5101-221
Flat-Plate Solar
Array Project

DOE/JPL-1012-76
Distribution Category UC-63b

Summary of Flat-Plate Solar Array Project Documentation

Abstracts of Published Documents, 1975 to June 1982

September 15, 1982

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration

by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL Publication 82-79)

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

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

This publication reports on work done under NASA Task RD-152, Amendment 66, DOE/NASA IAA No. DE-AI01-76ET20356.

SUMMARY

This document contains abstracts of final reports and latest quarterly reports of JPL and contracted efforts that have constituted The JPL Flat-Plate Solar Array (FSA) Project (formerly the Low-Cost Solar Array (LSA) Project).

This work has been conducted under a contract with the U.S. Department of Energy (DOE) as a part of the National Photovoltaics Program. The aim of this program is to stimulate the development of technology that will enable the private sector to manufacture and widely use photovoltaic systems for the generation of electricity in residential, commercial, industrial, and government applications at a cost per watt that is competitive with other means.

FSA Project activities have included the sponsoring of research and development efforts in silicon refinement processes, advanced silicon sheet growth techniques, solar cell development, encapsulation, automated fabrication process technology, advanced module/array design, and module/array test and evaluation techniques.

Due to the large number of documents involved, it is possible that some publications may have been overlooked. It is the intent of the Project to revise and update this document periodically and omissions called to our attention will be included at that time.

To obtain a full report on any of the contracts herein, order as follows:

Abstracts without DOE/JPL numbers can be obtained from

Jet Propulsion Laboratory
Solar Data Center, M.S. 502-422
4800 Oak Grove Dr.
Pasadena CA 91109

Abstracts with ERDA/JPL or DOE/JPL numbers can be obtained from

National Technical Information Service
5285 Port Royal Rd.
Springfield VA 22161

or

U. S. Department of Energy
Technical Information Center
Publication Request Section
P. O. Box 62
Oak Ridge TN 37830

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Contents

Project Office

TITLE: Energy Research and Development Agency Low-Cost Silicon Solar Array Project. Proceedings of the First Task Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1976

REPORT NO: ERDA/JPL-1012-76/1 - 5101-2

ABSTRACT: The Low-Cost Silicon Solar Array (LSSA) Project convened the first LSSA Task Integration Meeting at JPL on January 13, 14 and 15, 1976. The primary objectives of this first Task Integration Meeting were: To provide an overview of LSSA Project technical plans, progress, and problems for all Project participants; and to further identify and establish the technical interfaces within and between LSSA Project tasks.

A two-day working meeting was attended by technical representatives from all contractor organizations that are working on or will soon be working on the LSSA Project, ERDA Program Managers and representatives from ERDA/San Francisco Field Office, NASA Hq., NASA/LeRC, and Aerospace. On January 13, presentations were given by JPL Project personnel and by 23 contractor representatives covering all technical aspects of the Project technology development effort (four tasks: silicon material, large area silicon sheet, encapsulation, and array automated assembly). On the second day, each task of the five tasks convened separately and discussed plans, progress, interface requirements, and task problems. A LSSA Project review was held by Project, ERDA Program, and NASA headquarters personnel on the third day during which the results of the Task Integration Meeting were discussed.

The purpose of this document is to disseminate, as quickly as possible, the material that was presented at the meeting. This includes summaries of the second day task sessions as presented by each task manager during the review. The document consists of the vugraphs used in the presentations, a brief summary from each contractor, and a brief summary of the meeting.

The first LSSA Project Quarterly Report, to be published shortly, will supplement the proceedings. It will describe the Project plans and accomplishments with an emphasis on the technical accomplishments. The quarterly report will be sent to all people receiving this document.

TITLE: Energy Research and Development Agency Low-Cost Silicon Solar Array Project. Proceedings of the Second Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1976

REPORT NO: ERDA/JPL-1012-76/4 - 5101-5

ABSTRACT: The Low-Cost Silicon Solar Array (LSSA) Project convened its second Project Integration Meeting (the first meeting was called Task Integration Meeting) at the California Institute of Technology campus in Pasadena, California, on April 27-28, 1976. (An ERDA/JPL in-house review and critique of the previous two-day session was held on April 29.) The primary objectives of this meeting were to integrate the LSSA Project technical plans and activities, to further identify and establish the technical interfaces, and to provide an overview of Project technical plans and status.

The two-day working meeting was attended by technical representatives from all contractor organizations associated with the LSSA Project, the ERDA Program Manager, representatives from ERDA/Sandia and NASA/LeRc, a number of advisors, and JPL Project personnel.

On the morning of April 27, formal presentations were given by programs and project personnel to all attendees. That afternoon and the morning of April 28 were devoted to intratask and intertask sessions. On the second afternoon, status presentations were made by LeRC and Sandia representatives, followed by summary reports by each Task Manager stating the meeting results of their respective task sessions.

The purpose of this document is to disseminate the material that was presented at the meeting, including summaries of the second day task sessions as presented by each task manager. The document includes vugraphs used in the presentations, technical progress summaries from the contractor; and a brief summary of the meeting.

TITLE: Low-Cost Silicon Solar Array Project. Third Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: July 1976

REPORT NO: ERDA/JPL-1012-76/7 - 5101-8

ABSTRACT: The Third Project Integration Meeting (PIM) of the Low-Cost Silicon Solar Array (LSSA) Project was conducted July 28 and 29, 1976, at the California Institute of Technology; some technology-development task meetings were held during the preceding two days as well.

The PIM began with a general introductory session, in which the current status of the ERDA Photovoltaic Program, the LSSA Project, other Program elements, recent solar-cell module test experience at JPL, cost analysis methods developed by the Battelle contract with the Encapsulation Task were briefly reviewed. These are summarized in Section II of these proceedings.

Next, the participants were divided, and in each of two periods three Intratask or Intertask sessions were conducted. The Silicon Material Task (1) held an Intratask session and participated in an Intratask session with the Large Area Silicon Sheet Task (2). Task 2 had an Intratask Meeting prior to the PIM, and participated in Intertask sessions with Task 1 (above) and with Encapsulation (Task 3) and Automated Array Assembly (Task 4). Task 3 also held pre-PIM Intratask Meetings, and participated in the 2-3-4 session. Large Scale Production, Operations, and Engineering held one Intertask session among themselves and another with Task 3. These are summarized, sometimes from the perspective of more than one participating Task, in Section III.

Finally there was a concluding general session, which included statements of summary status, conclusions, and action items by the Task 1-5 Managers and the Project and Program Managers. The Task Summaries are included in Section III; the Management conclusions and action items are given in Section I.

TITLE: First Annual Report, January 1975--March 1976.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 9 August 1976

REPORT NO: ERDA/JPL-1012-76/5 and 5101-3

ABSTRACT: The Low-Cost Silicon Solar Array Project (LSSA) was established to greatly reduce the price of solar arrays by the improvement of manufacturing technology, by adaptation of mass production techniques, and by helping achievement of user acceptance. The project's approach included the development of technology, its transfer by industry to commercial practice, the evaluation of the economics involved, and the stimulation of market growth. The activities and progress of the LSSA Project during its first year are described in this document which covers all project activities, with primary emphasis on the technical plans and accomplishments. The development of manufacturing technology is now and will continue to be performed principally by industries and universities. To date, 24 contractors are working on new silicon-refinement processes, silicon-sheet-growth techniques, encapsulants, and automated-assembly studies. Nine more contractors have been selected to perform additional technology investigations and their contracts are being negotiated. Additional Contracts will be issued in the future as promising ideas appear.

TITLE:	Quarterly Report, April 1976--June 1976
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	October 1976
REPORT NO:	ERDA/JPL-1012-76/6 and 5101-7

ABSTRACT:

Activities and progress of the LSSA Project during April, May, and June 1976 are described. This involved the awarding of additional contracts, an evaluation and clarification of plans and working relationships with contractors, 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. 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. 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. (WDM)

TITLE: Low-Cost Silicon Solar Array Project Quarterly Report-2, July 1976--September 1976.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 1976

REPORT NO: ERDA/JPL-1012-77/1 and 5101-10

ABSTRACT: 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 (LCSSAP) 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.

TITLE: LSSA Project Quarterly Report 3, October 1976-December 1976

CORPORATE AUTHOR: Jet Propulsion Laboratory

DATE: 1976

REPORT NO: ERDA/JPL-1012-77/2 and 5101-24

ABSTRACT: 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-competetive photovoltaic systems. As part of the ERDA program, the Low-cost Silicon Solar Array Project (LSSA) was established in January 1975. The activities and progress of the LSSA Project during the months of October, November, and December 1976 are described. The Project objective is to develop the National capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year and a price of less than $500 per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years. 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. Forty-seven contracts have been awarded to date, to industrial firms and university and independent laboratories for experimental work, process development and analysis, technology assessment, and the production of solar-array modules. Approximately 58 kW of state-of-the-art modules have been delivered; design development is under way for a second block of moderately advanced modules, and planning for subsequent module procurements has begun.

TITLE: Low Cost Solar Array Project Report. 5th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1977

REPORT NO: 5101-18

ABSTRACTS

The Fifth Project Integration Meeting (PIM) was held January 17 and 18, 1977 at the San Diego Hilton Hotel, held in sequence with the ERDA Semiannual National Solar Photovoltaic Review.

The objectives of the Fifth PIM were to integrate the LSSA Project technical plans and activities, to assess Project activities in the areas of higher efficiencies, costs, economics, and manufacturing; to exchange technical data at the working level and provide an overview of LSSA Project technical plans and status.

The two major topics covered were cost versus efficiency and manufacturing processes for solar cells and solar arrays.

TITLE:	LSSA Low-Cost Silicon Solar Array Project. Project Quarterly Report - 4 for the period January 1977 - March 1977
CORPORATE AUTH:	Jet Propulsion Laboratory
REPORT NO:	DOE/JPL-1012-77/3 - 5101-32

ABSTRACT:

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

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

TITLE: Low Cost Sc.ar Array Project Report. 6th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: May 4-5, 1977

REPORT NO: 5101-29

ABSTRACTS

The Sixth LSSA Project Integration Meeting (PIM) was held May 4 and 5, 1977, on the campus of the California Institute of Technology. Invitation controlled attendance included Project participants form JPL and all LSSA Contractors, together with representatives of the ERDA Program Office and many agencies participating in the Program, as will as the new Director of the Solar Energy Research Institute and special invitees.

The general objectives of the PIM were to integrate the LSSA Project technical plans and activities, with specific emphasis on a review of ingot technology relative to meeting Project goals of $2/watt (1982) and $0.55/watt (1986); to discuss and strengthen the technical interfaces within the LSSA Project tasks and between the LSSA Project and other ERDA Photovoltaic Program elements; to exchange technical data, and to provide an overview of LSSA Project technical plans and status.

A special review of ingot technology in the light of interim cost goals was conducted at this meeting, as well as the normal task-level reviews, inter-task sessions, and general discussions.

TITLE: Low-Cost Silicon Solar Array Project. Project Quarterly Report 5, April 1977--June 1977.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 1977

REPORT NO: DOE/JPL-1012-77/4 and 5101-46

ABSTRACT: The activities of the Low-Cost Silicon Solar Array Project during the period April through June 1977, are described. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power systems early in the next decade. Set forth here are the goals and plans with which the project intends to accomplish this, and the progress that was made during the quarter. The project objective is to develop the national capability to produce low-cost, long-life photovoltaic arrays at a rate graater than 500 megawatts per year and a price of less than $500 (in 1975 dollars) per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years. The LSSA Project contractors and their technology areas are tabulated and discussed.

TITLE: LSA Project Quarterly Report No. 6, July - September 1977

CORPORATE AUTHOR: Jet Propulsion Laboratory

DATE: 1977

REPORT NO: DOE/JPL-1012-78/2 and 5101-55

ABSTRACT: The activities of the Low-Cost Solar Array Project during the period July through September 1977 are described. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this, and the progress that was made during the quarter. The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year at a price of less than $500 per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

TITLE: Low Cost Solar Array Project Report. 7th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: August 10-11, 1977

REPORT NO: 5101-37

ABSTRACTS

The Seventh LSSA Project Integration Meeting (PIM) was held August 10 and 11, 1977, on the campus of the California Institute of Technology. Invitation-controlled attendance included Project participants from JPL and all LSSA contractors, together with representatives of the ERDA Solar Program Office and many other agencies participating in the Program.

The objectives of this PIM were to review recent technical advances in light of the 1982 and 1986 goals; to orient the participants in this somewhat new state of the art in order to maintain direction toward the requirements of the 1982 and 1986 goals; to discuss and strengthen technical interfaces within and among LSSA Project elements and between the LSSA Project and other ERDA Photovoltaic Program elements, and to exchange technical data and to invite challenges to this data that may only effectively occur during face-to-face meetings.

A special review of progress relative to the 1982 goal of \$2/watt was conducted at this meeting, as well as task-level reviews, inter-task sessions, and general discussions.

TITLE: LSA Quarterly Project Report No. 7 For the Period October 1977 - December 1977

CORPORATE AUTHOR: Jet Propulsion Laboratory

DATE: October 1977

REPORT NO: DOE/JOL/1012-78/13 and 5101-81

ABSTRACT: This report describes the activities of the Low-cost Silicon Solar Array Project during the period October through December 1977. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish national capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year and a price of less than $500 per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

TITLE: Low Cost Solar Array Project. Prodeedings: 8th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 7-8, 1977

REPORT NO: 5101-52

ABSTRACTS The 8th LSA Project Integration Meeting (PIM) was held December 7 and 8, 1977, on the campus of the California Institute of Technology. Invitation-controlled attendance included Project participants from JPL and all LSA contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the Program.

The following highlights were noted at this PIM:

1. Technology developments required for the production of $2/W modules.

2. Silicon sheet progress.

3. Solar Array Manufacturing Industry Costing Standards (SAMICS).

4. Field performance of Block I and II modules.

5. Environmental tests for uncovering potential failures modes for modules installed in the field.

6. Elimination or control of the photon-induced instability phenomenon.

TITLE:	Project Quarterly Report - 8 for the period January 1978 - March 1978.
CORPORATE AUTH:	Jet Propulsion Laboratory
REPORT NO:	DOE/JPL-1012-2 - 5101-88
ABSTRACT:	This report describes progress made by the Low-Cost Silicon Solar Array Project during the period January through March 1978. It includes task reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, Project engineering and operations, and manufacturing techniques, plus the steps taken to integrate these efforts.

TITLE: PROCEEDINGS: 9th Project Integration Meeting

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 1978

REPORT NO: JPL 5101-67

ABSTRACT: Invitation-controlled attendance at the meeting included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the photovoltaic program. The status of the JPL Low-Cost Solar Array Project is described in detail. The report includes the following sections: (1) Project Analysis and Integration, (2) Technology Development Area (Silicon Material Task, Large Area Silicon Sheet Task, and Encapsulation Task), (3) Production Process and Equipment Area, (4) Engineering Area, and (5) Operations Area.

TITLE: LSA Project Quarterly Report No. 9, April-June 1978

CORPORATE AUTHOR: Jet Propulsion Laboratory

DATE: 1978

REPORT NO: DOE/JPL-1012-3 and 5101-99

ABSTRACT: Progress made by the Low-cost Solar Array Project during the period April through June 1978 is described. It includes reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, project engineering and operations activities, and manufacturing techniques, plus the steps taken to integrate these efforts.

TITLE: Project Quarterly Report - 10 for the period July 1978 - September 1978

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-4 - 5101-100

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

TITLE:	Low Cost Solar Array Project. Prodeedings: 10th Project Integration Meeting.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	August 16-17, 1978
REPORT NO:	5101-86
ABSTRACTS	The 10th LSA Project Integration Meeting (PIM) was held August 16 and 17, 1978, on the campus of the California Institute of Technology. Invitation-controlled attendance included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the Photovoltaic Program. A Metallization Workshop was held on Tuesday, August 15. Presentations were made on recent work in established technologies such as plated and thick film techniques and on novel methods.

TITLE: Quarterly Report - 11 for the period October 1978 - December 1978 and Proceedings of the 11th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-26 and 5101-109

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period October through December 1978. It includes task reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, Project engineering and operations, and manufacturing techniques, plus the steps taken to integrate these efforts. It also includes a report on and copies of viewgraphs presented at the Project Integration Meeting held December 13-14, 1978.

TITLE: LSA Progress Report 12, January - April 1979 and Proceedings of the 12th Project Integration Meeting

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 1979

REPORT NO: DOE/JPL/1012-27 and 5101-112

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period January through April 1979. It includes reports on Project Analysis and Integration; Technology Development in Silicon Material, Large-Area Sheet Silicon, and Encapsulation; Production Process and Equipment Development; Engineering and Operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at the Project Integration Meeting held April 4-5, 1979.

TITLE: Progress Report 13 for the Period April 1979 thru August and Proceedings of the 13th Project Integration Meeting

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-29 and 5101-133

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period April through August 1979. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at, the Project Integration Meeting held August 22-23, 1979.

TITLE: Progress Report 14 for the period August 1979 to December 1979 and Proceedings of the 14th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-42 ad 5101-142

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period August through November, 1979. It includes reports on project analysis and integration; technology development in silicon material, large-area sheet silicon, and encapsulation; production process and equipment development; engineering, and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of the visual materials presented at, the Project Integration Meeting held December 5-6, 1979.

TITLE: Progress Report 15 for the period December 1979 to April 1980 and Proceedings of the 15th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-44 and 5101-151

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period December 1979 to April 1980. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held April 2 and 3, 1980.

TITLE:	Progress Report 16 for the Period April to September 1980 and Proceedings of the 16th Project Integration Meeting.
CORPORATE AUTH:	Jet Propulsion Laboratory
REPORT NO:	DOE/JPL-1012-51 and 5101-160
ABSTRACT:	This report describes progress made by the Low-Cost Solar Array Project during the period April to September 1980. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held September 24 and 25, 1980.

TITLE: Progress Report 17 for the Period September 1980 to February 1981 and Proceedings of the 17th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-54 and 5101-172

ABSTRACT: This report describes progress made by the Low-Cost Solar Array Project during the period September 1980 to February 1981. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held at Pasadena, Calif, on February 4 and 5, 1981.

TITLE:	Progress Report 18 for the Period February to July 1981 and Proceedings of the 18th Project Integration Meeting
CORPORATE AUTH:	Jet Propulsion Laboratory
REPORT NO:	DOE/JPL-1012-58 - 5101-186
ABSTRACT:	This report describes progress made by the Low-Cost Solar Array Project during the period February to July 1981. It includes reports on project analysis and integration; technology development in silicon material, large-area silicon sheet and encapsulation; process development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the Project Integration Meeting held at Pasadena, California, on July 15 and 16, 1981.

TITLE:	Electricity from Photovoltaic Solar Cells Low-Cost Solar Array Project. Displayed at the 15th IEEE Photovoltaic Specialists Conference, May 1981 Revised for Project Integration Meeting.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	July 1981
REPORT NO:	5101-178C
ABSTRACT:	This is a copy of all display material.

TITLE: Progress Report 19 for the Period July to November 1981 and Proceedings of the 19th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-67 and 5101-194

ABSTRACT: This report describes progress made by the Flat-Plate Solar Array Project (formerly the Low-Cost Solar Array Project) during the period July to November 1981. It includes reports on project analysis and integration; technology research in silicon material, large area silicon sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis.

It includes a report on, and copies of visual presentations made at, the 19th Project Integration Meeting (PIM) held at Pasadena, California, on November 11, 1981. This PIM was a one day meeting, consisting primarily of parallel technology sesions. Two limited-attendance workshops were conducted on the day before the PIM: one on silicon materials and crystal-growth technology, and one on solar-cell and module technology. A two-day short course on the Solar Array Manufacturing Industry Costing Standards (SAMICS) was held following the PIM.

TITLE: Progress Report 20 for the Period November 1981 to April 1982 and Proceedings of the 20th Project Integration Meeting.

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: DOE/JPL-1012-71 and 5101-209

ABSTRACT: This report describes progress made by the Flat-Plate Solar Array Project during the period November 1981 to April 1982. It includes reports on project analysis and integration; technology research in silicon material, large area silicon sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis.

It includes a report on, and copies of visual presentations made at the 20th Project Integration Meeting (PIM) held at Pasadena, California, on April 21 and 22, 1982. This report also contains the presentations made by various speakers during the plenary session.

Project Analysis and Integration
JPL - In-House Abstracts

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TITLE The Cost of Energy from Utility - Owned Solar Electric Systems.

AUTHOR: J. W. Doane, R. R. O'Toole, R. G. Chamberlain, P. B. Bos and P. D. Maycock

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1976

REPORT NO: ERDA/JPL/-1012-76/3 - 5040-29

ABSTRACT: This methodology calculates the electric energy busbar cost from a utility-owned solar electric system. This approach is applicable to both publicly - and privately-owned utilities. Busbar cost represents the minimum price per unit of energy consistent with producting system-resultant revenues equal to the sum of system-resultant cost. This equality is expressed in present value terms, where the discount rate used reflects the rate of return required on invested capital. Major input variables describe the output capabilities and capital cost of the energy system, the cash flows required for system operation and maintenance, and the financial structure and tax environment of the utility.

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TITLE: The Penetration of the International Market by Domestically Produced Photovoltaic Power Systems: A Survey of Recent Estimates.

AUTHOR: G. M. Ziman and J. L. Smith

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: 1975

REPORT NO: 5101-75

ABSTRACT: Increasing interest in the potential market for photovoltaic power systems in foreign countries, particularly the lesser developed countries, has prompted a review of several studies that have attempted to quantify that market. The express purpose for this review is to see if any kind of consensus for foreign market size exists among those studies, and to judge whether such estimates can reasonably be done at all.

As expected, it has been found that estimating such markets is quite difficult. Various approaches have been tried, each with differing degrees of credibility, and a wide range of estimates has been produced, thus failing to substantially reduce the uncertainty associated with that market. This report presents and compares those estimates for the period 1984-86 from the studies referred to above (References [1], [2], [8], and [13]), and a discussion of factors not easily quantifiable (both favorable and unfavorable) that will impact photovoltaic power systems sales in foreign markets is included in Section II. A summary of the report and conclusions drawn is presented as Part III, and the methods used to derive the estimates are discussed in the Appendix.

TITLE: Preliminary Analysis of Industrial Growth and the Factors that Affect Industrial Growth Rates

AUTHOR: Edward Edelson and Tom K. Lee

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1976

REPORT NO: 5101-14

ABSTRACT:

Research on the experience of growth in industries other than silicon solar arrays has been undertaken to provide a perspective on the goals established for the U. S. Photovoltaic Conversion Program. Comparative information on the growth experienced by other industries will provide important research questions that must be addressed if the goals are to be achieved. Presently, this work has been conducted at three levels. The first level is purely analytical, and applies mathematical equations describing exponential growth and linear growth to the goals stated for the LSSA project. In the framework established by these equations, the growth rates implied by the LSSA goals may be computed. At the second level, some interpretation of these rates is provided by comparing them to growth rates experienced by other industries. Although a historical rate of growth is only a superficial indication of an industry's development, it does provide a first-order indicator of what levels of growth different industries have been able to achieve in the past. The use of growth rate comparisons does not detract from the importance of examining, in detail, those factors that determine the rate of growth. The factors presently under consideration are:

1. Level of industry investment.
2. Government subsidization and incentives.
3. Government regulation.
4. Competition within the industry and with other industries.
5. Market characteristics.
6. Consumer behavior.

Because information on these constraints and incentives is necessary to understand the observed growth rates, the third level of research is a case study on one relevent industry to examine what constrains and motivates an industry.

The nuclear industry, and specifically the civilian nuclear reactor program, was selected for the following two reasons:

(1) The extensive government R&D support and the participation by the government in a program to commercialize the use of nuclear reactors provides a good analogy to the U. S. Photovoltaic Conversion Program. Many of the problems faced in the early years (1954 - 1967) of nuclear reactor development will undoubtedly be faced by the Photovoltaic Conversion Program. During these early years, the federal government was trying to demonstrate the technical and commercial feasibility of nuclear reactors for the generation of electricity.

(2) Because of the similarity of the two programs, it is important that JPL and the National Program understand the implications and lessons to be learned from the civilian nuclear reactor development program.

As far as the lessons to be learned from the nuclear experience, the necessary research includes an analysis of:

1. The role and extent of government R&D.
2. The strength and weakness of different types of government incentives.
3. The type of industry participation required.

This report provides information on the research completed to date in this area. The mathematical work on the first two levels of research has been completed. Work on the case study of the nuclear experience has just begun. Necessary extensions of the research are noted throughout the report.

TITLE: The Cost of Energy from Utility - Owned Solar Electric Systems.

AUTHOR: J. W. Doane, R. R. O'Toole, R. G. Chamberlain, P. B. Bos and P. D. Maycock

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1976

REPORT NO: ERDA/JPL/-1012-76/3 - 5040-29

ABSTRACT: This methodology calculates the electric energy busbar cost from a utility-owned solar electric system. This approach is applicable to both publicly - and privately-owned utilities. Busbar cost represents the minimum price per unit of energy consistent with producing system-resultant revenues equal to the sum of system-resultant cost. This equality is expressed in present value terms, where the discount rate used reflects the rate of return required on invested capital. Major input variables describe the output capabilities and capital cost of the energy system, the cash flows required for system operation and maintenance, and the financial structure and tax environment of the utility.

TITLE: Low-Cost Silicon Solar Array Project. Solar Array Manufacturing Industry Costing Standards. SAMICS Workbook. Version I.

AUTHOR: Robert G. Chamberlain

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1977

REPORT NO: 5101-15

ABSTRACT: The Solar Array Manufacturing Industry Costing Standards (SAMICS) provide standard formats, data, assumptions, and procedures for estimating the price that a manufacturer would have to charge for the product of a specified manufacturing process sequence.

This document illustrates those formats, states the assumptions, and presents the procedure with step-by-step instructions for its application.

TITLE: Interim Price Estimation Guidelines: A precursor and an Adjunct to SAMIS III.

AUTHOR: Robert W. Aster and Robert G. Chamberlain

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1977

REPORT NO: 5101-33

ABSTRACT: The problem of estimating the market price of a product that is obtainable from an unproven technological process is a very difficult one. Direct costs can be estimated much more easily. However, if one can then estimate the indirect requirements for both the process and the organization employing the process, then a total cost estimate is possible. If this total cost includes estimates of all the production, administration, and financial costs, then the result is the minimum price that a firm requires to enter the market with that given process.

This problem faces the LSSA Project, which is charged with the task of developing technological processes which meet certain price goals. Accordingly, there have been numerous cost models developed by various Project elements. A growing need has been recognized for a standard methodology which allows (1) relative comparisons of the potential prices attributable to competing processes, and (2) a best possible estimate of the actual price obtainable from a process.

The Solar Array Manufacturing Industry Simulation computer program, SAMIS, will be a powerful tool for producing accurate, comparable estimates of the prices implied by sequences of manufacturing processes. SAMIS will not, however, be available for several months, and price estimates are being made now by various Project elements.

To provide a basis for consistency among these estimates, this document establishes an interim standard method to be used throughout the LSSA Project (except in the Silicon Material Task, where the Lamar University prodedure may be better suited than this interim standard method).

TITLE: Solar Array Manufacturing Industry Costing Standards.

AUTHOR: Robert G. Chamberlain and Robert W. Aster

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1978

REPORT NO: 5101-59

ABSTRACT:

The Solar Array Manufacturing Industry Costing Standards (SAMICS) are prepared by the LSSA Project Analysis and Integration Area and are intended to provide a standard procedure and data base for estimating, from descriptions of the manufacturing processes, the price at which solar modules would have to be sold to realize a specified after-tax rate of return on equity.

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

The purpose of this document is to answer those questions and to clarify and/or establish how to handle the following topics:

1. Elimination of the 42-hour work week
2. Clearer labels on Format A and on Process and Company Work Sheets
3. Relief labor
4. Partial inspection processes
5. Format A Column A22 - amount required per batch
6. Processes that draw power even when not in use
7. Format A Line A6 and Column A26 - output rate and yield factor
8. Rework loops
9. Processes that use parts that require processing
10. More general rework loops
11. General technological loops
12. Integerization of numbers of people and machines
13. When to burden and when not to burden materials and supplies.

TITLE:	Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems: Volume I Executive Summary.
AUTHOR:	J. L. Smith, W. R. Gates and T. Lee
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	April 1978
REPORT NO:	DOE/JPL-1012-78/1 - 5101-54 Vol. I
ABSTRACT:	This study was prepared by the Low Cost Silicon Solar Array Project staff on two somewhat disjoint subjects: the diffusion of new industrial production technologies and the determinants of success of previous federally funded demonstration projects. The research was limited to secondary sources. In essence, a literature search on these two subjects was the primary aim of the study.

That search led, however, to some fairly strong conclusions out of which specific recommendations for the future plans and conduct of the LSSA Project have been derived. It must be emphasized that these recommendations are made only on the basis of the evidence considered. That is, no attempt has been made here to incorporate the myriad other factors which bear significantly on the Project (e.g., funding levels or political imperatives). Thus, these recommendations are not intended as a comprehensive set of project management recommendations to the Photovoltaic Program or the Department of Energy. They are to be viewed as an input into such a comprehensive set.

TITLE: Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems: Volume II

AUTHOR: J. L. Smith, W. R. Gates and T. Lee

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1978

REPORT NO: DOE/JPL-1012-78/1 - 5101-54 Vol. II

ABSTRACT: This paper is one of a continuing series of economic analyses conducted by the Project Analysis and Integration Task of the Low Cost Silicon Solar Array Project of the National Photovoltaic Conversion Program. The intent of these studies is to anticipate problems which may arise as the Project pursues its objectives of lowering the production cost of photovoltaic arrays to a level competitive with other sources of electricity, and to insure a smooth transition from government R,D&D to private commercial production.

The study is concerned with two somewhat disjoint subjects - the diffusion of new industrial production processes and the determinants of success of previous federally funded demonstration projects. The research was limited to secondary sources. In essence, a literature search on these two subjects was the primary aim of the study.

That search led, however, to some fairly strong conclusions out of which specific recommendations for the future plans and conduct of the LSSA project have been derived. It must be emphasized that these recommendations are made only on the basis of the evidence considered. That is, no attempt has been made to incorporate the myriad other factors which bear significantly on the Project (e.g., funding levels or political imperatives). Thus, these recommendations are not a comprehensive set of project management recommendations to the Photovoltaic Program of the Department of Energy. They are to be viewed as an input into such a comprehensive set.

The guidance and direction for this and other studies in the series has been supplied by Dr. James Doane. Separately issued background papers, upon which this study draws heavily, have been prepared. These papers, "Prospects for Innovation and Diffusion of Photovoltaic Technology" by Bill Gates, and Sequential Pilot-Demonstration-Commercial Strategy and Its Relation to LSSA's Industrialization Plans" by Tom Lee, form the basis for Sections II and III, respectively.

