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DEPARTMENT OF ENERGY

LSA LOW-COST SOLAR ARRAY PROJECT

Project QUARTERLY REPORT-8

FOR THE PERIOD JANUARY 1978 - MARCH 1978

5101-88

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JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

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ABSTRACT

This report describes progress made by the Low-Cost Silicon Solar Array Project during the period January through March 1978. It includes task reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, Project engineering and operations, and manufacturing techniques, plus the steps taken to integrate these efforts.

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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 1978. 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 has been 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 at a price of less than $500 (in 1975 dollars) per peak kilowatt by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. PROJECT OVERVIEW

The advanced sensitivity analysis model, Rapid Amortization of Capital Investment (RACI), was developed by the Array Technology Cost Analysis group and used to complement the analyses performed by the Interim Price Estimation Guidelines (IPEG). RACI provides a means for estimating a minimum manufacturing price after all initial capital investment has been recovered, and for estimating an initial price during the period of accelerated capital recovery.

In order to enhance the usability of Solar Array Manufacturing Industry Costing Standards (SAMICS), "SAMICS Usage Update Number 1" (JPL/LSSA Project internal report 5101-59) was distributed. The report addresses questions raised earlier and establishes how to handle a number of situations.

The Solar Array Manufacturing Industry Simulation (SAMIS) methodology is a procedure for obtaining price estimates and cost breakdowns for a user-specified manufacturing process sequence. Used in conjunction with SAMICS, which supplies standardizing assumptions, SAMIS simulates an industry within the computer. Ensuring the validity of the SAMIS III program has been a major consideration.

Contractor analysis of five power plant design concepts made significant progress with completion expected by the end of the next quarter. Efforts are also under way to develop a simulation model explaining terrestrial solar insolation variation due to various factors, and an operations and maintenance model translating replacement and cleaning policy action into economic impact has been progressing.

"Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems," JPL/LSSA Project internal report 5101-54 (Vols. 1 and 2), has been published and support continues for the Solar Energy Research Institute's study entitled "Photovoltaic Venture Analysis."

Nine developments are under way in the Silicon Material Task. These are supported by contracts for studies of the effects of impurities on the characteristics of materials and on the performance of solar cells, for chemical engineering and economic analyses, and for composition measurements as well as by JPL in-house efforts in chemical engineering, metallurgy, and process analyses. The continuing main purpose of the development contracts is to obtain experimental data to characterize the chemical reactions and to determine the operating conditions of the various reactors. These data also form a part of the information pool which will be used to evaluate the relative capabilities of the process developments.

The processes being developed under the contracts with Union Carbide and Battelle lead the others in schedule. In the case of Union Carbide, the extended operation of major units of the SiH_4 preparation section was successful, and considerable amounts of experimental data have been obtained for the separate reactors. In addition, the development of the two alternative reactors for SiH_4 decomposition (the free space and fluidized bed reactors -- FSR and FBR) continues along with increased efforts for Si-material transfer and consolidation.

In the case of Battelle, the preliminary design of an Experimental Process System Development Unit (EPSDU) was completed concurrently with further experimental operation of the FBR, Zn vaporizer, and $ZnCl_2$ electrolysis cell. In addition, Si, produced in a mini-unit, was supplied periodically to JPL.

In the Westinghouse contract, a reaction-analysis which led to a major reactor design problem was submitted to intense investigations. The result was a revision of the operating conditions and of the reactor design to accommodate the recommendations that the production separation be by condensation. Theoretical analyses were made of impurity concentrations in Si under the operating conditions of this process to support the design of the arc heater reactor.

Modified reactors are being investigated for different steps of the process being developed in the Motorola contract, and limited data indicated high conversion rates.

Some runs were made in an experimental direct arc furnace for further explorations of the Dow Corning process. These were done to establish baseline operating conditions. Tolerable concentrations for P and B were calculated to be 4 ppma each for the C-redundant.

In the SRI International contract, experiments for the Na reduction of SiF_4 were performed in an enlarged reactor using a modified injection system. It was shown that the Na-salt of H_2SiF_6 is preferable to the K-salt for the reaction producing SiF_4.

In the AeroChem investigations of the flame chemistry of alkali metals and halosilanes it was shown that the formation of Si atoms occurs very rapidly. Experiments in a scaled-up tubular flow reactor yielded a mixture of Si and salt from which the salt could be leached.

An AeroChem contract for the development of a computer code for the description of reactions or decomposition of gaseous silicon hydrides and halides is under way. Efforts centered on reducing the code size and memory requirements; this will permit an increase in the number of gas phase species and particle mass classes which can be incorporated.

The chemical engineering and economic analysis of the Union Carbide process was continued by Lamar University. A revised flow sheet and modified operating conditions were taken into account. Preliminary SiH_4 product costs were calculated.

Several tentative conclusions were obtained in the studies of the effects of impurities on cell performance under the contracts of Westinghouse and C. T. Sah Associates. The data secured by Westinghouse revealed that (1) crystal structure breakdown can result in impurity concentration changes of two to three orders of magnitude; (2) a controlled final water rinse is more effective than complicated acid treatments in cleaning the Si surface; and (3) far greater decreases in cell performance take place in polycrystalline cells, as compared to single crystal cells, when the Si contains an impurity such as Mn, which affects single crystal cell performance very little.

A computer model has been devised by Sah Associates for the characterization of impurity effects. The early general conclusions, which were derived using gold (Au) as the impurity in the calculations, are: (1) emitter recombination is unimportant for a model using an idealized diffusion profile and an undistorted energy band; (2) the effect of substrate dopant concentration on cell efficiency varies inversely with the density of recombination centers; and (3) the impurity donor level (Au) reduces the efficiency of both p-base and n-base Si solar cells.

The Large-Area Silicon Sheet Task reported progress in all five areas.

In contracts supporting shaped ribbon technology, Mobil Tyco demonstrated a full five-ribbon multiple growth and Motorola increased the maximum non-dendritic growth rate by using active cooling. The first runs of the new Westinghouse furnace permitted growth of wider dendritic web crystals.

Working under contracts for supported film technology, Honeywell reported near completion in the design of a new, experimental dip coater, and RCA Labs accomplished epitaxial growth on two potentially low-cost polycrystalline silicon substrates.

Ingot technology contractor Crystal Systems made progress in casting square cross-section ingots by the HEM method. Kayex Corp., Texas Instruments, and Varian all reported gains in developments in the advanced Czochralski process.

Work by five contractors on the die and container material studies is in the experimental stages, but Coors Porcelain has successfully fabricated and fired large-area, thin, mullite substrates for the Honeywell supported film development.

The Encapsulation Task initiated a three-month experimental effort to evaluate the adequacy of existing materials and processes. Fifteen designs and 65 mini-modules were fabricated and experimentally evaluated, bringing to a focus several encapsulation studies and providing the opportunity to assess where the effort is relative to Program goals.

A UV radiation facility to support an in-house program to study promising encapsulation materials was constructed. The facility consists of four UV exposure reactors and is supported by a wet chemistry laboratory. The facility was used to support a continuing effort to develop accelerated exposure test methods that will cause delamination of silicone materials.

Rockwell Science Center confirmed earlier findings on the lack of environmental stability in particular interfaces. The contractor also demonstrated the use of ultrasonics and ellipsometry as nondestructive tools for locating debonds and mapping quality of internal interfaces.

A report on evaluation diagnostic methods was distributed by Battelle and JPL approved recommendations by the contractor to investigate experimentally three diagnostic techniques.

In work on experimental evaluation of accelerated/abbreviated encapsulant methods by Rockwell, Weibull correlations of degradation of Lexan polycarbonate films were completed with close agreement between observed and predicted degradations if the tests are segregated according to times of year when the tests were started.

Endurex has proceeded in developing an ion-plating technique to lay down non-porous and smooth metallization on test coupons and solar cells, while another firm began work on a contract to develop low-cost encapsulation systems containing silicones.

A theoretical model has been developed by Case Western University that predicts the establishment of a constant interfacial moisture level for films greater than a critical thickness. The contractor is also evaluating the effects of stress on photo-oxidation rates.

The Production Process and Equipment Area reported progress in surface preparation, junction formation, metallization, and advanced module development.

In work on surface preparation, one contractor reported excellent control over silicon nitrite deposition from dichlorosilane and ammonium mixtures. AR coating and photoresist coating by dip method on silicon web material were shown to be effective and cost enhancing, and new techniques for spray-on and reflective coatings are being evaluated. In addition, a transfer of technology was accomplished between two contractors.

Junction formation efforts stressed ion implantation, laser anneal, and pulse energy annealing. Motorola presented ion implantation/sheet resistivity curve measurements for initial equipment evaluations. Texas Instruments reported that use of lower processing temperatures for diffusions seems to improve I_{sc} values, and the use of silane deposited oxide in place of steam growth improves I_{sc} by about 3%.

Lockheed, RCA, Sensor Technology, and Spectrolab achieved screen printing of contacts in work on metallization. The Motorola technique uses a solvent paste wax mask to occlude plating from undesired areas.

Cell efficiency of an overlap cell high density module fabricated for the advanced module development effort is being evaluated.

Engineering Area activities centered on array design guidelines, reliability-durability requirements, and array specifications and standards.

In the area of design guidelines, the Bechtel and Boeing contracts accomplished extensive analysis of module-to-array structural interfaces. An RFP was issued for study of residential photovoltaic module design requirements, the first version of a computer program to analyze the characteristics of series/parallel cell and module arrangements was completed, and procurement activities were initiated for a study contract to investigate module output termination and interconnection devices. In-house investigation was conducted to evaluate the effect of cell-to-cell spacing parameters on insolation collection enhancement due to internal reflections from intercell spaces.

The Clemson University solar cell reliability contract proceeded into Phase I testing. In support of soiling studies, agreement was reached with the South Coast Air Quality Management District to deploy various encapsulation material samples. Work also was done on exposure methods for delamination effects and analysis of humidity testing results. The feasibility of using a scanning laser beam to detect broken silicon solar cells was demonstrated.

Significant interface activity with outside organizations occurred in the area of array specifications and standards. A flat-plate module design and qualification test specification was generated in support of the flat-plate PRDA being prepared by DOE.

The Large-Scale Production Task in the Operations Area completed procurement of Block II modules, and in January implemented the five contracts for the Block III procurement. In environmental testing of Block II production samples, only one of six type W production modules was affected by qualification testing. A crack in one cell of a type V module was the only change after humidity-heat testing of four modules each of types V, Y, and Z. Twenty-eight Block III type Y modules were received, of which ten were tested for temperature coefficients. Six type O and nine type Y high density Task 4 developmental modules were also tested for temperature coefficients, and problems were encountered with both types.

Installation of a xenon lamp in a temperature/humidity test chamber during the quarter provided a combined humidity/UV test facility. Four old type Y Block I modules were tested in this facility, but no encapsulant delamination resulted. Further tests are planned using higher moisture saturation and more intense UV sources.

In field testing, two data acquisition system milestones were reached at the JPL (Pasadena) Site: (1) the system began routinely collecting I-V data and semi-routinely collecting dedicated task data (I-V, weather, insolation, summary), and (2) the system was placed on a 24-hour, 7-day a week schedule with problems of only an intermittent nature.

Work on the photon effect problem continued; one contractor has eliminated the problem while two others have completed a matrix experiment aimed at isolating the problem.

Also during the quarter, modification of the existing large area pulsed solar simulator system was completed to increase the speed of data printout.

Ten Problem/Failure Reports were filed and 36 were closed. Two new failure analysis techniques were developed which allow more rapid detection of problem cells within the modules.

SECTION II

PROJECT ANALYSIS AND INTEGRATION AREA

A. ARRAY TECHNOLOGY COST ANALYSIS

Progress was significant this quarter in Solar Array Manufacturing Industry Costing Standards (SAMICS). An advanced sensitivity analysis model (RACI) was developed and used to complement the analyses performed by the Interim Price Estimation Guidelines (IPEG). The JPL/LSSA Project internal document "SAMICS Usage Update Number 1" was distributed to enhance the usability of SAMICS. Finally, at the end of the quarter, the SAMIS III computer program was released.

1. Rapid Amortization of Capital Investment -- 8th PIM Strawman

In IPEG, the initial capital investment is recovered at different rates for different components of that investment. Equipment investment is recovered in seven years (at which time it is assumed it is replaced). Facility investment is recovered over a lifetime of 40 years. Both of these are recovered according to a straightline schedule. The interest during construction and startup costs are recovered over the lifetime of the facility (40 years).

In the Rapid Amortization of Capital Investment (RACI) model, the inital capital investment is recovered over some arbitrary period of time, with no distinction made as to whether it resulted from equipment or facility or startup costs. Amortization periods of 1, 1.5, 2, 3, and 7 years were investigated. RACI provides a means for estimating a minimum manufacturing price after all initial capital investment has been recovered, and for estimating an initial price during the period of accelerated capital recovery. In the tables which follow, the sensitivity to recovery time is investigated, using data available from LSSA's 8th Project Integration Meeting (PIM) strawman 20 megawatt plant design. Further sensitivity analysis investigates the effects of having less than 20 megawatt production with the strawman type of semiautomated facility.

The original SAMICS analysis of the strawman factory, presented at the 8th LSSA Project PIM, was based on data for a 20 megawatt plant, and the initial capital investment is recovered at a uniform rate over the lifetime of the facility. The RACI model describes the effects of several combinations of recovery time and factory size.

In extrapolating factory size downward, the following assumptions were made:

- Integer numbers of machines of the same size and performance characteristics as for the 20 megawatt plant (but usually not as many machines are required).
- Integer numbers of operators for each group of machines in a process step for each shift.

The result of these assumptions is a very low rate of utilization of some machinery and some personnel, especially at and below the 5 megawatt size. It is expected that this 20 megawatt technology would require extensive redesign in order to be employed at a 1 megawatt level of production.

Table 2-1 presents initial capital recovery prices for several capital recovery periods and for several polysilicon prices. This table concentrates on a 20 megawatt annual production quantity from a plant operating at capacity.

