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LSSA PROJECT

Low-Cost Silicon Solar Array

Project Quarterly Report Number 4 for the Period January—March 1977

Work Performed Under Contract No. EX-76-A-29-1012

**California Institute of Technology
National Aeronautics and Space Administration
Jet Propulsion Laboratory
Pasadena, California**

U.S. Department of Energy

Solar Energy

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LSSA LOW-COST SILICON SOLAR ARRAY **PROJECT**

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Project QUARTERLY REPORT -4

FOR THE PERIOD JANUARY 1977-MARCH 1977

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JET PROPULSION LABORATORY
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 January through March 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

By the end of 1976, the Project had essentially attained its Phase I goals in assessing the state of the art of silicon solar cell technology, contracting for large-scale production of modules, and beginning advanced research. During January, February, and March 1977, Project efforts were expanded from this foundation.

The Block 1 solar array purchase of 43 kW and a 15 kW add-on had been completed in late 1976, and testing continued into the first quarter of 1977. Qualification and environmental testing detected technical shortcomings in Block 2 module prototypes; these were subsequently corrected by the manufacturers. About 3 kW of production modules in the Block 2 purchase had been received by the end of the quarter. A Request for Proposal and specification were completed for a projected 150 kW procurement, and requirements for a projected 160 kW buy were studied.

Forty-seven contracts were in effect at the end of the quarter for technology development and cost analysis. Acceptable progress had been made, but most studies were immature at the period's end. Technical development was effectively integrated with cost considerations as economic analysis work progressed.

*In 1975 dollars.

A plan was completed to revise the Project organization so as to provide a more focused effort for each of the technical areas as the scope of Project activities expanded. The Automated Array Task was consolidated under a new Area identified as Production Process and Equipment Development. The Project Analysis and Integration, Engineering, and Operations Tasks were elevated to Area level, and the Large-Scale Procurement Task was assigned under Operations. A new Task was added for the important function of cell development to provide emphasis on all facets of cell preparation and processing. A Deputy Project Manager, assigned to function essentially as general manager, was added to the Project staff.

Four task reports were issued during the quarter. Cyclic Pressure-Load Developmental Testing of Solar Panels (this work was summarized in LSSA Quarterly Report 2) described testing done with an apparatus created at JPL to simulate loading of winds of up to 100 mph. Test Program on Low-Cost Connector for Solar Panels (also see LSSA Quarterly Report 2) describes an inexpensive device developed for automotive use which was found to be promising for solar module application. Availability of Ultraviolet Radiation Data (for Encapsulation System Design) relates how data regarding the spectral composition of the ultraviolet portion of total irradiance at various sites is presently inadequate for Project purposes. Preliminary Analysis of Industrial Growth examined factors that affect industrial growth rates as they might apply to the LSSA Project.

The Project conducted a Project Integration Meeting on January 17th and 18th in San Diego. A key theme was the emergence of usable costing data and their integration with the technical sphere. During the PIM, presentation showed that cost vs. cell conversion efficiency was the dominant trade-off when technical development was analyzed from a cost perspective. Also, a presentation by the Economics and Industrialization Activity concluded that the initial cost of modules is the most important consideration in photovoltaic system life-cycle cost. The Engineering Area outlined the results of its work to define the parameters of the cost vs. efficiency trade-off, and presented a formula that illustrates the effects of efficiency changes on cost. The theme was further emphasized in discussions by the Silicon Material Task and the Production Process and Equipment Area.

A uniform costing methodology for manufacturing processes, called SAMICS, had been completed by the time of the PIM, and was discussed. SAMICS is a standard format for expressing a description of the economic characteristics of each manufacturing process, and was considered to be an important product of the Project's cost analysis function. In a final presentation in the area of cost, allocations for ingot and non-ingot technologies were set forth, and the allocation structure was shown graphically. Dramatic improvements were projected in ingot technology for crystal growth and slicing, and for cell fabrication and module assembly.

SECTION II

SUMMARY

A. PROJECT ANALYSIS AND INTEGRATION

During this quarter, a mission system interface analysis activity was started in an effort to enhance the information flow into the LSSA Project, particularly from the mission and systems contractors of the ERDA program. A preliminary version of the SAMICS workbook was published, and its application to a realistic processing sequence was about 50% complete; application to a wafer-to-module sequence was initiated. A contractor was selected to support the SAMICS program. Design of the SAMIS III computer program was about 75% complete at quarter's end. Price goal allocations were updated several times during this period, and presented at the Project Integration Meeting in May. Computer modeling of the life-cycle cost of energy systems was essentially completed. A price/quantity study based upon manufacturing process contract data furnished by the Production Process and Equipment Area found that approximately 50 MW/year is the optimum manufacturing quantity for solar modules.

B. TECHNOLOGY DEVELOPMENT AREA

1. Silicon Material Task

Continued experimentation with the fluidized bed reactor for production of Si by Zn reduction of SiCl_4 showed that 78% of theoretical conversion efficiency from SiCl_4 to Si was attainable using a hemispherical bed support, versus 68% when using the concise bed support. A smoother bed action was noted also; this is expected to result in higher reactant throughput. The high deposition rates demonstrated provide experimental verification for the 7-inch reactor selected for the 25 MT/yr process system development facility. A production rate of 5 kg/hr was reached for about one minute in the free space reactor designed to produce Si from SiH_4 , and a pyrolysis efficiency of 99% was demonstrated. However, continuous operation has not yet been demonstrated. Another contractor concluded that semiconductor-grade Si can be produced by SiF_2 transport from Si_{met} at rates of up to 40 gm/hr for short runs. An economic analysis of the Zn/ SiCl_4 process indicated that a \$10,510,000 fixed capital investment will be required for a 1000 MT/yr plant that will produce Si at \$9.63/kg.

2. Large-Area Silicon Sheet Task

The EFG process is now producing 2-inch wide ribbon at 2-3 inches per minute; however, conversion efficiencies remain low at 2%-3%. Work on the CAST process has stopped pending contract negotiation. Materials other than SiO_2 are being evaluated for the die used in the inverted Stepanov process. Erratic wetting of the SiO_2 die caused experiments using this material to be suspended. Problems associated with optimizing furnace geometry have created great problems with the web-dendritic

technique, but in the best furnace configuration found so far, ribbons 1 inch wide by 15 inches long were grown. In the investigation of substrate materials for the CVD process, it was found during this quarter that re-firing crystalline aluminas results in only limited grain growth in the wafer surfaces in contact with another surface. The heat exchanger method of casting large silicon ingots has demonstrated a crack-free ingot growth using crucibles which have been coated with sintered silica; the silica separates freely from the silicon ingot during cooldown and prevents cracking.

3. Encapsulation Task

Development of low-cost encapsulation materials and systems is continuing at Battelle (Study 3), Springborn, Simulation Physics, and Endurex. Battelle and Springborn have screened a large number of materials for encapsulation capability. These tests have included mechanical, physical, thermal, and electrical tests. Emphasis has been on radiation transmission, water vapor permeability, adhesion, and mechanical integrity. Battelle has performed a limited number of tests on single encapsulated active photovoltaic cells; this work will be continued under a contract extension with statistical numbers of samples and extended exposure to ultraviolet, temperature cycling, and high humidity. Springborn also began testing of encapsulated active photovoltaic cells. These are two-cell mini-modules assembled by Solar Power Corporation and encapsulated by Springborn; they are designed to test encapsulation materials combinations. Simulation Physics has produced electrically functioning four-cell electro-statically bonded (ESB) modules. These modules have shown no significant reduction in electrical output caused by the ESB process. No results were obtained from Endurex this quarter (the Endurex contract has just begun).

Development of life prediction methodology is being accomplished by Rockwell and Battelle. Rockwell has designed and is testing a universal test specimen (UTS) which shows promise of providing a low-cost method of testing encapsulation materials and encapsulating materials systems. Significant progress has been made in predicting degradation using mathematical models (for example, the Weibull model). This work is continuing under a contract extension employing improved UTS designs. Battelle has completed a literature/theoretical study of life prediction methodology and has developed an improved procedure for designing life prediction tests. This will be given in detail in the final report to be published in the next quarter.

Significant efforts were expended this quarter to support the Engineering and Operations Areas by conducting failure analyses on modules in tests, doing field repair work, taking part in design reviews, and participating in module design team efforts chaired by the Engineering Area. These efforts have become increasingly important in the Encapsulation Task and will receive increased emphasis in the next quarter.

C. PRODUCTION PROCESS AND EQUIPMENT AREA

With Phase I assessment concluded, emphasis was shifted to the cost-effectiveness of processes still being considered, and to the sensitivity of those processes to commercially realistic tolerances. Three add-on contracts were initiated during this quarter for study of these factors. Ten cm/hr Czochralski crystal pulling was accomplished, although attempts at pulling 12 cm/hr failed. During these tests, though, the program goal of an 80% yield of 12 cm-dia. crystals from a 12 kg charge was demonstrated. A technique for spinning ingots during multiblade sawing was tried, and showed cutting rates of almost 50 mm/hr. One contractor this quarter began to study the entire proposed manufacturing sequence from the perspective of "energy payback," appraising the amount of energy expended during manufacture of solar arrays versus the energy that is expected to be produced throughout the life of those arrays.

D. ENGINEERING AREA

Engineering Area work during the second quarter of Fiscal Year 1977 centered in two primary areas: (1) the finalizing of a substantially updated module design specification, and (2) expanded activity in the development of environmental design requirements.

The updated design specification is aimed at third generation modules beyond the designs associated with the 130-kW Block 2 procurement. The new specification emphasizes the needs of larger power systems in the range from 10 to 250 kW. Particular areas of emphasis include minimizing field labor and system construction cost through the use of standardized electrical connector and mechanical attachment interfaces. Increased emphasis is also placed on efficiency (minimum allowable is 7%) and on electrical isolation and safety. Increased compatibility with the requirements of 12-volt battery charging has been achieved with a new voltage specification based on the actual cell operating temperature in the field, referred to as Nominal Operating Cell Temperature (NOCT).

Thermal analyses continued during the past quarter with emphasis on determining the Nominal Operating Cell Temperature of the Block 1 and Block 2 module designs. Tests were also conducted to further examine the effect of fins and residential roof top mounting (insulated rear side).

Building upon the qualification and field test experience gained with the Block 1 and 2 large-scale production modules, a number of activities supportive of new environmental requirements are in work. The principal activity is associated with the development of an impact load (hail) test. Work is progressing both in the testing of modules with simulated hail and in the acquiring of hail impact probability statistics. The objectives of the effort include evaluating the current module construction approaches, developing design and cost data on approaches to increase ruggedness, developing easily implemented test procedures, and defining cost-effective ruggedness requirements.

Another area of environmental requirement generation is addressed toward obtaining quantitative data on the mechanical fatigue loading associated with field wind and thermal cycle environments. This activity uses computer analysis of continuous temperature and wind histories in conjunction with mechanical fatigue loading theories to estimate the total fatigue loading level associated with a projected photovoltaic plant lifetime. These data will ultimately be factored into updated specifications for the current thermal cycle and cyclic wind loading tests.

In conjunction with the cyclic loading analysis effort, work has also progressed on the design, fabrication, and checkout of a wind-loading spectrometer. This instrument eliminates the problem of determining the fatigue loading characteristics of wind at a particular site by integrating in real time the number of cyclic loads observed by the instrument. Use of the instrument at module test sites provides an accurate estimate of the fatigue environment seen by the test modules.

In the support of a Department of Defense photovoltaic range measuring system (RMS) application, work is near completion on the development of insolation deficit statistics associated with climatic variations (cloudy days). A unique methodology has been developed around the computer analysis of hour-by-hour historical weather records (tapes) which aids in the selection of the optimum collector and storage size for a given geographical site.

E. OPERATIONS AREA

The last of the Block 1 (15-kW add-on) modules was delivered early in this quarter for delivery to a DOD application. Approval for production was given to all four manufacturers for the Block 2 (130 kW) procurement. Ninety-seven additional modules were installed at the JPL and Table Mountain test sites, for a total of 218 at all three sites. Eight of the modules at the JPL site were mounted for a test of the effect of dirt on module performance. Work on the Pasadena test site automated data acquisition system peripheral hardware was largely completed, and was awaiting delivery of the data system itself. A summary of the inter-laboratory standards measurements was given at the Semiannual Photovoltaic Program Review in San Diego in January. The solar cell module problem/failure reporting procedure document was revised.

SECTION III

PROJECT ANALYSIS AND INTEGRATION AREA

A. PLANNING AND INTEGRATION TASK

During this quarter planning was initiated for an expanded integration effort among the Technology Development Area tasks, Project Analysis and Integration (PA&I) Area, and other ERDA program elements. A mission system interface analysis activity was started late in the quarter in an effort to enhance the information flow into the LSSA project, particularly from the mission and systems contractors of the ERDA program. The Planning and Integration Task supported the Program Planning Group* at meetings in January at Sandia Corporation, in February at MIT, and in March at Aerospace Corporation.

B. ARRAY TECHNOLOGY COST ANALYSIS TASK

A preliminary version of the SAMICS Workbook was published as JPL Document 5101-15. Toward the end of the quarter, some of the areas in which the Workbook will be revised had been identified. Application of the Workbook to a realistic processing sequence was about 50% complete. Meanwhile, the Automated Array Assembly Task included a requirement in its technology assessment contracts that the preliminary version of the Workbook's process description format be used. In addition, an application of the preliminary Workbook to a wafer-to-module processing sequence was initiated.

Requests for expressions of interest in serving as the SAMICS support contractor were sent to over 20 firms. After hearing two supplementary presentations, the JPL A&E Services Board selected a firm; negotiations were about to begin at the end of the quarter.