TITLE: Economic Analysis of a Candidate 50 cents/wpk Flat-Plate Photovoltaic Manufacturing Technology.

AUTHOR: Aster, R. W.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1978

REPORT NO: DOE/JPL/1012-78/17 and 5101-94

ABSTRACT: The SAMICS Methodology was used to analyze the first candidate manufacturing sequence that could meet the LSA Projects's 1986 price goal. That goal represents a reduction in photovoltaic prices by a factor of a hundred over a 10-year period, from approximately 50 $/wpk in 1975 to 50 cents/wpk in 1986. The results of analysis which has occurred since the original presentation of the 5 cents/wpk candidate factory at the 10th LSA Project Integration Meeting are described. Briefly, if a number of events occur, such as a High Cell Efficiency (14% for this technology), vertical industry integration, long periods of amortizing the initial capital investment, and full utilization of a large plant, then a price of 39.9 cents/wpk is possible. Non-optimal circumstances will increase this required price, and several of these circumstances are addressed.

TITLE: A Normative Price for a Manufactured Product: The SAMICS Methodology Volume II: Analysis.

AUTHOR: R. G. Chamberlain

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1979

REPORT NO: DOE/JPL-1012-79/5 - 5101-93

ABSTRACT: The Solar Array Manufacturing Industry Costing Standards (SAMICS) provide standard formats, data, assumptions, and procedures for determining the price a hypothetical solar array manufacturer would have to be able to obtain in the market to realize a specified after-tax rate of return on equity for a specified level of production.

This document presents the methodology and its theoretical background. It is contended that the model is sufficiently general to be used in any production-line manufacturing environment.

Implementation of this methodology by the Solar Array Manufacturing Industry Simulation Computer program (SAMIS III, Release 1) is discussed.

TITLE:	Energy Systems Economic Analysis (ESEA) Methodology and User's Guide.
AUTHOR:	M. L. Slonski
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	February 1979
REPORT NO:	5101-102

ABSTRACT:

The Energy Systems Economic Analysis (ESEA) capability is a flexible analytical tool which may be used for rank ordering (in terms of cost) alternative energy systems. The capability consists of a set of three computer programs, all developed around the same basic computational structure, depicted in Figure 1-1.

The conceptual basis of the ESEA capbility is described in <u>The Cost of Energy from Utility-Owned Solar Electric Systems</u> (JPL 5040-29, ERDA/JPL-1012-76/3), denoted hereafter as "USES." In particular, the ESEA capability utilizes the more flexible and generalized computational structure described in Appendix E of the USES document which incorporates a more explicit treatment of taxes and depreciation.

The ESEA program set provides three related but separate capabilities: analysis of a single system, comparative analysis of two systems, and graphical representation of both parametric and continuous sensitivity analyses on a single system, comparative analysis of two systems, and graphical representation of both parametric and continuous sensitivity analyses on a single system. The single system analysis produces essentially the USES output with expanded documentation. The program produces a printed summary that contains inputs, intermediate values, a capital expenditures table, life-cycle cost, net present value when applicable, and the busbar energy cost.

The comparative analysis contrasts two system; for example, a system which utilizes conventional technology and a system which utilizes a new or alternative technology. For each system the program produces a printed summary in the same format as the single system analysis. In addition, the primary economic differences between the two systems are highlighted.

The parametric representation provides a graphical presentation of continuous sensitivities on user-selected parameters over a selected range of values. In addition it optionally provides the single system analysis printed summary for the system in the "baseline" state before any sensitivities are performed.

Collectively, the ESEA program package offers the analyst considerable flexibility, such as break-even system and subsystem capital costs, break-even fuel costs, evaluations of net present value and internal rate of return, and sensitivities of busbar energy costs to a large variety of factors.

TITLE: Low Cost Solar Array Project. Technical Readiness 1982.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 31, 1979

REPORT NO: 5101-114

ABSTRACTS The need to find new methods to economically generate enough electrical power to meet future demand motivated the establishment of the Photovoltaic Conversion Program in January 1975. The long range Program objectives developed 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 Solar Array Project (LSA) was established at the Jet Propulsion Laboratory as part of the government's program. The Project goal is to greatly reduce the price of flat plate 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 development of the necessary photovoltaics supply industry infra-structure to ensure establishment of a viable source for solar-electric energy systems.

In October 1977, the Department of Energy (DOE) was formed and the LSA Project become part of the solar energy activities of DOE. The breadth of the Project was expanded to include materials other than silicon.

The Project activities have been divided into four phases: technology process identification, process development (including quantity scale-up), Technical Readiness, and commercial readiness. The first two phases have been completed and this document presents the plans for achieving Technical Readiness for Phase Three by the end of FY82.

TITLE: Price Allocation Guidelines.

AUTHOR: R. W. Aster

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1980

REPORT NO: DOE/JPL-1012-47 - 5101-68 Rev. A

ABSTRACT:

The price allocation guidelines (PAG) are an integrated set of specific cost targets for several task areas within the Low-cost Solar Array (LSA) Project. PAG is a working tool of LSA Project management designed to provide consistent and meaningful guidelines for costs of polycrystalline silicon material, sheet, cells, encapsulants, and module manufacturing.

It is expected that advanced photovoltaic concepts derived from industry and the research community can be developed so that it will be possible by the end of 1982 to demonstrate production processes, all process steps, and prototype equipment required to manufacture flat-plate photovoltaic modules. This demonstration would incorporate production rates and product quality consistent with a specific market price determined by the program. This stage of development has been referred to as "Technical Readiness". A goal of $0.70 per peak watt (1980 dollars) has been established for the cost of electricity generated by photovoltaic modules. The processes for producing modules demonstrated to be technically ready must be amenable to scale-up so that this price goal can eventually be achieved in the marketplace. The guidelines described in this document allocate portions of that goal to each module component.

Sheet materials derived from the following five technologies are considered: Czochralski, heat exchanger method (HEM), edge-defined film growth (EFG), dendritic web, and silicon on ceramic (SOC). Each type of material provides a unique combination of projected silicon yield, cell efficiency, and module packing efficiency.

Also included are tables describing actual inflation rates form 1975 to 1979, and projected inflation rates to mid-1980. Project goals are now expressed in 1980 dollars rather than 1975 dollars, and these tables enable conversion of dollar amounts from prior years (1974-1980) to their 1980 or 1975 equivalents.

TITLE: Handbook of Solar Energy Data for South-Facing Surfaces in the United States. Volume I: An Insolation, Array Shadowing, and Reflector Augmentation Model

AUTHOR: Jeff H. Smith

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1980

REPORT NO: DOE/JPL-1012-25 Vol. 1 and 5101-91 Vol. I

ABSTRACT: This handbook provides estimates of average available solar insolation to fixed, flat-plate, south-facing collector surfaces at various array tilt angles at numerous sites in the United States. This first volume contains average daily, total insolation estimates, by month, and annual totals for 235 locations. The second and third volumes contain the daily profiles by hour used to compute the daily totals for the 235 locations (at selected array tilt angles).

A model that estimates the direct, diffuse, and reflected components of total insolation on an hourly, daily, and monthly basis is presented. A shadow loss model and a reflector augmentation model providing estimates of the losses and gains associated with various fixed array geometries are also described. These models can be used with the insolation model provided or with other recorded data.

A FORTRAN computer program with users guide is presented. The program can be used to generate additional handbook values or to examine the effects of array shadowing and fixed reflector augmentation effects on a daily, monthly, or annual basis. Array shadowing depends on location, array size, array tilt, array separation, and time. The program can be used to examine trade-offs between array spacing and insolation losses due to shadowing. The reflector augmentation program can be used to examine trade-offs among array size and tilt, separation, and reflector tilt to determine the combination of design values that optimize the economic objectives or technical criteria of the system.

TITLE:	Handbook of Solar Energy Data for South-Facing Surfaces in the United States. Volume II: Average Hourly and Total Daily Insolation Data for 235 Localities (Alaska - Montana)
AUTHOR:	Jeff H. Smith
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	January 1980
REPORT NO:	DOE/JPL-1012-25 Vol. 2 and 5101-91 Vol. II
ABSTRACT:	No Abstract

TITLE: Handbook of Solar Energy Data for South-Facing Surfaces in the United States. Volume III: Average Hourly and Total Daily Insolation Data for 235 Localities (North Carolina - Wyoming)

AUTHOR: Jeff H. Smith

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1980

REPORT NO: DOE/JPL-1012-25 Vol. 3 - 5101-91 Vol. III

ABSTRACT: Appendix D of the three-volume report A Handbook of Solar Energy Da*a for South-Facing Surfaces in the United States is presented in Volumes II and III. It gives average hourly and daily total insolation estimates for 235 U.S. sites at a variety of array tilt angles.

The reader should refer to Volume I for the insolation, array shadowing, reflector augmentation models, and the computer program used to generate th. Appendix.

TITLE: Low Cost Solar Array Project. SAMICS Input Data Preparation.

AUTHOR: Robert G. Chamberlain and Robert W. Aster

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 21, 1980

REPORT NO: 5101-44, Rev. B

ABSTRACTS The Solar Array Manufacturing Industry Costing Standards (SAMICS) provide standard formats, data, assumptions, and procedures for estimating the price that a manufacturer would have to charge for the product of a specified manufacturing process sequence. This document gives a line-by-line explanation of the standard formats that describe the economically important characteristics of the manufacturing processes and the technological structure of the companies and the industry.

This revision provides an updated description of the data requirements of Release 3 of the SAMIS (Standard Assembly-line Manufacturing Industry Simulation) computer program. It also presents and describes the May 1980 versions of Format A - Process Description, Format B - Company Description, and Format C - Industry Description.

TITLE: Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) Computer Program User's Guide - Release 3.

AUTHOR: Paul J. Firnett

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1980

REPORT NO: 5101-60 Rev. B

ABSTRACT: The Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) is a user-oriented computer program that was designed to model a hypothetical U. S. industry which manufactures silicon solar modules. These modules are used to generate electricity directly from sunlight by the photoelectric effect. It is anticipated that this computer program will also be useful in producing price estimates for other products of production-line manufacturing industries and companies.

The most important capability of the SAMIS program is its ability to "simulate" an industry described by the user. The results of a simulation are a set of (user-selected) financial reports which detail all of the requirements, including quantities and costs, of the companies and processes that comprise the industry. Because of the large amount of data needed to describe an industry, a major portion of SAMIS is dedicated to data entry and maintenance -- an activity loosely referred to as model management. This activity requires a great deal more interaction between SAMIS and the user than simulation does; hence, the user will discover that the major portion of this document is concerned with describing the model management activities.

This document is designed to serve several purposes. It is intended primarily to provide all instruction necessary to execute the program and obtain results. Secondly, it provides an overview of the program philosophy. Finally, it provides a brief discussion of the components (entities that the program utilizes). User feedback is encouraged. Pertinent comments should be directed to Robert G. Chamberlain at the Jet Propulsion Laboratory.

TITLE:	Standard Assembly-Line Manufacturing Industry Simulation SAMIS Design Document.
AUTHOR:	R. G. Chamberlain, P. J. Firnett and M. H. Horton
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	April 1980
REPORT NO:	5101-70 Rev. B
ABSTRACT:	(This report contains no abstract. It is a computer run-out.)

TITLE: SAMICS Cost Account Catalog. Version 4

AUTHOR: R. G. Chamberlain, R. W. Aster and P. J. Firnett

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1980

REPORT NO: 5101-154

ABSTRACT: Version 4 of the Cost Account Catalog contains cosmetic as well as substantive changes and improvements relative to Version 3. Inflation rates have been given more realistic values, some indirect requirements have been modified, several obsolete commodities have been deleted, new commodities have been added, and a substantial change was made to Account B (Personnel) so that the catalog will be compatible with Release 3 of the SAMIS computer program. In order that the catalog maintain integrity and credibility, it will be updated whenever improved data become available.

TITLE:	Improved Price Estimation Guidelines (IPEG) Computer Program User's Guide.
AUTHOR:	P. J. Firnett
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	November 1980
REPORT NO:	5101-156 Rev. A
ABSTRACT:	The Improved Price Estimation Guidelines (IPEG) program is intended for use with the SAMIS program. In a typical application a SAMIS simulation is executed to generate an IPEG input file, and then IPEG is executed to perform various sensitivity studies. This is a considerably cheaper procedure than using SAMICS for sensitivity analyses. SAMIS has now been modified to produce an IPEG input file; however, the sample IPEG input file on JPL/SAMIS may be used (refer to Appendix A), or another may be built with the system text editor. If the input file on JPL/SAMIS is used, the IPEG "CHANGE" command will allow it to represent any alternative system that the user may choose.

TITLE:	Improved Price Estimation Guidelines (IPEG) Design Document Release 2
AUTHOR:	P. J. Firnett
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	November 1980
REPORT NO:	5101-158 Rev. A
ABSTRACT:	No abstract. All computer print-out.

TITLE:	Improved Price Estimation Guidelines (IPEG) Computer Program Source Code Release 2.
AUTHOR:	R. G. Chamberlain, P. J. Firnett and M. A. Miller
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	November 1980
REPORT NO:	5101-159 Rev. A
ABSTRACT:	The IPEG program is used to provide an estimate of the SAMIS-computed price of a manufactured product. The simplicity of the model and the speed of the program make IPEG very useful for performing sensitivity studies which would be prohibitively expensive using SAMIS. The program design is contained in JPL Document 5101-158, "IPEG Design Document." This document contains the SIMSCRIPT II.5 source code correspondig to that design.

TITLE: Solar Array Manufacturing Industry Costing Standards (SAMICS): Short Course.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1981

REPORT NO: 5101-196

ABSTRACT: This document contains viewgraphs used in the Short Course.

TITLE: Low-Cost Solar Array Project. Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) Industry-Specific Cost Account Catalog.

AUTHOR: Paul J. Firnett

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 5, 1981

REPORT NO: 5101-167

ABSTRACTS When one becomes aware of the rather high cost of loading the entire cost account catalog, which must be done for every simulation, it is immediately apparent that the catalog should be as small as possible. The contents of an industry-specific cost account catalog, one which contains only the expense items required by the industry being simulated, will vary from industry to industry. SAMIS can easily determine the requisite set of expense items, obtain them from a master catalog, and at the user's option generate a catalog containing only that set - an industry-specific catalog. This SAMIS-generated catalog, which is as small as possible, can be used for all subsequent simulations of the industry. Unfortunately, this new capability, along with the flexibility to access both a master catalog and an industry-specific catalog, requires some changes to the SAMIS commands; however, the potential cost saving for a simulation (15% to 20%) more than warrants the increased complexity. It may be noted, however, that the changes have been made in such a way that a user who does not care to enjoy the saving (as might be the case if he is facing an extremely tight deadline) need make no changes in procedure.

Section 2 discusses the concept of an industry-specific catalog and how it relates to the master catalog. It also desribes how and when to apply the (new) CHECK option of the SAMIS SIMULATE command to generate an industry-specific catalog. Section 3 discusses the changes to the other SAMIS commands such as QUERY, FIND, and LOAD. Section 4 discusses the task of generating and using an industry-specific catalog from the point of view of both a new and an old SAMIS user. Section 5 describes changes to the National CSS procedures.

TITLE: Flat-Plate Solar Array Project. Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) Computer Program Source Code.

AUTHOR: Robert G. Chamberlain and Paul J. Firnett

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 15, 1981

REPORT NO: 5101-71, Rev. C

ABSTRACTS

The SAMIS computer program constructs a model of a hypothetical manufacturing industry. Explanatory material (objectives, expected future changes, and acknowledgements) and the detailed design of the program are contained in JPL Document 5101-70, Rev. C, SAMIS Design Document (in press). This document contains the SIMSCRIPT II.5 source code corresponding to that design.

TITLE:	Flat-Plate Solar Array Project. SAMIS User's Reference Card.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	December 1981
REPORT NO:	5101-183
ABSTRACTS	This is a Standard Assembly Line Manufacturing Industry Simulation (SAMIS) User's Reference Caru. No abstract.

TITLE: Summary Guide to Using SAMIS.

AUTHOR: R. E. Daniel

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1982

REPORT NO: 5101-193

ABSTRACT: It is assumed that the reader of this document is aware of the intention of the Solar Array Manufacturing Industry Costing Standards (SAMICS) methodology.

This guide is not intended to replace the other SAMICS and Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) documents; it provides cross-referencing to these documents and avoids extensive duplication. It is organized to present the necessary details of the industry-creation and computer-terminal sessions in the order in which they will be confronted, and concludes with a discussion of the interpretation on the output reports. Moreover, this guide will assist the new SAMICS user in the creation and understanding of the modeled industry. The instruction includes the filling out of the standard forms (Formats A, B, and C) and using the interactive SAMIS program before the actual simulation. Although the examples chosen herein are oriented toward Flat-Plate Solar Array Project (FSA) needs, they are not done to the exclusion of usefulness for other types of industries.

TITLE:	Introduction to SIMRAND. SIMulation of Research ANd Development Project.
AUTHOR:	Ralph F. Miles, Jr.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	March 1982
REPORT NO:	DOE/JPL-1012-68 and 5101-204

ABSTRACT: SIMRAND: SIMulation of Research ANd Development Projects is a methodology developed at the Jet Propulsion Laboratory of the California Institute of Technology to aid the engineering and management decision process in the selection of the optimal set of systems of tasks to be funded on a research and development (R&D) Project. An R&D project may have a set of systems or tasks under consideration for which the total cost exceeds the allocated budget. Other factors such as personnel and facilities may also enter as constraints. Thus the project's management must select, from among the complete set of systems or tasks under consideration, a partial set that satisfies all project constraints. The SIMRAND methodology uses analytical techniques of probability the , decision analysis of management science, and comput simulation, in the selection of this optimal par .l set.

The SIMRAND methodology is truly a management tool. It initially specifies the information that must be generated by the engineers--thus providing information for the management direction of the engineers--and it ranks the alternatives according to the preferences of the decision makers. The decision makers could be either the project's management, the funding agency, or the end users.

TITLE:	Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) Computer Program User's Guide.
AUTHOR:	Paul J. Firnett
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	April 1982
REPORT NO:	5101-60 Rev. C
ABSTRACT:	This is a computer run-out.

Project Analysis and Integration
Contractor Abstracts

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TITLE: A Critical Review of the Solar Array Manufacturing Industry Costing Standards.

CORPORATE AUTH: Theodore Barry & Associates

CONTRACT NO: 954800

DATE: July 1977

REPORT NO: DOE/JPL-954800-77/1

ABSTRACT: This report documents the findings, analysis, and recommendations of the SAMICS critique. The SAMICS model is designed to compare the cost of producing solar arrays using alternative manufacturing processes. The critique focuses on three main elements of the SAMICS procedure: 1) Workbook format and presentation 2) Theoretical model validity and 3) Standard financial parameters. The SAMICS model is an excellent mathematical formulation; however the workbook presentation is too theoretical for a practical application procedure.

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TITLE: SAMICS Support Study; Cost Account Catalog.

CORPORATE AUTH: Theodore Barry & Associates

CONTRACT NO: 954800

DATE: September 1977

REPORT NO: DOE/JPL/954800-77/2.1

ABSTRACT: A standardized costing procedure has been developed to assist Jet Propulsion Laboratory in examining the feasibility of new industry to produce photovoltaic solar energy collectors similiar to those used on spacecraft. The name of the costing procedure is the Solar Array Manufacturing Industry Costing Standards (SAMICS). Volume I contains a description of the cost account structure and the cost account catalog. Volume II presents several submodel analyses, including the indirect requirements relationships, facilities capital cost estimating one-time costs. Volume III contains conceptual plant designs and the corresponding manufacturing price estimates for three alternative levels of solar array production: .5, 15, 500 MW of peak capacity per year.

TITLE: SAM'CS Cost Account Catalog.

CORPORATE AUTH: Theodore Barry & Associates

CONTRACT NO: 9'4909

DATE: April 1978

REPORT NO: DOE/JPL/954909-78/1

ABSTRACT: The Cost Account Catalog contains a list of all items that may be required directly or indirectly, by a solar array manufacturing firm. The list includes a catalog number, a name, and a unit of measure for each item. Where appropriate, it also provides price information (price year, inflation rate, and either a price or a price versus quantity table). The catalog expense items are organized into 6 accounts: 1) facitilies parameters, 2) personnel, 3) utilities and plant services, 4) by products, 5) commodities, and 6) resources.

TITLE: SAMICS Marketing & Distribution Model

CORPORATE AUTH: Theodore Barry & Associates,

CONTRACT NO: 954909

DATE: April 1978

REPORT NO: DOE/JPL/954909-78/2

ABSTRACT

This report presents a model for computing marketing and distribution costs. This marketing and distribution model is a simplification intended to recognize the added costs of marketing and transporting the solar arrays from the factory to the customer. The model covers selling, transportation, and storage costs in transit from the loading dock to the point of use.

TITLE: Final Technical Report. Terrestrial Central Station Array Life-Cycle Analysis Support Study

CORPORATE AUTH: Bechtel Corporation

CONTRACT NO: 954848

DATE: August 1978

REPORT NO: DOE/JPL 954848-78/1

ABSTRACT: The purpose of the study was to provide input cost data in support of array-life-cycle cost analysis being conducted by JPL for utility central station photovoltaic power plant application. Primary emphasis was on the solar cell modules and arrays, with balance-of-plant concepts developed only as far as necessary to determine their impact on module and array design and vice versa. Assessments were made of five alternate array configurations and the impact of parameters such as site weather, onside energy storage, system voltage, energy losses within the plant, maintenance requirements and module design. The plant design used as the baseline for this study is a 200 MW (nominal) central station photovoltaic power plant using 8 by 16 foot flat-plate silicon solar panels comprised of 4 by 8 foot glass superstrate modules. The five alternate array design configurations evaluated were rack, tandem, horizontal, seasonally adjusted and tracking-tape arrays.

TITLE: Lifetime Cost and Performance Model Support Study

CORPORATE AUTH: Theodore Barry & Associates

CONTRACT NO: 955161

DATE: September 1978

REPORT NO: 955161-78/01

ABSTRACT: This report represents the first definitive work that details photovoltaic central power plant installation, operation, and maintenance activities, thus avoiding the necessity to appeal to "rules of thumb" derived from experience with other types of power plants.

TITLE: Industrialization Study.

CORPORATE AUTH: Gnostic Concepts, Inc.

CONTRACT NO: 954899

DATE: September 1978

REPORT NO: DOE/JPL/954899-78/3

ABSTRACT: Information concerning the investment process within the US industry was collected. Emphasis was placed upon characterizing the critical elements in major high-risk investment decisions by industry. The relationship between these critical elements was interpreted as to how they influence the investment decision outcome. The results of this analysis found wide differences between companies in the manner in which evaluation criteria are applied. Even within similar industrial sectors, totally different behavior patterns were observed. Motivation was determined to be the greatest single force to induce a company to invest in a high-risk venture. The higher the motivation, both financial and personal, the greater the risk a company is prepared to accept in a new investment. The effect of government actions upon these motivations and the degree of risk acceptance by industry is discussed on a qualitative as well as a quantitative basis. The relative impact of alternative government programs and policies upon industry motivations, with its resulting impact upon photovltaic industrialization, is assessed. This assessment is based upon field interviews with a cross-section of industry decision-makers to solicit their attitudes toward alternative government programs and policies. The government alternatives have been ranked on the basis of their ease of implementation and their probable impact. A commentary is included on the recommended sequence in which these government policies should be applied to maximize the industrialization of the photovoltaic venture.

TITLE: Industrialization Study

CORPORATE AUTH: Gnostic Concepts, Inc.

CONTRACT NO: 954899

DATE: January 1979

REPORT NO: DOE/JPL/954899-78/6

ABSTRACT: Areas covered in this report include the technical assessments of selected advanced technologies. Information collected was in the area of manufacturing process steps and their implications on cell performance, along with present and future expected performance characteristic. A summary of the technical and manufacturing barriers and a summary of other influences is provided. A comparative assessment of the advanced technology bases was also constructed. It consists of comparing each of the advanced technologies to the present-day single-crystal silicon wafer technology that dominates commercial activities today and a comparison of the advanced technologies to each otheer. From this was extracted those technologies of industrialization efforts. A rank ordering of the advanced technologies is provided. The various ranking schemes were based upon present-day efficiency levels, their stability and long-term reliability prospects, material production level, and associated variable costs. A final selection was made of those advanced photovoltaic technologies that have a high potential for industrialization prospects and an estimate of the timing of the possible readiness of these advanced technologies for technology development programs and industrialization.

TITLE: Final Report. Samics Support Study-Phase III.

CORPORATE AUTH: Theodore Barry & Associates

CONTRACT NO: 955123

DATE: April 1979

REPORT NO: DOE/JPL-955123-79/1

ABSTRACT: This is a report of Theodore Barry & Associates' review and validation of the SAMICS model. The purposes for this review were the following: a. To test the computational validity of the computer model by comparison with preliminary TB&A hand calculations based on conventional cost estimating techniques. b. To review and improve the accuracy of the cost relationships being used by the model. c. To provide an independent verification to users of the model's value in decision making for allocation of research and development funds and for investment in manufacturing capacity. TB&A's conclusion is that the SAMICS model is a flexible, accurate, and useful tool for managerial decision making. Our comparison of model results with TB&A calculations shows close correlation. This report provides the basis for our conclusions. It also contains recommendations for increasing the usefulness of SAMICS. The purpose of SAMICS is to provide a consistent basis for estimating array costs and comparing production technology costs. The user of SAMICS provides detailed process information for calculating direct cost. To these are added indirect and overhead expenses. Although documentation of direct processes requires a significant initial effort, the process gives SAMICS its primary strength. A complete accounting of direct process resource requirements establishes an audit trail that will help to monitor the realism of assumptions before production and to later identify variations from forecasted operating parameters after production begins. SAMICS will be valuable to the LSA Project in monitoring program objectives. It integrates all the production processes involved in module manufacturing. Thus, technology transfer from task to task and to manufacturers under contract, followed by audits of operations, should help JPL's decision makers to allocate research funds more effectively to the lowest cost technologies. Some limitations of SAMICS should be noted. There are three components of profit that the model calculates. The first is the conventional profit after tax in the accounting sense. The other two are amortized one-time costs and return on equity. Output formats should

indicate that all three of these are returns on the capital investment. The SAMICS model calculates annual operating expense based on a steady state condition following a number of years of operation. In addition to these steady state operating costs, initial start-up costs are computed and amortized over the economic life of the facilities. The user should be aware of the difference that the two lifetimes may have on product price.

TITLE: Final Report. Production Management Handbook

CORPORATE AUTH: Theodore Barry and Associates

CONTRACT NO: 955519

DATE: January 1980

REPORT NO: DOE/JPL 955519-80/1

ABSTRACT: This handbook, which supplements the SAMIS model, will assist LSA production managers in reducing the cost of solar arrays. While the handbook includes mathematical models, it provides more than a set of analytical techniques. It discusses general principles for production economics, aggregate planning, facility design, production control, inventory management, quality control, maintenance management, materials handling, market strategy and risk management. The handbook emphasizes cost control and resource utilization. The general principles involve information measurement and evaluation. Management achieves control by setting performance goals and comparing actual performance to expected performance. All levels of management are held accountable for achieving results. In this way the performance management process assures that production resources are provided and utilized efficiently and effectively. The objectives of the Production Management Handbook are to: Outline decision-making processes for cost-effective LSA production; Develop industrial engineering tools applicable to the photovoltaic industry. Specifically, the handbook provides analytical models and algorithms to address: Production scheduling strategies; Inventory levels and storage requirements; Production process design and flow rates; Quality control criteria and implementation; Maintenance and outage strategies; Material handling methods; Market strategy, risk management, and contingency planning.

Silicon Material
JPL - In-House Abstract

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TITLE: Modeling of Fluidized Bed Silicon Deposition Process

AUTHOR: K. Kim, G. Hsu, R. Lutwack and A. Praturi

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1977

REPORT NO: 77-25, and 5101-50

ABSTRACT: Modeling of the fluidized bed for silicon deposition is described. The model is intended for use as a means of improving fluidized bed reactor design and for the formulation of the research program in support of the contracts of the Silicon Material Task for the development of the fluidized bed silicon deposition process. A computer program derived from the simple modeling is also described. Results of some sample calculations using the computer program are shown.

TITLE: Chemical Vapor Deposition of Silicon from Silane Pyrolysis

AUTHOR: A. K. Praturi, R. Lutwack and G. Hsu

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: July 1977

REPORT NO: 5101-51, JPL Publication 77-38

ABSTRACT: The four basic elements in the chemical vapor deposition (CVD) of silicon from silane are mass transport of silane, pyrolysis of silane, nucleation of silicon and silicon crystal growth. These four elements are analytically treated from a kinetic standpoint. Rate expressions that describe the various conceivable steps involved in the chemical vapor deposition of silicon are derived from elementary principles. Applications of the rate expressions for (1) modeling and the simulation of the silicon CVD process and (2) the analysis of experimental data on silicon CVD are discussed. The lack of an experimentally established mechanism of the silicon CVD process and established values for various constants involved in the rate expressions is the major impediment to the modeling of the CVD process. Experimental data are needed to determine the equilibrium adsorption coefficients for silane, hydrogen and silicon vapor and the activation energies and frequency factors for the various rate processes involved in the silicon CVD.

TITLE: Silicon Formation by Pyrolysis of Silane. Interim Report of the Continuous Flow Pyrolyzer Study.

AUTHOR: Harry Levin

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1978

REPORT NO: 5101-87

ABSTRACT: A study of the formation and growth of silicon was conducted in which silane was converted to silicon in a continuous flow pyrolyzer. The study employed a set of four experiments, factorially designed for a high and low level of gas stream temperature and for the presence and absence of silicon seed particles in the gas stream. The study was undertaken to support and complement those Low-Cost Solar Array (LSA) Project programs which utilize pyrolysis technology in the production of silicon. In most of these programs, the form and size of the silicon are important elements in the success of the program.

Under the conditions of the study, the silane decomposed and simultaneously produced a particulate silicon in the gas stream and a chemical-vapor-deposition silicon on the relatively hot surfaces in contact with the silane.

At the high temperature (790°C), nucleation and growth of the particulate form of silicon in the gas stream increased. At the low temperature (640°C), a widely varying sequence of silicon growth habits was observed in chemical vapor deposition under conditions of rapidly changing silane concentration. There was no evidence at either temperature of chemical vapor deposition on the silicon seed particles, which had been introduced unheated into the gas stream.

TITLE: In-House Study Fluidized Bed Silane Pyrolysis

AUTHOR: Richard Hogle, George Hsu and Ralph Lutwack

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1978

REPORT NO: 5101-89

ABSTRACT: As part of the LSA Task I in-house support effort, low-cost silicon production by silane pyrolysis is being studied using a 2-inch inside diameter fluidized bed reactor (FBR). The reactor as well as a quartz fluidization column were constructed and instrumented with electronic pressure transducers, and a computer data acquisition system to study general silicon fluidization along with the silane chemistry. The results of the reaction experiments indicate that a dense silicon deposit can be grown on seed particles with high SiH_4 conversion. At bed temperatures above 740°C and SiH_4 concentration around 6 percent, dense masses or clogs were formed in the reactor. Several solutions to the clogging problem, such as 650°C to 700°C reaction temperatures and/or shallow, vigorously bubbling beds, will be studied. The effect of SiH_4 concentration on dust production will also be carefully measured in a 1-inch inside diameter quartz FBR and in the 2-inch FBR.