Table 2-1. Prices for 20 Megawatt Production from 20 Megawatt Capacity (1975 $/Wpk)

LSSA 8th PIM Strawman 2$/Wpk Design		Silicon Cost (1975 Dollars)			
Recovery Period		0	10	25	60
1 year	Price during writeoff	3.89	4.22	4.71	5.86
	Minimum price afterward	1.16	1.31	1.55	2.08
1.5 years	Price during writeoff	3.02	3.29	3.70	4.66
	Minimum price afterward	1.16	1.31	1.55	2.08
2 years	Price during writeoff	2.58	2.83	3.19	4.05
	Minimum price afterward	1.16	1.31	1.55	2.08
3 years	Price during writeoff	2.16	2.38	2.71	3.47
	Minimum price afterward	1.16	1.31	1.55	2.08
7 years	Price during writeoff	1.71	1.90	2.18	2.84
	Minimum price afterward	1.16	1.31	1.55	2.08
Plant lifetime	SAMICS/IPEG uniform price	1.65	1.83	2.10	2.73

Table 2-2 estimates the prices required to meet all the costs of a plant which could produce 20 megawatts with a four shift operation, but which in fact produces only 10 megawatts.

Table 2-2. Prices for 10 Megawatt Production from 20 Megawatt Capacity (1975 $/Wpk)

LSSA 8th PIM Strawman 2$/Wpk Design		Silicon Cost (1975 Dollars)			
Recovery Period		0	10	25	60
1 year	Price during writeoff	5.80	6.13	6.62	7.77
	Minimum price afterward	1.38	1.53	1.76	2.30
1.5 years	Price during writeoff	4.39	4.66	5.07	6.03
	Minimum price afterward	1.38	1.53	1.76	2.30
2 years	Price during writeoff	3.68	3.93	4.29	5.15
	Minimum price afterward	1.38	1.53	1.76	2.30
3 years	Price during writeoff	3.00	3.22	3.55	4.31
	Minimum price afterward	1.38	1.53	1.76	2.30
7 years	Price during writeoff	2.27	2.46	2.74	3.40
	Minimum price afterward	1.38	1.53	1.76	2.30
Plant lifetime	SAMICS/IPEG uniform price	2.20	2.38	2.65	3.28

The SAMICS price estimate for 10 megawatt production from a 20 megawatt facility is about 0.55 $/Wpk greater than for 20 megawatt production from a 20 megawatt facility. This differential is much larger if very short recovery periods are used.

Table 2-3 estimates the prices required by a plant with the same technology but which produces 10 megawatts at full capacity. Although the production quantity is the same as in the last case, to some extent the equipment and facilities expenses are reduced. However, some economies of scale are lost because of poorer utilization of some equipment and some of the direct labor. Here the SAMICS price estimate is 0.23 $/Wpk higher than the 20 megawatt estimate, but 0.32 $/Wpk lower than the estimate for 10 megawatt production from a 20 megawatt capacity plant. Shorter recovery periods increase these differences.

Table 2-3. Prices for 10 Megawatt Production from 10 Megawatt Capacity (1975 $/Wpk)

LSSA 8th PIM Strawman 2$/Wpk Design		Silicon Cost (1975 Dollars)			
Recovery Period		0	10	25	60
1 year	Price during writeoff	4.43	4.76	5.25	6.40
	Minimum price afterward	1.33	1.48	1.71	2.25
1.5 years	Price during writeoff	3.44	3.71	4.12	5.08
	Minimum price afterward	1.33	1.48	1.71	2.25
2 years	Price during writeoff	2.95	3.20	3.56	4.42
	Minimum price afterward	1.33	1.48	1.71	2.25
3 years	Price during writeoff	2.47	2.69	3.02	3.78
	Minimum price afterward	1.33	1.48	1.71	2.25
7 years	Price during writeoff	1.96	2.15	2.43	3.09
	Minimum price afterward	1.33	1.48	1.71	2.25
Plant lifetime	SAMICS/IPEG uniform price	1.88	2.06	2.33	2.96

Table 2-4 shows the impact of the under-utilized capital investment is increasing with the smaller plant size.

Table 2-4. Prices for 5 Megawatt Production from 10 Megawatt Capacity (1975 $/Wpk)

LSSA 8th PIM Strawman 2$/Wpk Design

Recovery Period		Silicon Cost (1975 Dollars) 0	10	25	60
1 year	Price during writeoff	6.64	6.97	7.46	8.61
	Minimum price afterward	1.62	1.77	2.00	2.54
1.5 years	Price during writeoff	5.04	5.31	5.72	6.68
	Minimum price afterward	1.62	1.77	2.00	2.54
2 years	Price during writeoff	4.24	4.49	4.85	5.71
	Minimum price afterward	1.62	1.77	2.00	2.54
3 years	Price during writeoff	3.47	3.69	4.02	4.78
	Minimum price afterward	1.62	1.77	2.00	2.54
7 years	Price during writeoff	2.64	2.83	3.11	3.77
	Minimum price afterward	1.62	1.77	2.00	2.54
Plant lifetime	SAMICS/IPEG uniform price	2.54	2.72	2.99	3.62

Table 2-5 gives the estimated price for the case where 5 megawatts are produced in a facility which has a maximum (four shift) capacity of 5 megawatts.

Table 2-5. Prices for 5 Megawatt Production from 5 Megawatt Capacity (1975 $/Wpk)

LSSA 8th PIM Strawman 2$/Wpk Design

Recovery Period		Silicon Cost (1975 Dollars) 0	10	25	60
1 year	Price during writeoff	5.38	5.71	6.20	7.35
	Minimum price afterward	1.57	1.72	1.95	2.49
1.5 years	Price during writeoff	4.17	4.44	4.85	5.81
	Minimum price afterward	1.57	1.72	1.95	2.49
2 years	Price during writeoff	3.57	3.82	4.18	5.04
	Minimum price afterward	1.57	1.72	1.95	2.49
3 years	Price during writeoff	2.98	3.20	3.53	4.29
	Minimum price afterward	1.57	1.72	1.95	2.49
7 years	Price during writeoff	2.35	2.54	2.82	3.48
	Minimum price afterward	1.57	1.72	1.95	2.49
Plant lifetime	SAMICS/IPEG uniform price	2.25	2.43	2.70	3.33

2. Summary of "SAMICS Usage Update Number 1"

The first few weeks of use of the Solar Array Manufacturing Industry Costing Standards (SAMICS), along with the exercise performed prior to the 8th LSSA Project Integration Meeting in December, led to some very penetrating questions.

The purpose of the document "SAMICS Usage Update Number 1," JPL/LSSA Project internal report 5101-59, is to answer those questions and to clarify and/or establish how to handle the following:

1. Elimination of the 42-hour work week.

2. Clearer labels on Format A and on Process and Company Work Sheets.

3. Relief labor (17.5% more labor is allocated to cover vacations, absenteeism, training, breaks, etc.).

4. Partial inspection processes.

5. Format A Column A22 -- amount required per batch <u>is changed</u> to amount required per minute of operation.

6. Processes that draw power even when not in use.

7. Format A Line A6 and Column A26 -- output rate and yield factor.

8. Rework loops and how to incorporate them into SAMICS.

9. Processes that use parts that require processing.

10. More general rework loops.

11. General technological loops.

12. Integerization of numbers of machines.

13. When to burden and when not to burden materials and supplies when using the IPEG formula. Briefly, do not burden materials and supplies that move from one work station to the next. Also, do not burden silicon, which is treated as though it is coming from a work station.

3. Release of SAMIS III

The Solar Array Manufacturing Industry Simulation (SAMIS) methodology is a procedure for obtaining price estimates and cost breakdowns for a user-specified manufacturing process sequence. The user must supply a description of each manufacturing process step -- specifically, certain parameters such as output rate and machine costs and direct requirements of the process (labor, supplies, and facilities). SAMICS supplies standardizing assumptions -- input prices, indirect requirements relationships, and company structure. SAMIS then simulates the industry within the computer: It explicitly generates overhead (supervisors, guards, etc.), pays taxes, insurance premiums, bills, and salaries. It replaces capital, recovers start-up losses, repays loans, and produces a SAMICS-specified rate of return on equity.

SAMICS is available now, both as a manual procedure which uses simplifying assumptions for the generation of indirect expenses, and as a computer program (SAMIS III).

Ensuring validity of the SAMIS III program has been a major consideration throughout the development process. The validation plan includes the following steps:

1. Select a testable methodological approach. Analyze in sufficient detail to permit causal submodels; eschew "fudge factors" and avoid "rules of thumb," which may not apply; then synthesize.

2. Validate the methodology. Review existing literature; conduct seminars, hire an outside firm to critique the methodology; actively seek industry review.

3. Verify the computer program. Divorce design from coding, use modern programming procedures (structured design, etc.); check numerical calculations; compare results against the manual procedure.

4. Validate the input data. Obtain SAMICS economic parameters from reliable sources, striving for "representative" values; rely on LSA technology development tasks for process description data; get users to give careful consideration to details of results to ensure validity of input prices and indirect requirements.

5. Validate the results. Compare with experienced "common sense" and with other estimates; compare against a contracted independent plant design (at three scales of operation).

6. Increase the exposure of the methodology to a wider range of potential critics both within LSA and beyond.

Near-term future plans for SAMIS III call for further studies of the LSSA 8th PIM strawman manufacturing sequence, pricing of additional manufacturing sequences, and improving and enhancing the computer program.

B. ARRAY LIFE CYCLE ANALYSIS

The Bechtel contract to analyze five design concepts is under way with significant progress reported by the end of the quarter. Completion is expected by the end of the next quarter.

Cooperative effort is also under way with LSSA Project Operations to develop a simulation model that explains terrestrial solar insolation variation due to time of day, latitude, and other factors. Both indoor and outdoor tests will be conducted.

An operations and maintenance (O&M) model which translates replacement and cleaning policy action into economic impact has been moving rapidly through a preliminary design phase. The model is termed LCP (Lifetime Cost and Performance) and represents the first detailed examination of O&M costs for large-scale photovoltaic systems.

C. ECONOMICS/INDUSTRIALIZATION

The JPL/LSSA Project internal report 5101-54 (Vols. 1 and 2) "Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems" and executive summary have been published and are available for reference from the LSA Project Data Center.

The Gnostic Concepts, Inc., contract entitled "Industrialization Study" has proceeded on schedule and an interim report has been submitted and accepted by JPL.

Continuous and detailed support of the Solar Energy Research Institute's study entitled "Photovoltaic Venture Analysis" has been provided by JPL. Support will continue until completion of the effort in July. Preparation of an appendix to that study entitled "The Industrialization of Photovoltaic Systems" has begun.

SECTION III

TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

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

1. Technical Goals

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

2. Organization and Coordination

The Silicon Material Task effort is organized into four phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing and assessing processes (in Part III) for the production of solar-cell-grade Si. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies, and the most promising process will have been selected.

Table 3-1. Organization of the Silicon Material Task Effort

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

Phase II will be to obtain process 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 Experimental Process System Development Units (EPSDU).

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, EPSDU will be used to obtain technical and economic evidence of large-scale production potential. In the EPSDU phase (i.e., Phase III) there will be opportunities to correct design errors; to determine energy consumption; to establish practical operating procedures and production conditions for process optimization and steady state operation; and to 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 EPSDU and the commercial plant will be operated concurrently for some time so as to permit the use of the EPSDU for investigations of plant operations, i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task 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

Seventeen contracts are in progress and are listed in Table 3-2.

4. Silicon Material Task Technical Background

a. Processes for Producing Semiconductor-Grade Si

1) Production of Si by Zn Reduction of $SiCl_4$ -- Battelle. 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 MT/yr plant.

2) Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. The Union Carbide contract is for the development of processes for the production of SiH_4 and for the subsequent deposition of Si from SiH_4. The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of metallurgical grade Si and the by-product $SiCl_4$ to $SiHCl_3$, 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.

3) Production of Si by SiF_4/SiF_2 Transport -- Motorola. The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using $SiF_4/(SiF_2)_x$ transport purification reaction steps.

Table 3-2. Silicon Material Task Contractors

Contractor	Technology Area
AeroChem Research Princeton, New Jersey (JPL Contract No. 954560)	Nonequilibrium plasma jet process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954777)	Si halide-alkali metal flames process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954862)	Model of silicon hydride and halide reactions
Battelle Columbus, Ohio (JPL Contract No. 954339)	$Zn/SiCl_4$ fluid bed reactor process
Dow Corning Hemlock, Michigan (JPL Contract No. 954559)	Electric arc furnace process
Lamar University Beaumont, Texas (JPL Contract No. 954343)	Technology and economic analyses
Materials Research Salt Lake City, Utah (JPL PO No. JR-672583)	X-ray analysis of silicon wafers
Motorola Phoenix, Arizona (JPL Contract No. 954442)	SiF_4/SiF_2 transport process
National Bureau of Standards Washington, D.C. (JPL Interagency WO No. 8604)	Impurity concentration measurements
Northrop Research Hawthorne, California (JPL Contract No. 954614)	Lifetime and diffusion length measurements
Sah, C. T. Associates Urbana, Illinois (JPL Contract No. 954685)	Effects of impurities
Schumacher, J. C. Oceanside, California (JPL Contract No. 954914)	High-velocity continuous flow reactor process

Table 3-2. Silicon Material Task Contractors
(Continuation 1)

Contractor	Technology Area
Spectrolab Sylmar, California (JPL Contract No. 954694)	Measurements of effects of impurities on solar cells
Stanford Research Institute Menlo Park, California (JPL Contract No. 954471)	Na reduction of SiF_4 process
Union Carbide Sisterville, West Virginia (JPL Contract No. 954334)	Silane/Si process
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Effects of impurities on solar cells
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Plasma arc heater process

b. Effects of Impurities and Processing on Solar Cell Performance

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

2) Measurements of the Effects of Impurities on Solar Cells -- Spectrolab. In this contract impurity doped ingots are used as material for the fabrication of solar cells by established processing. Performance measurements are used for analyses.

3) Effect of Impurities -- C. T. Sah Associates. Deep level transient spectroscopy measurements are to be used for correlations with the development of a model for solar cell performance.

c. Processes for Producing Solar-Cell-Grade Si

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process -- Dow Corning. 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.

2) Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 Process -- 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.

3) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. This contract with Westinghouse is for the development of an electric arc heater for the production of Si using the reaction for the reduction of $SiCl_4$ by Na. The first phase consists of a review of the chemical and engineering feasibility and the designing of a system for experimental verification; it includes four subtasks: reaction analysis, plasma reactor, reactor storage and injection, and product collection and effluent disposal.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of $SiCl_4$ -- AeroChem Research. The objective of this program is to determine the feasibility of the production of high purity SiH_4 or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes are being studied.

5) Production of Si Using Si Halide-Alkali Metal Flames -- AeroChem Research. The objective of this contract is to determine the feasibility of the use of flame reactions involving Si halides and alkali metals for producing Si.