Design of the SAMIS III computer program was about 75% complete at quarter's end, but coding had not yet started. Several submodels of the methodology were clarified. The one-time costs, for example, were shown to be significant contributors to price.

Price goal allocations were reviewed and updated several times during the quarter, and the format for presenting the allocations was revised. Updated price goal allocations were prepared for the Project Integration Meeting in May.

*The Program Planning Group was established by ERDA Headquarters. It consists of representatives from all the Photovoltaic Program elements, including JPL. The purpose of the group is to write the National Photovoltaic Energy Conversion Plan.

C. ECONOMICS AND INDUSTRIALIZATION ANALYSIS TASK

The life-cycle cost of energy systems effort was continued at 0.5 person-month/month during the quarter. The major progress has been to consolidate a collection of ad hoc computer models into one integrated program set, and to begin non-oriented documentation. The computer modeling was nearly complete at quarter's end.

The Production Process and Equipment Area produced a major summary of the manufacturing process contracts, and this was integrated into the PA&I price/quantity study. The most important conclusion of this study to date was that, based on modest estimations of current technology, the minimum average cost of manufacturing modules seems attainable in a facility sized for ≈ 50 MW_{pk}/year output. This is an order of magnitude smaller than the 500 MW/year production goal of 1986. If correct, this implies that 450 MW/year of circa 1986 production must be justified, if at all, on grounds other than economies of scale.

It appears that the MIT Energy Laboratory will join the Program, specifically to provide support in the area of economic analysis. This effort will couple with MIT/Lincoln Laboratory responsibilities for test and demonstration activities, and will provide a strong analysis coverage of the demand side of the market. Economics and Industrialization Task personnel conducted several meetings with the MIT/Energy Laboratory staff, and the Energy Laboratory staff has collectively developed a work plan that covers market development analysis much more thoroughly than at any time in the past.

A formal workplan has been derived and staffed for JPL contributions to the Program Planning Group. A continuing problem is the lack of a firm contract from the Program Office to MIT/Energy Laboratory. The substantive analytical issues have been resolved, and work is under way on the relevant literature searches.

SECTION IV

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 silicon 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 can not be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade silicon. Consequently, it is necessary that either a different process be developed for producing semiconductor-grade silicon or a less pure and less costly silicon material (i.e., a solar-cell-grade silicon) be shown to be utilizable.

1. Technical Background

Solar cells are presently fabricated from semiconductor-grade silicon, 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 silicon material which is significantly less pure than semiconductor-grade silicon; the price goal for this material is less than \$10 per kilogram. However, the allowance for the cost of silicon 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 silicon 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 silicon.

2. Organization and Coordination of the Silicon Material Task Effort

The Silicon Material Task effort is organized into five phases. As Table 4-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade silicon will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal silicon 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 silicon. 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 silicon-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body

Table 4-1. Organization of the Silicon Material Task Effort

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

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 4-2. Additional contractors for subsequent phases will be selected from unsolicited proposals and from future RFPs.

4. Silicon Material Task Technical Activity

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 silicon at a markedly reduced cost.
- (2) Part II - Investigate the effects of impurities and process-steps on the properties of single-crystal silicon material and the performance characteristics of solar cells.
- (3) Part III - Establish the practicality of a process capable of the high volume production of solar-cell-grade silicon at a price of less than \$10 per kilogram.
- (4) Part IV - Evaluate the relative commercial practicality of the silicon-production processes developed under Phase I of the Silicon Material Task.

Table 4-2. Silicon Material Task Contractors

Contractor	Technology Area
SEMICONDUCTOR-GRADE PRODUCTION PROCESSES (Part I of Phase I)	
Battelle Memorial Institute, Columbus, Ohio (JPL Contract No. 954339)	Si from SiCl_4 reduction by Zn
Union Carbide, Sistersville, W. Virginia (JPL Contract No. 954334)	Si from SiH_4 derived by redistribution process
Motorola, Phoenix, Arizona (JPL Contract No. 954442)	Si using SiF_4 reaction with metal- lurgical grade Si and SiF_2 transfer
SOLAR-CELL-GRADE SPECIFICATIONS (Part II of Phase I)	
Westinghouse Electric, Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Investigation of effects of impur- ities on solar cell performance
SOLAR-CELL-GRADE PRODUCTION PROCESSES (Part III of Phase I)	
Dow Corning, Hemlock, Michigan (JPL Contract No. 954559)	Si from purer source materials using arc furnace processing
Stanford Research Institute Menlo Park, California (JPL Contract No. 954471)	Si by Na reduction of SiF_4
Westinghouse Electric Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Si by plasma-arc-heater reduction of SiCl_4 with H_2 and alkali metals as reducing agents
AeroChem Research Laboratories, Princeton, New Jersey (JPL Contract No. 954560)	Si by use of a nonequilibrium plasma jet

Table 4-2. Silicon Material Task Contractors
(Continuation 1)

Contractor	Technology Area
COMMERCIAL POTENTIAL OF PROCESSES (Part IV of Phase I)	
Lamar University, Beaumont, Texas (JPL Contract No. 954343)	Evaluate relative commercial potentials of Si-production processes developed under the Silicon Material Task

a. Processes for Producing Semiconductor-Grade Silicon.

1) Production of Si by Zn Reduction of SiCl_4 - Battelle Memorial Institute. The contract with Battelle Memorial Institute is for development of the reaction for the Zn reduction of SiCl_4 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.

A detailed flow sheet of the process for a 25 metric ton/year process system development facility was prepared. The subsystems of the process are for Si deposition, Zn recycle, SiCl_4 waste disposal, Cl_2 handling, and periodic chlorination to remove Si deposited on the walls of the reactor. Purchased SiCl_4 will be purified in the first step of this facility. The deposition product will be cooled and removed periodically. Zn recycling will be accomplished using a ZnCl_2 electrolysis cell. The major by-product to be disposed of is Cl_2 ; this will amount to about 5 kg for every kg Si produced. The plan for this facility is to dispose of it by forming NaHClO_2 , which is marketable. The other options are to use the Cl_2 to chlorinate metallurgical grade Si to make SiCl_4 and to sell the Cl_2 . Revisions of the flow diagram will follow calculations of experimental data and iterations of analyses.

A material/energy balance sheet was calculated using data from the literature. The waste disposal subsystem was not included at this time, since some physical data are not yet available. The basis for the calculations was an assumed production rate of 3.6 kg/hr and an 80% on-stream operation for 7000 hr/yr. The values for the efficiencies of reaction and of condensations were based either on experimental data or on extrapolations. Other assumptions were: operation at the Zn/ SiCl_4 ratio of 2:1; a bed deposition efficiency of 60%; wall deposition and Si carryover of 1.8 and 1.2%, using experimentally obtained values; a product of 5% seed and 95% deposit, and an electrolysis cell operation

of 100% current efficiency. The fluidized bed reactor is practically adiabatic. Since the exothermic heat of reaction can not be used to heat the SiCl_4 , the simplest operation of the fluidized bed reactor was taken to be with separate preheater (endothermic) and reaction (exothermic) sections. The energy balance will be revised to take into account factors which were not included in the simple treatment.

The experimental studies were linked to the fluidized bed reactor design, the by-product condensation and recovery, and the product production rate and yield. In addition, a series of experiments was directed to the development of a different Zn vaporizer and to the determination of the conditions for the Zn/ SiCl_4 reaction other than in the FBR. The last study was for the purpose of establishing conditions for maximizing the deposition on the seed material in the fluidized bed reactor.

Experiments involving the operating parameters and reactor design factors led to a series of tentative conclusions and inferences. The institution of a hemispherical bed support gave an increase in the SiCl_4 -to-Si conversion efficiency (79 and 78% of theory as compared with 68% with the concave bed support). In addition, the efficiency gain was accompanied by smoother bed action, indicating the capability for higher reactant throughput. Changing the inlet position to flow Zn through the axial inlet eliminated Si growth at the Zn inlet and reduced the amount of Si deposited on the reactor wall. Preliminary results indicate that operation as a graded temperature bed will lead to improved conversion efficiency. Increased feeds led to enhanced yields; an increase in total throughput in moles of gas per hour of 42% gave a bed deposition rate of 344 gm/hr, the highest achieved so far. The overall operability of the experimental facility was considerably improved. With minor design changes the by-product condensate collection subsystem performs satisfactorily. The fluidized bed reactor wall deposit, which has been shown to be as low as 3% of the Si product, is expected to decrease markedly with increased reactor size. While Si dust, which was reduced to 2.4% of the Si product, is undesirable, it is believed that this is controllable, allowing economical operation. The high deposition rates provide an experimental verification for the 7-inch reactor selected for the 25 metric ton/year process system development facility.

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

After a safety certification, the SiH_4 experimental facility was to determine the operational limits and the purity-yield characteristics of the unit. A maximum purity of 97 mole % SiH_4 was obtained without the use of the SiCl_4 or C purification traps using SiH_2Cl_2 as the feed. When the SiCl_4 absorber was put on stream, the expected purification

did not occur owing to an inability to overcome the heat loss of the system. Acceptable purification can be obtained with a redesigned, higher capacity unit or by increasing the size of the C-purification system.

The economic practicality of this SiH_4 process depends in large part on the capability of hydrogenating the by-product SiCl_4 to SiHCl_3 according to the reaction $3\text{SiCl}_4 + 2\text{H}_2 + \text{Si}_{\text{met}} = 4 \text{SiHCl}_3$ where Si_{met} is metallurgical grade Si. This reaction is not strongly exothermic, is probably surface area dependent, requires a catalyst, such as Cu, for the high reaction rates, and is favored by high pressure. From a series of experiments in a fixed bed reactor, it was concluded that this type of reactor is not suitable, because of low reaction rates and improper operating features. Experiments in a fluidized bed reactor showed that the rates of reaction, but not the final composition, were greatly affected by temperature over the range of 400 to 500°C; at 500°C the yield of 13.7% SiHCl_3 was reached in about 10 seconds. Attempts to hydrogenate SiHCl_3 to form SiH_2Cl_2 were unsuccessful. A fluidized bed reactor for the SiCl_4 -hydrogenation reaction with a throughput of 7 kg/hr was designed for use in the experimental facility.

An alternative process flow scheme has been devised for the integrated experimental facility. Originally this facility for converting SiHCl_3 to SiH_4 used three distillation columns, two redistribution reactors, an absorber-stripper enrichment section, and a C-trap for final purification. The alternative configuration would use less equipment and require less energy. The feed would be either pure SiHCl_3 or a $\text{SiHCl}_3/\text{SiCl}_4$ mixture resulting from the hydrogenation reaction; the $\text{SiHCl}_3/\text{SiCl}_4$ would first be put through a still. The sequence would be: SiHCl_3 into the first redistribution reactor; the mixture of chlorosilanes into a still to separate out the SiCl_3 ; and the distillate of $\text{SiH}_2\text{Cl}_2/\text{SiHCl}_3$ into a still to separate out the SiHCl_3 for recycling to the first redistribution reactor, the SiHCl_2 into a second redistribution reactor for the formation of SiH_4 , and a carbon trap to remove chlorosilane impurities from the product. The heat balance calculations for this scheme are not complete; the thermal energy needs should be lower due to the decrease in material for vaporization.

The nature of the resin catalyst for the redistribution reaction and the mechanism of the reaction were studied using deuterium-labeled compounds to test. Early experimental data had been interpreted as indicating that the active form of the catalyst for the redistribution reaction is the amine hydrochloride. The experimental data were surprising, indicating that the amine hydrochloride is not the active form of the catalyst. The apparent activation by HCl in previous work remains unexplained.

The economic feasibility of using either a fluidized bed reactor or a free space reactor for the deposition of Si from SiH_4 is being investigated. One of the original concepts was to use the small particles produced in the free space reactor as the seed for growth in the fluidized bed reactor. Subsequently, experimental results showed that this procedure was not practical, and the present program plan involves the concurrent developments of each reactor.

In the present study of the free space reactor the operating characteristics are being explored as functions of the important parameters. A production rate of 5 kg/hr was reached for about one minute and at a high gas velocity a pyrolysis efficiency of over 99% was attained. However, continuous operation has not yet been demonstrated. The Si powder product is composed of submicron-size particles. Consolidation of the powder by melting and compaction techniques is being investigated. Modifications of the reactor, which is capable of producing 1.5 kg of Si powder per run, are being designed so as to increase product purity and to allow automatic product transfer from the reactor chamber. Chemical analyses of the product are planned for the next quarter.

3) Production of Si by $\text{SiF}_4/\text{SiF}_2$ 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 SiF_2 transport purification reaction steps. In a series of experiments it was shown that (1) 75% of the SiF_4 reacts with Si_{met} at 1250°C and at 1350°C , (2) the rate of SiF_2 formation is not affected by the presence of impurities and (3) at 1350°C the $\text{SiF}_2/\text{SiF}_4$ ratio is constant at flows greater than 100 SCCM. No great differences in the $\text{SiF}_2/\text{SiF}_4$ ratios were observed when comparing reactions using purified and unpurified SiF_4 . The thermal decomposition of SiF_2 polymer was characterized between 20 and 1300°C , and a series of products was postulated to explain mass spectrometric data. The conversion of amorphous Si to dendritic Si at about 730°C evolves SiF_4 , FeSiOSiF_3 , and possibly AlF_3 . The conversion of the SiF_2 polymer releases volatile Si fluorides and forms Si-rich polymers which convert into Si at about 930°C . Motorola has concluded that semiconductor-grade Si can be produced by SiF_2 transport from Si_{met} at rates of up to 40 gm/hr for short run times.

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 carbon interactions with the impurities will be studied.