TITLE: Modeling of Silicon Particle Growth. A Progress Report.

AUTHOR: A. K. Praturi, G. C. Hsu and R. Lutwack

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April-1979

REPORT NO: DOE/JPL-1012-20 and 5101-105

ABSTRACT: Efforts at the Jet Propulsion Laboratory toward the production of pure polycrystalline silicon are centered on the concept of silicon particle growth in a fluidized bed reactor (FBR) and a continuous flow pyrolyzer (CFP). The CFP possibly can provide the seed particles which will be grown to longer sizes in the FBR. In both the reactors polycrystalline silicon is obtained from the pyrolysis of silane. A part of the JPL effort is to develop a model of silicon particle growth for the purpose of predicting particle growth rates and product particle size distributions in the FBR and the CFP. This report describes the mathematical models of silicon particle growth in the FBR and the CFP.

TITLE: On the Modeling of Silane Pyrolysis in a Continuous Flow Reactor.

AUTHOR: A. K. Praturi, G. C. Hsu and R. Jain

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1979

REPORT NO: DOE/JPL-1012-21 and 5101-106

ABSTRACT: Silane pyrolysis in a continuous flow pyrolyzer is a simple process that is currently being developed for producing solar cell grade silicon. The process involves complex phenomena, however, including thermal decomposition of silane, nucleation and growth of silicon particles, and mass and heat transfer. Modeling the effects of transport phenomena on silane pyrolysis in a continuous flow pyrolyzer is discussed in this report. One- and two-dimensional models are developed to predict velocity, temperature, and concentration profiles in the reactor. The one-dimensional model has been implemented as a computer code.

TITLE: Purification of Silicon by the Silicon Fluoride Transport Process A Thermochemical Study.

AUTHOR: R. A. Rhein

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1979

REPORT NO: DOE/JPL-1012-18 - 5101-107

ABSTRACT: A computer-assisted thermochemical equilibrium analysis was conducted for the silicon transport reaction:

$$Si(s) + SiF_4(g) = (intermediates) = Si(s) + SiF_4(g)$$

The calculations indicated that a substantial transport rate should be possible at temperatures of 1700 K and one atmosphere pressure.

Computations were made to determine whether the elemental impurities present in metallurgical-grade silicon would transfer in this process. It was concluded that aluminum, chromium, copper, iron, manganese, molybdenum, nickel, vanadium, and zirconium would not transfer, but that boron, magnesium, phosphorus, and titanium would transfer.

TITLE: Silicon Preparation and Purity from the Reaction of Sodium with Silicon Tetrafluoride and Silicon Tetrachloride.

AUTHOR: R. A. Rhein

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1979

REPORT NO: DOE/JPL-1012-19 and 5101-108

ABSTRACT: Thermochemical equilibrium computations for the preparation of silicon (Si) by the reaction between sodium (Na), either liquid or vapor, with silicon tetrafluoride (SiF_4) and silicon tetrachloride ($SiCl_4$) are presented. Computations indicate that SiF_4 reacts with either liquid or gaseous Na to produce temperatures sufficiently high to form molten Si. Liquid Na reacts with SiF_4 to produce substantially higher Si yields than does the free combustion reaction with Na vapor; however, the Na vapor/SiF_4 reaction, if temperature-constrained at the Si melting point, produces an expected Si yield close to 100%.

A stoichiometric mixture of liquid Na and $SiCl_4$ vapor reacts to produce liquid Si, gaseous sodium chloride (NaCl), and a small concentration of Si subhalides. Gaseous Na, however, reacts with $SiCl_4$ to form entirely gaseous reaction products and a high yield of Si (liquid) but subhalide concentrations are greater than when liquid Na is used.

The reactions of a number of impurity elements in Na, during the course of the Na-Si halide reaction, have been described. Of those considered, only calcium (Ca), magnesium (Mg), phosphorus (P), and strontium (Sr) are expected to co-exist to any extent in Na vapor and none is expected to be in the Si products if excess Si halide is used in the Na-Si halide reactions.

TITLE: The Effects of Impurities on the Performance of Silicon Solar Cells.

AUTHOR: K. A. Yamakawa

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1981

REPORT NO: DOE/JPL-1012-57 and 5101-189

ABSTRACT: The major factors that determine the tolerable concentrations of impurities in silicon feedstock for solar cells used in power generation are discussed in this report. It is concluded that a solar-grade silicon can be defined only for a specific manufacturing process. It is also concluded that it is the electrical effects, efficiency and resistivity, that are dominant in determining tolerable concentrations of impurities in the silicon feedstock. Crystal growth effects may become important when faster growth rates and larger crystal diameters are developed and used.

Silicon Material
Contractor Abstract

TITLE: Final Report. Silicon Material Task Part III.

AUTHOR: Roques, R. A.; Coldwell, D. M.

CORPORATE AUTH: Texas Instruments, Inc.

CONTRACT NO: 954412

DATE: January 1977

REPORT NO: ERDA/JPL/954412--77/1

ABSTRACT: The feasibility of a process for carbon reduction of low impurity silica in a plasma heat source was investigated to produce low-cost (less than $10 per kilogram) solar-grade silicon. Theoretical aspects of the reaction chemistry were studied with the aid of a computer program using iterative free energy minimization. These calculations indicate a threshold temperature exists at 2400 k below which no silicon is formed. The computer simulation technique of molecular dynamics was used to study the quenching of product species. An experimental laboratory-scale plasma reactor was fabricated and used to optimize process variables for reaction conditions which yielded the maximum amount of silicon product. The conditions for maximum yield were 14 kw power, 3 liters/min plasma gas flow, and reactant feed rate of 0.02 gm/min. Maximum silicon content, measured by wet analysis, of the sintered condensate was 33%. Reactant mixtures which yielded the greatest amount of silicon were those containing between 1.5:1 and 1.9:1 carbon to silica mole ratios. Silicon was observed to form "IN-SITU" on the tip of the feed rod of mixtures containing optimum reactant quantities. The plasma approach proved technically feasible to produce relatively pure silicon. However, the results from this very small scale unit suggest a highly inefficient energy utilization due to poor heat transfer characteristics of the plasma flame coupled with a low overall yield of recoverable silicon indicate the process to be economically unattractive. Carbon monoxide and CO_2 in the exhaust gases and silicon content of the product condensate support the identified condensed-phase reaction mechanism.

TITLE: Determination of a Definition of Solar Grade Silicon

AUTHOR: Henry W. Gutsche

CORPORATE AUTH: Monsanto Research Corporation,

CONTRACT NO: 954338

DATE: September 1977

REPORT NO: 954338-77/1

ABSTRACT: This final report gives the results of work performed by Monsanto Research Corporation to inquire into the effects of the impurities Al, C, Cr, Cu, Fe, Mg, Mn, Na, Ni, O, Ti, V, and Zr on the performance of silicon solar cells. A series of experimental silicon crystals were prepared containing controlled amounts of these impurities in otherwise semiconductor-grade silicon single crystals. Using these crystals, solar cells were prepared and the solar energy conversion efficiencies of these devices were measured against a standard cell provided by Jet Propulsion Laboratory. As expected, cell efficiency was found to be degraded in various degrees by most of the impurities under investigation. Degradation of efficiency was most severe in the presence of titanium and vanadium. Silicon solar cell material may contain as much as 10^{17} atoms/cm^3 of aluminum or carbon, 10^{16} atoms/cm^3 of nickel, but only about 10^{15} atoms/cm^3 of manganese, chromium, iron, copper, zirconium, and magnesium to yield a solar device of acceptable performance.

TITLE:	Final Report. Lifetime and Diffusion Length Measurements on Silicon Materials and Solar Cells.
AUTHOR:	Siegfried Othmer and Susan C. Chen
CORPORATE AUTH:	Northrop Research and Technology Center
CONTRACT NO:	954614
DATE:	November 1977
REPORT NO:	ERDA/JPL 954614-77/1

ABSTRACT: Experimental methods were evaluated for the determination of lifetime and diffusion length in silicon intentionally doped with potentially lifetime-degrading impurities found in metallurgical grade silicon, impurities which may be residual in low-cost silicon intended for use in terrestrial flat-plate arrays. Results obtained by these methods were compared for mutual consistency. Lifetime measurements were made using a steady-state photoconductivity method, which was compared with a photoconductivity decay technique. Diffusion length determinations were made using short-circuit current measurements under penetrating illumination. This method was compared with a direct measurement of diffusion length using a scanning electron microscope. Mutual consistency among all experimental methods was verified, but steady-state photoconductivity was found preferable to photoconductivity decay at short lifetimes and in the presence of traps. The effects of a number of impurities on lifetime in bulk material, and on diffusion were compared with those obtained by others on the same material and devices using different techniques. General agreement was found in terms of the hierarchy of impurities which degrade the lifetime.

C-2

TITLE: Final Report. Analysis of Effects of Impurities Intentionally Incorporated into Silicon

AUTHOR: Frank M. Uno

CORPORATE AUTH: Spectrolab, Inc.

CONTRACT NO: 954694

DATE: December 1977

REPORT NO: ERDA/JPL 954694-77/4

ABSTRACT: A methodology has been developed and implemented to allow silicon samples containing intentionally incorporated impurities to be fabricated into finished solar cells under carefully controlled conditions. The electrical and spectral properties were then measured for each group processed. All 33 lots of Group "C", 14 lots of Group "CM" and 16 lots of Group "F" have been fabricated into cells and tested.

TITLE:	Final Report, October 9, 1975-July 9, 1978. Evaluation of Selected Chemical Processes for Production of Low-Cost Silicon (Phases I and II). Silicon Material Task
AUTHOR:	Blocher, J.M, Jr.; Browning, M. F.
CORPORATE AUTH:	Battelle Columbus Laboratories
CONTRACT NO:	954339
DATE:	9 July 1978
REPORT NO:	DOE/JPL/954339-11
ABSTRACT:	The zinc reduction of silicon tetrachloride in a fluidized bed of seed particles to yield a granular product was studied along with several modifications of the thermal decomposition or hydrogen reduction of silicon tetraiodide. Although all contenders were believed to be capable of meeting the quality requirements of the LSA Project, it was concluded that only the zinc reduction of the chloride could be made economically feasible at a cost below $10/KG silicon (1975 dollars). Accordingly, subsequent effort was limited to evaluating that process. A miniplant, consisting of a 5-CM-diameter fluidized-bed reactor and associated equipment was used to study the deposition parameters, temperature, reactant composition, seed particle size, bed depth, reactant throughput, and methods of reactant introduction. It was confirmed that the permissible range of fluidized-bed temperature was limited at the lower end by zinc condensation (918°C) and at higher temperatures by rapidly decreasing conversion efficiency by 0.1 percent per degree C from 72 percent (thermodynamic) at 927 for a stoichiometric mixture. Use of a graded bed temperature was shown to increase the conversion efficiency over that obtained in an isothermal bed. Other aspects of the process such as the condensation and fused-salt electrolysis of the $ZNCL_2$ by-product for recycle of zinc and chlorine were studied to provide information required for design of a 50 MT/year experimental facility, visualized as the next stage in the development. Projected silicon costs of $7.35 and $8.71 per KG (1975 dollars) for a 1000 MT/year facility were obtained, depending upon the number and size of the fluidized-bed reactors and $ZNCL_2$ electrolytic cells used. An energy payback time of 5.9 months was calculated for the product silicon.

TITLE:	Synthesis of Silane and Silicon in a Non-Equilibrium Plasma Jet
AUTHOR:	H. F. Calcote
CORPORATE AUTH:	AeroChem Research Laboratories, Inc.
CONTRACT NO:	954560
DATE:	October 1978
REPORT NO:	954560-78/8

ABSTRACT:

The original objective of this program was to determine the feasibility of high volume, low-cost production of high purity silane or solar cell grade silicon using a non-equilibrium plasma jet. The emphasis was changed near the end of the program to determine the feasibility of preparing photovoltaic amorphous silicon films directly using this method. The non-equilibrium plasma jet is produced by partially dissociating hydrogen to hydrogen atoms in a 50 to 100 Torr glow discharge and expanding the H/H_2 mixture through a nozzle. A high flux density of hydrogen atoms is thus produced at concentrations of about 3 mol % with about 30% energy utilization efficiency. The jet is mixed with a second reactant and the reaction proceeds at a temperature of 400 to 600 K to produce products. Yields of SiH_4 $SiHCl_3$, or SiH_2Cl_2 from $SiCl_4$ and $SiHCl_3$ were too low to be economically attractive. However, both amorphous and polycrystalline silicon films which strongly adhered to Pyrex, Vycor, aluminum, or carbon where prepared with either $SiCl_4$ reactant were more difficult to prepare; they were prepared by carefully cleaning the aluminum substrate, diluting the SiH_4 with about 90% argon, and forming the glow discharge between the mixing nozzle and the aluminum substrate. Doping such films with P by adding PH_3 reduced the electrical resistivity by two orders of magnitude. The non-equilibrium plasma jet should be further evaluated as a technique for producing high efficiency photovoltaic amorphous silicon films.

TITLE:	Interim Report. LSA Silicon Material Task Closed-Cycle Process Development.
AUTHOR:	R. A. Roques
CORPORATE AUTH:	Texas Instruments Incorporated
CONTRACT NO:	955006
DATE:	December 1978
REPORT NO:	DOE/JPL-955006-78/2

ABSTRACT: This report summarizes the Jet Propulsion Laboratory Low-Cost Solar Array Project Contract 955006 "Closed-Cycle Process for Low-Cost Solar Silicon Using a Rotary Chamber Reactor", which was active from August 10, 1978 to December 8, 1978. This program was Phase I of an effort to achieve production of low-cost solar-grade polysilicon from metallurgical-grade silicon in a closed-cycle process. Impure silicon would be converted to trichlorosilane by reaction with by-product silicon tetrachloride, and the trichlorosilane thermally decomposed in a rotary drum reactor. The technical restrictions to development of the program approach were based on minimizing new technology requirements by using existing technology to reduce the timing, risk, and cost of achieving production capability. The deficiencies in the established Siemens polysilicon process were identified and systematically eliminated to achieve a simple, continuous, easily scalable, low-cost process. The process was begun with the design of the two major items of untested equipment, the silicon tetrachloride by-product converter and the Rotary Drum Reactor (RDR) for deposition of silicon from trichlorosilane. The design criteria of the initial laboratory equipment included consideration of the reaction chemistry, thermodynamics, and other technical factors. Design and construction of the laboratory equipment was completed. Preliminary silicon tetrachloride conversion experiments confirmed the expected high yield of trichlorosilane, up to 98% of theoretical conversion. A preliminary solar-grade polysilicon cost estimate, including capital costs considered extremely conservative, of $6.91/kg supports the potential of this approach to achieve the cost goal. The closed-cycle process appears to have a very likely potential to achieve LSA goals.

TITLE: Final Report. The Production of Solar Cell Grade Silicon from Bromosilanes

AUTHOR: J. Schumacher

CORPORATE AUTH: J. C. Schumacher Co.

CONTRACT NO: 954914

DATE: January 1979

REPORT NO: DOE/JPL-954914-79/5

ABSTRACT: Based upon a chemical engineering analysis of existing semiconductor grade polycrystalline silicon processes, Cost Element Objectives for (1) Capital Equipment, (2) Raw Materials, (3) Labor, and (4) Utilities were established to meet the LSA Project Silicon Materials Task Cost Objective of $10/kg for Solar Cell Grade (SCG) Silicon. A Continuous Flow Reactor (CFR) process based on the hydrogen reduction if the bromosilanes $SiBr_4$ and $SiHBr_3$ was proposed by the J. C. Schumacher Company to meet these Cost Element Objectives, which resulted in the letting of JPL Contract 954914 to the Company. Initial experiments carried out as part of this contract, directed at obtaining overall yield data for bromosilane reduction in the CFR, indicated the need for increased reactor residence time and deposition substrate particle packing density to fully characterize the kinetics (rate) and thermodynamics (yield) of observed silicon production. Fluidized bed experiments were therefore initiated to overcome these experimental difficulties, which showed both thermal decomposition and hydrogen reduction of $SiHBr_3$ in a fluid bed reactor to present attractive closed-loop processes for producing SCG polycrystalline silicon consistant with Cost Element Objectives derived earlier. No process selection could be made, however, due to the fact that preliminary optimization of 2 of 3 process stages in each case during the course of the experimental program showed comparable attainment of Cost Element Objectives. Further experiments to complete process selection and preliminary process economic evaluation and design are therefore suggested.

TITLE: Final Report Phases I and II. Feasibility of the Silane Process for Producing Semiconductor-Grade Silicon. Period Covered: October 1975 - March 1979

CORPORATE AUTH: Union Carbide Corporation

CONTRACT NO: 954334

DATE: June 1979

REPORT NO: DOE/JPL-954334-79/10

ABSTRACT: The commercial production of low-cost semiconductor-grade silicon is an essential requirement of the JPL/DOE (Department of Energy) Low-Cost Solar Array (LSA) Project. A 1000-metric-ton-per-year commercial facility using the Union Carbide Silane Process will produce molten silicon for an estimated price of $7.56/kg (1975 dollars, private financing), meeting the DOE goal of less than $10/kg.

Conclusions and technology status are reported for both contract phases, which had the following objectives: 1) establish the feasibility of Union Carbide's Silane Process for commercial application, and 2) Develop an integrated process design for an Experimental Process System Development Unit (EPSDU) and a commercial facility, and estimate the corresponding commercial plant economic performance.

To assemble the facility design, the following work was performed: (a) collection of Union Carbide's applicable background technology; (b) design, assembly, and operation of a small integrated silane-producing Process Development Unit (PDU); (c) analysis, testing, and comparison of two high-temperature methods for converting pure silane to silicon metal; and (d) determination of chemical reaction equilibria and kinetics, and vapor-liquid equilibria for chlorosilanes.

TITLE: Final Report. Composition Measurements by Analytical Photon Catalysis

AUTHOR: David G. Sutton, et al

CORPORATE AUTH: Aerospace Corporation

CONTRACT NO: 955201

DATE: September 1979

REPORT NO: DOE/JPL 955201-79/4

ABSTRACT: The object of this research is to assess the applicability of the photon catalysis technique for effecting composition analysis of silicon samples. In particular, our technique is to be evaluated as a detector for the impurities Al, Cr, Fe, Mn, Tr, V, Mo and Zr. During the first year we have detected Al, Cr, Fe, Mn, Ti and Si with the photon catalysis method. We have established the best flourescence lines to monitor and determined initial sensitivities to each of these elements by atomic absorption calibration. In the course of these tests vapor pressure curves for these six pure substances have also been mapped. We have also studied the detection of these impurities in silicon matrices. The evaporation process was shown to be congruent; thus, our spectral analysis of the vapor will yield the composition of the bulk sample. In addition to these mainline tasks, much ancillary information was obtained. The emission signatures were determined for several additional elements including As, Bi, B, Ca, Cu, Cr, Ga, Ge, MG, Na, P and Pb. Ionic emission lines for Ca and Mg were determined to be useful for analysis. Pulsed sample introduction was examined and determined that as little as 1 nanogram of lead is detectable in a single shot. As a result of these studies we have concluded that the photon catalysis technique is suitable for bulk analysis of solar grade silicon. The ancillary data also suggest that gaseous feedstocks in the form of metal hydrides can be analyzed by this technique and that pulsed sampling techniques are compatible. This last conclusion suggests the possibility of developing a surface analysis instrument by combining laser microprobe and photon catalysis technology.

TITLE: Final Report. Solar Silicon via the Dow Corning Process for the Silicon Material Task.

AUTHOR: L. P. Hunt and V. D. Dosaj

CORPORATE AUTH.: Dow Corning Corporation

CONTRACT NO: 954559

DATE: October 1979

REPORT NO: DOE/JPL 954559-78/7

ABSTRACT: The process developed under this contract meets the LSA Project objective of demonstrating technical feasibility for high-volume production of solar-cell-grade silicon. The process consists of producing silicon from pure raw materials via the carbothermic reduction of quartz. This silicon was then purified to solar grade by impurity segregation during Czochralski crystal growth. Commercially available raw materials were used to produce 100 kg quantities of silicon during 60-hour periods in a Direct Arc Reactor. This silicon had impurity concentrations of less than 10 ppmw each, except for Al and Fe (50-100 ppmw). Purification of this material by Czochralski crystal growth gave silicon of semiconductor purity, except for Al (1 ppma), B (7 ppma, 0.1 ohm-cm), and P (0.5) ppma. This silicon produced a single crystalline ingot, during a second Czochralski pull, that was fabricated into solar cells having AM1 efficiencies ranging from 8.2% to greater than 14% (AR-coated). An energy analysis of the entire process indicated a 5-month payback time. A price of $12.15 (1980 dollars, with profit) was estimated for a 3000-metric-ton-per-year plant. Further process development is recommended based upon technical success, estimated product cost, and commercially-available technology already existing in the industry that can be applied to process scale-up.

TITLE: Quarterly Report. Development of Model and Computer Code to Describe Solar Grade Silicon Production Processes.

AUTHOR: R. Srivastava and R. K. Gould

CORPORATE AUTH: AeroChem Research Laboratories, Inc.

CONTRACT NO: 954862

DATE: December 1979

REPORT NO: DOE/JPL-954862-79/8

ABSTRACT: This report describes models and computer codes which may be used to describe flow reactors in which high purity, solar grade silicon is produced via reduction of gaseous silicon halides. A prominent example of the type of process which may be studied using the codes developed in this program is the $SiCl_4$/Na reactor currently being developed by the Westinghouse Electric Corp. During this program two large computer codes were developed. The first is the CHEMPART code, an axisymmetric, marching code wich treats two-phase flows with models describing detailed gas-phase chemical kinetics, particle formation, and particle growth. This code, based on the AeroChem LAPP (Low Altitude Plume Program) code can be used to describe flow reactors in which reactants mix, react, and form a particulate phase. Detailed radial gas-phase composition, temperature, velocity, and particle size distribution profiles are computed. Also, deposition of heat, momentum, and mass (either particulate or vapor) on reactor walls is described. The second code is a modified version of the GENMIX boundary layer code which is used to compute rates of heat, momentum, and mass transfer to the reactor walls. This code lacks the detailed chemical kinetics and particle handling features of the CHEMPART code but has the virtue of running much more rapidly than CHEMPART, while treating the phenomena occurring in the boundary layer in more detail than can be afforded using CHEMPART. These two codes have been used in this program to predict particle formation characteristics and wall collection efficiencies for SiCl/ flow reactors. It is found that large input enthalpies (large H-atom inputs) are required to prevent Si(1) droplet formation. (This enthalpy is supplied by introducing large quantities of arc-heated hydrogen in the Westinghouse reactor.) On the other hand, large hydrogen flows mean short transit times of gas through the reactor and hence short times for wall collection of Si. It is anticipated that an important application of these codes will be their use in finding operation conditions where droplet formation may be minimized and high collection efficiencies may still be realized in reactors of the Westinghouse type.

TITLE: Final Report. Silicon Halide-Alkali Metal Flames as a Source of Solar Grade Silicon

AUTHOR: D. B. Olson and W. J. Miller

CORPORATE AUTH: AeroChem Research Laboratories, Inc.

CONTRACT NO: 954777

DATE: January 1980

REPORT NO: DOE/JPL 954777-80/8

ABSTRACT: The object of this program was to determine the feasibility of using continuous high-temperature reactions of alkali metals and silicon halides to produce silicon in large quantities and of suitable purity for use in the production of photovoltaic solar cells. Equilibrium calculations showed that a range of conditions were available where silicon was produced as a condensed phase but the byproduct alkali metal salt was a vapor. A process was proposed using the vapor phase reaction of Na with $SiCl_4$. Low pressure experiments were performed demonstrating that free silicon was produced and providing experience with the construction of reactant vapor generators. Further experiments at higher reagent flow rates were performed in a low temperature flow tube configuration with co-axial injection of reagents. Relatively pure silicon was produced in these experiments. A high temperature graphite flow tube was built and continuous separation of Si from NaCl was demonstrated. A larger-scaled well-stirred reactor was built. Experiments were performed to invesigate the compatibility of graphite-based reactor materials of constructions with sodium. At 1100-1200 K none of these materials were found to be suitable. At 1700 K the graphite and silicon carbide were damaged.

TITLE: Final Report. Analysis of The Effects of Impurities in Silicon.

AUTHOR: J. H. Wohlgemuth and M. N. Giuliano

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 955307

DATE: January 1980

REPORT NO: DOE/JPL-955307/4

ABSTRACT: The purpose of this program was to conduct a solar cell fabrication and analysis program to determine the effects on the resultant solar cell efficiency of impurities intentionally incorporated into silicon. The program employed "flight-quality" technologies and quality assurance typical of an experienced solar cell manufacturer to assure that variations in cell performance are due to the impurities incorporated in the silicon. A rigid program of documentation and decontamination procedures was instituted. The cells from control silicon including verification, monitor and control cells have exhibited average AM0 cell efficiencies of nearly 13% at 25°C (in excess of 15% AM1 at 25°C). No cross-contamination of control or monitor cells was observed. Cells with various doping materials and doping levels were fabricated.

TITLE: Final Report. Novel Dupl... Vapor-Electrochemical Method for Silicon Solar Cells.

AUTHOR: L. Nanis, A. Sanjurjo, K. M. Sancier, V. K. Kapur, etal

CORPORATE AUTH: SRI International

CONTRACT NO: 954471

DATE: March 1980

REPORT NO: DOE/JPL-9''471-80/13

ABSTRACT: A process has been developed for the economic production of high purity Si from inexpensive reactants, based on the Na reduction of SiF_4 gas. The products of reaction (NaF, Si) are separated by either aqueous leaching or by direct melting of the NaF-Si product mixture. Impurities known to degrade solar cell performance are all present at sufficiently low concentrations so that melt solidification (e.g., Czochralski) will provide a silicon material suitable for solar cells.

TITLE:	Final Report covering the period October 1, 1975-February 6, 1981. Process Feasibility Study in Support of Silicon Material Task I.
AUTHOR:	Carl L. Yaws, Ku-Yen Li, Jack R. Hopper, C. S. Fang and Keith C. Hansen
CORPORATE AUTH:	Lamar University
CONTRACT NO:	954343
DATE:	February 6, 1981
REPORT NO:	DOE/JPL 954343-81/21

ABSTRACT: The Low-Cost Solar Array (LSA) Project at Jet Propulsion Laboratory (JPL) in Pasadena, California is being funded by the Department of Energy (DOE) for effective cost reduction in the production of silicon for solar cells. This study reports work performed at Lamar University in support of the LSA Project and presents results for process system properties, chemical engineering and economic analyses of the new technologies and processes being developed for the production of lower cost silicon for solar cells.

Analyses of process system properties are important for chemical materials involved in the several processes under consideration for semiconductor and solar cell grade silicon production. Major physical, thermodynamic and transport property data are reported for the following silicon source and processing chemical materials: silane, silicon tetrachloride, trichlorosilane, dichlorosilane, silicon tetrafluoride and silicon.

The property data are reported for critical temperature, critical pressure, critical volume, vapor pressure, heat of vaporization, heat capacity, density, surface tension, viscosity, thermal conductivity, heat of formation and Gibb's free energy of formation. The reported property data are presented as a function of temperature to permit rapid usage in research, development and production engineering.

Chemical engineering analyses involving the preliminary process design of a plant (1000MT/yr capacity) to produce silicon via the technology under consideration were accomplished for the following processes: UCC silane process for silicon; BCL process of silicon - case A; BCL process for silicon - case B; conventional polysilicon process (Siemens Technology); SiI_4 decomposition process and DCS process (dichlorosilane).

TITLE: Final Report. Development of Processes for the Production of Solar Grade Silicon from Halides and Alkali Metals. Phase I & II

AUTHOR: C. R. Dickson and R. K. Gould (Phase I); C. R. Dickson, W. Felder and R. K. Gould (Phase II)

CORPORATE AUTH: AeroChem Research Laboratories, Inc.

CONTRACT NO 955491

DATE: March 1981

REPORT NO: DOE/JPL 955491-81/6

ABSTRACT: Phase I of this program was directed toward the development of processes involving high temperature reactions of silicon halides with alkali metals for the production of solar grade silicon in volume at low cost. Experiments were performed to evaluate product separation and collection processes, measure heat release parameters for scaling purposes, determine the effects of reactants and/or products on materials of reactor construction, and make preliminary engineering and economic analyses of a scaled-up process. Samples of the silicon product were delivered to JPL for evaluation of solar cell performance.

The objective of Phase II of the program was to characterize the kinetics and mechanism of the formation and growth of silicon particles from the decomposition of silane at high temperatures. The experiments were aimed at determining the rates at which gas-phase species form silicon particle precursors, the time required for silane decomposition to produce particles, and the competing rate of growth of silicon seed particles injected into a decomposing silane environment.

TITLE:	Final Report. For period July 1978 to January 1981. Evaluation of Selected Chemical Processes for Production of Low-Cost Silicon. Phase III
AUTHOR:	J. M. Blocher, Jr., M. F. Browning and D. H. Seifert
CORPORATE AUTH:	Battelle Columbus Laboratories
CONTRACT NO:	954339
DATE:	March 31, 1981
REPORT NO:	DOE/JPL-954339-81/21
ABSTRACT:	As a phase of a program to establish the engineering feasibility of the process for producing silicon by the zinc vapor reduction of silicon tetrachloride, a Process Development Unit (PDU), which consisted of the four major units of the process, was designed, installed, and experimentally operated. The PDU was sized to 50MT/yr. The deposition took place in a fluidized bed reactor. As a consequence of the experiments, improvements in the design and operation of these units were undertaken and their experimental limitations were partially established.

TITLE: Final Report. Investigation of the Hydrogenation of $SiCl_4$.

AUTHOR: Jeffrey Y. P. Mui and Dietmar Seyferth

CORPORATE AUTH: Massachusetts Institute of Technology

CONTRACT NO: 955382

DATE: April 1981

REPORT NO: DOE/JPL-955382-79/8

ABSTRACT: A two-year research and development program was initiated in April of 1979 to study the hydrochlorination of silicon tetrachloride and metallurgical grade (m.g.) silicon metal to trichlorosilane. This complementary research and development effort is conducted to supplement the engineering process development activities for the Experimental Process System Development Unit (EPSDU) under the Union Carbide Contract No. 954334 of the JPL Low-Cost Solar Array (LSA) Project. A laboratory scale pressure reactor was constructed to study this reaction at pressures up to 500 psig. Reaction kinetic measurements were carried out as a function of reactor pressure, reaction temperature and $H_2/SiCl_4$ feed ratio. The conditions for reaction kinetic data collected at 500 psig were specifically designed to complement the engineering design for the hydrochlorination reactor in the Union Carbide EPSDU, silane-to-silicon process. The effect of an added copper catalyst on the reaction rate was investigated. Different partical size distributions of the m.g. silicon metal were utilized to study the effect of total solid surface area on the rate of the hydrochlorination reaction. Experiments were carried out with the object to study the life of the silicon mass bed with and without the presence of a copper catalyst. The effect of a prolonged reaction on the reaction rate was investigated. A corrosion study was made on type 304 stainless steel and Incoloy 800H under the actual hydrochlorination reaction environment.

