes 50 8-mil wires. These are 6-mil steel wires surrounded by a 1-mil copper sheath, which is impregnated with diamond as an abrasive. The shape of the abrasives and their interaction with the copper and steel is an unknown variable and will be investigated. The individual wires within a multiple wire package are equitensioned by the use of a single jig in the form of a weaving machine.

The variables for slicing have been specifically identified. The independent variables are feed force, speed, rocking angle, and phase angle; the dependent variables are cutting rate, deflection, degradation of diamond, and cut profile of y versus x.

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

Figure 3-6. Crystal Growth Using the Heat Exchanger Method - Crystal Systems
5. Summary of Progress

Further analysis of the EFG ribbon growth scenario by Mobil-Tyco Solar Energy Corp. using SAMICS interim price estimation guidelines showed that a double five-ribbon furnace of the general type represented by Machine 3A can produce sheet material at <$20/m², the 1986 JPL goal. Technology requirements are one operator for two five-ribbon growth stations in which each ribbon grows at a speed of 7.5 cm/min. at 7.5 cm width. Minimum duty cycle is required to be 67% and minimum yields to be 75%. Finally, polysilicon growth material must be available at $10 to $25/kg, depending on yield assumptions made.

The major problem encountered in the 7.5-cm wide by 7.5-cm/min ribbon growth was a severe tendency toward buckling at larger widths and higher speeds. Several design changes in the growth cartridge were being investigated to cure this problem.

Utilization of the fluid flow phenomenon during growth showed that significant impurity redistribution can be achieved. Proper utilization of this phenomenon in material grown from a "duty" run produced ~10% efficiency solar cells from the central 2.5 cm of a 5-cm wide ribbon.

The 100-mm wide ribbon growth furnace was installed at IBM. Thermal profiling of the graphite die for proper operation of this machine was continued. A 94-mm wide ribbon was grown but it shattered upon withdrawal from the furnace.

Vitreous carbon and CVD Si₃N₄ were evaluated for die and material use.

Directional solidification of Si in a vitreous carbon crucible was achieved with grain sizes varying from 0.05 to 2 min. The solidified silicon was found to be intact and free from cracks. Small SiC particles were found at the SiC interface. Vitreous carbon has a thermal expansion coefficient equivalent to silicon, in the range 650°C to 20°C. The degree of C contamination in Si (20 ppm) is similar to the O₂ contamination of Si grown from SiO₂ (quartz) crucibles. However, C is not electrically active in Si.

Modifications to RTR #1 at Motorola increased laser output power. As a consequence, ribbon could be grown at 10 cm/min (for 2-cm wide ribbon stock). Accompanying this increase in growth velocity was a new growth phenomenon in the form of dendritic growth. The onset of dendritic growth is related to a critical velocity which is a function of the thermal environment. Non-dendritic growth was achieved at velocities up to 7.5 cm/min.

RTR growth from a doped polyribbon feedstock obtained from a CVD process was achieved. Initial diffusion length measurements of the ribbon obtained this way indicated equivalent performance to material regrown from single crystal feedstock.
Recent solar cell evaluation lots have shown metallization
degradation to be the cause for low measured efficiencies (average
of 7.7%).

Diffusion length studies on HTR solar cells showed: (1) large
diffusion lengths (>100 µm); (2) correlation between diffusion lengths
and dislocation densities; (3) variable diffusion lengths on grain
boundaries.

The large diffusion lengths measured on process cells contrasted
with the low values obtained from as-grown ribbons. The improvement
occurred during the junction diffusion and AR coating steps.

During the quarter, the experimental phase of the Westinghouse
Research program was oriented toward developing growth configurations
which produced crystals having low residual stress levels. Lid designs
influenced the web growth considerably: thick lids with narrow slots
produced minimum temperature fluctuations and flat temperature profiles,
but also produced high residual stress; thin lids with large slots
minimized stress levels, but temperature fluctuations caused spontaneous
web pull-out. Hybrid designs that reduce thermally generated stress
while maintaining good melt thermal conditions were being developed
with the help of the thermal modeling work accomplished in the previous
quarter.

Economic analysis of the silicon web process concluded that the
present area rate of growth capability (8 cm²/min) needs to be increased
by a factor of 2 to 3 in order to satisfy the 1986 cost goals.

During the last quarter, fabrication was begun at Varian Associates
on a prototype large capacity multiple blade slurry saw. Final concept
and design was nearly complete this quarter on a bladehead which will
tension up to 1000 blades, and cut a 45 cm long silicon ingot of up
to 12 cm in diameter. The large blade tensioning force of 270,000 kg
will be applied through two bolts acting on a pair of scissor toggles,
significantly reducing operator-applied torque to only 35 kg·m.

Poor wafering yields caused concern in slicing tests at Varian.
Perimeter fracture of slices was the main cause of poor yield. This
also impacted the solar cell production yield of thin (250 - 350 µm)
10-cm diameter silicon slices. Tests with an "upside-down" cutting
technique (where the ingot is placed above the saw blades and cutting
performed from the bottom up), resulted in 100% wafering yields and
the highest wafer accuracy yet achieved.

Variations in oil and abrasive mixes for low-cost slurry resulted
only in degraded slicing results. A technique of continuous abrasive
slurry separation to remove silicon debris and kerf was developed.

A Phase II add-on contract to the original contract was negotiated
with Crystal Systems.

The crystal casting emphasis will be placed on examining heat flow
and other thermal parameters to increase the growth rate of shaped ingots.
The crystal slicing portion of the program will continue to work on diamond-impregnated wire development along with further machine modifications to enable slicing of larger workpieces.

Seeding experiments performed at Honeywell, in which a small section of the EFG grown silicon ribbon is used to seed on SOC combing, promoted significant improvement in single crystal grain growth.

Initial tests indicated that the bond between the silicon film and the substrate is actually stronger than the silicon coating itself.

Smooth continuous silicon coatings were applied to substrates which had flared slots cut into the "green" substrates prior to high temperature firing.

Modeling studies show that the series-resistance problem in slotted substrate cells improves considerably if the silicon does not penetrate the slots. The degree of penetration can be controlled by control of the carbonization of the slots.

Construction of the continuous coating (SCIM) machine was completed. Initial tests show the need for a few modifications and thermal profiling tests are underway. The coater is designed to coat 10-cm x 100-cm substrates.

A new contract was negotiated with RCA this quarter for a program to develop and apply epitaxial growth techniques to the fabrication of efficient solar cells on low-cost forms of silicon sheet.

The work performed during the first quarter included the development of epitaxial baseline solar cell structures grown on conventional single-crystal substrates and initial studies of epitaxial growth and fabrication of solar cells on polycrystalline substrates (Wacker SILSO).

The results showed that solar cells fabricated on epitaxial layers of about 25 µm thickness can produce AM1 efficiencies of 12%.

Growth studies on polycrystalline substrates were started and x-ray topographic studies of the epitaxial layers showed that a substantially lower defect density was noted in the grown layer. Some difficulties associated with the grain boundaries and height differences between grains were observed with the cells fabricated. Low open-circuit voltages and fill factors were seen; however, short-circuit current densities were comparable to those for the single-crystal cells. AM1 efficiencies up to 9.3% were measured.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is 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 is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the parts 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. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions, e.g., structural, electrical, etc. - in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take - glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it, or installed as a window or lens remote from the device.

1. Technical Goals

Photovoltaic devices (solar cells) and the associated electrical conductors which together constitute solar arrays must be protected from exposure to the environment. Exposure would cause severe degradation of electrical performance as a result of corrosion, contamination, and mechanical damage.

In the past, test experience by government organizations and industry has confirmed that spacecraft solar arrays are poorly designed to survive the earth environment. Arrays designed for terrestrial use have shown mixed results. These results, and analyses performed as part of this task, suggest that long-life, low-cost encapsulation is possible under terrestrial conditions; however, at present, successful protection from degradation by the environment is associated with encapsulation materials and processing costs which are excessive for large-scale, low-cost use. Thus, an acceptable encapsulation system - one that possesses the required qualities and is compatible with low-cost, high-volume solar array processing - has yet to be developed.
2. Organization and Coordination of the Encapsulation Task Effort

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations will be conducted to assure timely accomplishment of objectives.

During Phase I the contractor efforts and the JPL in-house efforts consist primarily of a systematic assessment and documentation of the following items:

1. Potential candidate encapsulant materials based on past experience with the encapsulation of Si and other semiconductor devices and on available information on the properties and stability of other potential encapsulant materials and processes.

2. The environment which the encapsulation system must withstand.

3. The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.

4. Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The result of this effort will then be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For example, Phase I will include an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulated systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

1. Evaluate, develop, and/or modify test and analytical methods and then validate these methods.

2. Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.

3. Modify materials and processes used in encapsulation systems to improve automation and cost potential.
(4) Modify potential encapsulation system materials to optimize mechanical, thermal and aging properties.

(5) Implement research and development on new encapsulant materials.

3. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-4. In addition, Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University, serves as a consultant to this task (JPL Contract No. 954738) and will also implement selected supporting experimental investigations in the laboratories at Case.

Contractual negotiations in progress include follow-on contracts to the four major contractors, a contract with the Rockwell Science Center to study the surface characteristics of solar cells, a contract with the Motorola Solar Energy Department to investigate the feasibility of developing antireflectance coatings for glass, and a contract with Endurex of Mesquite, Texas, to study ion plating coating techniques. All of the above contracts were scheduled for execution in the third and fourth quarters of FY 1977.

In addition, considerable effort has been expended in preparing two Phase II statements of work. These are essentially complete, but may be held up pending release of the Battelle Study 4 report on life prediction methodology.

4. Encapsulation Task Technical Background

Program efforts to date have provided an assessment of the state of the art and a definition of the potential environmental and operational stresses imposed on the encapsulation system. A data base of candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

a. Study 3: Evaluation of Encapsulant Materials Properties and Test Methods—Battelle. The experimental evaluations under Study 3 were completed during this quarter and the draft of the final report was begun. Efforts directed toward achieving the objectives of the study were broken down into several substudies encompassing both polymeric materials and glasses. Substudies identified with the letter "P" relate to polymeric materials; those identified with "G" relate to studies in which glass is a major component.

Substudy P-1: Measurement of Properties of Polymeric Materials

This study provides information on the tensile properties (modulus, strength, and elongation), thermal coefficients of expansion, moisture barrier properties, and light transmittance of candidate polymer materials.
Table 3-5. Encapsulation Task Contractors

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Technology Area</th>
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<tbody>
<tr>
<td>Battelle Memorial Institute</td>
<td>Study 1: Identification of candidate encapsulant materials based on a review of (a) worldwide experience with encapsulant systems for Si solar cells and related devices and (b) the properties of other available materials.</td>
</tr>
<tr>
<td>Columbus, Ohio</td>
<td>Study 2: Definition of environmental conditions for qualifying encapsulant materials.</td>
</tr>
<tr>
<td>(JPL Contract No. 954328)</td>
<td>Study 3: Evaluation of encapsulant material properties and test methods.</td>
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<tr>
<td></td>
<td>Study 4: Analysis of accelerated/abbreviated encapsulant test methods.</td>
</tr>
<tr>
<td>Case Western University</td>
<td>System studies of basic aging and diffusion.</td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td>Ion plating process and testing.</td>
</tr>
<tr>
<td>(JPL Contract No. 954738)</td>
<td>Encapsulation coatings</td>
</tr>
<tr>
<td>Endurex</td>
<td>Experimental evaluation of accelerated/abbreviated encapsulant test methods.</td>
</tr>
<tr>
<td>Dallas, Texas</td>
<td>Materials properties and processing</td>
</tr>
<tr>
<td>(JPL Contract No. 954728)</td>
<td>Electrostatically-bonded glass covers.</td>
</tr>
<tr>
<td>Motorola, Inc.</td>
<td>Polymer properties and aging.</td>
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<td>Phoenix, Arizona</td>
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<td>(JPL Contract No. 954773)</td>
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<td>Rockwell International</td>
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<tr>
<td>Enfield, Connecticut</td>
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<td>(JPL Contract No. 954527)</td>
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in the as-received or prepared condition and after exposure to accelerated weathering (ultraviolet (UV) or thermal cycling). This information was used to help establish the aging resistance of the individual materials. The product of the tensile modulus and thermal coefficient of expansion was used, before and after aging, to estimate stress levels in materials laminates, as described by Carroll, Cuddihy, and Salama,* and indicate possible delamination at the encapsulant/cover/adhesive (or pottant) and adhesive (or pottant)/cell interfaces. Moisture barrier information was used in the selection of individual materials for use in encapsulant designs where barrier properties of the single component is critical. Light transmittance before and after environmental exposure was used to provide a measure of the utility of specific materials for cover applications.

Substudy P-2: Evaluations of Polymer Subsystems and Interfaces

Substudy P-2.1: Polymer Film Bonding. This study provided an evaluation of adhesive materials and the manner in which they are to be applied for use with the different polymer film material candidates (for the film-lamination encapsulation design), in order to reveal subsystems that are resistant to delamination and to moisture transport after test exposures to UV and to temperature cycling from -40 to 90°C.

Substudy P-2.2: Polymer Sheet Bonding. This study provided for polymer sheet candidates an output of the type described in Substudy P-2.1.

Substudy P-2.3: Cell Bonding/Sealing. This study provided an identification of adhesives and conformal coatings that are effective in protecting the metallic components of the system for moisture-induced corrosion. The effects of exposure of the materials to UV and temperature cycling are included in this substudy.

Substudy P-3: Polymer Encapsulation Systems Development and Evaluation

Substudy P-3.1: Polymer Film Lamination Design. Substudy P-3.1 provided information on candidate materials and procedures for the film-lamination type** of encapsulation design, which has significant potential for future low-cost arrays. The investigation included determination of (1) the effects of UV, humidity, and temperature cycling exposures on the output characteristics of the encapsulated cells and (2) the effects of encapsulation materials and processing on the electrical performance of encapsulated cells.

Substudy P-3.2. Polymer Sheet Bonding Design. This study provided for sheet laminates an output of the type described in Substudy P-3.1.


Substudy P-3.3. Polymer Conformal Coatings Design. This study provided for conformal coatings an output of the type described in Substudy P-3.1.

Encapsulated cells fabricated by laminating using selected films, sheets, conformal coatings, and adhesives have been prepared for evaluation before and after exposure to elevated temperature/high humidity, temperature cycling, and UV exposure. The effects of encapsulation and of aging on cell electrical performance were emphasized.

