LSSA
LOW-COST SILICON SOLAR ARRAY
PROJECT

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Project QUARTERLY REPORT - 1

FOR THE PERIOD APRIL 1976 - JUNE 1976

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The Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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ABSTRACT

The need to find new methods of economically generating enough electrical power to meet future requirements, motivated the establishment of the Photovoltaic Conversion Program of ERDA's Division of Solar Energy, in January 1975. The long range Program objectives are (1) to develop the technology for low-cost photovoltaic power and (2) to stimulate industry to produce, market, and distribute photovoltaic systems for widespread residential, commercial, and governmental use. The Low-Cost Silicon Solar Array Project (LSSA) was established at the Jet Propulsion Laboratory as part of the ERDA Program. Its goal is to greatly reduce the price of solar arrays by improving manufacturing technology, adapting mass production techniques, and promoting user acceptance. The Project's approach includes the development of improved solar array designs and manufacturing technologies, their transfer and deployment to commercial practice by industry, the evaluation of the economics involved, and the stimulation of market growth.

The Project is now in a stage of implementation by contractors and JPL. The activities of the Project from its start through March 1976 were reported in the LSSA Project First Annual Report. During this initial period emphasis was placed on the development of plans and organization and on the initiation of a broad spectrum of contracted activities. Activities and progress of the LSSA Project during April, May, and June 1976 are described in the present document. This involved the awarding of additional contracts, an evaluation and clarification of plans and working relationships with contractors and within the Project and Program, the receipt of initial technical results, and an expansion of activity in the evaluation and improvement of the solar cell modules that are included in the Project's first procurement (46 kilowatts).

For the most part, the new manufacturing technology is being developed under contract by industries and universities. It includes the consideration of new silicon-refinement processes, silicon sheet-growth techniques, encapsulants, and automated-assembly production. During this report period analytical and experimental accomplishments resulted from day-to-day activities that are the early efforts of a long range plan. Thirty-one contracts have been awarded and two more are being negotiated. In the future, additional contracts will be issued for investigating the more promising ideas submitted in unsolicited proposals.

Five companies have delivered 20 kilowatts out of a total purchase of 46 kilowatts of "off-the-shelf" modules that will be used in ERDA's test and demonstration activities. In some cases delivery of the modules was delayed until design weaknesses and manufacturing defects, discovered during acceptance inspection and testing, were remedied. The same five companies have just been awarded contracts for the purchase of 130 kilowatts of semistandardized modules at an average selling price of $15.50 per watt. During the past 18 months the size of the terrestrial photovoltaic market has doubled and the price has been reduced almost 50%.

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LIST OF ABBREVIATIONS

General

AM0	air mass zero
AM1	air mass one
CAST	capillary action shaping technique
CVD	chemical vapor deposition
DOD	Department of Defense
DPESA	Development, Procurement, and Evaluation of Solar Arrays
EFG	edge-defined film-fed growth
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
IST	Inverted Stepanov Technique
JPL	Jet Propulsion Laboratory
LED	light-emitting diode
LASS	Large Area Silicon Sheet Task
LeRC	Lewis Research Center
LSSA	Low-Cost Silicon Solar Array Project
NASA	National Aeronautics and Space Administration
NSF	National Space Foundation
OCVD	open circuit voltage decay
PA&I	Project Analysis and Integration Task
PCD	photoconductive decay
RANN	Research Applied to National Needs
RFP	Request for Proposal
SAMIS	solar-array manufacturing industry simulation
SSMS	spark-source mass spectroscopy

Chemical Symbols

Al	aluminum	Mg	magnesium
Ar	argon	Mn	manganese
B	boron	N	nitrogen
C	carbon	Na	sodium
Cl	chlorine	Ni	nickel
Cu	copper	O	oxygen
Cr	chromium	Si	silicon
F	fluorine	Sn	tin
Fe	iron	Ti	titanium
H	hydrogen	V	vanadium
He	helium	Zn	zinc
I	iodine	Zr	zirconium

PART I

SUMMARY

The potential for future widespread use of photovoltaic systems for the generation of electric power was the motivation for the establishment, in January 1975, of the Photovoltaic Conversion Program by ERDA's Division of Solar Energy. The Program's activities are planned to develop and to promote the use of photovoltaic systems to such an extent that the private sector will produce and utilize cost-competitive photovoltaic systems. As part of the ERDA Program, the Low-Cost Silicon Solar Array Project (LSSA) was established in January 1975.

The Project objective is:

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

The approach is to reduce the cost of solar cell arrays by improving solar array manufacturing technology and by increasing solar array production capacity and quantity. Thirty-one technology development contracts have been awarded to date, for analytical and experimental work on new silicon refinement processes, silicon-sheet-growth techniques, encapsulants, and automated-assembly studies (Table 1-1). Twenty kilowatts of 'off the shelf' modules have been delivered by five manufacturers out of a total 46 kilowatts purchased (Table 1-2). Contract awards have been made for 130 kilowatts of newly designed modules.

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*In 1975 dollars.

Table 1-1. Technology development contractors

Contractor		Technology Area
TASK 1. SILICON MATERIAL (11 contracts)		
Semiconductor-Grade Silicon Production Processes		
1. Battelle Memorial Institute	Columbus OH	Si from $SiCl_4$
2. Union Carbide	Sistersville WV	Si from SiH_4
3. Motorola	Phoeniz AZ	Si using SiF_4 transfer
Solar-Cell-Grade Specifications		
4. Westinghouse Electric	Pittsburgh PA	Investigation of effects of impurities on solar cell performance
5. Monsanto Research	St. Louis MO	Investigation of effects of impurities on solar cell performance
Solar-Cell-Grade Silicon Production Processes		
6. Dow Corning	Hemlock MI	Si from pure source materials using arc furnace processing
7. Stanford Research Institute	Menlo Park CA	Si by duplex vapor-electrochemical conversion of SiF_4
8. Texas Instruments	Dallas TX	Si from C reduction of SiO_2 using plasma processing
9. Westinghouse Electric	Pittsburgh PA	Si by plasma-arc-heater reduction of $SiCl_4$ with H_2 and alkali metals as reducing agents
10. AeroChem Research	Princeton NJ	Si by use of a nonequilibrium plasma jet
Commercial Potential of Processes		
11. Lamar University	Beaumont TX	Evaluate relative commercial potentials of Si production processes developed under Task 1.
TASK 2. LARGE AREA SILICON SHEET (11 contracts)		
Ribbon Growth Processes		
1. Mobil-Tyco	Waltham MA	Edge-defined, film-fed growth
2. IBM	Hopewell Junction NY	Edge-defined, film-fed growth
3. RCA	Princeton NJ	Inverted Stepanov growth
4. University of S. Carolina	Columbia SC	Web-dendritic growth
5. Motorola	Phoenix AZ	Laser zone ribbon growth
Sheet Growth Processes		
6. Honeywell	Bloomington MN	Dip-coating of low-cost substrates
7. Rockwell International	Anaheim CA	Chemical vapor deposition on low-cost substrates
8. General Electric	Schenectady NY	Chemical vapor deposition on floating silicon substrate
9. University of Pennsylvania	Pittsburgh PA	Hot-forming of silicon
Ingot Growth		
10. Crystal Systems	Salem MA	Heat-exchanger ingot casting*
Ingot Cutting		
Crystal Systems	Salem MA	Multiple-wire sawing*
11. Varian	Lexington MA	Breadknife sawing

*Crystal systems contract provides for both ingot casting and multiple-wire sawing.

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Table 1-1. (Contd)

Contractor		Technology Area
TASK 3. ENCAPSULATION (4 contracts)		
1. Battelle Memorial Institute	Columbus OH	Encapsulant experience and definition of environment; encapsulant test methods and capabilities
2. Rockwell International	Anaheim CA	Accelerated/abbreviated testing
3. Simulation Physics	Burlington MA	Bonded integral glass covers
4. DeBell and Richardson	Enfield CT	Polymeric properties and aging studies
TASK 4. AUTOMATED ASSEMBLY OF ARRAYS (5 contracts)		
1. Motorola	Phoenix AZ	Manufacturing processes assessment
2. RCA	Princeton NJ	Manufacturing processes assessment
3. Texas Instruments	Dallas TX	Manufacturing processes assessment
4. Simulation Physics	Burlington MA	Electron-beam solar cell fabrication
5. Texas Instruments	Dallas TX	Czochralski growth and wafering improvements

Table 1-2. Large-scale procurement contractors (10 contracts)

46-Kilowatt Solar Array Procurement		Kilowatts
M7 International	Arlington Heights IL	3
Sensor Technology	Chatsworth CA	8
Solar Power	Wakefield MA	15
Solarex	Rockville MD	10
Spectrolab	Sylmar CA	10
130-Kilowatt Solar Array Procurement		
M7 International	Arlington Heights IL	5
Sensor Technology	Chatsworth CA	40
Solar Power	Wakefield MA	15
Solarex	Rockville MD	30
Spectrolab	Sylmar CA	40

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A. SILICON MATERIAL TASK

The objectives of the Silicon Material Task are (1) to develop a process for producing silicon suitable for solar cells at a market price of less than $10 per kg and (2) to establish an information base relating the effects of impurities and processing steps to the properties of silicon and to the performance of solar cells.

The use of semiconductor-grade silicon for the fabrication of solar cells is a result of the development of solar-cell technology based upon this extremely pure material, which is being produced to meet the requirements of the semiconductor industry. As a consequence of the dependence of solar-cell technology on the particular properties of semiconductor-grade material, analyses relating the performance of solar cells to silicon composition as well as information relating various investigations of chemical processes for producing silicon less pure than semiconductor grade are unavailable. To achieve the LSSA Project price objectives, new areas of chemical processing and solar-cell technology must be developed.

This task is structured with three principal subtasks: The further development of cost-effective processes for semiconductor-grade silicon, the establishment of an information base for the effects of impurities and processing steps on material and solar-cell properties, and the development of processes for solar-cell-grade silicon. The rationale for the separate process-development subtasks for semiconductor-grade and solar-cell-grade silicon established at the program start was that both avenues must be explored, since the final composition of the silicon could not be specified until complete technical and economic trade-offs were performed.

The process developments being conducted by Battelle Memorial Institute and Union Carbide Corporation are the most advanced. The theoretical analyses and the experimental data in both cases have led to significant first phase conclusions. Both contracts are at the stage for the planning and initiation of the second phase for scale-up studies and the design of experimental production facilities.

A Battelle Memorial Institute economic analysis has led to cost estimations of \$9.12/kg for producing semiconductor-grade silicon by the $Zn/SiCl_4$ process. Experimental data support the contention that the process is technically feasible. Promising data have been obtained from preliminary runs with a $SiCl_4$ process miniplant, based on the use of fluidized bed reactors. Calculations of energy-uses have yielded an energy payback value of 2.2 months. No further work will be done on SiI_4 processes, since it was concluded from the economic analyses that none could meet the product cost goal.

Union Carbide has performed experimental investigations of steps in the process to produce SiH_4, a precursor for semiconductor-grade silicon. These steps involve reactions for the redistribution of a chlorosilane feed and for the hydrogenation of $SiCl_4$ to produce $SiHCl_3$. In the redistribution study, rate data were obtained and the equilibrium composition of 13% SiH_4 was shown to be nearly independent of the temperature. Products containing 15 to 22% mole % $SiHCl_3$ were obtained in runs of the hydrogenation of $SiCl_4$. The installation of the components for the SiH_4 miniplant is underway.

The reaction of SiF_4 with metallurgic grade Si and the use of the SiF_4/SiF_2 transport process is being investigated by Motorola. A series of experiments has shown that a 25 gm/hr Si transport rate can be obtained for short runs.

The effects of specific impurities in silicon on wafers and on solar cell performance continue to be investigated by Monsanto and Westinghouse. Monsanto is working with material prepared by Czochralski and float zone crystals while Westinghouse uses Czochralski and dendritic web crystals. Preliminary conclusions are: (1) minority carrier recombination lifetimes are affected at temperatures as low as 550°C, which is used during contact sintering; (2) cell measurements of short circuit current and efficiency decrease monotonically for wafer lifetimes below about 1 μsec; and cell efficiency varies as a function of composition; severe decreases of efficiency result from the presence of vanadium or titanium.

Silicon refinement processes for the less pure silicon continue but are not as advanced as the above efforts. The economic evaluations by Lamar University of the above processes continue as well as chemical engineering calculations for a 1000 metric tons/year plant.

B. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop an economical method of producing large silicon sheets that can be inexpensively made into solar cells with good electrical and physical properties. Contemporary solar cell fabrication requires the sawing of crystals into thin wafers with diamond saws followed by polishing. Approximately 75 percent of the crystal material is wasted. An ideal technique would be to grow crystalline sheet in a geometry that would require a minimum of cutting or polishing and yet would produce a material from which high efficiency solar cells could be fabricated. As yet, no one technique has been developed and perfected that attains this ideal solution. However, the progress made in development work on a number of growth techniques has been sufficient to indicate that the ideal technique may be achievable. Consequently, many growth techniques are being analytically and experimentally investigated. Backup work on crystal ingot growth and advanced cutting techniques is also being performed (see Table 1-1). The initial work has emphasized the determination of the technical feasibility of various processes. The successful processes will then be evaluated for their economic feasibility. The following work has been performed by contractors:

1) Ribbon growth, from a molten source based on (a) capillary action movement of material through a die (i.e., the EFG and CAST techniques) and (b) gravity feed of material from an inverted die (inverted Stepanov technique); improvement activities continue. Ribbons have been grown at rates up to 5 cm/minute but with built-in stresses created during cooling. Reduction of ribbon stresses by understanding and control of the thermal geometry in the ribbon is receiving much effort. Studies of new dies, ribbon contamination from the die, and correlations of crystal structure and electrical properties continue. A 3 inch wide ribbon growth machine is near completion.

2) Web-dendritic growth directly from a molten source without shaping continues with emphasis on web growth as a function of twin spacing and on control of the temperatures in the molten and solidified silicon.
3) Thin ribbons have been grown from ribbon material by laser zone crystallization. This has included regrowth of single crystal ribbons and polycrystalline ribbons.
4) Chemical vapor deposition experiments continue on a variety of low cost substrates and on a molten tin substrate saturated with silicon. The factors that influence nucleation and crystal growth are being investigated.
5) Dip coating of mullite and other substrates has been successfully achieved by brief immersion in molten silicon. The molten silicon will wick through small openings in the substrate, possibly permitting the formation of back contacts.
6) Hot forming of silicon by deforming it at low strain rates has been demonstrated.
7) Ingot growth by the "heat-exchanger" method has produced 15 experimental, 2500 gm ingots during the 3 month period. The requirements for control of the crucible and heat exchanger temperatures during melting and then solidification are under investigation.
8) Knowledge and control of the heat transfer involved in all the growth techniques is receiving considerable effort.
9) Extensive experimentation continues on ingot slicing by multiple wires and blades.

Spreading resistance measurements in silicon and silicon structural evaluation are being performed at JPL on material samples from the contractors.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop the capability to economically encapsulate solar arrays for a 20-year lifetime. Encapsulation materials must transmit a maximum amount of sunlight to the solar cells as well as protect the solar cells and electrical conductors from the detrimental effects of a variety of environmental conditions during the life of the arrays. They must be inexpensive and easy to process during mass production of the arrays. The encapsulant must be chemically stable over a range of temperatures, and resistant to fire, abrasion, impact, ultraviolet radiation, and microorganisms.

The world experience and available materials study by Battelle has been completed. More than 60 uses and experiments of terrestrial photovoltaics are included in the report, the longest continuous use being 16 years. Reliability, corrosion, and delamination problems have been frequent. Satisfactory protection and stability have been achieved but have been associated with encapsulation approaches which are incompatible with the cost goals of LSSA.

The environmental definition and requirements study by Battelle has also been completed. The data confirms earlier observation that simultaneous occurrence of degrading conditions is less than might be estimated or assumed based on distribution of individual occurrences. This data will have an impact on (1) conditions used to evaluate nominal performance, (2) correlation of outdoor and laboratory testing, and (3) accelerated/abbreviated test conditions and analytical interpretation.

Analytical and experimental evaluation of accelerated/abbreviated testing is continuing at Battelle and Rockwell. There appears to be a major deficiency in availability of effective diagnostic methods for studying the rates and mechanisms of encapsulant material degradation.

Assessment of integral cover options and candidate materials indicates the feasibility of a reliable, cost-effective encapsulation system incorporating electrostatic bonded glass covers. Potential modification of the (Simulation Physics) contract has been discussed to incorporate contacts and interconnects printed on the glass and operation in the plastic deformation range to accommodate these contacts as well as cell surface irregularities.

D. AUTOMATED ASSEMBLY TASK

The objective of the Array Automated Assembly Task is to develop and demonstrate the process and equipment technology for the mass production of low-cost solar arrays. The plan is to study and assess present and potential production processes and techniques that are adaptable to solar array production; design automated production equipment; and stimulate expansion of solar array production facilities. Three companies are assessing the current state-of-the-art technology to identify those areas of solar cell technology which require development to achieve low-cost high-volume production.

A preliminary economic model and cost analysis procedure have been applied to existing solar cell module technologies using Czochralski crystal growth and wafering processes. Many different individual manufacturing processes have been assessed as to their potential applicability to solar cell manufacturing. Cost effective approaches and the identification of cost/manufacturing obstacles is being performed. Laboratory experiments are underway to evaluate the applicability of various processes and the associated obstacles. The cost to produce higher efficiency cells has been weighed against the cost of added encapsulation, structure, and volume production with results indicating that higher efficiency cells are more cost effective. Solar cell fabrication studies indicate that cell metallization is the least cost effective step in cell fabrication. Alternate cell metallization processes are being studied, including experimental work on silk screening thick film metallization.

The manufacture of 9.5% AM0 solar cells using ion implantation and electron beam processing has been demonstrated. This processing approach uses no special forming gas atmosphere, results in no acid waste or other waste disposal problems, and no materials are used that do not form part of the solar cell. The process promises to be one of low energy consumption and capable of processing times of less than 30 seconds per cm^2 and potentially as low as 5 seconds per cm^2.

E. DEVELOPMENT, PROCUREMENT, AND EVALUATION OF SOLAR ARRAYS

The periodic purchase by the Project of increasing quantities of solar arrays at decreasing unit prices and with the latest state-of-the-art technology provides a continuing evaluation of current technology and expands and upgrades industry's capability to produce solar arrays. The arrays are being procured from industry on a commercial basis to meet performance specifications and environmental requirements for use in ERDA photovoltaic power system tests and demonstrations. To date, 20 kilowatts of solar cell modules have been received from five manufacturers out of a total purchase of 46 kilowatts of off-the-shelf modules (Table 1-2). The deliveries will be completed in October 1976, the delays caused by design weaknesses and manufacturing defects having been remedied. Extensive acceptance inspection, testing, and engineering analysis has been performed by JPL as a result of these early module deficiencies. Extensive communication and iterative engineering efforts have been performed by the five manufacturers and JPL.

The same five manufacturers have been selected to produce 130 kilowatts of semi-standardized modules from 13 proposals received in response to an RFP (request for proposal). These new modules will incorporate selected design improvements to provide easier installation, less maintenance, and improved interchangeability in the field. Preparations have been made for detailed design developments to be performed by the manufacturers during the next quarter. Design reviews will be held before and after the prototype modules are fabricated and tested.

During the past 18 months, since the Program was initiated, the size of the terrestrial photovoltaic market has doubled and the price has been reduced by almost 50%. The modules in the 130-kilowatt purchase are selling for an average price of $15.50 per watt.

PART II

PROJECT PLAN AND MANAGEMENT

A. BACKGROUND

Silicon solar cell technology was initially developed at Bell Telephone Laboratories in the early 1950s. In 1955, the first field test was conducted in which telephone amplifiers were successfully powered by solar cells. Experimental and special purpose terrestrial uses continued, but during the 1960s and early 1970s spacecraft electrical power systems were the major and only well-known application for this technology. By the early 1970s photovoltaic theory had been developed, and the silicon solar-cell technology to support space application was well developed, but relatively expensive.

Prior to approximately 1972, terrestrial arrays were constructed utilizing solar cells that were rejects of the space program; however, the growth of the market prompted the innovation of solar arrays designs which were specifically oriented for the technical and economic requirements of a terrestrial applications market. A "price breakthrough" that is mainly attributed to the utilization of large-area round cells reduced the price from $90 per peak watt to $30 per peak watt. The Project has recently signed contracts for 130 kilowatts of solar arrays at an average price of $15.50 per peak watt. During the 18 months of the ERDA Program the terrestrial market has doubled and the price has decreased by almost 50%.

In 1971 the National Science Foundation's Research Applied to National Needs (RANN) program established an R&D program in terrestrial applications of solar energy and collaborated with NASA in a major assessment and planning effort carried out by a jointly-supported Solar Energy Panel. This led to a major workshop on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, held at Cherry Hill, N. J., in October 1973.

These activities led to the development of a national photovoltaic plan from inputs such as (1) the recommendations of the technical part of the Cherry Hill Workshop, (2) the photovoltaic conversion section in "The Nation's Energy Future," by Dr. D. L. Ray, and (3) a report of the Interagency Panel for Terrestrial applications of Solar Energy by a JPL team under NSF sponsorship. This initial plan is contained in JPL Special Publication 43-11, "Assessment of the Technology Required to Develop Photovoltaic Power Systems for Large-Scale National Energy Applications," published October 15, 1974. The general 10-year goals of a solar array price less than 50¢ per peak watt and a production rate of 500 megawatts per year were formulated. Activities required in the areas of technology development, photovoltaic power systems, and demonstration were outlined.

When ERDA was formed it acquired most of the responsibilities of the earlier NSF/RANN solar photovoltaic activity, including the foregoing plan. Thereafter, ERDA, in conjunction with other government agencies, industry, and potential users, reviewed, reevaluated, and extended the original plan during the formulation of the ERDA Photovoltaic Conversion Program. The Low-Cost Silicon Solar Array (LSSA) Project at JPL was initiated on January 9, 1975 as a major element of the new Program. Its functional elements closely corresponded to relevant elements of the new plan. The internal LSSA Project organization was established and Project activities were initiated in accordance with JPL Program Plan 1200-181, dated November 15, 1974. On February 5, 1975, a major Industry Briefing was conducted jointly in Washington, D. C., and Pasadena, California, to prepare for the initiation of a broad procurement program both for solar array technology development and for the acquisition of state-of-the-art silicon solar arrays for tests. The Project plans, objectives, schedules, and details of related procurements were presented to the approximately 300 persons who attended, representing 105 companies and 15 universities.

Since the original Project authorization, the Project plans, organization, and management have evolved to those described under the following Project Plans and Project Management. During the first year the major accomplishments involved detailed planning and organizing, and the solicitation, negotiation, and awarding of contracts to industries and universities. Thus far, 31 technology development contracts and 10 solar-cell-module procurement contracts have been awarded, as is shown in Table 1-1. The momentum of the Project has now been well established with a broad-based flow of analytical and experimental results from the contractors regarding the technical and economic feasibilities of new silicon refinement processes, silicon-sheet-growth techniques, encapsulants, and automated-assembly studied. Twenty kilowatts of the initial purchase of 46 kilowatts have been delivered. Detailed design of the 130 kilowatt procurement prototype modules are being initiated by the manufacturers.

B. PROJECT PLAN

The LSSA Project objectives, approach, and 10 year plan described below are an integral part of the Photovoltaic Conversion Program of ERDA's Division of Solar Energy. The generation of electrical power by solar photovoltaic systems for widespread use in residential, commercial, industrial, and governmental applications is the prime objective of the ERDA Photovoltaic Conversion Program. The JPL LSSA Project objective is to develop low-cost, long-life photovoltaic arrays and to stimulate the creation of a viable industrial and commercial capability to produce and distribute these arrays. The major obstacle that must be overcome is the high price of the solar energy converters, the solar cell arrays.

JPL role in the ERDA plan is:

- To support silicon-solar-array manufacturing technology development and its transfer to manufacturers.
- To develop and evaluate advanced array designs.
- To encourage expansion of industrial capability to produce solar arrays.
- To support methods of promoting user acceptance.

The specific JPL Project goal for 1985-86:

- To reduce solar array prices to less than $500* per kilowatt in annual quantities greater than 500,000 kilowatts, and to

*In 1975 dollars.

achieve a lifetime greater than 20 years and an overall conversion efficiency greater than 10%.

To attain this goal requires the demonstration by 1980 of the technology and economic potential for producing arrays in 1986 at the specified rate, price, and performance. Realization of this 1980 milestone is necessary in order to allow time to develop advanced array designs, develop detailed manufacturing processes, define manufacturing procedures, design and construct equipment, and plan production facilities. This requires that the best ideas and talents of U.S. industry and universities be identified and brought into the effort. The Project will continue to identify, assess, incorporate, and integrate these ideas into low-cost solar arrays which are compatible with the requirements and applications being developed in the ERDA Photovoltaic Conversion Program.

The approach being implemented to achieve the Project's objectives consists of technology development, deployment to industry, and market stimulation. Technology development is directed toward the extraction and utilization of those items from past and current research activities that can reduce the cost of producing solar arrays. Industry involvement is being fostered by participation in the technology development, by the transfer of technology to commercial practice, and by planned early large annual procurements of solar arrays. Market growth is being supported and stimulated by the annual solar-array procurements, by ERDA's photovoltaic power system tests, by operational and economic evaluations of these arrays, and by active participation with array users in defining requirements for the design of arrays. The Project will conduct solar-array design and test activities and will manage and integrate the solar-array technology development activities.

Technology development involves the selection and support of potential solar-array manufacturing cost reduction efforts; continuing assessment of the technical feasibilities of the evolving techniques and hardware; and verification of the economic viability of new materials and manufacturing processes. These technology development activities are being accomplished principally by industries and universities and are divided into four tasks:

1) Development of low-cost silicon material and production processes.
2) Development of large area silicon sheet technology suitable for the manufacture of solar cells.

3) Development of economical encapsulation materials and techniques that will provide array lifetimes greater than 20 years.
4) Development of automated processes and equipment for low-cost high-volume production of solar arrays.

The major steps to be accomplished by the four tasks and the interrelationship of these tasks are shown in Fig. 2-1.

The large-scale production activity involves the periodic purchase of increasing quantities of solar arrays at decreasing unit prices and with the latest state-of-the-art technology. Commencing now, future arrays will be procured from industry on a two phase commercial basis, development and production. Design specifications and performance requirements are to be established in conjunction with ERDA, potential users, and the manufacturers to be compatible with the ERDA photovoltaic power system test and demonstration activities. This enables the evaluation of current manufacturing technology and array performance under numerous diverse environmental and operational conditions. The Project provides liaison with LeRC and other solar array users in regard to module delivery, interface compatibility, and field performance. JPL conducts in-house analyses, design and performance verification, and design integrity activities. The results of these efforts are reported and distributed to relevant Program and Project areas. The concept of incorporating the latest photovoltaic technology will facilitate early detection of manufacturing problems which will be communicated to the appropriate module manufacturers and related technology development tasks. Design, reliability, and performance requirements will be periodically updated based upon the characteristics of solar cells and modules, the effects of the terrestrial environment, and the requirements anticipated for future power system applications. The functional relationships within the LSSA Project and between the Project and ERDA are shown in Fig. 2-1.

In addition to the direct control of contracts, JPL augments the contracted efforts by utilizing its in-house expertise and facilities for selected development and by technical assessment of the materials, devices, and processes which are being obtained from the contractors.

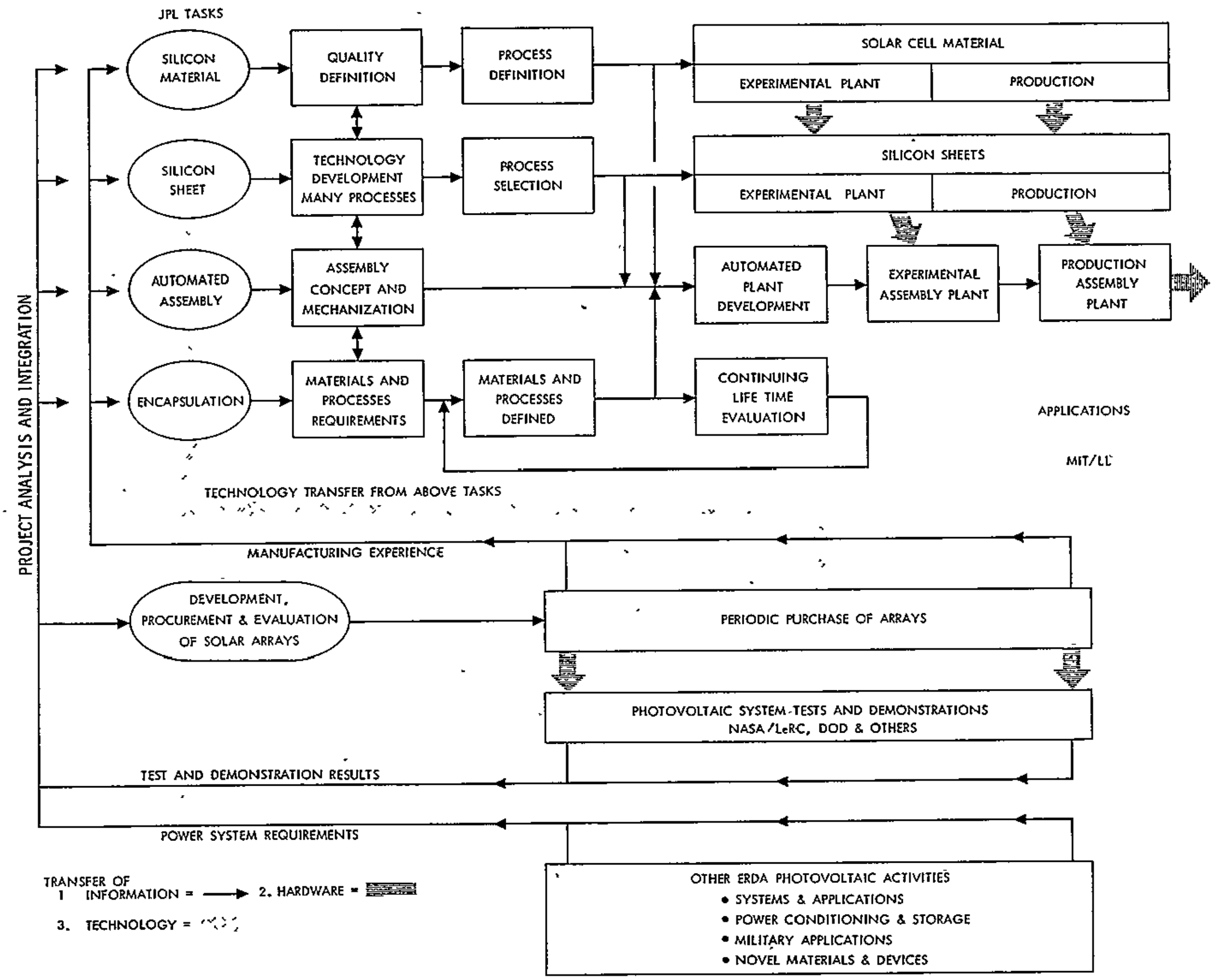

Fig. 2-1. Functional relationships within the Project and between the Project and ERDA

The project analysis and integration (PA&I) effort focuses on the planning, integration, and overall project analytical support which contributes to Project decision-making. This support will be implemented by providing assessments of array performance and economic influences on Project activities and plans, developing interface definitions among the Project tasks, supporting the derivation of interfaces between the LSSA Project and other ERDA Photovoltaic Conversion Program activities, and by developing the plans and procedures for integrating the tasks within the Project and between the Project activities and other elements of the Program.

The Project approach of conducting concurrent related efforts within each of the technology development tasks and the large scale production activities provides an opportunity for examination of alternative approaches in order to obtain the most cost-effective methods for achieving individual task objectives. To optimize the overall Project efforts, extensive examinations of the trade-offs between the task approaches are performed and the task efforts are adjusted accordingly. As photovoltaic system requirements evolve solar cell array requirements and specifications are iterated with potential users, the elements of the ERDA Program, and manufacturers, so that optimum array performance is achieved that is compatible with a most cost-effective power system. These activities are planned and directed to stimulate a systematic expansion of industry's solar array manufacturing capabilities.

It is anticipated that the industry will respond with increasing investments in the course of the Project. The degree of progress made by the Project and the evolving industry will be the subject for a continuing assessment such that by the late 1970s technical feasibility and industry status can be readily evaluated. The resulting information will subsequently be used to determine the requirements for experimental plants, production plants, and the Project general level of effort for continuing, future activity.

A 10-year master schedule for the Project (Fig. 2-2) displays specific milestones to be achieved by the functional elements shown in Fig. 2-1. The initial phase of the program, under way during FY 1976, the transition period, and part of FY 1977, is essentially devoted to assessment, the definition of

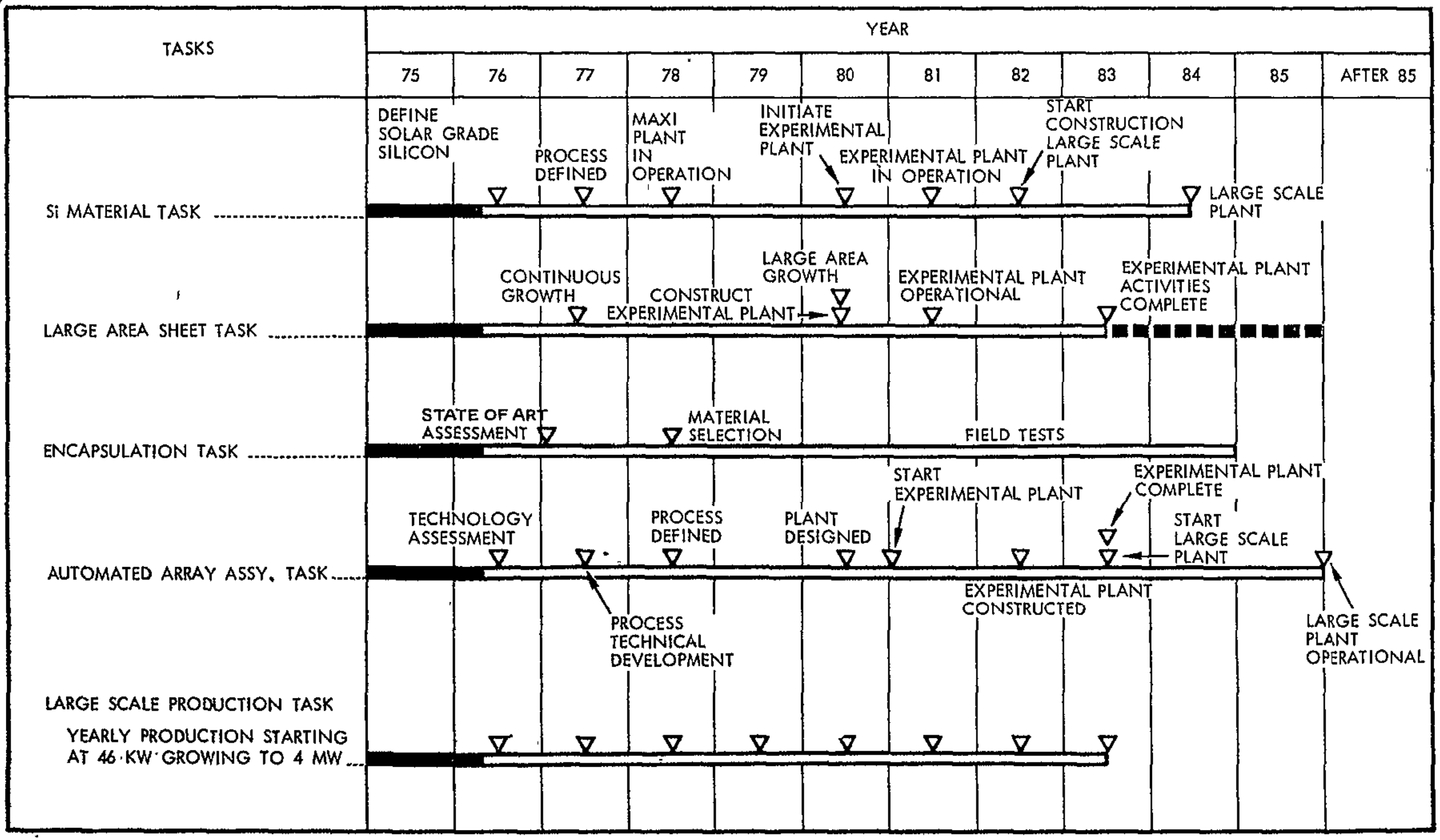

Fig. 2-2. Low-Cost Silicon Solar Array Project Master Schedule

technology requirements, and the evaluation of processes and techniques necessary to reach the Project's goals. The next phase of this effort, which will be initiated in FY 1977, will in general evaluate the scalability of the various processes and material being considered, which leads to the demonstration of technology readiness in FY 1980.

The following paragraphs describing the technology development tasks, in conjunction with Fig. 2-2, explain how the tasks will achieve their specific objectives. More details are presented in Part IV.

Solar cells can be fabricated from silicon that is less pure than the single-crystal, semiconductor-grade silicon that is presently used, and it can be in the polycrystalline form. Results of solar cell performance versus various quantities of specific impurities in silicon and crystalline structure will be used to define a solar-cell-grade silicon. Studies and experiments are indicating that significantly less expensive silicon refinement processes can be developed for both semiconductor grade and a less pure grade silicon than are in use today. The plan is to continue work on the various processes until the most cost-effective process can be selected. The goal is to reduce the present price level from approximately $65 to $10 per kilogram.

Methods are being evaluated for reducing the cost of contemporary silicon wafer fabrication, which consists of slicing thin wafers from grown single crystals. An ideal fabrication technique would be to grow crystalline sheet in a geometry that would require neither cutting nor polishing and yet would produce material from which high efficiency solar cells could be fabricated. The ideal has not been developed and perfected; however, sufficient progress has been made in development work on a number of growth techniques to indicate that more cost-effective techniques are achievable. Growth techniques being investigated include ribbon growth through a die by capillary action and by gravity feed, web-dendritic growth without shaping, laser heat zone crystallization of ribbon material, vapor deposition of solar cell material onto a solid substrate and onto a liquid, dip coating of solar cell material on substrates, and the hot forming of silicon.

The capability to economically encapsulate solar arrays for long times, preferably 20 years or more, is required. Throughout the life of the arrays, the encapsulant must transmit a maximum amount of sunlight to the solar cells as well as protect the solar cells and electrical conductors from detrimental effects of a variety of environmental conditions. Studies are continuing on existing materials that potentially could be encapsulants based upon past experience and a definition of the environmental conditions. Assessments will continue on potentially improved encapsulant materials and processes and on test methods required for encapsulant evaluation and verification. The most cost-effective encapsulant systems will be defined for a variety of applications.

Production processes, techniques, and automated production equipment that possibly could be adaptable to solar array mass production are being studied and assessed. These activities include evaluating various solar cell fabrication techniques for mass production, the feasibility of forming a solar cell junction at room temperature by use of an ion planter and an electron beam, identifying manufacturing costs, and conceiving and developing most cost-effective solar array manufacturing techniques. It is planned that this activity will culminate in low-cost solar arrays that have evolved from all of the technology development.

Preliminary detailed cost goals have been allocated, in 2-year increments, for each of the major manufacturing steps. These intermediate cost goals will permit an assessment of Project progress so that Project activities can be optimized. The detailed cost goals are shown in Fig. 2-3.

The monitoring and coordination of all these activities is accomplished by extensive written and oral communications within the Project and with all elements of the ERDA Program. This effort is highlighted by the ERDA Program Quarterly Review Meetings, the ERDA Semi-Annual Photovoltaic Meeting, and the Quarterly LSSA Project Integration Meetings.