TITLE: Final Technical Report. Development of a Process for High Capacity Arc Heater Production of Silicon for Solar Arrays for Silicon Materials Task

AUTHOR: Maurice G. Fey

CORPORATE AUTH: Westinghouse Electric Corporation

CONTRACT NO: 954589

DATE: May 1981

REPORT NO: DOE/JPL 954589-80/9

ABSTRACT: During the performance of the program, the experimental verification system for the production of silicon via the arc heater-sodium reduction of $SiCl_4$ was designed, fabricated, installed, and operated. Each of the attendant subsystems was checked out and operated to insure performance requirements. These subsystems included: the arc heaters/reactor, cooling water system, gas system, power system, control and instrumentation system, Na injection system, $SiCl_4$ injection system, effluent disposal system and gas burnoff system.

Prior to introducing the reactants (Na and $SiCl_4$) to the arc heater/reactor, a series of gas only-power tests was conducted to establish the operating parameters of the three arc heaters of the system. Following the successful completion of the gas only-power tests and the readiness tests of the sodium and $SiCl_4$ injection systems, a shakedown test of the complete experimental verification system was conducted.

TITLE: Sixth Quarterly Progress Report. 1 January to 31 March 1981. Development of a Polysilicon Process Based on Chemical Vapor Deposition (Phase I)

AUTHOR: J. McCormick, A. Arvidson, D. Sawyer and F. Plahutnik

CORPORATE AUTH: Hemlock Semiconductor Corporation

CONTRACT NO: 955533

DATE: June 1981

REPORT NO: DOE/JPL 955533-81-6

ABSTRACT: The goal of this program is to demonstrate that a dichlorosilane-based reductive chemical vapor deposition (CVD) process is capable of producing, at low cost, high quality polycrystalline silicon. Physical form and purity of this material will be consistent with LSA material requirements for use in the manufacture of high efficiency solar cells.

Testing of decomposition reactor heat shields to insure that the shield provides adequate personnel protection, assuming a worst case explosion, was completed. Minor modifications to a production reactor heat shield provided adequate heat shield integrity.

Construction of the redesigned PDU (Process Development Unit) to accommodate all safety related information is proceeding on schedule. Start-up is scheduled for June 1981.

Construction was completed on a feed system for supplying DCS to an intermediate sized reactor.

Preliminary EPSDU design was completed. Base case assumption was for a 220 ton/yr unit which would not include a hydrogenation process.

TITLE: Final Technical Report. Study of the Effects of Impurities on the Properties of Silicon Materials and Performance of Silicon Solar Cell

AUTHOR: C. T. Sah

CORPORATE AUTH: C. T. Sah Associates

CONTRACT NO: 954685

DATE: October 1981

REPORT NO: DOE/JPL 954685-81/5

ABSTRACT: This fifth technical report, also the final report, covers studies on the effect of impurities and defects on the performance of silicon solar cells which were not reported in the previous four technical reports. It describes a theoretical study of the effect of defects across the back-surface-field junction on the performance of high-efficiency and thin solar cells, using a developed-perimeter device model for the three-dimensional defects. It shows that very significant degradation of open-circuit voltage can occur even if there are only a few defects distributed in the bulk of the solar cell. Two new features in the thickness dependences of the fill factor and efficiency in impurity-doped back-surface-field solar cells are discovered in the exact numerical solution which are associated with the high injection level effect in the base and not predicted by the low-level analytical theory. What are believed to be the most accurate recombination parameters at the Ti center to date are also given and a new theory is developed which is capable of distinguishing an acceptor-like deep level from a donor-like deep level using the measured values of the thermal emission and capture cross sections. Using the measured emission-capture cross section ratio, this theory can also provide information concerning the magnitude of the lattice distortion around an impurity atom before and after the capture or emission of an electron or a hole at the impurity center.

TITLE: Quarterly Progress Report - July-September 1981. Phase III. Experimental Process System Development Unit for Producing Semiconductor-Grade Silicon Using the Silane-to-Silicon Process

CORPORATE AUTH: Union Carbide Corporation

CONTRACT NO: 954334

DATE: November 1981

REPORT NO: DOE/JPL 954334-81/20

ABSTRACT: This work covers work performed in July, August and September 1981 on the DOE/JPL Contract 954334, Phase III. This phase consists of the engineering design, fabrication, assembly, operation, economic analysis, and process support R&D for an Experimental Process System Development Unit (EPSDU).

Union Carbide has entered into negotiation with DOE/JPL to cost share in the EPSDU program by continuing with construction and start-up with company funds. This has been necessary due to severe government budget recisions in the solar and other energy related programs. As a consequence of such a plan, UCC will relocate the EPSDU facility to a West Coast location to complete and run the facility.

The design activity is complete and mechanical and electrical bid packages will be reissued to obtain bids at the new EPSDU location. About 95% of purchased equipment has been received and will be reshipped to the West Coast location.

The report generation part of the Data Collection System was completed in this quarter. The draft of the operations manual is about 50% complete and the design of the free-space system is continuing.

In the area of melting/consolidation, Kayex has demonstrated the system using silicon powder transfer, melting and shotting on a pseudo-continuous basis. Experimental activity ceases at the end of the quarter and documentation of the results and recommendations will be completed in the fourth quarter.

A proposal has been submitted to continue the very promising fluid-bed work in the next fiscal year with a relatively small budget. The EPSDU pilot plant will probably be funded by UCC in the next fiscal year pending a favorable agreement to be signed soon between DOE/JPL and Union Carbide.

TITLE: Quarterly Report. Investigation of the Hydrochlorination of $SiCl_4$.

AUTHOR: Jeffrey Y. P. Mui

CORPORATE AUTH: Solarelectronics, Inc.

CONTRACT NO: 956061

DATE: January 1982

REPORT NO: DOE/JPL-956061-2

ABSTRACT: A new two inch-diameter stainless steel reactor was designed and built to operate at pressures up to 500 psig for the experimental studies on the hydrochlorination of $SiCl_4$ and metallurgical grade (m.g.) silicon metal to $SiHCl_3$. The effect of pressure on the hydrochlorination reaction was studied. In order to clearly see the effect of pressure, the experiments were carried out at low reactor pressures of 73 psig and 150 psig, respectively. A large pressure effect on the hydrochlorination reaction was observed between the results of the low pressure experiments and the results of the high pressure experiments. Samples of the material for construction for the hydrochlorination reactor were prepared for the corrosion study. Materials include Type 304 stainless steel, carbon steel, Incoly 800H, Alloy 400 (Monel), Hastelloy B-2 (a Ni/Mo alloy), nickel and copper. These test samples were mounted in a stainless steel rack which was fitted inside the 2" reactor tube. The corrosion tests are in progress.

TITLE: Effect of Impurities and Processing on Silicon Solar Cells.

AUTHOR: R. H. Hopkins, J. R. Davis, A. Rohatgi, M. H. Hanes, and P. Rai-Choudhury

CORPORATE AUTH: Westinghouse R&D Center

CONTRACT NO: 954331

DATE: February 1982

REPORT NO: DOE/JPL 954331-82/13

ABSTRACT: This is the Final Report of a multiphase program conducted as part of the Silicon Materials Task of the LSA Project. The object of the program has been to investigate the effects of various processes, metal contaminants, and contaminant-process interactions on the properties of silicon and on the performance of terrestrial silicon solar cells. The study has encompassed topics such as thermochemical (gettering) treatments, base-doping concentration, base-doping type (n vs. p), grain boundary-impurity interaction in polycrystalline devices, and long-term effects of impurities and impurity impacts on high-efficiency cells, as well as a preliminary evaluation of some potential low-cost silicon materials. The work is now completed, and some of the highlights are given below.

Studies were made of the effects of various metallic impurities, introduced singly or in combination into Czochralski, float zone, and polycrystalline silicon ingots and into silicon ribbons grown by the dendritic web process. All crystals were analyzed chemically, microstructurally, electrically, and via solar cell fabrication and testing.

The solar cell data (collected from 238 experimental ingots) indicate that impurity-induced performance loss is caused primarily by a reduction in base diffusion length. An analytical model based on this observation has been developed and verified experimentally for both n- and p-base material.

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TITLE: Progress in Silicon Crystal Technology for Terrestrial Photovoltaic Solar Energy Conversion. Conducted as part of the Fourth Project Integration Meeting.

AUTHOR: John A. Zoutendyk

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1976

REPORT NO: 5101-12

ABSTRACT: During the course of the Fourth Project Intergration Meeting of the Low-Cost Silicon Solar Array Project, the Large Area Silicon Sheet Task conducted an intramural conference to discuss development progress in various aspects of the technology of preparing silicon ribbons, sheets, or wafers for use in the fabrication of solar cells. Brief papers were presented by the eleven contractors to the Task, as well as two by other laboratories and one by JPL.

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TITLE: Multi-Wire Slurry Wafering Demonstrations.

AUTHOR: C. P. Chen

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1978

REPORT NO: DOE/JPL-1012-78/7 - 5101-57

ABSTRACT: A series of ten slicing demonstrations on a multi-wire slurry saw, manufactured by Yasunaga Engineering Company of Japan and distributed by GEOS Corporation of Stamford, Connecticut, was made to evaluate the silicon ingot wafering capabilities. The results revealed that the present sawing capabilities can provide usable wafer area from an ingot 1.05 m^2/kg (e.g., kerf width 0.135 mm and wafer thickness 0.265 mm). Satisfactory surface qualities and excellent yield of silicon wafers were found. One drawback is that the add-on cost of producing wafers from this saw, as presently used, is considerably higher than the systems being developed by Varian and Crystal Systems for the Low Cost Silicon Solar Array Project (LSSA), Task II, primarily because the Yasunaga saw uses a large quantity of wire. The add-on cost can be significantly reduced by extending the wire life and/or by reuse of properly plated wire to restore the diameter.

TITLE:	Compatibility Studies of Various Refractory Materials in Contact with Molten Silicon.
AUTHOR:	T. O'Donnell, M. Leipold and M. Hagan
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	March 1978
REPORT NO:	DOE/JPL-1012-77/6 - 5101-53
ABSTRACT:	The production of low cost, efficient solar cells for terrestrial electric power generation involves the manipulation of molten silicon with a present need for noncontaminating high-temperature refractories to be used as containment vessels, ribbon-production dies and dip-coated substrates. Studies were conducted on the wetting behavior and chemical/physical interactions between molten silicon and various refractory materials.

TITLE: Structure of Deformed Silicon and Implications for Low Cost Solar Cells.

AUTHOR: N. Mardesich, M. H. Leipold, G. B. Turner and T. G. Digges

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1978

REPORT NO: DOE/JPL-1012-78/3 - 5101-56

ABSTRACT: The microstructure and minority carrier lifetime of silicon were investigated in uniaxially compressed silicon samples. The objective of the investigation was to determine if it is feasible to produce silicon solar cells from sheet formed by high temperature rolling. The initial structure of the silicon samples ranged from single crystal to fine-grained polycrystals. The samples had been deformed at strain rates of 0.1 to 8.5 sec^{-1} and temperatures of 1270-1380°C with subsequent annealing at 1270-1380°C.

Recrystallization was incomplete even after long anneals. A 10 hour anneal of fine-grained samples with as much as 51% strain only caused 95% of the samples to recrystallize and even then the recrystallized grains contained twin boundaries and dislocations. The recrystallization in the large grained samples was also incomplete and further, it has been shown that large grained material cracks readily during significant deformation (up to 40%). The major mode of recrystallization appears to be migration of existing boundaries into the deformed regions. Minority carrier diffusion length was drastically reduced by deformation and recovered only slightly with annealing. These results suggest that high temperature rolling of silicon to produce sheet for solar cells of high efficiency is not practical.

TITLE:	Determination of Bulk Diffusion Lengths for Angle-lapped Semiconductor Material via the Scanning Electron Microscope-A Theoretical Analysis.
AUTHOR:	Oldwig von Roos
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	May 1978
REPORT NO:	DOE/JPL-1012-78/8 and 5101-73
ABSTRACT:	A standard procedure for the determination of the minority carrier diffusion length by means of a scanning electron microscope (SEM) consists of scanning across an angle-lapped surface of a P-N junction and measuring the resultant short circuit current I_{sc} as a function of beam position. A detailed analysis of the I_{sc} originating from this configuration is presented. It is found that, for a point source excitation, the I_{sc} depends very simply on x, the variable distance between the surface and the junction edge. The expression for the I_{sc} of a <u>planar</u> junction device is well known. If d, the constant distance between the plane of the surface of the semiconductor and the junction edge in the expression for the I_{sc} of a planar junction is merely replaced by x, the variable distance of the corresponding <u>angle-lapped</u> junction, an expression results which is correct to within a small fraction of a percent as long as the angle between the surfaces is smaller than 10°.

TITLE: Effect of Grain Boundary in Silicon Sheet on Minority Carrier Diffusion Length and Solar Cell Efficiency

AUTHOR: T. Daud and K. M. Koliwad

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1978

REPORT NO: 5101-69

ABSTRACT: The diffusion length of minority charge carriers in silicon sheet containing grain boundaries has been measured by the electron beam induced current (EBIC) technique using a scanning electron microscope. Quantitative variation of diffusion length as a function of the distance from the grain boundary has been determined.

The results show that the effect of grain boundary extends to a distance equal to nearly one bulk diffusion length. Based on these results a concept of effective grain size has been proposed. The model shows that the difference between the effective grain size and the geometrical grain size depends strongly on the electronic properties of the silicon sheet. The effect of grain size on the efficiency of the solar cell has been analyzed within the framework of the model.

TITLE: Fracture Strength of Silicon Solar Cells.

AUTHOR: C. P. Chen

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1979

REPORT NO: DOE/JPL-1012-32 and 5101-137

ABSTRACT: In an effort to improve the reliability and lower the cost of solar cells, a test program has been developed to determine the nature and source of the flaw controlling the fracture of silicon solar cells and to provide information regarding the mechanical strength of cells.

This report contains results obtained in the first phase of a test program to develop improved methods for testing the mechanical strength of cells and to evaluate the fracture strength of typical Czochralski silicon solar cells 76 mm (3 in.) in diameter.

Significant changes in fracture strengths were found in seven selected in-process wafer-to-cell products from a manufacturer's production line. The fracture strength data were described by Weibull statistical analysis and can be interpreted in light of the exterior flaw distribution of the samples.

TITLE: Characterization of Deliberately Nickel-Doped Silicon Wafers and Solar Cells

AUTHOR: A. M. Salama

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1979

REPORT NO: DOE/JPL-1012-34, and 5101-139

ABSTRACT: Microstructural and electrical evaluation tests were performed on nickel-doped p-type silicon wafers before and after solar cell fabrication. The concentration levels of nickel in silicon were 5 x 10^{14}, 4 x 10^{15}, and 8 x 10^{15} atoms/cm^3. It was found that nickel precipitated out during the growth process in all three ingots. Clumps of precipitates, some of which exhibited star shapes, were present at different depths. If the clumps are distributed at depths ~20 μm apart and if they are larger than 10 μm in diameter, degradation occurs in solar cell electrical properties and cell conversion efficiency. The larger the size of the precipitate clump, the greater the degradation in solar cell efficiency. A large grain boundary around the cell effective area acted as a gettering center for the precipitates and impurities and caused improvement in solar cell efficiency. Details of the evaluation test results are given.

TITLE:	Sensitivity Analysis of the Add-On Price Estimate for the Edge-Defined Film-Fed Growth Process.
AUTHOR:	A. R. Mokashi and A. H. Kachare
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	March 1981
REPORT NO:	DOE/JPL-1012-55 and 5101-171

ABSTRACT:

The edge-defined film-fed growth (EFG) process is a silicon-sheet technology option that is being developed for the Low-Cost Solar Array (LSA) Project, which is sponsored by the Department of Energy.

In order to achieve the LSA price goal of $\$0.70/W_p$, certain required production-rate and sheet-quality standards must by met. One way to increase the production rate without seriously affecting the quality is to grow multiple ribbons simultaneously from a single machine.

This study presents a sensitivity analysis of the process add-on price in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and the production parameters such as growth rate, process yield and duty cycle, using a computer program developed specifically to do the sensitivity analysis with IPEG.

TITLE: Measurement of Surface Recombination Velocity for Silicon Solar Cells Using a Scanning Electron Microscope with Pulsed Beam.

AUTHOR: Taher Daud and Li-Jen Cheng

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1981

REPORT NO: DOE/JPL-1012-56 and 5101-176

ABSTRACT: In the design and fabrication of silicon solar cells approaching theoretically ultimate conversion efficiencies, surface recombination velocity plays a crucial role. A technique using a scanning electron microscope with pulsed electron beam has been developed for the measurement of this important parameter of silicon surfaces. It is shown that the surface recombination velocity, s, increases by an order of magnitude when an etched surface degrades, probably as a result of environmental reaction. A textured front-surface-field cell with a high-low junction near the surface shows the effect of minority carrier reflection and an apparent reduction of s, whereas a tandem-junction cell with n^+-p junction near the surface shows an increasing s value.

Electric fields at junction interfaces in front-surface-field and tandem-junction cells acting as minority carrier reflectors or sinks tend to alter the value of effective surface recombination velocity for different beam-penetration depths. A range of values of s from about 10^3 to 10^7 cm/sec has been found for different surfaces.

TITLE: Flat-Plate Solar Array Project. Sensitivity Analysis of the Add-On Price Estimate for the Silicon Web Growth Process.

AUTHOR: Anant R. Mokashi

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 15, 1981

REPORT NO: 5101-175

ABSTRACTS

The web growth process is a silicon-sheet technology option that is being developed for the Flat-Plate Solar Array (FSA) Project, which is sponsored by the U. S. Department of Energy.

In order to achieve the FSA price goal of $0.70/W$_p$, certain required production-rate and sheet-quality standards must be met. Based on research and development experience, base-case data for the technical and cost parameters that could be achieved for the technical and commercial readiness phase of the FSA project are projected.

This study presents a sensitivity analysis of the process add-on price, using the base-case data in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and the production parameters such as growth rate and run length, using a computer program developed specifically to do the sensitivity analysis with Improved Price Estimation Guidelines. The sensitivity analysis is also performed with respect to silicon price, sheet thickness and cell efficiency.

TITLE:	Flat-Plate Solar Array Project. Effect of Loading Rates on the Strength of Silicon Wafers.
AUTHOR:	C. P. Chen
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	December 15, 1981
REPORT NO:	5101-190
ABSTRACTS	The effect of loading rates on the strength of silicon wafers was evaluated under biaxial stress conditions at five loading rates and under four-point twisting at two loading rates and was found to be insignificant. The results showed no indication of time-dependent subcritical crack growth in silicon at room temperature in a laboratory environment. The mechanical-strength test of silicon solar cells can thus be determined at a rate as fast as a testing machine can respond, without loss of accuracy. This conclusion is important in that it shows that a high-speed solar-cell mechanical proof-testing machine can be sued in solar-cell manufacturing.

TITLE:	Low-Cost Solar Array Project. Proceedings of the Low-Cost Solar Array Wafering Workshop (8-10 June, 1981, The Pointe, Phoenix, Arizona).
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	February 1, 1982
REPORT NO:	5101-187
ABSTRACTS	The Low-Cost Solar Array Wafering Workshop was held on June 8-10, 1981, at The Pointe, Phoenix, Arizona, under the sponsorship of the Low-Cost Solar Array Project (since then renamed the Flat-Plate Array Project) of the Jet Propulsion Laboratory. The Workshop consisted of seven sessions covering all aspects of ingot wafering, including fixed- and free-abrasive sawing, materials, mechanisms, characterization, innovative concepts and economics. Twenty-seven papers were presented.

TITLE: Mathematical Analysis of the Photovoltage Decay (PVD) Method for Minority Carrier Lifetime Measurements.

AUTHOR: O. H. von Roos

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1982

REPORT NO: DOE/JPL-1012-65 and 5101-203

ABSTRACT: When the diffusion length of minority carriers becomes comparable with or larger than the thickness of a p-n junction solar cell, the characteristic decay of the photon-generated voltage results from a mixture of contributions with different time constants. The minority carrier recombination lifetime τ and the time constant ℓ^2/D where ℓ is essentially the thickness of the cell and D the minority carrier diffusion length, determine the signal as a function of time. It is shown that for ordinary solar cells (n^+-p junctions), particularly when the diffusion length L of the minority carriers is larger than the cell thickness ℓ, the excess carrier density decays according to $\exp(-t/\tau - \pi^2 Dt/4\ell^2)$, τ being the lifetime. Therefore, τ can be readily determined by the photovoltage decay (PVD) method once D and ℓ are known.

An analysis of this matter was published recently in the Journal of Applied Physics. This report offers details of its mathematical development.

Silicon Sheet
Contractor Abstracts

TITLE: Final Report. Thick Film Silicon Growth Techniques

AUTHOR: H. E. Bates

CORPORATE AUTH: Tyco Laboratories, Inc.

CONTRACT NO: 953365

DATE: April 1975

REPORT NO: DOE/JPL-953365-75/1

ABSTRACT: The development of the edge-defined, film-fed growth process for silicon ribbon is described. The selection of die materials is described emphasizing SiC, graphite, SiO_2 and Si_3N_4. Utilizing the graphite die, the process was developed to produce ribbons first 1 cm and then 2.5 cm wide and up to 40 cm long. The electrical quality on the ribbon has increased directly as the result of increasing the graphite die purity. Solar cells made from recent ribbons grown from purified dies have exhibited efficiencies on the order of 75% of control cells made from Czochralski silicon.

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TITLE: Final Report. Large Area Czochralski Silicon

AUTHOR: Samuel N. Rea, Raul S. Gleim.

CORPORATE AUTH: Texas Instruments, Inc.

CONTRACT NO: 954475

DATE: April 1977

REPORT NO: DOE/JPL-954475-77/4

ABSTRACT: The major purpose of this program was to determine the overall cost effectiveness of the Czochralski process for producing large-area silicon. The goal of the wafering process was a slice thickness of 0.25 mm with minimal kerf. A slice + kerf of 1.26 mm has been achieved of 12-cm crystal using both 200 grit B_4C and SiC abrasive slurries. Crystal growth experiments were performed at 12-cm diameter in a commercially available puller with both 10 and 12-kg melts. Several modifications to the puller hot zone were required to achieve stable crystal growth over the entire crystal length and to prevent crystallinity loss a few centimeters down the crystal. The maximum practical growth rate for 12-cm crystal in this puller design was 10cm/h, with 12-14cm/h being the absolute maximum, range at which melt freeze occurred. A nugget polysilicon feeder was fabricated, assembled, and successfully tested on several multicharge runs. Excessive oxide and carbon contamination in the nugget melts contributed to crystal growth problems. A number of 12-cm crystals were sawed in the multiblade slurry saw. A 100% of the yield was obtained with B_4C abrasive at a slice + kerf of 1.56 mm and an average cutting rate of 6.1 mm/h. Silicon carbide abrasive has demonstrated 3-5 mm/h sawing rates on 12-cm crystal, although yields have run lower (73%) than those with B4C at the 0.56mm dimension. A slightly thicker slice, 0.30 mm, can be sawed with SiC abrasive at 100% yield. Experiments in laser scribing silicon wafers into hexagons showed that a 10-W YAG laser can penetrate 0.2 mm at a scribe rate of 10 cm/s. Much higher writing rates on the order of 30-40 cm/s can penetrate 0.05 mm which is sufficient for scribe-and-break of 0.25-mm slices. Czochralski economics were examined using realistic estimates of technical parameters and a sheet cost in the $\$45/m^2$ area is indicated for a semicontinuous puller in the early 1980 time frame. To impact sheet cost in late 1970's, a multicharge growth mode is all that is technically possible and a sheet cost of $\$55/m^2$ is forecast.

TITLE: Final Report. Silicon Sheet Growth by the Inverted Stepanov Technique.

AUTHOR: K. M. Kim

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 954465

DATE: June 1977

REPORT NO: DOE/JPL-954465-77/2

ABSTRACT: The feasibility of growing silicon ribbons by the inverted ribbon growth process has been established using both nonwetting boron nitride (BN) dies as well as wetting composite dies coated with chemically vapor deposited silicon nitride (CVD Si_3N_4). Growth instablilites are associated primarily with the formation and evolution of the silicon monoxide; the escape of the gas causes hysteresis of the contact angle and mechanical vibration of the melt. As a result of this, the meniscus during the ribbon growth is not "pinned" at the die edge but is in constant motion, and growth is difficult to initiate. Although real progress was made, the instabilities have not been suppressed sufficiently to allow for initiation of ribbon growth. Preliminary evaluation of the reactivity of liquid silicon with CVD Si_3N_4 and CVD $Si_3O_xN_y$ indicated that these materials are considerably more resistant to reaction with and/or dissolution in silicon than other materials examined to date. Solar cells made in the epitaxially deposited silicon on a silicon ribbon grown by the inverted Stepanov process with the BN flat die had an efficiency of 8.2% (AM1). The stability of the ribbon growth, in terms of the dependence of the ribbon thickness on the change in the meniscus height, is theoretically greater in the inverted Stepanov or inverted EFG than in Stepanov or EFG process. A one-dimensional heat flow model has been developed to simulate numerically the major thermal aspects of the inverted Stepanov growth process. Our results show that for a given ribbon geometry, die temperature and ambient configuration, the height of the molten zone increases as the growth velocity is increased. The highest growth velocities are achieved with the lowest ambient temperatures coupled with experimental transfer coefficient as well as the conducted heat loss to the ribbon support clamp.

TITLE: Final Report. Heat Exchanger-Ingot Casting/Slicing Process

AUTHOR: Frederick Schmid and Chandra P. Khattak.

CORPORATE AUTH: Crystal Systems, Inc.

CONTRACT NO: 954373

DATE: December 1977

REPORT NO: ERDA/JPL 954373-77/4

ABSTRACT: The proof of concept for silicon casting by the Heat Exchanger Method has been established. One of the major hurdles of ingot cracking has been eliminated with the development of graded crucibles. Such crucibles are compatible with the casting process in that the integrity of the container is maintained at high temperature; however, during the cool-down cycle the crucible fails, thereby leaving a crack-free boule. Ingots as large as 3.3 kg have been cast using this approach. The controlled growth, heat-flow and cool-down cycle has yielded silicon with a high degree of single crystallinity. Even when the seed melted out, very large grains formed. Solar cell samples made from cast material have yielded conversion efficiency of over 9% (AM1). Representative characterizations of silicon grown has demonstrated a dislocation density of less than 100/cm^2 and a minority carrier diffusion length of 31 μm The source of silicon carbide in silicon ingots has been identified to be from graphite retainers in contact with silica crucibles. Higher growth rates have been achieved with the use of a graphite plug at the bottom of the silica crucible. Excellent surface quality, i.e., surface smoothness and 3-5 μm surface damage, was achieved by multiple wire slicing with fixed diamond abrasive. Tungsten wire was the best core material tested because of its high strength, high Young's modulus, and resistance to hydrogen embrittlement. Diamond costs were reduced by impregnating diamonds only on the cutting areas of the wire. A lighter and longer blade carriage can be used for slicing with wire. This will allow the blade carriage to be reciprocated more rapidly to increase the surface speed. A projected add-on cost calculation shows that these methods will yield silicon for solar cell application within ERDA/JPL cost goals.

TITLE: Final Report. Delayed Fracture of Silicon. Silicon Sheet Growth Development for the Large Area Silicon Sheet Task

CORPORATE AUTH: California Univ., Los Angeles, Dept. of Materials

AUTHOR: Chen, T. J. And Knapp, W. J.

CONTRACT NO: 954836

DATE: March 1978

REPORT NO: DOE/JPL/954836-78/1

ABSTRACT: Bar specimens were cut from ingots of single crystal silicon, and acid-etched prior to testing. Artificial surface flaws were introduced in specimens by indentation with a knoop hardness tester. The specimens were loaded in four-point bending to 95% of the nominal fracture stress, while keeping the surface area, containing the flaw, wet with test liquids. No evidence of delayed fracture, and, therefore stress corrosion, of single crystal silicon was observed for liquid environments including water, acetone and aqueous solutions of NACL, NH_4OH, and HNO_3, when tested with a flaw parallel to a (110) surface. The fracture toughness was calculated to be $K/_{1C}$=0.591x10^6 N/M 3/2.

TITLE:	Final Report, May 12, 1976--August 11, 1977. Hot forming of Silicon Sheet, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task.
AUTHOR:	Graham, C. D. Jr.; Pope, D. P.; Kulkarni, S.
CORPORATE AUTH:	Pennsylvania Univ., Philadelphia (USA)
CONTRACT NO:	954506
DATE:	April 1978
REPORT NO:	DOE/JPL/954506-78/1

ABSTRACT

Results of an experimental program investigating the hot workability of polytextucrystalline silicon are reported. Uniaxial stress-strain curves are given for strain rates in the range of 10^{-5} to 10^{1-1} and temperatures from 1100 to 1380°C. At the highest strain rates at 1380°C axial strains in excess of 20% were easily obtainable without cracking, although special preparation of the compression platens allows strains in excess of 50%. After deformations of 36%, recrystallization is completed within 0.1 hr at 1380°C. When the recrystallization is "complete," there is still a small volume fraction of unrecrystallized material which appears very stable and may degrade the electronic properties of the bulk material. Texture measurements show that the as-produced vapor deposited polycrystalline rods have a (110) fiber axis changes to (111) and the direction parallel to the growth direction and no preferred orientation about this axis. Upon axial compression perpendicular to the growth direction the former (110) fiber axis changes to (111) and the compression axis becomes (110). Recrystallization changes the texture to (110) along the former fiber axis and (100) along the compression axis.

TITLE: Final Report. Floating Substrate Process: Large-Area Silicon Sheet Task.

AUTHOR: Garfinkel, M.; Hall, R. N.