Specific cell parameters were measured in the as-received condition, after cleaning, after initial encapsulation, and after exposures to various environments (thermal cycling, UV, etc.) for a measured length of time. The parameters determined were:

1. Open-circuit voltage, $V_{oc}$.
2. Short-circuit current, $I_{sc}$.
3. Maximum power, $P_{max}$.
4. Current at maximum power, $I_{max}$.
5. Voltage at maximum power, $V_{max}$.
6. Fill-factor (electrical), F.F.
7. Series resistance, $R_s$.
8. Shunt resistance, $R_{sh}$.
9. Efficiency, in percent.

Because they form part of the optical path to the cell, encapsulants can affect profoundly the effective conversion efficiency of the photovoltaic module. Moreover, the service life of the cell is determined in a large measure by the choice of the encapsulant system. The critical measure of the utility of an encapsulant is its effects on the electrical output of the cells, initially and after exposure to service environments.

Short-Circuit Current, $I_{sc}$: With regard to the encapsulant top cover, the short-circuit current obviously is limited by how much light of the proper wavelength is allowed to reach the cell. Light can be reflected at any one of the interfaces in the optical path, it can be absorbed in the optical path, or it can be scattered in such a way that it will not be absorbed in the collection zone of the cell. In a common encapsulated-cell configuration, the optical path can consist of a top cover, an adhesive, and the antireflection (AR) coating of the cell. The amount of light reflected depends upon the index of refraction of the various layers and on their thickness. In this study, some of the encapsulant systems increased $I_{sc}$ over that measured when the cell had only the AR coating applied (unencapsulated). That is, the indices were such that a better optical coupling was obtained. In other cases, $I_{sc}$ decreased.
Clearly, the transmittance of the materials in the optical path also affects $I_{SC}$. Transmittance is a function of wavelength, and a sensitive one at some wavelength ranges for some polymeric materials. In this program, the normal transmittance was measured for some single materials. In designing the ultimate encapsulation system, the transmittance should be known for combinations of materials in the optical path, and as a function of wavelength. For composite materials especially, the diffuse and specular portions of transmittance should also be known. With such information, the "ideal" junction depth can be determined, or optical characteristics can be tailored to a given junction depth.

Open-Circuit Voltage, $V_{OC}$: For the ideal Si cell, the fundamental limitation of $V_{OC}$ is the Schottky diffusion current. $V_{OC}$ is then a function function of $I_{SC}$, the dark current, and temperature. Encapsulants might affect the junction temperature and the junction "perfection factor", $A_0$. They also can change the surface recombination velocity and space-charge recombination current, thereby affecting $V_{OC}$.

Series Resistance, $R_s$: An important effect the encapsulant has on the cell output is the protection, or lack of it, that the encapsulant system gives to the collecting metal grid. Grid corrosion and weakening of the metallization bond can lead to increased $R_s$. If the encapsulant element (adhesive, for example) interacts excessively with the AR coating-Si interface, the collection efficiency of the junction can be decreased.

Shunt Resistance, $R_{sh}$: Shunting current also can be increased within the area of the cell if the interaction of the encapsulant component is excessive. In the absence of high-temperature processes involved in the application of the encapsulant elements, the principal source of a change in shunting current is probably the degree to which the encapsulant passivates the exposed junction around the edge of the (conventional) cell. It is likely that the shunting currents can be decreased by encapsulation, which, of course, leads to a more efficient cell. The electrical conductivity of the encapsulant can also lead to a change in shunting currents, but conductivity, per se, is not likely to be a large factor in the results in this study. However, keeping water vapor away from the junction edge is, of course, an advantage.

b. Experimental Evaluation of Accelerated/Abbreviated Encapsulant Test Methods—Rockwell International. All materials degrade, however slowly, on exposure to the weather. To meet the goals of the LSSA program, solar cell encapsulants must provide protection for 20 years. Consequently, the objective of the present program is to develop methodology for making confident predictions of encapsulant performance at any exposure site in the U.S. The inherent weatherability factors of insolation, temperature, and moisture must be considered.

c. Electrostatically-Bonded Integral Glass Covers—Simulation Physics. This is a program to develop integral glass encapsulation for terrestrial solar cells, using electrostatic bonding. The feasibility of this technique has been shown and functional demonstration modules have been delivered to JPL for testing.
Electrostatic bonding is a process through which a variety of dissimilar materials may be permanently joined without use of adhesives. With elevated temperature to produce ionic conductivity and an externally applied electric field to drive the mobile ions, irreversible chemical bonds are formed at the interface of the pieces being joined. The process is applicable to joining bare solar cells or those with a variety of antireflective coatings to glass and to joining glass to glass with the aid of inorganic interface layers. Compatibility of the process with solar cells and with associated array hardware has been fully demonstrated. Developmental modules have shown no degradation of solar cell performance caused by electrostatic bonding.

d. Polymer Properties and Aging--Springborn Laboratories. The goal of the program is to develop and test materials and encapsulation or coating processes suitable for the protection of solar cells to provide a minimum 20-year service life in a terrestrial environment. The work is being conducted at Springborn’s facilities in Enfield, Connecticut, with cell performance being evaluated by Solar Power Corporation of Braintree, Massachusetts, under subcontract. The overall program is structured to include four other technical endeavors: cost analysis, selection of primers and enhancement of adhesion, upgrading ultraviolet stability, and processing repair studies.

e. Ion Plating Process and Testing--Endurex. Work under the Endurex contract began during this quarter. Endurex has developed a high-energy-level ion plating process which has proven to be a cost-effective means of applying coatings to both plastic and metallic parts. The encapsulation of Si solar cells appears to be achievable by means of the ion plating process. Both cost-effectiveness and functional improvement are anticipated.

Since virtually any material can be deposited, the major objective of this effort will be the determination of which of several candidate materials is optimum for this application. Concurrent with the material selection will be a determination of its response to variation of parameters of the ion plating process. Bias voltage, deposition rate, and chamber pressure will have significant effects upon composition hardness and growth morphology. These will, in turn, affect such important cell parameters as active band width, antireflection, electrical conduction, abrasion resistance, thermal cycling, and environmental stability. These effects will be measured and noted.

5. Summary of Progress

A comprehensive literature search being carried out in the Battelle Study 5 "diagnostics" work was partially completed. Approximately 9500 potentially relevant documents were identified, of which approximately 500 have been selected for detailed review. Contacts and discussions with experts internal and external to Battelle have been a major focus. These discussions have provided preliminary assessments of the suitability of various techniques for accelerated testing diagnostics application. These discussions have also led to the identification of additional literature.
of significant importance as well as equipment manufacturers and other technical personnel with extensive knowledge in specific areas.

Detailed outlines and background material for a discussion of "The Identification of Primary Mechanisms of Degradation Which Lead to Failure" are being prepared by Battelle. This discussion will be a key part of an interim report, and the information being compiled will be an important aid in the assessment of instruments and techniques.

Discussions are continuing with Battelle relative to a life prediction study which will include development of a test plan and testing of full size photovoltaic modules. This effort will endeavor to generate improved predictions of the service life of a specific photovoltaic array installed near Mead, Nebraska.* The test plan will include field measurements made at the Nebraska site on array modules, selected experiments at the Nebraska site on module components not a part of the array, selected laboratory aging measurements on module components under normally stressed and overstressed conditions, and diagnostic tear-down analyses on selected modules removed from the installed Nebraska array. Periodic predictions of the expected life of the Nebraska array modules will be made during the study.

An add-on to the Battelle Study 3 contract was executed. This work will evaluate selected encapsulation materials combinations shown to be viable candidates as a result of screening tests previously performed in Study 3. Evaluations will include the electrical performance of encapsulated single cells after exposure to temperature cycling, high humidity, and ultraviolet exposure. Issuance of the final report has been postponed until completion of the add-on contractual effort. A major portion of the final report which has been completed will be included in a monthly report together with preliminary data.

An approach was developed by Rockwell (Reference 1) for relating accelerated exposure data of polystyrene and polycarbonate (Lexan) film yellowing to outdoor exposure data. The stresses included temperature and ultraviolet radiation. A good fit was obtained in an Arrhenius-type relationship by regression analysis for humidities ranging from medium to high. A comparison of predicted with observed degradations in Miami (over a period of 15 to 300 days and degradations ranging from 0.97 down to 0.056) showed agreement ranging between -4% to +5% with a 95% confidence.

Acceleration factors of about 5 were found for yellowing and Lexan tensile strength loss on the EMMA and EMMAQUA sunlight concentrators at Desert Sunshine Inc. near Phoenix. In these devices, mirrors concentrate sunlight 8 times, but part of the outdoor UV comes from the sky (diffuse UV) rather than directly from the sun.

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*This field installation is a joint effort by the University of Nebraska and MIT/Lincoln Laboratory.
The Rockwell follow-on work has been started. New Universal Test Specimen (UTSs) were prepared with three different substrates: ceramic, epoxy/glass, and enameled steel. Pottingants include Parylene C (Union Carbide), Humiseal 2874 polyurethane, Humiseal 1873 acrylic, Fuller 3915 clear Silosyn nitrocellulose lacquer, and Sylgard 184 RTV Si rubber (Dow Corning). Specimens will be exposed to artificial accelerated weathering, natural weathering at Miami and Phoenix (45°C), and EMMA and EMMAQUA at Phoenix. In addition there will be a solar furnace experiment where specimens will be exposed to approximately 1000 times sun intensity.

SPIRE demonstrated simultaneous electrostatic bonding (ESB) of Type 7070 borosilicate glass plates to the front and back of a non-functional Si cell. A 97% transparent, one-mil-thick tantalum screen was successfully pressed between the front surface of the cell and the glass to represent metallization and/or interconnect. This work will be repeated with electrically functional cells and various mesh materials which have been ordered.

Modifications were started on the electrostatic bonder at SPIRE. Problems to be solved by the modifications are non-uniform heating of top and bottom platens and non-uniform application of pressure. A microprocessor and semi-automatic loading equipment will be installed.

Samples and data have been received from Corning Glass covering four experimental types of borosilicate glass. These glasses will be evaluated for electrostatic bonding by SPIRE.

The SPIRE contract was extended for 16 months. Future work on ESB will include equipment modifications, as discussed, determination of critical process parameters, and continuing development of module design and materials.

Special humidity-sensitive Si solar cells were supplied to Endurex for use in monitoring the efficiency of candidate ion-plated materials in hermetically sealing solar cells. Candidate materials are tantalum pentoxide, Si monoxide, aluminum oxide, and Si nitride. Hermetic sealing efficiencies were evaluated on specially designed printed circuit boards similar to ones developed by Bell Telephone Laboratories for similar investigations.

Preliminary results at Endurex indicated many pinholes in the approximately 10,000 A thick coatings. Work is progressing to eliminate pinholes by the application of multiple coats.

Endurex also started evaluating the ion plating of Si and silver to glass in support of SPIRE on electrostatic bonding of glass.

Case Western Reserve University completed experiments to determine the effect of photo-oxidation on the permeation and diffusion of water vapor and nitrogen/oxygen through polyethylene. Measurement techniques were shown to be very sensitive with changes in diffusion and permeability demonstrated after a few hours of exposure to UV. An important finding was that equilibrium water absorption increases rapidly with increase in polymer oxidation. Determinations by Fourier transform infrared spectroscopy
of the carbonyl content of the UV-degraded polyethylene were used to
measure the extent of oxidation.

The preparation and characterization of isoprene-methylmethacrylate
copolymers of varying compositions was completed and UV degradation/
permeability experiments were begun. This copolymer will be the main
system to be used in studies of effects of chemical structure and morphology
on degradation and permeation characteristics.

Techniques for staining plastic films for electron microscopy are
under development.

Rockwell Science Center demonstrated that moisture causes loss of
adhesive bond strength in Si encapsulants in a manner which can be
predicted quantitatively by an analysis that combines energetics of the
interface with fracture mechanics. Conventional experimental techniques
for measuring surface wetting and testing for peel strength were used. The
experiments were performed with RTV Si rubber bonded to soda-lime glass.
Peel tests were carried out at temperatures from 0° to 100°C and at
peel rates of from 0.005 to 5.0 cm/min. both dry and immersed in water.
Time-temperature master curves of peel fracture energy vs. peel rate
covering six log decades of time were plotted. Analysis of correlation
factors for the dry-wet master curves interconversion is in progress.
This analysis will provide a quantifiable basis for the prediction of
the effect of environmental cycling on adhesion.

Rockwell Science Center characterized a series of glass surfaces
which were cleaned (by Prof. Knauss of CIT) using different techniques.
Both the degree of cleanliness and the substrate chemical composition
could be qualified. The analytical methods included Auger spectroscopy,
ellipsometry and wettability measurements.

In-house work at JPL included the following:

a. Failure analysis was done on degradation observed in large
scale procurement modules including cell cracking in Sensor
Technology Block I modules and degradation of silicone gel
pottant (Dow Corning Q3-6527) in SPIRE R&D modules. Testing
was also done on materials from six types of modules from
a Cleveland demonstration site to support failure analyses.

b. Work was started to develop experimental techniques for
measuring "work-of-adhesion," a property which depends upon
the nature of the two materials (substrate and adhesive), and
their surface conditions (cleanliness). Preliminary tests
will be conducted to determine if the method will show the
effects of temperature, humidity, and surface cleanliness with
an encapsulant on glass. Two tests are being evaluated which
are derived from more conventional blister and peel adhesive
bond tests. Both tests will be continued until one is found
to be more convenient and reliable both experimentally
and mathematically than the other one.
c. Work was begun to test RTV 615 Si rubber for soil accumulation and RTV 615, polyvinylbutyral interlayer material, and Q3-6527 Si gel for UV resistance. Concurrently, atmospheric pollution data are being obtained, as available, for the exposure sites. Specimens will be sent to Lewis Research Center for exposure at seven locations. Specimens will also be retained by JPL for exposure at JPL, Table Mountain, Goldstone, and Point Vicente. The first set of specimens were prepared and shipped to LeRC for exposure on Mines Peak, Colorado.

d. Image processing techniques were used to measure dust accumulation on module encapsulant surfaces which had been exposed for six months in Cleveland, Ohio. Initial results were encouraging and development of this technique is continuing.

e. Techniques are being developed for measuring the relative humidity of the interior of encapsulant materials. This is done by embedding solid state humidity sensors (Thunder Scientific Corp. BR-101B) in the encapsulating material. Feasibility has been established and calibration measurements are being made.

f. A precision ultraviolet radiometer was designed and is being constructed. Development work was done with the aid of equipment obtained from Princeton Applied Research and the test facilities of the Oriel Company. Testing is planned at the Table Mountain facility followed by testing at remote sites.

g. A film actinometer was developed and used to measure solar irradiance at JPL and the output of a solar simulator at Oriel Corp. in Connecticut. A new technology report has been filed.

h. Data on the photodegradation of Lexan supplied by Rockwell was analyzed. The results of the analysis are being prepared for publication in the Micromolecules journal and a subsequent JPL report "Photodegradation of Selected Encapsulants" will be prepared. This report will also include data on the photodegradation of polyvinylbutyral (PVB), acrylics, and silicones.