6) High-Velocity, Continuous Flow Reactor for Producing Si -- Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes as the appropriate intermediates to produce Si.

d. Supporting Contracts

1) 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.

2) Impurity Concentration Measurements -- National Bureau of Standards. Methods for measurements of impurities at ppba levels are to be developed.

3) Model of Si-Producing Reactions -- AeroChem Research. This contract is for the formulation of a model and a computer code for the description of several of the Si processes now under development.

5. Summary of Progress

a. Production of Si by Zn Reduction of $SiCl_4$ -- Battelle. The preliminary design of an Experimental Process System Development Unit (EPSDU) sized for 50 MT/yr has been concluded. Battelle had overall responsibility for the design and subcontracted with Raphael Katzen Associates (RKA) to generate the design specifications of the conventional process equipment and with Pace Engineers, Inc., for the design of the $SiCl_4$ purification section. The Battelle efforts were focused on the design of the nonconventional process equipment which includes the fluidized bed reactor (FBR), electrolytic cell for Zn and Cl_2 recovery, the Zn vaporizer system, the main condenser for the FBR, critical valves, and assessment of experimental data for verification or optimization of design features. The overall design and associated costs will be reveiwed and refined prior to delivery to JPL in April. The design parameters for the EPSDU are given in Table 3-3. The concurrent experimental R/D support included activities for process optimization and equipment characterization: (1) Full-scale (16.5-cm diameter) mockups of two fluidized-bed support plate designs were evaluated under (air) flow conditions and bed (sand) weight utilizing slow-motion movies. As a result of the evaluations, a more optimized configuration was selected for inclusion in the EPSDU design. (2) The mockup tests were also used to determine the effectiveness of using bed weight (under pressure monitoring) as a determinant for withdrawal of Si product from the fluidized-bed reactors. (3) It was determined that Zn can be vaporized at a controlled rate (0.5 kg Zn/minute) by induction heating and that the delivery rate need for the process requirement can be met readily. (4) Electrolysis studies of by-product $ZnCl_2$ have shown that chlorination of Si suspended in the $ZnCl_2$ and coalescence of the regenerated Zn both occur.

The laboratory-sized mini-plant produced approximately 3 kg of Si product for JPL use.

b. Production of Si by SiF_4/SiF_2 Transport -- Motorola. In the Motorola process a three-step $(SiF_2)x$ polymer transport purification process is used. The chemical feasibility of the process was demonstrated previously at rates of 25 grams/hr for one to two hour runs. In the current period, the first-step reactor was modified. The former, horizontally-mounted reactor, which operated with a pack bed of mg-Si that did not completely fill the cross section, has been replaced by a fully-packed, vertically-mounted

Table 3-3. Battelle Design Parameters for 50 MT/Yr Silicon EPSDU

On-stream factor	80%
Zn/$SiCl_4$ stoichiometry	2/1
Reaction temperature	925°C
Operating pressure	~1 atmosphere above fluidized bed
Conversion of $SiCl_4$	63% per pass
Production rate	7.20 kg/hr (16.8 g/hr/cm^2 cross section)
Seed requirement (5%)	0.36 kg/hr
Fluidized-bed reactors (two)	16.5 cm diameter
$SiCl_4$ purification by distillation	92% center cut
Zn recycle by electrolysis	Six 5000 to 6000 amp cells
Zn recovery	95%
Cl_2 disposal	Conversion to NaOCl

reactor. Channeling of SiF_4 reactant gas should be minimized through the more uniformly packed vertical reactor.

Experimental runs at rates up to 30 grams/hr of Si for two-hour runs were made. A vertically-mounted, packed-bed condenser containing sg-Si particulates is now used as the substrate for the CVD of the volatilized Si_xF_y homologues. Limited data show 97% conversion of the homologues using a packed-bed maintained at 700°C to 800°C for harvesting Si product.

A preliminary economic analysis, incorporating recycle of Si_xF_y homologues, predicts a Si product cost of $7.68/kg at an assumed $10M fixed capital investment.

c. Production of Si Using Submerged Arc Furnace and Unidirectional Processes -- Dow Corning. The goal of the experimental studies is to produce solar-grade Si by a two-step process involving the carbothermic reduction of silica (SiO_2) in a direct arc reactor (DAR) that produces an intermediate Si product which is subjected to unidirectional solidification for further purification. The current scope of work centered on the production of the intermediate process stage Si.

A Dow Corning owned 200-KVA DAR was installed in the contractor's facility. The successful shakedown runs utilized high-purity quartzite and unpurified charcoal as reactants. The longest experimental run was for 48 hours and produced 110 kg of Si; at steady state conditions, Si was produced at 2.6 kg/hr using 28 kwh/kg Si. After baseline conditions are established, experiments in the DAR will be performed using high-purity forms of C.

A program was initiated to identify high-purity, reactive carbon reductants for use in the DAR. Based on the current goals of attaining 2ppma B and 1ppma P in the Si product, the tolerable levels of B and P in carbon reductant are estimated to be a maximum of 4ppma each.

d. Silicon Halide-Alkali Metal Reactions as a Source of Si -- AeroChem Research. The object of this program is to determine the feasibility of using continuous flames of alkali metals and silicon halides in a large scale process to produce solar-grade Si. Primary emphasis is being given to the reaction of Na with $SiCl_4$.

The measurements of K or Na + $SiCl_4$, Na + $SiHCl_3$, and K or Na + SiF_4 flame spectra have been completed. The dominant feature of these emission spectra is alkali metal atomic emission. Flames of $SiCl_4$ or $SiHCl_3$ also show several chemiluminescent bands of unknown origin in the visible. Molecular emission from SiH was observed in the $SiHCl_3$ spectra while both flames showed ultraviolet emission from SiCl and Si, the latter indicating that, despite the fact that different species must be involved (SiCl and SiH, respectively), the rate of formation of Si atoms must be very fast in both cases, although somewhat more rapid with $SiCl_4$. The Si emission was found to be nonthermal in origin preventing a spectroscopic determination of the flame temperature from those measurements.

Stable flames of Na + $SiCl_4$ diluted with H_2/Ar were achieved in a tubular flow reactor. Microscopic examination of the product showed it to be comprised of very small (<1 μm diameter) particles. Washing of this solid removed the NaCl in a stoichiometric (4:1) ratio of NaCl to Si.

Thermochemical calculations of the input conditions necessary to simulate the Westinghouse arc heater process showed that the same total enthalpy (and reaction zone temperature) can be achieved by using vaporized reactants with H_2/Ar heated to 1300°K.

e. Development of Model and Computer Code for Silicon Reactions -- AeroChem Research. The objective of this program is to develop a computer code which can be used to calculate rates of production and the properties of Si produced in processes involving reactions or decomposition of gaseous silicon hydrides and halides. Of particular interest are the effects of operating conditions on the amount and size distribution of particulate Si produced in such processes. The efforts have centered on optimizing the code to reduce its size and memory requirements to allow the number of gas-phase species and particle mass classes to be increased.

The code, with particle routines, is now being debugged. The major problem encountered is that the addition of particle routines has greatly increased the size of the code. As an example of the type of problem encountered, the code originally contained an array CM(NS, NS, MPSI) where NS is the FORTRAN variable equal to the number of "species" (all gas-phase species plus the number of particle size classes). MPSI is the number of stream tubes. It would be desirable to be able to treat (1) $\approx$40 gas-phase species other than Si n-mers, (2) 20 Si n-mers, and (3) 20 particle mass classes. There are typically 25 stream tubes. Thus, the dimension of the FORTRAN variable array CM is $80 \times 80 \times 25 = 1.6 \times 10^5$, a size which is unrealistically large. Fortunately this particular array can be reduced to a two-dimensional 80 x 80 array which is recomputed for each stream tube. Another major change has been to pull the calculations of chemical reaction rates out of the main routine and create a subroutine to perform such calculations.

The process of code optimization, which is necessary to allow the nucleation and coagulation models to be tested, should be completed soon. The condensation model has not yet been added but will be when the optimization process is completed. There should be fewer problems in adding this model than have resulted from adding the nucleation and coagulation models.

f. <u>Process Feasibility Studies and Economic Analyses -- Lamar University</u>. In analyses of process system properties, the efforts focused on the properties of silicon tetrachloride ($SiCl_4$), which is the source material for several processes under consideration for solar-cell-grade Si production. Physical, thermodynamic, and transport property data were reported.

The experimental determination of the gaseous thermal conductivities of silicon tetrafluoride (SiF_4) and trichlorosilane ($SiHCl_3$) were reported in the temperature ranges of 25°C to 400°C and 50°C to 400°C. These are the first experimental values for $SiHCl_3$ in this temperature range.

In the chemical engineering analyses, the preliminary design for the Union Carbide process was completed for Cases A and B, Regular and Minimum Process Storage. Seventy-six major pieces of process equipment are required for Case A versus fifty-eight for Case B.

The results for Cases A and B were used for economic analyses. Because of the large differences in surge tankage between major unit operations the fixed capital investment varied from \$19,094,000 to \$11,138,000. The product cost for Case A is \$5.54/lb of SiH_4 versus \$4.58/lb of SiH_4 for Case B.

g. <u>Si Process Using Na Reduction of SiF_4 -- SRI International</u>. Investigations of the SiF_4-Na reduction reaction were continued. The liquid Na container was modified and its capacity was enlarged to contain 1.0 kg of Na. The method of delivery of liquid Na into the reactor was changed from gravity dropping to forced liquid flow by applying a back pressure of an inert gas.

To determine whether or not liquid Na was picking up Fe and Cr impurities from the stainless steel container, Na samples were analyzed by emission spectroscopy. No increases in Cr or Fe concentration were found to result from contact with the stainless steel container for several days at 150°C to 200°C, but the analyses revealed trace amounts of Ca, Mg, and Ba. However, Ti, Zr, V, Mo, Mn, Ni, and Ag were below limits of detectability in all samples. It was also concluded that sodium fluorosilicate (Na_2SiF_6) is preferable to potassium fluorosilicate (K_2SiF_6) for the production of SiF_4 from H_2SiF_6, since the decomposition temperature of the K-compound was found to be too high for practical purposes.

h. Effects of Impurities on Solar Cell Performance - Westinghouse. The variation of impurity levels over the ingot length was studied using Mn as the dopant. The concentrations were determined by the neutron activation analyses of samples from the seed and tang ends. The concentration variation is small and within the range expected from impurity partitioning. Care was taken with regard to material taken from the tang end of heavily doped ingots to make sure that crystal breakdown had not occurred. When crystal breakdown occurred, the Mn concentrations were: seed 0.98×10^{15} at/cm^3; tang 645×10^{15} at/cm^3.

It had been demonstrated previously that the principal effect of impurities can be measured as a reduction of the minority carrier recombination lifetime. Methods to decrease the concentrations of the electrically active impurities are being explored. These include a thermal treatment to promote impurity clustering or precipitation and various gettering processes. A significant increase in lifetime was found to occur when HCl was added to the furnace atmosphere (i.e. 95% O_2, 5% HCl). Preliminary data indicate that improvement is primarily due to the HCl etching/cleaning of the Si surface. Cleaning procedures which minimize contamination also strongly affect lifetime; it was shown that a controlled final rinsing in DI water is more effective for cleaning than complicated and expensive acid techniques.

Since polycrystalline ingots or forms of Si sheet containing grain boundaries are potential low cost substrates for terrestrial solar cells, a section of this program is directed to determining the response of solar cells made from polycyrstalline Si to controlled additions of metal contaminants. Preliminary cell data for two impurities, Mn and Ti, are shown:

Impurity	Metal Conc. 10^{15} at/cm^3	η/η_{Bp}	η/η_{Bs}
Mn	0.9	0.29	0.80
Ti	0.2	0.38	0.35

The last two columns of the table compare the relative efficiency of cells made as impurity-doped polycrystalline material (η/η_{Bp}) and cells made as single crystal material containing the same amount of impurity (η/η_{Bs}). For Ti, which drastically reduces cell performance via minority carrier recombination, the single and polycrystalline materials behave similarly. For Mn, on the other hand, the cell efficiency of the polycrystalline material is generally much poorer than that exhibited in the single crystal ingot though a few individual polycrystalline cells exhibit relative efficiencies close to 0.80, or about equal to the Mn-doped single crystal cells. However, the majority of cells show significant reductions in V_{OC}. Thus, unlike the Ti-doped ingots, where recombination effects due to metal contamination apparently swamp out grain boundary effects, Mn seems to induce a far greater deterioration in cell performance in the polycrystalline material than in similarly doped single crystal cells.

The Deep Level Transient Spectroscopy (DLTS) apparatus at Carnegie-Mellon University is being used to measure deep trap levels and impurity concentrations in Si samples doped with Ti, Mo, V, Mn, Cr, Fe, Ni, and Al. These measurements make it possible to characterize trap levels introduced by impurities and to determine the effects of process steps on them. It is expected that the results of these measurements can be used as a guide for developing process steps that improve the performance of Si solar cells containing impurities. A DLTS apparatus is being set up at Westinghouse so that these measurements can be made more conveniently.

i. Determination of Effects of Impurities -- C. T. Sah Associates. A computer model involving four regions -- the diffused emitter, the junction space charge region, the quasi-neutral base, and the diffused back surface field regions -- and using nonuniform, but a smoothly varying, step-size has been constructed. It gives accurate solutions, with less than 0.5% error, which converge rapidly for all concentration levels of the impurity recombination centers. This model is being used for efficiency computations. The well characterized gold (Au) impurity levels are used because:

- The electron and hole thermal capture and emission rates are known with reasonable accuracy for Au and thus only small changes in these values are expected.

- The two-level Au recombination center and the one-level Au acceptor recombination center have properties which are expected to be similar to the transition metal elements, such as Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zr, which may appear in solar-cell-grade Si. The detailed recombination properties of these transition metals in Si are not known at present.

The following general conclusions were obtained from these calculations:

- The surface dopant concentration in the (5×10^{18} to 5×10^{20} atoms/cm^3) range has little effect on cell efficiency even when the Au concentration is made to be proportional to the dopant concentration. This indicates that emitter recombination is unimportant for the idealized diffusion profile and undistorted energy band model.

- The substrate dopant concentration has a larger effect on the efficiency at low density of recombination centers than at high densities.

- The Au donor level is important in reducing the efficiency in both p-Si and n-Si substrate cells.

A full discussion of these results and others will be included in a forthcoming annual report.

j. <u>Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse</u>. This contract is for the development of an electric arc heater process for the production of Si based on the reduction of $SiCl_4$ by Na.