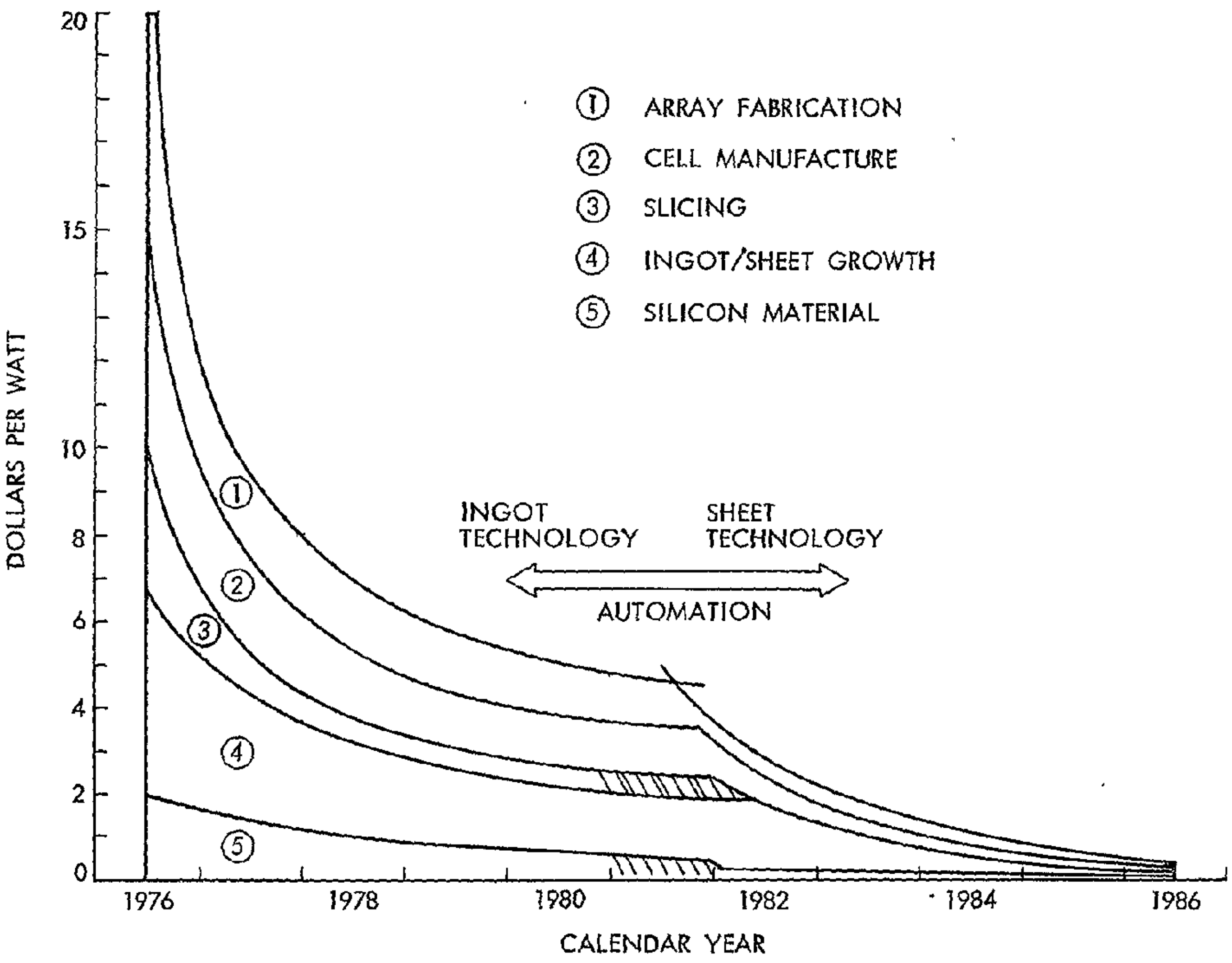

Fig. 2-3. Terrestrial solar array price goals

C. PROJECT MANAGEMENT

The objective of the LSSA Project management is to administer the Project in support of and within the constraints of the ERDA Photovoltaic Conversion Program to meet the established objectives by planning, organizing, directing, coordinating, controlling, and integrating the Project activities. To accomplish this, the Project management has been structured to implement the plans as described in the Project Plan. The major functional activities that are managed consist of: (1) solar array technology development, (2) purchase and evaluation of state-of-the-art solar arrays, (3) analysis and integration of Project technical activities, and planning for commercialization, (4) administration of Project activities, and (5) interaction, coordination, and communication oral and written within JPL and with the various participating organizations and the ERDA Program Office.

The Project is organized to operate within the JPL matrix organization as shown in Figs. 2-4 and 2-5. The organizational structure involves line organizations of expertise with horizontal commitment to Project and with Project line management responsibility assigned under the Assistant Laboratory Director for Civil Systems. The majority of the Project personnel including the Task Managers are assigned to the Project from the technical and administrative Divisions of the Laboratory (Fig. 2-5). Consequently, the Project has access to technical specialists and resources available for support as required which provides an efficient use of expertise and provides greater flexibility in management of the Project. The key personnel are assigned to the LSSA Project with long-term responsibilities. Thus a broad spectrum of diverse, qualified support is available to the LSSA Project to perform the following functions:

1) To establish and maintain the Project plans based upon an assessment of Project progress, goals, and long range plans and in accordance with the plans and requirements of ERDA and within the available resources.
2) To establish the Project organization and provide resources as required for implementation of the plan.

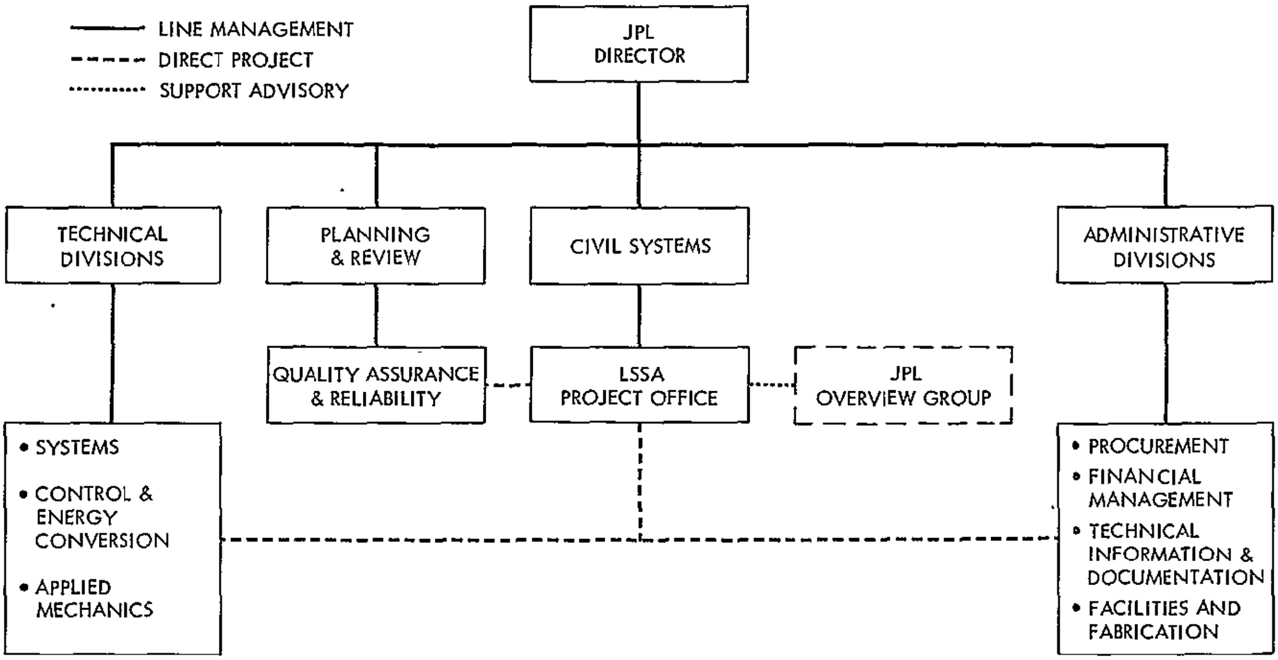

Fig. 2-4. LSSA Project - JPL Management structure

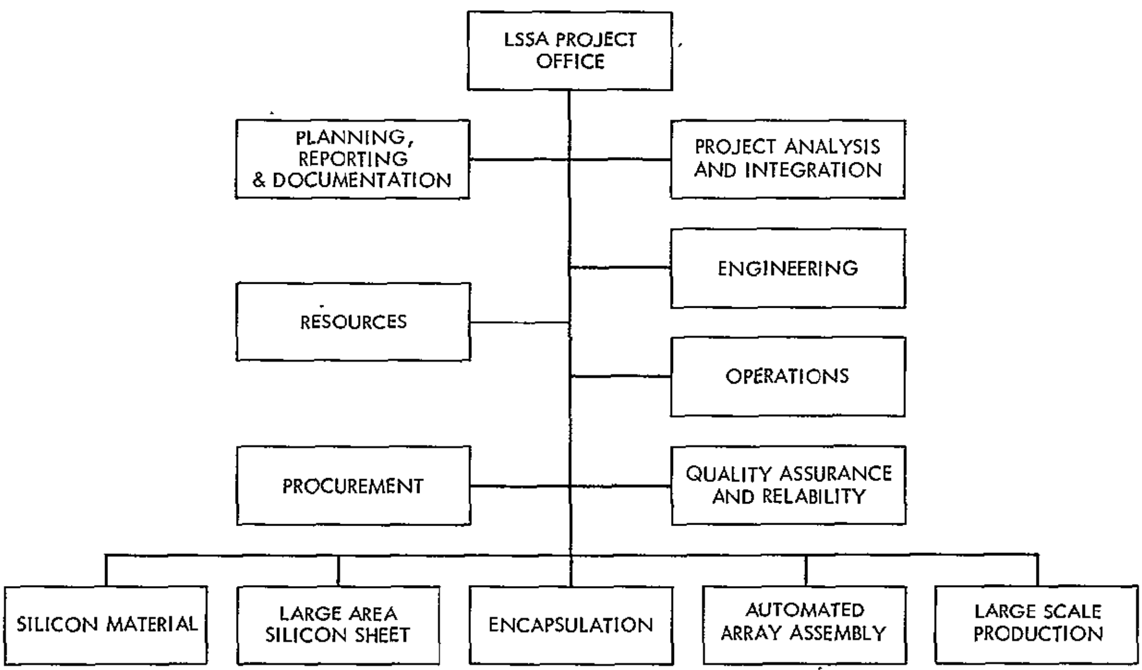

Fig. 2-5. LSSA Project Management structure

3) To define and assign responsibilities and delegation of authority necessary to carry out the assignments.
4) To direct, control, and integrate the in-house (JPL) and contracted activities required to meet the objectives.
5) To appraise the effectiveness of the management methods and adjust as necessary.
6) To evaluate the technical approaches, progress, and levels of effort used and adjust methods and/or the emphasis as required.
7) To document and report on the Project plans, status, and accomplishments as required. This includes the acquisition, organization, and dissemination of contracted activity reports.
8) To interact, coordinate, and make compatible the Project activities with all elements of the National Photovoltaic Program so that progress is maintained and the overall Program objectives are achieved.

The Project Manager is responsible for the JPL LSSA Project's achievement of its objectives in support of the ERDA Photovoltaic Conversion Program. He is responsible to the ERDA Division of Solar Energy through the JPL upper management as shown in Fig. 2-4. He is supported by a deputy manager. Each of the five technical tasks has a manager who is responsible for accomplishment of the task objectives within the financial and technical resources allocated. The Task Managers are responsible for the contracted and in-house activities associated with their task and are assigned technical and administrative support personnel including contract negotiators.

The Project Analysis and Integration (PA&I) Task Manager is responsible for conducting efforts that support the technical planning, integration, and economic analytical activities of the Project. This support will be implemented by providing assessments of possible performance and economic consequences of alternative Project plans, developing the interface requirements among the Project tasks, supporting the establishment of the interface requirements between the LSSA Project and other ERDA Photovoltaic Conversion Program activities, and by developing the plans and procedures for integrating the tasks within the Project and between the Project activities and other elements of the Program.

The Engineering Task Manager is responsible within the Project for the compilation, development, and definition of design, performance, and test requirements for solar cell modules and solar arrays. This activity requires an iterative, coordinated effort so that the inputs from all elements of the National Program, the array manufacturers, and users, can be incorporated into the requirements.

The Operations Manager coordinates and controls the solar cell module test planning, testing, performance analysis, and liaison with users. This includes liaison and coordination for JPL with solar cell module users regarding module delivery, interface compatibility, field performance, and failure analysis and reporting. In addition he is responsible to establish and maintain the JPL solar array test sites.

The Quality Assurance and Reliability Manager is responsible for the establishment and implementation of an effective quality program consistent with the Project overall objectives, including minimum quality and workmanship standards developed in collaboration with industry for the production of low-cost, reliable products.

The Project Planning, Documentation and Data Management Manager is responsible for providing the administrative planning, reporting, and documentation needed to plan, administer, control and document Project activities. The acquisition, organization, and dissemination of technical information, a key function in technology transfer, is performed by the Project Data Center. This maintains the timely dissemination of information among the Project contractor and other associated members of the government, industry and universities.

Contract negotiators are assigned to each of the Project's five technical tasks, and a Procurement Manager is assigned to administer the Project's contracting activities including the initial phase of contractor selection, contract execution, and the later phases of contract management.

A Resources Manager administers the Project financial management with supporting financial and contract analysts, making maximum use of the existing JPL financial reporting system. The primary functions include the support for defining the resource requirements necessary to accomplish the plan, the incorporation of the resource plans into the reporting systems and the analysis of the performance information derived from the system.

PART III

PROJECT ANALYSIS AND INTEGRATION TASK

The function of Project Analysis and Integration (PA&I) is to support the planning, integration, and decision-making activities of the Project. This role is being carried out by providing assessments of Project goals and of the progress toward the achievement of the goals by the various activities of the Project; by contributing to the generation and development of alternative Project plans through the assessment of possible achievements and economic consequences; by establishing standards for economic comparisons of items under Project study; by supporting the integration of the tasks within the Project and between the Project and the Photovoltaic Conversion Program elements through development of integration plans and procedures; by participating in integration activities; and by developing the analytical capabilities for, and performing or participating in the trade-off studies required.

A. TECHNICAL BACKGROUND

The Project approach of conducting parallel efforts within each of the technology development tasks maximizes the chances of obtaining the most cost-effective processes for achieving the individual task objectives. It is also necessary, however, to seek to optimize the achievement of the overall Project objectives, by means of adequate consideration of the trade-offs between tasks. This is reflected in allocation of resources and cost goals among the various tasks. Preparation for these decisions requires examination of the cost and performance potentials of the various technologies and their impact on the achievement of the Project goals, taking into account the influence of such outside factors as the predicted supply-demand relationships, the perceived degrees of commercial risk and profit, the character of the investment market, potential governmental actions, and so on. These considerations also depend upon close interaction with the efforts being carried out within each of the task areas as well as within the other activities of the ERDA Program. Thus, procedures and relationships which have been established will be maintained and extended as appropriate in order to obtain and coordinate the information being generated within the task areas and the ERDA Program activities.

Two primary goals of the LSSA Project — viz., the 1986 array price goal of $< \$500$/peak kilowatt and array production goal of > 500 megawatts/year — permeate the entire Project in terms of strategies and decisions affecting the direction of the Project. Thus, it is necessary to establish and maintain a thorough understanding of the relationship between these goals and the interaction with the goals, individually and collectively, of the four technology development tasks and the production task of the Project. This understanding must also take into account the further relationship between these price/production goals and another Project goal — the goal of fostering the growth of the solar array manufacturing industry. Furthermore, large scale applications of solar photovoltaic power systems suggest the need for array design specifications of performance and safety which exceed the design requirements for current, smaller applications, thereby indicating design/cost trade-offs which could affect strategies for achieving the price/production goals. The conduct of these assessments requires close interaction with the system and demonstration activities of the Program.

B. ORGANIZATION AND COORDINATION OF EFFORT

The LSSA PA&I is organized into three highly-interrelated functional areas: (1) Planning and Integration; (2) Array Technology Cost Analysis and (3) Economics and Business Analysis. The planning and integration activities include providing support to various Program and Project planning activities, developing Project integration designs and procedures, and providing an interface function between the Project and the Program's mission and systems activities.

The array technology cost activities include array production cost analyses and trade-off studies, array installation and operation costing analysis, array design/economic optimization, and cost goal allocation analyses for the technology development tasks.

The economic and business analysis activities focus on the economic prerequisites to achieving large scale, low cost commercial production of solar photovoltaic modules or arrays and the measurement of the industrial readiness for and actual movement toward the production growth capability to reach the Project and Program goals. These activities include analyses of manufacturing investment elements, investment behavior analyses, array market conditions, resources and materials cost/availability studies, institutional and policy analyses and analyses of the relationships between array prices and production levels under free market, subsidized, and mixed strategies.

In support of these activities, information is generated using inputs from Project Task Managers and their staffs, contractors, the Project Office and the ERDA Program Office as well as other governmental or industrial organizations as needed. The PA&I effort is primarily, but not exclusively an in-house activity: subcontractors and/or consultants will be used to support the development of some information, procuedures or techniques.

C. TECHNICAL ACTIVITY

1. Planning and Integration

During the quarter, plans were generated and support was provided for the second Project Integration Meeting (PIM). The plans developed provided for a greater emphasis on intertask integration activities and reviews of interface requirements and constraints between the tasks. Presentations were made at the PIM of the PA&I array cost analysis activities including a discussion of the SAMIS (Solar Array Manufacturing Industry Simulation) model and the cost goal allocations among the technology development tasks.

Planning was also initiated in the latter part of the quarter for the third PIM.

Work continued on the Project Implementation Plan. Draft sections developed during the quarter included the Project Technical Plan and the Project Assessment and Integration Plan, as well as drafts of the introductory and summary sections.

Program interface meetings attended during the quarter included the bi-monthly reviews of contractor activities for the conceptual systems design and analysis studies, the Program Quarterly Interface Meeting, and the Program Planning Group Meetings chaired by Sandia.

Support was also provided in preparing JPL testimony for a congressional hearing and in planning and/or making various ad-hoc presentations to Project visitors.

2. Array Technology Cost Analysis

Development of the SAMIS model continued during the quarter, particularly in the development of the industry descriptions for the Czochralski growth process using the most current parametric values from Tasks 2 and 4 contractor studies. This description was used to obtain a preliminary assessment of the relationship between array price and output level for various levels between 1 kilowatt and 1 megawatt. This preliminary assessment was only a first order evaluation since the models for detailed analyses have yet to be developed; however, these initial estimates do provide useful "ballpark" values.

In response to a need expressed at the second PIM, an effort was initiated to develop a uniform costing method for preparing manufacturing cost estimates. The method desired is one which both the LSSA contractors and the LSSA in-house studies can use to perform cost analyses of the manufacturing processes and allow comparison of the processes on the basis of the merits of the process and not the choice of economic parameter value or costing method. The requirements for the uniform costing method were developed and a plan was prepared for generating and reviewing the method.

In order to more fully examine array design trade-offs for developing the design requirements for the large scale procurements, and for developing the advanced designs associated with the large scale applications for the Program goals, it has become necessary to develop an analytical ability to examine array installation, operation, and maintenance costs. Thus, an effort was initiated during the quarter for developing an array installation and operation model which will interface with the Engineering Task array design activities. The requirements for the model have been determined and a development plan for the model has been prepared and implemented with the initial task of a literature search for existing installation and operation models.

3. Economics and Business Analysis

The economic methodology developed for ERDA and the Electric Power Research Institute (EPRI) to standardize the economic analyses of utility-owned solar electric systems was finalized during the quarter. The method was documented and published as document number ERDA/JPL-1012-76/3 entitled "The Cost of Energy from Utility-Owned Solar Electric Systems: A Required Revenue Methodology for ERDA/EPRI Evaluations".

The version of the methodology which was documented was modified somewhat from the version reported on in the LSSA Project First Annual Report. The modifications in the method include the addition of several classes of escalation rates instead of a single escalation rate. An additional formulation of the annualized fixed charge rate was provided as a generalization which explicitly considers accelerated depreciation and investment tax credits.

The generalized expression for the annualized fixed charge rate is:

$$\overline{FCR} = CRF_{k,N} \left(\frac{1 - \tau \cdot DPF_{m,k,n} - \alpha}{1 - \tau} \right) + \beta_1 + \beta_2$$

$\overline{FCR}$ = annualized fixed charge rate

$CRF_{k,N}$ = capital recovery factor for N periods at an interest rate of k per period

τ = effective corporate income tax rate

$DPF_{m,k,n}$ = depreciation factor for a depreciation method m at a discount rate k over an accounting lifetime n

α = investment tax credit fraction for one year

β_1 = the ratio of all non-income annual taxes to present value of the total capital investment

β_2 = the ratio of all insurance premiums to the present value of the total capital investment.

When the depreciation method used is a straight line method over the system engineering lifetime and there is no investment tax credit, then: n = N, $DPF_{m, k, n} = \left[N \cdot CRF_{k, n}\right]^{-1}$, and the expression is that for $\overline{FCR}$ given in the Annual Report, namely:

$$FCR = \frac{1}{1 - \tau} \left(CRF_{k, N} - \frac{\tau}{N} \right) + \beta_1 + \beta_2$$

Use of the generalized form of $\overline{FCR}$ with faster depreciation methods and investment tax credits will result in relative decreases in the annualized fixed charge rate, and therefore relative decreases in the busbar energy costs of the solar electric system under study.

As part of an effort performed in conjunction with the Engineering Task and the Department of Defense cost studies were made for a comparison between solar power systems and diesel-generator systems. The results of these studies show that, at array prices of $10/peak watt, solar photovoltaic power systems are generally not competitive with diesel-generator systems. Competitiveness can be found at this array price, however, when the application is at a remote site requiring higher operations and maintenance costs for the diesel-generator system and the load is limited to a maximum of 40 kilowatts.

During this quarter an effort has been initiated to plan and develop methods and procedures for measuring the economic growth of the manufacturing industry. This effort will lead to the development of a Project Plan for deploying the technology to commercial practise. A preliminary process for developing the economic growth measures has been developed and initial models for examining economies of scale and the diffusion of technology have been formulated. In addition, a study has been initiated to examine the growth rate implications of the Project goals, together with a survey of various industry growth experiences. This latter study is also being performed in support of the Program Planning Group activity.

PART IV

TECHNOLOGY DEVELOPMENT TASKS

TASK 1. SILICON MATERIAL

The objective of the Silicon Material Task is to establish, by 1984, an installed plant capability for producing silicon suitable for solar cells at a rate equivalent to 500 megawatts (peak) of solar arrays per year at a price of less than $10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal can not be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade silicon. Consequently, it is necessary that either a different process be developed for producing semiconductor-grade silicon or a less pure and less costly silicon material (i.e., a solar-cell-grade silicon) be shown to be utilizable.

A. TECHNICAL BACKGROUND

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

B. ORGANIZATION AND COORDINATION OF THE TASK 1 EFFORT

The Task 1 effort is organized into five phases. As Table 4-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade silicon will be demonstrated. In Part II the effects of impurities on the properties of single-crystal silicon material and the performance characteristics of solar cells, as well as the consequences of various processing procedures, will be investigated. This body of information will serve as a guide in developing processes (in Part III) for the production of solar-cell-grade silicon. The process developments in Parts I and III will be accomplished through chemical-reaction, chemical-engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various silicon-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies and the most promising processes will have been selected.

Phase II will be initiated to obtain scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of a large-scale production plant.

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

Table 4-1. Organization of the Task 1 effort

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

In the final phase of Task 1 (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The experimental plant and the commercial plant will be operated concurrently so as to permit the use of the experimental plant for investigations of plant operations, i.e., for problem solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of Task 1 will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

C. TASK 1 CONTRACTS

Eleven contracts are in progress: three for Part I, two for Part II, five for Part III, and one for Part IV. These contracts were negotiated after careful evaluations of responses to a Request for Proposal (RFP) and unsolicited proposals. The contracts are listed in Table 4-2. Additional contractors for subsequent phases will be selected from unsolicited proposals and from future RFPs.

D. TASK 1 TECHNICAL ACTIVITY

The objectives of Phase I of Task 1 are as follows:

- Part I — Establish the practicality of a process capable of the high volume production of semiconductor-grade silicon at a markedly reduced cost.
- Part II — Investigate the effects of impurities and process-steps on the properties of single-crystal silicon material and the performance characteristics of solar cells.
- Part III — Establish the practicality of a process capable of the high volume production of solar-cell-grade silicon at a price of less than $10 per kilogram.
- Part IV — Evaluate the relative commercial practicality of the silicon-production processes developed under Phase I of Task 1.

1. Processes for Producing Semiconductor-Grade Silicon

The approach for Part I incorporates theoretical studies involving thermodynamics, reaction chemistry, and chemical engineering; chemical reaction investigations consisting of the experimental determinations of reaction kinetics yields, and suitable process conditions; a chemical

Table 4-2. Task 1 Contractors

Note: All Task 1 contracts, current or proposed, are for work under Phase I

Contractor	Technology Area
SEMICONDUCTOR-GRADE PRODUCTION PROCESSES (Part I of Phase I)	
Battelle Memorial Institute, Columbus, Ohio	Si from $SiCl_4$ reduction by Zn
Union Carbide, Sistersville, W. Virginia	Si from SiH_4 derived by redistribution process
Motorola, Phoenix, Arizona	Si using SiF_4 reaction with metallurgical grade Si and SiF_2 transfer
SOLAR-CELL-GRADE SPECIFICATIONS (Part II of Phase I)	
Westinghouse Electric, Pittsburgh, Pennsylvania	Investigation of effects of impurities on solar cell performance
Monsanto Research, St. Louis, Missouri	Investigation of effects of impurities on solar cell performance
SOLAR-CELL-GRADE PRODUCTION PROCESSES (Part III of Phase I)	
Dow Corning, Hemlock, Michigan	Si from pure source materials using arc furnace processing
Stanford Research Institute Menlo Park, California	Si by duplex vapor-electrochemical conversion of SiF_4
Texas Instruments, Dallas, Texas	Si from C reduction of SiO_2 using plasma processing
Westinghouse Electric Pittsburgh, Pennsylvania	Si by plasma-arc-heater reduction of $SiCl_4$ with H_2 and alkali metals as reducing agents
AeroChem Research Laboratories, Princeton, New Jersey	Si by use of a non-equilibrium plasma jet
COMMERCIAL POTENTIAL OF PROCESSES (Part IV of Phase I)	
Lamar University, Beaumont, Texas	Evaluate relative commercial potentials of Si-production processes developed under Task 1

engineering effort for securing an experimental data base for preliminary process modeling; and energy-use and economic calculations for preliminary process models. In each case the contract requires a demonstration of technical feasibility and a projection of commercial practicality, involving the preliminary analysis of suitability for a scale-up study. The processes for the Phase II scale-up studies will be selected over a period of time, the decision point for each process-development being dependent upon the maturity of that process. The scale-up studies for the most mature processes will begin in early FY 1977.

a. Semiconductor-Grade Si Production by (1) Zn* Reduction of $SiCl_4$ and (2) Thermal Decomposition, or H_2 Reduction, of SiI_4 — Battelle Memorial Institute

The objective of the program at the Battelle Memorial Institute is to determine the practicality of utilizing processes for (1) the Zn reduction of $SiCl_4$ or (2) the thermal decomposition, or H_2 reduction, of SiI_4 to meet the goal of Part I. The selection of the process for the scale-up studies will be based on the results of chemistry and chemical engineering analysis and comparisons of the technology, economics, and energy-use of the two candidates. The practicality will then be demonstrated by the operation of a small processing unit.

These investigations have progressed with analyses of the economic practicality of a series of production-models based on the use of the $SiCl_4$ and SiI_4 processes and then, for the $Zn/SiCl_4$ process, with evaluations of the effects of some parametric variations and preliminary runs of a miniplant. The decision to concentrate effort on the $SiCl_4$ process was derived from engineering and economic analyses. This conclusion was supported by subsequent preliminary results from operation of the experimental plant.

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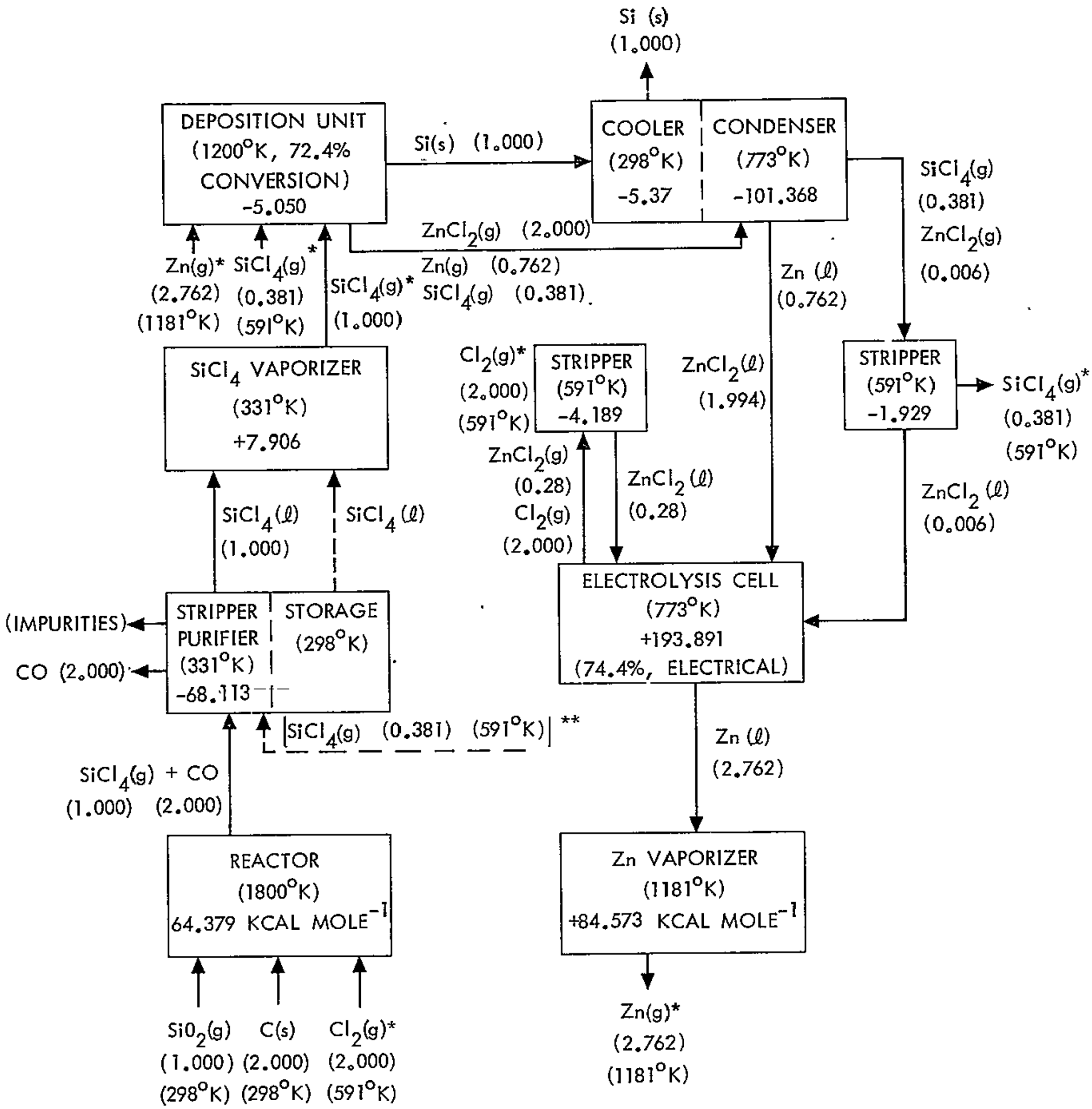
* Zinc. For identification of chemical symbols, see List of Abbreviations.

Economic Analyses

The analyses of the economic practicality of the $SiCl_4$ and SiI_4 processes involved steps for the (1) determination of operating ranges of temperature, pressure, and composition, using thermodynamic calculations and experimental data; (2) drafting of mass and energy flow diagrams; (3) sizing of equipment; (4) calculation of fixed capital investments for the major equipment; (5) determination of net process energy requirements; (6) determination of raw material costs; (7) calculation of mass flow requirements; and (8) conversion of fixed capital investment, manpower, material and utility costs to product costs. The costs, for January 1975 and a plant capacity of 1000 metric tons per year, were used in the models. In general, a conservative approach was used in estimating the costs of the processing units and in assigning manpower loadings. The conclusions are valid for comparison purposes. Optimization-iterations should be performed using operating data and including some process-elements that were omitted in this first estimate.

The primary conclusion was that the $Zn/SiCl_4$ process is the most economical, with a calculated product cost of \$9.12/kg Si. The flow sheet for this process is given in Fig. 4-1. The items included in the calculation of the product cost are shown in Table 4-3. The most economical SiI_4 process, which incorporated the iodination of metallurgical grade Si and a hot-wire deposition, yielded a product cost of \$20.65/kg Si, the principal cost items being for capital equipment and energy. The comparison of the energy-consumption factors also favored the $Zn/SiCl_4$ process over the closest economic SiI_4 process-competitor; the calculated values are 46 kwh/kg Si versus 216 kwh/kg Si for these processes.

On the basis of the results of these analyses, it was recommended that no further work be done with the SiI_4 processes and that only the $Zn/SiCl_4$-fluidized bed reactor process be investigated further. These investigations will involve the design, installation, and operation of a miniplant based on a fluidized bed reactor. The objective will be to obtain information regarding operating characteristics, product quality, and engineering data, for use in designing large production plants and in making more accurate economic analyses.



*RECYCLED MATERIAL

**RECYCLE ROUTE ADOPTED IN COST ANALYSIS

Fig. 4-1. Process flow sheet — Zn reduction of $SiCl_4$

Table 4-3. Product costs — process for reduction of $SiCl_4$ with Zn — Battelle

A. MANUFACTURING COST			
1. Direct Production Cost			
	a. Materials		$2, 590, 000*
	b. Operating labor		892, 790
	c. Supervisory and clerical	15% of b	133, 920
	d. Utilities		335, 000
	e. Maintenance and repairs	10% of fixed capital	862, 440
	f. Operating supplies	15% of e	129, 370
	g. Laboratory charges	15% of b	133, 920
	h. Patents and royalties	4% of product cost	364, 660
2. Fixed Charges			
	a. Depreciation	10% fixed capital	$ 862, 440
	b. Local taxes	2% fixed capital	172, 490
	c. Insurance	1% fixed capital	86, 240
	d. Interest	6% fixed capital	517, 460
3. Plant Overhead		60% of (lb + lc + le)	$1, 133, 490
B. GENERAL EXPENSES			
1. Administration		50% of lb	$ 446, 400
2. Distribution		2% of product cost	182, 330
3. Research and Development		3% of product cost	273, 490
C. TOTAL PRODUCT COST			$9, 116, 440/yr
1. Product Cost, per kg Si			$9. 12

*Includes all cost (operating and capital investment) for $SiCl_4$ used.

Effects of Non-Stoichiometric Ratios

An analysis of the economic effects of operating at non-stoichiometric ratios of $Zn/SiCl_4$ was performed to determine if factors for different ratios should be considered in the design and operation of a miniplant. The economic effects were calculated from equilibrium efficiencies of conversion of $SiCl_4$ to Si as a function of the $Zn/SiCl_4$ ratio, using the assumptions that (1) the sizes of the units are proportional to the number of moles of Zn or $SiCl_4$ necessary for the production of 1 mole of Si; (2) the size of the fluidized bed reactor varies as the total number of moles of Zn and $SiCl_4$; (3) the miniplant size is based on a production rate of 24 kg Si/hr; (4) the cost of the $ZnCl_2$ electrolysis unit is constant; (5) manpower costs are constant; and (6) energy costs are directly related to the assumed stoichiometry. The conclusions were that there is no marked advantage to operating at other than the stoichiometric 2/1 ratio and that the added cost of operating with as much as a 43% excess of either reactant is less than \$0.10 per kg Si. These conclusions are of particular value, since they lead to the inference that the careful control of the reactant ratio may not be required. Experimental data will be obtained to determine if the factors of product purity and kinetics support these conclusions, which were derived from thermodynamic calculations.

Miniplant

Operation of the miniplant (capable of a production rate of 200 gm/hr over a 4 to 6 hour period) is directed toward the verification of product purity; the determination of dependence of capacity, yield, and rate on operating parameters; and the development of information for the design criteria for process operation and for further economic analyses. The major items of equipment — the fluidized bed reactor, Zn feeder, Zn vaporizer, $SiCl_4$ vaporizer, and $ZnCl_2$ condenser — have been constructed and are being evaluated. The $ZnCl_2$ electrolysis cell is being modified for batch operation. A schematic diagram of the major miniplant components is shown in Fig. 4-2. The data for exploratory runs allowed reasonable material balances in most cases, although the need was evident for continued parametric studies to define the conditions for improved operation. The data for one run are cited

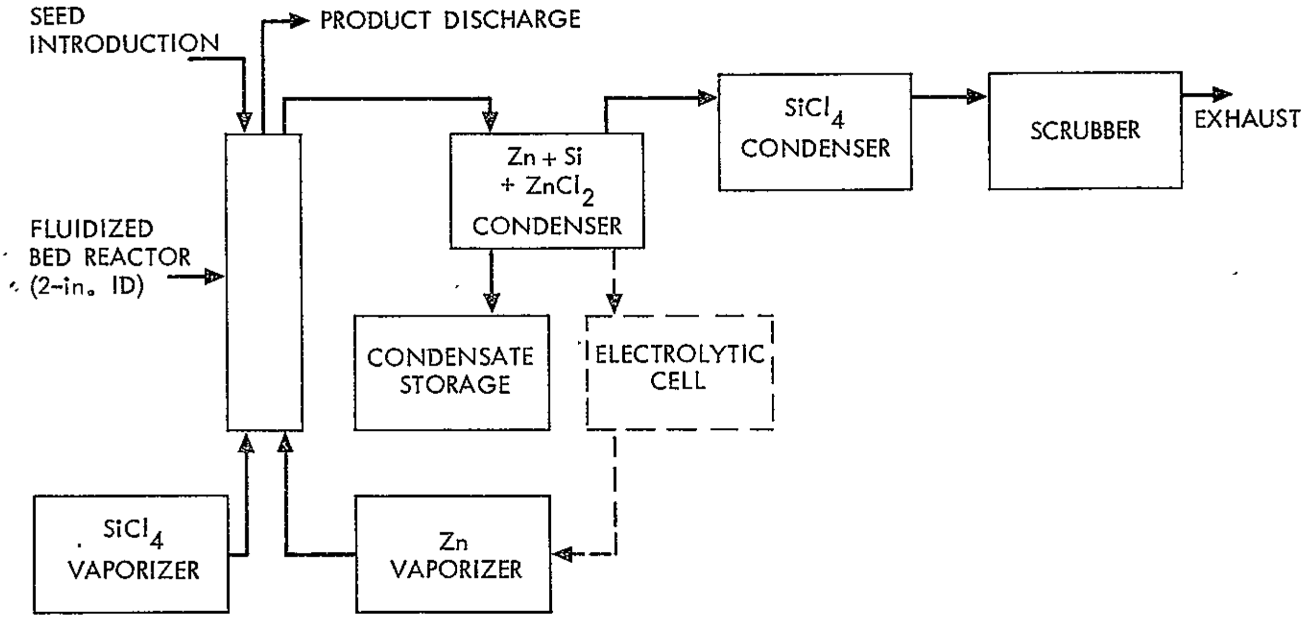


Fig. 4-2. Battelle process for reduction of $SiCl_4$ with Zn — schematic diagram of major miniplant components

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here to show the potential of the process: 86.3% of the product Si was deposited on the bed particles, and the total Si deposition was 94% of the thermodynamically predicted value. This corresponds to an overall bed yield of 67%, operating at a reactant ratio with a calculated thermodynamic-economic penalty of \$0.04/kg Si.