SECTION IV
PRODUCTION PROCESS AND EQUIPMENT AREA

The overall objective of the Production Process and Equipment Area is to develop the technology necessary to achieve high-volume, low-cost production of silicon solar array modules. The goal of this task is to develop the capability to fabricate solar array modules of 10% or better conversion efficiency at a selling price of $0.50/watt or less, at a rate of 500 megawatts per year, with a 20-year operating life. Many of the decisions that must be made during the task effort cannot be made independently and will result from trade-offs with other decisions that are made both within this task and in conjunction with other tasks of the Project.

A. TECHNICAL GOALS

The manufacture of solar cells and arrays is presently accomplished under the judgment and direct control of individual operators. Because of the limited quantities of solar cells and arrays produced, costs are high. Automated solar cell production, as proposed, will lead to significant reductions in manufacturing cost. In addition, automation will result in uniformity of cell processing with a reduction of waste due to rejected product.

B. ORGANIZATION AND COORDINATION OF THE PRODUCTION PROCESS AND EQUIPMENT AREA EFFORT

The Production Process and Equipment Area effort is divided into five phases, occurring over a 10-year period of time (Table 4-1). The phases are:

I. Technology assessment.

II. Process development.

III. Facility and equipment design.

IV. Experimental plant construction.

V. Conversion to mass production plant (by 1986).

The basic Phase I (technology assessment) activities focused upon the economics of semiconductor processes as they might be applied to the manufacturing of low-cost solar cells. A six month add-on effort was negotiated with each of PP & E's three contractors (RCA, Motorola, and Texas Instruments) to study the more promising processes with regard to their "sensitivity to variables," and to identify facilities and equipment required to achieve a selling price of $2.00/watt by 1982. The variables under study are the primary parameters specified in typical process specifications such as temperature, exposure time, chemical concentration, etc. Processes which are sensitive to minute variations

4-1
### Table 4-1. Production Process and Equipment Area Schedule

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<th>CY 76</th>
<th>CY 77</th>
<th>CY 78</th>
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<th>CY 83</th>
<th>CY 84</th>
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<td>PHASE I: TECHNOLOGY ASSESSMENT</td>
<td>PHASE I ADD-ON</td>
<td>PHASE II: DEFINE, SELECT, AND DEMONSTRATE MANUFACTURING PROCESSES</td>
<td>PHASE III TECHNOLOGY READY</td>
<td>PHASE IV EXPERIMENTAL PLANT IN OPERATION</td>
<td>PHASE V MASS PRODUCTION PLANT READY FOR OPERATION</td>
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<td>PHASE III SEQUENCE DEVELOPMENT</td>
<td>PHASE IV: MANUFACTURING READY</td>
<td>PHASE V: MANUFACTURING READY</td>
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- **Part 1 Process Development**
  - Analyze existing technologies
  - Identify costs of processing and testing steps
  - Develop cost-effective approaches and identify options available
  - Identify cost/manufacturing obstacles
  - Conceptual solutions to these obstacles
  - Demonstrate cost-effectiveness of solutions
  - Define the conceptual approach that appears most cost-effective for fabrication/assembly of solar cell/array modules

- **Part II Sequence Development**
  - Analyze processes sensitivity to variables
  - Identify facilities and equipment required to achieve $2.00/watt by 1982
  - Develop processes and demonstrate readiness
  - Identify the processing equipment and facilities required
  - Update the cost analysis
  - Combine most cost-effective process
  - Identify the manufacturing equipment and facilities required
  - Demonstrate manufacturing technology readiness
in basic inputs are expected to result in lower yields than processes which can tolerate small variations. The Phase I add-on effort was initiated in February, 1977, and completed in August, 1977.

Phase II, which has been initiated in September, 1977, will define, select and demonstrate manufacturing processes. Part 1 will concentrate on process development with the following specific objectives:

(1) Determine priorities for process development.
(2) Identify areas where new technology must be developed.
(3) Develop and demonstrate processes.
(4) Identify the processing equipment and facilities required.
(5) Update the cost analysis.

Contractors are shown in Table 4-2.

C. SUMMARY OF PROGRESS

1. Process Assessment Activities

$2.00/watt Assessment

Texas Instruments, Motorola and RCA reported the results of a detailed cost analysis of a factory designed to manufacture solar cell modules to be sold profitably at $2.00 per peak watt in 1982. This price goal is consistent with the LSSA Project intermediate goal for 1982. Accordingly the major emphasis of the study was placed on the utilization of near-term technology.

The basic assumptions of the study are that the factory input is semiconductor-grade polycrystalline silicon costing $25.00 per kilogram and the factory size should be optimized for cost at a several megawatt per year size.

Each contractor chose one or more process sequences which it deemed adequate to produce efficient modules and then analyzed the costs involved. All three contractors concluded the $2.00 per watt goal was achievable.

In all cases the basic silicon sheet process uses Czochralski crystal growth and sawing to produce single crystal wafers. This sheet processing cost is the major cost driver of the overall cost and as such received much detailed analysis by the contractors. Figure 4-1 shows one analysis by RCA having process and cost variables as a function of volume. Note that the specific process sequence chosen is a constant and is described above the curves.

An analysis of the effect of encapsulated efficiency on manufacturing cost is also a major consideration. Figure 4-2 shows the results of Motorola's approach.
Figure 4-1. Cost as a function of manufacturing volume with wafer preparation and polysilicon cost as parameters.
ANNUAL PRODUCTION VOLUME = 25 MEGAWATTS
POLYCRYSTALLINE SILICON COST = $25/kilogram
BUILDING PHASE = 6 months
EQUIPMENT PHASE = 6 months
LABOR PHASE = 6 months
PRODUCTION PHASE = 5 years
INTEREST RATE = 7%
POWER RATE = 2.5¢/kWH
COST REFERENCE = MID-1977 DOLLARS

7.6 cm DIAMETER CELL, DIFFUSION PROCESS

12 cm DIAMETER CELL, DIFFUSION PROCESS

12 cm DIAMETER CELL, ADVANCED ION IMPLANT PROCESS

Figure 4-2. Effect of encapsulated cell efficiency on manufacturing cost.
### Table 4-2. Production Process and Equipment Area Contractors

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<th>Technology Area</th>
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Table 4-2. Production Process and Equipment Area Contractors (Continued).

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The other major consideration in the study was the sensitivity of cost to production volume. Naturally a production facility cannot turn on to a predetermined volume output from time zero. The facility must be built, equipment purchased and debugged, labor obtained and trained before a production phase can be initiated. Taking these factors into consideration, Figure 4-3 shows this volume effect.

An interesting and important factor emerging from this study is the question of risk. The concern is over the risk, without additional incentives, for a manufacturer to build a factory utilizing available technology to meet a $2.00/watt goal in 1982. Technology advances can readily obsolete such a factory before it can be run long enough to be profitable. Due to competition, it is probable that no single manufacturer will have a market share of greater than 5 to 10 megawatts in a total market near 25 megawatts in 1982. This volume is marginal in affecting sufficient efficiency of operation to meet the $2.00/watt goal.

One (or both) of two courses is open to achieve the $2.00/watt goal at volume. First, forward contracting of several years production at $2.00/watt can be considered. Second, the amount of potentially obsolete capital dollars required to initiate the factory might be reduced. In either case, the government is the only probable source of such funding.

Another important factor must be considered. The advanced technology proposed to meet the LSSA Project goals after 1982 may not be timely. If advances are slowed by two years for example, the factory could be justified economically. If, however, the technology advances were accelerated, it is already too late to build the $2.00 per watt factory.

**Sensitivity to Variables**

The contractors performed an analysis of the influence of primary variables upon each process or process sequence. These analyses examined the effects and cost consequences of variations of each primary variable upon the quality and quantity of output from a process on a process sequence. Additionally, they examined the interactive effects of such variations upon each of the other variables that are pertinent to the same process or process sequence. For this analysis primary variables are defined as those that are mentioned in detailed process specifications. The purpose of these analyses are to optimize the processes and process controls required to minimize the cost in dollars per watt of the finished module.

An example of such a sensitivity analysis performed by Texas Instruments on metallization parameter variables is shown in Figure 4-4. The process variables of diffused sheet resistance and metal sheet resistance were kept constant and the finger width of the conductive metallization was varied. $I_{\Delta}$, an increment of the light-generated current lost due to shadowing, was plotted along with the resulting sheet resistance ($R_s$). Both were compared to the original values. The sensitivity to variations of all possible combinations, e.g., two of the three parameters held constant, while the other is varied, were also analyzed.
ENCAPSULATED CELL EFFICIENCY = 14%
POLYCRYSTALLINE SILICON COST = $25/kilogram
BUILDING PHASE = 6 months
EQUIPMENT PHASE = 6 months
LABOR PHASE = 6 months
PRODUCTION PHASE = 5 years
INTEREST RATE = 7%
POWER RATE = 2.5¢/kW
COST REFERENCE = MID-1977 DOLLARS

7.6 cm DIAMETER CELL, DIFFUSION PROCESS
12 cm DIAMETER CELLS, DIFFUSION PROCESS
12 cm DIAMETER CELLS, ADVANCED ION IMPLANT PROCESS

ANNUAL PRODUCTION (MEGAWATTS)

MANUFACTURING COST ($/WATT)

Figure 4-3. Effect of annual production volume on manufacturing cost
Figure 4-4. Variation of Series Resistance and Light-Generated Current with Finger Width for Constant Diffused Sheet Resistance and Metal Sheet Resistance.

\[ R_{SO} = 0.012 \Omega \]
\[ \frac{R_S}{R_{SO}} \]
\[ I_{\Delta}/I_{\Delta_0} \]

\[ r = 80 \Omega/\square \]
\[ m = 0.0033 \Omega/\square \]

FINGER WIDTH - cm

0.002 0.004 0.006 0.008 0.010 0.012 0.014 0.016

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
The sensitivity of current density as a function of the antireflective coating thickness for two evaporative coatings - silicon monoxide and silicon dioxide - is shown in Figure 4-5. These curves are interesting not only in that the maximum generated currents peak at highly different thicknesses (for such similar chemical coatings) but they give an indication of importance of thickness control and consequently the inherent cost implications of such processes.

In order to analyze the impact of emerging sheet technologies Motorola studied the effect of ribbon substrate width. The results are shown in Figure 4-6. This is actually a plot of the equation:

\[
C_T(W) = \frac{C_M}{n(W)^8} \left( \frac{1 + \frac{2}{K}}{W} \right)^{\frac{1}{n(W)}}
\]

where

- \( C_T \) is the total cost per unit area
- \( n \) is the efficiency
- \( C_M \) is material cost
- \( W \) is the ribbon width and
- \( K \) is defined as the ratio of materials cost per unit of solar cell area to processing cost per unit area for a baseline case of \( W = 2 \, \text{cm} \)

This shows that there is a practical limit which appears to be around 12 cm for a cost effective ribbon width using Motorola's assumptions.

2. Process Development

Seven Phase II, one year duration, Process Development contracts were executed during September. The remaining two Phase II contracts will be executed during the next quarter.

Three additional contracts initiated during this quarter provided for an assessment of slicing, metallization of large wafers and a follow-on contract for the manufacture of solar cells with pulse processes.

Computer software packages for laser scribing of hex and modified hex cells have been successfully implemented at Sensor Technology. The first three panels incorporating full hex cells (10% efficient) have been delivered to JPL.

Sensor Technology has shown that laser scribing techniques can be successfully utilized to shape the wafers from either the front or the back without degrading the junction characteristics.
Figure 4-5. Sensitivity of Generated Current Density as a Function of AR Coating Thickness at AM1
Figure 4-6. Total Cost Per Unit Efficiency (which is similar to dollars per watt) versus ribbon substrate width. This is shown as a function of the ratio of material costs to processing costs for the baseline case of 2 cm wide ribbon.
Preliminary findings reported by Solarex in late August indicate that the energy payback period for ion-implanting a 4" cell junction is less than the payback period for a 4" cell junction formed by conventional diffusion procedures. Solarex will next investigate various silicon refinement processes and will modify the computer model of the experimental facility to permit more sophisticated study.

The contract with Martin Wolf of the University of Pennsylvania is proceeding with efforts directed toward accumulating and reviewing energy data relating to various process options. The data will include information useful in determining module development and energy payback costs.

3. Advanced Panel Design

A contract with Solarex for the development of high efficiency (>12%), high packing density (>80%) solar panels with 5 cm square cells was begun in late August.

Xerox-EOS is having functional performance problems with its center hole cell and stud configuration panel, which is evidenced by varying power output on some panels. In-depth analysis is continuing which may result in a material modification to the aluminum backside cell.

Solar Technology, Inc. completed delivery of twelve contractually required solar modules. Six of the modules were fabricated by STI's conventional production processes and incorporated Ag metallization cells. The other six modules were developed by production processes that included Al P+ back metallization on cells. All modules will be tested at JPL in accordance with Specification 5-342-1B.

A contract with General Electric for the development and testing of roofing shingle type solar cell modules was awarded in early July. Module design has begun.

Lockheed has delivered all 14 advanced-design R&D solar panels (6 environmentally tested, 6 untested, 2 engineering prototype models) required by the contract. Additionally, studies on single cell failure impact and encapsulation performance trade-off studies are being conducted under an extension to the contract.

Motorola advanced R&D panels have experienced cracked cells during JPL environmental testing. This problem is being investigated.

A contract with OCLI to build high efficiency (>13%) solar panels was started in August.
A. SUMMARY OF PROGRESS

During the subject quarter the Engineering Area continued activities in the areas of 1) analysis and testing of solar array modules in conjunction with the development of future module and array design criteria and test methods, and 2) support to the Operations Area in the area of problem/failure analysis and coordination of engineering design interfaces for the Block III module procurement.

A survey of methods for calculating breaking strengths of simply supported rectangular glass plates subjected to uniform pressure loading was completed and indicated a lack of available data for determining the proper thickness for glass modules. The difficulty arose because of the non-linear structural behavior of thin plates when subjected to the large deflections associated with module wind loading. Conventional linear, small-deflection theories overestimate the imposed stress by as much as a factor of two. A non-linear stress analysis computer routine ANSYS was used to predict the actual principal stresses in glass panels of various geometries and thicknesses and excellent correlation with measured breaking loads was achieved. This work is in the process of being documented in a non-dimensional format for use by module designers.