CORPORATE AUTH: General Electric Company, Schenectady, NY

CONTRACT NO: 954350

DATE: June 1978

REPORT NO: DOE/JPL 954350-78/3

ABSTRACT: Supercooling of silicon-tin Alloy melts was studied. Values as high as 78 c at 1100 c and 39 c at 1200 c were observed, corresponding to supersaturation parameter values 0.025 and and 0.053 at 1050 c and 1150 c, respectively. The interaction of tin with silane gas streams was investigated over the temperature range 100 to 1200 c. Single-pass conversion efficiencies exceeding 30% were obtained. The growth habit of spontaneously-nucleated surface growth was determined to be consistent with dendritic and web growth from singly-twinned triangular nucleii. Surface growth of interlocking silicon crystals, thin enough to follow the surface of the liquid and with growth velocity as high as 5 mm/min, was obtained. Large area single-crystal growth along the melt surface was not achieved. Small single-crystal surface growth was obtained which did not propagate beyond a few millimeters.

TITLE: Final Report. Silicon Ribbon Growth by a Capillary Action Shaping Technique.

CORPORATE AUTH: IBM Corporation

CONTRACT NO: 954144

DATE: June 1978

REPORT NO: DOE/JPL-954144-78/1

ABSTRACT: Ribbon silicon produced by CAST yields 11.9% solar cell efficiency. CAST ribbons up to 95mm wide and 0.3mm thick were produced. CAST technology-single ribbon, 100mm wide ribbon, 0.3mm thick, 3.8m/hr growth rate, solar cell efficiency 13% - has the potential to meet a $50/m^2 target. This is based upon the availability of $10/kg polycrystalline silicon.

TITLE: Third Quarterly Progress Report. Development of Advanced Methods for Continuous Czochralski Growth.

AUTHOR: R. G. Wolfson, C. B. Sibley, C. P. Chartier

CORPORATE AUTH: Varian Associates

CONTRACT NO: 954884

DATE: July 1978

REPORT NO: DOE/JPL 954884-78/3

ABSTRACT: Six batch melt-replenishment runs were performed. In the most recent, five crystals were grown with a total throughput of 48 kg. In addition to its stated purpose of developing the growth and recharge process for continuous silicon production, this experimentation has served to prove completely both the concept of charging with granular (viz., "niblet") feed and the design of the pellet-feeder/isolation-lock assembly.

The design of the prototype Czochralski puller was begun on schedule. Layouts of all major components have been prepared, and detailing is currently in progress; bills of material for long-delivery items were released to manufacturing in June. Two critical components have already undergone advance trials: the recharging mechanism, which has been in use for four months, and the crystal lift mechanism, which has been bench-tested and is to be mounted on the laboratory Varian 2850 puller. Further, the fabrication of the transducer/control assembly -- the automation system -- has been accelerated in order to permit testing and preliminary process development on the 2850 furnace prior to the completion of the prototype puller.

The SAMICS analysis of ingot growth and wafering has been completely revised and has been extended to 1986.

TITLE:	Final Report. Chemical Vapor Depositon Growth
AUTHOR:	R. P. Ruth
CORPORATE AUTH:	Rockwell International
CONTRACT NO:	954372
DATE:	October 1978
REPORT NO:	DOE/JPL-954372-78/6

ABSTRACT:

The technical objective was to investigate and develop chemical vapor deposition (CVD) techniques for the growth of large areas of Si sheet on inexpensive substrate materials, with resulting sheet properties suitable for fabricating solar cells that would meet the technical goals of the Low Cost Silicon Solar Array (LSSA) Project. Several glasses were found that are compatible with CVD Si growth in an inert atmosphere in the 800-900 degrees C range, although a maximum in the Si deposition rate from SiH_4 pyrolysis in He at about 850 degrees C sets an upper limit on film growth rates. The polycrystalline Si films on glasses showed strong preferred orientation parallel to (100) and - to a smaller degree - (110) planes, depending upon deposition temperature, film thickness, and the glass involved as substrate. Evidence was found of unidentified donor impurities entering the fi' s, presumably from the glass substrates, to affect the electrical properties obtained and possibly set an upper limit on the available hole concentrations achievable in p-type B-doped polycrystalline films on these glasses. Low-purity alumina and similar ceramics were found not suitable as substrates for growth of CVD Si of uniform quality. High-purity aluminas permitted growth of polycrystalline CVD Si layers of controllable quality, highly preferred orientations, and grain sizes that scaled directly with the grain size in the substrate. Refired aluminas that has acquired large individual grains produced locally epitaxial Si grains of corresponding dimensions on those substrate grains that were favorably oriented crystallographically. The aluminas are too costly to be considered for meeting the LSSA Project goals. Generally poor photovoltaic performance was exhibited by solar cells fabricated in CVD Si sheet grown by SiH_4 pyrolys's directly onto substrates of aluminas, glasses, or even single-crystal sapphire. V_{OC} values up to about 80% of those of single-crystal Si control cells were obtained, but J_{SC} values only 40 to 70% of those of a control cell were obtained under simulated AMO illumination. Depressed long-wavelength response and other performance factors indicated low minority-carrier (electron) diffusion lengths were characteriastics of the n/p cell structures made in

this Si sheet material by the SiH_4 process. Epitaxial p-type (B-doped) CVD Si sheet grown on single-crystal Si substrates by SiH_2Cl_2 pyrolysis in H_2 at about 1075 degrees C provided relatively good photovoltaic performance in solar cell structures produced by P diffusion to form the p-n junctions. V_{oc} values of about 560 mV, J_{sc} values of about 22 mA cm^{-2}, curve fill factors of about 0.7, and power efficiencies of 6-7% were found in these cells. The presence of a p+ layer below and adjoining a p-type (B-doped) CVD Si polycrystalline or epitaxial layer (on alumina or sapphire, respectively) enhanced the photovoltaic response of solar cell structures formed by P diffusion into the p layer. A comparison of the photovoltaic response of P-diffused and P-doped in-situ-grown n+/p/p+ solar cell structures about 20 μm thick on polycrystalline fine-grained Si sheet, the two were about equal in the structures, for given doping concentrations in the p layer. In all cases the epitaxial cells were much better than the polycrystalline cells, mainly because of current collection effects and junction leakage current effects, and the large-grained polycrystalline cells were better than the fine-grained cells. A comparison of diffused-junction and deposited-junction n+/p/p+ structutes in three different p-layer thickness ranges on the same three classes of substrate showed a direct increase in photovoltaic response with p-layer thickness for the epitaxial cells but less distinct differences for the polycrystalline cells.

TITLE: Final Report. LSA Large Area Silicon Sheet Task Continuous Czochralski Process Development.

AUTHOR: Samuel N. Rea

CORPORATE AUTH: Texas Instruments Incorporated

CONTRACT NO: 954887

DATE: February 1979

REPORT NO: DOE/JPL-954887-79/5

ABSTRACT: A commercial Czochralski crystal growing furnace was converted to a continuous growth facility by installation of a small, in-situ premelter with attendant silicon storage and transport mechanisms. The premelter was situated immediately over the primary melt and provided a molten silicon flow into the large crucible simultaneously as crystal was being grown. The key element in this continuous Czochralski process is the premelter and a substantial portion of the program involved its evolution into a workable design. The best arrangement tested was a vertical, cylindrical graphite heater containing a small fused quartz test tube liner from which the molten silicon flowed out the bottom. Approximately 83 cm of nominal 5-cm diameter crystal was grown with continuous melt addition furnished by the test tube premelter. High-perfection crystal was not obtained, however, due primarily to particulate contamination of the melt. Elimination of this oxide buildup will require extensive study and experimentation and the ultimate sucess of continuous Czochralski depends on a successful solution to this problem. Economic modeling of the continuous Czochralski process utilized the IPEG option of SAMICS. The influence of both crystal size and total furnace run size were examined. Results of these studies indicate that for 10-cm diameter crystal, 100-kg furnace runs of four or five crystals each are near optimal. Costs tend to asymptote at the 100-kg level so little additional cost improvement occurs at larger runs. For these conditions, crystal cost in equivalent wafer area of around $16/m^2 exclusive of polysilicon and slicing is obtained. Lower crystal costs can be obtained by growing large diameter crystals in the 12 to 15-cm range. The outlook for achieving the overall 1986 wafer cost goals is not optimistic because of high slicing costs. Continuous Czochralski can, however, meet the near-term cost goals for silicon sheet material.

TITLE: Quarterly Report. Laser-zone Growth in a Ribbon-to-Ribbon (RTR) Process Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Solar Array Project

AUTHOR: A. Baghdadi, etal

CORPORATE AUTH: Motorola Inc. Semiconductor Group

CONTRACT NO 954376

DATE: March 1979

REPORT NO: DOE/JPL 954376-79/9

ABSTRACT: Appreciable progress has been witnessed in achieving high efficiency on RTR solar cells, with an average efficiency of 9.1% on the most recent lot. The best cell to date has a measured efficiency of 11.3%. A new technique for growing limited-length ribbons continually has been demonstrated. This "Rigid Edge" technique can be used to recrystallize about 95% of the polyribbon feedstock. A major advantage of this method is that only a single, constant length silicon ribbon is handled throughout the entire process sequence; this may be accomplished using cassettes similar to those presently in use for processing Czochralski wafers. Thus a transition from Cz to ribbon technology can be smoothly affected. The maximum size being considered, 3" x 24", is half a square foot, and will generate 6 watts for 12% efficiency at 1 sun. Silicon dioxide has been demonstrated as an effective, practical diffusion barrier for use during the polyribbon formation. Two different approaches for using the silicon dioxide are being pursued.

TITLE: Final Report. Development of Mullite Substrates and Containers.

CORPORATE AUTH: Coors Porcelain Company

CONTRACT NO: 954878

DATE: April 1979

REPORT NO: DOE/JPL-954878-79/5

ABSTRACT: The objective of this program was to evaluate mullite in contact with molten silicon to be used as a substrate for Honeywell's Silicon-On-Ceramic process and as a container for melting solar grade silicon. A further requirement was to fabricate respective substrates and containers. To maintain solar grade silicon purity levels, the mullite must generally introduce less than 10^{15} atoms/cc of impurities. To evaluate the mullite-molten silicon interaction, a series of bodies were made with variations in density, alumina-silica ratio and glass-crystalline ratio. These materials were tested in a sessile drop technique. None of the variations stood up to extended exposure to molten silicon sufficiently to be recommended as a container material. However, directional solidification experiments by JPL suggest that, under proper conditions, contamination of the silicon by mullite containers can be minimized. To improve an already good thermal expansion match between mullite and silicon, compositional variations were studied. Altering of the alumina-silica ratio was determined to give a continuously varying thermal expansion. Thus, a composition can be selected to give the desired thermal expansion match with silicon. Concurrent to this work, a standard mullite composition was selected to be used for fabrication development. The major fabrication development requirementes were to make substrates 40 x 4 x .040 inches and slotted substrates. Fabrication of standard mullite composition substrates, nominally 40 x 4 x .040 inches, have been made and delivered to Honeywell. Slotted substrates of various configurations and various compositions are regularly being supplied to Honeywell.

TITLE:	Final Report. Development and Evaluation of Die and Container Materials.
AUTHOR:	R. R. Wills and D. E. Niesz
CORPORATE AUTH:	Battelle Columbus Laboratories
CONTRACT NO:	954876
DATE:	May 1979
REPORT NO:	DOE/JPL-954876-79/6

ABSTRACT: Specific compositions of high purity silicon aluminum oxynitride (Sialon) and silicon beryllium oxynitride (Sibeon) solid solutions are shown to be promising refractory materials for handling and manipulating solar grade silicon into silicon ribbon.

Well controlled processing schedules were developed for fabricating high purity Sialon and Sibeon materials. Essentially the impurity content of the hot pressed ceramics was due only to impurities from the original starting powders. A ceramic shaping die was successfully formed by diamond machining of a hot pressed blank. Projected manufacturing cost estimate for 10^5 dies per year is \$5.40 per die.

Evaluation of the interaction of these materials in contact with molten silicon indicates that solid solutions based upon β-Si_3N_4 are more stable than those based on Si_2N_2O. Sibeon is more resistant to molten silicon attack than Sialon, and both materials should preferably be used in an inert atmosphere rather than under vacuum conditions. This is because removal of oxygen from the silicon melt in the form of SiO enhances the dissolution of aluminum and beryllium. The wetting angles of these materials are low enough (37^o for x = 0.75 β' Sialon and 49^o for x = 0.35 Sibeon) for these materials to be considered as both die and container materials.

TITLE: Final Report. X-Ray Measurements of Stresses and Defects in EFG and Large Grained Polycrystalline Silicon Ribbons

AUTHOR: C. N. J. Wagner

CORPORATE AUTH: University of California

CONTRACT NO: 954851

DATE: August 1979

REPORT NO: DOE/JPL 954851-79/2

ABSTRACT: The Bond method has been employed to measure the lattice parameter $\underline{a}$ in the area of 0.4 mm in diameter of EFG Si-ribbons to an accuracy of $\pm$ 0.00008 A. A Bond goniometer was built which included a goniostat with a special specimen holder to mount ribbons 1 m in length and 75 mm in width which could be rotated about two orthogonal axes, and a Leitz microscope for precision alignment of a particular area into the center of the goniostat and the small primary X-ray beam. The (321) planes were found to be parallel to the surface of the ribbons with an angular spread of about 15°. The poles of the (111) planes clustered about an angle of 20° away from the surface normal, again with a spread of 10°. The lattice parameter of a small piece of ribbon material was found to be a_o = 5.43075 A. Converting the observed strain (= $(a-a_o/a_o)$ into the sum of the principal surface stresses $\sigma_1 + \sigma_2$ assuming that the tilt angles of less than 15° can be neglected yielded values of $\sigma_1 + \sigma_2$ which were zero within the accuracy of our measurements of $\pm$ 10 MPa, but a maximum stress of 115 MPa was observed in a fractured ribbon which corresponded to the fracture stress of single crystals of Si.

TITLE: Final Report. Web-Dendritic Growth. Large Area Silicon Sheet Task.

AUTHOR: R. B. Hilborn, Jr., J. W. Faust, Jr., Curtis Rhodes

CORPORATE AUTH: University of South Carolina

CONTRACT NO: 954344

DATE: August 1979

REPORT NO: DOE/JPL 954344-78/1

ABSTRACT: This final report gives the results of work performed by the University of South Carolina to develop methods of producing large areas of silicon ribbon by the web-dentritic method. A prototype web-dendritic growth machine, on hand at the beginning of the contract, was assembled and activated. A program for investigating the role of the various machine design parameters on the contract. The development of the machine proceeded to the point where ribbons could be reproducibly grown to the lengths of 1 meter, with widths increasing linearly from a minimum, at the initiating seed button, up to 1 cm at the point of termination of growth. Considerable thermal data was collected and evaluations were made of actual seeding and growth for variations in a large number of parameters affecting heat loss. From this we found for achieving suitable growth that the mechanical system should be very rigid and stable, and the tolerances and specifications of the quartz crucibles must be far tighter than normal quartz tolerances. The widening rates of the ribbons were found to be a function of the temperature gradient rather than the temperature differences alone. A twin spacing in the seed of 3 - 2 was found to be unfavorable for growth; whereas spacing of .9 - 2 and 8 - 2 were favorable. It was found, however, that the spacing of 8 - 2 sets an upper limit of 4 cm/min on the maximum achievable rate. Extensive thermal modeling studies were carried out to investigate the effect of furnace design parameters on the temperature distributions in melt and the growth of the dendritic-web ribbon. From this study it was found that the pull rate of the ribbon is strongly dependent on the temperature of the top thermal shield, the spacing between this shield and the melt, and the thickness of the growing web.

TITLE: Final Report. Epitaxial Silicon Growth for Solar Cells

AUTHOR: R. V. D'Aiello, P. H. Robinson, and D. Richman

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 954817

DATE: September 1979

REPORT NO: DOE/JPL 954817-79/4

ABSTRACT: The objectives of this contract were:

To determine the feasibility of silicon epitaxial growth on low-cost silicon substrates for the development of silicon sheet capable of producing low-cost, high-efficiency solar cells.

To achieve a goal of 12% (AM-0) efficient solar cells fabricated on thin epitaxial layers grown on low-cost substrates.

To evaluate the add-on cost for the epitaxial process and to develop low-cost epitaxial growth procedures for application in conjunction with low-cost silicon substrates.

The basic epitaxial procedures and solar-cell fabrication and evaluation techniques are described, followed by a discussion of the development of baseline epitaxial solar-cell structures, grown on high-quality conventional silicon substrates.

A description of the crystallographic properties of such layers and the performance of epitaxially grown solar cells fabricated on these materials is given.

The major conclusions drawn from this work and recommendations for the further development needed to achieve the ultimate cost goals are given.

TITLE: Final Report. Vitre-Graf Coating on Mullite.

AUTHOR: Ronald C. Rossi

CORPORATE AUTH: Tylan Corporation

CONTRACT NO: 954896

DATE: September 1979

REPORT NO: DOE/JPL-954896-79/1

ABSTRACT: A technical and economic evaluation was made of a proprietary glass-like carbon glaze coating applied to mullite and graphite to be used either in thin-film silicon manufacture or in container ware applications. Preliminary evaluations had indicated that the glassy carbon coating reacts with molten silicon to form a silicon carbide reaction layer that may serve as a diffusion barrier to prevent silicon reaction with the substrate material. The technical evaluation consisted of manufacturing test samples by varying materials and process'- ; parameters in conformance with a pre-selected matrix. Various tests, primarily coating appearance, adherence and silicon reaction behavior was observed as a function of the test parameter variation. The results of these tests indicated that most graphite and carbonaceous materials used as substrates will produce a visually acceptable coating having excellent adherence over a wide range of processing parameters. However, no set of parameters produced a coating that could withstand the chemical attack from molten silicon and prevent reaction with a graphite substrate. The primary consideration of graphite substrates was in container ware applications requiring long-time molten silicon exposure. The conculsion of this study suggested that the glassy carbon coating might provide protection for time periods of 30 minutes or less, and therefore was not suitable for the intended application. The results of standard ceramic formulation indicated that a performance optimization did take place for the application of manufacturing silicon film solar arrays. When these optimized paramaters were tested on type K mullite developed specifically for the intended application it was found that performance was generally insensitive to processing parameters and the selected paramaters were then cost optimized. The economic analysis generated a process based on the selected parametes for coating glassy carbon onto newly developed mullite substrate

material. By using the interim standard price estimating equation a projected cost of \$1.30/m^2 was calculated based on 1975 dollars. If further development of the type K mullite could eliminate the requirement for HF etch preparation of the substrate surface, a unit cost of \$1.05/m^2 is calculated on 1979 dollars. Additionally, if normal advance in the Vitre-Graf technology is assumed, a unit cost of \$0.85/m^2 is projected on the 1975 dollar basis.

TITLE: Final Report. Slicing of Silicon into Sheet Material. Large Area Silicon Sheet Task.

CORPORATE AUTH: Varian Associates

CONTRACT NO: 954374

DATE: September 1979

REPORT NO: DOE/JPL 954374-79/10

ABSTRACT: Complete results, from raw data to interpretation to recommendations, of a program to investigate the use of multiblade slurry sawing to produce silicon wafers from ingots are presented in this report. During the course of this program, the commercially available "state-of-the-art" process was improved by 20% in terms of area of silicon wafers produced from an ingot. The process was improved 34% on an experimental basis. Production of 20 wafers per centimeter length of 100 mm diameter ingot is now possible on a production basis. Economic analyses presented show that further improvements are necessary to approach the desired wafer costs, mostly reduction in expendable materials costs. Tests which indicate that such reduction is possible are included, although demonstration of such reduction was not completed. A new, large capacity saw was designed and tested. Performance comparable with current equipment (in terms of number of wafers/cm) was demonstrated. Improved performance was partially demonstrated, but problems (both mechanical and of unknown origin) precluded full demonstration of improved performance.

TITLE: Final Report. Study Program to Develop and Evaluate Die and Container Materials for the Growth of Silicon Ribbons.

AUTHOR: Paul E. Grayson, Larry A. Addington

CORPORATE AUTH: Eagle-Picher Industries, Inc.

CONTRACT NO: 954877

DATE: December 1979

REPORT NO: DOE/JPL-954877-79/6

ABSTRACT: The Large Area Silicon Sheet Growth Task objective of lowering the cost of silicon photovoltaic material requires the development of materials which exhibit improved chemical and dimensional stability in contact with molten silicon. These materials may find application as containers and/or shaping dies in processes such as edge-defined film growth. This paper describes the development and evaluation of proprietary coatings of pure silicon carbide, silicon nitride and aluminum nitride on less pure hot pressed substrates of the respective ceramic materials. Silicon sessille drop experiments were performed on coated test specimens under controlled oxygen partial pressures. X-ray diffraction and SEM characterized after testing with optical and scanning electron microscopy and Auger electron spectroscopy. Increasing the oxygen partial pressure was found to increase the solid-vapor interfacial free energy. Adsorbed oxygen was also found to increase the degree of attack of molten silicon upon the chemical vapor deposited coatings. Prototypic containers and dies were delivered and cost projections show that reasonably priced, coated, molten silicon resistant refractory material shapes are obtainable.

TITLE: Final Report. Development and Evaluation of Die Materials for Use in the Growth of Silicon Ribbons By the Inverted Ribbon Growth Process-Task II-LSA Project.

AUTHOR: M. T. Duffy

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 954901

DATE: December 1979

REPORT NO: DOE/JPL-954901-79/6

ABSTRACT: Amorphous CVD layers of silicon nitride and silicon oxynitride are prepared by chemical vapor deposition (CVD) layers are converted to a- and B-Si_3N_4 with a low B-Si_3N_4 content. The a- phase is then slowly converted to the B phase accompanied by simultaneous decompositon. By contrast, silicon oxynitride (SiOxNy) layers are converted predominantly to B-Si_3N_4 with a low a-Si3N4 content. In this process, oxygen is evolved, and there is no evidence for the existence of an oxynitride phase in the resulting layers. The analysis also indicates that B-Si3N4 is much more resistant to chemical attack by molten silicon than a-Si3N4. Consequently, CVD silicon nitride coatings are useful for shorter exposure times. Crystallographic analysis of silicon ribbon test specimens, grown from CVD-coated vitreous carbon dies, indicates that silicon carbide inclusions are not present in the ribbon samples. The results of infrared analysis also show that the carbon content of the silicon ribbons is below detection level and lower than in the Czochralski seed material.

TITLE: Final Report. Silicon Sheet Growth Development of the Large Area Sheet Task of the Low Cost Silicon Solar Array Project.

AUTHOR: C. Moody Johnson

CORPORATE AUTH: Kayex Corporation

CONTRACT NO: 954888

DATE: March 1980

REPORT NO: DOE/JPL-954888-80/12

ABSTRACT: The production of low-cost silicon capable of being processed into solar cells yielding efficiencies of 14% AM1 is an essential requirement of the JPL/DOE Low-Cost Solar Array (LSA) Project. Kayex has developed a process for Czochralski-type crystal growth that significantly reduces the major cost item (other than the silicon itself) involved in state of the art Czochralski growth - the quartz crucible. The new technology generated under this contract can decrease the add-on cost for silicon production from at least $51/kg (present state of the art) to $16.14/kg (CZ #3). This translates into an add-on cost of $0.25/pk watt if the JPL/DOE goal of $14/kg is assumed for the polysilicon material used for the growth of crystal ingots. Conclusions and technology status are reported for both phases of the contract which had the following objectives: -The growth of 100 kg of silicon single crystal material of ten (10) cm in diameter or greater, utilizing one common silicon container material (one crucible). -The growth of 150 kg of silicon single crystal material of fifteen (15) cm in diameter, utilizing one common silicon container material (one crucible). The objectives of the project included: (a) Developing a new technology concept that would allow a Hamco CG2000 crystal grower to be recharged with a new supply of polysilicon material while still under vacuum and at temperatures above the melting point of silicon. (b) Modifying the Hamco CG2000 crystal grower to 1) accept large polysilicon charges - up to 30 kg 2) grow large crystal ingots (to 15 cm diameter and 25 kg in weight) 3) hold polysilicon material for recharging (rod or lump) while, at the same time, growing crystal ingots. (c) Designing special equipment to 1) recharge polysilicon rods 2) recharge polysilicon lumps 3) handle and store large, hot silicon crystal ingots. (d) Developing a new process and procedure for growing silicon crystal ingots and recharging polysilicon material without contaminating the furnace or

breaking the silicon container material (crucible). During the last two and one-half years, many continuous crystal growth runs have been performed. These runs have lasted as long as 109 hours and produced as many as ten (10) crystal ingots. Crystal sizes have reached 15 cm with weights progressing to 27 kg. The final phase of the program culminated in two 150 kg continuous runs being achieved by the growth of six (6) 25 kg ingots from one crucible.

TITLE: Final Report. Quantitative Analysis of Defects in Silicon

AUTHOR: R. Natesh

CORPORATE AUTH: Materials Research, Inc.

CONTRACT NO: 954977

DATE: April 1980

REPORT NO: DOE/JPL 954977-79/6

ABSTRACT: The analyses of one hundred and seventy four silicon sheet samples, about 1200 square centimeters, for twin boundary density, dislocation pit density, and grain boundary length has been accomplished. One hundred and thirty three of these samples were manufactured by Mobil Tyco, thirty two by Motorola, seven by IBM, one by Honeywell, and one by Wacker. Procedures have been developed for the quantitative analyses of the twin boundary and dislocation pit densities using the QTM-720 Quantitative Image Analyzing System. The QTM-720 system has been upgraded with the addition of a PDP 11/03 computer with dual floppy disc drive, a Digital Equipment Writer (111) high speed printer, and a Field-Image Feature Interface Module. These changes have greatly enhanced the speed and reliability of the QTM-720 System as well as improving the data storage and printout capability. Three versions of a computer program that controls the data acquisition and analysis on the QTM-720 have been written. Procedures for the chemical polishing and etching of Mobil Tyco, Motorola, IBM, and Wacker samples have been developed. This report describes the complete procedures for the effect analysis of silicon samples using a QTM-720 Image Analyzing System, and includes chemical polishing, etching, and ATM operation. The data from one hundred and seventy four samples, and a discussion of the data is also included herein. In addition to the above work, comparisons of the capabilities of a variety of powerful analytical techniques in analyzing impurities from four different silicon matrix was performed. The silicon matrix analyzed were Mobil Tyco (EFG-RH and EFG-RF), Honeywell (SOC), and Motorola (RTR). The techniques used were: neutron activation analysis, spark source mass spectrometry, ion scanning spectrometry, secondary ion mass spectrometry, scanning auger microanalysis, electron spectroscopy for chemical analysis, ion microprobe mass spectroscopy, and optical microscopy. The results showed significant

differences in the various analytical techniques for analyzing silicon impurities and, in addition, provided important information regarding the type and distribution of impurities present in the various silicon matrix. The details of this work is presented in a separate report (MRI-267) to JPL.

TITLE:	Final Report. Development of Methods of Producing Large Areas of Silicon Sheet by the Slicing of Silicon Ingots Using Inside Diameter Saws.
AUTHOR:	Peter Aharonyan
CORPORATE AUTH:	Silicon Technology Corporation
CONTRACT NO:	955131
DATE:	April 1980
REPORT NO:	DOE/JPL-955131-81/2

ABSTRACT:

I.D. wafering equipment, blades and processes were used to develop methods for producing large areas of silicon sheet.

Modifications to a 16 inch STC automated saw included: 1) programmable feed system; 2) crystal rotating system and 3) STC Dyna-Track Blade monitoring and control system.

By controlling the plating operation and by grinding of the cutting edge, we were able to produce 16 inch I.D. blades with a cutting edge thickness of .22 mm. Crystal rotation mechanism was used to slice 100 mm diameter crystals with a 16 inch blade down to a thickness of .20 mm.

Cutting rates with crystal rotation were generally slower than with standard plunge I.D. slicing techniques. Using programmed feeds and programmed rotation, maximum cutting rates were from 0.3 to 1.0 inches per minute.

TITLE: Final Report. Effects of Varying Oxygen Partial Pressure on Molten Silicon - Ceramic Substrate Interactions.

AUTHOR: P. Darrell Ownby, Harold V. Romero and Michel W. Barsoum

CORPORATE AUTH: University of Missouri-Rolla

CONTRACT NO: 955415

DATE: April 1980

REPORT NO: DOE/JPL-955415-2

ABSTRACT: The objective of the University of Missouri-Rolla program under the Jet Propulsion Laboratory Low Cost Silicon Solar Array contract is to investigate the interaction of molten silicon with various die and container candidate materials under varying oxygen partial pressures. This has been done by making silicon sessile drop contact angle measurements on the candidate materials to determine the degree to which silicon wets these substances, and subsequently sectioning the post-sessile drop experiment samples and taking photomicrographs of the silicon-substrate interface to observe the degree of surface dissolution and degradation.

TITLE: Final Report. Slicing of Single Crystal and Polycrystalline Silicon Ingots Using Multi-Blade Saws

AUTHOR: Jack B. Ross

CORPORATE AUTH: Norlin Industries, Inc. (P. R. Hoffman Co.)

CONTRACT NO: 955563

DATE: May 1980

REPORT NO: DOE/JPL 955563-80/1

ABSTRACT: This contract was issued by JPL to serve primarily as a feasibility study during which the capabilities of P. R. Hoffman Co., Division of Norlin Industries, Inc., could be evaluated with regard to our ability to satisfactorily provide the research and development effort which would lead to optimization of the Multi-Blade Slurry wafering technique as a contribution to the realization of the goals of the (DOE) Low-Cost Solar Array Project. In addition to making several wafering runs, we were to provide sufficient data necessary for a complete cost analysis of each of the three types of saws utilized.

TITLE: Quarterly Report. Continuous Liquid Feed Czochralski Growth

CORPORATE AUTH: Siltec Corporation

CONTRACT NO: 954886

DATE: June 1980

REPORT NO: DOE/JPL 954886-80/11

ABSTRACT: The purpose of this phase of the continuous liquid feed program is the design and development of equipment and processes in order to ultimately demonstrate the continuous growth of crystals, by the use of the Czochralski method, suitable for producing monocrystalline silicon for use in solar cells. This involves the growth of at least 150 kg monocrystalline silicon ingots, 150 mm in diameter, obtained from a single growth container. Our approach to meeting this goal is to develop a furnace with continuous liquid replenishment to the growth crucible. Demonstrations using the silicon polyrod feed mechanism continued this quarter providing continuous melt replenishment to the meltdown chamber, subsequent transfer of this melt, and the simultaneous growth of silicon ingots in the growth chamber. The frame to the CLF furnace was extended in order to accommodate 50 kg crystal ingots above the gate valve, hence enabling us to accomplish our goal of 150 kg throughput. Development work continued on various aspects of the melt transfer system.

TITLE:	Final Report. EBIC/TEM Investigations of Defects in Solar Silicon Ribbon Materials
AUTHOR:	D. G. Ast
CORPORATE AUTH:	Cornell University
CONTRACT NO:	954852
DATE:	January 1981
REPORT NO:	DOE/JPL 954852-81/4

ABSTRACT: Many of the growth methods which produce silicon material for the fabrication of inexpensive solar cells yield material which contains a relative high density of structural defects, such as grain boundaries, twin boundaries and dislocations. Because such defects will, in general, reduce the efficiency of a solar cell, there is a technological incentive to study the formation and structure of such defects, and their influence on the minority carrier lifetime.