Experimental operation of the miniplant will continue and will involve studies of the effects of the following items on process efficiency, product purity, and economics: seed particle size in the fluidized bed reactor, reactant gas flow rates, temperature, and $ZnCl_2$ electrolysis cell operation.

b. Production of SiH_4 by Redistribution of Chlorinated Silanes — Union Carbide

The objective of this program is to demonstrate the practicality of producing SiH_4 at a cost of \$3 to \$5 per kilogram, using as the basic process the redistribution of a mixture of chlorinated silanes to yield SiH_4. The redistribution is accomplished by using a tertiary amine ion exchange resin (Rohm and Haas Amberlyst A-21) for the catalytic disproportionation. This is followed by the purification of SiH_4 by fractional distillation, the chlorinated silanes being recycled and reprocessed. Other major efforts are directed toward the direct synthesis of SiH_2Cl_2, to provide an enriched feed for the redistribution process step, and the hydrogenation of the $SiCl_4$ by-product to yield $SiHCl_3$ for use as a feed. The effects of temperature, pressure, and feed composition on rate, yield, selectivity, and purity will be investigated to determine technical feasibility. These results will be incorporated into the calculations of mass and energy balances, the modeling of the full process, and economic and energy-use analyses. The first demonstration of the process will be conducted using a miniplant, consisting of one redistribution reactor and one distillation column, to produce SiH_4 at the rate of 10 pounds per day for 10 days. The final demonstration will utilize a maxiplant of two redistribution reactors and three distillation columns, with the same production goal.

Disproportionation of SiH_2Cl_2

The disproportionation of SiH_2Cl_2 to SiH_4 was studied in a reaction temperature range of 40° to 80° C at a wide range of SiH_2Cl_2 feed rates. The product mixture was analyzed by gas chromatography, and the rates of SiH_4 production were determined. Data illustrative of the effects of SiH_2Cl_2 flow rates and temperatures on the product composition for a single run through the resin bed are given in Figs. 4-3 and 4-4. The failure to reach steady-state concentrations in up to 8.5 seconds at 40° C is to be compared with the attainment of apparently steady-state concentrations for the components, with the exception of $SiCl_4$, within 2 seconds at 80° C. The evidence of increasing $SiCl_4$ concentration at 80° C and the small $SiCl_4$ concentrations indicates that the rate of disproportionation of $SiHCl_3$ is slow in comparison with the SiH_2Cl_2 and SiH_3Cl rates.

The dependence of the yield of SiH_4 on residence time and resin bed temperature confirmed the previous observations that equilibrium was rapidly reached, being established in about 7 seconds at 60° C and in about 2 seconds at 80° C. The data are shown in Fig. 4-5. The pseudo-equilibrium yield is about 14 mole %; a theoretical equilibrium yield based on a zero concentration of $SiCl_4$ is 33-1/3 mole %.

The optimum operating conditions to produce SiH_4 appear to be (1) a bed temperature between 60° and 80° C and (2) a corresponding residence time range of 1 to 2 seconds. This conclusion was derived from the data displayed in Fig. 4-5. The SiH_4 production rate dependence on the SiH_2Cl_2 feed rate at 60°, 70°, and 80° C (shown in Fig. 4-6) follows the expected temperature relationship. If it is assumed that the SiH_3Cl by-product and unreacted SiH_2Cl_2 are recycled in an attempt to achieve the theoretical SiH_4 yield, the dotted line in Fig. 4-6 is obtained for 80° C operation. Calculations based on the assumption of recycling indicate a decrease in residence time from 0.9 to 0.5 second at 80° C. Experimental data were obtained to confirm that the SiH_2Cl_2 disproportionation is a high-rate, high-throughput process. Concomitantly it was shown that disproportionation of SiH_2Cl_2 to SiH_4 is a very clean reaction, the only products being the chlorinated silanes.

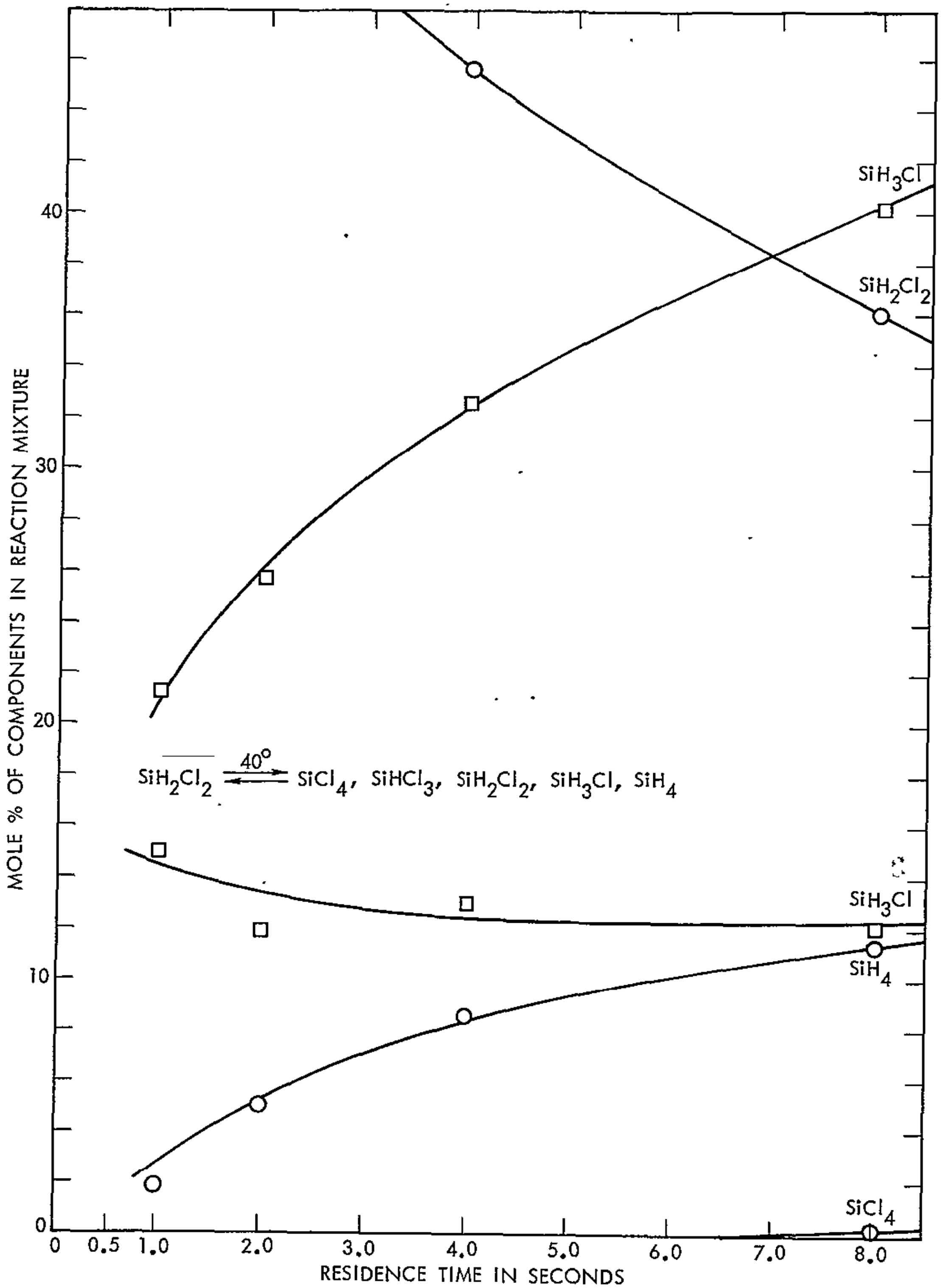

Fig. 4-3. Disproportionation of SiH_2Cl_2 over A-21 resin at 40° C

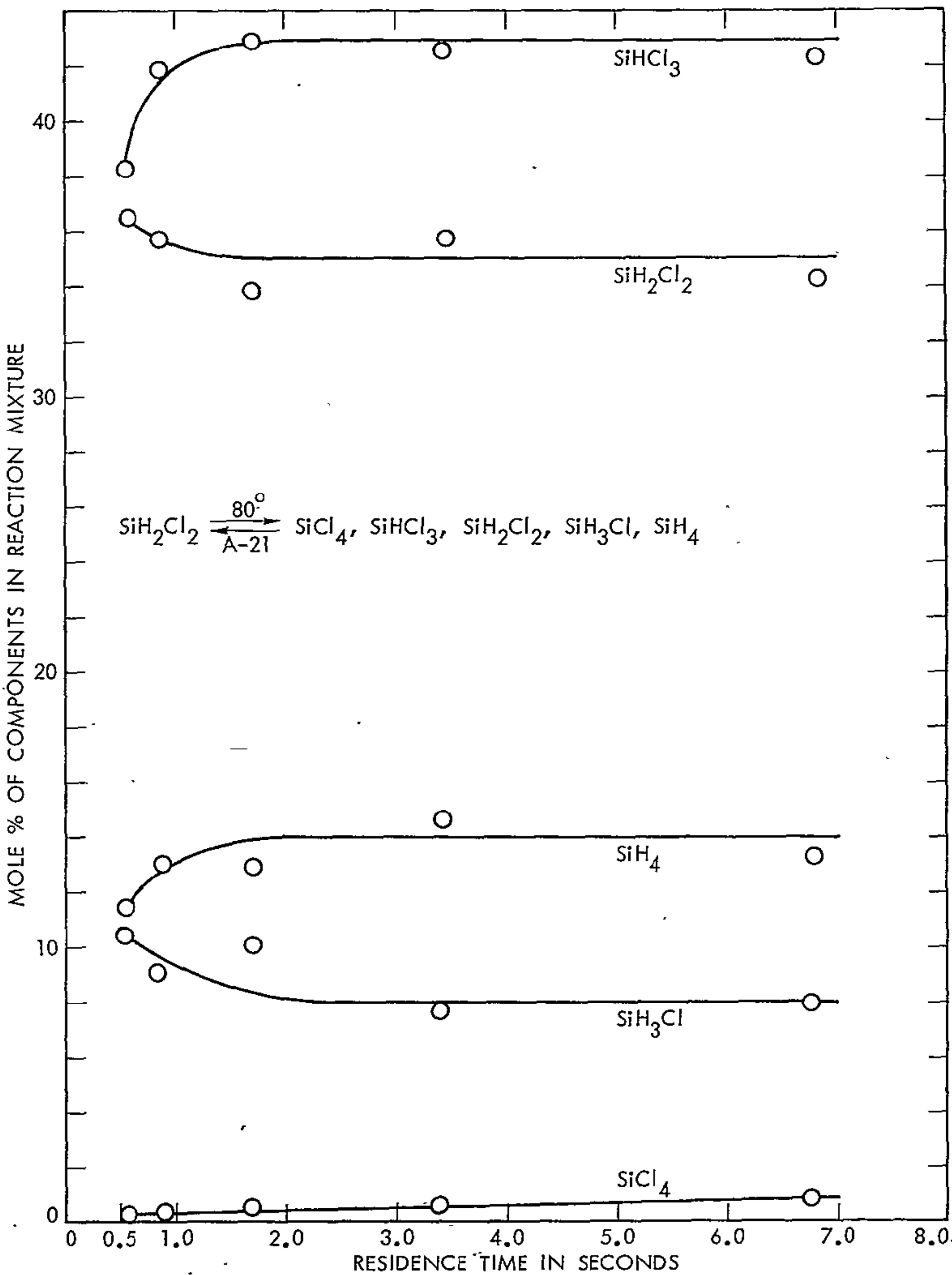

Fig. 4-4. Disproportionation of SiH_2Cl_2 over A-21 resin at 80° C

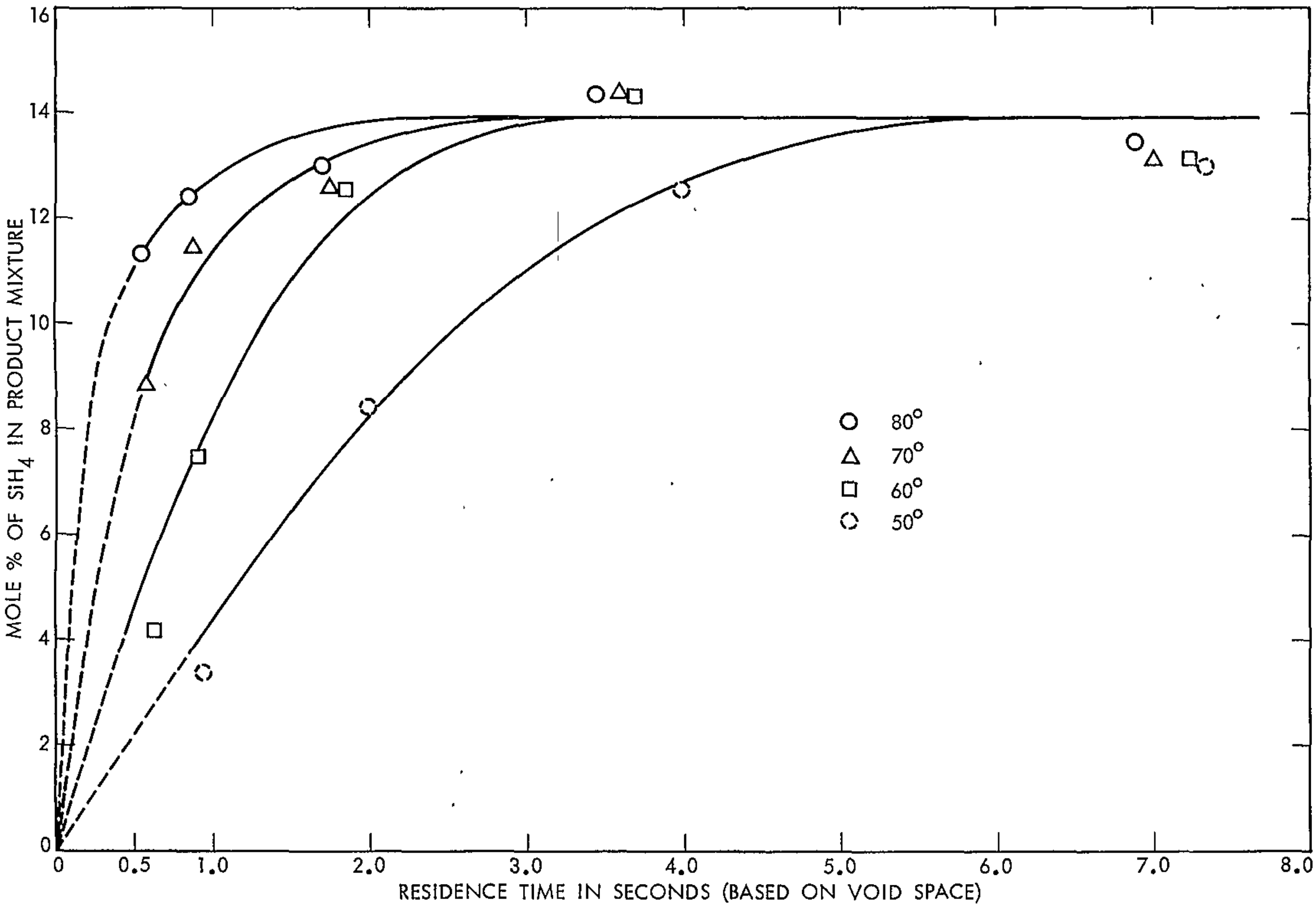

Fig. 4-5. SiH_4 yield in the disproportionation of SiH_2Cl_2 over A-21 resin at various temperatures

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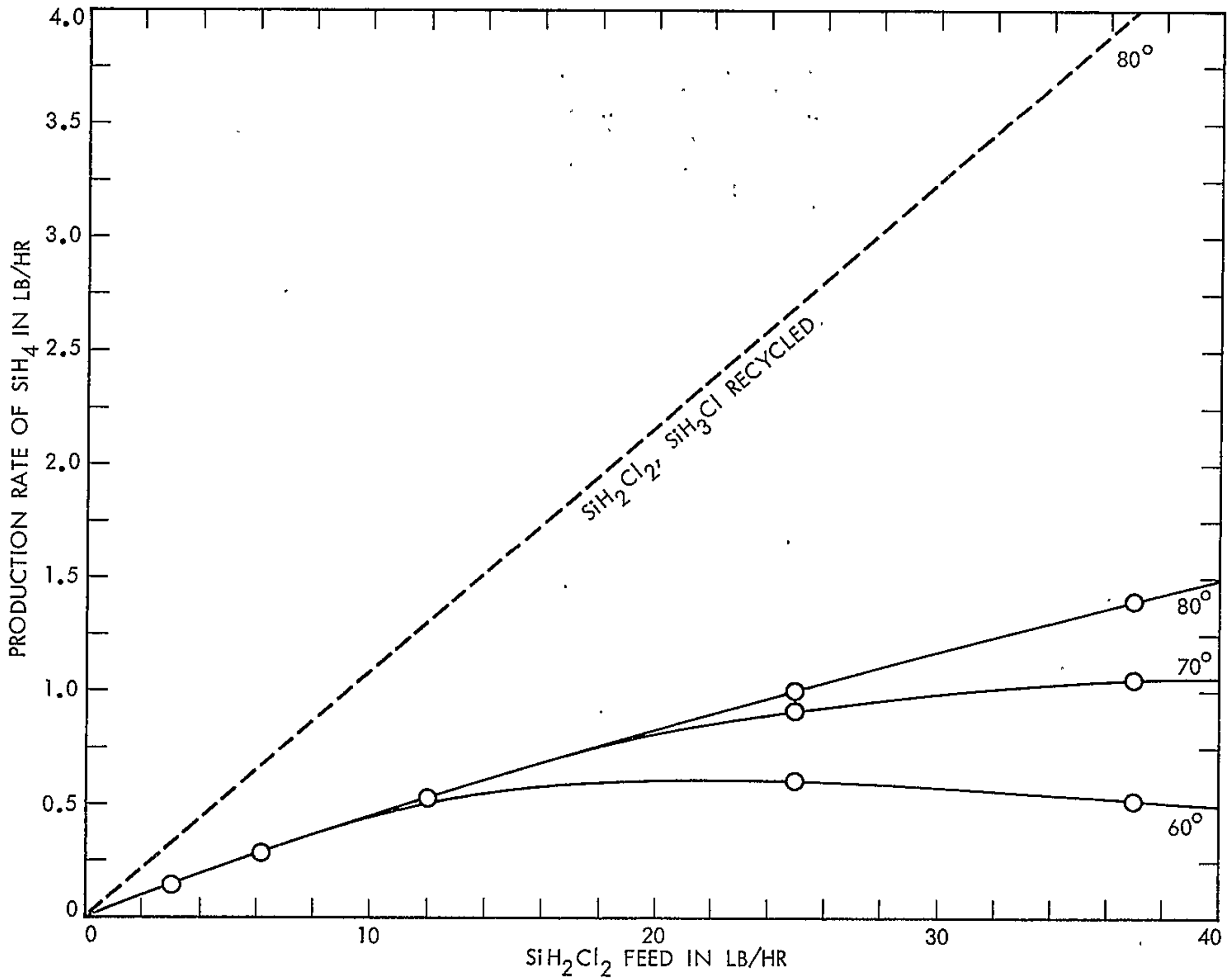


Fig. 4-6. Rate of disproportionation of SiH_2Cl_2 to SiH_4 based on one pound of A-21 resin

Based upon these results, production characteristics for a 1000 metric tons of Si per year plant were calculated. For a 60% service factor, a 30-cm-diameter by 300-cm-tall disproportionation reactor with a capacity of 227 kg SiH_4 per hour would be capable of producing the SiH_4 for 1000 metric tons of Si per year. A series of experiments was performed to provide support for the assumption of the effects of recycling, which were incorporated in this calculation. The observed SiH_4 rate was 79% of theoretical. It was calculated that the recycling of the distillation bottoms would result in a rate corresponding to 99% of theoretical.

Conversion of $SiCl_4$ to $SiHCl_3$

The hydrogenation-reaction of $SiCl_4$ with metallurgical grade Si to yield $SiHCl_3$ in the presence of a Cu catalyst in a fluidized bed reactor appears to be a suitable process for using the $SiCl_4$ by-product. The reaction rate and throughput of this reaction are very important factors in determining the mass flow and economics, since 16 kg of $SiCl_4$ must be recycled for every kg of SiH_4 generated. Although difficulties with temperature distribution and bed behavior occurred in the first runs of the operation of the fluidized bed reactor, the data showed that about 15 mole % of $SiHCl_3$ was produced in one pass through a Cu/Si mass. Steady-state levels of $SiHCl_3$ of 15% to 22% were obtained at 500°C at H_2-to-$SiCl_4$ ratios of between 1:1 and 2.3:1. Parametric studies with the variables of feed rates and temperatures are under way with a newly designed reactor.

Miniplant

A scaled-up plant for producing SiH_4 from SiH_2Cl_2 at the rate of 4.6 kg per day has been designed and installation is under way. Units for recycling the by-product SiH_3Cl and the unreacted SiH_2Cl_2, for on-line chromatographic analyses, for a NaOH vent scrubber, for the hydrogenation of $SiCl_4$, and for the removal of traces of chlorosilanes from the product SiH_4 are parts of the process scheme. The storage of SiH_4 is also being studied. The plant, with a closed cycle which includes the recovery of H_2 from the Si-deposition step, would convert metallurgical grade Si to high purity Si, using H_2 and chlorosilanes as intermediate reactants.

The program will proceed with fundamental studies of the reaction for the hydrogenation of $SiCl_4$; investigations of methods for purifying SiH_4; the design of a hydrogenation reactor capable of pressure operation at 600° C; and the calibration, pressure testing, and initial operation of the miniplant.

c. Semiconductor-Grade Si Production by SiF_4/SiF_2 Transport — Motorola Corporation

The objective of this contract is to develop a process in which SiF_4 is reacted with metallurgical grade Si to form SiF_2 as the Si transport species and Si is then deposited from an intermediate $(SiF_2)_n$ polymer. Effort in the first phase is directed toward the establishment of chemical feasibility, using yield, rate, and purity as criteria. Experiments are being conducted to determine the rate of Si transport, the purity of the deposited Si, the dependence of the chemical reactions on temperature and pressure, and the proper materials for the equipment.

2. Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells

The Phase I approach for Part II involves setting up a matrix of impurities and concentrations; preparing crystals, using techniques for Czochralski, float zone, and dendritic-web crystals, containing the baseline dopant B and selected concentrations of specific elements; performing a series of chemical, microstructural, and electrical tests; and analyzing the data for the purpose of correlating the impurities and concentrations with material properties and solar cell performance. The conclusions from the Phase I investigations will form a preliminary description upon which the more comprehensive, detailed plan for Phase II will be structured.

a. Investigation of Effects of Impurities on Solar Cell Performance — Westinghouse Electric Corporation

Crystal Preparation

The Czochralski crystal preparation has proceeded to the extent that all first, all second — and nearly all third — level impurity-concentration ingots have been grown. (The impurity elements are Cr, Mn, Cu, Ni, Fe, Ti, V, Mg, Zn, Al, and Zr.) In addition, ingots have been doped with these combinations of elements: Mn/Cu, Cr/Mn, Cr/Cu, and Zr/Ti. The status is shown in the element-concentration range matrix given in Table 4-4. Doping within the range of 5×10^{14} to 50×10^{14} atoms/cm^3 has not been accomplished for Mg and Zn because of their high volatility and for Ti, V, and Zr because of their extremely small segregation coefficients.

Several dendritic webs were grown, using only the B dopant. The first attempt to incorporate Zr along with the B resulted in a third dendrite at the point that a temperature fluctuation occurred. This feature, which has not been observed with B as the only dopant, may be the result of constitutional supercooling causing an interface breakdown of the rapidly grown web.

Ingot Measurements

The ingots were evaluated by measuring resistivity at the seed and tang ends, etch-pit density of the seed end C and O concentrations, and impurity concentration. The resistivity ranged from 3 to 5 ohms/cm, the target being 4 ohms/cm. The C concentrations varied from 2.5×10^{16} to 25×10^{16} atoms/cm^3. While the O concentrations were in the range from 50×10^{16} to 150×10^{16} atoms/cm^3 the O and C concentrations did not cause crystal-growth difficulties. The concentrations of impurities were measured by spark source mass spectroscopy, using multiple sampling; these data were supplemented by neutron-activation measurements for some elements in a few samples. The data were also used to calculate approximate segregation coefficients. The results indicate that the effective values for Mg and Zr are significantly less than the literature values. The Al concentration, which was measured by mass spectroscopy, was shown to be about 10 times greater than the electrically active concentration, which was based on resistivity data, confirming in general previous observations. The concentrations for some of the ingots were corrected, making use of a larger set of measurements, and the procedure of obtaining supporting, larger sets of data will be continued to provide a solid basis for subsequent analyses.

Table 4-4. Status of the metal-doped ingots that form the impurity matrix for the Westinghouse Electric program

Impurity Element	Concentration Range (atoms/cm^3)				
	10^{14}	5×10^{14} to 1×10^{15}	1×10^{15} to 5×10^{15}	5×10^{15} to 1×10^{16}	$> 10^{16}$
Cr	G, F	G, F, T	G, F, T		
Mn	G, F, T	G, F, T	G, F, T		
Cu		G, F, T	G, F, T	G, F, T	
Ni		G, F, T	G, F, T		
Fe			G, F, T		
Ti	G, F, T	G, F, T			
V	G, F, T	G, F, T			
Mg	G, F, T	G, F, T			
Zn	G, F, T				
Zr		G, F, T			
Al					G, F, T
Ingot status: G-grown; F = cell fabricated; T = cell tested					

Wafer Measurements

Wafer-evaluations consisted of measurements of spreading resistance microstructural characteristics and minority carrier recombination lifetimes. The resistivity data ranged between 3.6 and 6.8 ohms/cm for most of the ingots, the values being measured at both the seed and tang ends. In general, the variations in the impurity-doped ingots were somewhat larger than in the audit ingots. Pronounced resistivity striations were found in the Cr/Mn-doped ingots; these may be associated with the increased nonuniformity resulting from the incorporation of two impurity-elements.

X-ray topography was used as a quality assurance procedure to assure that there were no gross deviations in the crystalline perfection; at least one wafer from each ingot was examined. In general, the overall features of the topographs were consistent with the level of perfection described in the etch pit density evaluations, in which low dislocation densities, typically below $10^3 cm^{-2}$ and often below $10^2 cm^{-2}$, were seen. However, variations in the fine structure became evident in more detailed examinations. These were as follows: the baseline ingot has many long, straight dislocation segments which are sharply imaged and show no evidence of decoration; considerable decoration of the dislocation lines by precipitation occurs in wafers containing Cu and Ni, which are fast-diffusing impurities; the precipitation of Cu is so heavy that only the strain fields of the precipitates are imaged, the dislocation lines virtually disappearing; and Ti causes a fringed contrast of the dislocations, with difficultly-seen individual precipitates. The techniques of topography and etching will be used in further investigations of the effects of impurities on wafer structure at different process-steps.

Minority Carrier Recombination Lifetime

Bulk minority carrier recombination lifetimes (τ), being very sensitive to impurities, chemical complexes, and lattice imperfections, are good measures of the effects of impurities and process-steps. Since the measured lifetime is determined by a combination of the effects of the bulk lifetime and the surface recombination velocity, a mathematical correction factor and surface recombination velocity values were obtained to allow transformations of measured values into true bulk lifetimes. (The mathematical and analytical treatment is presented in Westinghouse Electric's Second Quarterly Report on this contract.) The effective lifetime was also shown to change rapidly with sample thickness; this variation was accounted for before applying the corrections for surface recombination velocity. In addition, refinements in the measuring technique and modifications of the equipment were made to increase the range and accuracy of the measurements.

A surface treatment, which yields the lowest recombination velocity (S_o), was determined. Use of this standard treatment allows measurements which are less sensitive to variations in S_o.

The direct proportionality of the recombination rate ($1/\tau$) to the density of recombination centers in Si and the effect of a diffusion-step were tested for a Cr-doped ingot. The expected relationship was obtained over a metallurgical concentration range from 10^{13} to 10^{15} atoms/cm^3; the conclusion was that apparently all of the Cr atoms were electrically active. However, the P-diffusion step causes a nonlinear relationship, indicating a decrease in recombination centers and suggesting the influence of gettering and precipitation. These data are shown in Fig. 4-7.

Some preliminary conclusions were derived from lifetime measurement experiments in which samples were subjected to an annealing-step at 500° C for 5 hours, to an annealing-step at 825° C for 50 minutes, and to a P-diffusion step at 825° C for 50 minutes. The conclusions were that (1) precipitation occurs at 550° for all the impurities except Ti and V; (2) annealing at 825° C produces selective precipitation and dissolution; and (3) P-diffusion causes gettering for all the impurities, except Cu and Ti. In these two cases, dissolution of precipitates or the formation of complexes may predominate.

Solar Cell Characterization

Solar cell evaluations have been completed for all first and second impurity-level, some third impurity-level, and a few multiply-doped ingots. The variations in cell performance with impurity doping are shown in Fig. 4-8,

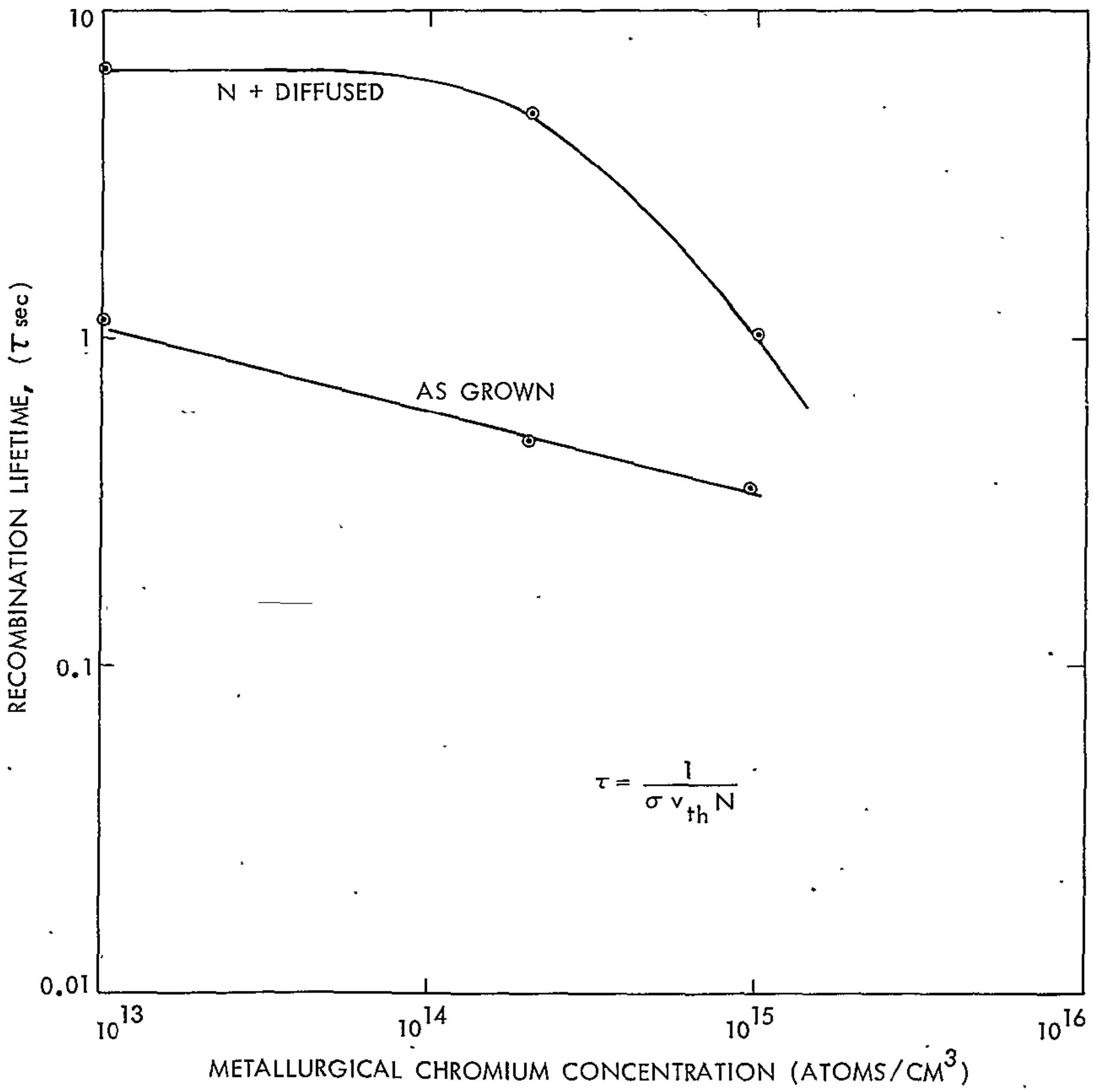


Fig. 4-7. Correlation between recombination lifetime and metallurgical concentration of chromium impurity

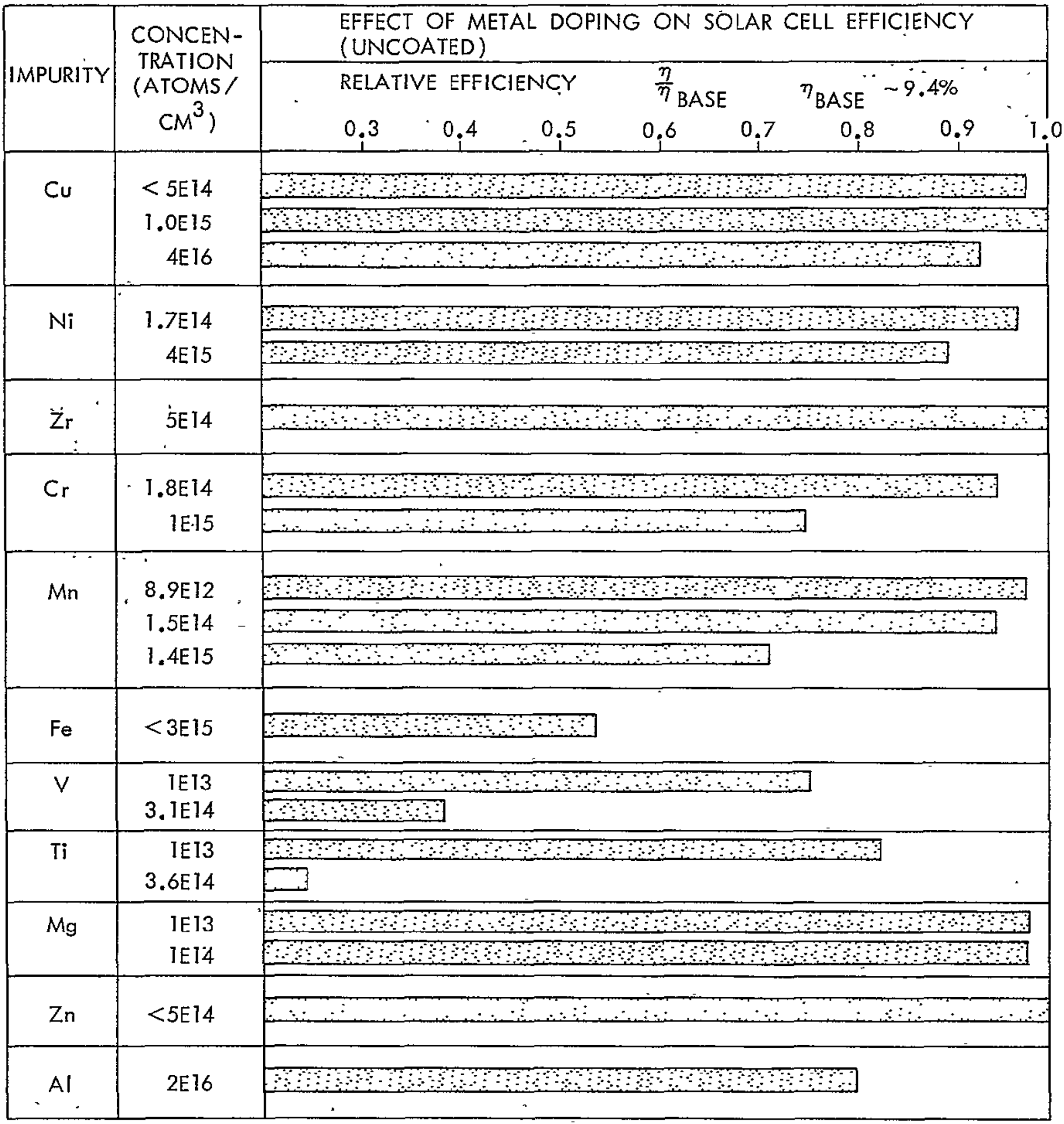


Fig. 4-8. Variation in solar cell performance with metal doping. No antireflective coating, AMI quartz-iodine illumination. Westinghouse Electric program.

the data being given as the dependence of relative solar cell efficiency on type and concentration of impurity. For impurity concentrations in the range of 10^{14} to 10^{15} atoms/cm^3 the impacts on cell performance tend to fall in three general groups: little degradation for Cu, Ni, and Zr; modest degradation for Cr, Mn, Fe, and Al; and severe degradation for Ti and V. A comparison of the results for Cu, Ti, and V is particularly striking. Even at the highest concentration of Cu, at 4×10^{16} atoms/cm^3, the effect on cell efficiency is barely measurable. On the other hand, even low concentrations of Ti drastically reduce cell efficiency; thus, at 3.6×10^{14} atoms/cm^3 of Ti, the relative efficiency is about 0.25, and at 1×10^{13} it is about 0.83. For V, the detrimental effects are similar: at 3.1×10^{14} atoms/cm^3 the relative efficiency is 0.38, and at 1×10^{13} it is about 0.77. In general, the magnitude of degradation seems to be directly dependent on impurity concentration.

The first data for multiply-doped ingots were obtained for the combinations: Cu/Mn, Cr/Mn, and Cr/Cu. The relative efficiencies for those containing Cu were about 0.69 and thus very nearly the same as for ingots containing either Cr or Mn without Cu. In these cases, therefore, the effects are as if each impurity acted independently, since Cu alone barely changes the efficiency of the baseline ingot. In contrast, the data for the Cr/Mn ingot indicate that the effects of these impurities are additive.

A correlation between solar-cell short-circuit current densities and minority carrier lifetime measurements on the processed cells has been obtained. These data are shown in Fig. 4-9. (The differences between the open circuit voltage decay (OCVD) and photoconductive decay (PCD) curves are due in part to differences in the carrier injection profiles of the two methods and the nonnegligible decay time of the LED. The application of mathematical corrections should yield closer agreement between these sets of data.) A good correlation was obtained between these data and the cell performance data.