Various module tradeoffs were also completed examining the cost effectiveness of module design features such as hexagonal cells and enhanced encapsulant transmission as a function of solar cell price. Detailed results are summarized in the technical data section which follows this summary. General conclusions were that most transmission enhancement technologies, such as the use of low-iron glass, are cost effective today and will continue to be so until module price drops well below $2/watt. On the other hand, hexagonal cells are not cost effective now and will not be until module price drops well below $2/watt.

Data was also acquired on module power output as a function of angle of incidence of the incident insolation. The data indicated that the assumption that power rolls off proportional to the cosine of the angle of incidence is quite accurate for angles up to about 50°. Beyond 50° the cosine law underestimates the power because of the contribution of diffuse sky radiation. For dirty modules, the percent short-circuit-current reduction due to the dirt was found to double at angles of incidence greater than 60°. Computer analyses of arrays tilted to the local latitude for various U.S. locations indicated that approximately 50% of the annual energy is obtained during periods when the angle of incidence is greater than 30°, 25% at angles greater than 45°, and 10% at angles greater than 60°. Details are presented in the Expanded Technical Report in the following section.

Thermal testing in natural sunlight continued during the quarter with emphasis on studying the effects of cooling modules with water and using modules to heat water for combined thermal/electric applications.
The results are summarized in the technical data section which follows this summary together with other test results reported on last quarter. The conclusion drawn from the thermal tests of combined thermal/photo-voltaic collectors is that the electrical efficiency loss due to the higher cell operating temperatures will make these collectors uneconomical until the combined price of the module system and array support structure amounts to more than 25% of the cost of the solar cells. This is likely to occur when the module price drops below $1/watt.

The first phase of exploratory bias-humidity testing has been completed using modules from each of the four Block II suppliers. This test is under study as a candidate for module qualification with respect to moisture-related failure mechanisms which are enhanced by the presence of an electrical potential between the solar cells and between the cells and the module's frame. Ion-migration and galvanic corrosion effects are of particular interest.

In the first phase test the four modules were subjected to 30 days of humidity cycling in the presence of a 250-volt reverse-bias voltage and a 100-volt bias to frame. Two of the four modules showed visible changes associated with material transfer and discoloration. In before-and-after measurements, it was found that the shunt resistance of the solar cells increased about 50% on the average. In general, however, the test had little effect on power output as indicated by maximum power losses of less than 5%. Failure analysis of the two degraded modules was initiated. Future bias-humidity testing was to focus on understanding the observed phenomena and developing a standard test procedure.

Hail test development was nearing completion, with present work focused on methods for enhancing the impact resistance of modules. High-speed movies were taken of simulated hail (ice balls) striking modules of various constructions in order to further understand the impact dynamics. Review of the photographs, an example of which is shown in Figure 5-1, indicates that the majority of the damage occurs in the first 200 µsec after impact. The key failure mode with soft encapsulants is cell crushing; with glass modules it is glass breakage due to excessive local plate bending.

Module requirement contracts with Bechtel and Boeing started work during the reporting period. The Bechtel contract is an add-on to its previous contract exploring module requirements for central power stations and will emphasize optimization with respect to module structural costs. The Boeing contract will explore the advantages and disadvantages of enclosing modules in a self-supporting transparent enclosure.

Compilation of industry comments on the preliminary module specification document #5101-16, "Silicon Solar Cell Module Design, Performance and Acceptance Test Requirements", was completed and briefly reported on last quarter. An expanded summary of the results is presented in the following section.
Figure 5-1. Simulated Hail (Ice Ball) Impacting Front Surface of Solar Module (Balls were Fired Upward)
B. EXPANDED TECHNICAL REPORT

Additional material reflecting work completed during the reporting period is presented here under the following titles:

"The Effect of Angle of Incidence on Annual Energy Output"
C. Gonzales, J. Stultz, and R. Ross, LSSA Project Engineering Area

"Industry Review of Third Generation Module Specifications"
J. Arnett, LSSA Project Engineering Area

"A Potpourri of Module Thermal Test Results"
J. Stultz, LSSA Project Engineering Area

"Module Optimization Analysis"
R. Grippi and R. Ross, LSSA Project Engineering Area
THE EFFECT OF ANGLE OF INCIDENCE ON ANNUAL ENERGY OUTPUT

C. Gonzalez, J. Stultz and R. Ross, LSSA Engineering Area

1. Introduction

The standard approach to measuring the performance of photovoltaic modules involves testing with the incident insolation normal to the module surface. However, in actual operation, the insolation will generally occur with a moderate angle of incidence to the module plane. This fact leads to underestimating degrading effects which increase with increasing angles of incidence. Such effects include reflection losses, encapsulant transmission losses, and losses due to module soiling. To help quantify these effects, an analysis was conducted to determine the fraction of the annual energy which is associated with various non-normal angles of incidence for a flat plate array, facing south, and tilted to the local latitude. Module soiling losses are then examined in the light of these data.

2. Analysis

The annual energy output of a flat plate photovoltaic solar collector was determined as a function of angle of incidence of the incoming direct solar radiation. Figure 5-2 shows the energy output versus incidence angle for a collector tilted at the local latitude and facing south for five geographic sites in the United States. The analysis was based on hour-by-hour integration of solar insolation data recorded on magnetic tape and provided by the National Climatic Center in Asheville, North Carolina. Solar cell I-V dependance on both insolation level and ambient temperature was included.

Figure 5-2 illustrates that about 50% of the annual energy output is obtained at angles of incidence greater than 30° from the normal. Figure 5-3 illustrates that changing the tilt angle of the array does not alter this result.

3. Tests

The module short-circuit current was measured in natural sunlight at solar noon for several angles of incidence obtained by changing the tilt angles of the module. Figure 5-4 summarizes the measurements for clean modules having a front surface of glass and Sylgard 184. When the module is clean, the short-circuit current varies as the cosine of the incidence angle for both types of modules. Figure 5-5 is a similar plot for the Sylgard 184 module illustrating the effect of dirt accumulation. After one week of dirt accumulation, the degradation is about 2% and constant for angles of incidence up to 60°. (From Figure 5-2, 95% of the annual energy is obtained at angles of incidence less than 60°.) After one month, the degradation is 6.5% at normal incidence and increases almost linearly to 11.5% at an angle of incidence of 60°.
Figure 5-2. Annual Energy Output Versus Angle of Incidence for Flat-Plate Arrays Tilted to the Local Latitude
Figure 5-3. Effect of Array Tilt Angle on Annual Energy Output Versus Angle of Incidence
Figure 5-4. Short-Circuit Current Versus Angle of Incidence
Figure 5-5. Short-Circuit Current Versus Angle of Incidence for Soiled Modules
4. Conclusions

Care must be taken in estimating the effect of various optical losses on annual energy output. Normal incidence measurements of the effect of dirt are only representative of "light" dirt accumulation as might be expected for modules washed on a two-week interval. In a "severe" dirt environment, the degradation is greater than indicated by the normal measurements. Example: Tests indicate a 6.5% degradation based on normal incidence, but degradation is 8% based on angles of incidence up to 60° as weighted according to the annual energy output as a function of incidence angle (Figure 5-2).
INDUSTRY REVIEW OF THIRD GENERATION MODULE SPECIFICATION

J. Arnett, LSSA Engineering Area

1. Introduction

During the quarter, results were compiled of a broadly-based industry critique of a preliminary requirements document for third generation solar cell modules. A summary presentation of the responses was given at the 7th Project Integration Meeting. The objectives, approach, and results of the industry review are described in the following paragraphs.

2. Objective

In support of the LSSA Project's stated goals, the Engineering Area prepared a preliminary requirements document, JPL 5101-16, "Silicon Solar Cell Module Design, Performance and Test Requirements, Preliminary", dated March 15, 1977. It was decided to request a review of this document by a cross section of the photovoltaic industry. The objective of this review was to obtain, for the Project, an improved understanding of user and manufacturer concerns related to the level and extent of requirements imposed on modules procured by the Project for test and demonstration applications. It was anticipated that the results of the review would provide suggestions and recommendations on the desirable design and performance features for the near-term module procurement specifications, as well as indications of trends and goals for advanced module requirements.

3. Approach

JPL 5101-16, Preliminary, was developed as a "strawman" procurement specification for third generation designs of silicon solar cell modules. This document evolved from experience with early module designs during initial large-scale procurements by the LSSA Project for DOE's Photovoltaic Test and Demonstration Program. For purposes of categorizing the applicable levels of technology associated with the designs, modules procured under Block I (usually referred to as the 46 kW buy) were considered to be basically off-the-shelf designs available from the emerging terrestrial manufacturers as first generation designs. During the initial environmental testing of these modules, changes and modifications were rapidly being made by all manufacturers in response to the need for improved ruggedness to meet test and qualification requirements which were simultaneously evolving. This process led to the second generation designs represented by the Block II and III procurements which were made against JPL Specification 5-342-1. The intent of the third generation specification then, is to provide a document which incorporates the design improvements gained from field exposure and environmental test experience of previous generations while assuring that the performance needs of photovoltaic users and the manufacturing needs of module fabricators are considered.
The approach was selected of submitting a preliminary draft of the third generation document to selected representatives of the photovoltaic community for review and comment. A review package was prepared which included the documents listed in Table 5-1. In addition to the draft specification, the supporting documentation consisted of two JPL drawings which provided guidelines for preparation of an Interface Control Drawing and the module configuration requirements, and a quality assurance document providing uniform visual inspection and workmanship criteria for modules.

This review package was forwarded to 23 companies representing a broad cross section of solar cell module manufacturers and users, systems contractors, architectural engineering firms, and silicon cell technology research and development firms. A list of the companies participating in this critique appears in Table 5-2. A letter describing the objectives of the review and requesting responses in particular areas of concern accompanied each review package.

The LSSA Project was particularly interested in assessing the influence of the following considerations on various elements of the preliminary requirement document:

(1) Compatibility with low-cost production in large quantities;
(2) Adaptability to a broad range of products and applications;

Table 5-1. Review Package Enclosures

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSSA DOCUMENT 5101-21</td>
<td>&quot;Rejection Criteria for JPL LSSA Modules,&quot; March 10, 1977</td>
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<tr>
<td>JPL DWG NO. 10082742</td>
<td>&quot;Guideline for Preparation of Interface Control Drawings&quot;</td>
</tr>
<tr>
<td>JPL DWG NO. 10082854</td>
<td>&quot;Configuration Requirements for LSSA Modules&quot;</td>
</tr>
<tr>
<td>Company</td>
<td>Address</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------------</td>
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<tr>
<td>Bechtel Corporation</td>
<td>P. O. Box 3965, Mail 301/3</td>
</tr>
<tr>
<td>Boeing Engineering &amp; Construction</td>
<td>P. O. Box 3707</td>
</tr>
<tr>
<td>Facilities Systems Engineering Corp.</td>
<td>8332 Osage Avenue</td>
</tr>
<tr>
<td>Farwest Corrosion Control Co.</td>
<td>1000 E. 220th Street</td>
</tr>
<tr>
<td>General Electric Company</td>
<td>Valley Forge Space Center</td>
</tr>
<tr>
<td>Lockheed Missiles &amp; Space Co., Inc.</td>
<td>Space Systems Division</td>
</tr>
<tr>
<td>Mobil Tyco Solar Energy</td>
<td>16 Hickory Drive</td>
</tr>
</tbody>
</table>

Table 5-2. List of Participants
Table 5-2. List of Participants (Continuation 1)

DOCUMENT
INDUSTRY CRITIQUE OF JPL #5101-16

<table>
<thead>
<tr>
<th>Company</th>
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<th>ATTN</th>
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<tr>
<td>Solarex</td>
<td>1335 Piccard Drive, Rockville, MD 20850</td>
<td>Joseph Lindmayer</td>
</tr>
<tr>
<td>Spectrolab</td>
<td>12484 Gladstone Avenue, Sylmar, CA 91342</td>
<td>E. L. Ralph</td>
</tr>
<tr>
<td>Texas Instruments, Inc.</td>
<td>Box 5012, Dallas, TX 75222</td>
<td>Gene Wakefield</td>
</tr>
<tr>
<td>Tideland-Signal Corp.</td>
<td>P. O. Box 52430, Houston, TX 77052</td>
<td>Carl Kotilla</td>
</tr>
<tr>
<td>Westinghouse Electric Corp.</td>
<td>R &amp; D Center, Pittsburgh, PA 15235</td>
<td>P. F. Pittman</td>
</tr>
<tr>
<td>Xerox</td>
<td>300 No. Halstead Street, Pasadena, CA 91107</td>
<td>J. A. Carlson</td>
</tr>
</tbody>
</table>

(3) Compatibility with a complete line of modules reflecting, for example, incremental variations in current and voltage;

(4) Consistency with minimizing system costs and interface complexity from both electrical and mechanical viewpoints;

(5) Consistency with user reliability, quality, safety, and lifetime requirements, and

(6) Compatibility with efficient, low-cost installation and maintenance.

It was requested that the participants review the following specific elements of the proposed documents with respect to the considerations listed above:

(1) Performance measurement standards and procedures;

(2) Level and procedures for qualification testing;

(3) Mechanical and electrical interface requirements and performance levels;

(4) Electrical, mechanical, environmental, and configuration design requirements;
(5) Acceptance/rejection criteria, especially visual inspection and workmanship standards.

Several features of the 5101-16 preliminary document which differed from previous specifications are worth noting. This document incorporates the use of the concept of power and performance rating of modules at the Nominal Operating Cell Temperature (NOCT). Rating modules at NOCT assures an equivalent comparison of performance between manufacturers. The selection of 15.0 volts as the performance test voltage was the result of JPL Engineering Area studies of optimum 12-volt battery charging voltage characteristics. Power performance of modules was based on the nominal average power of production modules exceeding 7% efficiency. To minimize mismatch losses and improve module interchangeability in field installations, individual modules were required to be not less than 90% of the average power. In order to improve overall module reliability and reduce the problem of hot-spot cell failures, the incorporation of series/parallel internal circuitry was permitted. An important feature of the specification was the standardization of the configuration of all modules to a common mounting pattern with a fixed module length. Design flexibility was provided by permitting module width to vary as a function of cell size and circuitry arrangement in 3/4-inch increments up to 4 feet. Two significant changes proposed to environmental testing procedures were the inclusion of a test procedure for the 1/4 inch/foot twist requirement and an increase in the number of ±50 PSF structural loading cycles to 10,000 cycles. The latter change reflects estimates of lifetime effects of cyclical fatigue-related wind loading environment. The visual inspection and workmanship document, JPL Document #5101-21, represents JPL's proposed minimum requirements for acceptance or rejection of modules, although it was expected that each manufacturer would develop in-house inspection requirements responsive to 5101-21. Details of the above features, and in particular, the configuration and mounting interface, had been previously presented to participants in the 6th Project Integration Meeting and are incorporated in the proceedings of that meeting.