This report discusses the applications of TEM and EBIC to the study of crystalline defects

TITLE: Quarterly Report. Silicon Ingot Casting-Heat Exchanger Method (HEM) Multi-Wire Slicing-Fixed Abrasive Slicing Technique (FAST) - Phase IV for Large Area Silicon Sheet Task

AUTHOR: F. Schmid and C. P. Khattak

CORPORATE AUTH: Crystal Systems, Inc.

CONTRACT NO: 954373

DATE: February 1981

REPORT NO: DOE/JPL 954373-80/16

ABSTRACT: The crystallinity of large-size ingots has been studied as a function of the heat flow conditions at the bottom of the ingot. The size of the ingot has an important effect on crystallinity. The breakdown in crystallinity across the bottom has been resolved to an area in the vicinity of the melted-back seed. Generally, homogeneous resistivity distribution has been achieved all over the ingot. Electroplating of diamonds on one side of the wirepack has an important effect on slicing performance. However, diamond electroplating must be carefully controlled to have a good seat in the grooved rollers. An in-house electroplating facility is now operational. Good performance was achieved with the initial in-house electroplated wirepacks. Projected add-on cost of HEM ingot casting process has been carried out using IPEG analysis. The value that was obtained is $\$8.65/m^2$ well below the allocation of $\$18.15/m^2$ to meet the 1986 goal.

TITLE: Final Report. Silicon-on Ceramic Process. Silicon Sheet Growth and Device Development for the Large-Area Silicon Sheet Task

AUTHOR: B. L. Grung, J. D. Heaps, F. M. Schmit, S. B. Schuldt and J. D. Zook

CORPORATE AUTH: Honeywell Corporate Material Sciences Center

CONTRACT NO: 954356

DATE: March 1981

REPORT NO: DOE/JPL 954356-80/15

ABSTRACT: The objective of this Research and Development program was to investigate the technical feasibility of producing solar-cell-quality sheet silicon to meet the DOE 1986 overall price goal of $0.70/watt. With the silicon-on-ceramic (SOC) approach, a low-cost ceramic substrate is coated with large-grain polycrystalline silicon by unidirectional solidification of molten silicon. This R&D effort was divided into several areas of investigation in order to most efficiently meet the goals of the program. These areas include: 1) dip coating; 2) continuous coating-designated SCIM-coating, an acronym for Silicon Coating by an Inverted Meniscus; 3) material characterization; 4) cell fabrication and evaluation; and 5) theoretical analysis.

Both coating approaches were successful in producing thin layers of large-grain, solar-cell-quality silicon. The dip-coating approach was initially investigated and considerable effort was given to this technique. The SCIM technique was adopted later because of its scale-up potentiality and its capability to more conveniently produce large areas of SOC.

TITLE:	Final Report. Silicon Solar Cell Process Development/Fabrication/Analysis.
AUTHOR:	J. A. Minahan
CORPORATE AUTH:	Spectrolab, Inc.
CONTRACT NO:	955055
DATE:	March 1981
REPORT NO:	DOE/JPL-955055-81/6

ABSTRACT: Solar cells have been fabricated from unconventional silicon materials in the second and final phase of the contract. In the most recent period of work, EFG, Web, HEM, and continuous CZ silicon materials were fabricated into solar cells, measured and analyzed. Current-voltage measurements under AM1 conditions, in addition to those under AM0 conditions, were introduced in Phase II. Several low-cost fabrication steps were included in that phase. Both Hem and Continuous CZ silicon were found to be superior to that which had been provided in Phase I. Correlation between quality of starting materials and cell conversion efficiency was observed for Hem-grown silicon. Correlation between position in the crystal growth sequence and cell quality was observed for Continuous CZ.

TITLE: Third Quarterly Progress Report. April 1 - June 30, 1981. Development of Advanced Czochralski Growth Process to Produce Low Cost 150 KG Silicon Ingots from a Single Crucible for Technology Readiness

AUTHOR: R. L. Lane

CORPORATE AUTH: Kayex Corporation

CONTRACT NO: 955733

DATE: June 1981

REPORT NO: DOE/JPL 955733-81/3

ABSTRACT: The program was extended from October 31, 1981 to March 31, 1982 with the same goals and budget.

The process development continued, with a total of nine crystal growth runs. One of these was a 150 kg run of 5 crystals of approximately 30 kg each. Several machine and process problems were corrected and the 150 kg run was as successful as previous long runs on CG2000 RCs. The accelerated recharge and growth will be attempted when the development program resumes at full capacity in FY82.

The automation controls were integrated to the seed dip temperature, shoulder, and diameter sensors on the CG2000 RC development grower. Test growths included four crystals, which were grown by the computer/sensor system from seed dip through tail-off. This system will be integrated on the Mod CG2000 grower during the next quarter.

The analytical task included the completion and preliminary testing of the gas chromotograph portion of the Furnace Atmosphere Analysis system.

The revised program plan is on schedule and is expected to remain close to the cost and schedule projections during the next quarter.

TITLE: Quarterly Report. Silicon Solar Cell Process Development, Fabrication, and Analysis.

AUTHOR: H. I. Yoo, P. A. Iles, and D. C. Leung

CORPORATE AUTH: Optical Coatings Laboratory, Inc.

CONTRACT NO: 955089

DATE: September 1981

REPORT NO: DOE/JPL-955089-81/13

ABSTRACT: During this reporting period, work has progressed in fabrication and characterization of solar cells from UCP wafers and LASS ribbons. Gettering tests applied to UCP wafers made little change on their performance compared with corresponding baseline data. Advanced processes such as SJ, BSF, and MLAR were also applied. While BSF by Al paste had shunting problems, cells with SJ and BSF by evaporated Al, and MLAR did achieve 14.1% AM1 on UCP silicon. The study of LASS material was very preliminary. Only a few cells with SJ, BSR, (no BSF) and MLAR were completed due to mechanical yield problems after lapping the material. Average efficiency was 10.7% AM1 with 13.4% AM1 for CZ controls. Relatively high minority carrier diffusion lengths were obtained. The lower than expected J_{sc} could be partially explained by low active area due to irregular sizes.

TITLE:	Large Area Silicon Sheet by EFG. Second Quarterly Report for period covering April 1, 1981 - June 30, 1981
AUTHOR:	Juris P. Kalejs
CORPORATE AUTH:	Mobil Tyco Solar Energy Corporation
CONTRACT NO:	954355
DATE:	September 1981
REPORT NO:	DOE/JPL 954355/81-18

ABSTRACT:

The influence of parameters such as CO_2 concentration, gas flow patterns, quartz in bulk melt, melt doping level and growth speed on ribbon properties has been examined for 10 cm wide ribbon. One of the more important findings is that ribbon quality is optimized for ambient CO_2 in argon concentrations in the range from 1000 to 5000 ppm. Cell performance degrades at CO_2 concentrations above 5000 ppm and IR interstitial oxygen levels decrease. These experiments have been done primarily at a growth speed of 3.5 cm/minute.

Cartridge parameters influencing the ribbon thickness have been studied and thickness uniformity at 200 micrometers (8 mils) has been improved. Growth stability at the target speed of 4.0 cm/minute has also been improved significantly.

A successful demonstration of interface ambient control in Furnace 16 has been carried out. Ribbon characterization has shown that SPV diffusion lengths and cell performance have improved with CO_2 introduced into the multiple furnace environment.

TITLE: Final Report. Silicon Web Process Development.

AUTHOR: C. S. Duncan, R. G. Seidensticker, J. P. McHugh, M. E. Skutch, J. M. Driggers, and R. H. Hopkins

CORPORATE AUTH: Westinghouse R&D Center

CONTRACT NO: 954654

DATE: October 1981

REPORT NO: DOE/JPL-954654-80/13

ABSTRACT: Silicon dendritic web is a single crystal silicon ribbon material with unique advantages for the manufacture of low cost solar cells. Shaped by the interplay of natural crystallographic and surface tension forces, rather than by potentially contaminating dies, the web produces solar cells with excellent conversion efficiency. For example, the maximum demonstrated AM1 efficiency, 15.5%, is so far the highest value reported for a ribbon material. The web process also conserves expensive silicon. Because impurities are rejected from the ribbon during crystal growth, it is feasible to use cheaper, less pure "solar" grades of silicon as feedstock for the web process. Moreover, long flexible web strips facilitate automation of both crystal growth and the subsequent cell-manufacturing operations. Taken together, these characteristics have made the web process a leading candidate to achieve or better the 1986 Low Cost Solar Array (LSA) Project cost objectives of 70 cents per peak watt (1980 dollars) of photovoltaic output power.

During the past three and a half years of steady technical progress, the web process has evolved from one with all the potential advantages suggested above to a method very close to technology readiness for commercial development of low cost solar cells. Web output rates were raised more than ten fold to 27 cm^2/min, and cell efficiencies were increased to 15.5% from about 13%. Melt replenished growth, which was merely a concept in 1977, has now been demonstrated under operator control for a full one-day growth cycle and for periods of one eight-hour shift with complete closed-loop control. The melt level was maintained constant to $\pm$ 0.1 mm, a degree of control better than the estimated requirements for automated continuous growth of web. The web produced under continuous operation produced solar cells with excellent efficiency. Besides these systems-related developments, we have shown that silicon web can routinely be grown with thicknesses below 150 μm to conserve silicon, and that the resultant ribbons have dislocation densities less than 10^4 cm^{-2}. Silicon web has been grown from experimental "low-cost" silicon (Battelle), as well as from purposely contaminated

feedstock, and yet has produced efficient solar cells. Hence, compatibility of the process with cheaper, less pure solar grade silicon seems likely.

Collectively these achievements imply that the web process has an excellent chance to better the DOE/JPL 1986 goal for sheet plus polysilicon cost of 22.4 cents per peak watt (1980$). Our projected web cost is in fact 17.3¢ per peak watt assuming area throughput rates of 25 cm^2/min, 15% AM1 cell efficiency, a three-day melt replenished growth cycle, system automation, and silicon at $14 per kg. Aside from a three-day growth cycle and the silicon cost, these objectives individually have been met. The next step is the design, assembly, and operation of a prototype automated web furnace to demonstrate the technology readiness of the process.

TITLE: Quarterly Report. Advanced Dentritic Web Growth Development

AUTHOR: C. S. Duncan, R. G. Seidensticker, J. P. McHugh, R. H. Hopkins, D. Meier, and J. Schruben

CORPORATE AUTH: Westinghouse R&D Center

CONTRACT NO: 955843

DATE: October 1981

REPORT NO: DOE/JPL 955843/81-3

ABSTRACT:

Silicon dendritic web is a single crystal ribbon form of silicon capable of fabrication into solar cells with AM1 conversion efficiency in excess of 15%.

During this third quarter, three major areas were emphasized: 1) Development and application of the thermal model for calculating buckling stresses as a function of temperature profile in the web, 2) systematic evaluation of lid and shield concepts to provide the data base for enhancing growth velocity, and 3) the design and construction of a new experimental web growth machine which embodies in one unit the mechanical and electronic features developed in previous work. In addition, evaluation of the new melt level control system was begun, along with preliminary tests of an elongated crucible design. The economic analysis was also updated to incorporate some minor cost changes.

Both the mechanical and electronic designs of the new experimental web growth machine are complete, purchased components ordered and fabrication is in progress.

The melt level control system has been tested during web growth and some minor but desirable modifications identified.

TITLE: Final Report. Analysis of Defect Structure in Silicon.

AUTHOR: R. Natesh, M. Mena, M. Plichta, J. M. Smith, and M. A. Sellani

CORPORATE AUTH: Materials Research, Inc.

CONTRACT NO: 955676

DATE: April 1982

REPORT NO: DOE/JPL-955676-1

ABSTRACT: The analyses of one hundred and ninety-three (193) silicon sheet samples, approximately 880 square centimeters, for twin boundary density, dislocation pit density, precipitate density, and grain boundary length has been accomplished in the past contract period. One hundred and fifteen (115) of these samples were manufactured by Crystal Systems, Inc., using their Heat Exchanger Method (HEM), thirty-eight (38) by Mobil Tyco using Edge-defined Film-fed Growth (EFG), twenty-three (23) by Honeywell using the Silicon-on-Ceramics (SOC) process, and ten (10) by Westinghouse using the Dendritic Web process. Seven (7) solar cells were also step-etched to determine the internal defect distribution on these samples.

Procedures have been developed for the quantitative characterization of structural defects such as dislocation pits, precipitates, twin & grain boundaries using a QTM 720 Quantitative Image Analyzing System interfaced with a PDP 11/03 mini-computer. These procedures were routinely applied to all the samples. Characterization of the grain boundary length per unit area for polycrystalline samples was done by using the "intercept method" on an Olympus HBM Microscope.

This report describes the steps involved in the characterization of structural defects in the various types of solar cell materials analyzed. A summary of results as well as discussions of the data are also presented.

Encapsulation
(Environmental Isolation)
JPL - In-House Abstracts

TITLE: Development and Validation of a Life Prediction Methodology for LSSA Encapsulated Modules.

AUTHOR: Clifford Coulbert

CORPORATE AUTH: Jet Propulsion Laboratory

AVAILABILITY: NTIS-346-223-CC

CONTRACT NO: 346-223-CC

DATE: June 1977

REPORT NO: 5101-40

ABSTRACT: This report outlines an approach to the development of a life prediction methodology for polymer encapsulated photovoltaic cell solar array hardware. The characteristics and output of an ideal life prediction model are described. Such a model depends on the development of quantitative intermediate relationships between the environmental exposure parameters and the basic chemical mechanisms of material aging. These are described conceptually along with suggested relationships which might be developed for 2 potential solar array failure modes, optical transmission loss and delaminations. The use of accelerated/abbreviated testing in the development of a life prediction methodology is reviewed. The distinction between testing to reveal failure modes and testing to define rates of degradation is presented. The point is also made that acceptance tests and performance tests which involve some degree of stress acceleration have very limited application to predicting module lifetimes.

TITLE: Encapsulation Material Trends Relative to 1986 Cost Goals.

EDITOR: Cuddihy, E.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: April 1978

REPORT NO: 5101-61

ABSTRACT: The status and an assessment of solar photovoltaic module encapsulation systems applicable to the Low-cost Solar Array (LSA) Project 1986 cost and performance goals are presented. The 1986 LSA cost goal for a 20-year life solar cell module is \$.50 per watt or \$5 per FT^2. Out of this cost goal, \$.25 per FT^2 is currently allocated for the encapsulation construction materials, including the mechanical support for the cells. Six basic construction elements were identified and their functions defined. These elements are outer covers, pottants, substrates, superstrates, adhesives, and back covers. For each construction element, a uniform costing basis was established for comparative analysis and an extensive survey of existing commercial materials which could be used was carried out. This survey generated an appreciation of the minimum costs which must be paid for the materials of each construction element and a better awareness of the likelihood of fabricating a \$.25 per FT^2 encapsulation system. The survey permitted identifiction of the lowest-costing material classes which could be used to meet the 1986 cost goals. Material deficiencies identified in this survey also permitted recognition of material developmental activities needed in the future. The resultant output from cost and materials analysis derived from these ongoing surveys, suggests that a \$.25 per FT^2 encapsulation cost goal is attainable, but not without some specifically directed material developmental activities. These activities will focus on modifications to existing materials and evolvement of new and specific product lines from existing and well-established material families.

TITLE: Encapsulant Candidate Materials for 1982 Cost Goals.

AUTHOR: H. Maxwell

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1978

REPORT NO: 5101-72

ABSTRACT: A cost of $2.00 per watt by 1982 has been established by the LSA Project as an intermediate goal to the primary Project goal of $0.50 per strawman designs for $2.00 per watt arrays including various options, tradeoffs, and cost. To support this primary output, information is presented on encapsulation experience, encapsulation system design criteria, and basic preparation and costs of candidate materials.

The encapsulation system can be subdivided into six basic elements: top covers, superstrates, pottants, adhesives, substrates, and bottom covers. The roles of these elements in the encapsulation system are described in this document. Candidate materials are examined in relationship to their usage as one or more of the six basic encapsulation elements. Their properties, cost considerations, availability, and processing characteristics are discussed.

TITLE: Photodegradation of Polymeric Encapsulants of Solar Cell Modules.

AUTHOR: A. Gupta

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: August 1978

REPORT NO: 5101-77

ABSTRACT: This report deals with the mechanisms of photodegradation of encapsulant materials in solar cell modules. Data have been presented on irradiation sources, their applications in simulative or accelerated testing or mechanistic studies, and their calibration. In discussing mechanisms, the emphasis has been on the possible application of these mechanisms in creating models which correlate a change in molecular structure to changes in physical properties, which, in turn, control performance in the field. For example, photooxidation of silicones has been shown to yield hydroxyl groups pendant on the siloxane chain which increases the polar character of the silicone surface, as indicated by surface energy analysis. A change in the surface polarity of silicones directly affects their interfacial bond strength to module substrates and causes weakening of bond strength to hydrophobic surfaces. Experiments prove that such a UV weakened bond may undergo delaminationg on exposure to moisture.

A major section of the report is devoted to acrylic photochemistry and the role of UV stabilizers and screening agents, because they are viewed as potential low-cost encapsulants capable of outdoor performance for 20 years or more. In addition to reviewing some of the rich literature in these areas, we have described some inhouse work of preliminary nature. It is hoped that the addition of these recent results will add a topical flavor to the report. Among the acrylics we have studied are the methacrylates, the acrylates, and their copolymers which often possess unique photochemical properties not ascribable to either of the two copolymers by themselves.

TITLE: Effect of Photodegradation on Chemical Structure and Surface Characteristics of Silicone Pottants Used in Solar Cell Modules.

AUTHOR: A. Gupta

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: August 1978

REPORT NO: 5101-79

ABSTRACT: Solar cell modules of Block I and Block II purchase delaminated in the field after passing JPL acceptance tests. Attempts to simulate field failure using conventional thermal and humidity cycling tests were unsuccessful. It was surmised that delamination might be caused by degradation of the adhesive bond caused by solar ultraviolet.

A failure analysis was carried out in terms of generic physiochemical mechanisms which included a careful assessment of time acceleration of ultraviolet radiation. The proposed model included rate of change of silicone material properties, including properties of the surface as a function of aging under well characterized ultraviolet irradiation and rate of change in bond strength. Failure observed in the field was then simulated in test specimens, and the failure rate was compared to that observed in the field.

The inherent variability of the silicone surface from point to point often exceeds changes in properties caused by aging, and it is therefore difficult to obtain unambiguous results from the failure analysis described above. This ambiguity may be resolved by monitoring more than one surface property whose degradation correlates with the failure mechanism under study. For delamination of silicones (RTV-615 and Sylgard-184) from certain hydrophobic substrates we have identified material properties of the polymer which correlate with bonding properties of its surface and therefore predict environmental aging conditions under which debonding would occur from a specific substrate. This type of analysis of the failure mechanism probes into the molecular basis of the failure and is of use in designing accelerated tests which would allow predicting lifetimes under given (or known) environments. Figure 1 summarizes this mechanistic approach to failure analysis and lifetime prodiction.

The focus of the discussion has always been pottants, since in our view the pottant is the central element in encapsulation design, and material choices for cover and substrates must take into account the protection the pottant needs. A low-cost pottant, for example, may need protection from UV, necessitating the addition of UV screening agents in the cover. Polyvinyl butyral needs a hermetically sealed environment in order to function outdoors without degradation. Hence, it must be sealed between two pieces of glass or other material impervious to moisture and oxygen. The choice of adhesives and primers is also based partically on the choice of the pottant. An example is provided by our work on RTV-615. It is found that RTV-615 (70 mil) will delaminate with ultraviolet light followed by water soak if either RTV 108 or QC 36-060 is used as primers. Thus, adoption of the material science approach to life prediction dictates that, initially, we study the mechanism of photodegradation of potential candidates for pottants.

TITLE: Low Cost Solar Array Project. Low-Cost Encapsulation Materials for Terrestrial Solar Cell Modules.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1978

REPORT NO: 5101-78

ABSTRACTS Solar cell modules must undergo dramatic reductions in cost in order to become economically attactive as practical devices for the production of electricity. A federal goal seeks to have, by 1986, and industrial capability of producing solar cell modules at a cost of 50¢ per watt (in 1975 dollars) and a service lifetime of 20 years. Today's modules cost more than $11.00 per watt, and they have an undefined lifetime. Part of the cost reductions must be realized by the encapsulation materials which are used to package, protect, and support the solar cells, electrical interconnects, and other ancillary components. It is estimated that to meet a cost goal of 50¢ per watt, encapsulation materials, including the structural substrate or superstrate, should cost between $2.70 and $5.00 per m^2 of module area (in 1975 dollars). This document presents the findings of material surveys intended to identify low cost materials which could be functional as encapsulants. This document further assesses the prognosis for achieving an encapsulation system at the lower cost goal of $2.70 per m^2, and identifies the technologies which must be advanced or developed to achieve 20-year life with the lowest costing materials.

TITLE: Experience with Silicones in Photovoltaic Modules.

AUTHOR: J. Repar

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1979

REPORT NO: DOE/JPL-1012-79/8A and 5101-103

ABSTRACT: Photovoltaic cells which are employed in terrestrial environments require extensive protection for various reasons. The cells are fragile, and metal components are subject to corrosion as the result of chemical reaction with various constituents in the atmosphere. Electrical insulation is required where metal substrates or frames are used. In addition, the deposition of atmospheric dust on surfaces requires that the surfaces be capable of withstanding repeated cleaning operations.

Materials covering the cells on the sunlit side must be transparent with low light absorption, particularly in the range of 400 to 1100 nanometers where silicon solar cells are most responsive. Although various types of glass and plastics have been employed as encapsulation materials, several room temperature curing silicones have processing characteristics which are readily applicable to encapsulation of silicon solar cells and also have excellent light transmission properties coupled with high dielectric strengths. This report will be confined to a discussion of experience with room temperature curing silicones.

Experience in both field and laboratory tests has indicated that delamination and other bond failures occur where silicones are used. The three which have been most widely used are General Electric's RTW-615 and two from Dow Corning, namely, Sylgard 184 and Q3-6527. A thin silicone film, Q1-2577, which is also a Dow Corning product, has been used as a hard cover over either RTV-615 or Sylgard 184. These studies were undertaken in an effort to determine the causes of delamination and other bond failures associated with the use of these silicones. The effects of deviation from recommended processing procedures during manufacture, and of various environmental factors during field exposure were examined.

TITLE: Low Cost Solar Array Project. Chemical Bonding Technology for Terrestrial Solar Cell Modules.

AUTHOR: Edwin P. Plueddemann

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1, 1979

REPORT NO: 5101-132

ABSTRACTS This report on chemical bonding technology for terrestrial solar cell modules includes an introduction to the state-of-the-art, general principles for module application, as well as test results and evolving recommendations of chemical bonding agents for ethylene vinyl acetate.

TITLE: Reactor for Simulation and Acceleration of Solar Ultraviolet Damage.

AUTHOR: E. Laue and A. Gupta

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1979

REPORT NO: DOE/JPL-1012-31 and 5101-135

ABSTRACT: An environmental test chamber providing acceleration of UV radiation and precise temperature control ($\pm$ 1°C) has been designed, constructed and tested. This chamber allows acceleration of solar ultraviolet up to 30 suns while maintaining temperature of the absorbing surface at 30°C - 60°C). This test chamber utilizes a filtered medium pressure mercury arc as the source of radiation, and a combination of selenium radiometer and silicon radiometer to monitor solar ultraviolet (295 - 340 nm) and total radiant power output, respectively.

Details of design and construction and operational procedures are presented along with typical test data.

TITLE: Encapsulation Materials Status to December 1979.

AUTHOR: E. F. Cuddihy

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1980

REPORT NO: 5101-144

ABSTRACT: The Encapsulation Task of the Low-Cost Solar Array Project (LSA) has defined two task objectives in achieving 1986 technology readiness of encapsulation systems:

Materials and Processes. Define, develop, demonstrate and qualify encapsulation systems, materials, and processes that meet the LSA project life, cost and performance goals.

Life Prediction Method. Develop and validate a module life prediction method based on modeling life-limiting failure modes and on conducting and analyzing accelerated aging tests of candidate encapsulation systems.

This is a status report on the first task objective, to date. The LSA project goal is to sponsor and stimulate activities that will reduce solar array prices to $0.14/W$_{pk}$ or $14/m^2 of completed module including an edge seal and gasket.

Surveys of encapsulation materials capable of meeting the LSA project goal have been carried out (References 2, 3) and were reported in April 1978 in the LSA Project report "Encapsulation Material Trends Relative to 1986 Cost Goals" (Reference 3). This was followed by a shortened version entitled "Low-Cost Encapsulation Materials for Terrestrial Solar Cell Modules" (Reference 4). The 1978 articles reported on a broad class of candidate materials by generic description, such as ethylene vinyl acetate, recognizing that many of the reported materials were not immediately useful for encapsulation. Since April 1978 no new generic classes of materials have been identified, and the emphasis in the intervening period has been on the identification, development and evaluation of specific materials within the generic classes, and the evolution of encapsulation processes and of module designs with the low-cost materials.

In April 1978, encapsulation materials industrially used consisted essentially of two castable silicone elastomers (Sylgard 184 and RTV 615), a silicone gel, polyvinyl butyral (PVB) laminating film, a hard silicone soil-resistant top coat, Tedlar and Mylar films, glass superstrate, and several substrate panels such as aluminum, NEMA-G10 epoxy board, and glass-reinforced polyester. Many of these materials are still being used and evaluated by module manufacturers; therefore the LSA program has chosen not to duplicate evaluation of them.

TITLE: Glass for Low-Cost Photovoltaic Solar Arrays.

AUTHOR: F. L. Bouquet

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1980

REPORT NO: DOE/JPL-1012-40 and 5101-147

ABSTRACT: In photovoltaic systems, the encapsulant material that protects the solar cells should be highly transparent and very durable. Glass satisfies these two criteria and is considered a primary candidate for low-cost, photovoltaic encapsulation systems. In this report, various aspects of glass encapsulation are treated that are important for the designer of photovoltaic systems. Candidate glasses and available information defining the state of the art of glass encapsulation materials and processes for automated, high volume production of terrestrial photovoltaic devices and related applications are presented. The criteria for consideration of the glass encapsulation systems were based on the (Low-cost Solar Array) Project goals for arrays: (a) a low degradation rate, (b) high reliablility, (c) an efficiency greater than 10 percent, (d) a total array price less than \$500/kW, and (e) a production capacity of 5 x 10^5 kW/yr.

The glass design areas treated herein include the types of glass, sources and costs, physical properties and glass modifications, such as antireflection coatings.

TITLE: Flat-Plate Solar Array Project. Development of Reduced-Variable Master Curves for Estimating Tensile Stresses of Encapsulated Solar Cells Caused by Module Deflection or Thermal Expansion.

AUTHOR: E. F. Cuddihy

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1, 1981

REPORT NO: 5101-182

ABSTRACTS Complex computer programs are being used by Spectrolab, Inc., to achieve encapsulation engineering optimization of photovoltaic modules under Low-Cost Solar Array Project Contract No. 955567. Optimization involves structural adequacy, electrical isolation (safety), maximum optical transmission, and minimum module temperature, at the lowest life-cycle energy cost. A goal of this activity is the generation, where possible, of encapsulation engineering generalities, principles, and design aids (tables or graphs) that would permit a ready, desktop capability to an engineering evaluation of encapsulation options involving materials or designs. This article reports the first efforts to generate reduced-variable master curves to serve as structural-analysis design aids.

TITLE:	Photovoltaic Module Encapsulation Design and Materials Selection: Volume I.
AUTHOR:	E. Cuddihy, W. Carroll, C. Coulbert, R. Liang and A. Gupta
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	June 1982
REPORT NO:	DOE/JPL-1012-60 and 5101-177

ABSTRACT:

Encapsulation-material system requirements, material-selection criteria, and the status and properties of encapsulation materials and processes available to the module manufacturer are presented in detail. Technical and economic goals established for photovoltaic modules and encapsulation systems and their status are described for material suppliers to assist them is assessing the suitability of materials in their product lines and the potential of new-material products.

A comprehensive discussion of available encapsulation technology and data is presented to facilitate design and material selection for silicon flat-plate photovoltaic modules, using the best materials available and processes optimized for specific power applications and geographic sites.

Section II provides a basis for specifying the operational and environmental loads that encapsulation material systems must resist. Potential deployment sites for which cost effectiveness may be achieved at a module price much greater than $0.70/W_p$, are also considered; data on higher-cost encapsulant materials and processes that may be in use and other material candidates that may be justified for special application are discussed.

Section III describes encapsulation-system functional requirements and candidate design concepts and materials that have been identified and analyzed as having the best potential to meet the cost and performance goals for the Flat-Plate Solar Array Project. Sections IV, V, and I present the available data on encapsulant material properties, fabrication processing, and module life and durability characteristics.

TITLE:	Photothermal Characterization of Encapsulant Materials for Photovoltaic Modules.
AUTHOR:	R. Liang, A. Gupta, and S. D. Stefano
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	June 1982
REPORT NO:	DOE/JPL-1012-72 and 5101-210
ABSTRACT:	A photothermal test matrix and a low-cost testing apparatus for encapsulant materials of photovoltaic modules have been defined and illustrated. Photothermal studies were conducted in order to screen and rank existing as well as future encapsulant candidate materials and/or material formulations in terms of their long-term physiochemical stability under accelerated photothermal aging conditions. Photothermal characterization of six candidate pottant materials and six candidate outer cover materials have been carried out. Principal products of photothermal degradation were identified. Certain critical properties were also monitored as a function of photothermal aging.

C-3

Encapsulation
(Environmental Isolation)
Contractor Abstracts

TITLE: Final Report. Terrestrial Service Environments for Selected Geographic Locations.

AUTHOR: R. E. Thomas and D. C. Carmichael

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: June 1976

REPORT NO: ERDA/JPL-954328-76/5

ABSTRACT: This report contains results obtained from analyses of climatic, precipitation, air pollution, and other environmental data for the years 1965-1974 at nine widely different geographic locations in the United States. In addition to descriptive and diurnal statistics for 24 individual climatic variables, "environmental cell" statistics were computed to obtain the frequencies, durations, and transitions for the simultaneous occurrence of various combinations of environmental variables. Results are presented for the simultaneous occurrence of specific levels of air temperature, relative humidity, wind speed, and insolation, in addition to representative results obtained for other combinations of variables.

The results characterize the environmental conditions to which terrestrial solar arrays would be exposed over a 20-year lifetime, and serve to identify environmental factors and levels that can be used in testing candidate encapsulation materials and systems for such terrestrial exposures. An innovative methodology was applied to obtain these results for combinations of environmental variables. Because of its generality and demonstrated feasibility, it is concluded that the methodology also has broad applications to other testing programs.