The growth of ingots for the studies proceeded. Observations indicated a relatively large variation in resistivity along the length of the n-type ingots due to the smaller effective segregation coefficient of P compared to B. Several of the ingots were free of dislocations, as was shown by a lack of etch pits. The calculated ingot concentrations of impurities, based on melt analysis, were in excellent agreement with the targeted values. The measured concentrations were in good

agreement except for the Mn-doped ingot. Additional measurements by spark source mass spectrometry and by neutron activation analysis are scheduled.

Difficulties were encountered in the analyses of dendrites and central web sections in the dendritic web crystal effort; there were no problems with the melt measurements. The data for the dendrites indicate a nonuniformity in the impurity distribution. Since previous data showed that the impurity concentrations in the web section were lower than in the dendrites, the present values for the dendrites may be assumed to be upper limits for the concentrations in the webs.

The plan for the low resistivity studies is to determine the effects of resistivity on cell performance, using a reliable, but non-optimized, process for cell fabrication and then to assess the effects of added impurities concomitantly with resistivity changes. In the first experiments it was found that heavily doped substrates were more sensitive to metallization sintering conditions, the cell fill factor degradation increasing with impurity concentrations. These results suggest that it is necessary to obtain data on long term reliability, adherence, stability of metallization and on long term cell performance.

Measurements were made on n+p cells using different Czochralski and float-zoned Si to establish an upper limit to the B doping concentration for reasonable cell performance. These data are shown in Figures 4-1, 4-2, and 4-3, which give open circuit voltage, short circuit current, and cell efficiency as functions of resistivity. V_{OC} data show a broad maximum in the range of 10^{16} to 10^{17} atoms/cm³; I_{SC} decreases gradually with increased B concentration and then decreases rapidly above 10^{17} atoms/cm³. The data for cell efficiency do not identify the maximum range as sharply. However, it appears that cells with efficiencies comparable to cells fabricated from 4 ohm/cm material can be fabricated from material having resistivities near 0.2 ohm/cm using TiPAg contacts and a reduced sintering temperature. Thus, the nominal 0.2 ohm/cm material will be the baseline material for the subsequent impurity-effect studies.

The conclusion from a series of experiments for the p/n cells was that slow cooling of the wafers after B diffusion appears necessary to maintain good lifetime and I_{SC} values. Some very good cells have been prepared; 16% efficiencies in p+/n/n+ baseline cells (with antireflection coating) have been obtained using BBr₃ diffusion at 875°C.

Figure 4-1. Dependence of Open Circuit Voltage, V_{OC} , on Substrate Resistivity of n+p Solar Cells

Figure 4-2. Dependence of Short Circuit Current, I_{SC} , on Substrate Resistivity of n+p Solar Cells

Figure 4-3. Variation of the Cell Efficiency, η , With Substrate Doping of n+p Cells

c. Processes for Producing Solar-Cell-Grade Silicon.

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. Tasks under the contract are raw materials selection and preparation, arc furnace studies, and unidirectional solidification, and Si analysis.

Since the major amounts of impurities in commercial metallurgical-grade Si are from the carbonaceous reducing materials, a large effort is being directed toward the preparative means of assuring a supply of suitable C-material, e.g., purified charcoal. Purification of a relatively pure charcoal by treatment with a fluorocarbon mixture at temperatures of 1500, 2000, and 2500°C produced a variety of results. The concentrations of Ca, Mg, Mn, and P were greatly reduced at each temperature. The concentration of B was significantly reduced only at 2500°C. Since a temperature below 2200°C would be preferable, to prevent graphitization and reduce energy use, the dependence of C-purity on source material was researched. The results again vary with the element; back-free charcoal contains much less B and less P, but the P concentration remains relatively high after fluorocarbon treatment at 2000°C and at 2500°C.

Analyses showed that quartzite would be the main source of Al, B, and Fe if purified charcoal were used in the arc furnace. Many large deposits have been surveyed for cost, availability, size of source, and purity.

A development-size arc furnace at Elkem, Norway, has been used to evaluate the use of purer raw materials. No runs were made during the last quarter.

In the unidirectional solidification studies, the effect of polycrystalline growth on the effective segregation coefficients was investigated prior to the onset of constitutional supercooling of the melt. In these experiments Cu and Mn were used as dopants, and Czochralski ingots were pulled using single crystal and polycrystal seeds. Composition analyses were made by neutron activation analysis from samples taken from just below the seed, just above the point where constitutional supercooling occurred, and from the tang end. The results were that the effective segregation coefficients for these regions were practically identical for the two ingots. Relatively large concentration and coefficient values were obtained for the points just prior to constitutional supercooling where very rapid changes in composition occur. Relatively large concentration and coefficient values were derived for the samples from the tang ends. The conclusion was that there are essentially no differences in the values for the effective segregation coefficients for single crystal and polycrystal growth provided the ingots are grown from reasonably dilute melts. The benefits of using polycrystalline ingots for purification by unidirectional solidification

are higher growth yields, reduced seeding problems, and the use of larger diameter seeds.

The suitability of the Bridgman type technique for purification by unidirectional solidification (solidification from the bottom to the top of a crucible by controllably decreasing the temperature so that the solid-liquid interface moves upward) was explored further. In experiments using Al-doped Si, the effect of Al segregation was shown. More experiments are to be performed to establish the capability of this procedure.

2) Production of Si from Na_2SiF_6 Source Material Using Na Reduction of SiF_4 and SiF_4 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 SiF_4 by Na to produce high purity Si and (2) the further purification of this product by reaction with SiF_4 to form SiF_2 followed by the disproportionation of the SiF_2 to yield Si with the regeneration of the SiF_4 . The work to date has dealt entirely with the first reaction.

Procedures for controlling the reaction were studied. To avoid carrying unreacted NA into the reaction product, the liquid NA and SiF_4 gas were pulse fed into the reaction vessel. An average temperature of 600°C was maintained by careful regulation of the pulse times. Batches of product of up to 250 g containing 25 to 30 g of Si were obtained. The by-products were NaF and Na_2SiF_6 .

Owing to the importance of Na_2SiF_6 both as a reaction product and as a possible intermediate for SiF_4 generation, the equilibrium pressure of $\text{SiF}_4(\text{g})$ above Na_2SiF_6 and during decomposition in the temperature range of 585 to 650°K was studied by an effusion method. The data were extrapolated to give an equilibrium pressure value of 1 atm at 734°C . The SiF_4 was analyzed by mass spectrometry to determine the nature and amount of volatile impurities. The major constituents were found to be silicon oxyfluorides (about 4%), sulfur oxyfluorides (about 0.1%), and SO_2 (about 0.05%).

A leach procedure to separate Si from the other reaction products, NaF and Na_2SiF_6 is under way. It is expected that these results will give an indication of the suitability of using this procedure for extracting Si from the Na reduction and will provide information for use in the subsequent purification step.

3) Production of Si Using Arc Heater Process for Reduction of SiCl_4 by Na, Mg, or H_2 - 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 SiCl_4 by either Na, 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.

The reaction analysis subtask has been completed. Calculations were performed using the developed model to predict vaporization lengths for liquid sodium droplets. Based on the operating parameters and the assumptions of the model, the results of these analyses indicate that droplet vaporization can occur in a very short distance (e.g., 7 cm). A method which incorporates the effect of turbulent gas flow on silicon particle growth was evaluated, since a previous analysis only considered silicon particle growth under quiescent conditions. (Turbulence is known to be present in the proposed arc heater system and should enhance particle growth, thus aiding silicon separation.) Results of the turbulence model indicate consistent growth times and lengths when compared to the reactor design.

Heat transfer analyses were conducted to substantiate both the design and materials selection for the reactor/separator. In addition, a heat transfer analysis was performed for the reactor based upon hydrogen reduction of SiCl_4 . Previous equilibrium calculation results for the H_2/SiCl_4 reaction were used in this analysis. Based upon the heat transfer analysis, the established reactor design is adequate for either sodium or hydrogen reduction of SiCl_4 .

System drawings for the components of the reactor/separator were completed and cost estimations are in progress. System safety considerations for the reactor/separator were developed.

Final designs for both the SiCl_4 and the Na storage and injection systems were completed. For the SiCl_4 system, handling, safety, and requirements for control of potential hazards relating to SiCl_4 systems were defined. Commercially available hydraulic atomizing nozzles for SiCl_4 injection were selected. Progress on the sodium system paralleled that on the SiCl_4 system. Based upon system requirements, a sonic-type atomizing nozzle was selected for sodium injection. Subsystem components and specifications have been defined for the sodium system. A review of both liquid metal safety and handling requirements was conducted and operational guidelines were established.

The silicon collection and the by-product (effluent) disposal systems have undergone extensive design refinements. Alternative designs for the silicon collection system design use a thermally-controlled valve of fused silica to control the flow from the cyclonic separator, or a quartz-lined sliding gate valve. A water-cooled casting carousel will be used to form ingots of the silicon product. Both heat transfer and thermal profile analyses were performed for the silicon collection design. The by-product disposal system was completed; the design consists of two water-jacketed condensers to separate the NaCl effluent from the Ar- H_2 gas mixture. This approach was favored over the competing water-spray chamber for reasons of safety, reduced product contamination, and direct application to a full scale process, in which the NaCl would be recycled to form Na and Cl_2 via electrolysis. Both heat transfer and condensate (NaCl) thickness calculations were performed to aid condenser sizing and design. A review of safety considerations was

conducted for the condensers and associated equipment. Final engineering drawings were completed and contacts with suppliers for cost estimations are in progress.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of SiCl_4 - AeroChem Research Corporation. The objective of this program is to determine the feasibility of high volume, low-cost production of high purity silane or solar-cell-grade silicon 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.

During this quarter calculations were made to define the experimental limits within which gas-phase reactions would be most likely to occur. These show that H-atom recombination does not compete significantly with the other reactions as a sink for H, and that, if the H/SiCl_4 overall reaction has an activation energy, the pressure ratio across the nozzle and the temperature in the discharge become very important parameters. Most importantly, the maximum operating pressure was shown to be limited by the pressure at which the glow discharge can be maintained or the pressure at which the hydrogen atom yields become small.

Solid products of the $\text{H/H}_2/\text{SiCl}_4$ reaction were recovered. Depending upon experimental conditions, these were (tentatively) identified as a polymeric material, amorphous silicon and polycrystalline silicon. The polycrystalline material was shown by X-ray fluorescence analysis to have nickel present at ppm levels; conspicuously absent at the ppm level were the heavy metals Fe, Cr, Pb, Sn, Cu, and Zn, materials of construction of the apparatus.

Quantitative analysis of solid and gas-phase material recovered in a synthesis experiment gave product yields of 12% SiHCl_3 , 1% SiH_4 , and 1.4% silicon, with 80% SiCl_4 starting material collected and 6% unaccounted for. The low yields are probably due to less-than-optimum mixing of the H/H_2 jet with SiCl_4 .

A new nozzle with SiCl_4 injection in the nozzle itself has been designed and preliminary tests indicate improved mixing with less disturbance to the stream than for the previous mixing systems.

d. 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.

1) Process System Properties. Major activities were continued on process system properties of silicon source materials under consideration

for solar-cell-grade silicon production. In property correlation efforts, property data results were obtained for heat of vaporization, gas heat capacity, liquid heat capacity, liquid density, surface tension and gas viscosity of silane (SiH_4) as a function of temperature.

The correlation results for gas heat capacity cover both the low and high temperature ranges which will be encountered in the specific process technology (low temperature range - silane production; high temperature range - silicon production from silane). These results will be used in performing the chemical engineering analysis of the silane process (Union Carbide).

2) Chemical Engineering. Major chemical engineering analysis activities are being devoted to preliminary process design for a silane (SiH_4) plant that will produce 1000 metric tons/year of solar-cell-grade silicon. The technology developed by Union Carbide for the production of silane uses hydrogen and metallurgical-grade silicon as raw materials. A preliminary process flow diagram and base conditions have been developed.

A preliminary process design was initiated for the conventional polysilicon process now used in the United States to produce semiconductor-grade silicon from SiHCl_3 .

3) Economic Analysis. Economic analysis activities focused on development of a computer model to aid in estimation of product and plant investment costs for the alternate solar-cell-grade silicon processes. Application of the computer model to the Battelle process (Zn/SiCl_4) indicated a \$10,510,000 fixed capital investment and a \$9.63/kg price of silicon for a 1000 metric ton/year plant.

Economic analysis activities also centered on developing cost standardization techniques for application to the alternate processes. These techniques and the information presented will allow valid comparisons between processes on a standardized basis.

e. JPL In-House Activities. The current computer model was tested against experimental fluidization data. The agreement is good considering the simplifications in the model.

The draft of the JPL report on fluidized bed modeling was revised and has been submitted for publication. The section on the computer program has been expanded and includes the latest comparison results.

The first draft of the technical report on the fundamental reaction aspects of silicon chemical vapor deposition has been typed and distributed for comments.

The fluidized bed experimental system received some final modification. Electronic pressure transducers were installed to monitor total bed pressure and differential pressures within the bed. The system is

undergoing final leak testing and calibrations in preparation for fluidization testing. A capacitance probe has been designed for measuring bubble size in the bed. This device is being tested. Other instrumentation improvements, including a digital data acquisition system and particle size analysis equipment, were ordered. Design work and equipment procurement for the reaction system were also conducted. A purge system was installed on the pressure taps of the fluidized bed apparatus. A differential pressure probe was designed and is being installed to help measure bed voltage and particle size in the bed. Pressure transducer and capacitance probe systems are being tested and installed into the fluidized bed reactor to improve the instrumentation function.

Preliminary experimental data on the stage-2 fluidized bed was obtained using coarse silicon particles and argon gas. The experimental setup appears to be operating properly. Differential pressure drop measurement technique to obtain internal fluidized bed data was chosen.

An initial fluidization experiment was conducted to check for equipment flaws and to set up operating procedures. The data compared reasonably well with predicted results, but a few improvements were indicated in the purge system and pressure devices.