The contractor will proceed with ingot, wafer, and solar cell measurements on the remaining third and fourth impurity-concentration level crystals, and on the multiply-doped and dendritic-web crystals. Data analysis will

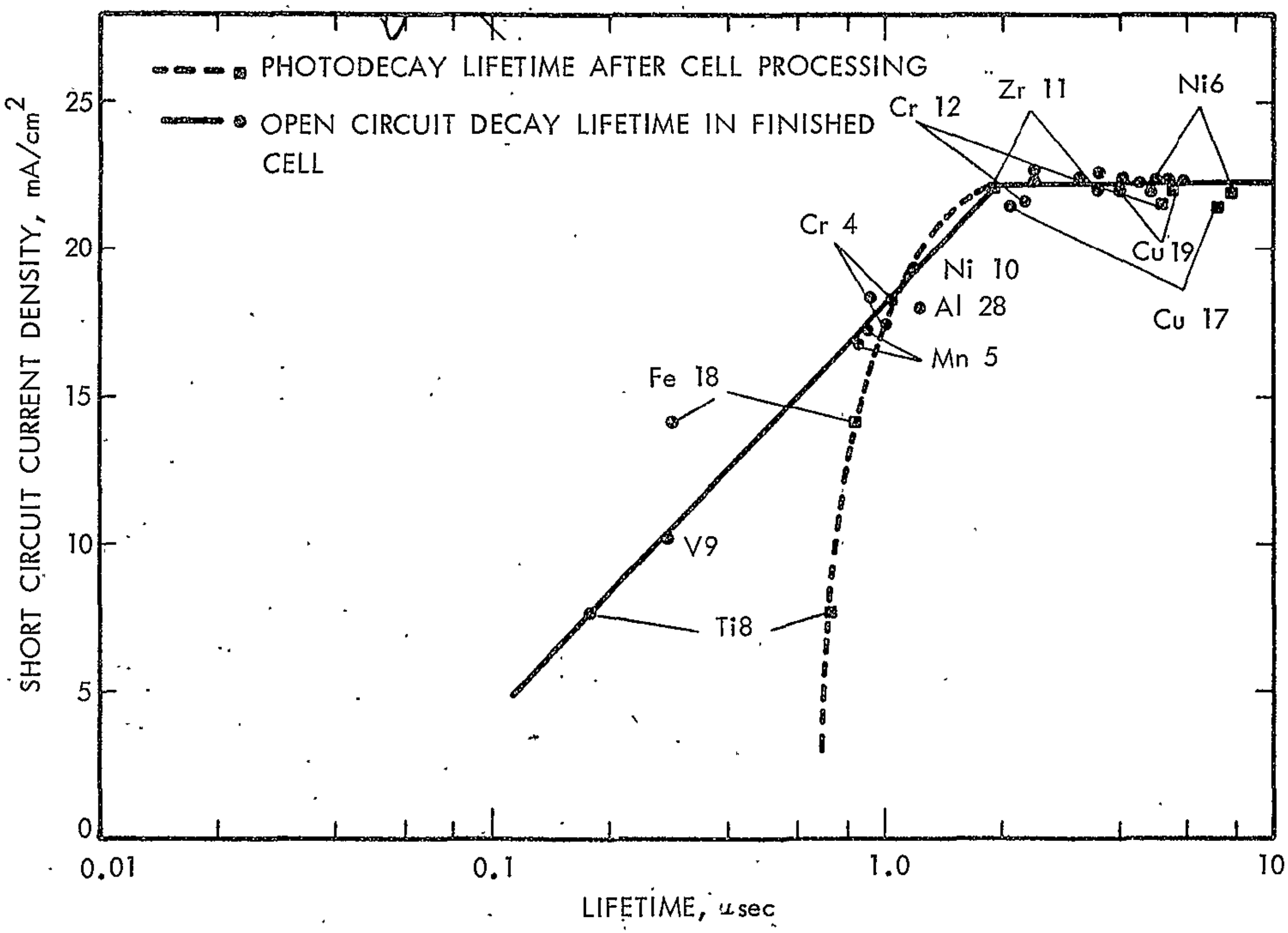


Fig. 4-9. Variation in short circuit current density of finished solar cells as a function of the PCD and OCVD lifetimes of the diffused material. The unmarked data points are from audit and baseline wafers.

continue with efforts to secure various correlations between impurity concentration, microstructural, lifetime, short-circuit current, and cell performance measurements.

b. Investigation of the Effects of Impurities on Solar Cell Performance — Monsanto Research Corporation

Crystal Preparation

All of the Czochralski- and float-zone-grown crystals have been prepared. The impurity elements are the same as those for the Westinghouse contract (Table 4-4), except that Zn is in the Westinghouse matrix only, and C and O are in the Monsanto matrix only. The effects of two levels of O concentration, 10^{18} atoms/cm^3 for the Czochralski ingots versus 10^{16} atoms/cm^3 for the Mon-X (float zone) ingots, were investigated. In addition, a Mon-X ingot containing Ni, Mg, and Mn was grown. Some of the mass spectroscopy measurements of Czochralski ingots failed to show the desired levels of impurities, and other crystals will have to be prepared to complete the matrix.

Ingot Measurements

The target resistivity for all ingots of this contract is 0.5 ohm/cm. Data from the resistivity measurements were analyzed and are represented in the relationships shown in Fig. 4-10. Measurements at the center of the seed of the Czochralski and Mon-X ingots prepared for this contract are compared wit with those for a typical production ingot. The comparisons are given as probabilities of obtaining particular resistivity values. (The large deviations of the line for the Czochralski ingots are due to the incorporation of three poor data points.)

An analysis of macro-variations in the dopant profile was made, using four-point probe resistivities taken at approximately 3-mm intervals across four equally spaced radii of a slice. This analysis is shown in Fig. 4-11, where the variability is given as a percent sigma. These data indicate that there are no detectable effects of added impurities.

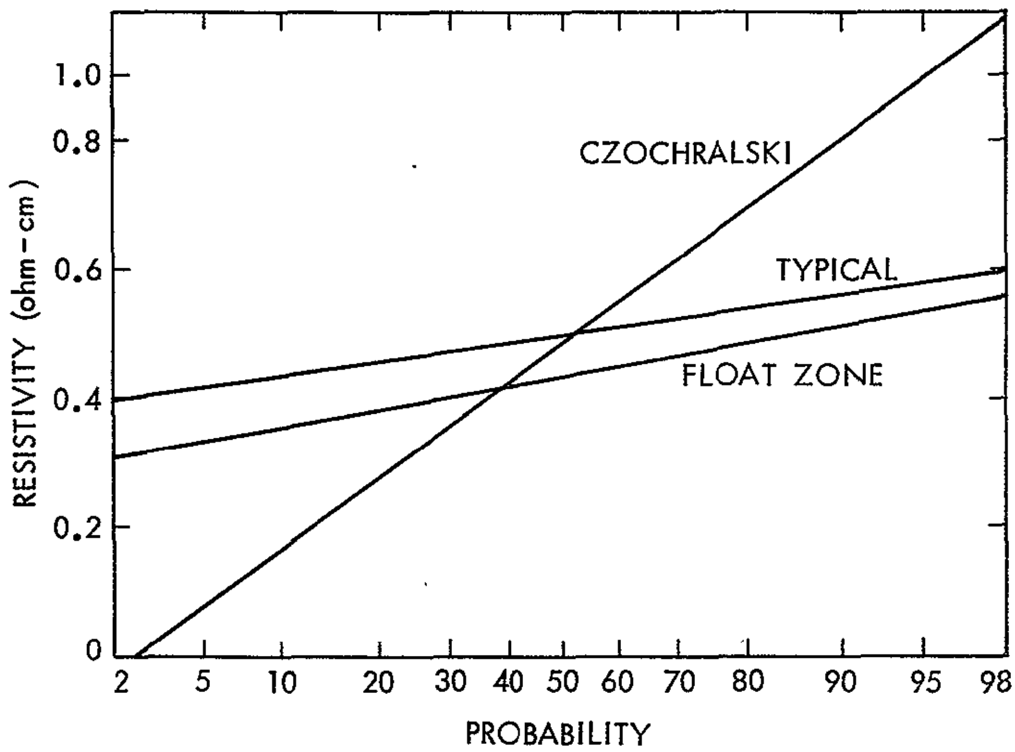


Fig. 4-10. Crystal section end resistivity probability

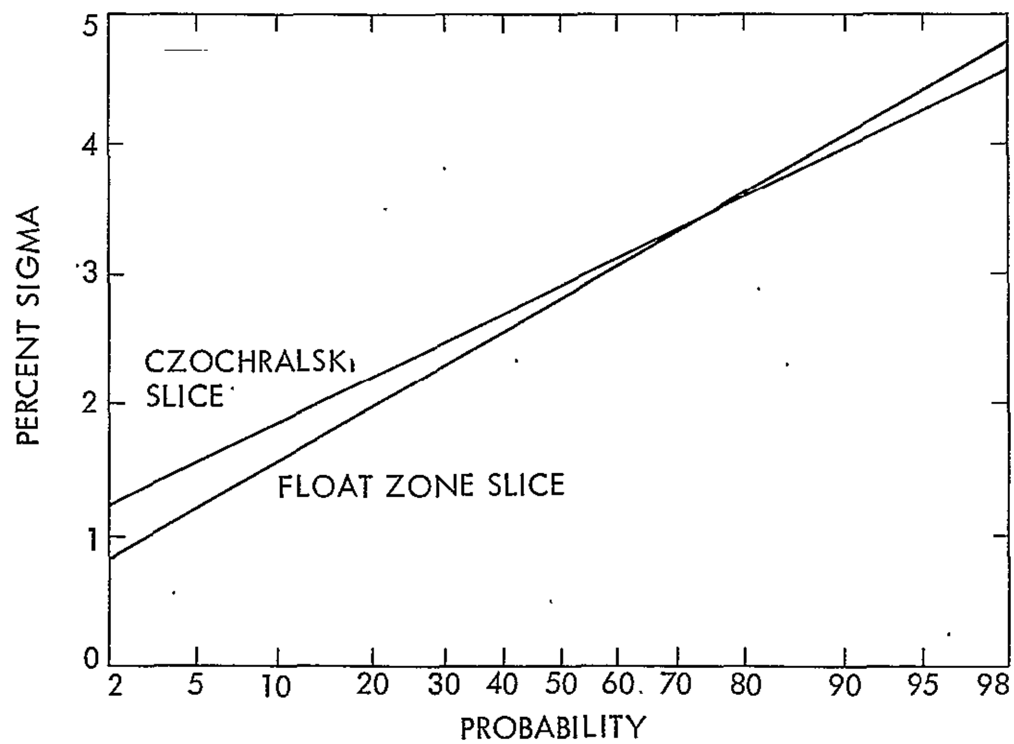


Fig. 4-11. Slice resistivity variability probability

The data obtained for B concentrations by spark-source mass spectroscopy (SSMS) were given special consideration. The measurements by SSMS were compared with values derived from the conversion of resistivity to carrier concentration (ASTM F-1 Document 6038) and with values obtained from a plot of total B concentration versus electrical B concentration, this plot being prepared from independent data by analyzing a series of samples of a wide range of resistivities. The concentration values for Czochralski and Mon-X crystals are given in Tables 4-5 and 4-6. The disparity of values for ingot C10B, containing Al, is probably due to the influence of Al atoms on the resistivity value, as well as the fact that only part of the Al atoms are electrically active.

Solar Cell Measurements

A simplified model was constructed to describe the data obtained for minority carrier recombination lifetimes; the data were obtained using the open-circuit-decay apparatus. The primary assumption is that the behavior of a solar cell can be represented as being directly dependent on a single effective diffusion length or lifetime. A mathematical expression was derived from consideration of (1) the limits for the diffusion length, (2) an assumed mathematical expression for an effective collection lifetime, and (3) an assumption of the proportionality of short circuit or cell efficiency to the effective collection diffusion length. The values of the constant of proportionality and the limiting lifetime were obtained by fitting curves to the lifetime data for both Czochralski and float zone solar cells; these data and the curves are shown in Figs. 4-12 and 4-13. The curve fittings are close except for the three data points representing very heavily doped samples and a Czochralski Al-doped sample. These plots suggest that lifetime or diffusion length measurements made on solar cells, fabricated from other Czochralski or float zone ingots, provide reasonable, correlatable indications of solar cell properties.

The efficiencies of the solar cells were compared with those for baseline cells prepared without the addition of impurities. The values for the comparative efficiencies are presented in Fig. 4-14. The preliminary conclusions are:

Table 4-5. Comparison of boron data from SSMS and values calculated from resistivity — Czochralski. (Note: All data are expressed as atoms/cm^3 x 10^{16}.)

Boron Data — SSMS	Boron Data — Correlated SSMS	Boron Data from Resistivity	Resistivity (ohms/cm)
0.62	2.5	3.6	0.52
110.	525.	660.	0.105
0.68	2.8	3.2	0.56
0.76	3.1	3.4	0.55
120	575.	660.	0.015
0.97	4.0	4.0	0.49
0.92	3.8	3.2	0.56
1.1	4.5	4.4	0.46
0.76	3.1	4.2	0.47
0.93	3.8	3.4	0.55
0.30	1.2	0.87	1.6
1.1	4.5	25.	0.15
1.2	5.0	3.4	0.54

Table 4-6. Comparison of boron data from SSMS and values calculated from resistivity — float zone. (Note: All data are expressed as atoms/cm^3 x 10^{16}.)

Boron Data — SSMS	Boron Data — Correlated SSMS	Boron Data from Resistivity	Resistivity (ohms/cm)
0.59	2.4	1.3	1.1
3.9	17.	2.4	0.015
34.	160.	190.	0.04
1.2	5.0	3.9	0.05
1.6	6.6	5.5	0.40
30.	140.	110.	0.058
1.2	5.0	4.7	0.44
0.55	2.2	3.0	0.59
0.88	3.7	4.1	0.48
0.75	3.1	3.9	0.50
1.1	4.5	4.1	0.48
1.2	5.0	4.4	0.46
1.1	4.5	4.1	0.48
0.60	2.4	4.4	0.46
1.4	5.8	6.2	0.37

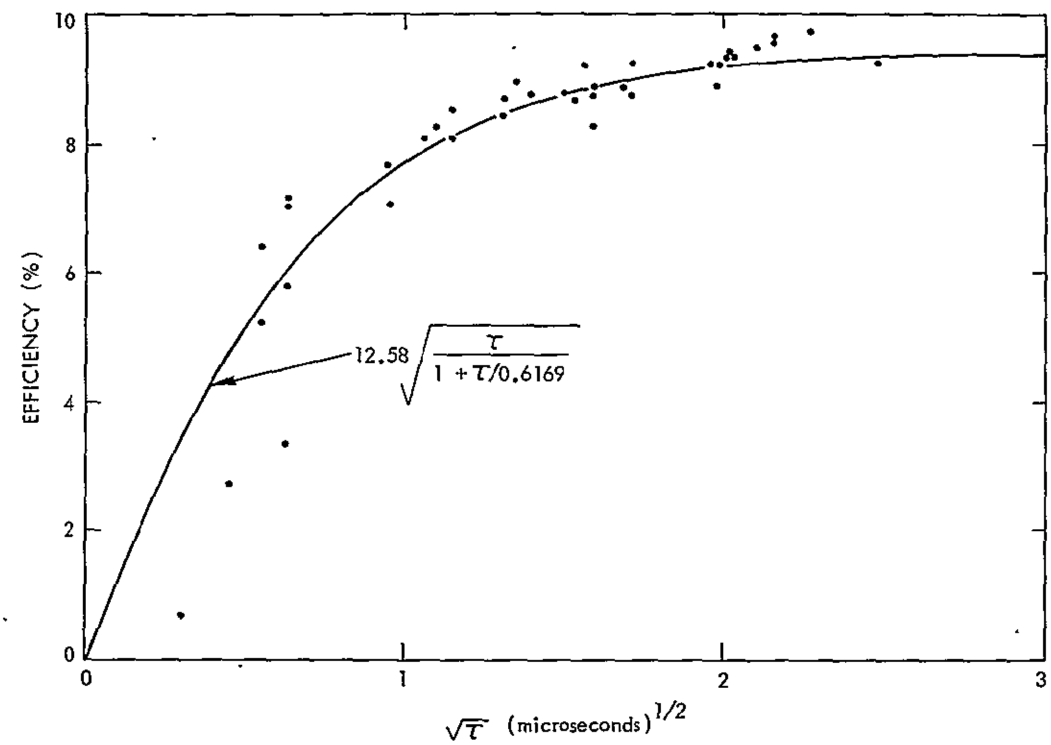


Fig. 4-12. Efficiency vs. $\sqrt{\tau}$ for Mon-X and Czochralski silicon

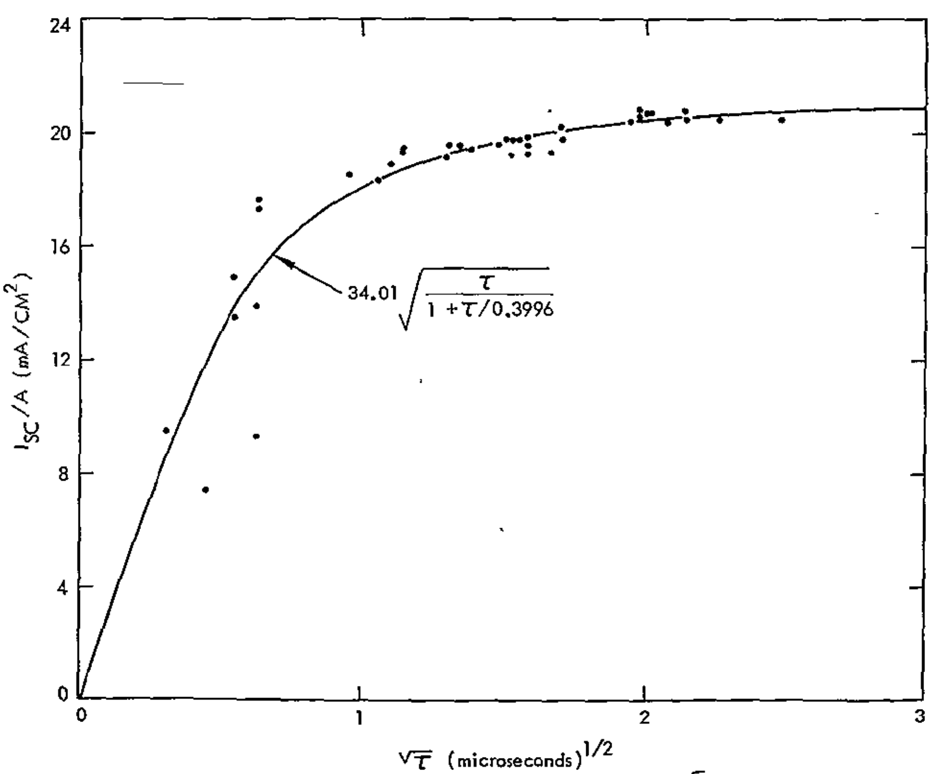


Fig. 4-13. Short circuit current density vs. $\sqrt{\tau}$ for Mon-X and Czochralski silicon

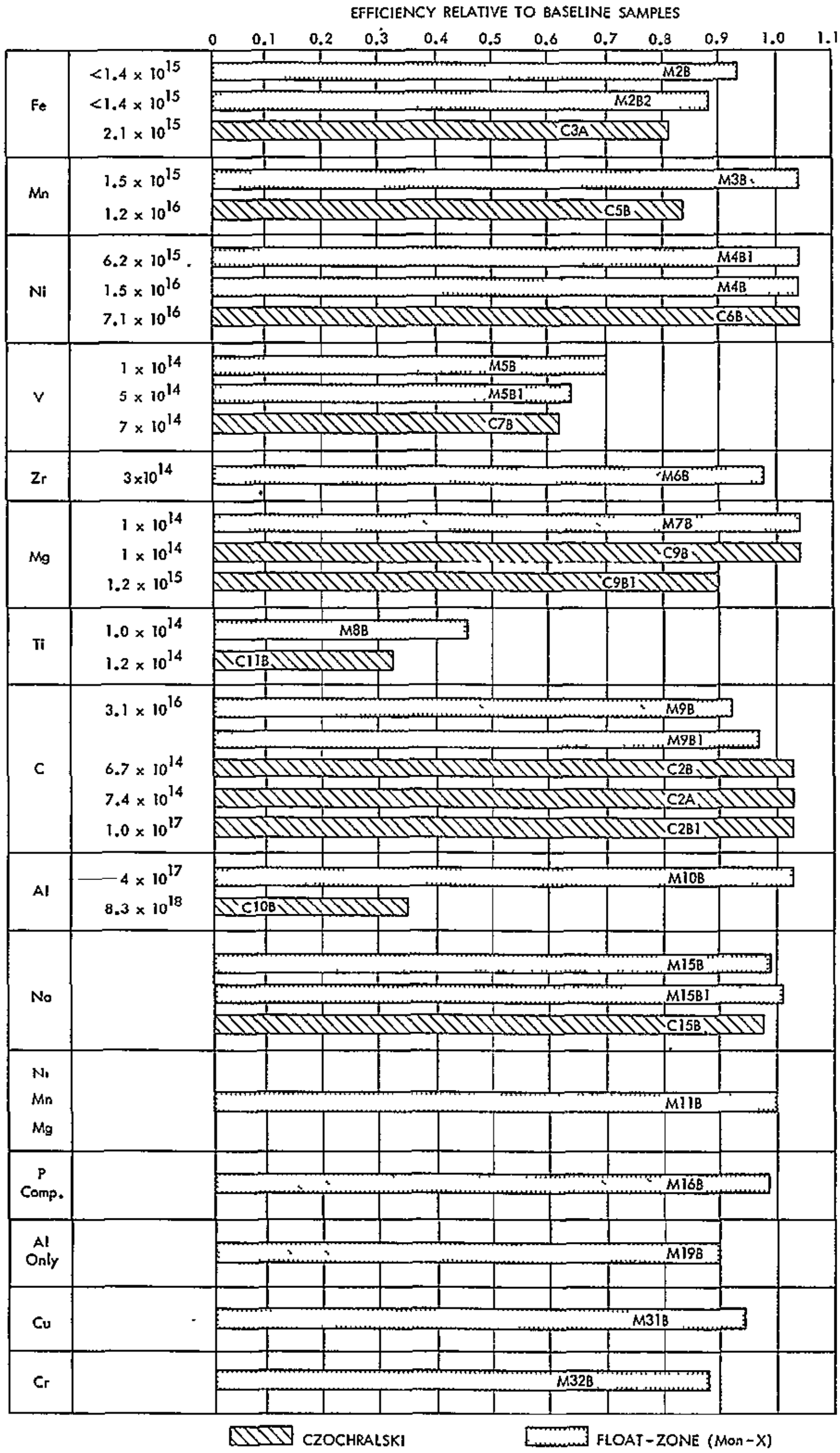


Fig. 4-14. Relative efficiency for various secondary impurities; baseline efficiency = 8.6% for Czochralski and 9.25% for Mon-X. Monsanto Research program.

1) The severe degradations caused by the incorporation of Ti or V are apparent; for concentrations of about 1×10^{14} atoms/cm^3, the value for Ti is 0.45 and for V it is 0.7.
2) Fe is somewhat less effective, reducing the efficiency to 0.8 at a concentration of about 2×10^{15} atoms/cm^3.
3) There are indications that the presence of Mn, Ni, or Mg in certain concentrations may increase the cell efficiency.
4) Although C seems to improve the Czochralski-cell efficiency even at 10^{17} atoms/cm^3, the performance of the float zone-cells containing C is slightly degraded.
5) The data for Al show the apparent severe effects of increasing concentration. However, since there is strong evidence that only a fraction, perhaps 20% of the metallurgical Al is electrically active, the large difference between the behavior of float zone- and Czochralski-cells indicates the involvement of oxygen-complexes.
6) The presence of Mg, Mn, and Ni in low O-concentration Si leads to insignificant synergism, the efficiency being comparable to the high values obtained for crystals containing single impurities.

In the next report period the remainder of the solar cells will be fabricated and evaluated. The data will be analyzed to form the basis for the set of conclusions and recommendations for this contract.

3. Processes for Producing Solar-Cell-Grade Si

The approach used for Part III of Phase I (see Table 4-1) incorporates theoretical studies involving thermodynamics, reaction chemistry, and chemical engineering; chemical reaction investigations consisting of experimental determinations of reaction kinetics, yields, and suitable process conditions; a chemical engineering effort for securing an experimental data base for preliminary process modeling; and energy-use and economic calculations for preliminary process models. In each case the contract requires a demonstration of technical feasibility and a projection of commercial practicality, involving the preliminary analysis of the suitability for a scale-up study. Each process candidate will be evaluated on a separate milestone schedule. Selections for the next phase of scale-up studies will be made at times which are appropriate for individual or collective assessments.

a. Solar-Cell-Grade Si Production Using Submerged-Arc-Furnace, Unidirectional-Freezing, and Vacuum-Evaporation Processes — Dow Corning Corporation

The effect on product purity of using purer C and SiO_2 materials in the submerged-arc-furnace process will be investigated, using a development furnace of Elkem Corporation, Norway. The subsequent additional purifications from the use of unidirectional freezing and vacuum evaporation will be studied. The energy use; production characteristics of rate, yield, and efficiency; and costs will be analyzed.

b. Solar-Cell-Grade Si Production Using Na_2SiF_6 Source Material and Processes for Na Reduction of SiF_4 and the SiF_4/SiF_2 Transport Reaction — Stanford Research Institute

The advantages of this two-step reaction sequence are that the starting raw materials are abundantly available and can be readily purified and the product Si is obtained in a few reaction steps. In preliminary experiments, Si has been produced in yields of 10 to 15%, together with Na_2SiF_6 as a by-product in the Na reduction reaction; the salts are leachable. Experiments are continuing with the variables of temperature, pressure of SiF_4, and the use of reaction initiators.

c. Solar-Cell-Grade Si Production by C Reduction of SiO_2 Using an Induction Plasma Torch — Texas Instruments Corporation

Tests have been conducted using a 350-kilowatt plasma reactor and a 40-kilowatt dc plasma torch. The products consisted mainly of SiC and SiO_x, with up to 3.5% of Si. The results were attributed to insufficient residence time at the temperature necessary for reaction. In a complementary thermodynamic study it was found that the optimum temperature range appears to be between 2400 and 3000°K. A solid rod feed and a liquid phase reaction are approaches being investigated in the attempt to demonstrate technical feasibility. A preliminary estimate of the manufacturing cost indicates that this plasma process will yield Si at \$5 to \$6 per kilogram.

d. Solar-Cell-Grade Si Production Using an Arc Heater Plasma Process for the Reduction of $SiCl_4$ with Na, Mg, or H_2 — Westinghouse Electric Corporation

Work under this contract has just begun. The first phase will consist of (1) thermodynamic analyses of the reduction of $SiCl_4$ using Na, Mg, or H_2 as reductants and (2) analyses and designs of the plasma reactor, the reactant storage and injection systems, and the product collection and effluent disposal systems. A free energy minimization technique will be used to calculate maximum product concentrations as functions of temperature, pressure, and initial composition conditions.

e. Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of $SiCl_4$ — AeroChem Research Corporation

Work under this contract has just started. The first phase will consist of thermodynamic analysis. Equipment is being installed for the first experimental runs.

4. Evaluation of Si Production Processes — Lamar University

The objective of this contract is to evaluate the potentials of the processes being developed in the Task I program. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing-economics. The evaluations will be performed for each stage of the Silicon Material Task — technical feasibility, scale-up, experimental plants, and commercial plant — using information which becomes available from the various process development contracts.

During this report period activities directed toward analysis of process-system properties dealt primarily with the Si-source materials, $SiCl_4$, SiI_4, and SiF_4. The data are being compiled and evaluated.

Preliminary process designs were initiated. These efforts centered on the formulation of key guideline items for use in preliminary process designs. These are specifications of base case conditions, definitions of chemical reactions, developments of process flow diagrams, calculations of material and energy balances, compilations of chemical properties data, calculations for equipment designs, determinations of production labor requirements, and developments of preliminary economic analyses. Information from the pertinent process development is being used in the analyses.

A review of methods for estimation of total product cost was started. Activity focused on adapting the methods for application to solar-cell-grade Si production processes. The major expense items — direct manufacturing cost, indirect manufacturing cost, by product cost or debit, and general expenses — were covered. In addition, provisions were included for raw materials, labor, and utilities requirements.

Analyses of material properties, chemical engineering studies, and preliminary product cost estimates will continue. Additional chemical equilibrium calculations and preliminary process designs will be initiated.

5. JPL Task 1 In-House Support

Studies of fluidized bed technology have proceeded in three areas: (1) development of a fluidized bed reactor, (2) development of a free space pyrolysis reactor, and (3) modeling of the fluidized bed process.

<u>Fluidized Bed Reactor</u>

Very little information on fine particle behavior in fluidized bed reactors appears in the literature. However, it is an important consideration for silicon production, since Si crystals can be grown from fine seed particles which result from the gas phase reaction of SiH_4. Early studies indicated that interparticle forces, such as Van der Waal's or capillary forces, cause fluidization difficulties. This study includes experimental determinations of the effects of parametric variations and theoretical analyses of model systems.

The first set of experimental studies dealt with the fluid dynamic aspects in the fluidization of a Si-particle bed. The objectives were to obtain data on the fluidization of Si powders using several inert gases; to characterize the Si fluidized bed using bed, particle, and operating parameters; and to establish suitable operating conditions. However, these results are mostly applicable to a nonreaction fluidizing bed condition. A subsequent, more sophisticated experimental and theoretical treatment will be necessary to describe the reaction-fluidization conditions.

The controlled parameters in this series of experiments were the fluidizing medium, the initial bed height, the porosity of the gas distributor, the average Si particle diameter, and the gas flow rate. The dependent variables were bed height and pressure drop across the bed. Only semi-quantitative effects could be determined from the set of data. In general, the results agreed remarkably well with the literature on fluidization. With regard to gas properties, it was found that gas density did not affect bed height or bed pressure drop but did affect bed behavior. Thus, the use of He, the lightest gas, caused more slugging in shallower beds than the use of air or Ar did. On the other hand, the data for Ar showed that its greater viscosity caused a lower pressure drop and a higher bed height. Examination of the effects of particle size showed that the bed pressure drop increased and the bed height decreased with particle diameter. Finally, it was shown that increasing the particle size, flow rate, distributor pore size, and initial bed height and decreasing the gas density tend to increase the probability of slugging. This effort will proceed with studies of reactive systems as well as a more extended investigation of the effects of different fluidized bed conditions for non-reacting systems. This will be accomplished in a 2-inch stainless steel fluidized bed reactor, which was recently designed and fabricated.

The feasibility of applying induction heating to the silicon fluidized bed reactor was also studied, in a determination of this method for increasing the temperature of the solid particles without increasing the temperature of the reactor wall. A small quartz fluidized bed was designed and fabricated to test the practicality of induction heating technique.

Free Space Pyrolysis Reactor

In the SiH_4 pyrolysis study area, the theoretical treatment and the detailed design of a SiH_4 free space pyrolysis reactor have been completed. The reactor product sampling system has been checked out and is now operational. Design of a mini-electrostatic precipitator to collect product silicon particles is in progress.

Fluidized Bed Process Modeling

The purpose of the fluidized bed modeling is to establish theoretical models which can be used to describe the Si fluidized bed deposition process. This will be done by modifying the existing models and by setting up a simplified mathematical-computer model for the experimental system to be investigated at JPL. This will permit the determination of the design parameters of the experimental fluidized bed reactor.

Modeling of the process of Si deposition from SiH_4 requires that a series of reaction conditions be considered. These are: (1) the SiH_4 gas can be homogeneously and/or heterogeneously pyrolyzed in the bed. At very high temperatures ($>1000°C$) and at relatively high pressures (1 atm) a homogeneous reaction is expected to be the dominant one. (2) In the heterogeneous reaction, Si diffuses to the Si surface. At moderately high temperatures of about 800° C, adsorption and desorption are the rate controlling steps. (3) If conditions lead to diffusion being the rate controlling process, the complete reaction mechanisms in the emulsion phase, bubble phase, and interface need to be studied. The initial modeling work was based on the assumptions that adsorption and desorption are the rate controlling processes and that the temperature of the reactor bed is essentially uniform.

The model of the heterogeneous pyrolysis of SiH_4 in a fluidized bed was prepared using a modification of the bubbling bed model of Kunii and Levenspiel. The computer program of the model was upgraded to handle particulate fluidization and the concentration variation of SiH_4 along the axis of the bed. A complete description of this modeling effort including the computer program is being prepared for a JPL Technical Memorandum.

TASK 2. LARGE-AREA SILICON SHEETS

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

A. TECHNICAL BACKGROUND

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

Growth of silicon crystalline material in a geometry which does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections), requiring very little manpower and machinery would also appear plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

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

B. ORGANIZATION AND COORDINATION OF THE TASK 2 EFFORT

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

The Task 2 effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); development, fabrication, and operation of production growth plants (1983-86).

C. TASK 2 CONTRACTS

The pursuit of optimal techniques for growing silicon crystalline material for solar cell production has led to the awarding of R&D contracts to 11 organizations. Two of these were initiated during the report period: (1) RCA Laboratories, Princeton, New Jersey began work on the Inverted Stepanov Technique (IST) on March 22, 1976 and (2) the University of Pennsylvania, Philadelphia, Pennsylvania started investigating the hot-forming of silicon on May 12, 1976. The processes being developed by the Phase 2 contractors are shown in Table 4-7.

Figure 4-15 shows the schedule for each contract as it was initially negotiated. Follow-on work anticipated for each contract is indicated by the cross-hatched horizontal bars. Research and development work will continue through the end of FY 1977, by which time it is expected that technical feasibility will have been demonstrated. Selection of "preferred" growth methods for

Table 4-7. Task 2 contractors

Contractor	Technology Area
RIBBON GROWTH PROCESSES	
Mobil-Tyco, Waltham, Massachusetts	Edge-defined, film-fed growth
IBM, Hopewell Junction, New York	Edge-defined, film-fed growth
RCA, Princeton, New Jersey	Inverted Stepanov growth
Univ. of So. Carolina, Columbia, So. Carolina	Web-dendritic growth
Motorola, Phoenix, Arizona	Laser zone ribbon growth
SHEET GROWTH PROCESSES	
Honeywell, Bloomington, Minnesota	Dip-coating of low-cost substrates
Rockwell, Anaheim, California	Chemical vapor deposition on low-cost substrates
General Electric, Schenectady, New York	Chemical vapor deposition on floating silicon substrate
Univ. of Pennsylvania, Philadelphia, Pennsylvania	Hot-forming of silicon sheet
INGOT GROWTH	
Crystal Systems, Salem, Massachusetts	Heat-exchanger ingot casting*
INGOT CUTTING	
Crystal Systems, Salem, Massachusetts	Multiple wire sawing*
Varian, Lexington, Massachusetts	Breadknife sawing

*Single contract provides for both ingot casting and multiple wire sawing

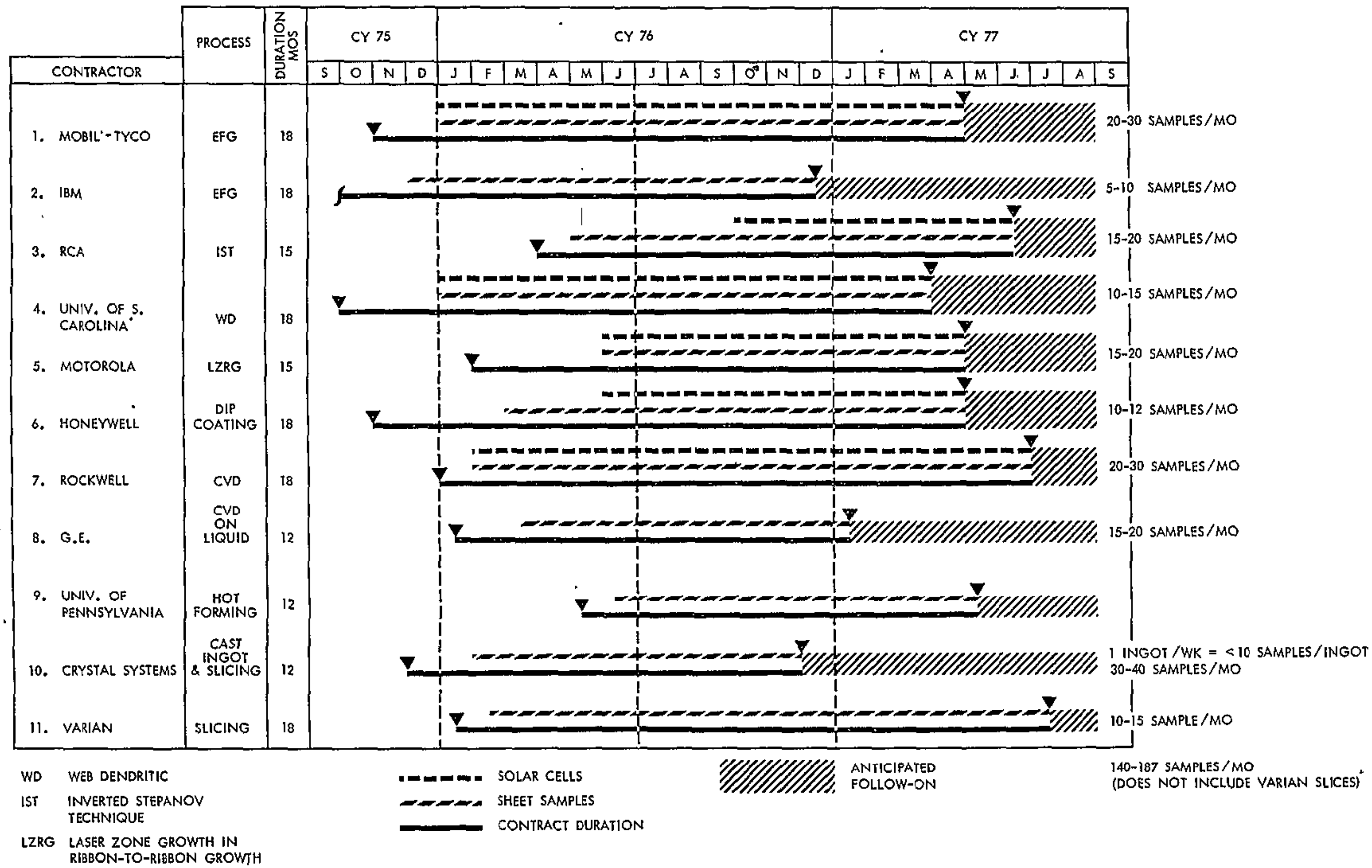


Fig. 4-15. Large Area Silicon Sheet Task schedule

further development during FY 1978-80 is planned for late FY 1977 or early FY 1978. By 1980, both technical and economic feasibility should be demonstrated by individual growth methods.

Figure 4-15 also indicates the receipt of silicon "sheet" samples and solar cells from the various growth-process R&D programs. Sheet samples are now being characterized at JPL, with solar cell evaluation to follow.

D. TASK 2 TECHNICAL ACTIVITY

1. Silicon Ribbon Growth: EFG Method - Mobil-Tyco Solar Energy Corporation

The edge-defined film-fed growth (EFG) technique is based on feeding molten silicon through a slotted die (as illustrated in Fig. 4-16). In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material which is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm per minute and a width of 7.5 cm. The program includes theoretical analysis of stresses and thermal geometry, experimental demonstration of growth, and characterization.

During this report period previously developed EFG machines have demonstrated a ribbon growth rate of nearly 7.5 cm per minute — but only for very limited periods and in a definitely nonequilibrium mode. In general, it has been demonstrated that, at growth rates greater than 3.8 cm per minute, stress within the ribbon becomes a serious problem and fracture of the ribbon frequently occurs during or after growth. Experiments have confirmed that the (110) $\langle 211 \rangle$ growth direction offers the specific advantage that the parallel twin structure, which is stable for long-term growth, is obtained quickly, without resorting to periods of random structure variation prior to achieving this equilibrium configuration. Furthermore, it has been demonstrated that the use of (110) $\langle 211 \rangle$ seeds already containing twins results in continuation of this structure in detail.