4. Results

Responses to the industry critique were received by both letter and telephone conference. A summary of the participation by industry in this review appears in Table 5-3. For purposes generally characterizing the scope and significance of the comments received, the review package enclosures were broken into major categories and the number of individual comments were tabulated with respect to these categories. This tabulation appears in Table 5-4, Summary of Responses by Category. While the majority of comments dealt with the specification, substantial numbers of suggestions were received on the configuration drawing and inspection document.

The three companies representing users responding to the review include one company utilizing modules in cathodic protection systems and two companies producing navigation aids. The comments received reflect the fact that these types of applications are relatively remote, low power systems, usually with special environmental constraints. A general summary of comments and suggestions from these companies appears as Table 5-5.
Table 5-3. Review Participation by Industry

| Total Companies Receiving Review Data | 23 |
| Block II Module Manufacturers | 4 |
| Technology/Module Development Firms | 11* |
| Module/Array Users | 3 |
| A&E Firms | 5* |
| Systems Engineering Firms | 4* |

*Includes Firms Active in Multiple Areas

The comments from manufacturers of modules, including both the Block II contractors and manufacturers of experimental modules, reflect more concern with the details of configurations, tolerances and testing procedures as related to the manufacturability of modules designed to meet the specification. A general summary of comments and suggestions from the manufacturers' points of view is listed in Table 5-6.

Other respondents to the review provided detailed comments with respect to many of the same areas mentioned by the users and manufacturers. In addition, three other specific concerns were listed which will influence future specifications. The A&E firms generally felt that tolerances and clearances should be relaxed to represent practical applications, such as bolt-together structure for arraying modules or for "glazing" type installations. Many reviewers pointed out the need for incorporation of a hail (or impact) requirement. The incorporation of other environmental tests for salt-fog and UV were recommended. The UV tests were considered by a number of reviewers to be especially critical with respect to predicting the ability of module designs to meet the Project's lifetime reliability goals.

5. Conclusions and Recommendations

The results of this industry review of the preliminary third generation specification, 5101-16, and its supporting documentation indicate that the draft specification is generally well accepted. Specific areas where improvements are needed were identified. The 5101-16 preliminary document provides an effective starting point for development of near-term and future design and performance requirements.
Table 5-4. Summary of Responses by Category

<table>
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<tr>
<th>Comments From/On</th>
<th>5101-16</th>
<th>DWG 10082854</th>
<th>5101-21</th>
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<td>NOCT</td>
<td>Mntg. Config.</td>
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<td>Users</td>
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<tr>
<td>A&amp;E Firms</td>
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<td>8</td>
</tr>
<tr>
<td>Systems</td>
<td>6</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 5-5. General Summary of Users Comments

- Module size (power) should relate to marketable cost increments
- Fixed length/variable width promotes simplified mounting and installation
- Voltage isolation requirement too high for current applications
- Separate ground not needed for metal-structure-supported applications
- Connector/termination designs needed
- Specify extent and level of repairability
- NOCT rating improves user's ability to specify realistic power requirements
- Need for impact and dust requirements emphasized
- Inclusion of environmental tests for marine applications suggested

Recommendations call for using the 5101-16 document as a baseline third generation design guideline. Little or no changes are anticipated from the proposed document in the following areas:

(1) Electrical performance measurement and efficiency;
(2) Use of the NOCT test procedure, though with minor clarification;
(3) Configuration controlled to a fixed length, variable width, with standard mounting spacing;
(4) Existing environmental testing; and
(5) Visual inspection criteria.

Significant changes to the document are expected to occur in the following areas:
Table 5-6. General Summary of Manufacturers' Comments

- Performance/efficiency requirements acceptable for near-term technology
- Design flexibility compatible with product line
- Mechanical configuration promotes modularity
- NOCT procedure is complicated, but necessary
- 15.0 VDC requirement still restricts use of some cell sizes
- Alternate connector/termination designs and locations needed
- Structural loading test (no. of cycles) questioned
- Use of DC instead of AC for voltage isolation suggested
- Clarification of edge vs thru-hole mounting requested
- Inspection criteria may be too detailed, if warranty provisions are made
- MIL-STD-105 sampling for inspection recommended

(1) Addition of a hail (impact) requirement;
(2) Addition of a dust accumulation requirement;
(3) Revised output termination provisions;
(4) Reassessment of electrical isolation and grounding requirements;
(5) Conversion to metric dimensioning and tolerances.

In addition to development of a baseline third generation design guideline based on near-term requirements, the use is recommended of this preliminary specification as the basis for a companion document with variable requirements to permit innovation approaches for module design R&D.
A POTPOURRI OF MODULE THERMAL TEST RESULTS

J. Stultz, Engineering Area

INTRODUCTION

Thermal testing in natural sunlight during this period falls into three categories. First, there were several test series whose results are characterized by a change in the nominal operating cell temperature (NOCT).* The effect on NOCT of dirt accumulation, of a residential-type roof installation, and of adding cooling fins was determined. Also, during this period, tests at NASA Lewis Research Center (LeRC) have verified that nearly identical values of NOCT can be determined at another location using the NOCT test procedure defined in Reference 1. Second, a series of tests were carried out which illustrate the improvement in photovoltaic module performance achieved by cooling the module with water. Third, a final series of tests provided data on the reduction in electrical performance for a combined photovoltaic and solar water-heating module. The following discussion elaborates on each of these test categories.

DISCUSSION

NOCT Testing

NOCT of the Block I and II Modules: A summary of the NOCT for the Block I and II modules is shown in Figure 5-6. For the same manufacturers, NOCT remained approximately the same from Block I to Block II. This result was expected because the flat plate configurations are estimated to be within 4% of the thermally optimum design (Reference 2).

NOCT and Dirt Accumulation: Figures 5-7 and 5-8 show the increase in NOCT with dirt accumulation for modules with glass and nonglass front surfaces respectively. The results indicate that NOCT for the nonglass modules increased 1.3°C to 2.2°C during the first week and remained constant during the next three weeks. For the glass front surface modules, less than a 0.5°C increase was observed during a three-week period. For the test period, the tilt angles were small (13° to 18°) so that the dirt accumulation would represent a maximum for the JPL test site (roof of Building 248). The effect on NOCT is not significant.

NOCT for Roof Installation: A 4' x 4' segment of a photovoltaic residential roof installation was simulated. The mounting technique approximated that proposed by Lincoln Lab for the residential demonstration. The modules are stood off from the roof about 3" by supports which attach at

---

*The NOCT of a module is the operating temperature of the cells when the module is mounted in a standard environment defined by: Insolation = 80 mW/cm², Air Temperature = 20°C, Wind Velocity = 1 m/s, Mounting Configuration = Open Back, tilted, open circuit. For more information see Reference 1.
Figure 5-6. NOCT Summary for Block I and Block II Modules
Figure 5-7. The Effect of Dirt Accumulation on NOCT (Glass Front Surface)
Fig. 5-8. The Effect of Dirt Accumulation on NOCT (Silicone Rubber Front Surface)
the top and bottom edges of the module. Air flow beneath the modules is
discouraged by this type of a design, and only the modules mounted along
the east and west edges will benefit by sporadic wind-induced air movement
beneath the modules. The 4' x 4' array consisted of three identical
modules, and the NOCT of the center module was determined. A summary of
the results is presented in Table 5-7.

With no air flow beneath the modules, as would be typical of the
innermost-mounted modules, the NOCT is 9.5°C warmer (55.5°C compared to
46.0°C) than the NOCT for the same module mounted in the normal field
installation. Modules along the east or west edge would be 3.9°C warmer
because some air flow is possible through the open sides. If the modules
were attached along the sides rather than along the top and bottom edges,
the module is 4.8°C warmer. If the module was stood off from the roof by
legs rather than rails, the module is 3.4°C warmer.

This test series illustrates that higher operating temperatures will
occur for residential roof installations and the decrease in electrical
performance will be 2% to 5% in the worst case. A mounting technique,
permitting more air flow could cut this penalty in half. However, the
module support structure is also utilized to support ladders (or the
equivalent) which enable the initial installation of the modules as well
as future servicing to be carried out safely and with no damage to the
modules or the existing roof. A mounting technique which assures the
latter is well worth the 1% to 2-1/2% decrease in electrical performance.

Table 5-7. NOCT Summary for a Residential Roof Installation

<table>
<thead>
<tr>
<th>Proposed Configuration</th>
<th>NOCT °C</th>
<th>ΔNOCT* °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Module at the center of the roof</td>
<td>55.5</td>
<td>9.5</td>
</tr>
<tr>
<td>(No flow beneath module)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Module at the east/west edge</td>
<td>49.9</td>
<td>3.9</td>
</tr>
<tr>
<td>(Permits east-west air flow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Sides closed, top/bottom edges open</td>
<td>50.8</td>
<td>4.8</td>
</tr>
<tr>
<td>(Permits flow bottom to top)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. All edges open</td>
<td>49.4</td>
<td>3.4</td>
</tr>
<tr>
<td>(Permits flow in all directions)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*NOCT of this module is 46°C for the normal field installation.
NOCT and Cooling Fins: The NOCT of two identical modules having a finned aluminum extruded substrate was measured. The fins were then machined off and the NOCT tests repeated. As shown in Fig. 5-8, the increase in NOCT by removing the fins was 2.9°C and 2.6°C for the two modules. Therefore, the fins were increasing the electrical performance by no more than 1.5%. If the fins are for thermal purposes only, the cost effectiveness is very questionable at present module prices and definitely would not be cost-effective in the mid-1980s.

NOCT and Maximum Power: The standard NOCT is performed with a zero power output (open circuit conditions) purposely to reduce the complexity of the test. A test was performed during which maximum power was continuously removed from the module. The effect on NOCT was a reduction of 2.9°C.

LeRC NOCT Tests: JPL requested LeRC to perform the NOCT test on the Block II modules to verify the test procedure and to verify that approximately identical results would be determined at a location other than JPL. Table 5-8 is a comparison of the LeRC tests (Reference 3) with previous JPL tests; the agreement is very good. No changes in the test procedure were recommended by LeRC.

NOCT Testing Summary: Table 5-9 presents a summary of observations based on the NOCT tests and is self-explanatory. Determining the NOCT of a module has proven not only to be an accurate way of evaluating the module thermal design but also provides a way of evaluating changes in the thermal design and/or the effect thermally of an installation other than the standard field mount.

Increasing Photovoltaic Module Performance by Water Cooling

This study was prompted because some applications involve the movement of a large amount of water. For example, the irrigation project in Nebraska pumps 60,000 gals/hr or 1,542 gal/hr-ft² of module area. While this flowrate is adequate, much larger flowrates are possible with a simple gravity feed configuration (such as a common trough feeding the water into the top of tubes, attached or built into the back of the modules, and discharging it into a holding pond or into the supply system) which would improve the performance slightly.

Test Configuration: Water was circulated through two copper tubes bonded to the backside of a Block I Spectrolab module. This module has two rows of cells mounted in a staggered pattern on an aluminum I-beam. The copper tubes were bonded on either side of the I-beam beneath the cells (as illustrated in Figure 5-9) with a thermally conductive adhesive (ECOBON 57C). The inlet water temperature was maintained constant during the test. Maximum power was continuously drawn from the module.

Test Results: Figure 5-9 presents temperatures of the module as measured at noon. With water cooling the gradient through the module is cut almost in half, and the cell is about 3°C warmer than the local water temperature. Reversing the flow (bottom to top) had no effect on the temperature profile, and there was no measurable change in P_{max} when the flow was increased by a factor of five.
Table 5-8. LeRC and JPL NOCT Test Summary

<table>
<thead>
<tr>
<th>Block II Module</th>
<th>LeRC NOCT</th>
<th>JPL NOCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solarex</td>
<td>46.0</td>
<td>47.1</td>
</tr>
<tr>
<td>Solar Power</td>
<td>45.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Spectrolab</td>
<td>41.0</td>
<td>41.1</td>
</tr>
<tr>
<td>Sensor Technology</td>
<td>40.5</td>
<td>42.9</td>
</tr>
</tbody>
</table>

Table 5-9. NOCT Conclusions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Δ NOCT °C</th>
<th>Δ Power %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Mount (No air flow beneath module)</td>
<td>+10.</td>
<td>-5.</td>
</tr>
<tr>
<td>Roof Mount (Good air flow beneath module)</td>
<td>+4.</td>
<td>-2.</td>
</tr>
<tr>
<td>Dirty Module: Non-glass</td>
<td>+2.</td>
<td>-1.</td>
</tr>
<tr>
<td>Dirty Module: Glass</td>
<td>+0.5</td>
<td>-0.2</td>
</tr>
<tr>
<td>Metal Substrate (vs opaque non-metal subt.)</td>
<td>-4.</td>
<td>+2.</td>
</tr>
<tr>
<td>Metal Substrate with Fins (vs metal subt. without fins)</td>
<td>-3.</td>
<td>+1.5</td>
</tr>
<tr>
<td>Metal Substrate (vs transparent non-metal subst.)</td>
<td>+1.</td>
<td>-.5</td>
</tr>
<tr>
<td>Max. Power Out (vs zero power: open circuit)</td>
<td>-3.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Fig. 5-9. Module Temperature Profile At Noon
(Insolation = 95 ± 2 mw/cm²)

<table>
<thead>
<tr>
<th>THERMOCOUPLE</th>
<th>T/C SL-1</th>
<th>T/C SL-2</th>
<th>T/C SL-3</th>
<th>T/C SL-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-1</td>
<td>47.8</td>
<td>38.9</td>
<td>32.8</td>
<td>25.0</td>
</tr>
<tr>
<td>SL-2</td>
<td>46.1</td>
<td>37.2</td>
<td>31.1</td>
<td>23.3</td>
</tr>
<tr>
<td>SL-3</td>
<td>43.3</td>
<td>35.0</td>
<td>29.4</td>
<td>21.7</td>
</tr>
<tr>
<td>SL-4</td>
<td>41.7</td>
<td>34.4</td>
<td>29.4</td>
<td>22.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T/C SL-1</th>
<th>T/C SL-2</th>
<th>T/C SL-3</th>
<th>T/C SL-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-1</td>
<td>47.8</td>
<td>38.9</td>
<td>32.8</td>
</tr>
<tr>
<td>SL-2</td>
<td>46.1</td>
<td>37.2</td>
<td>31.1</td>
</tr>
<tr>
<td>SL-3</td>
<td>43.3</td>
<td>35.0</td>
<td>29.4</td>
</tr>
<tr>
<td>SL-4</td>
<td>41.7</td>
<td>34.4</td>
<td>29.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T/C SL-1</th>
<th>T/C SL-2</th>
<th>T/C SL-3</th>
<th>T/C SL-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-1</td>
<td>47.8</td>
<td>38.9</td>
<td>32.8</td>
</tr>
<tr>
<td>SL-2</td>
<td>46.1</td>
<td>37.2</td>
<td>31.1</td>
</tr>
<tr>
<td>SL-3</td>
<td>43.3</td>
<td>35.0</td>
<td>29.4</td>
</tr>
<tr>
<td>SL-4</td>
<td>41.7</td>
<td>34.4</td>
<td>29.4</td>
</tr>
</tbody>
</table>

GLASS RTV SILICONE RUBBER

H₂O INLET WATER TEMP

<table>
<thead>
<tr>
<th>T/MODULE TEMPERATURES °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>32°C</td>
</tr>
<tr>
<td>38.9</td>
</tr>
<tr>
<td>37.2</td>
</tr>
<tr>
<td>35.0</td>
</tr>
<tr>
<td>34.4</td>
</tr>
</tbody>
</table>
The module average electrical efficiency ($\eta_e$) as determined by:

$$\eta_e = \frac{\int P_{\text{max}} \, d\theta}{\int L \, Ad \theta}$$

where

- $\theta$ = time
- $L$ = total intensity
- $A$ = module area
- $P_{\text{max}}$ = maximum power

The $\eta_e$ values for the tests are presented in Figure 5-10. Also shown is the $\eta_e$ without water cooling and the expected $\eta_e$ for other air temperatures assuming the calculated change in $\eta_e$ of 0.038%/°C change in average air temperature. On a hot summer day (35°C average air temperature), $\eta_e$ would be about 5.2% for the normal field installation (air cooling only). With 23°C (75°F) and 15°C (60°F) water, power generation on this same hot day could be increased 16.0% ($\eta_e = 6.03\%$) and 20.8% ($\eta_e = 6.28\%$), respectively. Even with 32.2°C (90°F) water, power generation would improve 11.0% (5.77% compared to 5.2%) on the summer-type day.