The flange-gasket method to effect completely leak-proof seals, for the silane pyrolyzer (including a way to seal in the quartz sight tube) was finalized. The system for silane pyrolysis-separation-collection has been proceeding through stages of leak-testing, revisions, and corrections to fabrication, and installation in the fume hood. The electrostatic precipitator is being slightly modified and prepared for power/efficiency testing. Instruments were installed in the control panel. In the present experimental system, testing and development of an electrostatic precipitator to function with hydrogen gas and silicon dust are in progress. Because of the nature of these materials (dielectric constants, etc.), a special unit has been designed and tested.

An investigation was made into various types of digital data acquisition systems for use with the fluidized bed and the pyrolysis reactor system to enhance data reduction and process control. These systems range from small computer systems with instrumentation interfaces to data loggers for recording data for a large computer such as the Univac 1108. Recommendations by Dr. Fitzgerald, the fluidization instrumentation consultant, and others indicate that the small computer system has the most flexibility. An investigation was also made into hydrogen detectors, particle size analyzers, and grinding equipment.

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 silicon 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 silicon. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

1. Technical Background

Current solar cell technology is based on the use of silicon 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 silicon 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 silicon "real estate" production techniques which would result in low-cost electrical energy.

Growth of silicon 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 silicon crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed 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 silicon crystalline material for solar cell production are shown in Table 4-3. 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 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.

RFPs were started during this quarter to investigate these two areas. Two or three contracts are expected to result from the continuous growth interest, one or two for the sawing work. It is intended that both these efforts will become active in FY78.

4. Large-Area Silicon Sheet Task Technical Activity

a. Silicon Ribbon Growth: EFG Method--Mobil-Tyco Solar Energy Corporation. The edge-defined film-fed growth (EFG) technique is based on feeding molten silicon through a slotted die (as illustrated in Figure 4-4. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material which is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

The EFG process, which had been directed toward producing wider ribbons faster, is now routinely operating. Two-inch-wide ribbon is being produced at somewhat faster than 2 inches per minute, with occasional output at close to 3 inches per minute. Three-inch-wide designs are being produced, as are cartridges. Conversion efficiencies of cells on EFG ribbons remain rather low, in the range of 2% to 6%, owing primarily to impurities introduced by the resistance furnaces. Various possibilities are being explored to raise cell efficiency. A planned extension of this work will be aimed at machines capable of growing five ribbons simultaneously, each 2 inches wide.

Table 4-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
RIBBON GROWTH PROCESSES	
Mobil-Tyco, Waltham, Massachusetts (JPL Contract No. 954355)	Edge-defined, film-fed growth
IBM, Hopewell Junction, New York (JPL Contract No. 954144)	Edge-defined, film-fed growth
RCA, Princeton, New Jersey (JPL Contract No. 954465)	Inverted Stepanov growth
Univ. of So. Carolina, Columbia, So. Carolina (JPL Contract No. 954344)	Web-dendritic growth
Motorola, Phoenix, Arizona (JPL Contract No. 954376)	Laser zone ribbon growth
SHEET GROWTH PROCESSES	
Honeywell, Bloomington, Minnesota (JPL Contract No. 954356)	Dip-coating of low-cost substrates
Rockwell, Anaheim, California (JPL Contract No. 954372)	Chemical vapor deposition on low-cost substrates
General Electric, Schenectady, New York (JPL Contract No. 954350)	Chemical vapor deposition on floating silicon substrate
Univ. of Pennsylvania, Philadelphia, Pennsylvania (JPL Contract No. 954506)	Hot-forming of silicon sheet
INGOT GROWTH PROCESS	
Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)	Heat-exchanger ingot casting*

Table 4-3. Large-Area Silicon Sheet Task Contractors
(Continuation 1)

Contractor	Technology Area
INGOT CUTTING	
Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)	Multiple wire sawing*
Varian, Lexington, Massachusetts (JPL Contract No. 954374)	Breadknife sawing
*Single contract provides for both ingot casting and multiple wire sawing.

Figure 4-4. Capillary Die Growth (EFG and CAST) -
Mobil-Tyco and IBM

b. Silicon Ribbon Growth: CAST Method - IBM. The capillary action shaping technique (CAST) is based on the same principle as EFG growth (Figure 4-4); i.e., it utilizes a die constructed from material which is wetted by molten silicon. Work under this contract is directed toward evaluation of the technical and economic potential of CAST for the preparation of silicon 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 silicon growth by this and other growth techniques.

When administrative and other problems are overcome in renewal of the CAST process program, work will advance to develop greater insight into this ribbon process; these understandings will also aid the EFG technique exploration. Growth analysis, ribbon characterization, and economic analysis will be looked into. It is not presently clear when the program extension will be negotiated.

c. Silicon Ribbon Growth: Inverted Stepanov Technique - RCA. In this program emphasis is placed on developing a technique for growing ribbon-shaped silicon using a "nonwetted" die (Figure 4-5). The use of the "nonwetted" die provides the possibility of minimizing the reaction between the molten silicon and the die material. Reaction between molten silicon and wetted dies is one source of degradation in the crystallographic quality of silicon 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 silicon rod.

Work on the inverted Stepanov process is still being held up because of erratic wetting of the SiO_2 die. The SiO_2 experimentation has been suspended and other materials are being evaluated for their suitability for growing ribbons with the process.

d. Silicon Ribbon Growth: Web-Dendritic Method - University of South Carolina. Web-dendritic growth makes its own guides of silicon, whereas most other ribbon processes must rely on materials other than silicon for the guides (i.e., dies) (Figure 4-6). The guides are thin dendrites that grow ahead of the sheet and support the molten silicon between them to form the sheet. The dendrite guides grow in a very precise orientation dictated by their unique growth habit. Thus the 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.

Figure 4-5. Inverted Stepanov Technique - RCA

The web-dendritic effort is riddled with problems in optimizing furnace geometry. In the best furnace configuration so far developed, ribbons 1 inch wide by 15 inches long have been grown. The thermal radiation analysis was completed during this quarter.

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 silicon ribbon (Figure 4-7). The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid silicon 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.

The machine being used for the RTR process was shut down for most of this quarter because of problems with the transport system. To date, 2-1/2 cm-wide ribbons have been grown. Owing to laser power and scan limitations, growth speeds have been limited to 0.25 cm/min. The high-temperature postheater was installed, and the ribbons grown have been shown to have negligible thermal stresses. Testing indicates that the RTR ribbons are still 20% to 30% lower in conversion efficiency than the equivalent single crystal cells. It is considered very important that this degradation mechanism be understood. A follow-on contract is being prepared to further this.

Figure 4-6. Web-Dendritic Growth - University of South Carolina

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 silicon sheet on inexpensive substrate materials (Figure 4-8). As applied to silicon sheet growth, the method involves pyrolysis, or reduction, of a suitable silicon compound at elevated temperature and approximately atmospheric pressure. A laboratory-type CVD reactor system with a flow-through (open-tube) vertical deposition chamber is used for these investigations. The substrate is mounted on a silicon carbide-coated carbon 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 cm², is used as a research vehicle in an attempt to reach the goals of 100 μ m grains deposited 20 to 100 μ m thick on inexpensive substrates at rates up to 5 μ m per minute.

During this quarter, 20 different suppliers were investigated for substrate materials, which included glasses, ceramics, glass-ceramics, and composites. It was found that re-firing polycrystalline aluminas results in only limited grain growth in the wafer surfaces in contact with another surface. There has been repeated evidence of contamination of films deposited on various glass substrates.

Figure 4-7. Laser Zone Crystallization - Motorola

g. Silicon Sheet Growth: Hot-Forming of Silicon - University of Pennsylvania. This contract is designed to determine the feasibility of hot-forming silicon in a cost-effective manner. The procedure to be followed is high-strain-rate ($\dot{\epsilon} > 1$), high-compression deformation of silicon. From this information, one can construct the hot-forming diagram for silicon 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.

During this quarter, stress and strain rates in the hot rolling program have been increased up to 5/sec at 1380°C and at 1300°C . The stresses increased precipitously with increasing strain rate at 1100°C , but for high temperatures the increase is rather slow. A preliminary economic analysis was performed with the goal of identifying the most important controlling parameters.

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 4-9). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves

Figure 4-8. Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International

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 silicon 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 silicon.

The Heat Exchanger Method of casting large silicon ingots has demonstrated a crack-free ingot growth using crucibles which have been coated with sintered silica. The sintered silica separates freely from the silicon ingot during cooldown and prevents cracking.

h. Ingot Cutting: Multiple Wiring Sawing - Crystal Systems. Today most silicon 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

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 4-9. Crystal Growth Using the Heat Exchanger Method - Crystal Systems

can be utilized to slice silicon. The multiblade slicer has not been developed for the semiconductor industry since this method produces bow and taper unacceptable for integrated-circuit applications.

The overall goal of the slicing program is to optimize multiblade (wire) silicon 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.

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.

Wire wander has been identified as the most important problem affecting the wire sawing process. This wandering has been reduced by an order of magnitude by installing a grooved roller support and a guide system for the wires. During the quarter, more than 12 runs were made with one set of tungsten wires impregnated with diamond without causing degradation of wire failure.

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 Background

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 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 silicon 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 4-4. 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 are 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.

Table 4-4. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Memorial Institute Columbus, Ohio (JPL Contract No. 954328)	Study 1: Identification of candidate encapsulant materials based on a review of (a) world-wide experience with encapsulant systems for silicon solar cells and related devices and (b) the properties of other available materials. Study 2: Definition of environmental conditions for qualifying encapsulant materials. Study 3: Evaluation of encapsulant material properties and test methods. Study 4: Analysis of accelerated/abbreviated encapsulant test methods.
Rockwell International Anaheim, California (JPL Contract No. 954458)	Experimental evaluation of accelerated/abbreviated encapsulant test methods.
Simulation Physics Burlington, Massachusetts (JPL Contract No. 954521)	Electrostatically-bonded glass covers.
Springborn Laboratories Enfield, Connecticut (JPL Contract No. 954527)	Polymer properties and aging.
Endurex Dallas, Texas (JPL Contract No. 954728)	Ion plating process and testing.

4. Encapsulation Task Technical Activities

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 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.

Ultraviolet and temperature cycling exposures through 1000 hours have been completed on polymer films of "Teflon" FEP, weatherable Mylar, UV-stabilized Lexan, Korad A, Tedlar, Flexigard, Halar, and Aclar and

*Final reports on Studies 1 and 2 under the Battelle contract (refer to Table 4-4) have been published. Work on Study 4 was completed early in the present quarter, and the final report is scheduled for publication early in July.

**Carroll, W., Cuddihy, E., and Salama, M., Materials and Design Considerations of Encapsulants for Photovoltaic Arrays in Terrestrial Applications, IEEE Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

on Acrylite, Lexan, and Sun-Lite polymer sheet materials. Water-vapor transmission rate measurements are currently being performed on unexposed samples of each and on samples which have been exposed to UV or temperature cycling. Data will be included in the final report.

Test samples of "Teflon" FEP, Korad A, Sun-Lite, Tedlar, and Halar film and sheet materials and free films of the Acryloid B-7, Silgrip SR-573, and Scotch-Weld 2216 B/A adhesives were exposed to UV, temperature cycling, and high humidity (100% R.H., 100°F (38°C)). These samples were used in studies of the effects of the various exposure conditions on normal light transmittance. The work also includes measurements of the transmittance of film and sheet subsystems with the several adhesives before and after exposures.

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.

Studies of film-to-film adhesive bonding, determined by lap-shear-strength measurements before and after thermal and UV exposures were computed. Data were reported earlier for subsystems of "Teflon" FEP, weatherable Mylar, and UV-stabilized Lexan films bonded with various adhesives through 1000 hours of UV and temperature cycling exposures. Similar evaluations have been completed for Korad A and Tedlar subsystems. Five hundred-hour exposures of Flexigard (sheet material) subsystems have been completed. Selected adhesives for Korad A film through 1000 hours of temperature cycling showed no significant decrease in bonding performance. After 1000 hours of UV exposure, two adhesives, Scotch-Grip 4475 and 4693, did show bond strength decrease. Cohesive failure occurred with the 4693; breaking of the film adjacent to the bonded area occurred with 4475. Neither subsystem had failed after a 500-hour exposure. No significant decrease in bonding performance was noted for the other adhesives evaluated.

Evaluations of adhesives for bonding Tedlar film after 1000-hour exposures to thermal cycling and UV showed no significant decrease in bonding performance. Bond strength values obtained with the Cavalon 3100S (using benzoyl peroxide as the catalyst) suggest that cure was incomplete. Thermal controls and experimental samples all

had higher bond strength values. Benzoyl peroxide was used in order to eliminate the dark color noted with catalysts 3300S and 3303S. The adhesive area does have some milkiness which might be overcome by appropriate combinations of catalyst concentration, cure time, and temperature. Data on all of the film/sheet and adhesive materials will be presented in the final report.

Water vapor transmission rate measurements of Acrylite, Lexan, and Sun-Lite (fiberglass reinforced polyester) sheet-adhesive subsystems were performed.

Bubble formation occurred during laminations involving the thermoplastic acrylic adhesive (Acryloid B-7) and the Acrylite and Lexan sheet materials. It is likely that solvent in the adhesive formulation was absorbed on the surface of these sheet materials and was released to produce bubbles when heat and pressure are applied. A number of failures (high rate of water-vapor transmission depleting the desiccant) were observed in the unexposed and temperature-cycled samples. No bubbles were noted with the Sun-Lite Acryloid B-7 subsystem.

The Acryloid B-7 and Scotch-Grip 4693 perform better than Silgrip SR-573 with the Sun-Lite material. With the Acrylite and Lexan materials the Scotch-Grip 4693 and Silgrip SR-573 are superior to Acryloid B-7.