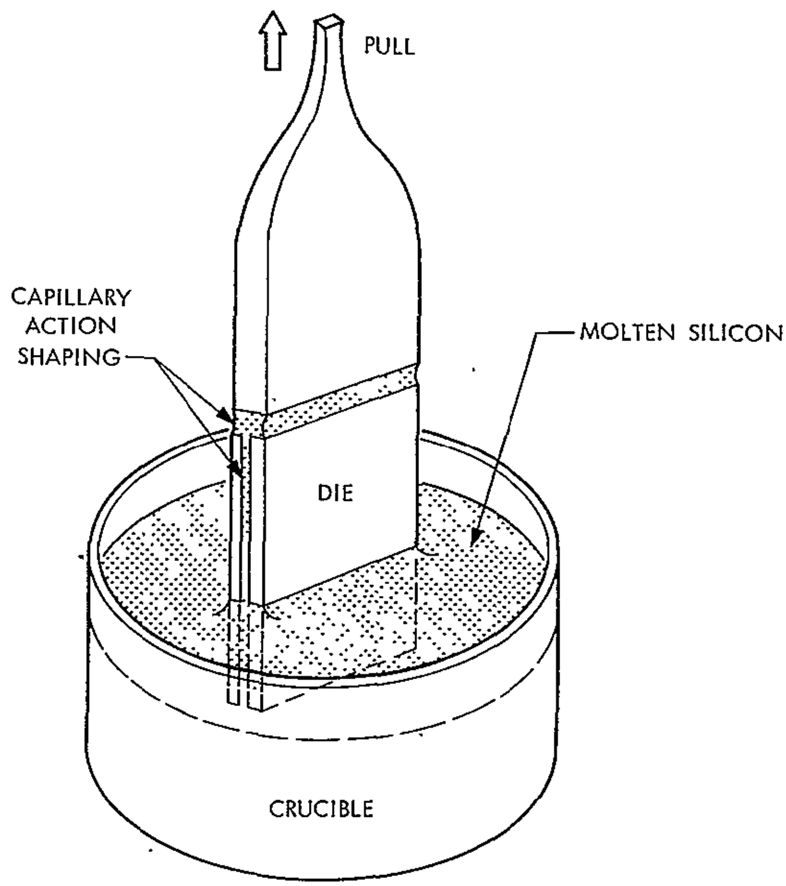


Fig. 4-16.—Capillary die growth (EFG and CAST).- Mobil-Tyco and IBM

Thermal and stress analyses indicate that it will be necessary to provide a controlled temperature gradient for the cooling period that is linear along the ribbon growth direction. Such a gradient would normally not be achieved with uncontrolled cooling. The thermal analyses are also directed toward increasing the theoretical maximum growth rate by a factor of 2 to 4 over the presently predicted 7.5 to 10 cm per minute. The approach includes cooled, heat-absorber blocks near the growth interface and improved gas transport mechanisms. Experimental confirmation of these analytically predicted improvements is in progress.

A machine for growing 7.5 cm wide ribbon, now under construction, is expected to become available during the next quarter. Its design includes all state-of-the-art knowledge concerning the thermal control required for ribbon growth.

During this report period, efforts to characterize the ribbon grown in this program have yielded two significant generalizations:

- The surface of the equilibrium (110) ⟨211⟩ twinned structure developed during EFG growth exhibits twins of predominantly identical orientation. This suggests that the configuration consists of a large percentage of twins of one orientation interspersed with a small volume or fraction of twins having the complementary orientation.
- Experiments using electron-beam induced current (EBIC) indicate that grain boundaries may be described as active or inactive according to their response in the EBIC mode. Preliminary correlation suggests that grain boundaries and twins associated with dislocation networks (incoherent twins) are active, while true twins are not.

2. Silicon Ribbon Growth: CAST Method - IBM

The capillary action shaping technique (CAST) is based on the same principle as EFG growth (Fig. 4-16); i.e., it utilizes a die constructed from material which is wetted by molten silicon. Work under this contract is directed toward the CAST method of producing silicon ribbon suitable for solar cells, characterization of that ribbon, and economic analysis of a number of means of producing silicon sheet.

Efforts during this report period have emphasized the empirical evaluation of thermal modifiers to adjust the cooling environment of the crystallized ribbon and the preparation of samples for delivery to JPL. Studies of the effect of thermal modifiers are under way and the results indicate that such modifiers are capable of changing the ribbon's thickness profile (edge to center) as well as adjusting the stress level within the ribbon. Modifiers interfere with convenience of ribbon growth and their use is therefore being limited.

The efforts toward characterization of EFG ribbon under this contract have taken many approaches. Electron channeling patterns have been shown to be useful in determining ribbon orientation, provided that an extensive computer program is available to permit analysis of the pattern. The technique has been used to extensively analyze and document the detail structure in a selected portion of ribbon. The conclusion drawn from this analysis was that the structure is complex as a result of multiple twinning on the expected (110) twin plane, with formation of accommodating grain boundaries. Ribbon surface structure tends to orient toward the (110) surface with a ⟨112⟩ growth direction. Other in-process characterization efforts now in progress are directed toward correlating local ribbon structure and solar cell performance with lifetime measurements made on MOS structures by capacitance-time-delay techniques. There are preliminary implications that long lifetime as measured by this technique does not necessarily correlate with solar cell efficiency.

Efforts directed toward the growth of silicon ribbons from other than graphite dies were completed during this period. The results suggest that silicon carbide dies are potentially useful for ribbon growth, although not offering marked improvement over present dies. Ribbons formed from a very limited choice of silicon carbide dies were found to be comparable to those from the presently used graphite dies.

Analyses of the potential economic viability of the EFG ribbon growth process are continuing. The results indicate that added value for silicon growth by this technique can achieve costs on the order of several hundred dollars per kilowatt, using reasonable estimates of technology advancement. A sensitivity analysis for the effect of changes in growth parameters has indicated that priority should be given to increasing the width of the ribbon. A major unknown in predicting potential costs is the capital cost of a ribbon grower, especially when comparing the complexity of a single versus multiple ribbon machine. Economic analyses of competing silicon sheet technologies are planned.

3. Silicon Ribbon Growth: Inverted Stepanov Technique - RCA

In this program emphasis is placed on the development of the growth of ribbon-shaped silicon using a "non-wetted" die (Fig. 4-17). The use of the "non-wetted" die provides the possibility of minimizing the reaction between the molten silicon and the die material. Reaction between molten silicon and wetted dies is one source of degradation in the crystallographic quality of silicon grown using a wetted die (i. e., the edge-defined film-fed growth method). The introduction of the feed from above and the growth of the single crystal in a downward direction (the inverted Stepanov technique) in part compensates for the hydrodynamic drag in the slot and for the lack of capillary rise. (The capillary rise feeds the material to the die edge in the EFG method.) The inverted geometry also leads to considerable flexibility in the growth configuration when the feed is introduced from a molten zone at the end of a solid silicon rod.

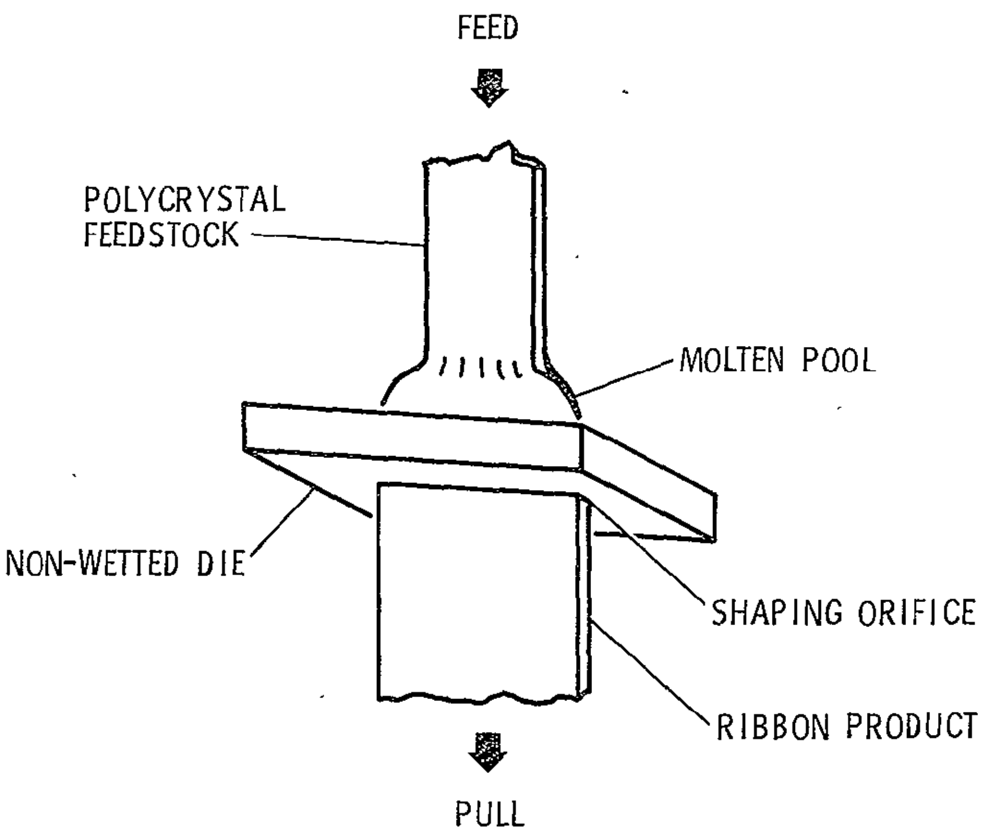


Fig. 4-17. Inverted Stepanov Technique - RCA

The primary objective of the program is to investigate the basic seeding and growth processes involved in the growth of silicon sheet from "non-wetted" dies. The goal is to establish whether or not significant improvement in the crystallographic properties of the silicon can be realized by the use of "non-wetted" rather than "wetted" shaping dies. Silica and boron nitride shaping dies will be used. Methods will be sought to compensate for the lack of mechanical strength of silica at the growth temperature. Although boron nitride leads to unacceptable doping of the grown silicon ribbon, it is more rigid than silica and therefore is useful in the identification of fundamental limiting factors in the Stepanov growth method.

During this report period major efforts were expended in modifying the Inverted Stepanov Technique (IST) growth apparatus, Model 1, to accommodate the use of a silicon dioxide die and in designing the Model 2 growth apparatus. The essential difference between Models 1 and 2 is that the latter provides a larger mechanical stroke. Both of these efforts have been completed.

The modifications to Model 1 include a new design of the susceptor and die and the addition of an X-Y-Z micromanipulator at the ribbon pulling stage for the fine alignment of the seed during growth.

In the new susceptor and die geometry, the flat plates which constitute the die are positioned in the susceptor. In cross-section the plates are in a "v"-shaped geometry (Fig. 4-18). This setup was adopted to facilitate the use of silicon dioxide as the shaping guide. Silicon ribbon growth with a silicon dioxide die in this configuration has been in progress. The die slot (0.05 cm thick, 0.3 cm high, 2.5 cm wide) is readily filled with silicon. Attempts were made to seed and grow the ribbon. Immediately after ribbon growth started, the thickness increased and the silicon froze to the die after about 2-3 mm growth. Vertical temperature gradients and isotherms at the solid-liquid growth interface are being modified to optimize the growth.

The mechanical design of Model 2 consists of an rf heated furnace mounted between a lower and upper puller. The lower puller has a stroke of 71 cm for

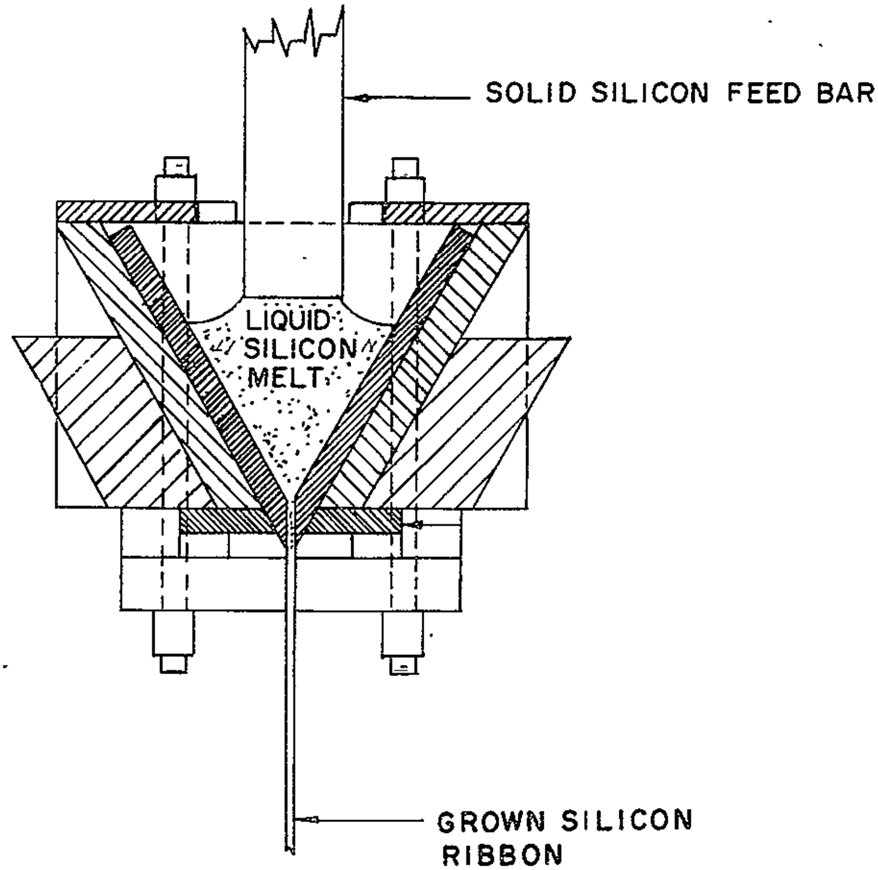


Fig. 4-18. Model 1 IST growth apparatus

withdrawing the silicon ribbon from the die. The upper puller, which lowers the silicon charge into the melt, has a stroke of 25 cm. Provisions are being made for afterheaters and adjustable reflectors inside and outside of the growth chamber.

A computer program has been written and successfully tested to determine the steady-state temperature profile along the silicon ribbon.

The standard operating procedure document for IST Model 1 has been delivered to JPL.

Plans for the next quarter call for:

- Growing 15 ± 5 mil thick, 2 cm wide ribbon using a silicon dioxide die.
- Assessing 4 mil thick ribbon using a boron nitride die.
- Developing 10 mil thick, 2 cm wide ribbon using a silicon dioxide die.
- Characterization of ribbons.
- Development of Model 2.

4. Silicon Ribbon Growth: Web-Dendritic Method - University of South Carolina

Web-dendritic growth makes its own guides of silicon, whereas most other ribbon processes must rely on materials other than silicon for the guides (i.e., dies) (Fig. 4-19). The guides are thin dendrites that grow ahead of the sheet and support the molten silicon between them to form the sheet. The dendrite guides grow in a very precise orientation dictated by their unique growth habit. Thus the orientation of the sheet which grows between them takes on this precise orientation. The twin plane reentrant edge mechanism (TPREM) controls the growth of the edge dendrites, giving them their unique and internally-controlled growth direction allowing them to grow ahead of the sheet and thus acts as guides.

The basic steps, then, in web sheet growth are (1) dip a seed of the proper orientation into a slightly undercooled melt, (2) hold the seed stationary while growth takes place laterally on the surface of the melt, forming what is termed the button and (3) when the lateral growth has proceeded to the desired width, start the pulling. As the pulling proceeds, two coplanar dendrites grow downward from each end of the button, propagating to a depth of 1-3 millimeters beneath the surface of the melt. As the button and its dendrites emerge from the melt, silicon is pulled up between them by surface tension, and the resulting sheet solidifies just above the melt surface. The unique orientation and slight undercooling to insure faceted growth give the sheet its almost mirror-flat surface finish. The overall goal of this contract is to develop a better understanding

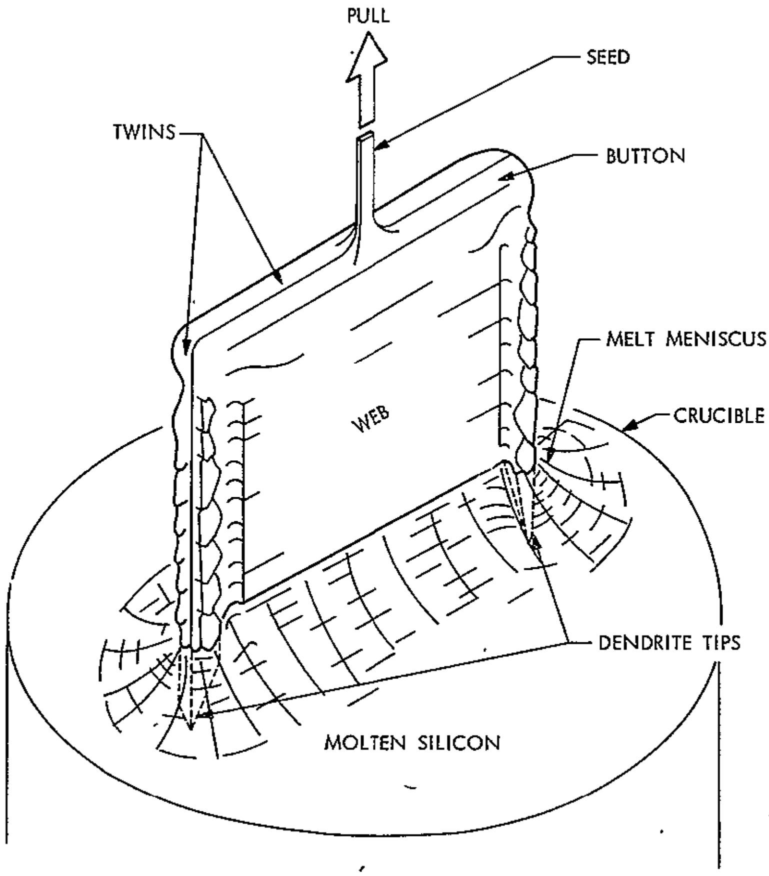


Fig. 4-19. Web-dendritic growth - University of South Carolina

of the web-dendrite process and define in greater detail the basic limitations to the process (especially the maximum growth rate and width).

A large number of primary dendrites and web-dendrite ribbons have been grown. Improper thermal gradients in the melt have caused nucleation of a third dendrite in the web material. The following modifications were made:

- Different geometrical designs of the top reflector plate.
- Different positioning and spacing of the rf coil.
- Thermal insulators below the susceptor.
- Sand blasting of the top reflector plate.

Sand blasting the molybdenum heat shield reduced the thermal asymmetry and thereby reduced the presence of third dendrites. A major portion of the time during the report period was spent on producing primitive dendrites of varying twin spacings.

A mathematical model encompassing the growth interface, liquid, and solid regions has been formulated. An IBM computer program (CSMP III) is available to solve the differential equations. Efforts are under way to match this program to the boundary conditions in the above-cited regions.

In addition, a mathematical model for the overall system is available and a computer program (LION-4) has been satisfactorily utilized for these conditions. An experimental thermal profile of the web puller is to be obtained in order to check these equations and to give direction. The two separate computer programs (CSMP III and LION-4) will be tied to the same common boundary condition in the final analysis.

During the next quarter, the major effort will be thermal modeling of the web-dendritic growth process and performing experiments that will help define the systems involved. Some of these experiments will include varying the pull rate, heat flow, etc., as functions of twin spacing, width, and crystallographic properties.

5. Silicon Ribbon Growth: Laser Zone Growth in a Ribbon-to-Ribbon Process - Motorola

The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline silicon ribbon (Fig. 4-20). The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid silicon is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

C-2

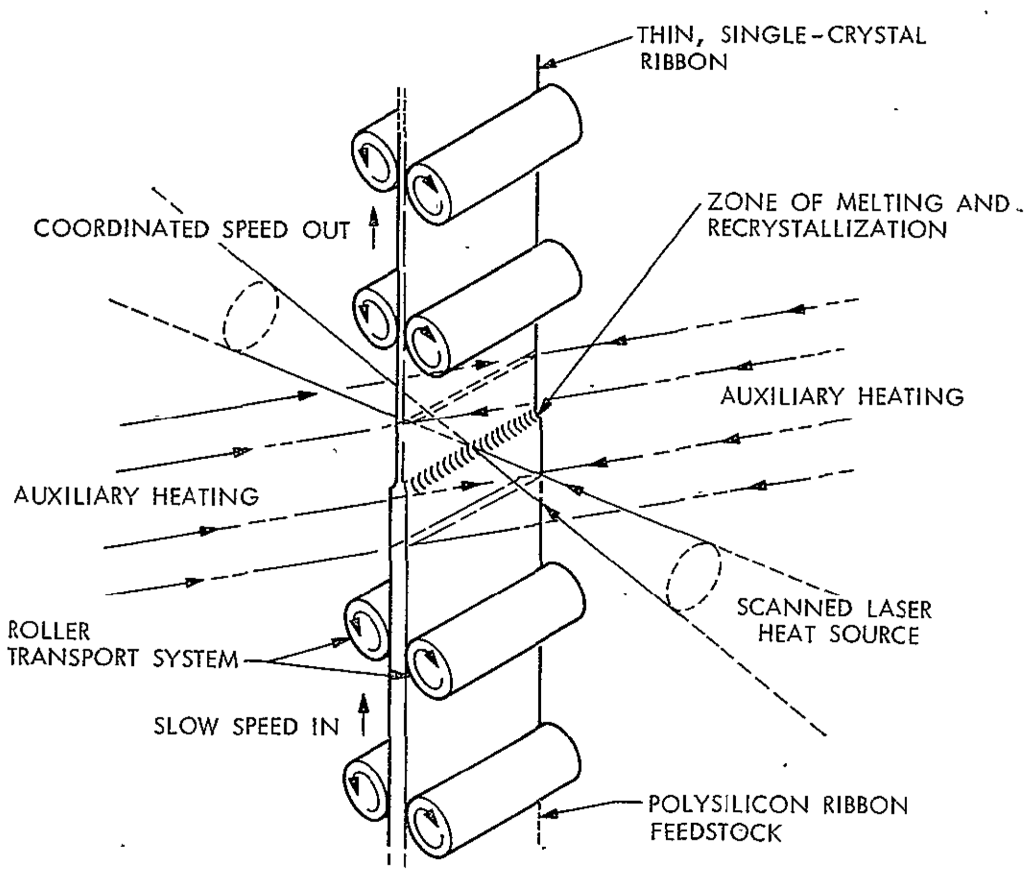


Fig. 4-20. Laser zone crystallization - Motorola

The primary efforts under this contract are to:

- Modify and evaluate the existing ribbon-to-ribbon growth facility to meet the contract goals.
- Operate the facility on a regular basis to study and optimize the growth capabilities of the ribbon-to-ribbon process with particular emphasis on thermal environment, seeding, ribbon velocity, laser input configuration, and throughput.
- Perform characterizations/tests on ribbon samples from each growth run.
- Fabricate and characterize solar cells.

Progress under this contract during the past quarter has been on schedule. The major accomplishment has been the completion and evaluation of the ribbon-to-ribbon growth facility. The significant parts of the apparatus are:

- Three TV cameras which allow the sample to be viewed from two faces and one side of the ribbon. The actual ribbon growth can be viewed on a TV monitor.
- Motor programmer for high speed growth runs. At present an initial velocity and 11 velocity-time segments may be programmed. Each segment allows a programmed time duration (10 ms - 655.35 sec) and a programmed velocity ramp (0 ± 1 in./min/sec) with a 10 mil/min velocity resolution. A small microprocessor based unit is used for the program memory and data.
- CO_2 laser with a 375 watt continuous-wave output. To optimize the laser operation, various gas mixtures (He, CO_2, N_2) need to be adjusted. The beam does not exhibit an ideal Gaussian profile; it is sharply peaked with no 'ringing' or 'doughnut' modes. The $1/e^2$ points are about 9 mm apart.

Various auxiliary heating techniques have been investigated. Experiments have been conducted using direct electrical heating. It is found that auxiliary heating of the ribbon up to 1200°C effects only a 25% reduction in required laser power. In the dynamic experiments it has been observed that at higher velocities the preheated ribbon requires <u>less</u> power than a stationary one whereas the non-preheated ribbon requires more. However, because of the modest reduction in power, in the future auxiliary heating is going to be considered for stress relief only.

Growth experiments were initiated in May. The purpose of the early efforts has been to demonstrate the feasibility of controlling ribbon thickness by controlling the feed-uptake speed ratios. This would allow the thickness of the output ribbon to be nearly independent of the starting ribbon's thickness. This has been successfully demonstrated with an uptake-feed ratio as high as 2.5:1. The starting ribbon was 0.28 mm thick, 1.27 cm wide, and 12.7 cm long. The resulting ribbon was 0.15 mm thick and 17.8 cm long.

A ribbon characterization procedure is being established. Plans for the next quarter call for growing ribbon at 1 cm/min and for growth analysis and ribbon evaluation.

6. Silicon Sheet Growth: Dip-Coating on Low-Cost Substrates - Honeywell

This program is directed toward the evaluation of silicon films crystallized from the melt on low-cost ceramic substrates (Fig. 4-21). Ceramics have been selected because of their superior thermal expansion match with silicon and the greater ease with which this expansion may be adjusted. The ceramics are coated with a film of carbon or silicon carbide to enhance the adhesion. The concept has been demonstrated previously. The total program includes construction of a dipping facility, selection and evaluation of substrates and associated coatings, production of dip films and their characterization by

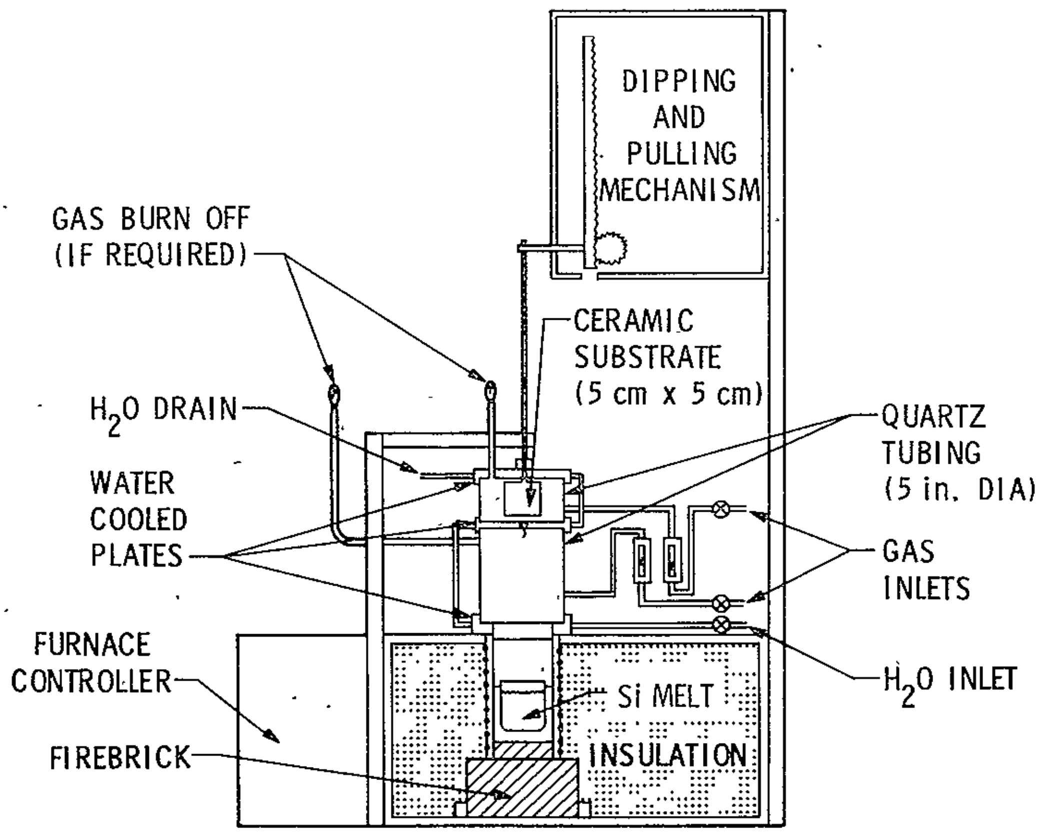


Fig. 4-21. Cross-sectional sketch of basic sheet dip coating growth facility - Honeywell

various structural, chemical and solar cell performance methods. The solar cells will require some specialized techniques because of the nonconductive nature of the substrate.

During this report period the dipping facility was completed and put into operation. It has successfully produced films of silicon on ceramic substrates, 5 cm square and approximately 1 mm thick. The substrates were withdrawn from the molten silicon at rates of up to 3 cm per second.

The substrates are obtained either from manufacturing sources or produced in-house at Honeywell as part of this program. To date, most of the effort has been expended on mullite (2 $SiO_2 \cdot 3Al_2O_3$) substrates of a commercial composition, but prepared at Honeywell. Substrates are mechanically coated with high purity carbon prior to dipping.

To date, approximately 20 dip-coating operations have been conducted. Initial results indicate mullite to be a suitable substrate. The use of alumina, on the other hand, was accompanied by spalling of the silicon film, apparently as a result of a thermal expansion mismatch. The roles of melt temperature and pull speed in film formation have not yet been defined, partly as a result of failure of melt thermocouples. This problem has been corrected.

The silicon films produced to date have ranged in thickness between 10 and 50 microns. The grains of the film measure 1 to 2 mm in a perpendicular to the pull direction and 1 to 2 cm parallel to it. Some twinning has been observed within individual grains. Initial analysis suggests that the grain configurations have not reached equilibrium when the pull capacity of the machine has been reached (5 cm). If this is true, larger grains could be developed as longer pull dimensions are achieved. Few electrical measurements on these films have been made to date. Resistivity measurements indicated that the films were of the same resistivity as the melt charge. No solar cells have been fabricated and no diffusion length measurements have yet been made.

7. Silicon Sheet Growth: Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International

The purpose of this contract is to explore the chemical vapor deposition (CVD) method for the growth of silicon sheet on inexpensive substrate materials (Fig. 4-22).

As applied to silicon sheet growth, the method involves pyrolysis, or reduction, of a suitable silicon compound at elevated temperature and approximately atmospheric pressure in a flow-through (open-tube) deposition chamber in which the substrate is mounted on a silicon carbide-coated carbon pedestal heated by rf from outside the chamber. The properties of the silicon sheet are determined by deposition temperature, reactant concentrations, the nature of the carrier gas, the silicon source compound used, growth rate, doping impurities (added by introduction of appropriate compounds into the carrier gas stream), and the properties of the substrate.

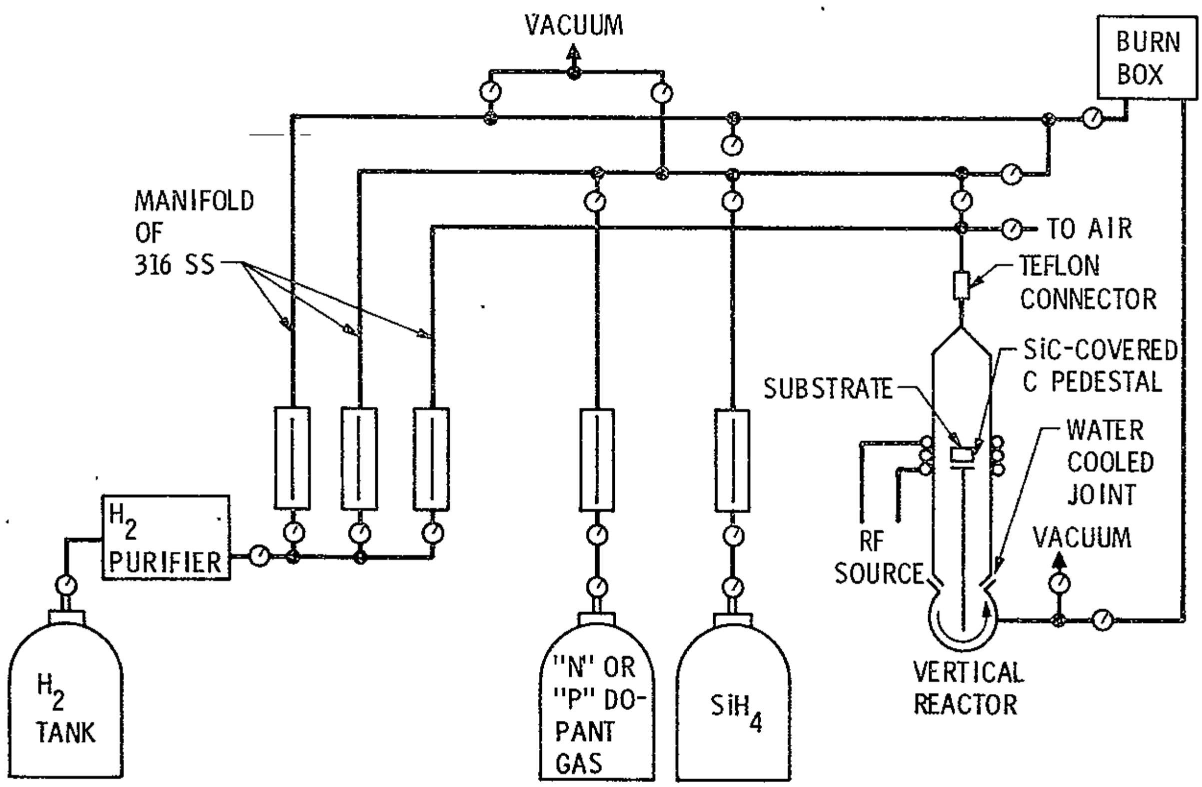


Fig. 4-22. Chemical vapor deposition on low-cost substrates - Rockwell International

The specific technical goals established for the contract include the following:

Silicon sheet:

Area (per sample)	30 cm^2
Deposition rate	5 μm per minute
Thickness	20 to 100 μm
Crystal structure	100 μm average grain size
Intragrain dislocation density	$<10^4$ per cm^2

The contract program is structured in terms of six main technical tasks, as follows:

- Modification and test of an existing CVD reactor system.
- Identification and/or development of suitable inexpensive substrate materials.
- Experimental investigation of CVD process parameters using various candidate substrate materials.
- Preparation of silicon sheet samples for various special studies, including solar cell fabrication.
- Evaluation of the properties of the silicon sheet material produced by the CVD process.
- Fabrication and evaluation of experimental solar cell structures by Optical Coating Laboratories, Inc., using standards and near-standard processing techniques.

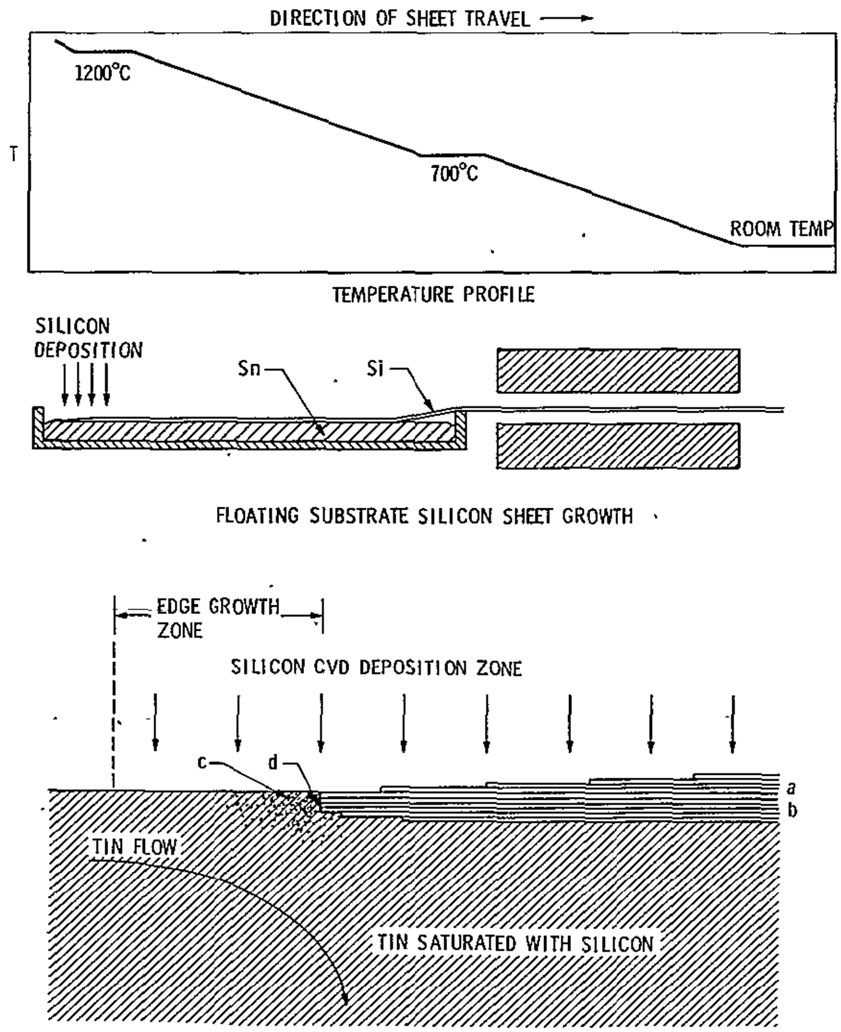
During this report period an existing CVD reactor system was extensively modified by addition of mass flow controllers, automatic sequence timers, and other improvements. Some initial problems with defective controllers were solved and the baseline performance for various temperatures, flow rates, and carrier gases was characterized. Since some glasses were found to react with the normal hydrogen carrier gas, helium was also tried. Deposition in helium was found to occur by a different mechanism, and with a different activation energy, above 850°C. By the end of May, 75 runs had been made in the reactor.

A variety of special substrate materials (glasses, polycrystalline ceramics (e.g., aluminas), and glass-ceramics) have been obtained and evaluated experimentally in the hydrogen and helium carrier gases in the range 600-1100°C. Experiments with most glasses were not encouraging, but two have now been found (Corning 1715, a calcium aluminosilicate and Owens Illinois GS211, a high-temperature proprietary glass) that are stable in helium (but not in hydrogen) and silane at 850°C. Silicon layers with grain sizes of about 0.9 μm, and with strong (100) preferred orientation, were grown on both. A variety of fired polycrystalline aluminas have been tried at temperatures above 1000°C and showed both the preferred orientation and columnar growth. For one alumina (Coors Vistal, refired) deposition was epitaxial on some 200-300 μm-sized substrate grains, but was fine-grained on others.

By the end of next quarter, a two-step process of deposition should have been tried and evaluated as a means of enhancing grain-growth. The solar cells made to date have utilized undoped material and were not meaningful, but cells using doped films will become available next quarter.

8. Silicon Sheet Growth: Chemical Vapor Deposition on a Floating Silicon Substrate - General Electric

The purpose of this contract is to demonstrate the feasibility of growing silicon sheet on a floating silicon substrate (Fig. 4-23). In the process single crystal silicon is formed by direct epitaxial conversion from gaseous silane. In an appropriate reactor, silane is passed over silicon substrate which is supported on a thin film of molten tin. Single crystal silicon grows to the desired thickness by vapor phase epitaxy. Nucleation of fresh substrate silicon takes place at one end of the reactor where the edge of the growing sheet is in contact with a region of the tin which is supersaturated with silicon. The process lends itself to continuous operation, with the finished sheet being withdrawn from the opposite end of the growth zone. The major portion of the program will focus on nucleation studies and the rapid growth of silicon substrate from supercooled melts. These efforts should lead to a sheet growth demonstration by the end of the first contract year and a design and cost analysis for a prototype sheet growth apparatus by contract close. Explicit studies for the contract include:



ENLARGED SCHEMATIC VIEW OF GROWING EDGE OF SHEET. (a = FIRST FEW ATOMIC LAYERS OF EPITAXIALLY DEPOSITED SILICON, b = THIN LOWER LAYER FORMED BY GROWTH FROM SILICON SOLUTION, c = SURFACE OF LIQUID TIN SUPERSATURATED WITH SILICON BY DEPOSITION FROM VAPOR PHASE, AND d = LEADING EDGE)

Fig. 4-23. Silicon sheet growth through chemical vapor deposition on floating silicon substrate - General Electric

- Supercooling in Sn-Si melts.
- Crystal growth from a super cooled Sn-Si melt.
- Silicon uptake by tin from silanes.
- Surface growth.
- Prototype design and cost analysis.