Considerable emphasis was placed on the Si separation problem which arose in the previous quarter. Analyses were continued to define a design which would provide effective Si product separation. Two approaches to this separation were pursued, one involving condensation of superheated Si vapor produced by a high-temperature reaction and the other depending on a heterogeneous reaction mode.

A review, held at JPL on February 6 and 7, was attended by representatives from Westinghouse, University of Minnesota, Oregon State University, Lamar University, Caltech, AeroChem Research Laboratories, and JPL. Westinghouse presented the results of its studies and proposed a reactor design which can be operated in three different modes with only minor configuration changes. There was agreement that the condensation mode offered the highest chances of success.

As a result of the product separation analysis, the process analysis was revised to include the homogeneous mode. Based on a 3000-MT/yr cycle process and 1975 dollars and assuming 100% yield, the estimated product cost is $8.98 for the homogeneous mode, compared with $7.20 for the heterogeneous mode.

The System Purity Analysis, which utilizes a computer program to predict impurity concentrations in the liquid Si product based on amounts assumed to be present in the feedstocks, was completed. The impurities considered are Cu, Mo, Ti, and Zr (Al, B, Cr, Fe, Mn, P, and V were previously analyzed). The analyses revealed that essentially all of each impurity ends up in the product Si.

Work continued on fabrication of the experimental system for the kinetics study of the Na reduction of $SiCl_4$, the reactant injection techniques studies, and the demonstration of the $Na/SiCl_4$ reaction.

k. <u>Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of Silicon Chlorides -- Aerochem Research</u>. The objective of this program is to determine the feasibility of high-volume, low-cost production of high-purity silane (SiH_4) or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet.

Additional testing to determine H-atom concentration and efficiency of H-atom production was conducted with the new annular nozzle which was designed to give better mixing of the hydrogen plasma jet with chlorosilanes. A concentration of H-atoms of about 4% was obtained with about 30% of the total energy utilized in producing H-atoms; these results are very similar to those obtained with an earlier nozzle.

Experiments were performed with two configurations of reactor and substrate holder to investigate depositions of Si films. Strongly adhering Si films were obtained on substrates of Vycor, Pyrex, Al, and C. Infrared analysis gave no indications of polymeric material (i.e., no Si-O-Si, Si-OH, or Si-H bonds). The Cu content was measured to be about 0.1% and other metallic elements were present to less than 10 ppm, the limit of measurement accuracy.

l. <u>Production of Si by Hydrogen Reduction of Bromosilanes in a High-Velocity, Continuous-Flow Reactor -- J. C. Schumacher</u>. The objective of this contract is to determine the feasibility of using bromosilanes as reactants for the high-volume, high-velocity, continuous reduction process for producing solar-cell-grade Si. Preheated Si particles fed to the reactor are to be used as deposition sites.

Tests in the previous quarter had demonstrated that the desired temperatures could not be attained in the mixing or reaction chamber. An analysis indicated that rapid expansion caused the mixed streams to cool to the point where the free energy for the Si-producing reaction was no longer favorable. To circumvent this problem, a mixer was constructed which did not depend on gas expansion to produce mixing. It was found that tetrabromosilane can be reduced to Si in the reactor and that homogeneous nucleation of amorphous Si can take place at conditions of 1300°K and 1 atm. To produce a reasonable yield, heat must be added to the reactor from an external source; supplying energy to the reactant streams and the Si particles does not suffice. The other products obtained were: hydrogen bromide, hexabromodisilane, and lower homologs of the H_x-$SiBr_{4-x}$ series. Polymer formation was not detected.

m. <u>Production of Si Using SiH_4 Prepared by Redistribution Reactions -- Union Carbide</u>. The extended operation of a small process development (i.e., mini-plant in the contract) routinely produced high-quality silane (SiH_4) in 97+% yield from dichlorosilane (SiH_2Cl_2). The SiH_4 was used to prepare 50 ohm-cm "N" type Si on epitaxial deposition.

The maxi-plant SiH_4 process development unit (PDU) was operated to demonstrate the closed cycle production of SiH_4, and the integration of the $HSiCl_3$ disproportionation reactor and fractionating column with the hydrogenation reactor and SiH_4 units. The $SiHCl_3$ to SiH_2Cl_2 unit met the design standards of 20 mole % equilibrium conversion of $HSiCl_3$, and a material balance around the hydrogenation unit showed a Si utilization efficiency of 84%. Analyses of the $HSiCl_3$ reactor inlet and outlet and of the $HSiCl_3$ still distillate indicated B levels would be well below the acceptable range for this sector of the system. The data indicate a close agreement between the design and operation of the PDU.

Extensive data were obtained for the characterization of the Cu catalyzed hydrogenation of metallurgical grade Si and $SiCl_4$. The reaction for $SiCl_4$ was shown to be mildly endothermic (8.9 kcal/mole) with a modest activation energy of about 10 kcal/mole. The reaction kinetics are not strongly dependent on the bulk concentration of the catalyst and diffusion appears to be an important kinetic factor.

Thermodynamic data for a H/Cl/Si system are being gathered to provide support for the process design effort.

SiH_4 diluted with He was injected into a quartz fluid-bed reactor in a series of preliminary equipment evaluation experiments. No Si was deposited on the reactor walls in runs up to two hours. Conditions were determined for stable fluidized beds at room temperature over a wide range of gas velocities. The elevated temperature data were in good agreement with calculated values for onset of fluidization and for the behavior predictable from the thermal expansion of the fluidizing gas.

SiH_4 was converted into Si powder at a rate of 0.45 kg/hr for eight continuous hours as a partial demonstration of the capability of the free space reactor. The powder was subsequently pneumatically transferred from the free space reactor to a melt consolidation apparatus and melted in a commercial grade quartz crucible at an average rate of 1.14 kg/hr.

Semiconductor-grade Si and free space reactor powder were vacuum-melted and cast into pellets in standard grade quartz. The electrical resistivities were 30 ohm-cm and 20 ohm-cm, respectively. A pellet cast from melted free space reactor powder had a resistivity of 120 ohm-cm.

In a preliminary process design and plant cost of a 1000 MT/yr production plant, the plant cost was estimated at $6 million. Plant costs for 25, 50, and 100 MT/yr experimental facilities were also calculated by scaling down from the 1000 MT/yr plant estimate.

n. JPL In-House Program. A SiH_4 FBR experiment was conducted with 1% SiH_4 in He. The decomposition reaction proceeded at 920°C for a scheduled one-hour run to yield greater than 90% reaction conversion. Scanning electron microscope pictures showed a dense, coherent coating on the surface of the free-flowing product. A thin coating was also noted on the reactor walls in the heated zone.

Another run was operated with a concentration of SiH_4 of 6.24%. Large, coherent, dense deposition of spherical Si particles as large as 30 micron size was evident from SEM pictures. The reactor, however, became clogged with a semi-solid mass of Si particles after one hour. This clogging is probably caused by interparticle locking and chemical sintering due to the exothermic reaction heat and insufficient solid movement in that part of the bed.

The characteristics of orifice plate fluidization in a room temperature quartz column were studied using electronic pressure transducers to obtain pressure fluctuation data for comparison with the pressure trace from the stainless steel reactor. A qualitative view of the bed behavior in the stainless steel reactor can be obtained using these traces.

The mathematical modeling efforts for the continuous flow pyrolyzer system and the generalized fluidized bed silicon deposition system continue.

B. LARGE-AREA SILICON SHEET TASK

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

1. Technical Goals

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

Growth of Si crystalline material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, 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

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

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 3-4. "Preferred" growth methods for further development during FY 1979-80 have been selected.

4. Large-Area Silicon Sheet Task Technical Background

a. Shaped Ribbon Technology: EFG Method -- Mobil-Tyco Solar Energy Corp. The edge-defined film-fed growth (EFG) technique is based on feeding molten Si through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material that is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/mi. and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

b. Shaped Ribbon Technology: Laser Zone Growth in a Ribbon-to-Ribbon Process -- Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 3-2). The polysilicon ribbon is fed into a preheated region that is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

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

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

Contractor	Technology Area
SHAPED RIBBON TECHNOLOGY	
Mobil-Tyco Solar Energy Waltham, Massachusetts (JPL Contract No. 954355)	Edge defined film fed growth (EFG)
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954376)	Ribbon growth Laser zone regrowth
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)	Dendritic web process
SUPPORTED FILM TECHNOLOGY	
Honeywell Corp. Bloomington, Minnesota (JPL Contract No. 954356)	Silicon on ceramic substrate
RCA Labs Princeton, New Jersey (JPL Contract No. 954817)	Epitaxial film growth on low-cost silicon substrates
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem, Massachusets (JPL Contract No. 954373)	Heat exchanger method (HEM), cast ingot, and multiwire fixed abrasive slicing
Kayex Corp. Rochester, New York (JPL Contract No. 954888)	Advanced CZ growth

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

Contractor	Technology Area
INGOT TECHNOLOGY	
Siltec Corp. Menlo Park, California (JPL Contract No. 954886)	Advanced CZ growth
Texas Instruments Dallas, Texas (JPL Contract No. 954887)	Advanced CZ growth
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954374)	Multiblade slurry sawing
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954884)	Advanced CZ growth
DIE AND CONTAINER MATERIALS STUDIES	
Battelle Labs Columbus, Ohio (JPL Contract No. 954876)	Silicon nitride for dies
Coors Porcelain Golden, Colorado (JPL Contract No. 954878)	Mullite for container and substrates
Eagle Picher Miami, Oklahoma (JPL Contract No. 954877)	CVD silicon nitride and carbide
RCA Labs Princeton, New Jersey (JPL Contract No. 954901)	CVD silicon nitride
Tylan Torrance, California (JPL Contract No. 954896)	Vitreous carbon

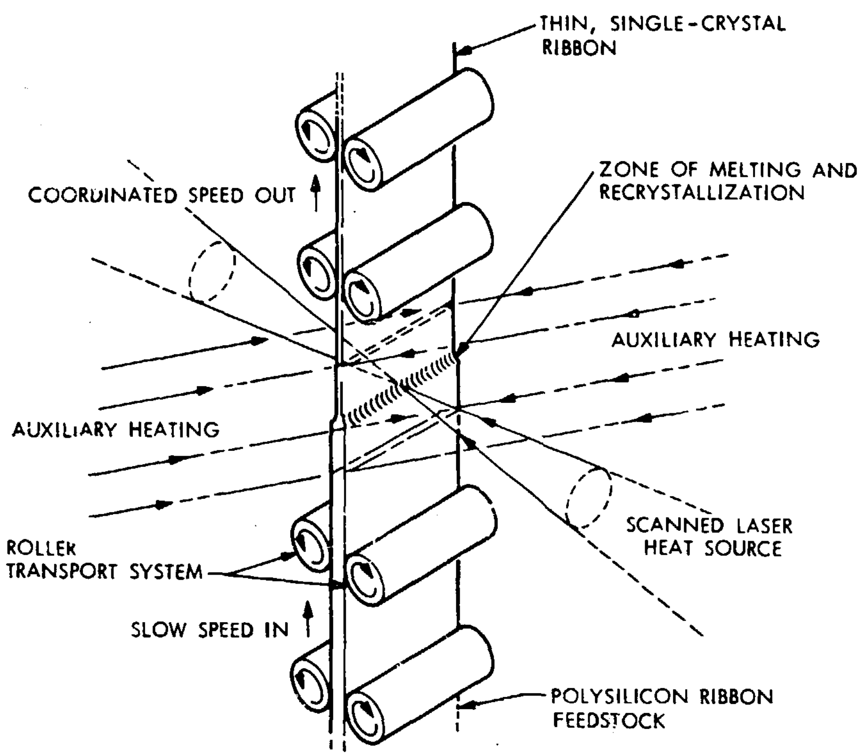


Figure 3-1. Edge-Defined Film-Fed Growth (EFG) -- Mobil-Tyco

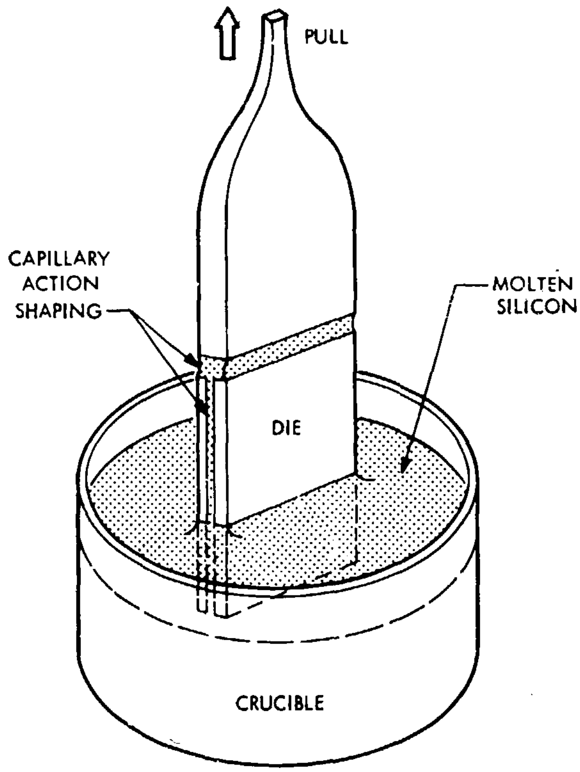


Figure 3-2. Laser Zone Regrowth -- Motorola

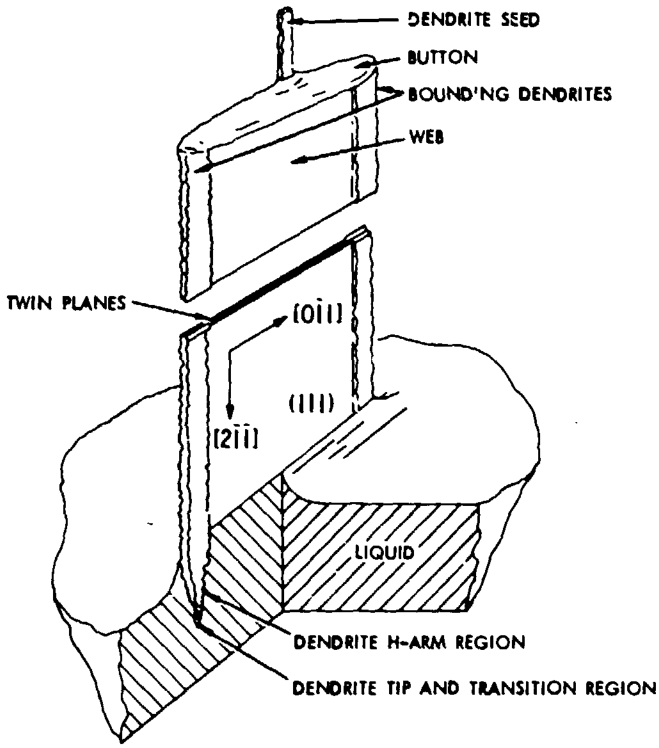
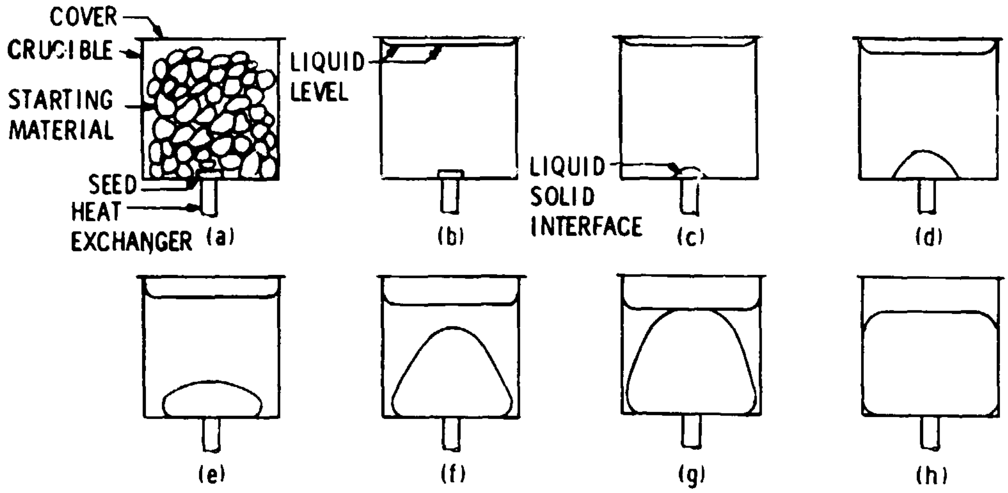