If not already available, pumping power will consume most or all of the improvement in power production. Therefore, while each application must be treated separately, cooling with water is not expected to be cost-effective unless the application already involves the pumping of water or unless a gravity water feed system is possible. Assuming either of the latter conditions exists, the one-time plumbing cost will not be a significant cost factor; and the cost of a module should not be increased significantly by building into the module substrate the cooling channels or the provision for bonding/inserting copper cooling tubes (which could be optional).

**Electrical Performance of a Combined Photovoltaic and Solar Water Heating Module**

Absorber area requirements for heating water or some other fluid for home space and hot water heating are very large. For example, Reference 4 shows that locally the solar absorber area required for an average home is 400 sq. ft. This same home in the high desert of California requires 750 sq. ft. of absorber area. Solar House 1 at Fort Collins, Colorado (Reference 5) uses all the south facing roof area (768 ft²) for solar collector area. Therefore, there will be many locales where there is not sufficient south-facing residential roof space available for both photovoltaic and solar heating modules.

Since solar cells have a solar absorptance as good as the average black absorber, the cells can replace the black coating of the solar water heater without affecting significantly its heating characteristics.
Figure 5-10. Electrical Efficiency of a Water-Cooled Flat Plate Photovoltaic Module
However, the electrical performance is significantly degraded by the one to two glass layers covering the absorber plate to minimize the front thermal losses. Tests were performed to evaluate this expected reduction in electrical efficiency that will result from the marriage of a photovoltaic and solar heating module.

**Test Configuration:** Figure 5-11 illustrates the combined module. The Spectrolab Block I module used previously for the water cooling tests was surrounded on the backside by three inches of Foamglas insulation. The Foamglas is an excellent insulator and has structural characteristics allowing it to be machined to the desired configuration. Double strength window glass 0.125 inches thick was used for the glazing. Separation distance between the glass and the photovoltaic module (single glass configuration) was 1/2 inch.

The module was mounted in an east-west direction to minimize shadowing of the cells. The active side of the module was normal to the sun at solar noon. Water flow was from east to west at 15.1 ± 3 liters/hr. This flow rate corresponds to 4.5 gal/hr-ft² of absorber area and is about three times that commonly used in solar water collectors. The test flow rate was the lower practical limit for the circulation equipment and minimized the electrical mismatch losses due to different cell temperatures. Cell temperature differences of up to 7°C (cell near the water inlet compared to a cell at the water outlet) can be expected at the lower flow rate. The higher test flow rate cut this difference in half. In an actual system, the pump requirements will dictate the more common lower flow rate and an additional 1% to 2% decrease in photovoltaic power is probable.

Three tests were made. The first test was with a single glass; the water temperature increased linearly to 130°F (54°C) by 1400 PST. Test two was for a double glass configuration and had approximately the same water temperature profile. In the third test, also with the double glass, an electrical heater was turned on at 10:45 PST to simulate a slightly higher temperature system. The final water temperature reached was 148°F (64.4°C).

**Test Results:** Figure 5-12 presents cell temperature as a function of time for the three tests just described plus the cell temperature for this same photovoltaic module in a normal field installation with air cooling only. Cell temperatures for the first half of the morning for the combined configuration are not too different and on occasion may be lower than the air-cooled-only configuration depending on the initial temperature of the storage water. By mid- or late morning, the cell temperature for the combined configuration exceeds and remains significantly warmer throughout the afternoon than the air-cooled-only configuration, whose temperature actually decreases significantly during this period. Since power decreases at a rate of 0.4%/°C increase in cell temperature (for this module) the higher module temperatures, especially in the afternoon, contribute significantly to lessening the electrical performance.

Figure 5-13 presents the electrical efficiency $\eta_\varepsilon$ as a function of time for the same tests and the corresponding cell temperatures presented in Figure 5-11 ($\eta_\varepsilon$ is as defined previously.)
Figure 5-11. Combined Module Configuration
Figure 5-12. Solar Cell Temperature Versus Time of day for Photovoltaic Only and Combined Photovoltaic/Solar Water Heating Collectors
Figure 5-13. Electrical Efficiency Versus Time of Day for Photovoltaic Only and Combined Photovoltaic/Thermal Collectors (Based on Photovoltaic Module Area.)
Table 5-10 summarizes $\eta_e$ for an 8-hour operating period as well as the solar noon measurements. To obtain the 8-hour average it was necessary to extrapolate the curves in Figure 5-13. The $\eta_e$ of the photovoltaic module alone was assumed to be the same in the morning as measured in the afternoon. Analysis indicates this to be approximately true, but generally, the efficiency will be slightly higher in the morning because of cooler air temperatures. The effect of a single glass and double glass and the effect of the higher afternoon water temperatures on $\eta_e$ are illustrated in Table 5-10. Table 5-10 also shows that $\eta_e$ for the noon hour is less than the daily average for the photovoltaic module alone but greater than the 8-hour daily average for the combined configurations. Compared to the daily average, the noon average performance predicts a higher performance by 2%, 7% and 9% for the single and two double glass configurations respectively, and a 2% lower performance for the photovoltaic-only module.

The purpose of the last two tests was to estimate the change in $\eta_e$ for a change in water storage temperature. The comparison was not as ideal as desired because of the different initial water storage temperatures. However, assuming the morning $\eta_e$ to be the same and basing the change on only the change in afternoon performance gives a minimum but representative value of the actual. Therefore, the minimum change in daily electrical performance for a change in water storage temperature ($\Delta \eta_e / \Delta T$ STR.) is estimated at 0.014%/°C for the double glass configuration. Figure 5-14 graphically illustrates this effect. A 50% reduction in $\eta_e$ (compared to the photovoltaic module alone) would be approached with a combined module and 100°C fluid storage (as occurs for Solar House 1).

The danger of a loss of flow rate is a concern with this type of a combined module, and a test was made to illustrate this effect.

Table 5-10. Electrical Efficiency of Photovoltaic Only and Combined Photovoltaic/Thermal Collectors

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Photov. Only</th>
<th>Single Glass</th>
<th>Double Glass Water Storage 55.6°C</th>
<th>Double Glass Water Storage 64.4°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>5.49</td>
<td>4.64</td>
<td>3.72</td>
<td>3.85</td>
</tr>
<tr>
<td>Afternoon</td>
<td>5.49</td>
<td>4.32</td>
<td>3.34</td>
<td>3.10</td>
</tr>
<tr>
<td>Daily</td>
<td>5.49</td>
<td>4.48</td>
<td>3.53</td>
<td>3.48</td>
</tr>
<tr>
<td>Noon</td>
<td>5.37</td>
<td>4.58</td>
<td>3.78</td>
<td>3.78</td>
</tr>
</tbody>
</table>
Figure 5-14. The Effect of Water Storage Temperature on the Electrical Efficiency of a Combined Photovoltaic-Thermal Collector
Additional heat was added to the storage water and the cell temperature was elevated to 75.6°C by 11:00 PST, at which time the flow was stopped. The cell temperature continued to increase to a maximum of 91.1°C at 12:30 PST. This temperature is not a concern. However, such a failure on a hot day and with a thermally more efficient system would result in cell temperatures greater than 100°C and perhaps as high as 130°C. New material problems may begin to show up at this latter temperature.

Cost Effectiveness: Table 5-11 is a $/watt summary formulated from the preceding efficiencies and 1980 and 1986 photovoltaic module cost goals. The optimistic estimates assume all non-cell related costs are absorbed by the solar water heating module. Sometime in the 1980 to 1984 time period the marriage configurations will be cost effective in remote applications. Beginning in 1985, the combined module for moderate storage temperatures could reduce the cost per watt to less than 50¢/watt. For residential applications the combined module will be most desirable. Using the current LSSA price goals and assumptions shown in Table 5-8, the relationship of projected implementation cost and system benefit versus module cost ($/watt) for several improvements in optical transmission efficiency is shown in Figure 5-10. Referring to Figure 5-9, a 2% efficiency improvement is achieved by the use of low-iron glass, a 5% improvement by the use of water-white glass and an 8% improvement by water-white glass with an anti-reflective coating on the outer surface. These improvements are above an 86% solar transmission efficiency of 1/8 inch standard window glass.

Clearly, all three optical transmission efficiency improvements are cost-effective today. As shown on Figure 5-10, the 2% improvement meets a breakeven point at approximately $2/watt and the 5% improvement is cost effective until roughly $1/watt. The 8% improvement is cost effective for all LSSA price goals.

Table 5-11. Preliminary Economic Implications of Combined Collectors

<table>
<thead>
<tr>
<th>Collector Configuration</th>
<th>Water Exit Temp (°C)</th>
<th>1982 Cost ($/Watt)</th>
<th>1986 Cost ($/Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cells</td>
<td>Sub</td>
</tr>
<tr>
<td>PV Only</td>
<td>-</td>
<td>1.80</td>
<td>0.20</td>
</tr>
<tr>
<td>Combined (Single Glass)</td>
<td>60</td>
<td>2.21</td>
<td>0</td>
</tr>
<tr>
<td>Combined (Double Glass)</td>
<td>60</td>
<td>2.45</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2.70</td>
<td>0</td>
</tr>
</tbody>
</table>
To meet the LSSA project dollar-per-watt goals, the major emphasis has been on reducing silicon, cell processing, and encapsulation costs. An additional approach is to improve module efficiency and/or dollar-per-watt cost by optimizing the module design. To establish an optimum module requires an evaluation of design features from a cost-to-implement versus system benefit viewpoint. A beneficial design trade is defined as one where the incremental benefit is larger than the incremental expense, i.e. the incremental change in the total system cost is negative. This can be expressed mathematically as

\[
\frac{\partial C_T}{\partial \text{(Design Parameters)}} \leq 0
\]

\(C_T\) is the total system life-cycle cost directly associated with the purchase, installation, support and maintenance of a photovoltaic module. Example costs include the module itself, mounting hardware, installation labor, support structure cost, land costs, and any other cost which will change when a module design parameter is changed.

For convenience in conducting subsequent optimization analyses the total system cost was broken down mathematically as follows:

\[
C_T = \text{MODULE COST + OTHER SYSTEM COST PER MODULE}
\]

\[
C_T = \frac{\eta P}{\eta M} \left[ \frac{1}{\eta P} \left( \frac{C_F}{A_M} + C_A \right) \right] + \frac{CMD}{\eta M}
\]

(1)

where:

- \(C_T\) = TOTAL MODULE DEPENDENT SYSTEM COST ($/kW)
- \(C_C\) = CELL-RELATED COST PER MODULE ($/M^2\) OF CELL
- \(C_F\) = FIXED COST PER MODULE ($)
- \(C_A\) = AREA-RELATED COST PER MODULE ($/M^2\) OF MOD
- \(CMD\) = SYSTEM COST DIRECTLY PROPORTIONAL TO TOTAL MODULE AREA OR NUMBER OF MODULES, LESS MODULE COST ($/M^2\) OF MOD
- \(A_M\) = MODULE AREA ($M^2$)
Various cost/benefit relationships can be derived by appropriately differentiating Equation (1) with respect to the design variable of interest. Doing this leads to the following cost/benefit relationships:

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Benefit Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL EFFICIENCY</td>
<td>( \Delta C_C \leq \frac{\Delta \eta_C}{\eta_C} (C_T \eta_{EC}) ) (2)</td>
</tr>
<tr>
<td>CELL MISMATCH</td>
<td>( \Delta C_C \leq \frac{\Delta \eta_{MIS}}{\eta_{MIS}} (C_T \eta_{EC}) ) (3)</td>
</tr>
<tr>
<td>OPTICAL TRANSMISSION</td>
<td>( \Delta C_A \leq \frac{\Delta \eta_T}{\eta_T} (C_T \eta_M) ) (4)</td>
</tr>
<tr>
<td>OPERATING TEMPERATURE</td>
<td>( \Delta C_A \leq \frac{\Delta \eta_{NOCT}}{\eta_{NOCT}} (C_T \eta_M) ) (5)</td>
</tr>
<tr>
<td>CELL SHAPE</td>
<td>( \Delta C_C \leq \frac{\Delta \eta_N \eta_B}{\eta_B \eta_N} (\frac{C_F}{A_M} + \frac{C_A + C_M}{C_{NOCT}}) ) (6)</td>
</tr>
<tr>
<td>BORDER/BUS AREA</td>
<td>( \Delta C_F \leq \frac{\Delta \eta_B}{\eta_B} (C_F + C_{AA} + C_{MD}) ) (7)</td>
</tr>
</tbody>
</table>

WHERE:

\( \eta_M = \text{OVERALL MODULE EFFICIENCY AT 100 mW/cm}^2, \text{ NOCT} \)
\( = \eta_p \times \eta_{NOCT} \times \eta_{EC} \)
\( \eta_p = \text{MODULE PACKING EFFICIENCY} = \eta_B \times \eta_N \)
\( \eta_B = \text{MODULE BORDER/BUS/INTERCONNECT AREA EFFICIENCY} \)
\( \eta_N = \text{CELL NESTING EFFICIENCY} \)
\( \eta_{NOCT} = \text{NOMINAL OPERATING CELL TEMPERATURE EFFICIENCY} \)
\( \eta_{EC} = \text{ENCAPSULATED CELL EFFICIENCY AT 100mW/cm}^2, \text{ 28°C} \)
\[ \eta_{\text{C}} = \text{BARE CELL EFFICIENCY (100 mW/cm}^2, 28^\circ \text{C)} \]

\[ \eta_{\text{T}} = \text{OPTICAL TRANSMISSION EFFICIENCY} \]

\[ \eta_{\text{MIS}} = \text{ELECTRICAL MISMATCH/SERIES RESISTANCE EFFICIENCY} \]

Detail on the above efficiency definitions is included in Reference (7). Discussion of the nominal operating cell temperature (NOCT) is given in Section 5B of this report and in Reference (8).