TITLE: Final Report. Review of World Experience and Properties of Materials for Encapsulation of Terrestrial Photovoltaic Arrays.

AUTHOR: D. C. Carmichael, G. B. Gaines and F. A. Sliemers, etal

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: July 1976

REPORT NO: ERDA/JPL-954328-76/4

ABSTRACT: Available information defining the state of the art of encapsulation materials and processes for terrestrial photovoltaic devices and related applications were collected and analyzed. Based on criteria of properties, processability, availability, and cost, candidate materials were identified which have potential for use in encapsulation systems for low-cost, long-life terrestrial photovoltaic arrays manufactured by automated, high-volume processes. The study was in support of the Encapsulation Task of the ERDA Low-Cost Silicon Solar Array (LSSA) Project, managed by JPL. The criteria for consideration of the encapsulation systems were based on the LSSA goals for arrays with a lifetime of over 20 years high reliablility, an efficiency greater than 10 percent, a total array price less than $500.kW, and a production capacity of 5 x 10^5 kW/yr.

Published and unpublished information relating to encapsulation systems and materials properties was collected by searching the literature and appropriate data bases and by personal contacts including site and company visits. A data tabulation summarizing World experience with terrestrial photovoltaic arrays (50 installations) is presented in the report. None of the encapsulation materials used meets all of the LSSA Criteria (particularly cost), but some have performed well.

Since the design of the ultimate LSSA device is yet to be established, selection of candidate materials was based upon both the LSSA criteria and specific materials properties (e.g., light transmission) requisite to the functions of various components (e.g., covers, pottants, etc.) in potential encapsulation systems, as well as upon temperature and processing constraints associated with the cell structure. The recommended materials (all commercially available) include, depending upon the device design, various borosilicate and soda-lime glasses and numerous polymerics suitable for specific encapsulation-system functions.

TITLE: Final Report. Methodclogy for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays.

AUTHOR: G. B. Gaines, R. E. Thomas, G. C. Derringer, etal

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: February 1977

REPORT NO: ERDA/JPL-954328-77/1

ABSTRACT: Current analyses dictate that for economic viability photovoltaic arrays should have a service life of 20 years or more. A need exists for meaningful accelerated tests to predict array life so that a relatively quick assessment can be made of the potential of present developmental designs and of the extent to which improvements in life are needed. As a part of the Encapsulation Task of the LSSA Project, this study undertook to develop a methodology for designing aging tests in which life prediction was paramount.

The methodology developed builds upon past experience with regard to aging behavior in those material classes which are expected to be utilized as encapsulant elements, viz., glasses and polymers, and upon past experience with the design of aging tests. Accordingly, these experiences were reviewed; the results constitute Part I of the technical discussion.

Part II presents the improved methodology developed in this study. The implementation of the methodology is illustrated using an example design for a solar-cell module. The developed methodology emphasizes the importance of incorporating substantial contributions at the time of initiation of the test design from statisticians, materials scientists, and test engineers in order to achieve a test design that is both statistically satisfactory and is practical in terms of the number of tests to be run. The first six steps of the developed methodology focus on the explicit identification of necessary engineering input information, identification of possible failure modes and environmental variables (stresses) that may affect the time rates of degradation for each failure mode without changing the failure mode, estimation of expected overall severity of each combination of environmental stresses, and analysis of severity ratings as a complete factorial experiment, with the results graphically represented by a hierarchical tree.

TITLE: Final Report on Accelerated/Abbreviated Test Methods for Predicting Life of Solar Cell Encapsulants to Encapsulation Task period covered: October 25, 1977--April 30, 1978

AUTHOR: Kolyer, J. M.; Mann, N. R.; Farrar, J.

CORPORATE AUTH: Rockwell International Corp. Autonetics Strategic Systems Div.

CONTRACT NO: 954458

DATE: April 1978

REPORT NO: DOE/JPL/954458-78/10

ABSTRACT: Accelerated and abbreviated test methods were developed for predicting the outdoor lifetime of solar cell encapsulants. Encapsulants are clear materials applied as covers to protect the cells from environmental hazards. An important principle is that encapsulants should be tested in a total array system allowing realistic interaction of components. Therefore, micromodule test specimens were fabricated with a variety of encapsulants, substrates, and types of circuitry. Interactions, sometimes favorable, were observed between these components. One common failure mode was corrosion of circuitry and solar cell metallization due to moisture penetration. Another was darkening and/or opacification of encapsulant. However the power output remained high despite drastic visual changes. A test program plan was proposed. It includes multicondition accelerated exposure, which was demonstrated to give successful predictions for property changes. Another method was hyperaccelerated photochemical exposure using a solar concentrator. It simulates 20 years of sunlight exposure in a short time period of one to two weeks. The study was beneficial in identifying some cost-effective encapsulants and array designs. It was shown that silicon junctions are remarkably resistant to moisture and contaminants. With corrosion-resistant circuitry, the encapsulant could be a low-cost plastic which protects cells from dust, abrasion, and mechanical shock.

TITLE: Final Report. Studies and Testing of Antireflective (AR) Coatings for Soda-Lime Glass

AUTHOR: Edward M. Pastirik, Terry G. Sparks, and Michael G. Coleman

CORPORATE AUTH: Motorola Inc. Semiconductor Group

CONTRACT NO: 954733

DATE: May 1978

REPORT NO: DOE/JPL-954733-78/1

ABSTRACT: Experimental results on this feasibility study to establish processes for producing antireflection films on glass are very encouraging. Efforts have been concentrated in three areas: acid etching of glass, plasma etching of glass, and acid development of sodium silicate films on glass. The best transmission to date has been achieved through the acid etching technique, while the most durable films have been produced from development of sodium silicate films. Control of the acid etching technique is presently inadequate for production implementation, and large scale application methods for sodium silicate films need further definition. While films having excellent antireflective properties have been fabricated by plasma etching techniques, all have been water soluble, disqualifying the films from a weatherability standpoint.

TITLE: Final Report. Evaluation of Available Encapsulation Materials for Low-Cost Long-Life Silicon Photovoltaic Arrays.

AUTHOR: D. C. Carmichael, G. B. Gaines and F. A. Sliemers, etal

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: June 1978

REPORT NO: DOE/JPL-954328-78/2

ABSTRACT: This investigation was conducted as part of the Low-Cost Solar Array (LSA) Project that is managed by the Jet Propulsion Laboratory for the Department of Energy, Division of Solar Technology. The 1986 objectives of the LSA Project are to develop the technology and manufacturing capability to produce 500,000 kW/year of photovoltaic arrays at a cost of less than $500/kW, with an efficiency of greater than 10 percent and a service life of 20 years. One of the tasks (Encapsulation Task) of this project is concerned with the development and evaluation of the protective encapsulation-material systems which will be required to meet these cost and service life objectives, as well as the production and performance objectives for terrestrial photovoltaic arrays.

To help evaluate the requirements and potential of encapsulation systems for arrays, an extensive review and analysis was made, in a previous study, of prior world experience with photovoltaic arrays in the field and the service behavior of encapsulation materials for photovoltaic and related applications. In addition to an appraisal of field experience and problems, candidate materials for various functions in the array encapsulation system were recommended for investigation and pertinent properties of these materials were collected and reported in that study. The study that is reported here consists of the experimental evaluation of selected encapsulation designs and materials based on the earlier study which have potential for use in low-cost, long-life photovoltaic arrays.

TITLE: Final Report. Ion Plating of Solar Cell Arrays

CORPORATE AUTH: Endurex Corporation

CONTRACT NO: 954728

DATE: December 1978

REPORT NO: DOE/JPL 954728-78/2

ABSTRACT: Endurex has been engaged in a feasibility study to determine practicality of utilizing Endurex ion plated films to serve as anti-reflective and/or protective encapsulants for solar cell arrays. It has been demonstrated that thin films of oxide materials between 1000 and 2000 A thick will protect a photovoltaic device from degradation in salt spray. Additionally, transmissivity data accumulated on Endurex coatings show that the anti-reflective (AR) properties of this film are equal to any achieved by more widely used processes. The Endurex ion plating process is capable of being scaled up to meet 1986 throughput goals at a cost which is in line with 1986 cost goals. An additional benefit that may be realized by the utilization of ion plating is that it is an effluent free process utilizing no wet chemistry.

TITLE: Final Report. Measurement Techniques and Instruments Suitable for Life-Prediction Testing of Photovoltaic Arrays.

AUTHOR: G. T. Noel, V. E. Wood, V. D. McGinniss, etal

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: March 1979

REPORT NO: DOE/JPL-954328-79/12

ABSTRACT: The validation of a 20-year service life for low-cost photovoltaic arrays is a critical requirement in the Low-Cost Solar Array (LSA) Project that is being conducted by the Jet Propulsion Laboratory for the Department of Energy. Of necessity, this validation must be accomplished through accelerated life-prediction tests. A methodology for such tests has been developed in a preceding study at Battelle for the LSA Project. Remaining needs before such tests are carried out are the identification, assessment, and experimental evaluation of diagnostic techniques and instruments that make it possible to measure failure-related degradative property changes over a short time period with sufficient precision to allow the prediction of sevice life exceeding 20 years.

A two-phase study has been conducted addressing these needs. Phase I, the results of which were discussed in the interim report on this study, accomplished the initial identification and assessment of all known measurement techniques and instruments that might be used in these life-prediction tests and included recommendations on their use. The results and recommended techniques from the Phase I investigation are summarized in the Appendix of this report.

Phase II of the study, covered in this report, consisted of experimental evaluations of three techniques selected from those recommended as a result of the Phase I findings. The three techniques evaluated were specular and nonspecular optical reflectometry, chemiluminescence measurements, and electrical current noise measurements.

TITLE: Final Report. Development of an Accelerated Test Design for Predicting the Service Life of The Solar Array at Mead, Nebraska.

AUTHOR: G. B. Gaines, R. E. Thomas and G. T. Noel, etal

CORPORATE AUTH: Battelle Columbus Laboratories

CONTRACT NO: 954328

DATE: June 1979

REPORT NO: DOE/JPL-954328-79/13

ABSTRACT: This report describes an accelerated test which is designed to predict the life of the 25-kW photovoltaic array installed near Mead, Nebraska. Emphasis is placed on the power-output degradation at the module level and on long-term degradation modes, as appropriate for life prediction of mature devices for which infant failures are few.

A quantitative model for accelerating testing using multiple environmental stresses is used to develop the test design. The model accounts for the effects of thermal stress by a relation of the Arrhenius form. This relation is then corrected for the effects of nonthermal environmental stresses, such as relative humidity, atmospheric pollutants, and ultraviolet radiation. The correction factors for the nonthermal stresses include temperature-dependent exponents to account for the effects of interactions between thermal and nonthermal stresses on the rate of degradation of power output. A priori quantitative estimates of the model parameters are then used to compute expected degradation rates under various test conditions associated with a complete factorial experimental design.

The test conditions, measurements, and data analyses for the accelerated tests are presented for determining the predicted life of the modules in service at Mead. Constant-temperature, cyclic-temperature, and UV types of tests are specified, incorporating selected levels of relative humidity and chemical contamination and an imposed forward-bias current and static electric field. It is recommended that as a first step in test implementation, the model be selectively validated using identified portions of the accelerated test design.

TITLE:	Final Report. Develop Silicone Encapsulation Systems for Terrestrial Silicon Solar Arrays.
CORPORATE AUTH:	Dow Corning Corporation
CONTRACT NO:	954995
DATE:	December 1979
REPORT NO:	DOE/JPL-954995-80/6

ABSTRACT:

This work resulted in two basic accomplishments. The first was the identification of DOW CORNING Q1-2577 as a suitable encapsulant material for use in cost effective encapsulation systems. The second was the preparation of a silicone-acrylic cover material containing a durable ultraviolet screening agent for the protection of photo-oxidatively sensitive polymers. The most expeditious method of fabrication is one in which the encapsulant material performs the combined function of adhesive, pottant, and outer cover. The costs of the encapsulant can be minimized by using it as a thin conformal coating. Our evaluation of methods by which to process encapsulation systems and the screening of candidate materials took those factors into consideration. One encapsulation system using silicones was identified from this work which provided protection to photovoltaic cells and survived the JPL qualification tests. This encapsulation system uses DOW CORNING as the combined adhesive, pottant and cover material. The lowest cost encapsulation system using Q1-2577 had Super Dorlux as the substrate structural member. The overall material cost of this encapsulation system is 0.74¢/ft^2 (1980 dollars) based on current material prices, which could decrease with increased production of Q1-2577.

TITLE:	Annual Report. Study Progr... for Encapsulation Materials Interface for Low-Cost Solar Array. Period Covered: January 1, 1980 through December 31, 1980
AUTHOR:	D. H. Kaelble, F. B. Mansfeld, M. Kendig, C. Leung
CORPORATE AUTH:	Rockwell International Corporation
CONTRACT NO:	954739
DATE:	February 1981
REPORT NO:	DOE/JPL 954739-4
ABSTRACT:	The early validation of a 20-year service integrity for the bonded interface in solar cell modules is an important requirement in the Low Cost Solar Array (LSA) Project.

The first annual report (Science Center Report No. SC5106.22AR) outlines and implements a physical/chemical evaluation program for solar cell encapsulants. The results of computer controlled ultrasonic and optical/ellipsometric mapping for interfacial defect characterization in solar modules is summarized in the second annual report (SC5106.49AR). The development and validation of an atmospheric corrosion model and test plan for LSA outdoor service at the Mead, Nebraska test site is presented in the third annual report (SC5106.86AR).

In the present fourth phase of study detailed in this annual report emphasis is placed on the development of AC impedance as a nondestructive evaluation (NDE) methodology for solar arrays and the further development of corrosion models and materials selection criteria for corrosion resistant interfaces.

TITLE: Second Quarterly Progress Report. April 1980 to June 1980. Ion-Plating of Solar Cell Arrays - Encapsulation Task

AUTHOR: William R. Conley

CORPORATE AUTH: Illinois Tool Works, Inc.

CONTRACT NO: 955506

DATE: March 1981

REPORT NO: DOE/JPL 955506-80/2

ABSTRACT: In the second quarter of this contract, functional solar cells were produced having ion-plated metallizations on both front and back surfaces. These cells consisted of 3.25" diameter n on p type silicon wafers with silver front and back contacts. The performance of these cells, although encouraging, was less than that of cells currently available on the photovoltaic market. Attempts were also made to produce a cell having nonnoble (inexpensive) metallizations, utilizing aluminum, copper and 302 stainless steel. These attempts proved less successful than those utilizing silver.

TITLE: Final Report. Anti-Reflection Coatings Applied by Acid Leaching Process

AUTHOR: E. Pastirik

CORPORATE AUTH: Motorola Inc. Semiconductor Group.

CONTRACT NO: 955387

DATE: September 1980

REPORT NO: DOE/JPL-955387-80/3

ABSTRACT: The Magicote C process developed by S. M. Thompsen was evaluated for use in applying an antireflective coating to the cover plates of solar panels. The process uses a flourosilicic acid solution supersaturated with silica at elevated temperature to selectively attack the surface of soda-lime glass cover plates and alter the physical and chemical composition of a thin layer of glass. The altered glass layer constitutes an antireflective coating. The process produces coatings of excellent optical quality which possess outstanding resistance to soiling and staining. The coatings produced are not resistant to mechanical abrasion and are attacked to some extent by glass cleansers. Control of the filming process was found to be difficult.

TITLE: Final Report. Integral Glass Encapsulation for Solar Arrays

CORPORATE AUTH: Spire Corporation

CONTRACT NO: 954521

DATE: July 1981

REPORT NO: DOE/JPL 954521-81/15

ABSTRACT: This program has developed the technology of electrostatic bonding as an encapsulation technique for terrestrial solar arrays. The process produces full integral, hermetic bonds with no adhesives or pottants. Demonstration panels of six solar cells on a single glass superstrate were produced.

Electrostatic bonding was also developed as a means of making the cell front contact. A metal mesh is trapped into contact with the cell front during the bonding process. Demonstration six-cell panels using the bonded mesh as the only cell front contract were produced.

Exploratory development was done on the possibility of using lower cost glass, with a higher thermal expansion mismatch to silicon, by making lower temperature (250-300°C) bonds. This was shown to require a planar surface cell (no front contacts). Demonstration panels of twelve 3" round wafers on a 12 x 18" glass sheet were made.

TITLE: Quarterl. Technical Progress Report. April 1-June 30, 1981. Mo elling of Polymer Photodegradation for Solar Cell Modules

AUTHOR: A. C. Somersall and J. E. Guillet

CORPORATE AUTH: University of Toronto

CONTRACT NO: 955591

DATE: July 1981

REPORT NO: 955591-81/3

ABSTRACT: As part of the Encapsulation Task, this research program is intended to model the photodegradation of synthetic polymers used as pottants and/or cover sheets in the LSA solar cell module designs. It involves the development of a computer simulaion of the chemical processes that take place under weathering conditions which could, in principle, relate directly to the performance of these materials and afford some basis for predicting and/or controlling their useful lifetimes.

The program can be divided into three main parts:

The development of a computer program to model the weathering/photooxidation of an ethylene-vinyl acetate copolymer as a typical candidate for LSA applications.

The development of new analytical procedures for the determination of photooxidation and photodegradation at early stages in solid polymer samples.

The development of weathering tests suitable for use with a computer kinetic model to provide a basis for extrapolated predictions.

TITLE: Annual Report. Grafting of 2(2-Hydroxy-5-Vinylphenyl)2H-Benzotriazole onto Polymers with Aliphatic Groups. Synthesis and Polymerization of 2(2-Hydroxy-5-Isopropenylphenyl)2H-Benzotriazole and A New Synthesis of 2(2-Hydroxy-5-Vinylphenyl)2H-Benzotriazole

AUTHOR: W. Pradellok, Zohar Nir and Otto Vogl

CORPORATE AUTH: University of Massachusetts

CONTRACT NO: 955531

DATE: August 15, 1981

REPORT NO: DOE/JPL-955531-81/1

ABSTRACT: Successful grafting of 2(2-hydroxy-5-vinylphenyl) 2H-benzotriazole onto saturated aliphatic C-H groups of polymers has been accomplished. When the grafting reaction was carried out in chlorobenzene at 150-160°C with di-tertiary-butylperoxide as the grafting initiator, grafts as high as 20-30% at a grafting efficiency of 50 and 80% have readily been obtained. It was very important to carry out the grafting reaction in tubes sealed under high vacuum since trace amounts of oxygen cause complete inhibition of the grafting reaction by the phenolic monomer. Grafting reactions were carried out on a variety of different polymers including atactic polypropylene, ethylene/vinyl acetate copolymer, poly (methyl methacrylate), poly (butyl acrylate), and polycarbonate.

TITLE: Twenty First Quarterly Progress Report for period ending August 12, 1981. Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants

AUTHOR: P. B. Willis, B. Baum

CORPORATE AUTH: Springborn Laboratories, Inc.

CONTRACT NO: 954527

DATE: October 1981

REPORT NO: DOE/JPL 954527-81/20

ABSTRACT: Springborn Laboratories is engaged in a study of evaluating potentially useful encapsulating materials for the Flat-plate Solar Array Project (FSA) funded by DOE. The goal of this program is to identify, evaluate, and recommend encapsulant materials and processes for the production of cost-effective, long-life solar cell modules.

During this quarter research work continued on the evaluation of soil resistant surface treatments, the investigation of corrosion protecting coatings for mild steel substrates, the identification of primers for bonding module interfaces, and the continuation of RS/4 accelerated aging of candidate encapsulation compounds.

TITLE: Triannual Report. Design, Analysis, and Test Verification of Advanced Encapsulation Systems

AUTHOR: Alec Garcia, Chuck Minning

CORPORATE AUTH: Spectrolab, Inc.

CONTRACT NO: 955567

DATE: November 1981

REPORT NO: DOE/JPL 955567-81/5

ABSTRACT: The objective of this program is to develop analytical methodology for advanced encapsulation systems which will aid in the determination of optimum systems for meeting the Low Cost Solar Array Project goals. The program consists of three phases. In Phase I, analytical models were developed to perform optical, thermal, electrical, and structural analyses on candidate encapsulation systems. From these analyses a candidate system will be selected for qualification testing during Phase II.

Additionally, during Phase II, test specimens of various types will be constructed and tested to determine the validity of the analysis methodology developed in Phase I.

In Phase III, a finalized optimum design based on knowledge gained in Phases I and II will be developed and delivered to JPL.

Production Process and Equipment
(Process Research)
JPL - In-House Abstracts

TITLE:	LSA Project Technology Development Update
AUTHOR:	Goldsmith, J. V. and Bickler, D. B.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	August 1978
REPORT NO:	DOE/JPL-1012-7B and 5101-104
ABSTRACT:	This document presents copies of the viewgraphs and a condensation of the comments by John V. Goldsmith and Donald B. Bickler of the LSA Project at its 10th Project Integration Meeting, August 16 and 17, 1978, at Caltech University, Pasadena, California. Their presentations focus on the state of the technology aimed at achieving the \$500/kW goal by 1986.

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TITLE: LSA Project Basic Sample Preparation Procedures and Evaluation of Silicon Sheet

AUTHOR: C. Radics

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1979

REPORT NO: 5101-128

ABSTRACT: Study of silicon material for solar cell fabrication involves various sample preparation and examination techniques. The procedures for evaluation and characterization of silicon are outlined, with special emphasis on the techniques for evaluating low-cost silicon sheets.

Standard techniques of metallography for evaluation on the basic structure of silicon material are extensively described. Surface etching, lapping and polishing operations are described in detail. Cross-sectional characterization and junction evaluation procedures through angle-lapping and staining techniques are covered.

Definitions of terms, scope and important safety precautions are given. These are followed by descriptions of procedures, materials and equipment to facilitate their effective use in the characterization laboratory.

Spreading resistance measurement, a strong tool in the evaluation of low-cost silicon sheet, is described with details of the equipment used and of operating procedures. Its use is emphasized as a high-resolution technique for checking of surface and depth homogeneity, multilayer characterization and effects associated with precipitates, grain boundaries, interfaces, etc.

TITLE: LSA Project Cost of Czochralski Wafers as a Function of Diameter.

AUTHOR: M. H. Leipold, C. Radics, and A. Kachare

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1980

REPORT NO: DOE/JPL-1012-37 and 5101-146

ABSTRACT: The impact of diameter in the range of 10 to 15 cm on the cost of wafers sliced from Czochralski ingots is analyzed. Increasing silicon waste and decreasing ingot cost with increasing ingot size are estimated along with projected costs. Results indicate a small but continuous decrease in sheet cost with increasing ingot size in this size range. Sheet costs including silicon are projected to be \$50 to \$60/m^2 (1980 \$) depending upon technique used.

TITLE: Low-Cost Solar Array Project. Near-Term Implementation of Flat-Plate Photovoltaic Cost-Reduction Task.

AUTHOR: Boyd, D. W.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1981

REPORT NO: 5101-180

ABSTRACT: In early 1978, the U.S. Department of Energy (DOE) committed $4.5 million to the Jet Propulsion Laboratory's (JPL) Low-Cost Solar Array (LSA) Project for use from 1979 through 1981 to investigate techniques for reducing the cost of producing flat-plate photovoltaic (PV) modules. In response, JPL designated the near-term cost reduction of modules to be a distinct Project task.

JPL invited proposals and evaluated them on the basis of maximum potential for producing techniques that would lead to near-term cost reduction. Based on this evaluation, which included solar array manufacturing industry costing standards (SAMICS) computer simulation, JPL awarded 14 contracts to industry and various universities for the development and description of cost reduction processes for solar cell and solar-cell module manufacturing. Predictions of manufacturing cost reductions achievable from the implementation of these process developments, on an individual basis, range from \$0.09 to \$1.76/W_p. Manufacturing cost reductions, greater than \$2.00/W_p, seem possible by simultaneous implementation of several compatible process developments.

Several of the processes developed within this program are now being used in commercial production lines. In some cases, the process development itself is commercially available in the form of hardware or technology documentation.

Project task objectives, contract awards, technology development, and cost-reduction results are summarized. Complete module manufacturing sequences including near-term cost-reduction process steps are also presented.

The term "cost," as used in this report, usually means cost to consumer. Cost reduction is measured at JPL by using the SAMICS method, which includes a reasonable rate of return on equity, income taxes, and all other normal costs of doing business.

TITLE: Flat-Plate Solar Array Project. Vacuum Lamination of Photovoltaic Modules.

AUTHOR: Burger, D. R.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1982

REPORT NO: DOE/JPL-1012-63 and 5101-188

ABSTRACT: Vacuum lamination of terrestrial photovoltaic modules is a new high-volume process requiring new equipment and newly developed materials. Equipment development, materials research, and some research in related fields and testing methods are discussed.

Production Process and Equipment
(Process Research)
Contract Abstracts

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TITLE: Final Report. Solar Cell Testing Vol. 2 - Appendix IV.

AUTHOR: A. S. Cherdak and Dr. G. M. Haas

CORPORATE AUTH: The Mitre Corporation

CONTRACT NO: 954342

DATE: May 1976

REPORT NO: ERDA/JPL-954342-1&2

ABSTRACT: In 1974, the MITRE Corporation purchased and installed on the roof of its building in McLean, Virginia, a 1 kilowatt peak photovoltaic array consisting of 20, 50 watt panels. These solar panels represented the state-of-the-art in terrestrial photovoltaics at the time. The primary purpose for establishing the MITRE Photovoltaic Array was to build a tool with which problems of designing, integrating, and operating terrestrial photovoltaic power systems could be studied.

Little attention was paid initially to monitoring the array itself due to preoccupation with the overall system design and installation. During and after the first year of exposure to the environment, a variety of changes were noticed in many of the panels: a reduction in short circuit currents and reduced power output from the array. MITRE, funded by ERDA through the Jet Propulsion Laboratory, undertook to investigate more thoroughly these apparently degraded panels.

MITRE proceeded to fabricate and install a data acquisition system, discussed in detail in this report, to provide more accurate and consistent measurements, in situ, of all of the panels and modules in the array.

The I-V curves measured in this program show that the Solarex panels have a much lower output power than the other panels in the array. In fact, they measure significantly lower than their original power rating. The poor fill-factors obtained from these panels suggest a high series resistance. Visual observation of the physical condition of these panels after two years of exposure to the terrestrial environment shows significant deterioration of the packaging materials.

TITLE: Final Technical Report. Development of Methods and Procedures for High Rate Low Energy Expenditure Fabrication of Solar Cells.

AUTHOR: A. R. Kirkpatrick, J. A. Minnucci, A. C. Greenwald.

CORPORATE AUTH: Simulation Physics

CONTRACT NO: 954289

DATE: 15 November 1976

REPORT NO: DOE/JPL-954289-76/4

ABSTRACT: A one year program to develop a new concept for silicon solar cell production based upon the use of pulsed electron beam processes combined with ion implantation has been completed. Feasibility of producing solar cells at high speed by a simplified vacuum-room temperature processing sequence has been demonstrated. The method has many advantages, particularly for large scale production at lowest possible cost.

TITLE: Final Report. Terrestrial Solar Cell Module.

CORPORATE AUTH: ARCO Solar, Inc.

CONTRACT NO: 954751

DATE: January 1977

REPORT NO: DOE/JPL-954751-78/1

ABSTRACT: ASI's objective on this program was to establish a cost effective design and manufacturing process that would produce solar cell modules capable of meeting the JPL qualification test criteria. Emphasis was placed on the development of an aluminum paste back contact process. The use of aluminum paste as a silicon solar cell back contact has the potential advantage of low resistance at low temperature firing and a highly doped P+ region contributing to improved cell putput. The aluminum has a substantial cost advantage when compared to silver paste.

TITLE: Final Report. Automated Array Assembly Task Phase I.

AUTHOR: Bernard G. Carbajal

CORPORATE AUTH: Texas Instruments, Inc.,

CONTRACT NO: 954405

DATE: October 1977

REPORT NO: DOE/JPL-954405-77/7

ABSTRACT: This contract consists of an assessment of the state-of-the-art technologies that are applicable to silicon solar cell and solar cell module fabrication. The assessment consists of a technical feasibility evaluation and a cost projection for high-volume production of silicon solar cell modules. A novel approach to metal pattern design based on minimum power loss was developed. The quantitative nature of the design equations provided a solid technical basis for the choice of a metallization technology. A hermetic module was proposed that has a high probalility of meeting the 20 year life goal. Solar cell processing and module fabrication cost projections exceed the 1985 cost goal by only a factor of 3.

TITLE: Final Report. Transparent Superstrate Terrestrial Solar Cell Module.

CORPORATE AUTH: Lockheed Missiles & Space Co.

CONTRACT NO: 954653

DATE: October 1977

REPORT NO: DOE/JPL-954653-77/1

ABSTRACT: The mechanical features of the module design incorporate high transmission glass superstrate, custom extruded aluminum side and end rails, a backside center stiffening web which also served as a mounting for two electrical output connectors, and three compliant grommets for mounting the unit into subarray frames. The electrical protion of the design incorporates 3-inch diameter circular cells from two vendors. The modules fabricated during the program are representative of the general design and of terrestrial cells currently available. To assess the value of primed versus unprimed glass, selected modules used no primer and other used two types of silicone primer. Also to gain additional comparative data in this developmental program, two types of encapsulants were used. Two methods of frame mechanical fastening were assessed, self-drilling tapping screws and blind or pop rivets. Riveting was found to be far superior.

TITLE: Final Technical Report. Automated Array Assembly.

AUTHOR: R. V. D'Aiello

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 954352

DATE: December 1977

REPORT NO: DOE/JPL-954352-77/4

ABSTRACT: This report contains three main sections which describe technology assessment and manufacturing cost analysis; a near-term (1982) factory design; and the results of an experimental production study for the large-scale production of flat-panel silicon solar-cell arrays. We have found a minimum manufacturing cost in a highly automated line of \$0.30/W assuming the silicon is free. The panels are of a double-glass construction and are based on round wafers. Screen-printed silver has been used as the metallization with a spray-coated antireflection (AR) layer. The least expensive junction-formation technology appears to be ion implantation. Based on the required investment, a profit of \$0.05 W appears reasonable. If silicon wafers are available at a price of \$20 to $40/M^2$, a selling price for these array modules of \$0.50 to 0.66/W is projected. An analysis of the impact of factory size in the 1986 time frame has been made. A factory processing 50MW/yr using the same technology would sell modules for \$0.54/W to 0.70/W.

TITLE: Final Report. Energy Requirement for the Production of Silicon Solar Arrays.

AUTHOR: Joseph Lindmayer

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 954606

DATE: December 1977

REPORT NO: DOE/JPL-954606-77/4

ABSTRACT: This report investigates the feasibility of manufacturing photovoltaic solar array modules by the use of energy obtained from similar or identical photovoltaic sources. The primary objective was the characterization of the energy requirements of current and developing technologies which comprise the photovoltaic field. These energy requirements were subsequently compared to the energy production potential of a future solar power plant and, as a result, the concept of the SOLAR BREEDER was refined and manifested in a computer program. The breeder model allows to take the energy requirements for any photovoltaic technology into account and calculate its energy economics. The report documents the energy assessment of the prevailing technologies and many alternative technologies currently under development. For cross-checking the energies of prevailing technologies Solarex data were also used and the wide-range assessment of alternative technologies included different refinement methods, various ways of producing light sheets, semicrystalline cells, etc. These energy data are utilized to model the behavior of a future SOLAR BREEDER plant under various operational conditions.