Figure 3-3. Schematic Section of Web Growth -- Westinghouse

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

e. Ingot Technology: Heat Exchanger Method -- Crystal Systems. The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-4). 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 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 be applied to the growth of large shaped Si crystals (>8 in cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished



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

Figure 3-4. Crystal Growth Using the Heat Exchanger Method -- Crystal Systems

by the transfer of sapphire growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for Si.

f. Ingot Technology: Advanced CZO -- Varian, Texas Instruments, Siltec, and Kayex Corp. In the advanced CZO contracts, efforts are geared toward developing equipment and a process in order to achieve the cost goals and demonstrate the feasibility of continuous CZ solar-grade crystal production (Figure 3-5). Varian will modify an existing furnace for continuous growth using granular silicon for recharging (molten silicon will also be considered), and a new puller is to be designed. Texas Instruments' technique is based on an incoming flow of solid granular or nugget polysilicon, premelted in a small auxiliary crucible from which liquid silicon will be introduced into the primary crucible. Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Kayex will demonstrate the growth of 100 kg of single crystal material using only one crucible by perodic melt replenishment.

g. Ingot Technology: Multiwire Sawing -- Crystal Systems; Multiblade Sawing -- Varian. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal.

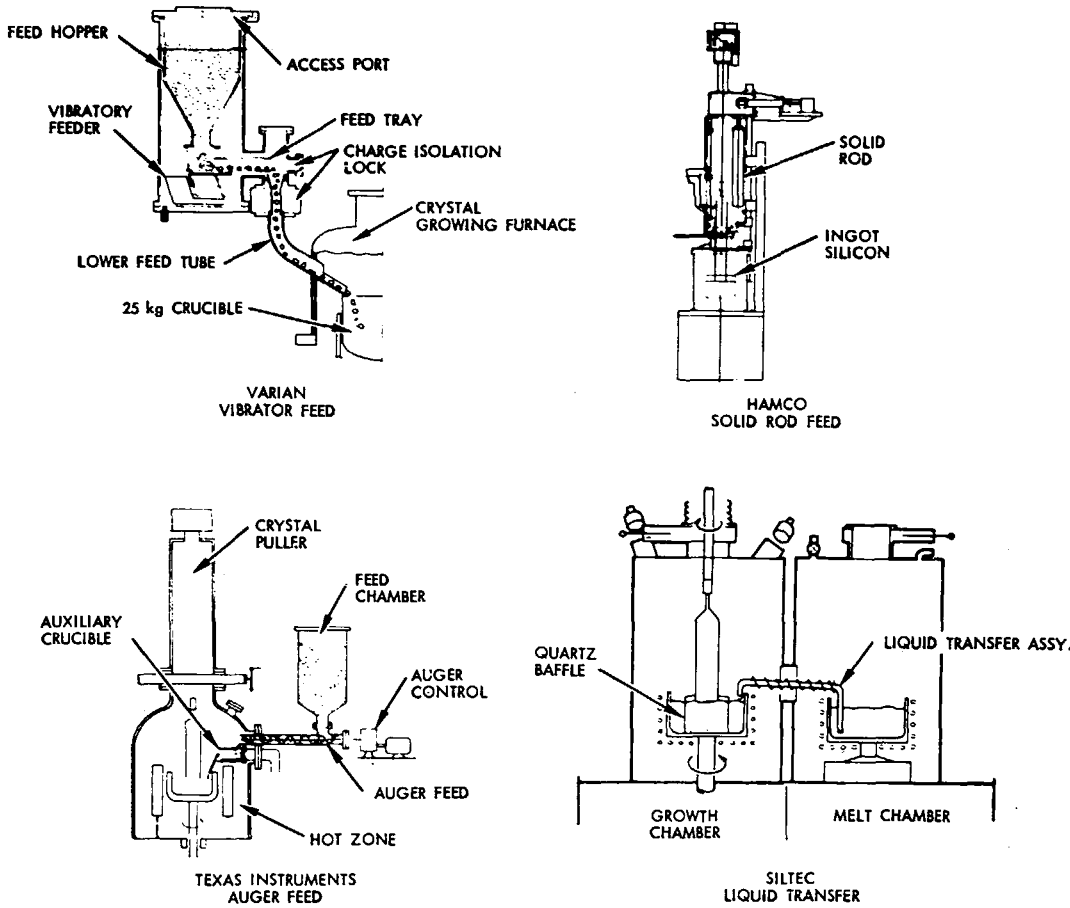


Figure 3-5. Continuous CZ Crystal Growth Machines

This is a large cost factor in producing solar cells. The multiblade and multiwire slicing operations employ similar reciprocating blade head motion with a fixed workpiece. Multiblade slicing is accomplished with a slurry suspension of cutting fluid and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheet, which is impregnated with diamond as an abrasive.

h. Contact Material -- Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, and Tylan. In the crystal-growing processes, a refractory crucible is required to hold the molten silicon, while in the ribbon processes an additional refractory shaping die is needed. The objective of these contracts is to develop and evaluate cost effective refractory die and container materials. The material must be mechanically stable to temperatures above the melting point of silicon, must not excessively contaminate the silicon processed through it, be amenable to the fabrication of dies and containers with close tolerances and of varying geometries, and be cost effective.

Two of the contracts in this area, RCA and Tylan, are to develop a substrate material for supported film growth and a coating for substrates, dies, and containers.

5. Summary of Progress

a. Shaped Ribbon Technology. Mobil Tyco has demonstrated a full five-ribbon multiple growth in JPL No. 3A. Motorola has increased the maximum nondendritic growth rate to 8-9 cm/min by using active cooling and has also grown RTR ribbon from 2.5 cm wide CVD polycrystalline feedstock. The first runs of the new Westinghouse furnace permitted growth of wider dendritic web crystals. The average width of the crystals increased to about 24 mm.

b. Supported Film Technology. Design of a new, experimental dip coater to be used to study methods for increasing the throughput of the SOC process without sacrificing thickness is nearly complete at Honeywell. At RCA Labs, expitaxial growth on two potentially low-cost polycrystalline silicon substrates was accomplished.

c. Ingot Technology. At Crystal Systems progress has been made in casting square cross-section ingots by the HEM method. Developments in the advanced Czochralski process are as follows: Kayex Corp. -- the crystal growth facility is now operational and a suitable means of melt replenishment has been demonstrated using a polycrystalline rod of silicon; Texas Instruments -- experiments have been run in existing equipment examining suitable configurations of auxiliary melters; Varian -- final assembly of the recharging system on the Cz furnace is completed and the feasibility of a 100 kg continuous growth process has been demonstrated by a recharge simulation.

d. Contact Material. Work on the die and container material studies at Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, and Tylan is in the initial experimental stages. Coors Porcelain has successfully fabricated and fired large-area, thin, mullite substrates for the Honeywell supported film development.

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.

1. Organization and Coordination

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 are being conducted to assure timely accomplishment of objectives.

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

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

(b) The environment that the encapsulation system must withstand.

(c) The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.

(d) 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 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 includes 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:

(a) Evaluate, develop, and/or modify solar module testing and analytical methods and then validate these methods.

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

(c) Modify materials and processes used in encapsulation systems to improve automation and cost potential.

(d) Modify potential encapsulation system materials to optimize mechanical, thermal, and aging properties.

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

2. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-5. 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 four major contractors, a contract with the Rockwell Science Center to study the interface characteristics of encapsulated solar cells, a contract with the Motorola Solar Energy Department to develop antireflectance coatings for glass, a contract with Endurex of Mesquite, Texas, to continue the study of ion-plating coating techniques, and a contract with Battelle to develop a life prediction testing plan for solar arrays at a specific deployment site.

3. Encapsulation Task Technical Approach

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 on candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

Table 3-3. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Labs Columbus, Ohio (JPL Contract No. 954328)	Measurement techniques and instruments for life prediction testing
Case Western University Cleveland, Ohio (JPL Contract No. 954738)	System studies of basic aging and diffusion
Dow Corning Corp. Midland, Michigan (JPL Contract No. 954995)	Develop silicon encapsulation systems for terrestrial silicon solar arrays
Endurex Corp. Dallas, Texas (JPL Contract No. 954728)	Ion-plating process and testing
Rockwell International Anaheim, California (JPL Contract No. 954458)	Test methods and aging mechanisms
Rockwell Science Center Thousand Oaks, California (JPL Contract No. 954739)	Materials interface problem study
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954521)	Electrostatic bonding process
Springborn Labs, Inc. Enfield, Connecticut (JPL Contract No. 954527)	Encapsulation test methods and materials properties evaluation

4. Summary of Progress

a. In-House Work. A three-month experimental effort was initiated to evaluate the adequacy of existing materials and processes to meet the LSSA 1986 cost and performance goals. Fifteen designs and 65 modules were fabricated and experimentally evaluated for presentation of the results at the 9th PIM in April 1978. This short-term fabrication and test effort brought to a focus the ongoing encapsulation studies at Springborn, SPIRE, Battelle, OCLI, Lockheed, and JPL, and will provide an assessment of where the program is relative to the LSSA 1986 50¢/watt goal and the need for new R&D approaches. Specific activities to support this experimental program were as follows:

- Material surveys were continued at Springborn Laboratories in order to identify as completely as possible materials and material options for the 1986 cost goals. Wood products, specifically plywood and particle board, have been recently identified as the lowest costing candidate substrate materials. Selected encapsulation concepts were incorporated in 30.5 x 30.5 cm (12 x 12 in) solar cell mini-modules.

- Prototype solar cell mini-modules (30.5 x 30.5 cm or 12 x 12 in) were built at JPL from low cost materials identified to date from encapsulation material surveys. The encapsulation concepts were different from those selected by Springborn. In addition, JPL continued to develop encapsulation concepts and to encapsulate mini-modules supplied by SPIRE. These latter modules were approximately 15 x 15 cm (6 x 6 in) and contained four solar cells, each 5.7 cm (2 1/4 in) in diameter, bonded to Type 7070 borosilicate glass by the electrostatic bonding process.

- Battelle also supported the experimental program by building 30.5 x 30.5 cm (12 x 12 in) mini-modules using concepts developed in its Study 3/Study 6 testing program.

- Mini-modules (30.5 x 30.5 cm or 12 x 12 in) to be procured from Lockheed will incorporate Spraylon as encapsulant. Mini-modules (30.5 x 30.5 cm or 12 x 12 in) were received from OCLI with encapsulation concepts representative of their production designs.

JPL constructed a UV radiation facility to support an in-house program to study promising encapsulation materials including fluorocarbons, silicones, and polyvinylbutyral (PVB). The facility consists of four UV exposure reactors equipped with sample holders designed to accurately control sample environment including incident radiation, temperature, relative humidity, oxygen, and other gases. Radiation calibration measurements are made using a JPL developed actinometer together with conventional radiometry. A brief description of the four exposure reactors follows:

Reactor A is a rotary photochemical reactor which is equipped with a 1.6 kW high pressure xenon lamp with an ozone free quartz envelope. The lamp is vertically mounted on slip rings so that it can rotate at 60 rpm. It is placed at the axis of an aluminum cylinder (inner diameter 61 cm or 24 in) which oscillates 360° back and forth at 1/3 rpm. The inner surface of the cylinder holds the sample compartments or bare samples. Optimum sample size is 5 x 5 cm (2 x 2 in). Samples of 15 x 15 cm (6 x 6 in) can be accommodated on short notice.

Reactor B is a smaller rotary reactor equipped with a 1 kW xenon lamp mainly used for preliminary studies, as well as studies requiring high acceleration.

Reactors C and D are high intensity, short and medium wavelength UV reactors equipped with medium pressure mercury lamps (450 watts) and various optical and infrared filters. High acceleration of Solar (AM 1) UV (up to 1000 suns) without concurrent increase in visible and infrared radiation intensities is possible in these reactors, thus avoiding thermal effects.

These irradiation facilites are supported by a wet chemistry laboratory for the study of changes in sample chemistry during irradiation, and an analytical laboratory facility which includes conventional and FT IR spectrometers equipped with reflectance measurement devices, electronic (UV, visible, near IR) absorption spectrometers, atomic absorption spectrometer, thermal properties measurement devices, gel permeation chromatograph, etc.