The technical goals for the contract require growth of a single crystal of silicon having an area of 0.5 cm^2 and the determination of the propagation velocity of single crystal silicon growth along a supersaturated hot tin melt surface.

Efforts during this quarter have been directed at studies of (1) silane uptake by the molten tin and (2) supercooling of the tin-silicon melt. In both cases the studies have been successful to the extent that the effects noted should be sufficient to support attainment of the contract goals. Current contract efforts have been directed at seeded surface growth.

Values of supercooling as high as 78° have been observed at 1100° C, and as high as 39° C at 1200° C. Spontaneous nucleation of planar platelet growth was observed on the tin-silicon melt but the nucleation studies and the ability to obtain consistent measurements of supercooling were limited by nucleation at contaminants on the surface of the melt. The surface orientation of the platelet structures was analyzed as approximately (110). Sectioning of these crystals also revealed closely space parallel crystals with (111) faces growing into the melt from the underside of the platelet. Silane uptake and decomposition experiments were carried out in two cold wall horizontal reactors. Process characterization studies consisted of determining the onset of homogeneous gas phase nucleation for SiH_4, H_2, and HCl flows. In the range of 1100° C - 1200° C, gas phase nucleation occurred at flow rates in excess of 10 to 100 cm^3/min of silane, depending on H_2, N_2, and HCl flows. It was noted that 100 cm^3/min HCl flows resulted in tin losses of about 0.1%/min. Studies of silicon uptake by the tin melt from silane has shown linear uptake rates to saturation with typically 20% of the silicon in gas stream being incorporated into the tin melt. These measurements were complicated by tin melt instabilities due to silicon deposition on the walls of the quartz tray used to hold the molten tin. Solution of these problems for seeded surface growth studies will probably require some sort of gas screening.

Project resources have been directed toward seeded surface growth studies. Several novel furnace modifications are under way to facilitate this work. The first seeding studies will be tried using web-dendritic material.

9. Silicon Sheet Growth: Hot-Forming of Silicon - University of Pennsylvania

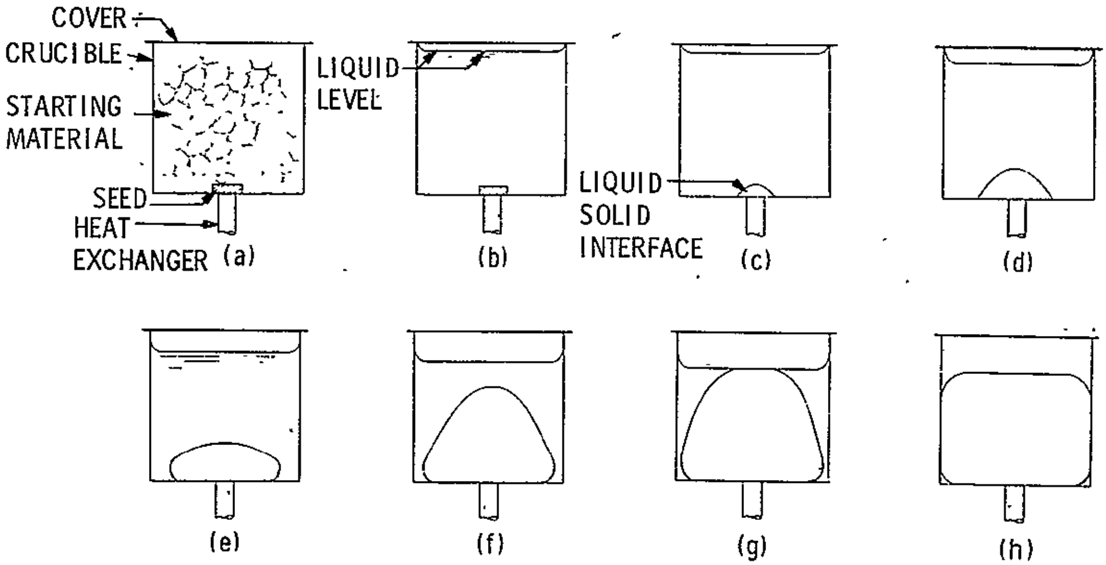
This contract is designed to determine the feasibility of hot-forming silicon in a cost-effective manner. The procedure to be followed is high-strain-rate ($\dot{\epsilon} > 1$), high-compression deformation of silicon. From this information, one can construct the hot-forming diagram for silicon and make some extrapolations of the economics of the process.

Several samples have been deformed at medium strain rates ($\dot{\epsilon} \leq 0.1$) and several points on the strain rate versus stress diagram have been obtained for a temperature of 1380°C. A new system, utilizing a MTS machine for high deformation rates, is being constructed for this program. The program also includes evaluations of metallurgical properties such as hot-forming texture; recrystallization texture, and grain size, and of electrical properties. The initial texturing experiments have indicated that a change of crystallographic orientation takes place on hot forming, followed by another change in texture on annealing.

During the next quarter, work under this contract will emphasize making the MTS machine system functional and collecting strain rate versus stress data for different temperatures.

10. Ingot Growth: Heat Exchanger Method - Crystal Systems

The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Fig. 4-24). Heat is removed



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.

Fig. 4-24. Crystal growth using the Heat Exchanger Method - Crystal Systems

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 grow large silicon crystals (6 inches in diameter by 4 inches in height) in a form suitable for the eventual fabrication of solar cells.

This goal is to be accomplished by the transfer of sapphire growth technology (50 lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

During the report period approximately 15 castings of 2500 gms each were made. It was noticed in the first few castings that it was difficult to prevent complete melting of the seed. It was found that a delicate balance must be maintained between the two controls that determine the crystallographic output. The heat exchanger temperature control, which was adequate for controlling sapphire solidification, does not control silicon solidification satisfactorily because the thermal conductivity of silicon is much higher. Adjustment of the furnace temperature control, which was not extremely critical in the sapphire process, is very sensitive and is the key to silicon solidification. However, the proper balance of these two parameters is required for successful silicon castings.

Initial variation of the two parameters was accomplished in such a way as to prevent complete seed melting. Epitaxial growth took place at the seed interface (as determined metallographically and by X-ray techniques) for only 0.5 cm before interface breakdown occurred. The interface breakdown (formation of twins of polycrystalline material) occurred because the growth rate was excessive (the furnace temperature was lowered too fast after dipping the seed). During the past 8 to 10 growth runs the investigators have been adjusting the rate of heat removal to find a satisfactory setting. In most growth runs directional freezing has occurred and in several runs large areas of single crystal (from the seed to the top of the melt) have been observed. In several of these particular samples, the single crystalline portion was examined by the Berg-Barrett and etching techniques and the crystal found to have a low dislocation density and no lineage. However, all crystals examined to date have had polycrystalline regions near the quartz-silicon interface. The investigators have identified the sensitivity of the growth parameters, and made appropriate changes in instrumentation to control the parameters.

A major problem that has not yet received full attention is the cracking of the silicon sample during the cooling period. The strong quartz-silicon chemical bond causes cracking in the silicon since quartz and silicon have quite different thermal expansion coefficients. Every sample grown to date has cracked during cooling.

Another early problem has been silicon carbide contamination in the melt (silicon carbide was identified by X-ray diffraction). The silicon carbide was not found between the seed and the quartz; this indicates an outside source of contamination. The origin of this contamination has not yet been identified.

During the next quarter, the investigators will continue to attack the seeding problem by adjustment of the two primary parameters as well as by possible changes in seed geometry. In addition, some effort will be addressed to the cracking problem.

11. Ingot Cutting: Multiple Wire Sawing - Crystal Systems

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

The overall goal of the slicing program is to optimize multiblade (wire) silicon slicing, investigating the following parameters in particular:

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

The slicing operation employs a rocking motion and utilizes 50 8-mil wires. These are 6-mil steel wires surrounded by a 1-mil copper sheath, which is impregnated with diamond as an abrasive. The shape of the abrasives and their interaction with the copper and steel is an unknown variable and will be investigated.

The slicing machine is constructed in such a way that it is well suited to an experimental program. More time was spent during construction than was originally intended, but the excellent design and construction should enhance the success of the experimental program.

The individual wires within a multiple wire package are equitensioned by the use of a single jig in the form of a weaving machine.

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

12. Ingot Cutting: Breadknife Sawing - Varian Corporation

The purpose of this contract is to develop a multiple-blade sawing process that will significantly reduce the cost of cutting wafers from ingots or blocks of single crystal silicon for solar cell fabrication and has the potential to be scaled up for eventual large production environments (Fig. 4-25). The major portion of the program consists of a systematic experimental investigation of:

- Variation in cutting loads.
- Speed of slicing head.
- Blade dimensions.
- Abrasive, size, and concentrations.
- Blade material properties and costs.
- Lubricants.
- Specimen mountings.

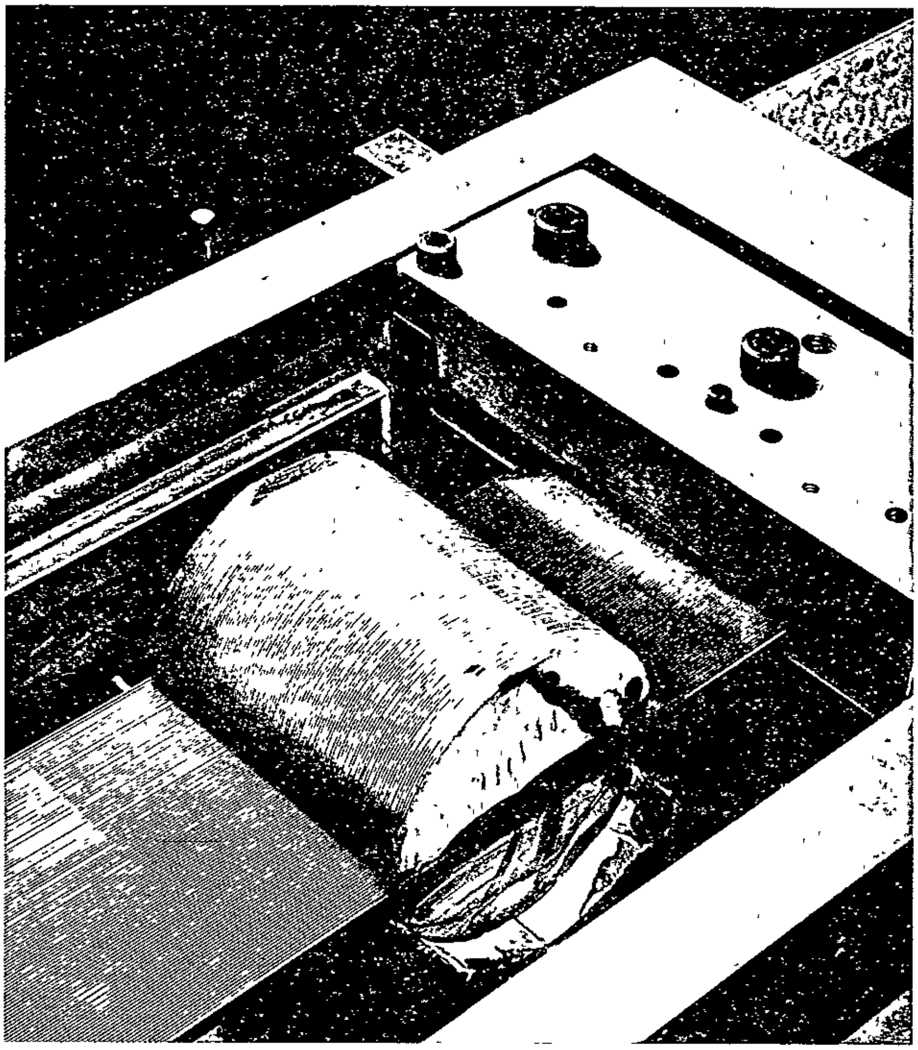


Fig. 4-25. Three-inch diameter silicon ingot in multiblade wafer saw - Varian

The investigations will be conducted on a Varian 686 wafering machine which will be modified for experimental studies. It will be supplemented by a parallel theoretical effort to parametrize system performance as affected by modified abrasive wear and to establish practical limits to wafer accuracy and thickness, blade instability, abrasive blunting, etc. The major technical goals for the program are:

- Wafer thickness: 5 mils
- Slicing rate: 10 miles per minute
- Kerf loss: 5 mils
- Number of parallel slices: 100
- Stock size: 4 inches

The baseline parameter study is nearing completion. The principal independent variables considered were blade loading (2-10 oz/per blade), kerf length (0.5-4.2 in.), blade thickness (0.004, 0.006, and 0.008 in.) and blade speed (480-1920 in./sec). All tests were run with a standard 600-grit silicon carbide slurry. Cutting rate, kerf loss, wafer accuracy, and 1 oz blade wear were followed for each experiment.

The results for cutting agree with the two body abrasive wear model developed last quarter. In particular, the cutting rate is linear with force per blade and blade speed. It is inversely proportional to kerf width and length. Cutting efficiencies show a tendency to decrease with higher cutting pressures. Efficiencies ranged from 1.2 to 0.8 for blade pressures of 100 to 670 oz/in.^{2}, respectively. Thickness measurements also showed a decrease in wafer accuracy (i.e., thickness variations) with increasing cutting load and speed.

Kerf loss during the cutting tests was found to be nominally equal to the blade thickness plus 0.004 in. This was an average performance over all tests and a ±0.001 in. variation was noted. Blade thicknesses considered were 0.004, 0.006, and 0.008 in. and the slurry was a standard 600-grit silicon carbide mix.

The ratio of blade wear to work material removal was typically 1:15 by volume.

Activities for the next quarter will include tests of abrasive and slurry variables to complete baseline studies. New efforts will be directed at thin slicing (0.005-0.010 in.), damage characterization and optimization of blade materials, and slurry mix and slurry applications.

13. JPL In-House Task 2 Activity

Spreading Resistance Measurements

Resistivity variations across silicon ribbon width have been measured on several ribbons from IBM and Mobil-Tyco Solar Energy Corporation (MTSEC). MTSEC samples exhibit an essentially uniform resistivity whereas in the IBM material the resistivity drops by about 70% in the middle of the ribbon (this has been observed by IBM). On annealing at 1200°C for 30 minutes, the amplitude of the resistivity variation decreased by nearly 40%. More annealing experiments are under way.

No effects of individual boundaries on the resistivity distribution in ribbon material have been observed. It appears that all of the grain boundaries examined so far are characterized by very low angles.

Surface Photovoltage

The steady-state surface photovoltage method is used to measure minority carrier diffusion length — probably the best figure of merit for solar cell material. Only minor chemical treatment of the surface is necessary and the problem of surface recombination is avoided by maintaining front surface conditions constant. The surface photovoltage signal is produced by chopped monochromatic light between 0.8-1.04 μm in wavelength and is capacitively coupled to the lock-in amplifier. The data are plotted to obtain the diffusion length graphically.

An ASTM standard is now available for this method and it indicates a single-laboratory one-sigma precision of about 10% plus 1 μm. This apparatus is now operational.

Deep-Level Transient Spectroscopy

When a sample displays short minority carrier diffusion length, the reason must be sought either in barriers to diffusion, such as grain boundaries, or in the recombination of electron-hole pairs. Deep levels within the energy gap, whether due to native (structural) defects or to impurities, are a major source of recombination centers. The problem is to characterize the center, identify it, and remove it.

In this method, deep levels in the depletion region of a p-n junction or Schottky barrier are operated as traps which cause a transient capacitance when the device is pulsed. This transient is used to characterize the trap (type, concentration, and energy level) as a clue to the identity of the center. This apparatus is operational in a primitive state between 100°K and 400°K and will be improved in an evolutionary manner.

Hall Effect

With unconventional growth techniques it is often difficult to predict the level of doping of crystals and even more difficult to measure it chemically. If both the resistivity and Hall coefficient are known, the mobility and carrier concentration may be calculated. If this is done at a series of temperatures, the behavior of these quantities give clues as to whether the material is heavily compensated or not. Apparatus for doing this is now operational for temperatures between 12°K and room temperature at fields up to 5 kilogauss.

Structure Studies

The activities in the JPL in-house structure studies include (1) routine analysis of contractor-supplied samples to verify their structure, (2) investigation of residual stress in ribbon samples, and (3) investigation of ultra-fine precipitates and detailed twin structure by transmission electron microscopy. The latter, the transmission electron microscopy studies, are conducted under an agreement with an external consultant.

Routine cross-sections of EFG ribbons grown by IBM using nonconventional dies have indicated that several of these dies are soluble in silicon to the point of producing an internal cored structure, similar to that observed in metallurgical casting. In this structure, the central portion consists of saturated silicon grains interspersed with a eutectic structure, surrounded by a sheath of saturated silicon grains. The existence of this structure clearly indicates the inward motion of the crystallization front during the formation of the ribbon.

Studies of cast ingots by Crystal Systems continue to indicate difficulties with controlling seeding during casting. When seeding is properly controlled, good single-crystal ingots are obtained (although fractured).

Examination of early Honeywell dip-coating specimens has confirmed the grain size as being several millimeters wide by several centimeters long, relative to the pull direction. Furthermore, the individual grains are columnar from the substrate outward, but do exhibit significant twinning perpendicular to the substrate surface. Early indications of preferred orientation indicate a minimum of such orientation.

Attempts are under way to develop a nondestructive technique for determining the stress remaining in the silicon ribbons after cooling to room temperature, to replace the presently used splitting technique, which of course destroys the ribbon for future use. An analysis was made to determine the shift in interplanar spacings in silicon relative to a standard unstressed material. This analysis indicated that the sensitivity of the technique would be, at best, marginal, especially when the difficulties in obtaining proper diffraction geometry with the long silicon ribbons was included. Consequently, attempts are now being made to modify the Bond technique to be usable with the ribbon geometry. This technique does not require external standardization and has frequently been used to measure stresses accompanying soluble dopents in silicon.

Investigations of silicon ribbon by transmission electron microscopy under a consulting agreement with R. J. DeAngelis at the University of Kentucky have indicated that there are structural variations in EFG ribbon on a scale of less than 1000 Å. These imperfections include an apparent second phase precipitate, not presently identified, and a coherent region, exhibiting differing diffraction contrast. In addition, evidence has been obtained for the existence of incoherent twins; that is, twins associated with regularly spaced dislocations. These investigations are continuing.

Investigations are also under way to determine the usefulness of quantitative microscopy in analyzing defects in silicon sheet materials. Efforts to obtain support on a contract basis are being investigated.

A second Czochralski crystal was grown during this report period. This crystal was sliced into three sections. The first section was dislocation free, the second section contained several large twins, and the third section was polycrystalline. Parts of this crystal will be sent to the University of Pennsylvania for studies on the effect of initial orientation on hot-rolling textures.

Refractory Materials Evaluation

This program was established to determine the compatibility of selected high temperature refractory materials with molten silicon. The program involves the measurement of wetting angles of sessile drops of molten silicon on the selected refractories. Approximately 50 sessile drop experiments will be conducted to provide a basic core of data, and to permit conclusions to be drawn concerning the influence of physical and chemical variables of the refractories. Several materials have been ordered and are due for delivery within the next four weeks, including:

Hot Pressed:

- Silicon nitride
- Boron nitride

Reaction Sintered:

- Silicon nitride

Pyrolytic or Chemical Vapor Formed:

- Boron nitride
- Silicon carbide

- Aluminum nitride
- Hafnium oxide
- Hafnium carbide

Materials currently on hand include silicon nitride, silicon carbide, graphite, and silicon oxynitride.

The basic experiments to be conducted will be measurements of the contact angle of drops of molten silicon on solid substrates at a temperature just above the melting temperature of silicon. A photographic system will be utilized to permit actual measurements to be made from a series of photographs depicting preselected time and temperature conditions. These photographs will serve as permanent records and records for comparison where some modifications are made, such as changed atmosphere, in otherwise identical test conditions.

Post-test analyses will involve measurement of the amount and mode of penetration of molten silicon into the solid substrates, as well as chemical changes in the silicon and substrate during the tests.

Silicon for test samples has been ordered from the Wacker Chemical Company and is scheduled for delivery on June 16, 1976. It will be in the form of 2 inch diameter disks. Test samples will be core drilled from the disks by means of an S. L. Fusco, Inc. Model No. DHI-I diamond core drill assembly. These cores will be cleaned, etched, and weighed prior to melting.

A Hoffman crystal growing furnace will be utilized for the sessile drop experiments. This furnace is now operational. Heater element modification experiments have been completed. These experiments involved designing and machining a viewing hole through the element to permit photographic access to the molten silicon drop on the selected refractory materials. A 2 inch diameter viewport is being installed in the furnace shell in alignment with the hole in the heater element. The modified furnace will then permit photographic records of the sessile drop experiments to be made.

A 35mm Nikon F-2 camera equipped with an F/2.8 lens and motor drive will be utilized. The camera will permit photographs to be taken at selected and variable time intervals through the incorporation of an intervalometer. The camera drive and furnace temperature recording instrumentation will permit accurate identification of time, temperature, and wetting angle sequentially through each experiment.

Equipment testing to date has shown that a uniform and controllable temperature can be achieved in the furnace with the modified heater element. A crucible positioning and rotating mechanism incorporated in the Hoffman furnace permits accurate alignment of refractory test specimens of differing thicknesses within the field of view of the camera. A top port permits visual observations during the tests and permits temperature checks to be made by means of an optical pyrometer.

Sample preparation and characterization has begun for those materials on hand.

TASK 3. ENCAPSULATION

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the parts of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

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

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

A. TECHNICAL BACKGROUND

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

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

B. ORGANIZATION AND COORDINATION OF THE TASK 3 EFFORT

The approach to be used in achieving the overall objective of Task 3 will include an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations will be conducted to assure timely accomplishment of objectives.

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

- Potential candidate encapsulant materials based on past experience with the encapsulation of silicon and other semiconductor devices and on available information on the properties and stability of other potential encapsulant materials and processes.
- The environment which the encapsulation system must withstand.

- The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.
- Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

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

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

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulation 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:

- Evaluate, develop, and/or modify test and analytical methods and then validate these methods.
- Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.
- Modify materials and processes used in encapsulation systems to improve automation and cost potential.
- Modify potential encapsulation system materials to optimize mechanical, thermal and aging properties.
- Implement research and development on new encapsulant materials.

A detailed Task Management Plan has been prepared. It identifies key milestones for current and Phase II technical activities and defines duties and responsibilities of the JPL technical people.

During the past quarter, support to current array module procurement and testing efforts under the Large Scale Production Task reached a significantly higher level than had been anticipated in earlier planning. This support took the form of analytical and experimental evaluation of module configurations and of JPL test results.

The Project Integration Meeting, April 27-28, 1976, included the following issues:

- An initial discussion on accelerated/abbreviated testing which, among other things, indicated the necessity for a follow-up meeting. Such a meeting is currently scheduled to be held contiguous with the July 1976 Project Integration Meeting.
- The need for improved interfaces with activities of other tasks.
- Clarification of the scope of the encapsulation system as addressed by Task 3.
- Informal discussion on the comparison and contrast between the Low-Cost Silicon Solar Array Project and the Federal Seawater Desalinization Program of several years ago.
- The need for feedback of test results and failures of current procurement modules to current and potential manufacturers.

C. TASK 3 CONTRACTS

During the report period, three additional Task 3 contracts (Table 4-8) were awarded:

- Rockwell International. An experimental evaluate accelerated/ abbreviated test methods. The objective is to develop test methodology and the associated data analysis, complimenting the more analytically oriented Battelle contract. Starting date: March 23, 1976.

Table 4-8. Task 3 contractors

Contractor	Technology Area
Battelle Memorial Institute Columbus, Ohio	• Identification of candidate encapsulant materials based on a review of (a) worldwide experience with encapsulant systems for silicon solar cells and related devices and (b) the properties of other available materials. • Definition of environmental conditions for qualifying encapsulant materials. • Evaluation of encapsulant material properties and test methods. • Analysis of accelerated/abbreviated encapsulant test methods.
Rockwell Anaheim, California	Experimental evaluation of accelerated/abbreviated encapsulant test methods.
Simulation Physics Burlington, Massachusetts	Electrostatically-bonded glass covers.
DeBell and Richardson Enfield, Connecticut	Polymer properties and aging.

- Simulation Physics, Inc. An examination of the feasibility of utilizing electrostatically-bonded integral glass covers as the transparent element of the encapsulation system. Starting date: May 7, 1976.
- DeBell and Richardson. A study of the properties, processing, and aging of polymer encapsulant materials and the use high-stress testing to evaluate encapsulation systems utilizing these materials. Starting date: May 12, 1976.

During this report period a consulting agreement was concluded with Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University. Dr. Rogers is a recognized specialist in polymer characteristics and aging as well as the field of diffusion through polymers. He will serve as a technical specialist, provide assistance in defining the overall scope and direction of the task activities and may, at a later date, implement selected supporting experimental investigations in the laboratories at Case.

D. TASK 3 TECHNICAL ACTIVITY

The sequence of Task 3 technical activities is shown in Fig. 4-26.

1. Identification of Candidate Encapsulant Materials: Worldwide Experience and Available Materials - Battelle

Over 1000 documents have been reviewed out of the approximately 6000 identified in various literature searches. These documents relate primarily to world experience in encapsulation in various kinds of devices and the terrestrial use of transparent materials. Specific references on appropriate materials and their properties were also included. No one or group of outstanding candidate encapsulant materials has been identified from this effort. The lack of definition of module design implementation requirements precluded specific identification of leading candidates. The information gathered will provide the basis for candidate selection as module design requirements are defined.

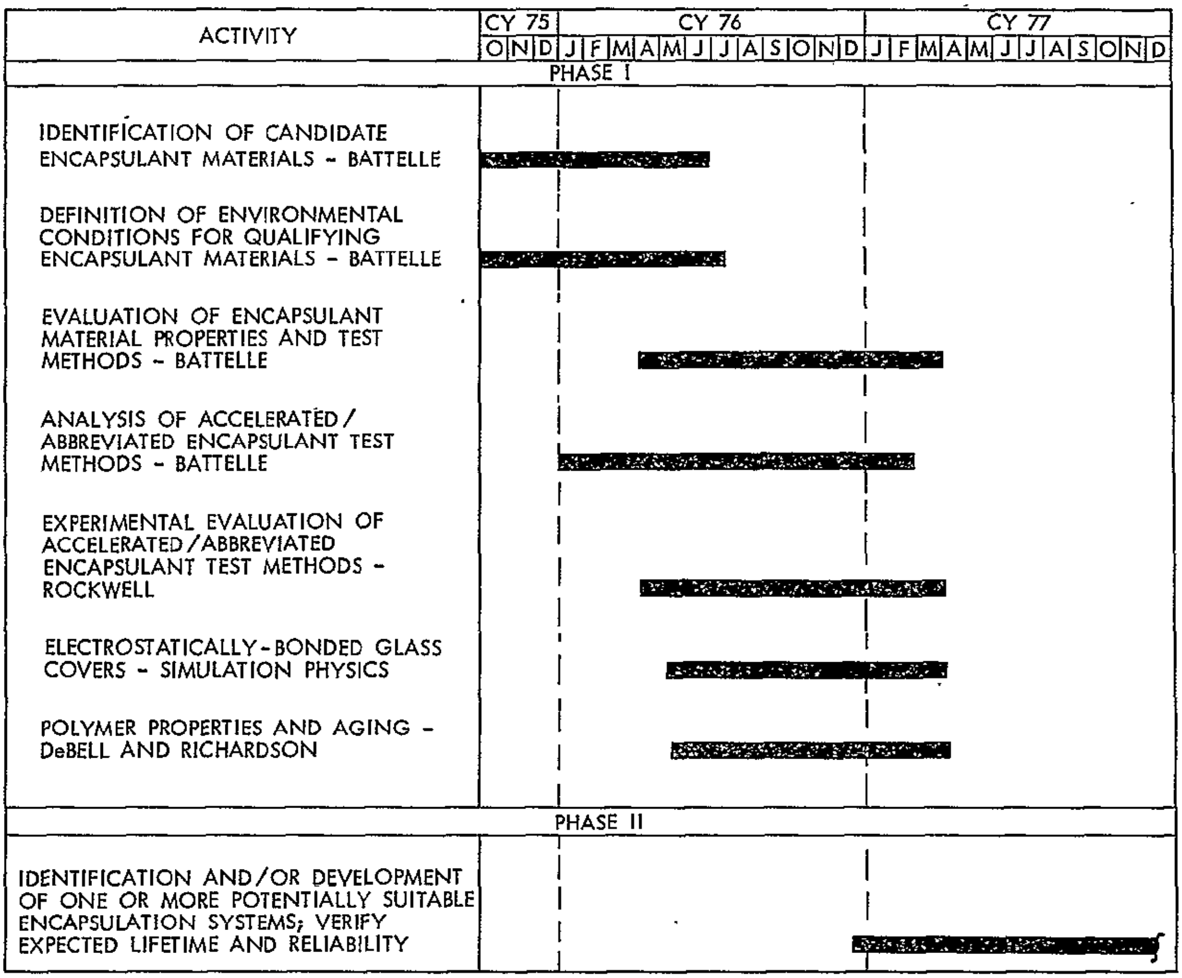


Fig. 4-26. Encapsulation Task schedule

Specific experience with the encapsulation of terrestrial photovoltaic devices includes approximately 60 identified citations. The earliest of these was a French-manufactured array in Chile which has been in use for 15 years. Most such experience is much more recent, the bulk of it occurring in the last 5 years.

The materials used as the transparent element of the encapsulation system for these photovoltaic devices include glass, polycarbonate, acrylic, epoxy, silicone, and fluorocarbon. In some cases the substrate is identified, in others it is not.

The history of the terrestrial use of photovoltaics includes observations of satisfactory performance, changes and anomalies, and failures. Many of the citations provide either no information or information too inadequate to be of major value in the present effort. Observed failures include corrosion, delamination, and discoloration. In many cases the starting material and associated processing were inadequately characterized; the failures, changes, and anomalies are typically characterized by visual observation and electrical performance, rather than by measured changes in material properties.

From these results, it can be concluded that adequate protection and stability for a 20-year module lifetime is feasible. In the past, such success has been associated with higher cost approaches than will be feasible for this project. A further conclusion is that serious problems and failures have occurred and can be expected if suitable encapsulation cannot be achieved.

2. Definition of Environmental Conditions for Qualifying Encapsulant Materials - Battelle

NOTE

> The scope and complexity of analysis required to achieve the objectives of this study have proved to be significantly more complex than anyone anticipated at the beginning. As a result, it was necessary to extend the period of performance on the study by 2 months (to mid-July 1976) in order to achieve the objectives in a cost-effective way. Furthermore, additional computer costs were encountered; the objectives were achieved without additional labor and other costs.

The development and testing of a cost-effective encapsulation system for terrestrial photovoltaics requires an understanding of the environments which the module must withstand. Real time field testing to the 20-year lifetime is obviously impossible; testing in a wide variety of locations is impractical; and materials selection to unrealistic environmental requirements would prove excessively costly. The validity of extrapolating available aging data, laboratory test data, or field test data to 20 years in a particular environment depends on the relationship of the test environment to that of the longer period.

The decision as to whether to seek a single encapsulant suitable for all possible locations or several climate-unique designs depends on many factors including production, economics, etc. In either case, a knowledge of the various environments is essential to such a decision.

The degradation of materials in any environment depends on the levels and sequence of a variety of environmental factors (e.g., temperature, humidity, ultraviolet). It was found that data on the frequency distribution of combinations of environmental "stresses" did not exist to the degree necessary for a systematic approach to development and testing of a cost-effective encapsulation system. Individual climatic conditions, their extremes, distributions, etc. could not be used. It was therefore necessary to analyze existing environmental data from which an assessment of an expected 20-year lifetime could be predicted. For this purpose, nine sites in the U.S. were selected on the basis that (1) they were "representative extremes" of U.S. climatic conditions, (2) suitable data were available, and (3) they were representative of areas where significant photovoltaic installations might be implemented. The specific sites and criteria were discussed in detail in the First Annual Report of the LSSA Project (JPL Doc. 5101-3).

It has been well established that temperature, relative humidity, and ultraviolet radiation are key parameters in the outdoor degradation of polymeric materials. In order to determine the temperature of the encapsulant on a passively cooled photovoltaic array, it is necessary to know, simultaneously, the air temperature, wind speed, and insolation (as well as the module and array design). For these reasons, one of the major efforts in this study was a statistical analysis of the simultaneous occurrence of various levels of air temperature, relative humidity, wind speed, and insolation over a 10-year period. This data permits an assessment of the encapsulant temperature (for a given design), relative humidity, and an estimate of ultraviolet based on total insolation (actual ultraviolet data is particularly sparse and an estimate is the best approach for the present time). Other statistics have also been developed to establish daily and annual transients.

It is anticipated that similar analyses of other sites will be required in the future and that analysis of additional combinations may be required. Using the methodology and programs developed under this study, such additional analyses can be accomplished rapidly and economically.

A key conclusion that can be drawn from this study is that "abusive" conditions – that is, combinations of environmental factors which would be expected to cause higher-than-normal degradation – actually occur with limited frequency. If it is found, when degradation rates as a function of environmental combinations have been established, that the "abusive" combinations are the major contributors to degradation, then the limited occurrence and established frequency of such combinations may permit effective time-compression tests for a 20-year lifetime.

A preliminary "test set" approach to testing for all sites has been developed. Some obvious problems of such a universal test have become evident as a result of this development. Consequently, a universal test for all climatic types does not appear feasible; however, considerable commonality in test conditions does appear feasible.

3. Evaluation of Encapsulant Materials Properties and Test Methods - Battelle

Detailed experimental plans have been developed. Owing to inadequacies in available test data for the accelerated/abbreviated test study, part of the output of this investigation will be data to support a mathematical model for aging.

4. Analysis of Accelerated/Abbreviated Encapsulant Test Methods - Battelle

Substantial confusion has been evident in the terminology associated with lifetime and predictive testing. As a result, the following definitions have been adopted for this task:

- **ACCELERATED TEST** — A test in which one or more environmental "stresses" (temperature, ultraviolet, moisture) are increased above the level that would be expected in the real environment in order to shorten the time necessary to evaluate system lifetime.
- **ABBREVIATED TEST** — A test in which normal or expected stress levels are used but which is conducted over a time period shorter than expected lifetime. The mechanisms and rates are determined with sufficient accuracy to permit the extrapolation to real lifetime.
- **TIME-COMPRESSED TEST** — A test in which conditions which produce less-than-normal or no degradation are shortened or eliminated. For example, if dark reactions are insignificant or occur over a relatively short time after sundown, nighttime can be simulated with substantially less than the normal period.
- **EVENT-COMPRESSED TESTS** — These are tests conducted at selected (e.g., most abusive) real conditions wherein these events occur more frequently or for longer duration than in the real environment.

The above definitions are significant primarily in a semantic sense. Obviously, many tests are combinations or permutations of the specifics. For example, a test under simulated or actual worst conditions would be a real-time test for those conditions, but an accelerated test for all less severe combinations.

Analysis of available laboratory and outdoor weathering test results has shown that these results are inadequate for validation of the design of accelerated and abbreviated test and analysis procedures. Additional laboratory and weathering data will be required to develop and validate a methodology.

A number of excellent investigations have been carried out in this field, but all are deficient in one or more of the following key areas:

- Statistical analysis carried out after the fact rather than a consideration at the outset.
- Sufficient replicate samples for data accuracy and statistical significance.
- Sufficient frequency of data points during the life of the test.
- Sufficient and appropriate properties measured.
- The "random" distribution of properties, sample to sample, and batch to batch, of a particular material class.
- Adequate characterization and recording of the actual test environment.

A preliminary predictive test design has been developed and analyzed for frequency and accuracy of property measurements required. The key conclusion to be drawn at this time is the need for careful attention to and probably development of new techniques for diagnostics (that is, the means for determining changes in properties).

5. Experimental Evaluation of Accelerated/Abbreviated Encapsulant Test Methods - Rockwell International

The objective of this contract is to experimentally evaluate accelerated/abbreviated test methodology and the associated analysis of data. Data analysis and diagnostics for determining changes and rates of change will be key elements in the experimental design in addition to the normally considered environmental factors. The program will involve duplicate specimens, exposed to outdoor environments and to accelerated environmental levels in the laboratory.

The accelerated stress parameters have been defined, based on the requirements for data analysis, for diagnostics, for environmental duplication and taking into consideration the practicality of the experimental equipment. The laboratory tests will use a complete factorial of simulated solar radiation at 0.0, 0.5, and 1.0 AM-1 levels, and "day-night" cycles (intermittent), temperatures of 5°C and 50°C, and three levels of relative humidity. Duplicate samples will be exposed to real-time outdoor weathering in Florida and Arizona and accelerated outdoor weathering in Arizona.

The data analysis approaches to be used have been developed in sufficient detail to establish test-approach requirements.

Material-change diagnostics are still being considered; the priorities, frequency, and emphasis remain to be defined in detail. During this program, particularly in the early stages, a large number of diagnostic approaches will be explored.

6. Electrostatically-Bonded Integral Glass Covers - Simulation Physics

An interim large-scale bonder has been designed and construction has started. Initial experiments with 2-inch diameter cells will be undertaken in the next month.

7. Polymer Properties and Aging - DeBell and Richardson

A detailed experimental plan has been completed. Materials have been selected and procured and sample fabrication started. Additional test equipment has been ordered.

8. JPL In-House Task 3 Activity

During this report period a significant amount of effort was devoted to the evaluation of encapsulant systems for the 46 kW and 130 kW solar array procurements which are being carried out under the Large Scale Production Task (see Part V). This included analysis of the designs, and experimental and analytical evaluation of test results. Problems encountered during the testing of 46 kW modules were found to be the direct result of misunderstanding of, misuse of, and the misleading nature of available materials properties information. All of the encapsulant designs which utilized a "potting" approach incorporated some type of silicone rubber as the encapsulant. These silicone rubbers, although possessing the advantageous characteristics of softness and transparency, also have the disadvantages of high moisture permeability, a high coefficient of expansion, and poor resistance to mechanical damage. Results appear to confirm the earlier hypothesis that, because of the hazard of moisture permeability, cells encapsulated in silicone (or any other polymer) must have inherent corrosion resistance built into the metallization and interconnect system.

One silicone product described by the manufacturer as having 50% elongation was found to post-cure to approximately 20%. Data scatter and elongation measurements of the post-cured material led to discussions with the manufacturer which confirmed the hypothesis that the product is a two-part system and is difficult to keep homogeneous during manufacture. An analysis of cylic fatigue and biaxial elongation predicted that tearing would occur — as has been observed. This same analysis indicated corrective action; this will be implemented during the next report period.

Because of the large amount of effort expended in support of solar array procurements by the Large Scale Production Task during this report period, Task 3 JPL in-house progress in the following areas was substantially less than had been planned: development of detail plans; implementation of effort in long-range, in-house testing and analysis; data bank development; and aging mechanisms studies. Although support of current array procurements will continue at a significant level, these other efforts will be stepped up during the Transition Quarter and early in FY 1977.