Adhesives, coatings, and pottant material were conformally coated on solar cells, and the subsystems were evaluated for resistance to high humidity, using visual observations and electrical measurements. In this work, seven coatings, nine adhesives, and one pottant were applied directly to silicon cells. The electrical responses of the cells were measured after high-humidity exposure (100% R.H., 38°C) and were compared with those of the uncoated cell. Four of the seven conformal coatings took on a milky appearance as a result of the high-humidity exposure. Three of six adhesives on test also showed some degree of milkiness. Thus far the milkiness has been restricted to two classes of materials, the acrylics and the polyvinyl butyral resins. The Scotch-Grip adhesives 4693 and 4475 showed some effects of the high-humidity exposure. The electrical characterizations will be discussed in the final report.

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)

*Carmichael, D.C., Gaines, G.B., Sliemers, F.A., and Kistler, C.W., Materials for Encapsulation Systems for Terrestrial Photovoltaic Arrays, IEEE. Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

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 silicon cell, the fundamental limitation of V_{oc} is the Schottky diffusion current. V_{oc} is then a 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-silicon 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.

To predict how long and how well the encapsulants can perform, it is necessary to have a mathematical model which describes the degradation processes. In principle, by inserting measured values for degradation rate constants into a suitable equation, any property can be predicted as a function of time.

Phoenix, Arizona and Miami, Florida, were selected as suitable sites for the weathering tests. Complete weather data and outdoor exposure services are available at both locations. Encapsulated Universal Test Specimens (UTSs) were placed outdoors on racks and were returned for examination at appropriate time intervals. Upon receipt, they were examined chemically, physically, and electrically to establish degradation rates. Based on this data, probable failure mechanisms are being developed.

Similar test specimens were exposed in a weathering chamber. The factor studied were light intensity, temperature, and humidity. There were 24 combinations of these. Degradation rates were measured and are being compared with those found for outdoor exposure.

The indoor tests have been concluded and the outdoor tests are proceeding as planned. One mode of deterioration is a progressive yellowing of the encapsulant films due to photochemical reactions near the surface. This change in optical transmittance is precisely measurable and therefore especially useful for mathematical modeling. Other failure modes of polymeric materials observed included loss of clarity, formation of surface carbonyl groups by oxidation, loss of tensile properties, and lowering of the glass transition temperature. Moisture-related failures of the solar cells themselves are now being analyzed. So far, these cell failures have been confined to the accelerated test.

Statistical analysis of the results eventually will permit the development of a predictive model for the inherent weatherability of encapsulants. Effects of complex conditions, such as rapid temperature changes, will be superimposed on the baseline estimate during the follow-up program. The continuing abbreviated testing program, involving determination of seasonal model equation parameters, is a necessary complement to accelerated testing in the methodology.

The Universal Test Specimens (UTSs) showed only a slight reduction (average 4%) in solar cell power output after 150 days of outdoor exposure, including exposure on the EMMA and EMMAQUA sunlight-concentrators. In the accelerated test at continuous high humidity, moisture-related degradation of some cells was observed. Failure analysis is in progress.

The yellowing of Lexan film was attributed to light at 290-300 nanometers. The effect was greatly accelerated by Pyrex-filtered xenon light. As expected, the yellowing rate dropped with age of the lamp. This effect was due to the solarization of the lamp envelope and/or filter. On the other hand, the yellowing of polystyrene film was due to light of higher wavelengths (319 nanometers according to the literature). Consequently, the yellowing

rate in this case was unaffected by lamp aging. Yellowness of the film represents a decrease in the transmittance only for violet light. It has negligible effect on solar cell performance. This is because the cell has a low response at the lower (violet) end of the visible spectrum.

Because transmittance at 360 nanometers can be measured quickly, nondestructively, and precisely, it has been given most of the attention in the development of model equations. This property is not itself critical to cell performance, but it might be correlated with a more significant property such as tensile strength. However, this correlation must be made advisedly. For example, under xenon light the yellowing rate was unusually rapid compared with the rate of chain scission (tensile loss).

Other film properties studied were tensile strength and elongation, carbonyl formation by attenuated total reflectance--infrared, transmittance of 600 nanometers, glass transition temperature by thermal mechanical analysis (or differential scanning calorimetry), and thermal stability by thermal gravimetric analysis. A study of a series of weathered polystyrene films by electron surface chemical analysis is pending.

Proposed abbreviated testing methodology includes outdoor exposures beginning on the summer and winter solstices to get seasonal parameters for model equations. A much higher rate of degradation (as judged by transmittance at 360 nanometers) was observed for Lexan when exposure began early in September than when it began on the winter solstice (December 22). Model equations will be discussed at length in the final report. No general conclusions or recommendations are appropriate at the present time.

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.

By the end of the previous quarter, functioning bonded solar cell modules had been fabricated for the first time. Process optimization was being conducted in preparation for fabrication of deliverable demonstration modules of the first type. These single glass sheet (Type 1)

modules have been delivered and are undergoing tests at JPL. Two more module types (Types II and III) are to be produced as part of the current effort. Both of these designs will provide front and back glass encapsulation. Development of both series is nearly completed. Single cell prototypes have demonstrated most of the design features to be incorporated into these modules. Fabrication of both types should begin in the near future.

Efforts of the last 3 months have included:

- (1) Bonding of metal foils with application to module output terminals and cell interconnection.
- (2) Major deformation bonding with evaporated film metallization.
- (3) Bonding to silk-screened interconnection patterns applied to glass.
- (4) Hot pressing of glass to produce major deformation as would be used in preshaped glass forms.
- (5) Bonding to ground glass surfaces.
- (6) Preparation of bonded evaporated film and silk-screened lap shear test samples; evaluation of shear strength test results.
- (7) Delivery of the first series of demonstration modules produced with electrostatic bonding.
- (8) Development of module configurations to be fabricated as part of this program.

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.

Efforts during the quarter involved the following studies:

- (1) The inclusion of 24 potentially useful encapsulant materials into a program of accelerated aging and evaluation.
- (2) Tabulation and correlation of the changes in optical characteristics after 120 days of accelerated aging.

- (3) Tabulation and correlation of changes in mechanical properties after 120 days of accelerated aging.
- (4) Measurement of the effects of 6 months of soil accumulation.
- (5) Continuation of an adhesion study involving the screening of commercially available primers, adhesives, and processes to bond candidate encapsulant materials to solar cells and substrates.
- (6) Evaluation of fungus attack on candidate materials.
- (7) Considerations of processing and design parameters.
- (8) Preparation of test modules (mini-modules) by Solar Power Corporation.

The results of optical testing over the visible range after the 120-day exposure period indicate that all materials decrease in transmission from their control values. The most dramatic changes can be seen in the most severe conditions (Weather-Ometer, RS-4/100°C) and degradation to the point of disintegration was observed in Tedlar, C-4 polycarbonate, and Tenite 479. The worst decreases in transmission were found for Udel 1700 (polyaryl sulfone), Tedlar, Sylgard 184, and RTV 615 after Weather-Ometer exposure. The least affected were PFA, CR-39, Plexiglas DR-61K, and Plexiglas V-811.

Transmissions measured over the ultraviolet range (after 120 days exposure) showed generally decreasing values with no particular connection to the type of exposure condition. Uniform increases in ultraviolet transmissions were found for Kynar 460 and Tenite 479.

An RS-4/55°C condition was set up with provisions for maintaining 70% relative humidity, the purpose being to further examine hydrolytic instabilities. No great differences were observed between these results and those of the Weather-Ometer, except in the cases of Udel 1700, RTV 615, and Sylgard 184, which appeared to be less severely affected. The overall trend was to decrease in transmission value, as usual.

Ultraviolet transmissions of the RS-4/55°C, 70% RH exposure appeared to decrease to a certain value after 30 days and change little with increasing time. Tedlar showed the greatest loss, retaining only 7% of control measurement.

A table of "Material Transmission Index" values was compiled by multiplying the control value (%) by the exposure value (%) for three conditions; RS-4/55°C, Weather-Ometer and RS-4/55°C, 70% RH. The values are indicative of overall material performance and suitability. The best performance is found for CR-39, PFA, and both Plexiglas formulas. Again, no great difference was noticed between Weather-Ometer and RS-4 high humidity exposures.

Results of hardness (ASTM D-2240) evaluations demonstrate the tendency for all materials to decrease in surface hardness with time

in all conditions. The only exceptions are the two silicone rubbers, Sylgard 184 and RTV 615, which steadily increase in hardness.

Mechanical properties were determined by conventional Instron testing; values for tensile strength and elongation were obtained after aging 30, 60, and 120 days. The results for tensile strength were variable but showed tendencies to increase in most cases. Some materials appeared to be unaffected. Generally, the variations were more pronounced with increasing severity of condition.

Elongation at break appears to be the most sensitive indication of polymer degradation, showing the widest changes in values as aging proceeds. Increases in elongation were found for some materials, (Kynar, Halar, PFA, Tefzel) in certain conditions but in some instances (high temperature) a decrease was found. Fluorocarbons tended to gain in this property and most other materials lost. Again, the most dramatic variations were noticed in the most severe conditions.

Because of poor overall performance and potential the following materials have been dropped from the program and will undergo no further evaluation:

Resin

Reason for Rejection

Tefzel 280

- (1) Low optical transmission.
- (2) Poor optical stability.
- (3) Ultraviolet degradation.
- (4) Poor processability.
- (5) High cost.

Kel-F 800

- (1) Very poor mechanical stability.
- (2) Low flow temperature.
- (3) High cost.

Udel 1700

- (4) Very poor optical stability.
- (5) Very poor mechanical stability.

CR-39

- (1) Decay of tensile strength.
- (2) Development of fractures.
- (3) Completely unprocessable.

Soil accumulation specimens all lost a small percentage of the original optical transmission (except for Udel 1700 which degrades) but retained relatively clean surfaces. RTV 615, Sylgard 184, and

Viton AHV were the only materials that were severely affected and will have to be used outdoors with protective (high modulus) coatings.

Fungus testing demonstrated that most of the resins supported only light growth and were generally unaffected. Only RTV 615 and Tenite 479 showed persistent splotches of fungus and surface attack.

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 silicon 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.

f. JPL In-House Activities. Basic studies of adhesive bonding from a fracture mechanics standpoint are being continued by Dr. W. Knauss of Caltech.

Ongoing in-house activities are concentrated on failure analyses of modules from the 46 kW (Block 1) procurement, a limited amount of materials testing to support corrective action or design change recommendations, and field repairs.

SECTION V

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 BACKGROUND

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 (Figure 5-1). 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).

Phase I, which was initiated in February 1976, has these specific objectives:

- (1) To identify the requirements for economical manufacturing processes and facilities.
- (2) To assess the technology currently used in the manufacture and assembly processes that could be applied to solar arrays.

Figure 5-1. Production Process and Equipment Area Schedule

- (3) To determine the level of technology readiness to achieve high-volume, low-cost production.
- (4) To propose processes for development.

C. PRODUCTION PROCESS AND EQUIPMENT AREA CONTRACTS

Under Phase I contracts, three contractors (Motorola, RCA, and Texas Instruments) are performing parallel efforts (Table 5-1). The three-contractor parallel-effort philosophy was selected to obtain the broadest possible view of recommendations and conclusions upon which to base the contractual efforts of Phase II (Figure 5-1). During Phase I, these contractors are defining the requirements for an automated solar cell manufacturing sequence by evaluating processes now used by the semiconductor industry and the ways in which these processes can be modified/selected for high-volume, low-cost production of solar cell modules. Cost analyses are being conducted to provide economic guidelines to maintain an overall view of LSSA Project objectives.

The Phase I contractors nearly completed the technology assessment activities during the Oct.-Dec. 1976 quarter. Under the basic contract, it was planned that these studies would conclude in January; however, selected contracts are being extended approximately 6 months to pursue analysis of key process variables.

Several unsolicited proposals were received for advanced solar panel designs. Contracts are being negotiated for most of them. These include unique cell shapes, contacting methods, encapsulation techniques, and various means of achieving higher electrical efficiencies.

Two contracts were let for advanced panel designs as "fallout" from the 130 kW panel procurement. One of these, given to Lockheed Missiles and Space Company, is for investigation of a high transmission glass structure. The other, with Xerox Electro-Optical Systems, is for study of a panel fabricated of solar cells with holes in the centers which accommodate fasteners serving both mechanical and electrical functions.

Table 5-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
Motorola Phoenix, Arizona (JPL Contract No. 954363)	Phase I	Manufacturing processes assessment
RCA Princeton, New Jersey (JPL Contract No. 954352)	Phase I	Manufacturing processes assessment
Texas Instruments Dallas, Texas (JPL Contract No. 954405)	Phase I	Manufacturing processes assessment
Texas Instruments Dallas, Texas (JPL Contract No. 954475)	Support	Large area Czochralski silicon ingot growth and wafering improvements
Solarex Rockville, Maryland (JPL Contract No. 954606)		Processing energy study

D. PRODUCTION PROCESS AND EQUIPMENT AREA TECHNICAL ACTIVITIES

1. Manufacturing Processes Assessment -- Motorola, RCA, and Texas Instruments

Phase I assessment of state-of-the-art silicon solar array technology was formally concluded during this quarter. The Task's predominant activity during the quarter was to begin to manipulate the data resulting from those studies into increasingly practical forms. Much of this will, in turn, form a base for technology and industry development activities when Phase II procurements come into effect.

As was set forth at the 5th Project Integration Meeting in January, Phase I produced some key understandings related to the cost of manufacturing processes. One of the most important was that, because of automation, labor costs in solar module manufacturing will be minor. It was found that the major price driver will be the cost of materials and supplies consumed during fabrication. This puts the focus on the cost-effectiveness of processes and the sensitivity of those processes to tolerance variables in commercial production.