**HEXAGON AND SQUARE CELL COST/BENEFIT RELATIONSHIPS**

One relationship of current interest is the cost/benefit for improved cell nesting by shaping round cells into hexagons or squares. Figure 5-15 shows examples of shaped hexagon and square cells. Clearly, an improvement in cell nesting reduces the encapsulant and system area-related costs and will lower the dollar-per-watt system cost if the feature provides a positive cost/benefit.

Analysis of the circular/shaped-cell tradeoff requires the cost/benefit relationship defined previously as Equation (6) and reproduced here:

\[
\Delta C_\text{c} \leq \frac{\Delta \eta N}{\eta N \eta P} \left( \frac{C_F}{A_M} + C_A + C_M D \right)
\]

**WHERE:**

\[ \Delta C_\text{c} = \text{INCREMENTAL COST OF SHAPING THE CELLS ($/M}^2 \text{ OF CELL)} \]

\[ \Delta \eta N = \text{CHANGE IN CELL NESTING EFFICIENCY FOR SHAPED CELLS} \]

\[ \eta N = \text{ROUND CELL NESTING EFFICIENCY} \]

\[ \eta P = \text{PACKING EFFICIENCY OF ROUND CELL MODULE} \]

\[ C_F = \text{MODULE FIXED COST, NON-AREA RELATED ($)} \]

\[ C_A = \text{MODULE AREA-RELATED COSTS ($/M}^2 \text{ MODULE)} \]

\[ C_M D = \text{SYSTEM AREA-RELATED COSTS ($/M}^2 \text{ MODULE)} \]

\[ A_M = \text{MODULE AREA (M}^2) \]
Figure 5-15. Modified Hexagon and Square All Shapes
To be cost effective, the incremental cost of shaping the cells, \((ΔC_0)\), must be less than the system benefit accrued from the improved nesting, and defined by the right-hand side of the above equation. Before the above relationship could be applied, the incremental cost of shaping the cells had to be determined.

To determine the cost differential between circular and shaped cells, a detailed list of the processing steps was compiled for each, taking advantage of reduced metallization requirements, junction cleaning requirements, silicon salvage value, etc. The costs shown on Table 5-12 are a compilation of contractor and JPL estimates for the listed cell processing steps. Obviously, the major cell processing costs are in the silicon, ingot growth and round wafer slicing steps. Any anticipated savings attributed to combining laser wafer cutting with cleaning the junction are not realized, since the cost to shape a cell is approximately the same as to clean the junction on a round cell. Another potential saving is to salvage the silicon. In order to salvage the cut-off wafer pieces, the junction must be etched away. As shown in Table 5-12, the cost to reclaim the silicon is about the same as the salvage value, at a silicon value of $25/Kg. However, a minor cost saving is realized for shaping cells due to less metallization.

The conclusion from Table 5-12 is that the cost per square meter of circular wafer is nearly equal for circular or shaped solar cells. The cost per square meter of finished cell is therefore inversely proportional to the final area of the cell. A modified hex cell with 10% less area than a circular cell will thus cost 10% more per square meter of finished cell.

The following is an example of a shaped cell cost/benefit tradeoff for a pure hexagonal cell assuming 1977 costs:

\[
\begin{align*}
C_F &= \text{Module fixed cost, non-area related} \\
&= $3 \\
C_A &= \text{Module area related costs} \\
&= $64/m^2 \\
C_{MD} &= \text{System area related costs} \\
&= $36/m^2 \\
A_M &= \text{Module area} \\
&= 1.44m^2 \\
\eta_N &= \text{Round cell nesting efficiency} \\
&= .853 \\
\Delta\eta_N &= \text{Change in cell nesting efficiency} \\
&= .0867 \\
\eta_P &= \text{Packing efficiency of baseline circular-cell module} \\
&= .864 \\
\end{align*}
\]
Table 5-12. Typical Round Cell Versus Hex Cell Cost Breakdown for the 1982 Timeframe

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Round Cell</th>
<th>Hex Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon*</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Ingot Growth and Crop</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>Centerless Grind</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Slice</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Surface Prep/Clean</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Junction Formation</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Junction Cleaning/Etch</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Wafer Shaping</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Metallization</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>AR Coating</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Reclaim Silicon</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Silicon Salvage</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>Total Cost Per Wafer</td>
<td>211</td>
<td>208</td>
</tr>
</tbody>
</table>

*0.010 in. Thick Cell
Therefore:

\[ C_o = \frac{\Delta \eta_N}{\eta_N} \frac{1}{P} \left( \frac{C_F}{A_M} + \frac{CA + C_{MD}}{1.44} \right) \]

\[ = \frac{0.867}{0.853} \times 1 \frac{1}{0.864} \left( \frac{3}{1.44} + 64 + 36 \right) \]

\[ = \$12/m^2 \text{ of module} \]

This benefit value, \$12/m^2, is now compared with the increased area related cost (\$/m^2 of cell) of a 60° hex cell.

As established previously, the cost to manufacture a 60° hex and a round cell from the same wafer size is essentially the same; however, there is a significant difference in the cell area and power. If the 1977 round cell cost is \$1,000/m^2, then the increased cost for a true hex cell is:

\[ \Delta \text{Hex.} = 0.211 \text{ C_{cir.}} \]

\[ = 0.211 \times (1,000) \]

\[ = \$211/m^2 \]

Therefore, the 60° hex cell is not cost effective at this time, since the benefit is \$12/m^2 and the cost is \$211/m^2.

Using the current LSSA price goals with encapsulation cost modifications, the relationship of projected cost and system benefit versus module cost (\$/watt) for hex and modified hex cells are shown in Figure 5-16. Referring to Figure 5-16 a true hex cell will not be cost effective, a 45° modified hex is cost-effective at around \$60/m^2 of cell, and a 30° modified hex cell is cost effective at \$130/m^2 of cell.

Using the current LSSA price goals with encapsulation cost modifications, the relationship of projected cost and system benefit versus cell cost (\$/m^2 of cell) for modified square cells is shown in Figure 5-17. Referring to Figure 5-17, 40°, 70° or 90° modified squares will not be cost effective.

Clearly, the break-even point values shown in Figures 5-16 and 5-17 will change if encapsulation and system area-related goals are not achieved. Also, there is some indication that modified shapes may provide a higher efficiency since the center portion of the cell is more efficient. If so, the break-even points for modified cell shapes will change. This concept is the basis of a current study.
Figure 5-16. Cell Shaping Cost Versus System Benefit for Various Degrees of Hexagonal Shaping
Figure 5-17. Cell Shaping Cost Versus System Benefit for Various Degrees of Square Shaping
Optical Transmission Cost/Benefit Relationship

An additional approach to improve module efficiency and/or dollar-per-watt is the cost/benefit for an improvement in optical transmission through the front surface encapsulant. An improvement in optical transmission efficiency is directly related to module efficiency and therefore, to a lower dollar-per-watt system cost.

Using Equation (4) the system benefit for optical transmission improvement is:

\[ \Delta C_A \leq \frac{\Delta \eta T}{\eta T \cdot \eta_M} (C_T \cdot \eta_M) \]

where:

- \( \Delta C_A \) = Incremental cost of transmission improvement ($/m^2 of module)
- \( \Delta \eta T \) = Change in optical transmission efficiency
- \( C_T \) = Total module-related cost ($/kw module)
- \( \eta_M \) = Module efficiency
- \( \eta_T \) = Optical transmission efficiency

To be cost effective the system benefit should be greater than the cost to implement the design feature.

The following is an example of an optical transmission cost/benefit tradeoff:

Assume:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module costs</td>
<td>$7,000/kw</td>
</tr>
<tr>
<td>System costs</td>
<td>$360/kw</td>
</tr>
<tr>
<td>( C_T ) Total module-related costs</td>
<td>$7,360/kw</td>
</tr>
<tr>
<td>( \eta_M ) Module efficiency</td>
<td>9%</td>
</tr>
<tr>
<td>( \eta_T ) Optical transmission efficiency</td>
<td>85% (The basic design uses standard float glass)</td>
</tr>
<tr>
<td>( \Delta \eta T ) Change in optical transmission efficiency through the use of low-iron water-white glass</td>
<td>5%</td>
</tr>
</tbody>
</table>
Therefore:

\[
\Delta C_A = \frac{\Delta \eta T}{\eta T} (C_T \eta m)
\]

\[
= .05 \times (7,360 \times .09) / .85
\]

\[= \$39/m^2 \text{ of module}
\]

This benefit value is now compared with the additional cost for low-iron water-white and tempered glass. If 1/8 inch annealed glass is \$0.33/FT^2 (\$3.6/m^2) and 1/8 inch low-iron water-white tempered glass is \$1.16/FT^2 (\$12.5/m^2) then the additional cost for the design feature is \$0.83/FT^2 (\$8.9/m^2). Therefore the cost to implement, \$8.9/m^2, is less than the system benefit, \$39/m^2, and the feature becomes cost effective.

Using the current LSSA price goals and assumptions, shown in Table 5-13, the relationship of projected implementation cost and system benefit versus module cost (\$/watt) for several improvements in optical transmission efficiency is shown in Figure 5-16. Referring to Figure 5-16, a 2% efficiency improvement is achieved by the use of low-iron glass, a 5% improvement by the use of water-white glass and an 8% improvement by water-white glass with an antireflective coating on the outer surface. These improvements are above an 86% solar transmission efficiency of 1/8 inch standard window glass.

Clearly, all three optical transmission efficiency improvements are cost effective today. As shown in Figure 5-16, the 2% improvement meets a break-even point at approximately \$2/watt and the 5% improvement is cost effective until roughly \$1/watt. The 8% improvement is cost effective for all LSSA price goals.
Table 5-13. Module Cost Goals and Assumptions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$/kw (Module)</td>
<td>7,000</td>
<td>4,000</td>
<td>2,000</td>
<td>1,000</td>
</tr>
<tr>
<td>$/kw (System)</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Total $/kw</td>
<td>7,360</td>
<td>4,360</td>
<td>2,360</td>
<td>1,360</td>
</tr>
<tr>
<td>Encapsulated Cell Eff.</td>
<td>.13</td>
<td>.14</td>
<td>.15</td>
<td>.15</td>
</tr>
<tr>
<td>Packing Efficiency</td>
<td>.75</td>
<td>.78</td>
<td>.80</td>
<td>.85</td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>.098</td>
<td>.109</td>
<td>.120</td>
<td>.128</td>
</tr>
</tbody>
</table>
Figure 5-18. Cost of Optical Transmission Improvements Versus System Benefits
SECTION VI
OPERATIONS AREA

A. SUMMARY OF PROGRESS

1. Large-Scale Production (LSP) Task

   a. Block II. Module deliveries for the quarter ending September, 1977, totaled 33.4 kW, off 14.9 kW from the deliveries the preceding quarter. This decrease resulted from one supplier completing delivery the preceding quarter, and from completion of deliveries to the agricultural pumping project. A summary of the deliveries for the four contractors involved is shown in the table below. Solarex Corporation completed delivery of its modules during this quarter.

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Total to be Delivered kW</th>
<th>July-Sept. Shipped kW</th>
<th>Total Shipped through Sept. kW</th>
<th>Complete %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Technology, Inc.</td>
<td>40</td>
<td>18.8</td>
<td>38.2</td>
<td>95.5</td>
</tr>
<tr>
<td>Solar Power Corp.</td>
<td>15</td>
<td>0</td>
<td>15.0</td>
<td>100</td>
</tr>
<tr>
<td>Solarex Corporation</td>
<td>30</td>
<td>11.7</td>
<td>30.0</td>
<td>100</td>
</tr>
<tr>
<td>Spectrolab, Inc.</td>
<td>40</td>
<td>2.9</td>
<td>3.6</td>
<td>9.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>125</strong></td>
<td><strong>33.4</strong></td>
<td><strong>86.8</strong></td>
<td><strong>69.4</strong></td>
</tr>
</tbody>
</table>

Numerous apparent module defects continued to crop up during the production runs, and are a cause for concern since there is no accepted body of knowledge that defines the consequences of the apparent defects. The inspection and rejection criteria applied to these defects had been selected to apply bounds to encourage the contractor to minimize the occurrence of defects without significantly increasing the cost of the modules. Among the defects which still resulted in rejections were the delamination of the encapsulant from substrate, cells, and terminals; the inclusion of bubbles in the encapsulant; and cells that were cracked or include severe edge defects. In the case of one contractor, a design change was incorporated to alleviate the development of cracks in cells which are parallel to the longitudinal axis of the module.

Observations regarding production continued to be much as reported for the last quarter.

(1) Scheduling remained an uncertain venture.
(2) Module delivery was not steady; quantities fluctuated from week to week.

(3) Production was still subjected to 100% source inspection.

b. Block III. The request for proposals to supply 100 kW to 200 kW of solar cell modules under the Block III procurement action was issued July 14. The solicitation was limited to those potential contractors having certain defined experience in making modules meeting the specifications extant for Block II. Eight responses were received by the closing date for receipt of proposals, August 9, and the bids were subjected to a formal review and allocation process which will result in awards to be made known in October.

2. Environmental Testing

Activity continued at a high level this quarter with the testing of Block II production samples and three sets of Task 4 developmental modules. Flashing and inspection of the Engineering Area's minimodules also started.