Presentations on generalized materials characteristics and stress analysis principles are being prepared. These will describe the nature and cause of failures without identifying a particular design, configuration, or manufacturer.

The proprietary nature of the designs requires that this generalized approach be taken. The presentations will be initially offered at the Project Integration Meeting in July 1976; a paper based on these presentations has been submitted for the Photovoltaic Specialists Conference to be held in the fall.

It has long been recognized that, as expected, the extent of outdoor weathering encountered during a test is dependent on the season of the year at which the weathering cycle begins. Analysis of the available aging data and theoretical aging models confirms hypotheses indicated in the literature that at least one full annual cycle of weathering is required if extrapolation to multi-year performance is to be attempted with any degree of accuracy.

TASK 4. SOLAR ARRAY AUTOMATED ASSEMBLY

The overall objective of Task 4 is to use the results and experience gained from Tasks 1, 2, 3, and 5 to fabricate solar arrays of 10% or better conversion efficiency at a price of $0.50/watt or less at a rate of 500 megawatts per year with a 20-year operating life. Phase I (technology assessment) of this task has these specific objectives:

- To identify the requirements for economical manufacturing processes and facilities.
- To assess the current technology used in the manufacture and assembly processes that could be applied to solar arrays.
- To determine the level of technology readiness to achieve the high-volume, low-cost production.
- To propose processes for development.

A. TECHNICAL BACKGROUND

The manufacture of solar cells and arrays is presently performed under the direct judgment and control of individual operators. Because of the limited quantities of solar cells and arrays produced, costs are high. Automation accomplishes more than the obvious reduction of labor. In addition, automation causes a uniformity of processing which results in a more uniform product with a corresponding reduction of waste due to rejected product.

B. ORGANIZATION AND COORDINATION OF THE TASK 4 EFFORT

Task 4 is divided into five phases, occurring over a 10-year period of time; 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).

Many of the decisions that must be made during the Task 4 effort cannot be made independently. They will result from trade-offs with other decisions that are made both within the task and in conjunction with other tasks of the Project.

C. TASK 4 CONTRACTS

Phase I contracts have been awarded to three contractors (Motorola, RCA, and Texas Instruments) to perform parallel efforts (Table 4-9). The three-contractor parallel effort philosophy was selected to obtain the broadest possible view of recommendations and conclusions upon which to base the contractual efforts of Phase II (Fig. 4-27). During Phase I, these contractors will address the areas of defining the requirements for automation as applicable to solar cell manufacturing by evaluation of processes which are now used by the semiconductor industry and how these processes could be modified for high-volume, low-cost production of solar cell modules. Cost analyses will be performed to provide economic guidelines to maintain an overall view of LSSA Project objectives.

Contracts for two support efforts have been awarded which will contribute to achievement of the Task 4 objectives: Simulation Physics is exploring the feasibility of a unique process for forming a solar cell P/N junctions at room temperature, and Texas Instruments has just started work on the optimization of current proven semiconductor techniques to produce silicon wafers in the most cost-effective manner.

CY 76	CY 77	CY 78	CY 80	CY 83	CY 84	CY 85	CY 86
PHASE I: TECHNOLOGY ASSESSMENT	PHASE II: DEFINE, SELECT, AND DEMONSTRATE MANUFACTURING PROCESSES		TECHNOLOGY READY	EXPERIMENTAL PLANT IN OPERATION		MASS PRODUCTION PLANT READY FOR OPERATION	

PHASE I: TECHNOLOGY ASSESSMENT

- Analyze existing technologies
- Identify costs of processing and testing steps
- Develop cost effective approaches and identify options available
- Identify cost/manufacture obstacles
- Conceptual solutions to these obstacles
- Demonstrate cost effectiveness of solutions
- Define the conceptual approach that appears most cost effective for fabrication/assembly of solar cell/array modules

PHASE II: DEFINE, SELECT, AND DEMONSTRATE MANUFACTURING PROCESSES

- Determine priority for process development
- Identify areas where new technology must be developed
- Develop processes and demonstrate technology readiness
- Identify the manufacturing equipment and facilities required
- Update conceptual design developed Phase I
- Update the cost analysis

Fig. 4-27. Solar Array Automated Assembly Task schedule

Table 4-9. Task 4 contractors

Contractor	Technology Area
Motorola Phoenix, Arizona	Manufacturing processes assessment
RCA Princeton, New Jersey	Manufacturing processes assessment
Texas Instruments Dallas, Texas	Manufacturing processes assessment
Simulation Physics Burlington, Massachusetts	Electron-beam solar cell fabrication
Texas Instruments Dallas, Texas	Large area Czochralski silicon ingot growth and wafering improvements

D. TASK 4 TECHNICAL ACTIVITY

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

Motorola

Motorola's program plan milestone chart for Manufacturing Processes Assessment is shown in Fig. 4-28. It starts out with work on designs of solar cells and with process adaptation. This is followed by process sequencing and encapsulation design. Costing, cell fabrication, and encapsulation experiments will be carried out. These will be followed by selection of a recommended sequence and concepts for scaling up to the required production volume.

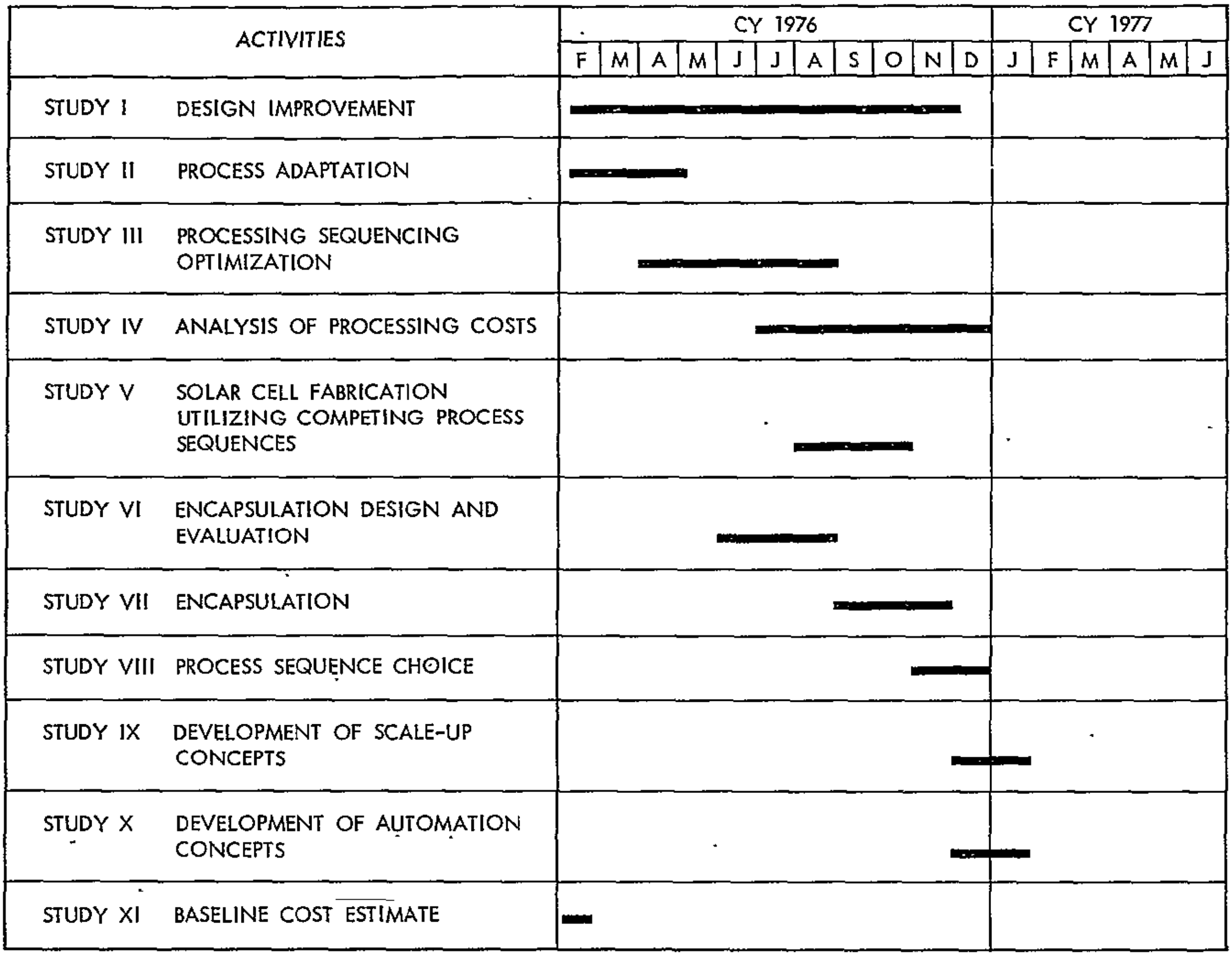


Fig. 4-28. Motorola program plan for Manufacturing Processes Assessment

A list of 45 individual processes was assembled for study. The processes have been categorized into four groups with respect to their applicability to solar cells: (1) judged unlikely, (2) potentially promising, (3) presently in solar cell use, and (4) semiconductor processes not usually applied to solar cells. Eight of these processes are being studied by laboratory experimentation. The results of a literature survey have indicated that solar cells made by Schottky barriers are of too low efficiency to be considered for this project. Higher efficiency cells require less encapsulation and structure. When the cost of slight increases in efficiency is weighed against the cost of slight reductions in the need for encapsulation and structure, it indicates that medium-to-high efficiencies are the most cost-effective. Experiments have been conducted with a textured front cell surface which absorbs more light to make the cell more efficient. This surface is shown in Fig. 4-29. The textured surface has the additional advantages of increased area for lower contact resistance of metallized areas and a damage-free etched surface, which promotes better efficiency.

Motorola is investigating the benefits of making the back of the cell reflective, to increase efficiency.

In order to evaluate various metallization processes, a test pattern and method of use has been developed which tests the ability of a process to produce electrical collector grids as fine as one-third of a thousandth of an inch wide.

Experimental tooling has been used to fabricate various metal-backed solar panels. Various metals and materials are being tested for their ability to withstand the outdoor environment and seal out moisture which may degrade the solar cells in time.

RCA Laboratories

The RCA program plan milestone chart for Manufacturing Processes Assessment is shown in Fig. 4-30. The effort begins with the development of a cost analysis procedure. This procedure has been applied to existing process technologies to obtain very detailed costs. The development of cost-effective approaches and the identification of cost/manufacturing obstacles also began at the onset. Work on the solutions to the obstacles, with experimental demonstrations, has begun. The final step will be to define the most cost-effective approach for manufacturing solar cell modules.

RCA is using an analytical system which relies on three organizational diagrams. These are (1) a silicon quality materials matrix, (2) a processing matrix, and (3) an array module cost analysis interaction diagram. The silicon quality matrix is a 5 row by 7 column pattern of possible silicon

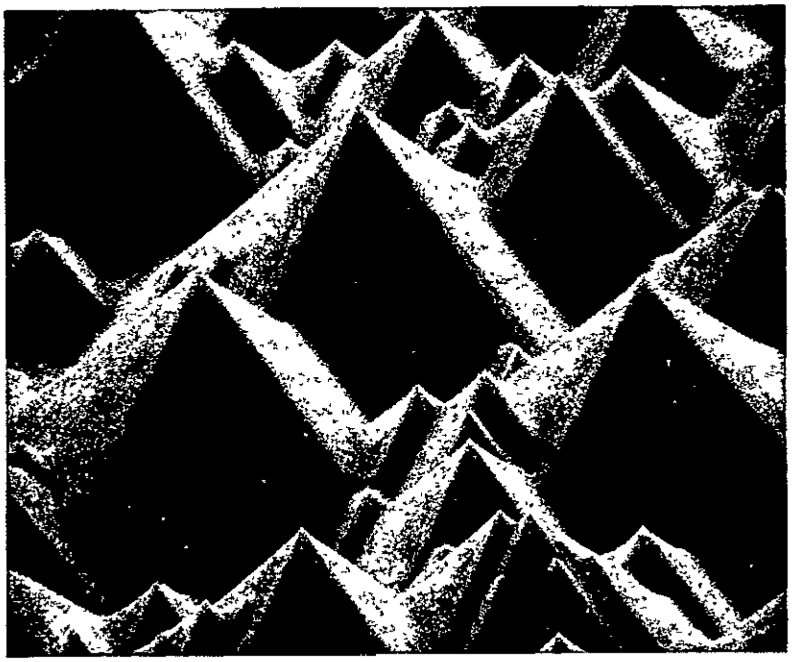


Fig. 4-29. Scanning electron photomicrograph of textured silicon surface following removal of deposited silicon nitride surface layer (magnification, 5000X; 60° tilt)

purity levels and physical forms. The processing matrix catalogs 28 separate processes which contain the many options for fabricating solar cells from the different grades of silicon quality as determined in the silicon quality matrix. Every reasonable alternative in these matrices is being evaluated and detailed costs are being defined. Development of the costing system has comprised a major portion of the RCA effort during the months of March, April, and May. The costing procedure at present uses eight basic elements. These are (1) incoming unit cost; (2) supplies, materials, gases, electricity, etc.; (3) direct labor; (4) indirect labor; (5) labor overhead; (6) interest; (7) depreciation; (8) factory overhead; and (9) investment.

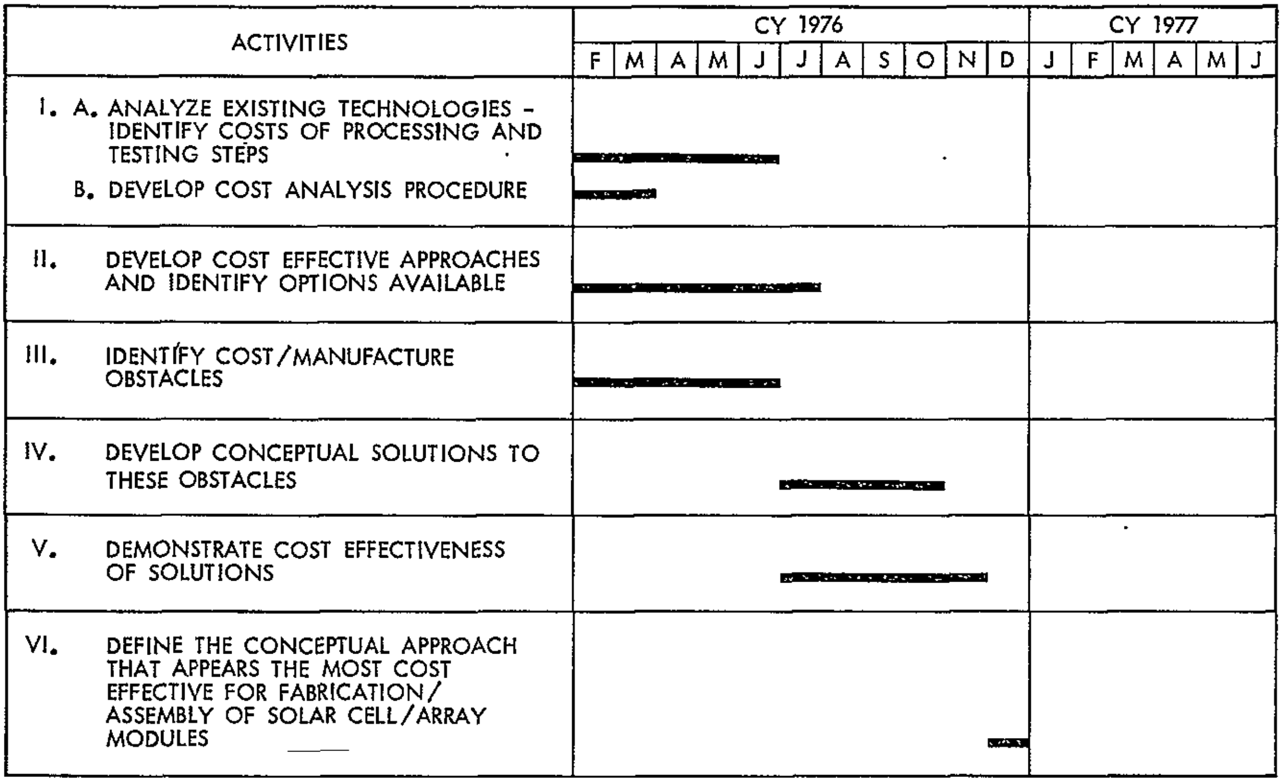


Fig. 4-30. RCA program plan for Manufacturing Processes Assessment

RCA recognizes that this cost accounting approach to process evaluation has weaknesses. Because of differences in the quality of the output of two alternative processes, this method may not permit direct comparisons. In general, each step is integrated into some entire manufacturing sequence of processes and then the costs are compared. A performance index is determined for each process as it relates to the way it affects cell parameters. A manufacturing sequence has an overall figure of merit which is the product of the individual process performance indices. In this way evaluations are accomplished which relate to solar cell costs in terms of dollars per watt.

Texas Instruments

Texas Instrument's program plan milestone chart for the Manufacturing Processes Assessment is shown in Fig. 4-31. Technology analysis was started with cell design, junction formation, and metallization. Cost studies were immediately begun for cell design and automation. Within 2 months, experimental studies were under way on cell design, junction formation, and metallization.

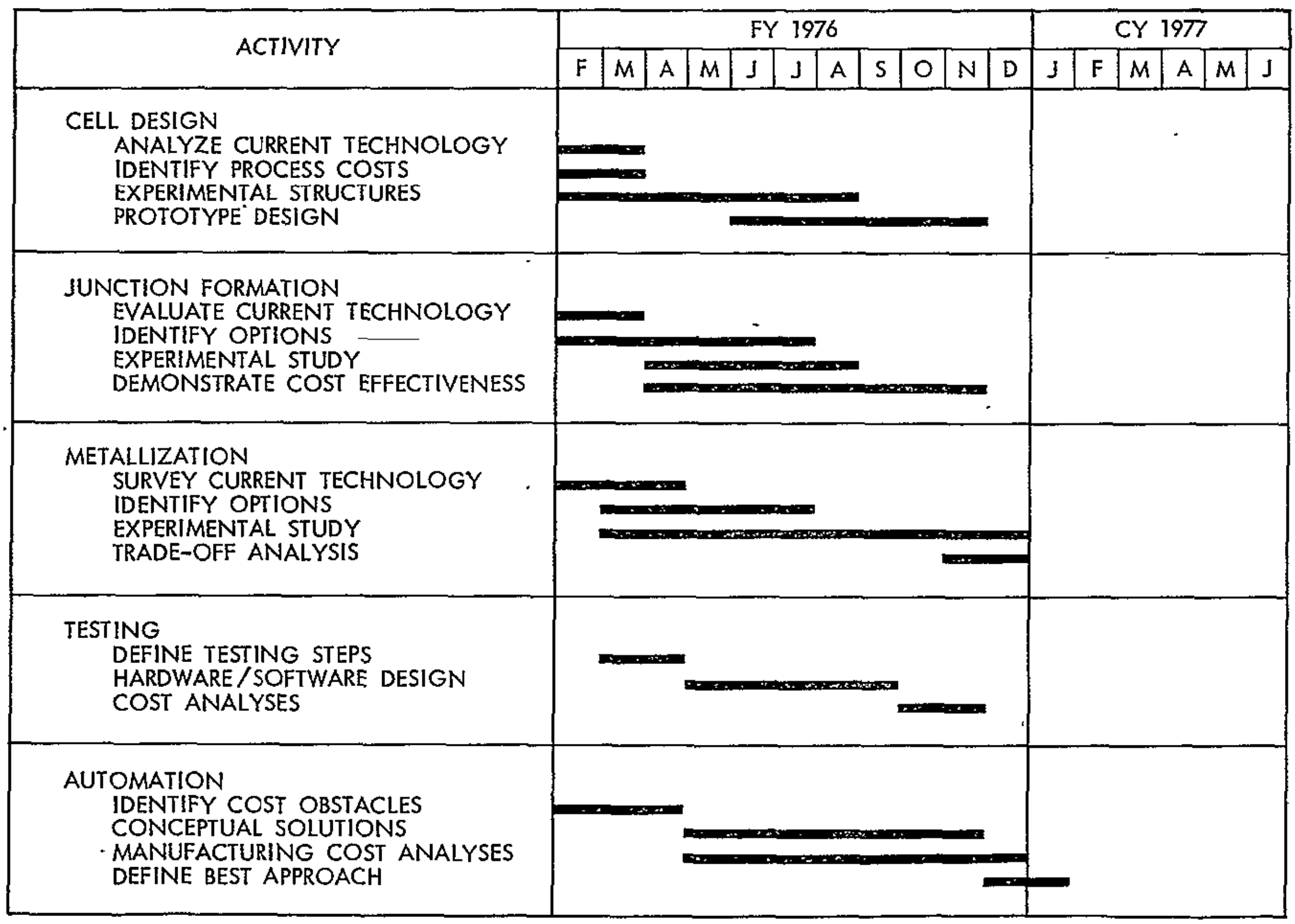


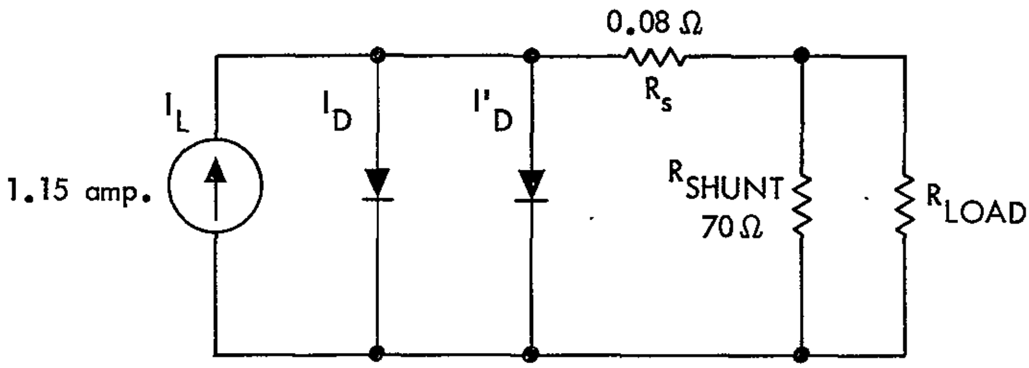
Fig. 4-31. Texas Instruments program plan for Manufacturing Processes Assessment

A design-to-cost analysis has been used to set allowable cost goals for each process element of the solar cell module fabrication process. A base line process, using current technology, was costed out and showed that current technology is about an order of magnitude too expensive at each process element when compared to the design-to-cost goals. The cell metallization step has been shown to be the least cost-effective step in the baseline cell process. Several alternate cell metallization processes are being studied and a test pattern has been developed and used to evaluate the specific contact resistance. Experiments and development work on silk-screened thick film metallization systems are being carried out with the assistance of expert additional help. This metallization system will be very cost-effective if the process is compatible with the fabrication of high efficiency silicon solar cells.

The allowable cost goals for each process element derived from Texas Instrument's design-to-cost analysis have been further broken down to give models of labor, overhead, material, and depreciation cost goals. These cost goals are related to a set of factory throughput values. A model for a metallization system that would meet the cost goals of the program has been described.

A computer model of a solar cell and of a 16 cell (4 x 4 matrix) solar cell module has been developed. This computer model coupled with actual device characterization is being used to direct experimental work aimed at improved cell efficiency. The model gives excellent agreement with observed cell characteristics (see Figs. 4-32 and 4-33). The computer model of the 4 x 4 module is being used to define test limits for individual cells so that module parameters will be optimized.

The Texas Instruments baseline design focuses on hexagonal cells close packed on an encapsulated 10-watt module. This geometry has a more efficient cell packing density than circular solar cells. TI points out that both packing density and cell efficiency must be improved to meet the Project goals. Their analyses using the design-to-cost concept show that low efficiency solar cells are not justified with expected costs per unit area for module fabrication and encapsulation.



$$I_D = I_S\left(e^{\frac{qV}{KT}} - 1\right)$$

WHERE:

$$I_S = 4.379 \times 10^{-11} A$$

$$I'_D = I'_S\left(e^{\frac{qV}{nKT}} - 1\right)$$

WHERE:

$$n = 4$$

$$I'_S = 8.4 \times 10^{-4} A$$

Fig. 4-32. Best fit model of actual solar cell characteristics

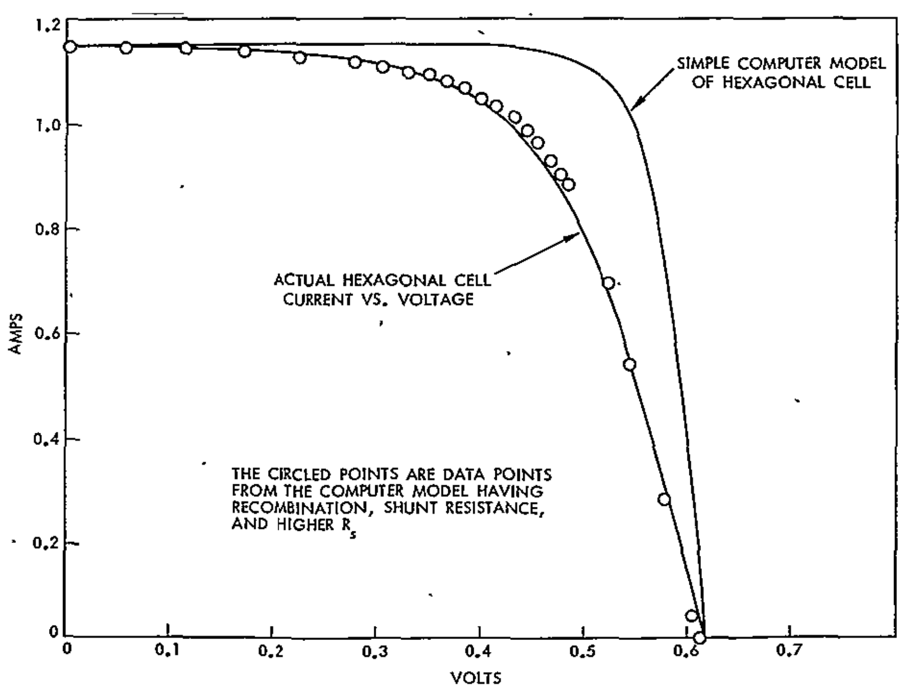


Fig. 4-33. Current-voltage characteristics of hexagonal cells

2. Electron-Beam Solar Cell Fabrication - Simulation Physics

The objective of this program is to demonstrate the feasibility of a unique process for solar cell manufacture. The technique incorporates the use of an ion implanter and an electron beam processor to manufacture solar cells in a vacuum environment at room temperature. An ion implant of phosphorus is made on the front surface of the cell; boron or an aluminum eutectic is implanted on its rear surface. An electron beam is used for the implant annealing process and also for sintering the aluminum contacts and antireflective coating.

The program, after approximately 8 months of its scheduled 12 months duration, has demonstrated the feasibility of the process: Efficient solar cells have been produced at room temperature in vacuum.

Advantages of the process, as it is being developed, over conventional solar cell fabrication processes include:

- Simplified Cell Manufacturing. There is no present need for wafer cleaning, acid etching, or sandblasting processes. No special forming gas atmosphere is required. There is no acid waste or other waste disposal problem. No materials are used that do not form part of the cell.
- Noncritical Materials. The process places little constraint upon the type of silicon or gallium arsenide, etc. used, or upon its raw form, or upon the completed device configuration. Room temperature processes would accommodate cells processed upon plastic substrates. Extremely fast pulse sintering prevents cell-degrading diffusion of impure low grade materials into the base material (low grade aluminum is used as cell contacts and coatings).
- Controlled, Reproducible Processes. Ion species of a given quantity delivered at given energies can be precisely implanted at given depths and annealed. This technique offers a much wider selection for cell development and for cell production processes than does the conventional diffusion furnace process.

- Low Manufacturing Energy Requirement. Measured in microseconds or fractions thereof, pulses used in the processes have little power content. Net cell power payback time for processing is measured in hours rather than months.
- Small Net Process Time. Net wafer-to-cell process time on this program has now been reduced to 36 seconds per cm^2 of wafer area. The program goal is a time of less than 30 seconds per cm^2 for a 2 x 2 cm cell. Less than 5 seconds per cm^2 is a possibility. The times are a summation of the various steps for cell processing. Equipment does not yet exist for a continuous process line.
- Automation. All manufacturing steps in this process are readily automated.
- Low Cost. This technique promotes low cost solar cell processing. Inherent manufacturing simplicity permits high volume processing at high speed with good process control requiring little labor surveillance. The method also promises high yield with little material waste and with efficient energy utilization. Equipments costs are moderate.

Solar cells (2 x 2 cm) are now being produced with 9.5% air mass zero efficiency, better than 10% air mass one. Three-inch diameter cells are produced in 371 seconds net, about 8 seconds per cm^2. At the moment, the weakest link in this process is the electron beam pulse annealing. Still requiring development, the electron beam in use is somewhat dirty because it attracts and deposits at the cell junction unwanted contamination ions. The present lack of electron beam flux uniformity may contribute to crystal lattice damage. The consequence is a slight reduction in cell V_{oc}, about 30 mV typically for a 2 x 2 cm cell. However, the typical cell output current and its current-voltage curve fill factor are very good.

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

The purpose of work under this contract, initiated during the current report period, is to optimize current proven semiconductor techniques so as to produce silicon wafers in the most cost-effective manner. The major goals are as follows:

- Using melt replenishment techniques, 30 kilograms of silicon in the form of three crystals 12 cm in diameter will be grown during one continuous heat cycle.
- Multiblade sawing techniques will be optimized to produce 0.025 cm (.010 in.) thick wafers from 12 cm diameter crystals.
- Laser shaping techniques will be developed to produce hexagons from the 12 cm diameter wafers at an edge rate of 10 cm per second.
- An economic model of the crystal growth, wafering, and shaping techniques described above will be developed and continually updated. (Although listed last, this goal is probably the most important.)

The initial 2 months of the contract have provided the following results:

1) The preliminary economic model of the Czochralski crystal growing and wafering processes has resulted in the curves shown in Fig. 4-34, which describes silicon sheet costs as a function of slice plus kerf width, with crystal growth yields and saw yields as variables. These curves are interesting in that they show graphically the effect of kerf losses and allow cost estimates to be made rapidly based on silicon growth yields and sawing yields. In fact they show that the processing techniques optimization effort will result in sheet costs of less than \$30 per square meter, for a polysilicon starting material input cost of \$10 per kilogram.
2) Theoretical yields for the melt replenishment technique described above show that 80% yields should be obtainable (in the specified resistivity range) rather than the 60% originally anticipated. In addition, thermal modeling has shown that 15 cm

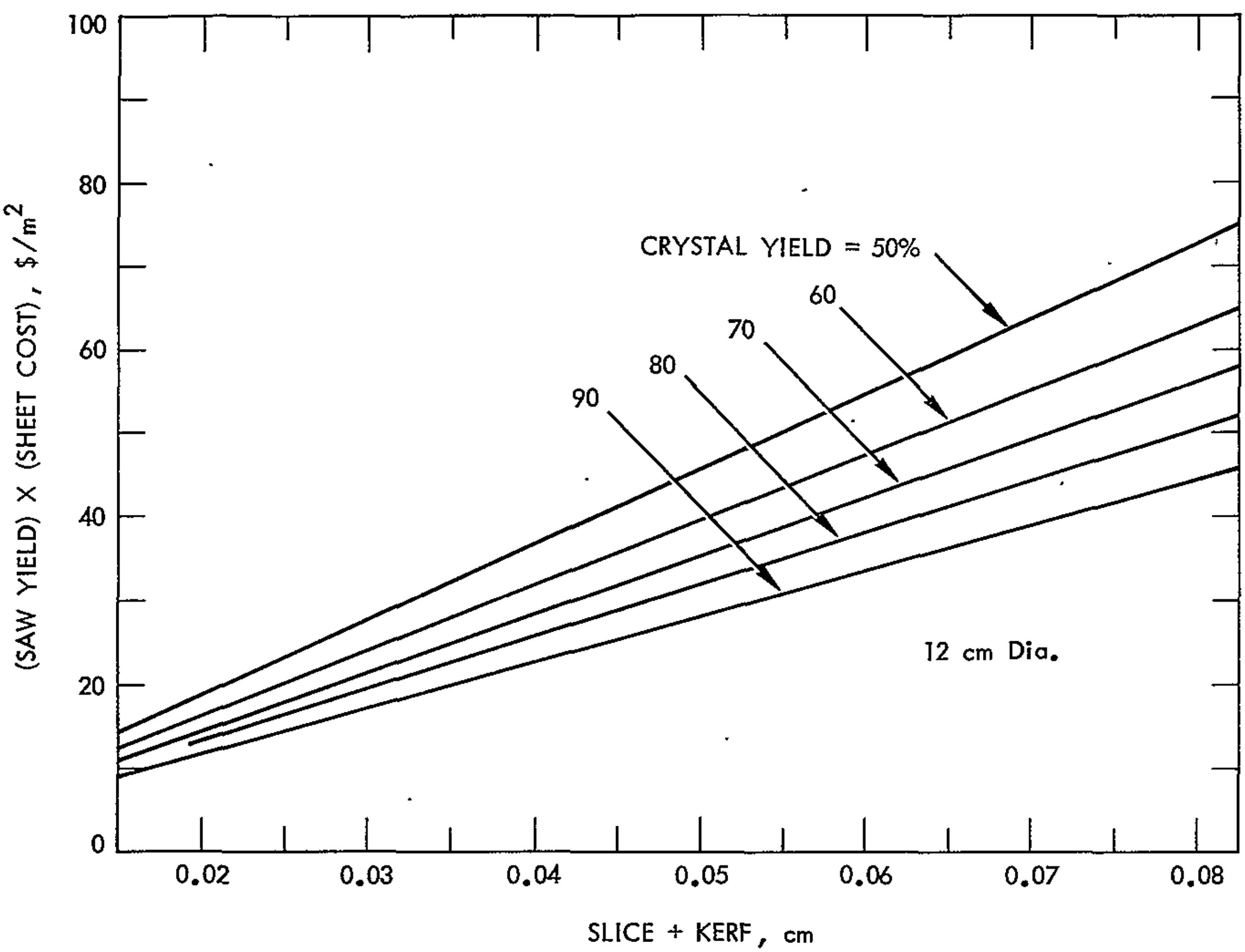


Fig. 4-34. Czochralski silicon sheet cost

per hour growth rates should be obtainable and that the 12 cm per hour specified in the contract is reasonable. Furnace modifications are under way that will permit a test of the accuracy of the theoretical models.

3) Sawing experiments using 400 grit SiC abrasive and both 0.02 cm (0.008 in.) and 0.01 cm (.004 in.) thick blades have shown very reasonable yields (98%). The results also indicate that several crystals could be sliced simultaneously at the same rate as a single crystal provided the blade load is kept constant. This will be investigated during the next report

period. It is expected, in addition, that the slice plus kerf thickness will be reduced to the contract goal of 0.05 cm (0.020 in.). If successful, these sawing experiments will have considerable effect on the overall costs for silicon wafers.

PART V

DEVELOPMENT, PROCUREMENT, AND EVALUATION OF SOLAR ARRAYS

The objective of the Development, Procurement, and Evaluation of Solar Arrays (DPESA) activity is to stimulate industry to produce larger quantities of improved, less expensive silicon solar arrays in support of the ERDA Photovoltaic Test and Demonstration Project. This involves the periodic purchase of increasing quantities of solar arrays at decreasing unit prices, using the latest state-of-the art technology. The arrays will be procured from industry on a commercial basis to meet performance specifications and environmental requirements for use in numerous and diverse ERDA tests and demonstrations.

These activities are expected to bring about improved designs in order to achieve production and cost improvements. The arrays will be manufactured by production contractors, under Project sponsorship. In addition, whenever and wherever practical, technology improvements achieved in other tasks of the Project will be applied to contemporary array production. This will aid in the achievement of task objectives, and also in testing the new technology in the context of actual commercial manufacturing conditions.

A. BACKGROUND

At the inception of the LSSA program in January 1975, the solar cell manufacturing industry in the United States was in decline. A solar cell production capacity of about 10 kilowatts per year, for use in space, had been reached in 1970, at the peak of the NASA program. Production of solar cells for spacecraft has been declining since. By comparison, the rate of production of cells for terrestrial application was very low and was increasing only very slowly. A few small companies were making terrestrial modules. These companies could be considered offshoots of the large U. S. semiconductor industry. Silicon solar cells were made of semiconductor-grade silicon, which has been expensive for large-scale terrestrial use. Large variations in availability and price of pure silicon have been a feature of the dynamic semiconductor industry. In terms of the total production of silicon, the solar cell manufacturers are small consumers. Having limited resources, these companies have been occasionally subjected to strong economic forces, resulting in some instability.

The intervention of the LSSA Project in this market should provide a strong stabilizing force and large cost reductions. An assured and growing market for solar modules should provide the incentives for private capital investment, process development, improved availability of raw materials at lower prices, and lower product costs from increased scale of production. Additional cost reductions will result when the developments generated by the technology development tasks of the LSSA Project are incorporated into the final product during the coming decade.

B. ORGANIZATION AND COORDINATION OF THE DPESA EFFORT

The Project state-of-the-art solar array activities involve the efforts associated with planning, acquiring, evaluating, and interfacing required by the Project/Program with regard to contemporary modules/arrays. These activities are performed by the following Project tasks: engineering, large scale production, quality assurance and reliability, and operations. The Engineering Task defines module/array design, performance, and test requirements in conjunction with appropriate personnel in and out of the Project. The Large Scale Production Task is responsible for the array procurement activities and the interfaces with the array manufacturers. The Quality Assurance and Reliability Task defines and verifies module/array hardware quality including inspection of the manufacturing activities. The Operations Task coordinates and controls module test planning, testing, performance analysis, and liaison with users. More details of these activities are provided in Part II under Project Management.