It was these two factors that were addressed in the 6-month add-on procurements initiated during this quarter. Motorola, RCA, and Texas Instruments were contracted to assess the cost effect of manufacturing

tolerances regarding the decreased cell efficiency that may result from the tolerances. They will then recommend the most promising sequences for potential development. Allowance was made for discrete process emphasis, so that steps from the candidate sequences may be commingled to form a fine-tuned master sequence or sequences.

2. Large-Area Czochralski Silicon Ingot Growth and Wafering Improvements - Texas Instruments

The purpose of work under this contract is to optimize current proven semiconductor techniques so as to produce silicon wafers in the most cost-effective manner. Accordingly, technical activity has primarily centered on establishing acceptable silicon crystal pulling and slicing rates.

Crystal Pulling

Continuing experimentation at Texas Instruments showed that an average growth rate of 12 cm/hr for 12-cm-dia. Czochralski crystals cannot be consistently sustained, but that 10 cm/hr can be. At the 10-cm/hr growth rate, the program goal of an 80% yield of 12-cm-dia. crystals from a 12-kg charge was demonstrated. Modified melt replenishment tooling was completed at Texas Instruments and was installed on a 12-kg puller. It was thought that this would allow the silicon poly to be added from an airtight feed system and that this would reduce the oxide problem that had plagued previous melt replenishment attempts. However, melt replenishment techniques for growing three crystals from one heat cycle were unsuccessful.

Crystal Slicing

Texas Instruments also began working on a new concept for cutting ingots on multiblade abrasive saws which called for the ingot to be rotated during cutting to increase the speed of the abrasive action. Sawing experiments using diamond blades in the multiblade saw and spinning the ingot have resulted in cutting rates approaching 50 mm/hr.

3. Processing Energy Study - Solarex

During this quarter, Solarex began to study the energy consumed during solar module manufacturing. The entire sequence of processes is being examined from this perspective, starting with the chemical reduction of silicon and finishing with the fabricated module. The energy requirements are being dealt with in regard to "energy payback" by relating the energy consumed during manufacture to the energy expected to be generated during the life of the solar module.

SECTION VI

ENGINEERING AREA

A. FUTURE MODULE REQUIREMENTS

During this quarter, work on future module requirements centered on finalizing the draft requirement for third generation large-scale production modules. This requirement was originally slated for the 150-kw procurement and has been under development since early FY77. Modifications to previous requirements typified by the Block 2 Large-Scale Procurement Specification, 5-342-1, Rev. B, were considered in areas which address the needs of future larger-scale photovoltaic applications. In particular, the needs for longer lifetime, increased standardization, compatibility with higher operating voltages, minimum installation costs, and improved performance were considered.

1. Electrical Performance

Based on the analysis reported during the previous quarter, to select a suitable module output voltage with respect to charging requirements for lead-acid batteries, the module voltage at Standard Operating Conditions was selected a 15.0 Vdc. This value makes provision for inclusion of a diode in small battery-charging applications but is also compatible with the use of modules in series-connected higher-operating-voltage applications. A concern has been expressed that large differences in the measured power of individual modules incorporated in series strings could reduce overall system output because of mismatch losses. During the quarter, preliminary analyses of the effect of such losses were conducted. As a result, the allowable variance of module output power for a minimum acceptable module has been reduced to 10% below the average module power. That is, $P_{\min} = 90.0 P_{\text{avg}}$.

2. Module Interconnections/Terminations

Near-term planning for ERDA demonstrations indicates that modules will be employed in applications where operating voltages are at least 250 Vac. Thus, it is important that the modules be easily connected, when installed, into series strings. Further, it is necessary to reduce installation time in the field, and minimize the need for field-installed inter-module cabling. For future module designs, an inexpensive quick-disconnect connector pair has been proposed. By hard-mounting the connector receptacle on the module near one edge, and at the opposite edge and the same end of the module, providing a short pigtail cable with the mating plug, it is possible to directly connect modules together into series strings. A further advantage to the use of the quick disconnect is that personnel safety is enhanced by not having to work with exposed contacts or studs. A number of connector types were actively investigated as design candidates during the quarter. The baseline connector selection is a two-contact connector manufactured by ITT Cannon for use by the automotive industry. Test experience with this connector was obtained

during the quarter through a JPL test program, the results of which were published in LSSA Task Report 5101-20, and through the use of the connector on one of the Block 2 modules.

3. Mechanical Configuration Requirements

An assessment of a variety of planned applications, experiments, tests, and demonstrations in the FY77-79 time frame and conceptual system design studies have shown a requirement for standardization of module configurations. Previous LSSA procurements have required that modules of any size be configured within a 46 inch by 46 inch subarray. This requirement has resulted in three to eight modules per subarray. Obviously, the larger the number of modules in an array, the greater the system-related costs for transportation, handling, installation, and electrical interconnects.

To decrease handling and installation costs associated with multi-kilowatt photovoltaic installations, it has been proposed that all future modules have the same length (48 inches) and a uniform mounting hole spacing (47 inches between rows, width spacing in increments of 3/4 inch). The width of the module would be selectable in increments of 3/4 inch up to a maximum of 48 inches to allow the manufacturers flexibility in choosing cell sizes and packing schemes to provide the required voltage and improved packing factor. The 3/4 inch variable width provides interchangeability of manufacturer's modules through the use of standard prepunched steel and aluminum for mounting modules into arrays.

To accommodate the 50 lb/ft² structural loading requirement, a depth of 2 inches below the mounting plane is allowed for stiffening ribs or other structural members. The module mounting interface is designed to allow front and back side access to the attachment fasteners. In the design of specific modules, efficient packing allows for mounting holes only at the rear since the cells cover the entire 48 inch length. In this case, the mounting holes may be accessible only at the rear if the module is capable of being attached from the front by clamping at four corners. This configuration is typical of installations on the roof of a residence, where only front side attachment is available.

4. Module Efficiency Requirements

Because of the importance of module efficiency to overall system area-related costs, increased emphasis has been placed on providing a standard method for specifying, comparing, and discussing module efficiency. Module efficiency is the module peak power output at an insolation level of 100 mW/cm² and cell temperature equal to the Nominal Operating Cell Temperature (NOCT), divided by the insolation level (100 mW/cm²) and the gross module area.* Gross module area is defined as the maximum overall length times the maximum overall width.

*For a discussion of the definition of the Nominal Operating Cell Temperature, see the LSSA Project Quarterly Report.

This definition has the advantage of providing accurate performance comparisons at expected field conditions for various module designs with different thermal performance and cell I-V temperature characteristics. It also provides an incentive to optimize the module - cell performance and costs for actual field conditions.

Module efficiency is considered to be the product of two major efficiency terms, operating cell efficiency and module packing efficiency:

$$\eta_m = \eta_{oc} \times \eta_p$$

where

η_m = module efficiency

η_{oc} = operating cell efficiency at NOCT, 100 mW/cm²

η_p = module packing efficiency

Operating cell efficiency is calculated as an average within an encapsulated module with the cells at NOCT and 100 mW/cm² insolation:

$$\eta_{oc} = \frac{\text{module peak power}}{\text{number cells} \times \text{projected cell area} \times \text{insolation } 100 \text{ mW/cm}^2, \text{ NOCT}}$$

Module packing efficiency is the ratio of projected cell area and gross module area:

$$\eta_p = \frac{\text{number of cells} \times \text{projected cell area}}{\text{gross module area}}$$

Obviously, these efficiency terms can be expanded into a product of several sub-efficiencies. A second study is under way to define these sub-efficiencies and provide typical examples for current state-of-the-art modules manufactured during Block 1 (46 kW), Block 2 (130 kW), and research and development procurements.

To determine an appropriate minimum efficiency level for future third generation procurements, a study was conducted utilizing a cross-section of existing solar cell and encapsulation technologies together with the proposed mechanical configuration requirements described above. Key assumptions used in the study were

- (1) The module maximum power voltage equals 15 volts at 100 mW/cm², NOCT. This is consistent with the charging requirements

of conventional 12 volt lead-acid batteries and corresponds to approximately 36 series solar cells.

- (2) The module geometry is constrained to 48 inches in length by any width from 10 to 48 inches.
- (3) Based on Block 1 and Block 2 procurements and minor improvements by several manufacturers, an operating cell efficiency of 10.35% at an NOCT of 45°C was assumed. Table 6-1 summarizes the cell efficiencies of the Block 1 and Block 2 procurements. Assuming a 5%/°C cell maximum-power temperature coefficient, an encapsulated cell efficiency of 11.5% is expected at STC (28°C).
- (4) Since several manufacturers have expressed risk/yield concerns for modules exceeding \$500, the configurations were held to approximately 50 watts.

Table 6-1. Cell Characteristics for Block 1 and Block 2 Modules

Module Mfg.	Encapsulated Cell Eff., STC	NOCT Eff.	Operating Cell Eff.	Procurement
V	0.110	0.94*	0.103	Block 1
	0.109	0.92	0.100	Block 2
W	0.125	0.96*	0.120	Block 1
	0.111	0.93	0.103	Block 2
Y	0.110	0.91*	0.100	Block 1
	0.107	0.91	0.097	Block 2
Z	0.105	0.87*	0.091	Block 1
	0.108	0.90	0.097	Block 2

*Estimated Value

$$\text{NOCT Eff.} = \frac{\frac{\Delta P}{\Delta T (\text{NOCT} - 28)}}{P @ 28^\circ\text{C}}$$

- (5) To preclude eliminating any existing production facilities or manufacturers, the module configurations used the six standard round cell sizes. Obviously, special cell sizes will nest more efficiently in the specified envelope and therefore produce a higher module efficiency.

Table 6-2 summarizes the characteristics of candidate module configurations with efficiencies greater than 7%. As shown in Table 6-2, by eliminating several module configurations, a minimum efficiency of approximately 7.5% is achievable with any standard cell size. As shown in the table, each module contains from 72 to 216 cells, a practical number of cells as expressed by the industry considering reliability and cost risks. Cell nesting lengths of less than 46 inches provide adequate room for module end features, bus bars, and termination features. Each cell layout configuration uses a 30° staggered pattern spaced 0.080 inch apart. This cell separation distance is adequate for normal variations in cell diameter and interconnect design.

Typically, glass style modules have a larger border than pan style modules since a 1/8 inch sheet of glass requires a frame bite of 0.5 inch beyond the cell nesting envelope as compared to 0.3 inch for the pan style modules. Based on the results of this study, a minimum module efficiency at standard operating conditions of 7% is proposed for future procurements.

B. THERMAL TEST RESULTS

Thermal testing continued during the past quarter with emphasis on determining the Nominal Operating Cell Temperature (NOCT) of the Block 1 (46 kW) and Block 2 (130 kW) procurements modules. Tests were completed on all of the Block 2 modules and two of the five Block 1 modules. Two special tests were also conducted to further examine the effect of fins and residential roof top mounting (enclosed rear). A summary of the measured NOCT and cell operating temperature efficiency (η_{NOCT}) values is given in Table 6-3.

The results show that the modules with nonmetallic, nontransparent substrates (130 kW - Y,Z and 46 kW - Y) have the highest NOCT (46°C to 48°C). The modules with a metallic substrate (with and without fins) or a transparent nonmetallic substrate operate at a lower temperature (41°C to 43°C). All of these modules have good thermal configurations and as a result the spread in NOCT is only 8°C.

In general, all of the modules utilize thin substrates which have a high infrared emittance. Very little additional thermal improvement is possible with these flat plate configurations. This is made evident by observing the η_{NOCT} displayed in Table 6-3 and the two parameters whose product results in η_{NOCT} . For the Block 2 modules, η_{NOCT} is between 0.90 and 0.93. If the lowest power temperature coefficient is combined with the lowest temperature difference (NOCT-28°C) then a η_{NOCT} of 0.94 is obtained. If, as suspected, 0.94 represents a practical upper limit for η_{NOCT} for a flat plate module, then all of the Block 2 modules are within 4% of the thermally optimum design.

Table 6-2. Characteristics of Candidate Modules with Efficiencies Greater Than 7%

Cell Dia.	No. Cells	Watts/ Module	Nesting Length	<u>Module Width</u>		<u>Module Efficiency</u>	
				Pan	Glass	Pan	Glass
3.937 (100cm)	72	65	43.9	25.4	26.1	7.5	7.3
3.543 (90cm)	72	53	44.8	20.1	20.1	7.7	7.7
3.150 (80cm)	108	62	44.7	23.9	23.9	7.6	7.6
3.000 (76cm)	72	38	45.6	14.9	14.9	7.4	7.4
	108	57	42.6	22.4	23.1	7.4	7.1
2.150	144	39	46.0	14.9	14.9	7.6	7.6
2.000	108	25	44.9	10.4	10.4	7.1	7.1
	144	34	43.9	13.4	14.1	7.3	6.9
	216	50	45.9	18.6	19.4	7.9	7.6

Notes:

- (1) Encapsulated cell efficiency 10.35% @ NOCT = 45°C.
- (2) Cell spacing is 0.080 inch.
- (3) 36 cells equals 15 volts @ NOCT = 45°C.
- (4) Min. pan style border 0.35 inch; min. glass style border 0.5 inch.
- (5) 3/4 inch support structure hole spacing.