The objectives of the program are to: (1) determine the rate of chemical change as a function of environmental variables (UV, temperature, humidity, oxygen, smog) and deduce an overall mechanism for each which can be used to interpret experimental results; (2) establish the model (or mechanism) of photodegradation as a link between phenomena observed in the laboratory and observations made on outdoor exposure; (3) test/iterate this link by predicting lifetime or performance loss as a function of time for each encapsulant from the mechanism of photoreaction; (4) develop new experimental techniques to determine mechanisms of photochemical change and generate diagnostic procedures which facilitate quality control through short term testing.

Work continued at JPL to develop accelerated exposure test methods that will cause delamination (debonding) of silicone materials, principally General Electric RTV-615 and Dow Corning Sylgard 184. This work was initiated because although delamination is widespread in photovoltaic modules exposed to outdoor weathering, the JPL qualification and acceptance tests do not cause delamination at all.

It was found that photodegradation of RTV-615 at room temperature using properly filtered UV from a medium pressure mercury arc (500X to 1000X) results in formation of aliphatic hydroxyl groups. In addition, surface energy analyses carried out by the Rockwell Science Center indicated that UV irradiated surfaces of RTV-615 and Sylgard 184 become more polar. Hence, it was predicted that UV irradiation would weaken the interfacial bond between silicones and hydrophobic surfaces. This prediction was verified in laboratory tests when samples irradiated with UV delaminated after soaking in water. Another piece of evidence supporting the above failure mechanism is the fact that delamination samples from field exposure show the presence of aliphatic hydroxyl groups when examined by attenuated total reflectance-infrared analysis (ATR-IR). These results imply that (1) solar UV is the causative entity in delamination of outdoor exposed modules, (2) the time needed for outdoor exposure to cause delamination can be approximated from indoor test results, and (3) an acceptance test can be designed that will forecast the effect of outdoor weathering in causing delamination of RTV silicone rubber interfaces.

b. Encapsulation Materials Interfaces -- Rockwell Science Center. Rockwell Science Center confirmed by additional testing the (lack of) environmental stability of the Sylgard 184/soda lime glass and Sylgard 184/solar cell (OCLI) interfaces. This was done by confirming the previously developed surface energetics predictions of bond strength sensitivity to moisture. For the glass interface, the work of adhesion, as determined by a peel test, decreases and increases gradually and reversibly as the bond is hydrated and dehydrated, respectively. For the solar cell interface, the bond is similar, except that there is a decrease in the work of adhesion caused by the initial hydration, and upon dehydrating the final value exceeds that of the original bond. A computer analysis of the combined effects of debonding and antireflective (AR) coatings showed that an optimized AR coating will minimize the effect of debonding on reflectance, and hence on cell efficiency.

Computerized optical/ellipsometric mapping of solar array surfaces and interfaces at Rockwell Science Center has been demonstrated as a preventive nondestructive evaluation tool for in-process inspection for surface quality prior to encapsulation. Also, the feasibility of combined use of ultrasonic and optical ellipsometric probes to locate debonds and to map quality of internal interfaces was shown.

c. Measurement Techniques -- Battelle Study 5. A Battelle interim report* on the Study 5 evaluation of diagnostic methods was distributed. Recommendations for candidate measurement techniques to be investigated experimentally at Battelle, as the Phase II part of the Study 5 effort to evaluate diagnostic techniques, were made and approved by JPL. The three candidate techniques are:

- Specular and non-specular reflectometry for evaluation of weathering and surface damage on cover materials.
- Electrical current noise measurements for evaluation of metallic corrosion and debonding effects.
- Chemiluminescence measurements to detect early degradation of polymeric materials.

d. Electrostatic Bonded Integral Glass Covers -- SPIRE. SPIRE completed modifications to its electrostatic bonder including installation of a microprocessor and a real time data display.

SPIRE received a letter from Corning Glass Works outlining the production quantities of glass necessary to obtain lower costs.

*G. T. Noel et al, "Measurement Techniques and Instruments Suitable for Life-Prediction Testing of Photovoltaic Arrays," DOE/JPL-954328-78/7, January 15, 1978.

Projections are for costs of 45¢/ft^2 in 50 million square-foot quantities and price drops to 35¢/ft^2 in still larger amounts.

e. Experimental Evaluation of Accelerated/Abbreviated Encapsulant Methods -- Rockwell International. Weibull correlations of degradation of Lexan polycarbonate films have been completed at Rockwell International. Close agreement between observed and predicted degradations is obtained if the tests are segregated according to the various times during the year when the tests were started. Good agreement was also found for both optical and mechanical degradation of polystyrene exposed at Miami, xenon lamp exposure, and hyperaccelerated exposure in the White Sands (Army) solar furnace at 1400 suns. Agreement was good for natural exposure of Lexan (at Miami and in the solar furnace), but a different relationship between mechanical and optical degradation exists in Lexan specimens exposed to a xenon lamp.

Twenty-four universal test specimens (UTS) with six cells each and with nine different encapsulation combinations were exposed to up to 61 days of accelerated, indoor weathering. Only one cell, covered with nitrocellulose lacquer, lost more than 10% power. Some corrosion of copper circuitry was observed. Subsequent exposure of these specimens to steam for 12 and 31 days results in considerable degradation (mostly in the copper circuitry) and drastic power loss. The other observed results were debonding and yellowing.

f. Ion-Plating Process and Testing -- Endurex. Endurex is presently developing its ion-plating technique to lay down nonporous and smooth metallization on test coupons and solar cells. This is because corrosion protection by the use of thin refractory oxide coatings (approximately 1000 to 2000 Å) requires that surface irregularities and porosity be of a smaller dimensional scale than the metallization. Following development of a nonporous metallization, efforts at demonstrating corrosion protection by ion-plating will be resumed.

g. Development of Silicon Encapsulant Systems -- Dow Corning Corp. A contract with Dow Corning Corp. to develop low-cost encapsulation systems containing silicones was begun. A Phase I program plan was prepared and reviewed by JPL.

h. System Studies of Basic Aging and Diffusion -- Case Western University. A theoretical model developed at Case Western Reserve University to predict the effects of temperature/humidity cycling on encapsulation systems predicts the establishment of a constant interfacial sorption level for films greater than a critical thickness. The exposed surface layers of the film undergo swelling-deswelling modes which increase in intensity with increasing degradation.

Case Western Reserve University is also evaluating the effects of stress on photo-oxidation rates. A mathematical model is under development for the prediction of rates of water sorption buildup at coating/substrate interfaces under field conditions. Failure modes related to this type of environmental cycling are known to occur in cable insulation and conformally coated electronic circuit board.

SECTION IV

PRODUCTION PROCESS AND EQUIPMENT AREA

The objective of the Production Process and Equipment Area is to identify, develop, and demonstrate energy-conservative, economical processes for the fabrication of solar cells and arrays at a production price of less than $500 per peak kilowatt.

A. TECHNICAL GOALS

The goal is to develop and implement commercial, practical, low-cost, high-production, automated-rate processes for the conversion of silicon sheet material into solar cells and arrays.

B. ORGANIZATION AND COORDINATION

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

I. Technology assessment.

II. Process development.

III. Facility and equipment design.

IV. Experimental plant construction.

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

A milestone chart with major milestones identified is contained in Figure 4-2.

Phase II, initiated in September 1977, is well under way at this time. The original goals to define, select, and demonstrate manufacturing processes are being pursued. Part 1 is concentrating on process development, with the following specific objectives:

(1) Determine priority for process development.

(2) Identify areas where new technology must be developed.

(3) Develop processes and demonstrate.

(4) Identify the processing equipment and facilities required.

(5) Update the cost analysis.

Contractors involved in these efforts are shown in Table 4-1.

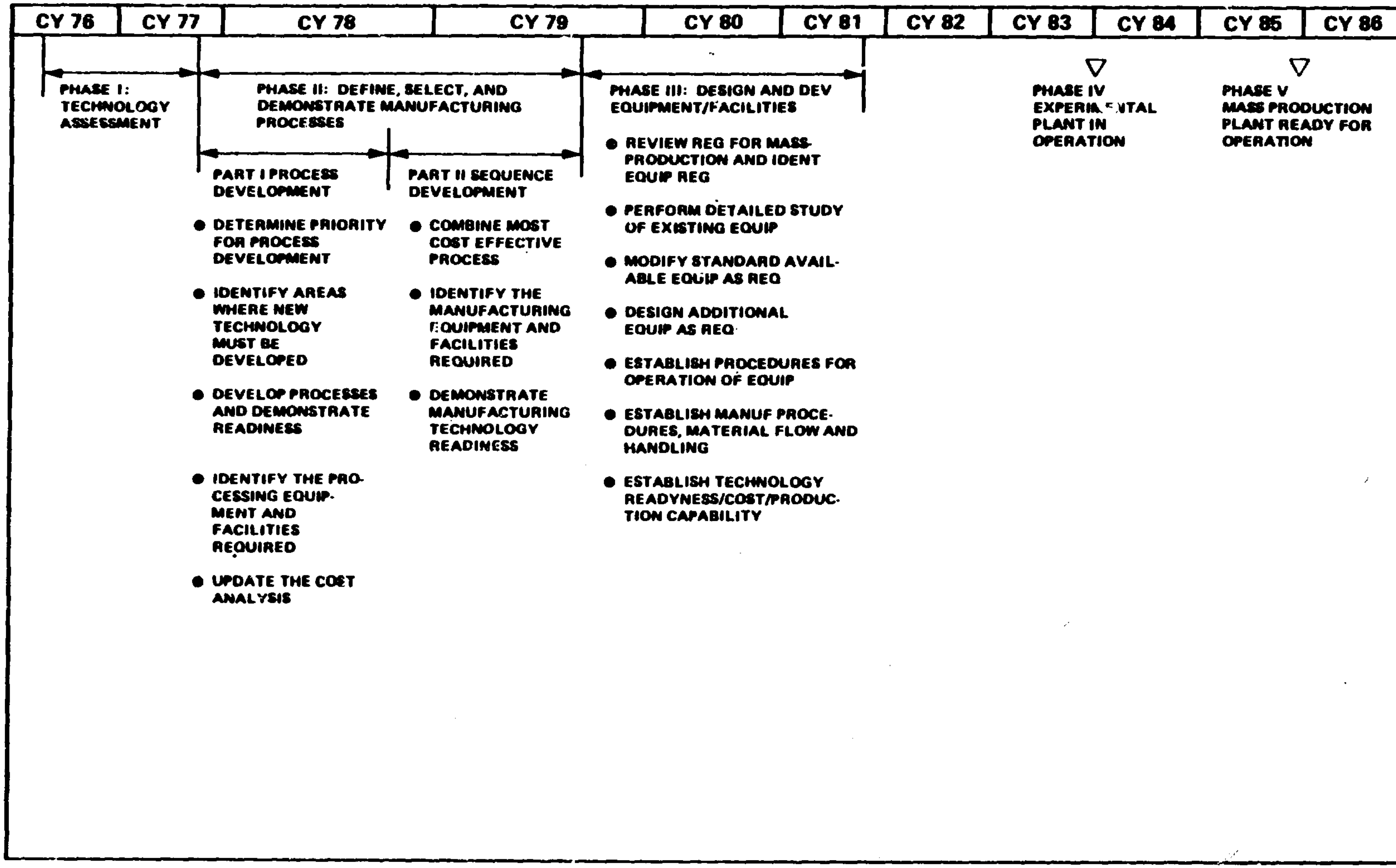


Figure 4-1. Production Process and Equipment Area Schedule

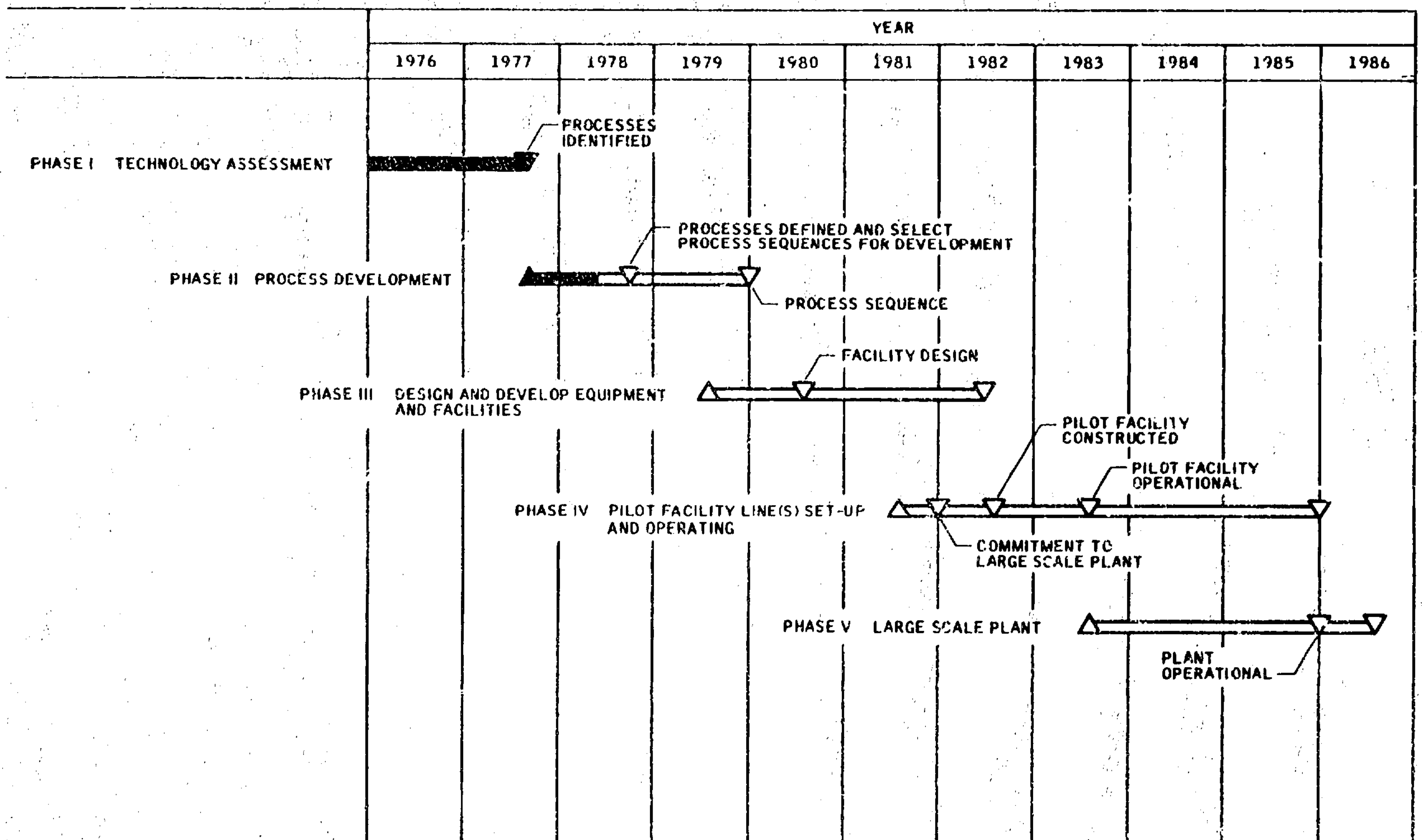


Figure 4-2. Production Process and Equipment Area Major Milestones

Table 4-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
General Electric R&D Philadelphia, Pennsylvania (JPL Contract No. 954607)		Shingle type modules
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954410)		Spraylon
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954898)	Phase II	Process development
Mobil Tyco Solar Waltham, Massachusetts (JPL Contract No. 954999)		Developmental solar modules
MBA San Ramon, California (JPL Contract No. 954882)	Phase II	Process development
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954363)		Technology assessment
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954689)		Metallization of Si wafers
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954847)	Phase II	Process development
Optical Coating Lab City of Industry, California (JPL Contract No. 954831)		High efficiency, long-life solar panels
Optical Coating Lab City of Industry, California (JPL Contract No. 954830)		Slicing
RCA Labs Princeton, New Jersey (JPL Contract No. 954352)		Technology assessment
RCA Corp. Princeton, New Jersey (JPL Contract No. 954868)	Phase II	Process development