Contracts have been awarded to industry through competitive bidding processes for the production of large quantities of solar cell modules. A summary schedule is shown in Fig. 5-1; a plan for future procurements is given in Fig. 5-2. The contracts will be awarded on essentially an annual basis for

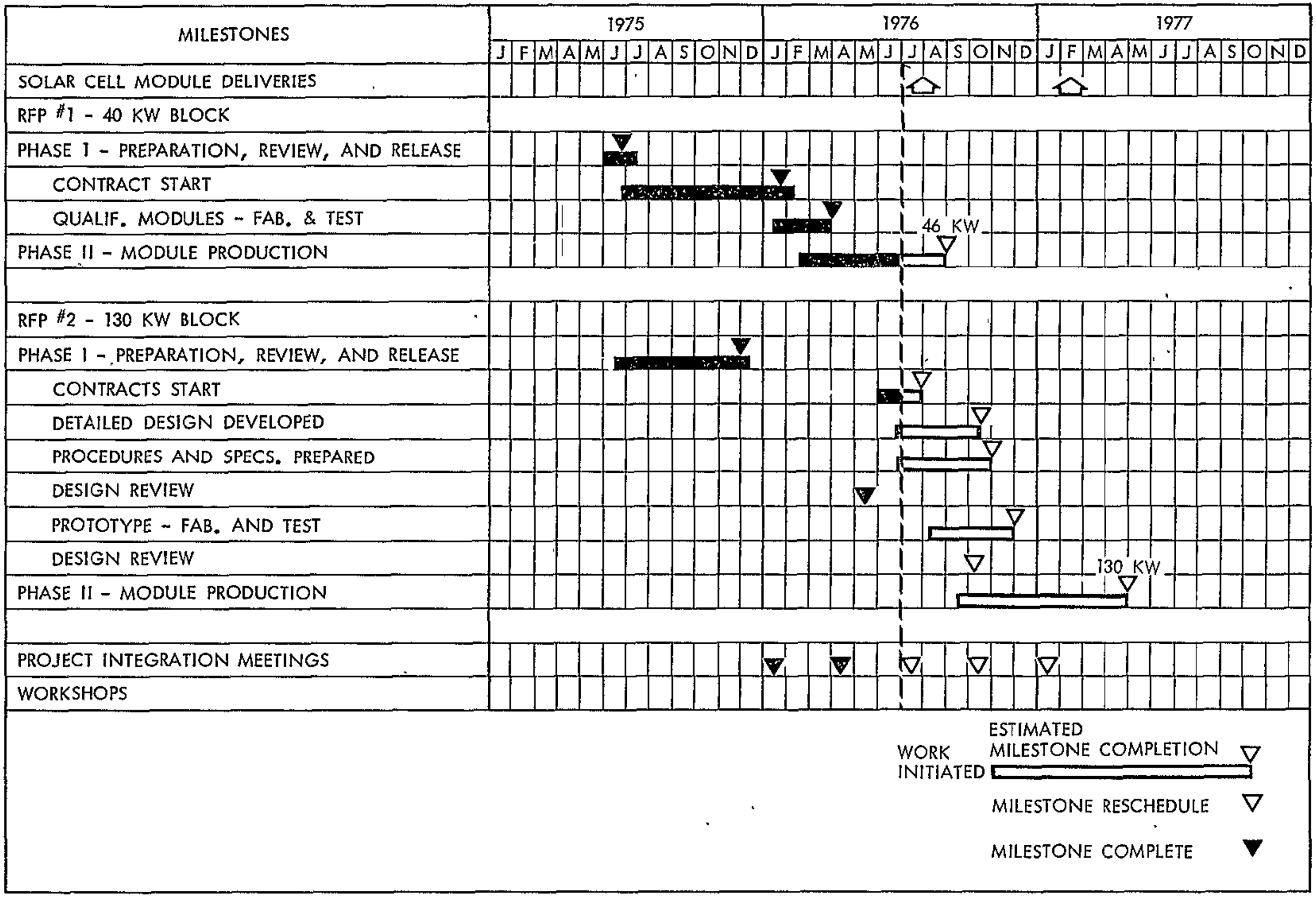


Fig. 5-1. Large-Scale Production Task schedule

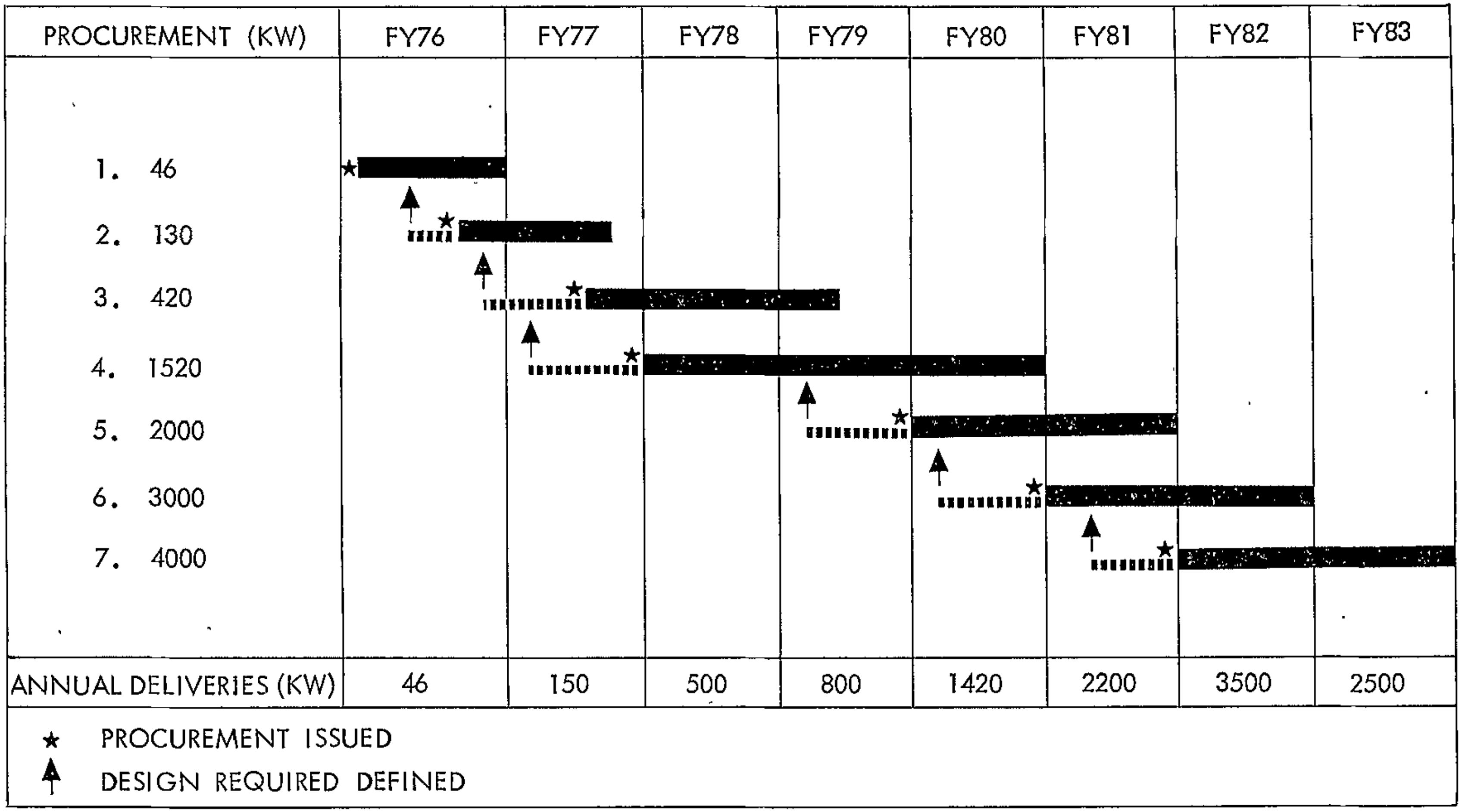


Fig. 5-2. Solar array procurement plan

progressively increasing quantities of hardware. Beginning with the 130-kilowatt procurement, small business concerns were solicited through a set-aside procedure. The initial modules produced will be used in applications requiring low power, such as for isolated installations of the Department of Defense. Future modules will be for systems testing of a photovoltaic power source tie-in to a commercial power grid.

The purchase of 130 kilowatts of solar arrays will incorporate changes to obtain a more uniform design, to provide greater flexibility in the demonstrations while encouraging further cost reductions. Participation in this procurement was more widely solicited and will involve the many companies presently preparing or extending manufacturing capability.

The RFP for the initial (46 kilowatt) procurement specified the temperature cycling and humidity requirements that the modules must meet. Qualifying the modules to these requirements is the responsibility of the supplier. At JPL, sample modules were subjected to these environments and their performance was evaluated. In addition, the modules were exposed to other environments they are likely to meet during the ERDA demonstration program. These are humidity-freezing, rain-heat, salt fog, and fungus. Also, samples were set up in racks at JPL as a field test in the Pasadena, California environment.

The 130-kilowatt procurement is not limited to state-of-the-art modules of existing design. A contract period for design upgrading is provided and design criteria are given. Module designs are specified that will fit into a 4 x 4-foot subarray. Other requirements of this purchase are:

1) A minimum of 60 watts of power based on the 4 x 4-foot array.
2) Fifty thermal cycles from -40 to +90°C.
3) Five temperature cycles at high relative humidity (RH).
4) One-hundred cyclical applications of structural loads.

A comparison between the procurement specifications for the 46 kilowatt purchase and those for the 130-kilowatt purchase is shown in Table 5-1.

Table 5-1. Key specifications for the LSSA 46-kilowatt and 130-kilowatt solar array purchases

Specification	46-Kilowatt Purchase	130-Kilowatt Purchase
Electrical Performance	100 milliwatts/cm^2, 28°C	100 milliwatts/cm^2, 60°C
Temperature Cycling	100 cycles, -40 to +90°C at less than 100°/hr	50 cycles, -40 to +90°C
Humidity	168 hours, 95% RH, 70°C	5 cycles, 95% RH, 23 to 41°C
Wind Loading	N/R	100 cycles, ± 50 lb/ft^2
Insulation Resistance	N/R	100 MΩ, 1000 vdc
High Voltage Breakdown	N/R	1500 vdc, 1 minute
Packaging Envelope	N/R	Envelope of 4 x 4 ft frame
Redundancy	N/R	Terminal and in some cases cell-to-cell redundancy

C. DPESA TECHNICAL ACTIVITY

1. Large-Scale Procurement Activity

Solar Power Corporation

Solar Power Corporation is under contract to deliver solar cell modules equivalent to 15 kilowatts of electrical power measured under standard conditions (100 mW/cm^2 and 28°C cell temperature). The Solar Power Corporation module, shown in Fig. 5-3, employs 1/8-inch G-10 glass laminate as the substrate for solar cell mounting. The 3 1/2-inch diameter solar cells are encapsulated in clear silicone and a thin, smooth, slightly harder coating is bonded to the encapsulant to make the module more resistant to the adherence

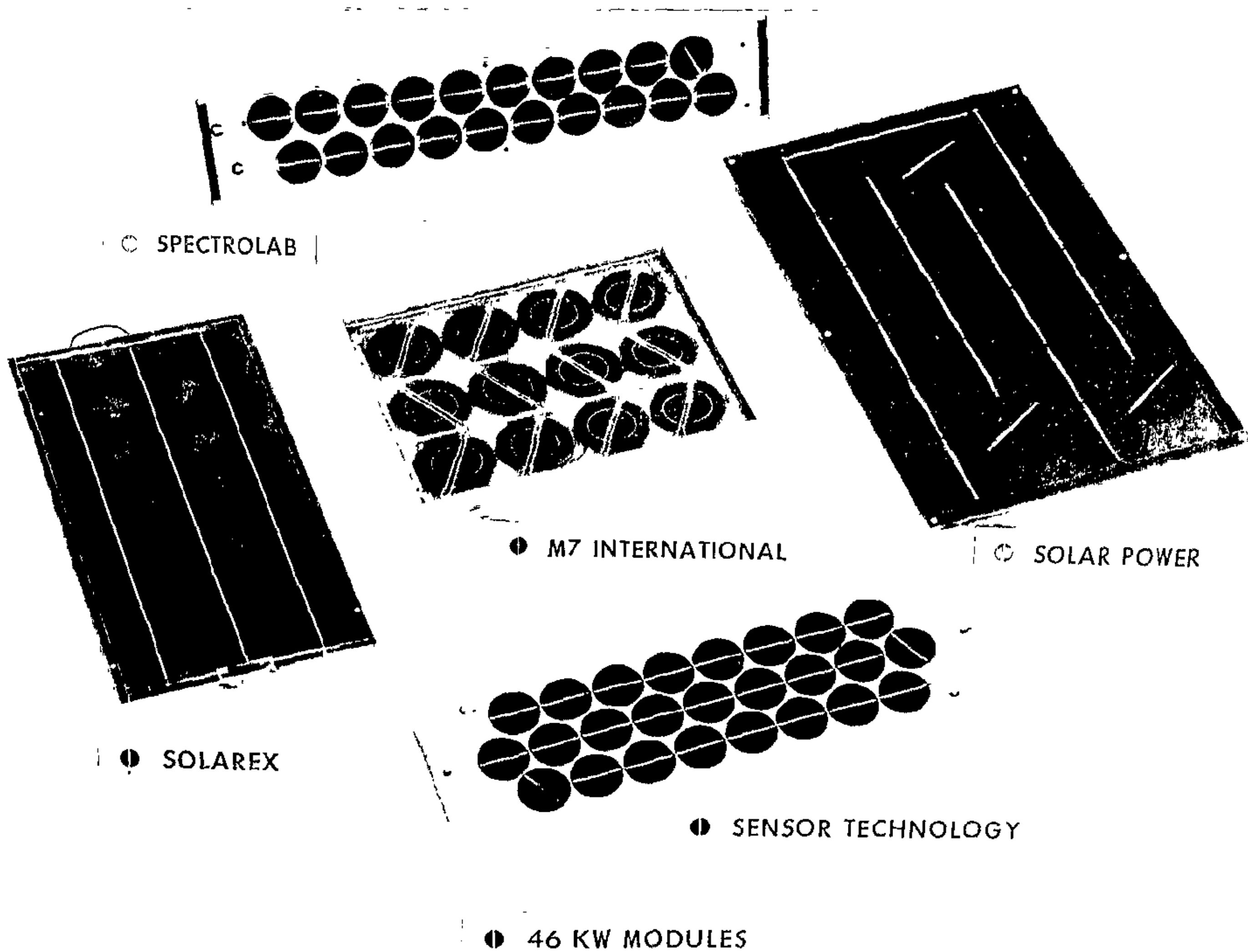


Fig. 5-3. Forty-six kilowatts of the above modules are being delivered by the indicated manufacturers for test and demonstration purposes

Table 5-2. Module description, 46-kilowatt procurement

Contractor	Total Pwr (kW)	Module Pwr (watts)	Cells in Series	Nominal Voltage @ Rated Pwr (volts)	Module Weight (lb)	Module Size (in.)	Module Area (in.^{2})	Conversion Efficiency* (%)
M7 Internatl.	3	5.0	24	9.2 to 10.0	3.46	12.875 x 16.250	209	3.7
Sensor Tech	8	5.5	25	9.2 min.	2.66	6.50 x 22.50	146	5.8
Solarex	10	9.2	18	7.0	2.20	10.25 x 20.00	205	7.0
Solar Power	15	15.0	22	9.2 min.	5.66	14.750 x 23.875	352	6.6
Spectrolab	10	5.0	20	9.2 to 10.0	3.28	4.88 x 26.12	128	6.1

*Conversion efficiency of the module at 100 milliwatts/cm^2 and 28°C cell temperature.

of dust and other contaminates. Additional details of the Solar Power module are shown in Table 5-2. During this report period a total of 390 modules having an equivalent electrical power of 5.64 kilowatts were fabricated.

Qualification testing of the modules at JPL revealed some strengths and some weaknesses in module design. It was noted that the sunlit surface of the modules could be cleaned easily because of the relatively hard, smooth outer coating and that the modules degraded only slightly as a result of humidity exposure. Thermal cycling, however, caused cracks to develop in the smooth outer coating. In subsequent tests, cracking of the coating became minimal when the modules were cycled at a reduced-temperature rate. Since environmental testing cannot exactly duplicate actual terrestrial conditions, a decision was made to produce two types of modules at Solar Power: (1) Modules with the smooth outer coating as described above and (2) modules without the coating, having only the silicon encapsulant exposed to the elements. It is anticipated that field testing of the two module types will indicate which is the better system.

M7 International

My International was awarded a contract to produce 3 kilowatts of solar cell modules. M7 took the approach for module design of using commercially available components, most of which were currently being used in terrestrial applications. The module is shown in Fig. 5-3. Basically, the module consists of 24 half-cells bonded to an acrylic sheet with a second acrylic sheet above the cells, but not in physical contact. An aluminum frame and rubber gasket secure the assembly. Other details of the M7 module are listed in Table 5-2.

Modules produced for qualification testing successfully passed the humidity environment but were not able to withstand the effects of the thermal cycling. After analyzing the problem, M7 proposed several modifications to improve their module design which would meet the requirements of the qualification tests. However, prior to completion of the module design changes, M7 reported technical difficulty in the solar cell production process. Evaluation of the cell production problem is continuing.

During the period ending June 30, a total of 42 modules representing 210 watts had been produced.

Solarex Corporation

Solarex Corporation has contracted to supply 10 kilowatts of solar cell modules. Details of the module design are shown in Table 5-2 and a photograph of the module is presented in Fig. 5-3. The module uses a fiberglass epoxy substrate and clear silicone encapsulant. Eighteen cells are connected in series to produce 9.2 watts at 7.0 volts. Electrical connections are made to color-coded teflon wires exiting from the module.

Qualification testing revealed that the modules were able to withstand the thermal cycling without degradation. It was also found that structural cycling simulating wind loading had little, if any effect on the module's electrical or mechanical integrity. Humidity testing indicated significant electrical degradation. A study of the solar cell contact by Solarex revealed that by adding palladium to the contacts, the solar cell, and thus the entire module could be made humidity resistant. The change to humidity-resistant modules took place in early May 1976. A total of 841 modules (7.73 kilowatts) were produced during this report period.

Sensor Technology, Inc.

Sensor Technology, Inc. with facilities in Chatsworth, CA, was awarded a contract to produce 8 kilowatts of solar cell modules. Sensor Tech uses a finned, aluminum substrate in their module design. Electrical isolation from the substrate is accomplished by the use of RTV-615 which also serves as the solar cell encapsulant. Additional details of the module design are listed in Table 5-2 and a photograph of the module is shown in Fig. 5-3.

There were no significant problems with Sensor Tech modules as related to thermal cycling and humidity testing. Testing in direct sunlight showed this module ran cooler than modules with glass laminate substrates. Prior to production, the intended encapsulant supply became unavailable and an equivalent substitute encapsulant (RTV-615) was used as a replacement.

Production rates increased from about 30 modules per week to approximately 100 modules per week over this report period. Module production by the end of June had totaled 578 modules, equivalent to 2.9 kilowatts.

Spectrolab, Inc.

Spectrolab, Inc. is contracted to deliver 2000 5-watt solar cell modules or the equivalent of 10 kilowatts of electric power. The Spectrolab module design consists of an aluminum "T" angle substrate as shown in Fig. 5-3. Twenty 2-inch-diameter solar cells are connected in series and encapsulated in clear silicone which also serves as electrical isolation from the substrate. A glass sheet is bonded to the encapsulant and becomes the top surface of the module. Electrical terminals are provided beneath the solar cell substrate. Additional module details are given in Table 5-2.

The Spectrolab module design proved to be easy to clean and operated in direct sunlight at a lower temperature than other modules with glass laminate substrates. Some problems with cell cracking and interconnect fatigue fracture in thermal cycling tests were evident on early design modules. Module redesign eliminated these problems and production was initiated in May 1976. Humidity testing revealed that the modules were somewhat susceptible to long-term electrical degradation because of humidity penetration to the cell contacts. By the end of June, Spectrolab had produced a total of 219 modules having a power output of 1.1 kilowatts.

2. Engineering Activities

Engineering accomplishments during the past quarter have centered in three areas: (1) continued analysis and testing of solar array modules in support of the generation of array requirements, (2) support to the large-scale procurement task in the evaluation of the modules of the 46-kilowatt purchase and the proposals of the 130-kilowatt purchase, and (3) initiation of work on a limited, but highly accessible field test site at JPL to allow continuous observation and improved instrumentation of selected solar cell module field performance experiments. Specific analysis and test activities have included work on array mechanical configurations, module electrical performance, module and solar array electrical interconnection, module thermal design, and structural design.

Array configuration investigations have been conducted to evaluate the affect of module size on both module cost and support structure cost. Parametric analyses were conducted using 2 x 2, 2 x 4, 4 x 4, and 4 x 8 foot modules of five different constructions typical of present and proposed module designs. The structural parameters of each module were sized for the same structural design load of 50 lb/ft^2. The materials cost of each module was then calculated in terms of dollars per square foot of active cell area. The materials cost of the modules was found to be almost independent of module size, with larger modules having the higher cost (less than 10% higher). It is concluded that larger modules will be slightly less expensive per watt than smaller modules because of decreased assembly and installation costs. However, the cost of materials is essentially insensitive to module size.

A similar analysis was conducted to evaluate the sensitivity of the support structure cost to the size of the modules to be supported. The results indicate that the support structure cost is also essentially insensitive to the support point spacing, but is quite sensitive to distance off the ground and to the overall height of the array. The higher the array, the higher the cost per square foot of array area. The optimum height is a function of the relative cost of foundations to above-ground-truss-structure, and is the subject of continuing investigation.

Electrical terminations fabricated and procured during the previous quarter have been subjected to a matrix of environmental tests to evaluate their suitability for use on terrestrial solar cell modules. Testing included electrical insulation measurements before and after a series of ozone, salt spray, temperature cycling, humidity, ultraviolet, and high temperature tests. The tests included various types of bare contacts as well as several types of two and three conductor automotive type connectors. At least one developmental automotive connector shows considerable promise for use as a solar-cell-module or solar-array connector. Final evaluation of the test results is under way and documentation should be completed during next quarter.

Structural loading tests of each of the module types of the 46-kilowatt purchase have been nearly completed using the uniform cyclic loading fixture developed last quarter (Fig. 5-4). These tests indicate that all of the module designs of this purchase, except for possibly one, are capable of surviving in excess of 10, 000 cycles of structural loading from +50 to -50 lb/ft^2 while supported only at their attachment points. Even thin fiberglass modules designed for continuous rear support, worked satisfactorily with only three line supports as shown in Fig. 5-5. Interconnect fatigue failures were observed in one module type and are the subject of continued investigation. Documentation of the structural tests is planned for next quarter.

Expanded thermal testing of the modules of the 46-kilowatt purchase has also taken place during the past quarter. Special thermal test fixtures were fabricated to support the modules in a manner similar to the near-term ERDA and DOD demonstrations (Fig. 5-6). Thermocouples were embedded in each

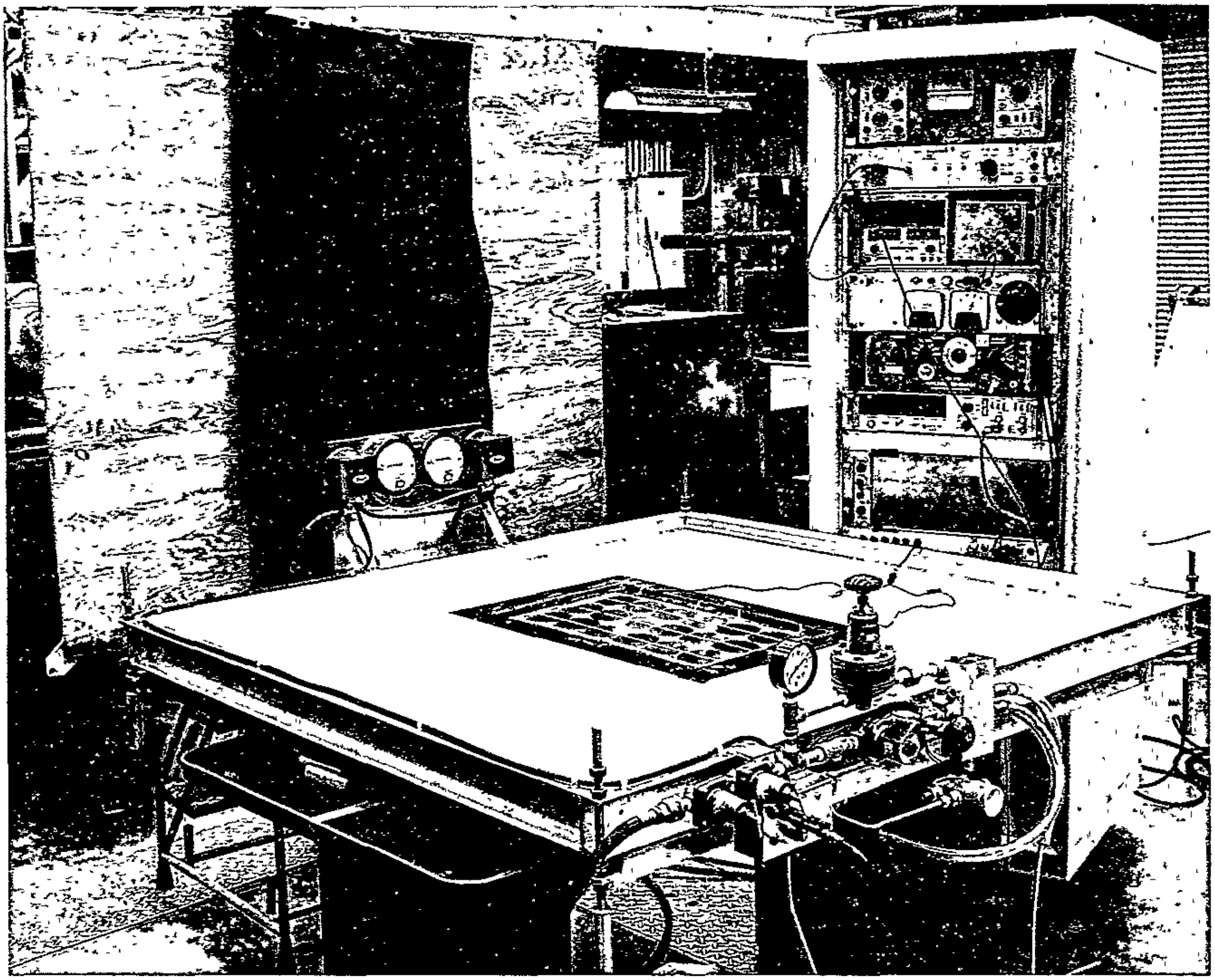


Fig. 5-4. Uniform cyclic loading fixture for module structural testing

module type to measure cell temperature directly. Others were placed to measure exterior temperatures and the temperatures of calibration surfaces with known thermal properties. The latter are being used to determine the effect of wind conditions and to allow the generation of accurate thermal models of each module type. Preliminary thermal results are indicated in Fig. 5-7. Note that the hottest module design runs nearly 30°C hotter than the coolest under typical open back conditions. Final evaluation of the test results is under way with documentation expected next quarter.

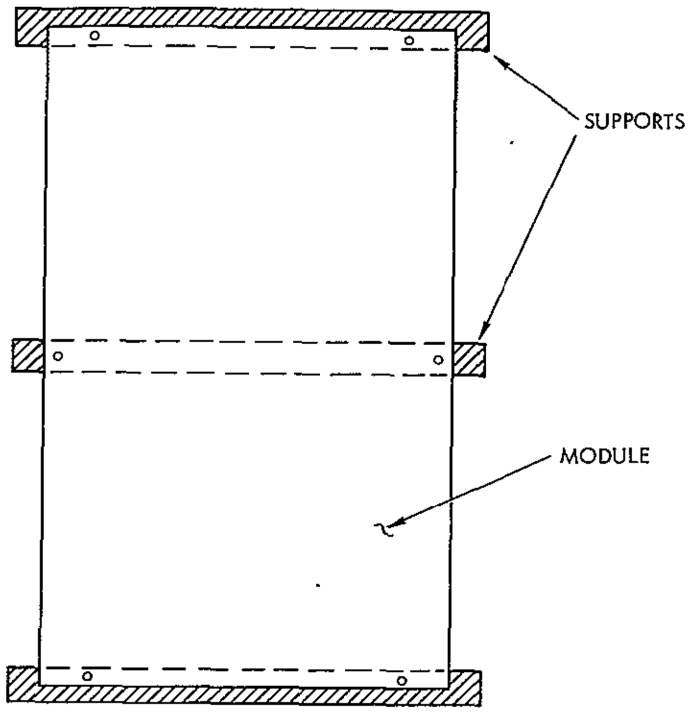


Fig. 5-5. Module support for structural cyclic loading test of fiberglass modules

Discussions with module manufacturers and potential and past photovoltaic users also provide valuable information which is incorporated into solar array requirements. A number of visits were made during the past quarter to commercial users of photovoltaic power supplies. These applications include military field electronics, navigational aids on buoys and oil platforms, pipeline and well corrosion protection systems, and various types of remote climatological and environmental instrumentation. These visits have provided valuable insight into the operational, environmental, and competitive market conditions surrounding the use and procurement of present solar array systems.

In addition to the JPL in-house investigations described above, close liaison is maintained with the NASA Lewis Research Center demonstration activities, the Sandia Laboratories system analysis activities, and DOD

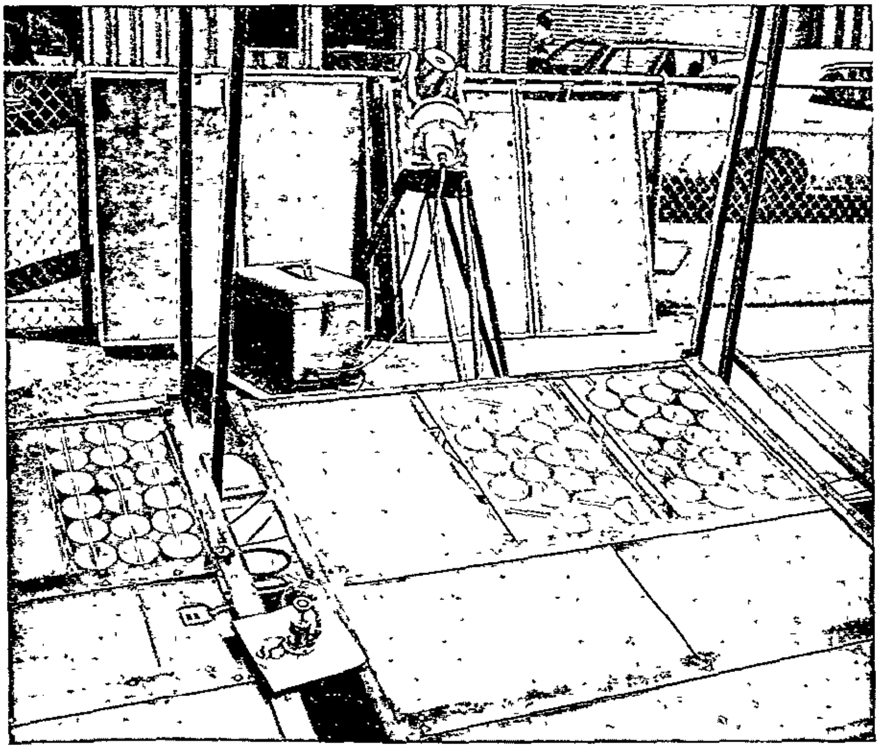


Fig. 5-6. Thermal testing of modules of the 46-kilowatt purchase

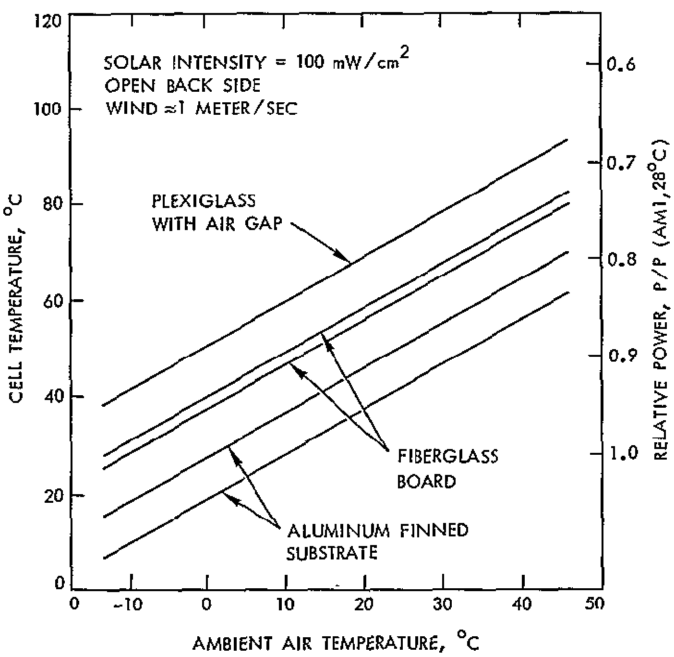


Fig. 5-7. Typical operating temperatures of modules of the 46-kilowatt purchase

demonstration activities. Design requirements emanating from these studies are incorporated into the solar array requirements activity on a continuous basis.

3. Operations Activities

In early May, the coordination and control of module testing, performance analysis, and delivery to users was placed under the cognizance of an Operations Manager. This reorganization resulted from the need to identify and understand design defects so that module performance can be improved and includes the following activities:

1) Liaison between JPL and module users on matters regarding delivery, interface compatibility, and field performance of modules.
2) Implementation of acceptance and life testing at JPL for representative samplings of modules.
3) Acquisition, interpretation, and reporting of module performance data from environmental testing and field service.
4) Module failure analysis and implementation of a problem/failure reporting system.
5) Management of traceability and configuration control systems for modules.

Close contact with LeRC has been maintained during this quarter, primarily by telephone, to keep LeRC advised on project developments affecting their Test and Demonstration Project and to follow up on items of mutual concern. Beginning May 20, a weekly TWX from JPL to LeRC has been transmitted which provides the latest information regarding the 46-kilowatt module procurement status and other information of current interest. The TWX typically contains module shipment data for a three-week period (past week's actuals; current and next week's projections). These measures appear to have improved JPL/LeRC coordination of operational matters.

Environmental qualification (or acceptance) tests were completed on sets of modules from all manufacturers. In all, humidity tests on 84 modules and temperature cycling tests on 93 modules have been completed to date, most of them during this quarter.

During the initial humidity and temperature testing, all manufacturers' modules experienced some physical and functional degradation. The types of degradation, indicated corrective action, and distribution by manufacturer are summarized in Table 5-3. Requalification of the modules was performed successfully.

During May and June, plans were firmed up for the proposed field test sites at the JPL Pasadena (urban), Goldstone (high desert), and Table Mountain (alpine) facilities. Visits were made to the Goldstone and Table Mountain sites, which are about 170 and 100 miles northeast of Pasadena, respectively, and are completely contained within JPL-access-controlled areas. Layouts for the test sites have been completed, and a prototype test stand has been designed and ordered. The layout of the 4 x 8 foot test frames at Pasadena is shown in Fig. 5-8. The remote sites will each have a total test capacity of one-quarter to one-third that of the main site in Pasadena. The purpose of these small-scale field test activities is to complement the JPL environmental tests and LeRC field tests, to provide outdoor test facilities for quick turnaround special purpose testing, and to develop techniques and experience in on-site evaluation of module performance.

In early June, guidelines were issued for the initiation and processing of Problem/Failure Reports (P/FR's) for in-test or in-service modules. The P/FR format was reworked to facilitate processing and to conform to Project requirements. The purpose of the problem/failure reporting and analysis system at JPL is to focus the talents of qualified specialists on observed problems and failures in order to determine their causes and remedies, and to make these findings known to the module manufacturers in order to improve the quality and reliability of their product. Efforts are under way to formally review, document, and follow up on those problems and failures which have occurred to date during environmental testing.

Table 5-3. Test results summary

Test	Degradation	Remedy	Occurrences — by Manufacturer				
			A	B	C	D	E
Thermal Cycle	Encapsulant delamination and cracking	Improved cleaning; primers; improved quality control		X	X	X	X
	Cell cracking	Increased bond thickness under cell	X		X		X
	Structural fatique of interconnects	Stress relief loops added; less solder used	X	X			X
	Electrical terminal cracking and delamination	Rework	X	X			X
Humidity	Cell contact degradation (30% power loss)	Palladium in contact; improved sealing			X		X
	Structural bond delamination	New adhesives		X			

A review of Project requirements for module status and history reporting and for module test results reporting has resulted in revised "flash report" formats for these two areas. Data for the 46-kilowatt block procurement are being compiled for the first issues of these reports. Subsequent reports will be distributed as the level of activity dictates, but not less than once a month.

4. Quality Assurance Activities

During this report period, the JPL Quality Assurance activities were primarily concerned with modules received at JPL. These modules were inspected "as received" from the five contractors and again inspected after

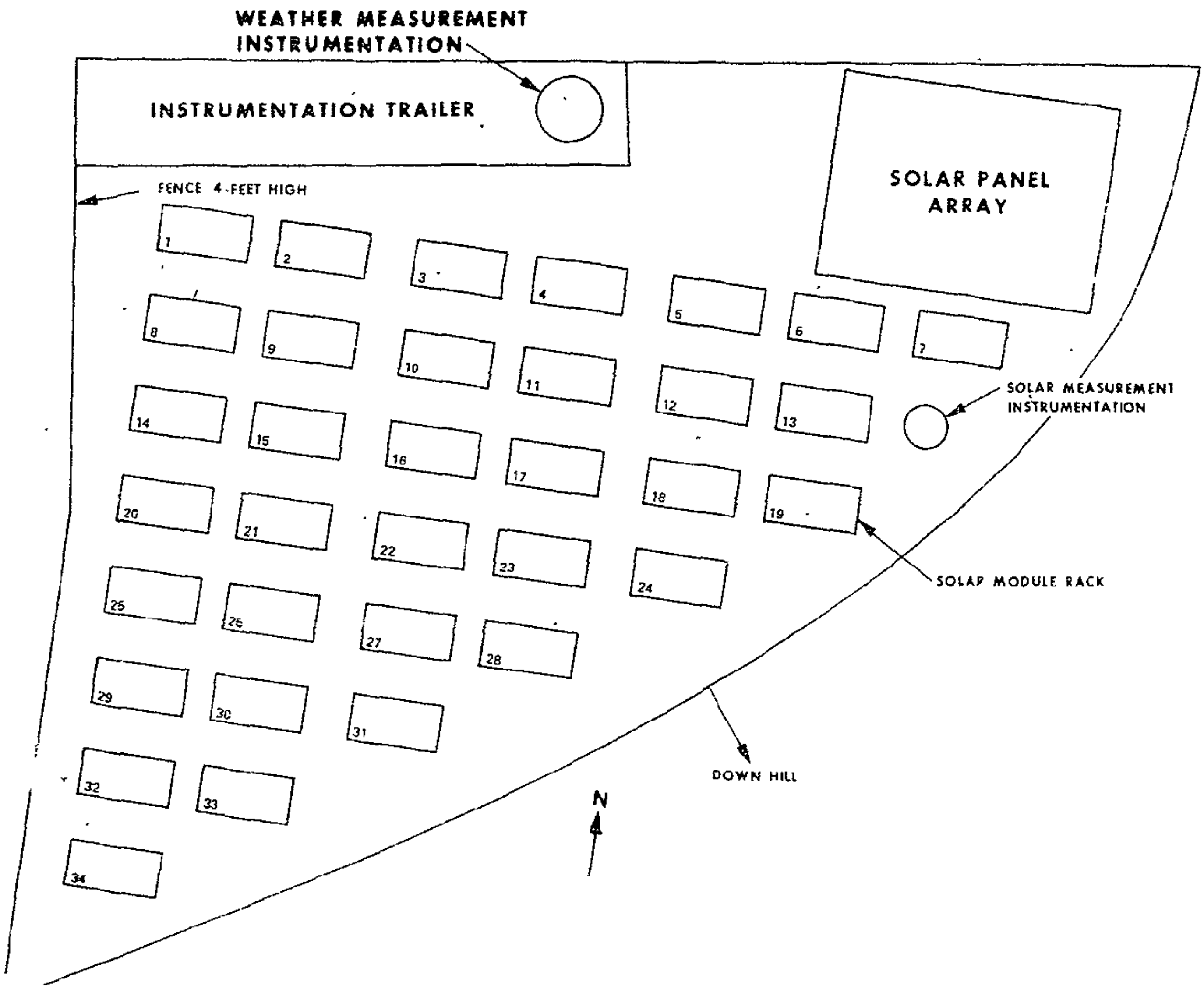


Fig. 5-8. Layout of JPL solar module field test site at Pasadena

each environmental exposure. Modules were rejected which failed to meet contractual requirements. A significant number of defects were recorded; e.g., dimensional discrepancies, air bubbles in encapsulants, and surface contamination.

JPL inspection instructions and methods were developed to permit maximum utilization of JPL manpower and equipment, both at the contractor's facilities and JPL.

Source inspection is now proceeding at the five contractors. Visits to each contractor were conducted with emphasis on contractors having the most significant problems. All but one contractor has voluntarily eased their restrictions regarding JPL Quality Assurance involvement at their facilities. Each contractor now looks forward to JPL's inspection results. Contractors when apprised of contractual workmanship problems on their respective modules now agree and remove them from the shipping lot. In general, contractor and JPL source inspection relationships no longer seem to be a problem.

NASA—JPL—Coml., L.A., Calif