Characterization tests of Block II modules were performed with one cell partially shadowed. Such shadowing is roughly equivalent to certain cell cracks, mismatched cells in a module, or dirt accumulation over a small portion of a module. The effect on power output varied from mild to severe depending on the module type. In the most severe case, total power output of the module was nearly inversely proportional to the percent of shadowing of only one cell.

a. Large Scale Production (Task 5) Modules. Results of the environmental qualification tests for production samples are given in the technical data section below. Temperature cycling caused serious cell cracking in most of the Manufacturer "V" modules, and qualification tests for this manufacturer were discontinued after sample #20. These tests will be resumed after corrective design changes have been implemented. Qualification tests of several varieties of modules with glass covers from this manufacturer were also completed.

Qualification tests began for a subarray of modules from Manufacturer "W" which incorporate an improved printed cell contact.

b. Task 4 Developmental Modules

Three of the five Task 4 suppliers which delivered modules to JPL completed qual test. These data are shown in the technical data section which follows this summary. All modules passed the test functionally (power output degradation < 5%), but some cases of cell cracking and encapsulant delamination did occur.
c. **Cell Tests.** Humidity and temperature cycling tests on Manufacturer "W" evaporated contact cells were completed. This work is documented in JPL Document 5101-42. These contacts showed good adhesion. Additional tests of a less expensive, improved printed contact from this manufacturer were planned for next quarter.


d. **Field Testing.** During this quarter most of the work required to enlarge the JPL site from 15 stands to 33 was completed, including construction of the concrete wireway trenches, installation of the stands, installation of the conduits and wireways, and installation of the multiplexer (MUX) boxes. The wiring from the data system to the new MUX boxes is to be completed when the allocation of the stands for specific modules is defined.

The installation of these 18 stands marked the completion of the stand installation at the three current sites. The complement at Table Mountain and Goldstone were already increased to eight. The final four were added at the Table Mountain Site in June and at Goldstone in July.

Official approval to establish a seaside site at the Coast Guard facility at Point Vicente was received at the end of the quarter. A work order was placed with Facilities and final arrangements for the installation of the stands (which have already been procured) were to be made in early October. It was anticipated that the stands would be installed in November.

By the end of the quarter all of the modules, except the Block II Spectrolab Modules, were deployed at the three current sites. The following table summarizes their deployment:

<table>
<thead>
<tr>
<th></th>
<th>JPL</th>
<th>Table Mountain</th>
<th>Goldstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Tech</td>
<td>58</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Spectrolab</td>
<td>39</td>
<td>4*</td>
<td>18</td>
</tr>
<tr>
<td>Solarex</td>
<td>35</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Solar Power</td>
<td>14</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>146</td>
<td>68</td>
<td>46</td>
</tr>
</tbody>
</table>

*Preproduction
As of the end of the quarter, the data system and specifically the dynamic load was still not functioning properly. However, the problem with the dynamic load had been isolated and a total solution was expected shortly. Meanwhile, progress was made in the supporting software. The routines for the acquisition part of the dedicated mode were completed; this software will automatically bring in data daily and store the data from all the modules, reference cells, pyranometers and weather instrumentation. The companion software for the data handling, correcting, comparing, and final storage was concurrently being developed. Several stand-alone diagnostic programs were written. These include programs for testing all the DORIC channels, the dynamic load channels, and the operation of the reference cell relays, for comparing the pyranometers and the reference cells, for comparing the dynamic load short circuit current with an independent DORIC short circuit current, and for determining the dynamic load repeatability. These programs had been and were to be very useful in the future for pinpointing problems and determining system accuracies.

3. Performance Measurements and Standards

The primary effort in the last quarter was directed to the silicon instability problem. This effect can be briefly described as a change in short circuit current induced by exposure to solar or ambient illumination. Under high intensity illumination, (approximately 100 mW/cm²), the change can be induced in a few minutes whereas ambient room light requires hours of exposure to induce this effect. In the absence of illumination the short circuit current recovers to its initial condition in times of hours to a few days. A test program was initiated to determine the degree of the effect for all vendors in the Large Scale Procurement Task since its inception. The results of this test program to date are summarized as follows:

(1) Cells and modules supplied by Spectrolab and Solarex do not exhibit the effect to a statistically significant degree.

(2) All Solar Power cells and modules exhibit an initial increase in short circuit current of approximately 5% to 10% which returns to the original value after 24 hours of dark storage.

(3) Some Sensor Tech cells and modules exhibit an initial decrease in short circuit current of approximately 5% to 10% which returns to the original value after 24 hours of dark storage.

(4) Preliminary indications in both of the above cases are that the problem can be reduced or eliminated by choosing different silicon wafer suppliers.

Due to the silicon instabilities discussed above, shifts in vendors' red/blue ratios, and the change to the new international pyrheliometric reference scale (IPRS), the standard reference cells to be used in the Block III procurement were to be new cells fabricated by LeRC and distributed to the manufacturers by JPL. Any resulting differences in measured module output power due to the change of reference cells were to
be determined by JPL for subsequent negotiation with each manufacturer. It was anticipated that the new reference cells would result in an apparent drop of module output power of 1.5% to 4.5% for the reasons previously stated.

4. Failure Analysis

Sixty Problem/Failure Reports (P/FRs) were filed during the quarter and 46 were closed out. The most significant closures concerned Manufacturer "V" Block II modules which were suffering cracked cells due to differential thermal expansion of encapsulant under the cells; a design modification was being implemented to correct this problem. Final closure of the P/FR's for four Block I modules returned from the water purification system at MERADCOM were also completed; the design problems which caused these failures were corrected for Block II production.

Two additional Manufacturer "Z" Block I modules were returned from the same MERADCOM application with evidence of severe cell overheating, encapsulant delamination, and cell cracking. Efforts were underway to reconstruct the failure sequence in order to determine the underlying cause.

Three developmental modules from Task 4 environmentally tested by the manufacturer suffered cracked cells and severe degradation of power output. High priority was being given this investigation.

Further details on problem/failure analysis status and progress is given in the technical data section which follows.

B. EXPANDED TECHNICAL REPORT

1. Environmental Testing

Table 6-1 summarizes environmental test results for the quarter for Large-Scale Production (Task 5) modules. Table 6-2 gives similar data for Automated Array (Task 4) developmental modules.

2. Failure Analysis

The P/FR system during this quarter had 60 new inputs and 46 closures. Table 6-3 summarizes the activity for Task 4 and Blocks I and II of Task 5 module testing and application experience. Table 6-4 shows the problem category for the problem/failures reported in Table 6-3.

a. Manufacturer "V". Analysis of a Block I module returned from the USDA insect survey trap application showed an open circuit caused by an unsoldered interconnect to the bottom of one cell. This was the second such module failure caused by unsoldered interconnects.

As reported in the last quarter, Block II modules were found to be developing cracked cells after temperature cycling because of differential
<table>
<thead>
<tr>
<th>Vendor</th>
<th>Number Modules</th>
<th>Type</th>
<th>Test</th>
<th>Elect. Degrad.</th>
<th>Physical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>12</td>
<td>1 kW samples</td>
<td>Qual.</td>
<td>1 5-10%</td>
<td>All mdls. had cracked cells after temp cycling, many were severe. 22nd and 31st kW samples had power below min.</td>
</tr>
<tr>
<td>V</td>
<td>8</td>
<td>Glass Cover</td>
<td>Qual, mech. int. &amp; hum. in reverse order</td>
<td>OK</td>
<td>Some delamination in all modules occurring at cells, corners, and at terminals. Discoloration, some mdls. No cracked cells.</td>
</tr>
<tr>
<td>V</td>
<td>4</td>
<td>.020 Al. Sht.</td>
<td>Qual</td>
<td>OK</td>
<td>1 cracked cell. 2 mdls. had some delam.</td>
</tr>
<tr>
<td>V</td>
<td>3</td>
<td>Filled Grooves</td>
<td>Qual</td>
<td>OK</td>
<td>1 cracked cell. Filler yellows. Some delam.</td>
</tr>
<tr>
<td>V</td>
<td>3</td>
<td>.040, .060 &amp; .070 cover glass</td>
<td>Qual</td>
<td>1 5%</td>
<td>Delamination at cells No cracks.</td>
</tr>
<tr>
<td>V</td>
<td>2</td>
<td>Sandblasted terminals</td>
<td>Qual</td>
<td>OK</td>
<td>No delam. One crack, each module.</td>
</tr>
<tr>
<td>W</td>
<td>3</td>
<td>G, printed contact, Proc. B</td>
<td>50 temp. cycles</td>
<td>2 OK</td>
<td>One cracked cell</td>
</tr>
</tbody>
</table>
Table 6-1. Results of Task 5 Module Testing. July-Sept., 1977
(Continuation 1)

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Number Modules</th>
<th>Type</th>
<th>Test</th>
<th>Results</th>
<th>Physical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>12</td>
<td>1 kW samples</td>
<td>50 temp. cycles</td>
<td>OK</td>
<td>None</td>
</tr>
<tr>
<td>Z</td>
<td>15</td>
<td>1 kW samples</td>
<td>Qual.</td>
<td>14/OK</td>
<td>Minor surf. coat splitting. Top coat delamination, sometimes serious. Corrosion or discin on 3 mdls. Also, 3 with cracked cells.</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>Qual.</td>
<td>OK</td>
<td>Cell cracks, 2 mdls. (3 cracks)</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>5</td>
<td>Qual. by vendor</td>
<td>3 lo pwr</td>
<td>2/OK</td>
<td>Cell cracks in 3 lo pwr mdls (5 cracks total)</td>
</tr>
<tr>
<td>S</td>
<td>4</td>
<td>Qual.</td>
<td>OK</td>
<td>Delamination. Some cell discoloration</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>6</td>
<td>Qual. by vendor</td>
<td>OK</td>
<td>Delam. &amp; cracking of encap.</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td>Evap. contacts</td>
<td>Qual.</td>
<td>OK</td>
<td>Delam. at cells</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td>Print. contacts</td>
<td>Qual.</td>
<td>OK</td>
<td>Satisfactory</td>
</tr>
</tbody>
</table>
Table 6-2. Module Testing - Task 4 July - Sept, 1977 Results

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Number of Modules</th>
<th>Type</th>
<th>Test</th>
<th>Electrical Degradation</th>
<th>Physical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>4</td>
<td>Qual</td>
<td>OK</td>
<td></td>
<td>Cell cracks, 2 mdls. (3 cracks)</td>
</tr>
<tr>
<td>R</td>
<td>5</td>
<td>Qual by vendor</td>
<td>2 OK</td>
<td>3 lo pwr</td>
<td>Cell cracks in 3 lo pwr mdls. (5 cracks total)</td>
</tr>
<tr>
<td>S</td>
<td>4</td>
<td>Qual</td>
<td>OK</td>
<td></td>
<td>Delamination. Some cell discoloration</td>
</tr>
<tr>
<td>S</td>
<td>6</td>
<td>Qual by vendor</td>
<td>OK</td>
<td></td>
<td>Delam &amp; cracking of encap.</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td>Evap. contacts</td>
<td>Qual</td>
<td>OK</td>
<td>Delam at cells</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td>Print. contacts</td>
<td>Qual</td>
<td>OK</td>
<td>Satisfactory</td>
</tr>
</tbody>
</table>
### Table 6-3. Summary of P/FR Activity

<table>
<thead>
<tr>
<th>Manuf.</th>
<th>Procurement</th>
<th>New P/FRs</th>
<th>Closed P/FRs</th>
<th>Env Test</th>
<th>Field Test</th>
<th>Application Centers</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Block I</td>
<td>2</td>
<td>4</td>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>30</td>
<td>31</td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Block I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Block I</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Block I</td>
<td>3</td>
<td>2</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>T4</td>
<td>6</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>T4</td>
<td>3</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
Table 6-3. Breakdown of P/FR Problem Categories

<table>
<thead>
<tr>
<th>Manuf. Proc.</th>
<th>Electrical</th>
<th>Mechanical</th>
<th>Materials</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>V I</td>
<td>2</td>
<td></td>
<td>2</td>
<td>Opens and delamination</td>
</tr>
<tr>
<td>II</td>
<td>14</td>
<td>38</td>
<td></td>
<td>Differential expansion 8 encapsulations, voltage breakdown, cracked cells</td>
</tr>
<tr>
<td>W I</td>
<td></td>
<td></td>
<td>7</td>
<td>Delamination</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>1</td>
<td></td>
<td>Power degradation, cracked cells</td>
</tr>
<tr>
<td>Y I</td>
<td>2</td>
<td></td>
<td>2</td>
<td>Open circuit, delamination</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>2</td>
<td></td>
<td>Power degradation, cracked cells</td>
</tr>
<tr>
<td>Z I</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>Cracked cells, power degradation, delamination</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td></td>
<td>3</td>
<td>Power degradation, cracked cells</td>
</tr>
<tr>
<td>R T4</td>
<td>3</td>
<td></td>
<td>3</td>
<td>Cracked cells, power degradation, encapsulant leakage</td>
</tr>
<tr>
<td>S T4</td>
<td></td>
<td></td>
<td>3</td>
<td>Delamination</td>
</tr>
</tbody>
</table>
expansion of the encapsulant. This problem was corrected by covering the reinforcing grooves with a thin aluminum plate to prevent uneven distribution of encapsulant under cells.

b. Manufacturer "Y". The previously reported, failure of Block I modules under use at Fort Belvoir (MERADCOM) was conclusively ascribed to poor adherence of interconnect to back metal of the cell.

Two P/FR's for Block II modules with cracked cells after temperature cycling were filed. This was the first such occurrence for this manufacturer.

c. Manufacturer "Z". Analysis of two failed Block I modules from Fort Belvoir was completed. The metallization to the back of the cell was found to be satisfactory; the cause of the failure was attributed to the improper stress relief of the interconnects.

Two additional modules from Fort Belvoir were being analyzed. The problem was manifested as delamination, heat discoloration of the substrate, and power degradation. Figures 6-1a and 6-1b are X-ray prints of the damage observed. An effort was being made to determine the sequence of the failure.

d. Manufacturer "R". A developmental module from Task 4 was being analyzed to determine the cause of power degradation and the effect cracked cells have on reduced power. The results of this analysis will be covered in next quarter's report.

Figures 6-2a, 6-2b, and 6-2c are examples of encapsulant delamination reported from the LeRC System Test Facility. Six Block I modules were being subjected to analysis by materials specialists.
Accumulation of melted solder
Solder voided due to overheating
Normal solder coated back of cell
Crack in cell

Cracked and solder voided area
Solder buildup
Evidence of heating of adjacent cells

Figures 6-1a and 6-1b. X-ray Images of Manufacturer "Z" Solar Cells
Figures 6-2a and 6-2b. Encapsulant Delamination in Manufacturer "R" Modules
Figure 6-2c. Delamination in Manufacturer "R" Module
REFERENCES


3. JPL Document 5101-32; LSSA Project Quarterly Report-4" (an internal document).