Table 4-1. Production Process and Equipment Area Contractors (Continuation 1)

Contractor	Type Contract	Technology Area
Sensor Technology Chatsworth, California (JPL Contract No. 954605)		High efficiency panels
Sensor Technology Chatsworth, California (JPL Contract No. 954865)	Phase II	Production process sequence
Solarex Corp. Rockville, Maryland (JPL Contract No. 954822)		High density panels
Solarex Corp. Rockville, Maryland (JPL Contract No. 954854)	Phase II	Process development
Spectrolab, Inc. Sylmar, California (JPL Contract No. 954853)	Phase II	Process development
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954786)		Ion implanter
Texas Instruments Dallas, Texas (JPL Contract No. 954881)	Phase II	Process development
University of Pennsylvania Philadelphia, Pennsylvania (JPL Contract No. 954796)		Automated array
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954873)	Phase II	Process development

C. SUMMARY OF PROGRESS

1. Surface Preparation

One contractor has reported excellent control over silicon nitrite deposition from dichlorosilane and ammonium mixtures. AR coating and photoresist coating by dip method on silicon web material have been shown to be effective and very cost enhancing. In one of the first technology transfers to be performed, the surface texturing techniques developed by Sensor Technology were transferred to Lockheed Missiles and Space Corporation and subsequently modified by them to become more cost effective. Two separate techniques for spray-on and reflective coating have been developed and both are being evaluated by the developers. Texture etching is also being pursued by a third contractor.

2. Junction Formation

An intense amount of effort has been put into ion-implantation. This has been followed with laser anneal and pulse energy annealing. Motorola has presented ion implantation/sheet resistivity curve measurements, which are shown in Figures 4-3 and 4-4, for initial equipment evaluations. Work is progressing on laser beam annealing.

Motorola, Lockheed, RCA, and SPIRE Corporation are all working on improving ion implantation. Texas Instruments reports that use of lower processing temperatures for diffusions, i.e., temperatures less than 900°C, seems to improve the I_{sc} values, and the use of silane deposited oxide in place of steam growth improves I_{sc} by about 3%. It is also postulated by TI that a deeper diffusion under the metallization area would increase the V_{OC}. This is due to the premise that dark current is dominated by current injected into the diffused region. A deeper diffusion would reduce dark current and therefore raise V_{OC}. Test results of these experiments appear to support the premise. It is also reported that tandem junction cells yield better I_{sc} on thinner cells.

3. Metallization

Screen printing of contacts has been achieved by Lockheed, RCA, Sensor Technology, and Spectrolab. While Motorola has been pursuing plating of palladium base contacts, the unique feature of the Motorola technique is the use of a solvent paste wax mask to occlude the plating from the undesired areas. Investigation by one contractor has shown the use of Spraylon to be less than optimum. Laser scribing of web has been done and the previous p oblems encountered have been overcome. It is currently being done with no degradation of cell performance.

4. Advanced Module Development

An overlap cell module has been fabricated. The packing density is at its maximum and the cell efficiency is being evaluated at this time.

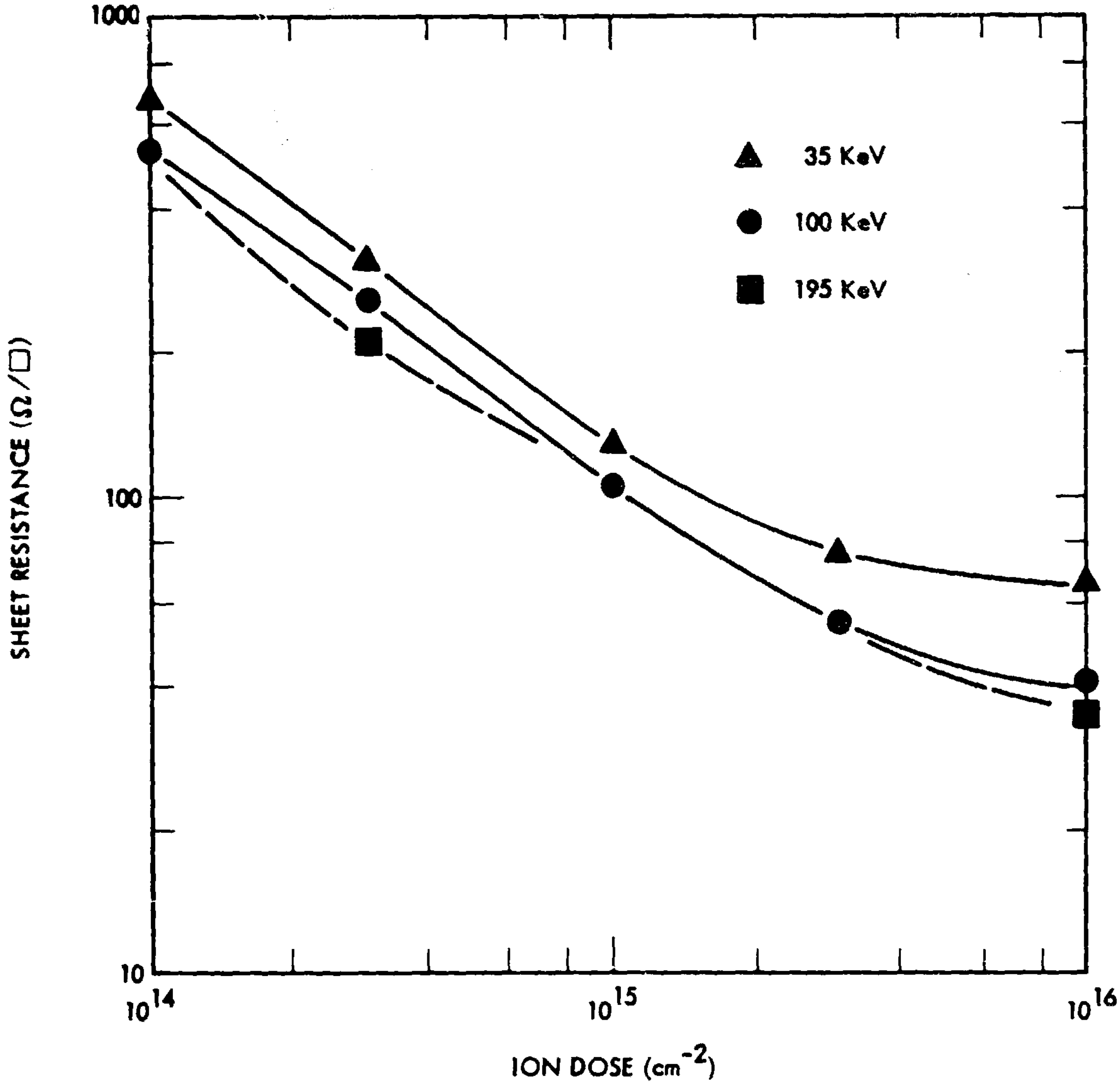


Figure 4-3. Junction Sheet Resistance vs Dose and Energy for Boron Implant

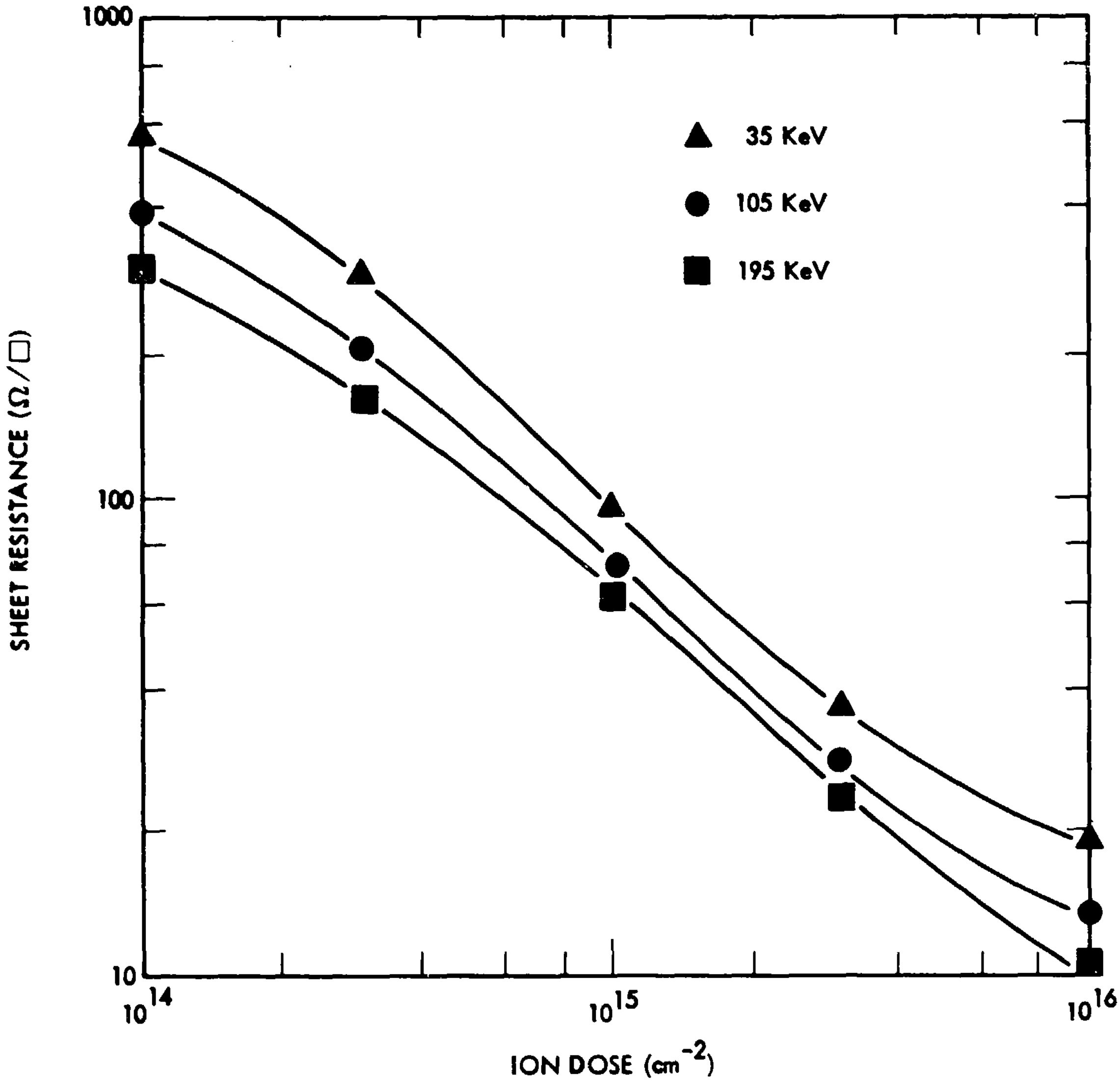


Figure 4-4. Junction Sheet Resistance vs Dose and Energy for Phosphorous Implant

SECTION V

ENGINEERING AREA

During this quarter, Engineering Area activities were centered on three main areas receiving emphasis in FY'78: array design guidelines, reliability-durability requirements, and array specifications and standards.

In the area of design guidelines, the Bechtel and Boeing contracts accomplished extensive analysis of module-to-array structural interfaces. Both contracts, which are investigating central power station module design and evaluation, proceeded on schedule through the quarter. An RFP was issued on March 17 for study of residential photovoltaic module design requirements. The work is expected to develop detailed interface requirements for both panel- and shingle-type modules for residential applications. An important output of the study is expected to be an assessment of the influence of existing codes and standards on design factors. The first version of a computer program to analyze the characteristics of series/parallel cell and module arrangements was completed. The program calculates the system I-V characteristics for any combination of several thousand series/parallel photovoltaic devices and allows detailed assessment of mismatch losses and "hot-spot" effects due to shadowing, device mismatch, circuit failures, cracked cells, etc. The program was applied to assess the relative importance of various device mismatch parameters such as fill-factor and variation in short circuit current, and of alternate circuit configurations. Procurement activities were initiated for a study contract to investigate module output termination and interconnection devices. A letter-of-interest was sent to 35 companies with the intent of developing an RFP package during the next quarter. In-house investigation was conducted to evaluate the effect of cell-to-cell spacing parameters on insolation collection enhancement due to internal reflections from intercell spaces. The empirical results, which provided up to 20% increase in power, indicate that investigation of optimum cell spacing and intercell treatments should be undertaken as part of the module design process.