Table 6-3. NOCT and η_{NOCT} Summary

Module	NOCT °C	Max. Pwr. Coeff.	NOCT-28°C	η_{NOCT}	No. of Tests Performed
<u>130 kW</u>					
V	43.0	0.00505	15.0	0.924	6
W	41.1	0.00524	13.1	0.931	9
Y	47.0	0.00451	19.0	0.914	6
Z	46.0	0.00546	18.0	0.902	2
<u>46 kW</u>					
V	39.0	Not meas.	N/A	N/A	6
Y	47.5	Not meas.	N/A	N/A	10

To further explore the usefulness of cooling fins on the rear surface of modules, a number of tests were conducted using module V, which has a finned metal substrate. After obtaining a NOCT value for this module (three different tests), the fins were machined off of the module and the NOCT redetermined (three different tests).

Removing the fins increased the NOCT approximately 2.8°C. Assuming a maximum-power temperature coefficient of 0.5%/°C, the effect of the fins is to increase the power out of the module by about 1.4%.

In a third test, designed to evaluate the effect of a roof installation, three Block 2 Solar Power Corporation modules were mounted in a 4 x 4 foot array with the back side enclosed. Based on two tests, the NOCT increased from the normal 46.0°C (open back side) to 55.5°C for the roof mount simulation. Therefore, about a 5% reduction in power is indicated for a roof installation as compared to a field installation which has the back side open.

C. IMPACT LOADING (HAIL) TEST DEVELOPMENT

Discussions with environmental test personnel around the country have indicated a lack of suitable procedures for an impact (hail) loading

test for photovoltaic modules.* Furthermore, the impact tolerance (fragility) of the current state-of-the-art modules was unknown. During this past quarter analyses have been performed and development tests initiated to provide information for specifying an impact loading test requirement for the next solar array procurement as well as recommendations for impact loading tolerance.

The impact loading test development has concentrated on hailstorms because of their high damage potential to solar arrays throughout the country, but especially in the hailbelt of the central U.S. Other objects such as rocks, toy balls, and falling tools can also cause impact damage to solar arrays. Damage associated with these types of discrete events, although potentially significant, may not be as catastrophic as a hailstorm. The ultimate goal of the impact loading effort is to provide data so that cost trade-offs between the replacement costs of damaged solar arrays and the costs of strengthening the protective system can be performed.

Efforts for this program are directed toward accomplishing four objectives:

- (1) Develop a probability model for predicting the probability of a solar array being hit by a hailstone of a damaging size during its lifetime.
- (2) Establish hail impact strength and failure modes of current state-of-the-art photovoltaic modules.
- (3) Develop simplified test methods to be used for qualification testing by manufacturers.
- (4) Develop impact-resistant design concepts.

1. Hailstone Probability Model and Data Acquisition

The probability model developed for the hail environment is based mainly on the use of the Poisson distribution. Three quantities are used in the model. These are the average annual number of hailstorms at a given locality, the probability of occurrence of a hailstone of a given size or larger, given that a hailstorm occurs, and the number of hailstones of a given size or larger per unit area.

If the average number of hailstorms per year is λ , the probability of obtaining n hailstorms in a given year is $(e^{-\lambda}/n!)\lambda^n$, assuming a Poisson distribution. If $Q(d)$ is the probability of obtaining hailstones of a given diameter d or less, the probability of obtaining hailstones of diameter d or less in a year is

*Ross, R. G. Jr., "Design Considerations of Solar Arrays for Terrestrial Applications," Proceedings of the 1976 Solar Energy Society Conference, Winnipeg, Canada, Aug. 15-20, 1976, Vol. 6, pp. 48-56.

$$\sum_{n=0}^N \frac{e^{-\lambda} \lambda^n}{n!} Q^n(d)$$

where N is chosen sufficiently large so that subsequent terms are insignificant in contributing to the total probability; for this application N = 20 has been found to be sufficiently large. Therefore, the probability of obtaining hailstones of a diameter d or greater in K years is given by

$$P(d) = 1 - \left[\sum_{n=0}^{20} \frac{e^{-\lambda} \lambda^n Q^n(d)}{n!} \right]$$

The probability of having an area A, impacted by hailstones of diameter d or greater, given that such hailstones occur, is given by

$$P_I(A) = 1 - e^{-A \cdot M(d)}$$

where M(d) is the average number of stones of size d or greater per unit area and the Poisson distribution is used to determine the probability of a hit. Therefore, the probability of an area A being impacted by hailstones of diameter d or greater in K years is given by the product of these two probabilities:

$$\left(1 - \left[\sum_{n=0}^{20} \frac{e^{-\lambda} \lambda^n Q^n(d)}{n!} \right]^K \right) \cdot \left(1 - e^{-A \cdot M(d)} \right)$$

With this model established, the task of assessing the probability of hail damage reduces to the acquisition of the quantities needed to exercise the model. The average number of hailstorms, λ , is well known for most of the U.S. This quantity has been measured by the Weather Bureau and other agencies, in many localities for over 60 years. The other two quantities, Q(d) and M(d), are not as well determined. Some data exists, but it becomes very sparse for diameters of 1 inch or greater. For diameters less than this, there is data for a few selected localities. Values of M(d) are more difficult to obtain than Q(d). The literature has been consulted along with several hail experts, including Dr. Stanley Changnon of the Illinois State Water Survey in Champaign, Illinois and Dr. Peter Summers of the National Center for Atmospheric Research in Boulder, Colorado.

The remaining part of the hail assessment effort will involve an attempt to obtain as much data as possible for the above values. One of the main difficulties is the great variability in the values of the important hail parameters with locality. The values of the hail parameters for a given region are determined primarily by the meteorological conditions prevalent in that region. Therefore, generalization from one region to another may not be valid.

Table 6-4 gives the probability of an area 10 ft² being hit by hailstones of diameter equal to or greater than 1 inch in 20 years using the probability model described above.

2. Hail Testing

In simulating impact phenomena, parameters pertaining to weight, velocity, material properties (hardness, strength, stiffness, etc.) and geometry of both the target and projectile are important. To establish the hail impact strength of current state-of-the-art modules, it was decided, therefore, to duplicate all of the above parameters as closely as possible by impacting molded ice spheres on actual photovoltaic panels at velocities corresponding to the terminal velocity of naturally occurring hail. Five module designs of the 46 kW procurement and the four module designs of the 130 kW procurement were tested using simulated hailstones ranging from 1/2 to 2 inches in diameter. Table 6-5 shows the weight, velocity, and kinetic energy for various hailstone diameters.

A mold for making ice spheres was obtained from a previous JPL program of the mid-1960s where hail impact on antenna reflecting surfaces had been studied. This mold has a hemispherical cavity of the appropriate size in each of the aluminum mold halves. The mold is opened, a piece of ice somewhat larger than desired hailstone is inserted, and a combination of heat and pressure is used to mold the ice into an ice sphere as the mold is closed.

Table 6-4. The Probability of a 10 Ft² Area Being Hit by a Hailstone of Diameter 1 Inch or Greater in 20 Years

Average Number of Hailstones Per Year	Probability of a Hit
0	0.15×10^{-4}
2	0.94729
4	0.99703
6	0.99983
8	0.99999

Table 6-5. Hailstone Characteristics as a Function of Diameter

Dia. (in.)	Weight (lb)	Terminal Velocity (mph)	Kinetic Energy (ft - lb)
0.50	0.0021	34	0.03
0.75	0.0072	44	0.47
1.00	0.017	53	1.59
1.25	0.033	60	3.97
1.50	0.057	65	8.04
2.00	0.136	75	25.55

A pneumatic gun (see Figure 6-1) was constructed to fire the simulated hailstones at the solar panels. To simplify aiming, the gun fires vertically upward at the target solar panel, which is mounted overhead. The gun consists of a large reservoir which is pre-pressurized to the desired firing pressure. A simulated hailstone is dropped into the vertical barrel, and a fast-opening valve is opened which admits the pressure in the reservoir to the barrel, thus propelling the ice sphere at the desired velocity. To verify that the simulated hailstone achieves the desired velocity, a photo-electronic velocity measuring system is installed between the muzzle of the gun and the test article as shown in Figure 6-1. Tests using this apparatus are currently in progress.

D. CYCLIC LOADING ANALYSIS

1. Objective

A solar array in the field will be subjected to various cyclic stresses, primarily cyclic thermal stresses and cyclic wind loading stresses. The result of this cyclic loading environment generally manifests itself in the form of mechanical fatigue of various materials within the module. The solar cell electrical interconnection strip is often the weakest component with respect to this environment.

Current attempts to qualify modules with respect to the cyclic loading environment utilize two types of testing: thermal cycle tests and mechanical uniform load (wind) cyclic loading tests. Although the chosen loading levels and number of load cycles have been estimated on the basis of the best environmental and field performance data available the current levels must be considered preliminary at best.

Figure 6-1. Schematic of Hail Test Setup

To obtain improved qualification test methods, a study has been initiated to (1) accurately characterize the terrestrial thermal and wind cyclic loading environment, and (2) derive appropriate thermal and mechanical test environments. These test environments will be chosen to recreate the same level of material fatigue expected in the field in a power plant lifetime, and if possible will be defined so as to minimize testing time, complexity, and expense.

2. Program Development

The first step in the task was to develop a computerized approach for counting thermal cycles over an annual period. The approach involves reading weather tapes containing hourly temperature and insolation data and modeling the calculated module temperature history as a sequence of discrete loading cycles of fixed amplitude and mean value. The approach to counting cycles involves the concept of a system of equally spaced grid lines against which the actual temperature data is compared. Cycles are counted in terms of the grid lines which are crossed, as illustrated in Figure 6-2. Small cycles which do not involve the crossing of at least two grid lines are not counted (see Section A of Figure 6-2). A trade-off develops in determining the fineness of the grid system between neglecting small cycles and optimizing the time involved in computer analysis.

Figure 6-2. Use of Grid System to Determine Temperature Cycles

By use of this technique, the cyclic variations for a site over a given time period are categorized based on the grid system selected. Therefore a large number of cyclic variations are collected into discrete categories and counted as members of these categories. Lumped into a given category are cycles which may have differed in amplitude by an amount slightly less than the distance between two grid lines.

After the array temperature history is modeled as a collection of discrete loading cycles, the loading cycles are further aggregated into a limited number of categories according to the fatigue stress level associated with the particular type of cycle. Soderberg's law is utilized to quantify the fatigue stress level of cycles with different cyclic stress and mean stress levels. To determine the total fatigue loading imposed on the module, the cycle-ratio theory is used to combine the fatigue damage potential of each of the final loading levels based on an estimated stress-level/number-of-cycles-to-failure (s-n) relationship for the photovoltaic module of interest.

Word to date has involved debugging the cycle-counting program and digitizing actual wind data records for analysis by the same program.

E. WIND-LOADING SPECTROMETER DEVELOPMENT

Complementing the cyclic loading analysis described in the preceding section, the same methodology for counting fatigue loading cycles has

been incorporated during the past quarter into an instrument for directly characterizing the cyclic loading level of in situ winds. Recognizing that a large number of cycles of low intensity wind loading can eventually create as much fatigue damage as a relatively few cycles of high intensity wind it was decided to construct a "wind-loading spectrometer" which would record the full spectrum of wind loading. Furthermore, it was desired to measure, not the wind velocity, but the effective normal loading applied to solar panels resulting from the wind. These considerations dictated the design of the "wind-loading spectrometer" shown schematically in Figure 6-3.

The wind-loading spectrometer automatically constructs a wind-load intensity spectrum as follows: The strain-gaged panel produces a signal proportional to the effective wind pressure normal to the panel. Each time the wind intensity fluctuates between any two pre-set levels, a count is recorded by one of the 28 electromechanical counters provided. The set-points at which the counters are tripped are adjustable. This device has been completed, checked out, and installed in the JPL photovoltaic field test facility.

Figure 6-4 shows the 28 categories into which the effective normal wind intensity is categorized and recorded. The counts which would be recorded for the sample analog trace of wind intensity are also shown.

F. CLOUDY-DAY ANALYSIS

1. Summary

The impetus for performing the task described here was derived from Department of Defense requirements for criteria for selecting the optimal array/storage size for a given load. In the present work the mean insolation deficit, based on 10 years of weather data, has been determined for various numbers of consecutive days, up to 60.

Figure 6-3. Schematic of Wind-Load Spectrometer

Figure 6-4. Wind-Load Spectrometer (Illustration of Function)

This approach allows a comparison of the effect of a small number of high deficit days versus a larger number of low-to-moderate deficit days in succession. An equation giving the amount of battery and array required to ameliorate a given deficit was derived for a coordinate system representing insolation deficit and number of consecutive days. From this equation families of curves were derived and plotted. These curves may be used to determine the optimal array/storage size.

2. Preliminary Results

The actual insolation deficit for periods of N consecutive days (where $N = 1, 2, 3, \dots, 60$) was determined for six bimonthly periods based on 10 years of solar insolation data. The analysis was performed for 11 continental U.S. sites. The largest deficits were for short periods of time (insolation down 80-90% from the 10 year average); the deficits for longer periods tended toward values of 0-10%.

Results from each of the 10 given bimonthly periods (based on 10 years) were combined to give a 10-year worst-case composite. An average was determined by weighting each percentage deviation by the number of occurrences in 10 years. The average values were plotted as a function of the given number of days for which the deficit occurred. Figure 6-5 shows the average and the average plus 2σ plotted for Seattle for the bimonthly period centered in April

Figure 6-5. Insolation Deficit Versus Period Length for Seattle in April

The curves shown in Figure 6-5 can be scaled to demonstrate several effects. The curves can be normalized to the yearly average and each bimonthly curve plotted to this scale. Another type of scaling which can be applied is the increase or decrease of insolation over the horizontal-flat-plate expected value due to the tilting of the receiving plane. The combined effect of the two types of scaling can be seen in Figure 6-6, which shows the results for Seattle for a 60° tilt.

Comparison of results from different sites shows that the average and average plus 2σ curves are generally similar, although the levels may differ. It can also be seen which sites are more cloudy than others; comparison also indicates which sites have stormy periods in summer and which sites have them in winter.