In the area of reliability-durability requirements, the Clemson University solar cell reliability contract, which was negotiated in December 1977, proceeded into Phase I testing. Sample quantities were significantly increased from initial plans to broaden the statistical base. The cells are to be exposed to various environmental qualification tests including 85-85 bias-humidity, "pressure cooker," power pulsing, and high temperature bias. The objective of the contract is the development of solar cell reliability criteria and test methods. Work on environmental test development continued during the quarter addressing module soiling, delamination, and bias-humidity testing. In support of soiling studies, agreement was reached with the South Coast Air Quality Management District to deploy various encapsulation material samples at sites where total particulate measurements are made weekly. The effort will attempt to correlate dust accumulation rate with atmospheric contaminant content. Other soiling studies addressing the physics of module soiling, including coordination with current studies in progress at Sandia Labs, are proceeding toward a goal of generation of design criteria and test standards for soiling. The use of several UV exposure methods, including weatherometer and combined UV-humidity testing, were investigated in the area of delamination effects. The results of the Phase I bias-humidity testing program were analyzed and modification of test procedures implemented for Phase II tests in order to emphasize examination of the causes of corrosion observed in the early tests. The feasibility of using a scanning laser beam to detect broken silicon solar cells was demonstrated. One method under investigation detects the drop in photoresponse as a small-diameter chopped laser spot scans across a crack, and directly plots the output level with respect to scan position. A second approach uses photodetectors positioned above the cell to monitor reflected light patterns that are then displayed on a high resolution CRT. These techniques could ultimately lead to high-speed, automated cell inspection for cracked cells. Plans were made to obtain hail impact test results on the Block III modules and several R&D module designs before release of the task report covering hail resistance testing.

In the area of array specifications and standards, significant interface activity with outside organizations occurred during the quarter. A flat-plate module design and qualification test specification was generated in support of the upcoming flat-plate PRDA being prepared by DOE's Albuquerque Operations Office. The specification draws heavily on the third generation specification prepared by JPL and subjected to industry review last summer. Work on flat-plate module design criteria and standards was addressed to the needs of the larger photovoltaic community through DOE's SERI-led standards effort. Engineering personnel participated in the advisory committee of the newly formed DOE subprogram on Photovoltaic Design Criteria and Standards led by SERI, attended the DOE photovoltaic semi-annual review in Denver, the MIT/LL Natural Bridges Design Review, and quarterly contractor review meetings at Sandia, and took part in the concentrator PRDA proposal reviews. Support was provided to the Sandia contracts investigating novel structural concepts for flat-plate solar collectors through JPL site visits and discussions with Motorola, one of the Sandia contractors. In other activities, Engineering personnel presented papers and chaired sessions at several conferences/workshops, including presentations of the status of hail testing and hail risk assessment at the IES conference.

SECTION VI

OPERATIONS AREA

A. SUMMARY OF PROGRESS

1. Large-Scale Production Task

a. Block II. The Block II procurement was completed in this quarter with the delivery of 12 kW of modules by Spectrolab. Early in the quarter the scope of the contract with Spectrolab was reduced, at its request, and the total for the block likewise was reduced to 110 kW.

b. Block III. In January the contracts with Sensor Technology, Inc., and Solarex Corp. were implemented, putting into operation the five contracts comprising the Block III complement. To compensate for the reduction in the Block II buy, the procurement of an additional 15 kW of modules from ARCO Solar was negotiated this quarter.

Startup activities at the various contractors were under way, with Solarex delivering 5.2 kW by the end of the quarter and the other contractors anticipating deliveries starting early in the next quarter.

Additional procurements of 5 kW of a glass-faced module from Sensor Technology and 5 kW of a high efficiency module from Solarex were negotiated, with implementation planned for early in the next quarter.

2. Environmental Testing

a. Large-Scale Production (Task 5) Modules

1) Block II. Six production modules of type W were qualification tested. Only one module was affected -- a cracked cell occurred in humidity testing with 7% electrical degradation. After wind simulation, the degradation increased to 12.5%.

Four modules each of types V, Y, and Z were tested in humidity-heat. The only change was a crack in one cell of a V module.

2) Block III. Twenty-eight Block III type Y modules were received, of which ten were tested for temperature coefficients. Nominal Average Power was 16.9 W at 60°C, 15.8 V using the new Block III reference cell and the revised pyrehliometric scale.

b. Task 4 Developmental Modules. Six type O and nine type Y high density modules were tested for temperature coefficients. Problems were encountered with both types.

1) Type O. One module showed open circuit at 60°C and another had a nontypical thermal coefficient. Also, one module leaked uncured encapsulant gel from both ends. The manufacturer repaired this module by applying cement to the end seals.

2) Type Y (High Density). Three of the nine modules showed open at 60°C and one was open at 28°C. Loose terminals were tightened by the Failure Analysis Lab, but two modules remained open. Failure analysis was continuing at the close of the quarter.

A subarray of each of these module types has been assembled and will be qualification tested early in the next quarter.

c. Combined Environments Test. A xenon lamp has been installed in a 91.5 x 91.5 x 91.5 cm (3 x 3 x 3 ft) temperature/humidity test chamber to provide a combined humidity/UV test facility. After lamp adjustment and calibration, four old type Y Block I modules were tested using high humidity and UV-rich xenon light and heat from the lamp. Two-hundred-forty two-hour cycles were run with 38 minutes of light during each cycle, but no encapsulant delamination resulted. Studies by Engineering Area and Encapsulation Task personnel indicate that UV/humidity effects are likely causes of encapsulant delamination, and further tests are planned using higher moisture saturation and more intense UV sources.

3. Field Testing

Two data acquisition system milestones were reached at the JPL (Pasadena) Site during this quarter. By mid-February most system deficiencies were corrected and the system was routinely collecting I-V data. During the following month, the dedicated task data (I-V, weather, insolation, summary) was obtained on a semi-routine basis, i.e., a half time schedule. The remaining system time was devoted to program development. A critical product of the programming effort was the enabling of concurrent performance of interactive programs and dedicated tasks (except during mid-day when a special data pack was mounted to accept the dedicated I-V data).

The second milestone was reached in late March when the data system was placed on a 24-hour, 7-day a week schedule. A few outstanding problems still remained at quarter's end, but these were of an intermittent nature.

In order to define a baseline module performance level for tasks using the data system, a study was undertaken to determine the degradation histories of all the modules at the JPL Site. The data was obtained by comparing the fill-factors obtained with the large area pulsed solar simulator (LAPSS) system before going into the field with the current fill-factors obtained with the field test data system. A control test indicated that the fill-factors obtained from the two testing techniques, for a non-degraded module, would agree by 2% to 3%. The results of the study are shown in Table 6-2 in the Technical Data portion following. The table also includes a tabulation of failures at the JPL Site.

There was a delay of several months in starting work on the Point Vicente Site due to concerns regarding site safety. This problem was resolved and a "walk-through" by prospective bidders for the job is scheduled for April 25. The site should be ready for occupancy by early June.

4. Performance Measurements and Standards

Work on the photon effect problem continued this quarter. The problem at Sensor Technology has been eliminated, but the corrective action has been classified as proprietary. The matrix experiment described in the last progress report has been completed with ARCO Solar and OCLI. The results indicate the effect is introduced in ARCO Solar's diffusion process independent of any of the other variables. This work will be reported in the upcoming 13th Photovoltaics Specialists Conference. Systematic changes in ARCO Solar's diffusion process to date have shown that the effect can be eliminated from its cells. More definite effort remains before changes are introduced in ARCO Solar's production line. It is anticipated that by the end of the next quarter the problem will be eliminated at ARCO Solar. Solar Power modules still exhibit this effect, with little progress at this time due primarily to schedule conflicts.

Block III reference cells have been fabricated and calibrated by Lewis Research Center. Delivery of Block III reference cells to all vendors will be completed by April. Modification of the existing LAPSS system has been completed, increasing the data throughput by a factor of three. Expected delivery of the second LAPSS system remains July 1. The Block II/Block III vendor reference cell comparisons are scheduled to begin early in April in order to adjust Block III contract prices to reflect the Block III reference cell calibrations.

5. Failure Analysis

The activity during this quarter comprised the filing of ten new Problem/Failure Reports (P/FRs) and the closure of 36 P/FRs. Distribution of the reports was made on a monthly basis to affected manufacturers and Test and Application Projects.

Two new failure analysis techniques were developed which allow more rapid detection of problem cells within the modules. These two methods are: (1) Scanning Laser Beam Induced Current Output. The laser light can detect cracks, discontinuities, shorted cells, and degraded cells. (2) Reverse bias voltage measurement using a shadowing technique, which provides the capability of measuring short circuit resistance and shunt resistance of a cell. Both the laser and shadowing techniques are nondestructive tools for performing failure analysis of solar modules. Details of the failure analysis activity are given in the Technical Data portion following.

B. TECHNICAL DATA

1. Large-Scale Production Task

a. Block II. Production detail for the quarter is shown.

	Total Shipped (kW)	Shipped Jan.-Mar. (kW)
Sensor Technology, Inc.	40	0
Solar Power Corp.	15	0
Solarex Corp.	30	0
Spectrolab, Inc.	25	12
	110	12

b. Block III. The reduction in the size of the Block II procurement caused a readjustment of quantities of modules to be procured under Block III in order to meet the requirements of the test and applications program. The current quantities and module prices are displayed in Table 6-1. The price cited in the second column is the price in dollars per watt in effect at the start of the contract, which is taken to be January 1978. The third column deflates the price from first quarter 1978 to first quarter 1975 and applies a correction to reduce the temperature to 28°C.

Table 6-1. Block III Quantites and Module Prices

	Allocation kW	\$/W 1-1978 60°C	\$/W 1-1975 28°C
ARCO Solar, Inc.	35	14.64	10.15
Motorola, Inc.	50	13.40	9.37
Sensor Technology, Inc.	40	16.00	11.38
Solar Power Corp.	50	14.50	10.40
Solarex Corp.	30	17.81	12.99
	205	15.03*	10.67*

*Weighted average

2. Field Testing

Table 6-2 presents fill-factor data for those modules under test at the JPL Site. Block I degradation is mainly the result of cracked cells, interconnect fractures, and lead wire corrosion. Block II modules under test are in much better shape physically and functionally than their Block I counterparts after equivalent exposure times.

Table 6-2. JPL Site Module Experience

	Vendor	Quantity	Avg. Time In Field (Months)	% Fill-Factor Decrease in Field				
				<2	<5	<10	>10	Failed
Block I	V	62	17	53	5			4
	W	39	13	31	7	1		
	Y	38	15	28	5	2		3
	Z	21	14	4	2	5	3	7
Block II	V	34	9	34				
	W	13	4	13				
	Y	17	7	15	2			
	Z	13	8	11	2			

3. Failure Analysis

Table 6-3 summarizes Block I, Block II, and Task 4 module problems during environmental test, field test, and user application.

Table 6-3. Summary of P/FR Activity

Mfr.	Procurement Block	New P/FRs	Closed P/FRs	Envir. Test	Field Test	Application Centers
V	Block I	1	1		1	
	Block II	4	18	17		5
W	Block I		1		1	
Y	Block II		4			4
Z	Block I	3	5		6	2
	Block II	2				2
R	Task 4		6	6		

Problem categories for P/FRs summarized in Table 6-3 are shown in Table 6-4.

Table 6-4. Problem Categories

Mfr.	Procurement Block	Modules with Electrical Degradation	Total P/FRs	Comments
V	Block I	1	1	Open circuit.
	Block II	10	22	Open circuit. Differential expansion of silicone rubber caused cracked cells.
W	Block I	1	1	Cracked cell.
Y	Block II	1	4	Exposed interconnects, cracked cell/open circuit.
Z	Block I	8	8	Fractured interconnects.
	Block II	2	2	Delamination. Intermittent + open. Delamination.
R	Task 4	3	6	Encapsulant seepage. Electrical degradation.

a. Manufacturer V. Analysis of the Block I module failure in the JPL field test site showed a fractured interconnect and delamination of encapsulant.

Block II module environmental test P/FRs were the result of previously reported differential expansion design problems. Modules returned from Mead, Nebraska, by MIT/Lincoln Laboratory were reported open. Of five modules returned by MIT, two were found open due to cracked cells. The remaining three problems were not confirmed; these modules will be returned to MIT for additional service. Figure 6-1 shows a laser scan photo of a cracked cell from the MIT application.

b. Manufacturer W. One Block I module was returned from JPL field test and found to have a cracked cell, which caused the reported power degradation.

c. Manufacturer Y. Four Block II modules were returned from Mead. One was open due to a cracked cell. Three modules had exposed interconnects detected when washing the modules in the field. These modules were repaired and returned to service.

d. Manufacturer Z. Block I modules returned from JPL field test were all open circuited at fractured interconnects, caused by insufficient stress relief. Major delamination of encapsulant was also observed.

Two Block II modules returned from MIT for open circuit were not confirmed by JPL. These modules will be subjected to JPL field test for observation.

e. Manufacturer R. Six Task 4 modules were found to have a combination of electrical and encapsulant problems, which the manufacturer is addressing.

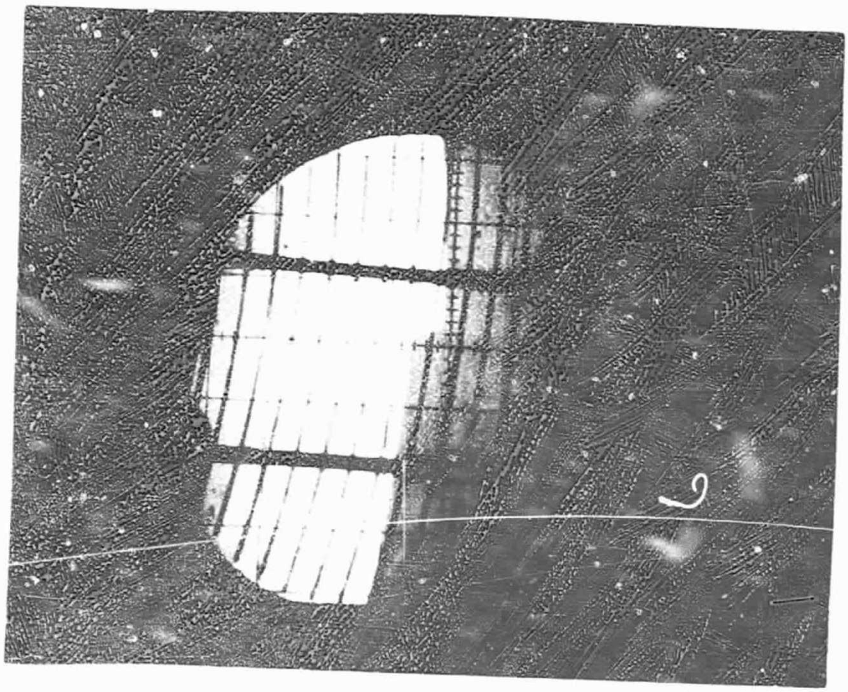


Figure 6-1. Laser Photograph of Manufacturer V Module. The Photo of the Oscilloscope Image Shows the "Scanning Laser Beam Induced Current Output" of a Cracked Cell. The Light Area Represents the Functioning Half of the Cell.