Figure 6-6. Ten-Year Mean of Maximum Deficits During Each Bimonthly Period (60° Tilt, Seattle)

Figure 6-7 shows one of a family of parametric plots giving the amount of battery and array required to satisfy a given deviation from the average (100 indicates a 100% deficit or no sun). This plot is constructed for a particular fixed battery-to-array ratio; thus each curve represents a different size system with the same battery to array ratio. The number to the right of each curve is the ratio of the required system size to the size required if the system were sized for the mean insolation level with no deficits. Similar curves for other battery-to-array ratios allow selection of the optimum system to satisfy the expected or 2 σ insolation deficit for the site of interest.

A complete report with data for each of the bimonthly periods (Feb, Apr, Jun, Aug, Oct, Dec) and each of the 11 geographic sites is in preparation.

Figure 6-7. System Size Versus Deficit Covering Capability for a Fixed Battery/Array Ratio = 50 kW-h/kW

SECTION VII

OPERATIONS AREA

A. LARGE-SCALE PRODUCTION TASK

The last Block 1 (15 kW add-on) modules were delivered by Solar Power in mid-January to Lewis Research Center for Department of Defense applications.

Final design reviews were conducted for three Block 2 (130 kW) manufacturers during this quarter, and approval for production was given to all four. Production data as of the end of March:

	Final Design Review	Production Go-Ahead	Production Modules Shipped
Sensor Technology	01/31/77	02/07/77	2.5 kW
Solar Power	03/22/77	03/22/77	0
Solarex	01/26/77	02/16/77	0.86 kW
Spectrolab	11/05/76	03/18/77	0

At the request of MIT's Lincoln Laboratory, Sensor Technology module design was changed from 42 cells to 44 cells in mid-March.

Some delays were experienced in the initiation of production. Prime factors in these delays included the time required to implement design changes resulting from design reviews, to implement revised provisions of the JPL design and test specification (5-342-1), to obtain needed tooling and materials from suppliers, and to overcome production problems associated with new module designs.

Top priority on Sensor Technology and Solarex module shipments is being given to deliveries to MIT's Lincoln Laboratory for the agricultural pumping application in Nebraska slated for turn-on in July.

B. ENVIRONMENTAL TESTING

1. Block 1 (46 kW)

Essentially all of the planned Block 1 testing was completed by the end of the quarter. Table 7-1 shows the tests performed and the results obtained. Late production modules (Phase 2) were used for most of the exploratory testing. The fungus test was performed on older nonoperating modules from the initial production lot. In addition, samples from the 15 kW add-on were run through qualification tests. Tables 7-2 and 7-3 summarize the test results.

Table 7-1. Brief Description of Exploratory Test Procedures

Humidity/freezing	Two temperature cycles, from 23 to 65°C, at 95% relative humidity (R.H.) followed by 3 hours at -10°C; 10 times.
Hard rain	Rotate the module in a water spray from nozzles set to provide 17 m/s velocity at an average 2 mm droplet size, deionized water, 15 min.
Heat/rain	Heat in sunlight (or under heat lamps) to typical warm, midday temperatures. Then spray with deionized water at 2.5 cm/hr or more simulated rain until stable temperatures are reached; 5 times.
Humidity/heat	Saturate modules with moisture overnight (40°C, 95% R H.); then, quickly move modules under heat lamps set to the equivalent of 100 mW/cm ² until temperatures stabilize; 10 times.
Salt fog	Concentrated salt spary for two days in a chamber at 35°C and high humidity.
Fungus	Inoculate modules with 5 types of fungi. Place in a chamber at 29°C and 95% R.H. for 28 days.

Table 7-2. 46 kW, Phase 2 - Exploratory Test Results

Vendor	No. of Modules	Salt Fog		Hard Rain		Heat/Rain		Humidity/Freez.		Humidity/Heat		Fungus
		Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change	Phys. Change
V	4	<1%	0	0	0	1.5%	0	-	-	1.2%	(4)	(5)
W	4	<1%	0	0	0	1.5%	0	-	-	3.0%	0	(5)
Y	4	-	-	1.6%	0	<1%	0	-	-	<1%	0	(5)
Z	4	-	-	(1)	0	(2)	0	1.8%	(3)	2.3%	0	(5)

Notes:

- (1) Anomalous increase of about 5% observed in electrical output after hard rain.
- (2) A decrease in power output of about 8.5% after heat/rain.
- (3) Delamination, J-box degradation.
- (4) One cm of encapsulant peeled off one cell.
- (5) No fungus growth (electrical degradation not measured).

Electrical degradation is average percent decrease.

0 No observable physical change.

Table 7-3. Add-On Procurement - Qualification Test Results

Module Number	Temperature Cycling		Humidity	
	Elect. Degrad.	Phys. Change	Elect. Degrad.	Physical Change
1	8.7%	0	0	Encapsulant splitting
2	3.0%	0	<1%	0
3	(1)	0	(2)	J-box cover off
4	1.6%	0	<1%	0

Notes:

- (1) Erratic electrical output. 12% average degradation.
- (2) Output still erratic.

2. Block 2 (130 kW)

Qualification testing of the remaining Block 2 modules was essentially complete at the end of the quarter (see Table 7-4). Modules from the first of the four suppliers had been qualification tested in the previous quarter. The only test in this quarter on these modules (W type) was humidity/freezing. No degradation was observed.

Modules from one supplier (Z) showed evidences of cell cracking, encapsulant delamination, and cell lifting after a chamber malfunction. The chamber dropped in temperature about 20% faster than the specified rate. The test was discontinued, and two more subarrays were assembled and started again through the test series. A fourth subarray in which the cell-to-substrate adhesive has been eliminated is also undergoing tests. None of these later tests have shown the cell lifting problem, although encapsulant delamination has been noted.

In a problem unrelated to environmental testing, the W-type modules have shown a tendency to degrade electrically with time, even when stored in an air-conditioned laboratory. After 3 to 4 months, a loss of power of about 3 to 4% in most cases (but around 7% for two modules) has been observed.

Table 7-4. Block 2 (130 kW) Modules - Qualification Test Results

Supplier	No. of Modules	Temperature Cycling		Humidity Cycling		Mechanical Integrity (Wind)	
		Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change	Elect. Degrad.	Phys. Change
V	8	<1%	(8)D	0	(7)D	<1%	0
W	3	(1)	0	(1)	(1)VB	(1)	(1)CC
Y	4	1.2%	0	0	0	<1%	0
Z (cement)	6	(1)	(6)D, (3)CC	(1)	(5)D	0	0
Z (no cement)	3	(1)	(2)D, (1)CC	-	-	-	-

Notes:

- ()D Number of modules showing encapsulant delamination.
- ()VB Number of modules showing high-voltage breakdown.
- ()CC Number of modules showing one or more cracked solar cells.
- 0 No physical change.
- (1) Stored modules of these types showed erratic or drifting electrical output. Electrical degradation from environmental test not significantly more than observed with untested modules.

C. FIELD TESTING

During this quarter, 81 additional modules were placed in the field at JPL and 16 at Table Mountain, providing a total of 218 in the field at the three sites. The distribution for the Block 1 (46 kW) modules was as follows:

	<u>JPL</u>	<u>Table Mountain</u>	<u>Goldstone</u>
Solar Power	11	6	6
Spectrolab	38	18	9
Solarex	35	8	8
Sensor Technology	58	14	7

It is anticipated that by the end of April, the planned deployment of Block 1 modules will be complete. Eight of the modules deployed at the JPL site -- one Solar Power, two Spectrolab, three Solarex, and two Sensor Technology -- were mounted on a "long-term dirt subarray" for the purpose of investigating the prolonged effect of dirt on performance. In addition to these modules, a subarray containing three 130 kW Spectrolab modules was deployed at the JPL site and the Table Mountain site.

Thirty-two additional test stands have been delivered. Seven were installed at the JPL site, forming the second column of stands (Stands 9 to 15). Early in April a facilities work order will be initiated to install the remaining 18 stands to complete the JPL site. Work orders will also be initiated to add four more stands at both the Table Mountain and Goldstone sites to complete those sites.

The process of obtaining a periodic Large-Area Pulsed Solar Simulator (LAPSS) I-V record for each module in the field at Pasadena was continued during the quarter. The recording and tabulation of the data were mechanized with the aid of a computer program. Figure 7-1 is a representative computer tabulation for one module in the field. Basic performance data and trends are displayed.

The Table Mountain modules were also recycled back to JPL for flashing during the quarter. A computer record of those I-V data is also being maintained, and a similar record of the Goldstone modules will be initiated when they are recycled in April.

Work continued in several areas in connection with the automated data acquisition system for the Pasadena site: work at the system contractor on the actual data system, modification of the trailer to accommodate the system, installation of the electrical wiring connecting the modules and sensors to the data system, installation of the meteorological equipment, and formulation and implementation of the software. These individual efforts will come together next quarter when the data system is delivered. The scheduled delivery to JPL is during the last week in April.

SDLAREX 46 NO 1220

ENV. TEST T-106 IN FIELD 10/12/76 STAND 5 WEST PFR 1017

	DATE	ISC	VOC	P MAX	FILL FACTOR	DEL ISC	DEL VOC	DEL P-MAX	DEL FF
INITIAL	04/02/76	1.470	10.410	9.700	.6339				
REF.	11/22/76	1.460	10.230	9.470	.6340				
	12/02/76	1.460	10.300	9.370	.6231	.000	-.684	1.056	1.726
	12/16/76	1.440	10.300	9.300	.6270	1.370	-.684	1.795	1.108
	12/29/76	1.460	10.290	9.310	.6203	.000	-.409	1.690	2.168
DIRTY	01/12/77	1.400	10.250	8.990	.6265	4.110	-.196	5.069	1.193
	01/20/77	1.440	10.300	9.310	.6277	1.370	-.684	1.690	1.002
	02/10/77	1.460	10.400	9.420	.6204	.000	-1.662	.528	2.154
	02/24/77	1.460	10.200	9.270	.6225	.000	.293	2.112	1.824
	03/10/77	1.458	10.350	9.370	.6209	.137	-1.173	1.056	2.069
	03/24/77	1.440	10.380	9.220	.6168	1.370	-1.466	2.640	2.714

FIELD SUMMARY, DIRTY DATA EXCLUDED FROM THIS SUMMARY

AVERAGE DELTA ISC .531 AVERAGE DELTA VOC -.819 AVERAGE DELTA P-MAX 1.571

Figure 7-1. Representative Computer Tabulation of LAPSS I-V Data for a Module in the Field at Pasadena

D. PERFORMANCE MEASUREMENTS AND STANDARDS

A summary report of the interlaboratory standards measurements, performed last quarter, was made at the Semiannual Photovoltaic Program Review in San Diego in January.

Intermediate standard cells for the 130 kW procurement have been delivered to the large-scale procurement manufacturers. Prior to delivery, characterization tests and comparison tests with the 46 kW standards were completed.

Spectrolab prototype modules red/blue ratios have been compared to the standard cells to verify that the standards are spectrally representative of the production modules. The findings of the comparison tests indicate that the spectral matching is adequate for production testing.

Testing of Lewis Research Center and JPL reference cells in sunlight was continued during this quarter and is expected to be continued through the next quarter.

Design and fabrication of a laboratory water vapor/turbidity photometer was completed; final checkout and calibration will take place during the next quarter. A hand-held battery-power water vapor/turbidity photometer with self-contained readout display has been designed. Fabrication of this unit is in progress and will be completed during the next quarter.

During this quarter 1,712 module tests and 86 cell tests were run on the JPL LAPSS. The same level of effort is expected to continue through the next quarter.

E. FAILURE ANALYSIS

The solar cell module problem/failure reporting procedure document draft has been reviewed and revised. The released document (JPL 5101-26) is expected to be available in early May. The document will provide a unified reporting system for problem/failures resulting from environmental testing and field application.

During this quarter problem/failure report (P/FRs) and analysis activity occurred as outlined in Table 7-5 for Blocks 1 and 2. The P/FR reporting has been solely from JPL environmental and field testing.

The Block 1 failure analysis showed problems with interconnects for Vendors V, Y, and Z. Cable and terminal problems in Vendor Z modules caused power input degradation during add-on qualification testing. Vendor W module power degradation after humidity testing was found to be caused by moisture penetration to the cell metallization, causing contact problems.

Table 7-5. Summary of P/FR Activity

Vendor	Procurement	New P/FRs	Closed P/FRs	Environmental Test	Field Test
V	Block 1	1		7	1
	Block 2	6	1	7	1
W	Block 1	9		9	
	Block 2			9	
Y	Block 1	1	13	13	1
	Block 2			13	1
Z	Block 1	7	17	33	4
	Block 2	10	3	33	4

Block 2 problem/failure analysis experience with Vendor V modules relates to cracked cells and delamination of encapsulant from the substrate after environmental qualification testing. Analysis shows a lack of bond between layers of silicone rubber. A materials study of the problem is in progress. Other module problems observed were cracks in the metal substrate reinforcing ribs caused by forming-die clearance. The vendor has reworked these dies to prevent damage to future modules. Solder joints were found to exhibit cracking at the terminals due to handling. The vendor has changed his assembly procedure to prevent excessive working of soldered wire in the assembly process.

From an analysis of Vendor Y modules, it was found that the voltage breakdown was caused by nicked egress wires, which resulted in a decrease in insulation resistance when subjected to humidity or salt fog tests. These problems are attributable to workmanship.

Vendor Z modules have experienced cracking of cells, delamination of encapsulant and changes in electrical output after environmental testing. The vendor has changed his prototype design by eliminating the use of adhesives to fix cells to the substrate (other than silicone rubber) to reduce cell cracking tendencies. Analysis is continuing to determine other causes of cell cracking and shifting of electrical output.