TITLE:	Final Report. Analysis of Effects of Impurities Intentionally Incorporated into Silicon.
AUTHOR:	Frank M. Uno
CORPORATE AUTH:	Spectrolab, Inc.
CONTRACT NO:	954694
DATE:	December 1977
REPORT NO:	DOE/JPL-954694-77/4
ABSTRACT:	A methodology has been developed and implemented to allow silicon samples containing intentionally incorporated impurities to be fabricated into finished solar cells under carefully controlled conditions. The electrical properties and spectral responses were then measured for each group processed. All 33 lots of group "C", 14 lots of Group "CM" and 16 lots of Group "F" have been fabricated into cells and tested.

TITLE: Final Report. Phase I of the Automated Array Assembly Task.

EDITOR: Pryor, R. A.; Grenon, L. A.; Coleman, M. G.

CORPORATE AUTH: Motorola, Inc. Phoenix, AZ (USA). Semiconductor Group

CONTRACT NO: 954363

DATE: January 1978

REPORT NO: DOE/JPL/954363-78/8

ABSTRACT: The solar cell which is considered for these studies is a silicon solar cell with a shallow (less than 1MU) metallurgical p-n junction, a back surface high-low junction (enhancement layer), and patterned front and full back contact metallizations. The cell also has a antireflection coating covering a texture-etched front surface. Detailed results of a study of process variables and solar cell variables are presented. Emphasis is on identifying interactions between variables and their effects upon control ranges of the variables. Also, the results of a detailed cost analysis for manufacturing solar cells are reported. This cost analysis includes a sensitivity analysis of a number of key cost factors.

TITLE: Final Report. Assessment of Present State-of-the-Art Sawing Technology of Large Diameter Ingots for Solar Sheet Material

AUTHOR: Yoo, H. I.

CORPORATE AUTH: Optical Coating Laboratory, Inc. (Now Applied Solar Energy Corporation)

CONTRACT NO: 954830

DATE: February 1978

REPORT NO: DOE/JPL 954830-78/2

ABSTRACT: The objective of this program is to assess the present state-of-the-art sawing technology of large diameter silicon ingots (3" and 4" diameter) for solar sheet materials. During this program, work has progressed in: (1) Slicing of the ingots with the multiblade slurry (MBS) saw, the multiwire slurry (MWS) saw and the I.D. saw, (2) Characterization of the sliced wafers, and (3) Analysis of add-on slicing cost based on SAMICS. Multiblade slurry slicing resulted in mechanical wafer yields of 95% for the 3" diameter ingot and 84% for the 4" diameter ingot (using a 230 blade package to cut 6" ingot in length). A slicing test with the I.D. saw was performed to obtain mechanical yield versus both wafer thickness and cut rate, and the result showed a good yield (above 95%) down to 7-8 mils of wafer thickness of the 3" wafers and 11-12 mils for the 4" wafers if the cut rates were reduced to one (1) inch per minute. An ingot of 3" in diameter and 3" in length was sliced with a multiwire slurry saw to obtain wafer yield of about 97%; 163 wires were used, and wafer thickness and kerf width were 10-1 mils and 8 mils respectively. Thickness, taper, bow, and roughness (RMS) were measured to characterize the sliced wafers. Four inch wafers sliced with the multiblade slurry saw showed larger thickness variations (wafer to wafer) and more taper than 3" wafers. Wafers sliced with the I.D. saw indicated that taper, bow and roughness increased as the cut rate increased (this effect was significant when cut rate was increased to above three (3) inches per minute). Comparison of the above parameters showed the wafers cut with the I.D. saw (sliced below three inch per minute of cut rate) and the multiwire slurry saw have much smaller values and variations than those cut with the multiblade slurry saw, indicating the need for less removal of silicon before solar cell formation. Also, the I.D. saw wafers showed slightly better characteristics in parameters than those of the multiwire slurry saw. Add-on slicing cost was evaluated based on

Solar Array Manufacturing Industry Costing Standard (SAMICS) for three slicing types: MBS saw indicated a cost of \$.80/wafer for 3" wafers. I.D. saw sliced at two (2) IPM of cut rate gave \$.17/wafer for 3" wafer and \$.24/wafer for 4" wafers showing significant advantages over the other two methods at present.

TITLE: Final Report. Spraylon Fluorocarbon Encapsulation for Silicon Solar Cell Arrays.

AUTHOR: L. G. Naes

CORPORATE AUTH: Lockheed Missiles & Space Company, Inc.

CONTRACT NO: 954410

DATE: April 1978

REPORT NO: DOE/JPL-954410-78/1

ABSTRACT: This program was a research and development program to evaluate the Lockheed-formulated liquid transparent film-forming, flurocarbon, SPRAYLON, protective coating for terrestrial solar cell modules. Two modules were completed and field-tested for periods of up to two weeks. Problems developed early in the field testing which led to the shortened test period, specifically, lifting of the antireflection coating, followed in some areas by complete film delamination.

TITLE:	Final Report. Development of Low-Cost, High Energy-Per-Unit-Area Solar Cell Modules.
AUTHOR:	Sang S. Rhee
CORPORATE AUTH:	Sensor Technology, Inc.
CONTRACT NO:	954605
DATE:	April 1978
REPORT NO:	DOE/JPL-954605-78/5

ABSTRACT: Development of low-cost, high energy-per-unit-area solar cell modules was conducted in this program. This final report covers the development of two hexagonal solar cell process sequences, a laser-scribing process technique for scribing hexagonal and modified hexagonal solar cells, a large through-put diffusion process, and two surface macrostructure processes suitable for large scale production. Experimental analysis was made on automated spin-on anti-reflective coating equipment and high pressure wafer cleaning equipment. Six hexagonal solar cell modules were fabricated; they demonstrated that module efficiency can be significantly improved by the utilization of hexagonal or modified hexagonal solar cells replacing round solar cells due to increased solar cell packing ratio and increased solar cell photovoltaic energy conversion efficiency. Also covered in this report is a detailed theoretical analysis on the optimum silicon utilization by modified hexagonal solar cells for low-cost, high energy-per-unit-area solar cell modules. It was shown that an optimum modified hexagonal solar cell module will produce a cost savings compared to a round cell module.

TITLE: Final Report. Design and Fabrication of Solar Cell Modules.

AUTHOR: Thomas P. Shaughnessy

CORPORATE AUTH: Spire Corporation

CONTRACT NO: 954655

DATE: April 1978

REPORT NO: DOE/JPL-954655-78/1

ABSTRACT: This program achieved its objective of producing 12 solar cell modules utilizing ion implanted solar cells and an all-glass encapsulation system. These modules have exhibited only cosmetic degradation after environmental testing. The principal problem encountered was the formation of bubbles in the silicon gel due to gasket air leakage during thermal cycling. Developmental effort, after delivery of the modules to JPL, indicates that this can be rectified by the use of a polysulfide gasket. Significant improvements in the module design that can be recognized are the use of tempered, low iron content glass for increased module output, and the substitution of a custom aluminum extrusion for reduced weight and increased rigidity.

TITLE: Final Report. High Efficiency, Long Life Terrestrial Solar Panel.

AUTHOR: S. Khemthong

CORPORATE AUTH: Optical Coating Laboratory, Inc.

CONTRACT NO: 954831

DATE: April 1978

REPORT NO: DOE/JPL-954831-78/3

ABSTRACT: Six high efficiency, long life terrestrial modules were designed, fabricated and delivered to JPL. The module utilized 256 large area, rectangalar, high efficiency solar cells. A flexible, overlapping design to connect cells in series was used to maximize the packing density. The efficiency of the six modules delivered, based on the overall dimensions at 100 mW/cm^2 and 28 degrees C is tabulated in Table 2, and the contract goal of 13% array efficiency was achieved.

TITLE: Final Report. Center Punched Solar Cell Module Development Effort.

AUTHOR: R. E. Ross and W. E. Mortensen

CORPORATE AUTH: Xerox Electro-Optical Systems

CONTRACT NO: 954693

DATE: June 1978

REPORT NO: DOE/JPL-954693-78/1

ABSTRACT: This report describes the results of an advanced module development program with the objective of providing a low cost solar cell mechanical interconnect design. The design approach, which avoids soldering or welding operations, lends itself to automated assembly techniques thus supporting the Low-Cost Silicon Solar Array Project goals. A total of twelve modules were delivered to JPL for qualification testing. The first group of six modules contained aluminum-palladium contact cells. This final report discusses the module design, manufacturing procedure, test program, significant problem areas and solutions, and conclusions and recommendations as formulated and conducted by XEOS.

TITLE: Final Report. EFG Solar Modules.

CORPORATE AUTH: Mobil Tyco Solar Energy Corporation

CONTRACT NO: 954999

DATE: September 1978

REPORT NO: DOE/JPL-954999-78/1

ABSTRACT: 6 photovoltaic modules using solar cells fabricated from silicon ribbons were assembled. Each module was comprised of 4 separate submodules which were parallel connected. The submodules contained 45 EFG cells which were series interconnected by a "shingle" or overlapping design. The inherent rectangular shape of the cells allowed a high packing factor to be achieved. The average efficiency of the 6 modules, corrected to AM1 at 28 degrees C was 8.7%, which indicates that the average encapsulated cell efficiency was 10.0%.

TITLE: Final Report. Phase 2, Automated Array Assembly, Task IV

CORPORATE AUTH: Lockheed Missiles and Space Co., Inc., Sunnyvale, CA (USA)

CONTRACT NO: 954898

DATE: October 1978

REPORT NO: DOE/JPL/954898-78/4

ABSTRACT: This contract was a process development effort to verify the technological readiness of a selected process sequence from that as-sawn Czochralski grown silicon wafers to the module assembly. The process investigated consisted of the following sequence: Starting Material: 3-inch as-sawn CZ silicon wafers; texture etching of silicon wafers using sodium hydroxide; junction formation by ion implantation of phosphorus; laser annealing of ion implanted wafers; screen printing of AG, AG-AL for ohmic contact; spraying of tantalum oxide AR coating; and assembly of modules using the LMSC module design, developed under the JPL contract 954653, as baseline. This selected process sequence was evaluated for its technical potential of achieving the economic goals of the low cost solar array project of $.50/watt for 500 megawatt/year production by 1986. Evaluation procedures and results are reported.

TITLE: Final Report. Development and Testing of Shingle-Type Solar Cell Modules

CORPORATE AUTH: General Electric Company

CONTRACT NO: 954607

DATE: February 28, 1979

REPORT NO: DOE/JPL 954607-79/4

ABSTRACT: The design, development, fabrication and testing of a shingle-type terrestrial solar cell module which produces 98 watts/m^2 of exposed module area at 1 kW/m^2 insolation and 61°C are reported. These modules make it possible to easily incorporate photovoltaic power generation into the sloping roofs of residential or commercial buildings by simply nailing the modules to the plywood roof sheathing. This design consists of nineteen series-connected 53mm diameter solar cells arranged in a closely packed hexagon configuration. These cells are individually bonded to the embossed surface of a 3mm thick thermally tempered hexagon-shaped piece of ASG SUNADEX glass. Monsanto SAFLEX polyvinyl butyral is used as the laminating adhesive. RTVII functions as the encapsulant between the underside of the glass superstrate and a rear protective sheet of 0.8 mm thick TEXTOLITE. The semi-flexible portion of each shingle module is a composite laminate construction consisting of outer layers of B. F. Goodrich FLEXSEAL and an epichlorohydrin closed cell foam core. The module design has satisfactorily survived the JPL-defined qualification testing program which includes 50 thermal cycles between -40 and +90°C, a seven day temperature - humidity exposure test and a mechanical integrity test consisting of a bidirectional cyclic loading at 2390 Pa (50 lb/ft^2) which is intended to simulate loads due to a 45 m/s (100 mph) wind.

TITLE: Final Report. High Efficiency, High Density Terrestrial Panel

AUTHOR: John Wohlgemuth

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 954822

DATE: February 1979

REPORT NO: DOE/JPL 954822-78/1

ABSTRACT: Most commercially available photovoltaic modules employ the standard round cells. Because of the geometry limitations the packing density in these panels is typically 60 to 70%. The low packing density results in total area panel efficiencies of 6 to 7%. With these low efficiencies, excess encapsulation, framing and mounting materials are required per watt of power delivered, thereby significantly increasing the cost per watt to the consumer. In addition, because of the low panel efficiency many potential applications, with limited area available for array deployment, are not feasible. Solarex has developed the technology for producing large area square and rectangular cells with high (14 to 15%) conversion efficiencies at AM1 ($1kW/m^2$) at 28°C. In this program terrestrial panels have been fabricated using these rectangular cells resulting in the achievement of packing densities in excess of 90% with panel conversion efficiencies greater than 13% being obtained. Most importantly, higher density panels can be produced today on a cost competitive basis with the standard salami panels, with bright prospects of significant cost reductions in the near future.

TITLE: Final Report. High Efficiency Cell Development.

AUTHOR: Bernard G. Carbajal

CORPORATE AUTH: Texas Instruments Incorporated

CONTRACT NO: 954881

DATE: February 1979

REPORT NO: DOE/JPL-954881-79/5

ABSTRACT: This program, High Efficiency Cell Development, was run as an activity under contract JPL 954881, AAA, Phase 2. the goal of this specific activity was to improve the Texas Instruments developed Tandem Junction Cell (TJC) as a high efficiency solar cell. The TJC development must be consistent with module assembly and should contribute to the overall goals of the LSA Project. During 1978, TJC excess of 42 mA/cm^2 were observed at AMO. Open circuit voltages as high as 0.615 V were measured at AMO. Fill Factor was only 0.68 - 0.75 due to a non-optimum metal contact design. A device model was conceived in which the solar cell is modelled as a transistor. This model will be very useful in directing future development activities. The planar back contact system of the TJC coupled with the high cell efficiency makes the TJC an excellent candidate solar cell for the fabrication of high efficiency modules, since there are virtually no interconnect or packing factor losses. The TJC is compatible with all conventional module fabrication systems. The back contact system lends itself readily to series, parallel or series-parallel interconnect schemes. A modification of the TJC, the Front Surface Field (FSF) cell was also explored. The FSF cell using a floating P+ layer on the front of the cell in place of the N+ layer of the TJC. The FSF cell also features the planar back contact system. Photoresponse of FSF cells, while good, was not quite as good as the TJC.

TITLE: Final Report. Metallization of Large Silicon Wafers

AUTHOR Robert A. Pryor

CORPORATE AUTH: Motorola Inc. Semiconductor Group

CONTRACT NO: 954689

DATE: March 1979

REPORT NO: DOE/JPL 954689-78/4

ABSTRACT: A metallization scheme has been developed which allows selective plating of silicon solar cell surfaces. The system is comprised of three layers. Palladium, through the formation of palladium silicide at 300°C in nitrogen, makes ohmic contact to the silicon surface. Nickel, plated on top of the palladium silicide layer, forms a solerable interface. Lead-tin solder on the nickel provides conductivity and allows a convenient means for interconnection of cells.

To apply this metallization, three chemical plating baths are employed. Palladium is deposited with an immersion palladium solution and an electroless palladium solution, and nickel is deposited with an elecroless nickel solution. Solder is applied with a molten solder dip. Extensive development work has been performed to achieve an effective immersion palladium silicide contact layer.

This metallization system has been repeatedly demonstrated to be extremely effective. Current-voltage characteristic curve fill factors of 78% are easily achieved. This has been done while maintaining metal contact adhesion at such a strength as to fail by fracturing silicon upon perpendicular pull testing rather than by delaminating the metal system.

Demonstrations have been performed on a laboratory scale using beakers, hot plates, and lots of 24 three inch diameter solar cells. On this basis, process specifications and procedurs have been prepared. The laboratory process could be easily scaled to full production volume.

Although this metallization system has been shown to be cost effecive in its present state of readiness, specific areas have been identified which would profit from additional development, leading to appreciable further cost reductions which would make the metallization cost a minor factor in 50¢/watt solar cell economics. A document, "Material, Supply, and Process Specifications and Procedures for Metallization of Large Silicon Wafers with the Palladium-Nickel-Solder Metallization System," has been prepared and will be available from JPL upon request.

TITLE: Final Report. Development of Economical Improved Thick Film Solar Cell Contact

CORPORATE AUTH: Bernd Ross Associates

CONTRACT NO: 955164

DATE: April 1979

REPORT NO: DOE/JPL 955164-77/2

ABSTRACT: Materials were surveyed to provide candidates for an all metal electrode paste system. These consisted of a major constituent metal powder, a low melting metal powder material suitable as an etchant for silicon dioxide at sintering temperatures. By means of thermal gravimetric analysis, a suitable binder was identified for low temperature fired inks. The all metal ink concept was first demonstrated with the silver system to avoid the problems of limited process windows encountered with base metal systems. A number of solid materials capable of selectively etching silicon dioxide at modest temperatures were identified.

The results of the study suggest further experimentation with eutectic additives to enable formation of a thin highly doped regrowth layer.

TITLE: Final Report. Development of Pulsed Processes for the Manufacture of Solar Cells

CORPORATE AUTH: Spire Corporation

CONTRACT NO: 954786

DATE: April 1979

REPORT NO: DOE/JPL 954786-79/7

ABSTRACT: This report describes the results of a one and a half year program to develop the processes required for low-energy ion implantation for the automated production of silicon solar cells. The program included (1) demonstrating state-of-the-art ion implantation equipment and designing an automated ion implanter, (2) making efforts to improve the performance of ion-implanted solar cells to 16.5 percent AM1, (3) developing a model of the pulse annealing process used in solar cell production, and (4) preparing an economic analysis of the process costs of ion implantation and furnace annealing. During the program, phosphorus ions at an energy of 10 keV and dose of $2 \times 10^{15} cm^{-2}$ were implanted in silicon solar cells to produce junctions, while boron ions at 25 keV and $5 \times 10^{15} cm^{-2}$ were implanted in the cells to produce effective back surface fields. An ion implantation facility with a beam current up to 4 mA and a production throughput of 300 wafers per hour was designed and installed. A design was prepared for a 100-mA, automated implanter with a production capacity of 100 MW_e per year. Two process sequences were developed which employ ion implantation and furnace or pulse annealing. The JPL-Solar Array Manufacturing Industry Simulation (SAMIS) computer program was used to determine costs for junction formation by ion implantation and various furnace annealing cycles to demonstrate cost effectiveness of these methods.

TITLE: Final Report. Solar Cell Modules with Parallel Oriented Interconnections.

AUTHOR: Motorola Inc., Semiconductor Group

CORPORATE AUTH: 954716

DATE: June 1979

REPORT NO: DOE/JPL 954716-79/1

ABSTRACT: This report documents activities and pertinent results which have been obtained on JPL Contract 954716. This contract provided for delivery of 24 solar modules, half of which were to be 48 cells in an all-series electrical configuration and half of a 6 paralleled cells by 8 series cells. Upon delivery of environmentally tested modules to JPL, low power outputs were discovered. These low power modules were determined to have cracked cells which were thought to cause the low output power. The cracks tended to be circular or linear, which were caused by different stressing mechanisms. A subsequent contract amendment to the original contract was made to fully explore these stressing mechanisms. The contract amendment also provided for delivery of 36 cells with selected interconnect configurations and two additional modules. The series-parallel configuration modules were also changed to 4PX12S. Efforts were undertaken to determine the causes of cell fracture. This resulted in module design and process modifications, foremost among which was the decision to utilize a multiple back contact interconnect design. The design and process changes were subsequently implemented in production.

TITLE: Final Report. Evaluation of the Technical Feasibility and Effective Cost of Various Thickness for the Manufacture of Solar Cells.

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 955077

DATE: July 1979

REPORT NO: DOE/JPL-955077-79/5

ABSTRACT: The principal activities in the performance of this contract effort include practical evaluation of the Yasunaga YQ-100 saw in a production environment. The wafering system is a free-abrasive multiple-loop single wire machine where the number of wafers/cm is determined by the wire pitch. In addition, the effects of wire diameter and abrasive size were studied. Solar cells were manufactured from each saw run to analyze surface damage and effects of varying thickness on efficiency. It was determined that surface damage was much reduced compared to fixed abrasive saws, and as little as 5-10 micrometers of surface removal from each side of the wafer was sufficient to obtain optimum efficiency for the particular process which was used. Since thin wafers were produced, an analysis of panel manufacture using thin cells was made with special concern for flexibility of the panels and breakage. The saw was found to be much more labor intense than expected, and wafering system modifications are recommended which can result in effective cost reduction for the manufacture of solar cells.

TITLE:	Final Report. Automated Array Assembly Task In-Depth Study of Silicon Wafer Surface Texturizing.
AUTHOR:	Gregory T. Jones
CORPORATE AUTH:	Sensor Technology, Inc.
CONTRACT NO:	955266
DATE:	July 1979
REPORT NO:	DOE/JPL-955266-79/2

ABSTRACT: An in-depth study of silicon wafer surface texturizing was conducted in this program. The work discussed in this final report covers four tasks. Task (1) investigated a low-cost cleaning method that utilized recycled Freon in an ultrasonic vapor degreaser to remove organic and inorganic contaminants from the surface of silicon wafers as received from silicon suppliers. Task (2) demonstrated the use of clean dry air and high throughput wafer batch drying techniques to lower the cost of wafer drying. Task (3) examined the two stage texturizing process for suitability in large scale production. Task (4) performed an in-depth gettering study with the two stage texturizing process for the enhancement of solar cell efficiency, minimization of I-V curve dispersion, and improvement in process reproducability. The 10% efficiency improvement goal was exceeded for the wafer surface texturizing study for the near term implementation of flat plate photovoltaic cost reduction. Production solar cells were produced with 18.3% higher efficiencies than similar solar cells without texturization. Gettering in combination with a two-stage texturizing process had a significant effect on solar cell batch electrical performance. An 11.8% average batch efficiency improvement was observed for low temperature intermediate gettered solar cells over texturized (no gettering) solar cells. The wafer cleaning cost reduction goal for the wafer surface texturizing study was achieved. The cleaning materials cost was reduced from 3.7 cents per peak watt (1975 cents) to less than 0.7 cents per peak watt. The texturizing process cost including cleaning, drying, and texturizing, amounted to 1.26 cents per peak watt. The gettering cost, which used recycled $POCl_3$, was found to be .97 cents per peak watt. These costs are in line with the 1986 DOE/JPL Low-Cost Solar Array Project goal.

TITLE: Final Report. A New Method of Metallization for Silicon Solar Cells.

AUTHOR: Dr. Milo Macha

CORPORATE AUTH: Sol/Los Incorporated

CONTRACT NO: 955318

DATE: September 1979

REPORT NO: DOE/JPL-955318-79/3

ABSTRACT: The new metallization process based on Mo-Sn system is the subject of this nine months program. MoO_3 is used as the source of Mo, since its relatively low melting point and ease of reduction to metallic molybdenum. The first part of the contract, the reaction mechanism study of MoO_3 and its mixture with Sn, was conducted in an experimental station consisting of a graphite strip-heater and a Pyrex belljar, under close control of temperature-atmosphere-time, while allowing visual observations of the reactions. The metallization of the cells was done in a diffusion tube furnace. In order to obtain a low ohmic contact to the cell, the basic ink composition was modified with a small addition of titanium in the form of titanium resinate. The electrical characteristics of the cells were comparable with the existing metallization processes. The firing cycle still has to be optimized for the process used in the continuous conveyor belt furnace, especially in the cooling cycle around 450°C, which indicated a significant effect on the electrical characteristics. The cost analysis of the process was based on projected production output of one MegaWatt per year, using 2" diam. silicon crystal wafers and the current material cost. Therefore the calculated cost deviates from the projected price goal set up for the year 1986. In comparison with the standard processes using silver as the contacting metal, the saving obtained by the use of this new process is a direct result of the price difference between silver and molybdenum oxide with tin.

TITLE: Final Report. Phase 2 of the AAA Task for the LSA Project.

AUTHOR: R. B. Campbell

CORPORATE AUTH: Westinghouse R&D Center

CONTRACT NO: 954873

DATE: October 1979

REPORT NO: DOE/JPL-954873-79/8

ABSTRACT: The process sequence for the fabrication of dendritic web silicon into solar panels has been modified to include aluminum back surface field formation. Sputtering is the preferred method for depositing the aluminum. Plasma etching has been shown to be a feasible technique for pre-diffusion cleaning of the web. This would replace wet chemical cleaning. Several contacting systems have been studied. The total plated Pd-Ni system (Motorola Process) is not compatible with our process sequence; however, the evaporated TiPd-electroplated Cu system has been shown stable under life testing. Ultrasonic bonding parameters have been determined for various interconnect and contact metals but the yield of the process is not sufficiently high to use for module fabrication at this time. Over 400 solar cells, about 11 cm^2 in area have been fabricated according to the modified sequence. No sub-process incompatibility was een. These cells have been used to fabricate four demonstration modules. A cost analysis (SAMICS) of the modified process sequence resulted in a selling price of $0.75/peak watt (1980$ in 1986).

TITLE: Final Report. Development of Economical Improved Thick Film Solar Cell Contact

CORPORATE AUTH: Bernd Ross Associates

CONTRACT NO: 955164

DATE: December 1979

REPORT NO: DOE/JPL 955164-79/4

ABSTRACT: In the second half of the investigation of all metal screened electrodes, the focus was on base metal pastes in addition to further work with the silver systems. Contact resistance measurements were refined. A facility allowing firing in hydrogen and other atmospheres was acquired. Several experiments were made applying screenable pastes to solar cells. Doping investigations emphasized eutectic alloys reduced to powders. Metal systems were reviewed. A previously published vapor pressure curve for silver flouride was corrected. Base metal experiments were done with nickel and copper using lead and tin as the frit metals. No electrical experiments were done with the nickel ink.

TITLE: Final Report. Evaluation of Ion Implanted Silicon.

AUTHOR: P. A. Iles

CORPORATE AUTH: Optical Coating Laboratory Inc.

CONTRACT NO: 955118

DATE: February 1980

REPORT NO: DOE/JPL-955118-80/2

ABSTRACT: This contract is a three-way joint effort, between California Institute of Technology, Jet Propulsion Laboratory and Optical Coating Laboratory, Inc. (OCLI). The goal is to investigate the potential for reduced cost ion-implantation to fabricate low cost solar cells. The team obtains overall guidance and some support related to low cost ion sources from JPL, Cal-Tech performs all ion-implants (including variations in energy, fluence and ion species) and OCLI provides suitable silicon slices, and processes and evaluates the implanted wafers as solar cells using a "baseline" process.

To date about 280 slices have been prepared, implanted, and processed as cells. The detailed summary of the cell performance as a function of the various ion implantation parameters is contained in the Cal-Tech final report on this phase of the work.

TITLE: Final Report. Use of Glass Reinforced Concrete (GRC) as a Substrate for Photovoltaic Modules.

CORPORATE AUTH: MBAssociates

CONTRACT NO: 955281

DATE: March 1980

REPORT NO: DOE/JPL-955281-80/4

ABSTRACT: MBAssociates (MBA), under contract to Jet Propulsion Laboratories (JPL) developed as substrate for flat plate photovoltaic solar panel arrays using a glass fiber reinforced concrete (GRC) material. The installed cost of this GRC panel (designed, developed and fabricated by MBA) is 30% less than the JPL cost goal of the Near Term Low-Cost Flat Plate Photovoltaic Solar Array Program. The 4' x 8' panel is fabricated from readily available inexpensive materials, weighs a nominal 190 lbs., has exceptionally good strength and durability properties (rigid and resists weathering), is amenable to mass production and is easily installed on simple mountings. Solar cells are encapsulated in ethylene/vinyl acetate (EVA) with Tedlar backing and Korad cover film. The laminates are attached to the GRC substrate with acrylic transfer tape and edge sealed with a silicone RTV adhesive.

TITLE: Final Report. Phase 2 of the AAA Task of the LSA Project

AUTHOR: M. G. Coleman, etal

CORPORATE AUTH: Motorola Inc. Semiconductor Group

CONTRACT NO: 954847

DATE: March 1980

REPORT NO: DOE/JPL 954847-80/8

ABSTRACT: Several specific processing steps, as part of a total process sequence for manufacturing silicon solar cells, were studied during this contract. Ion implantation has been identified as the Motorola preferred process step for impurity doping. Unanalyzed beam ion implantation has been shown to have major cost advantages over analyzed beam implantation. Further, high quality cells have been fabricated using a high current unanalyzed beam. Mechanically masked plasma patterning of silicon nitride has been shown to be capable of forming fine lines on silicon surfaces with spacings between mask and substrate as great as 250 μm (10 mils). Extensive work was performed on advances in plated metallization. The need for the thick electroless palladium layer has been eliminated. Further, copper has been successfully utilized as a conductor layer, utilizing nickel as a barrier to copper diffusion into the silicon. Plasma etching of silicon for texturing and saw damage removal has been shown technically feasible, but not cost-effective compared to wet chemical etching techniques.

TITLE: Final Report. Development of Low Cost Contacts to Silicon Solar Cells

AUTHOR: D. P. Tanner and P. A. Iles

CORPORATE AUTH: Optical Coating Laboratory, Inc.

CONTRACT NO: 955244

DATE: October 1978 to April 1980

REPORT NO: DOE/JPL 955244-80/5

ABSTRACT: This report is a summary of work done on the development of a copper based contact system for silicon solar cells. The work has proceeded in three phases:

PHASE I:

Development of a copper based contact system using plated Pd-Cr-Cu. Good cells were made but cells degraded under low temperature (300°C) heat treatments.

PHASE II:

The degradation in Phase I was identified as copper migration into the cells junction region. A paper study was conducted to find a proper barrier to the copper migration problem. Nickel was identified as the best candidate barrier and this was verified in a heat treatment study using evaporated metal layers.

PHASE III:

An electroless nickel solution was substituted for the electroless chrominum solution in the original process. Efforts were made to replace the palladium bath with an appropriate nickel layer, but these were unsuccessful.

150 cells using the Pd-Ni-Cu contact system were delivered to JPL. Also a cost study was made on the plating process to assess the chance of reaching 5¢/watt.

TITLE: Final Report. Silicon Solar Cell Fabrication Technology.

AUTHOR: O. M. Stafsudd

CORPORATE AUTH: University of California at Los Angeles

CONTRACT NO: 954902

DATE: May 1980

REPORT NO: DOE/JPL-954902-80/6

ABSTRACT: The initial program at U.C.L.A. was to assist JPL during the building and expansion of their laboratory and device fabrication facilities. This work consisted of device fabrication which was composed of the following processing procedures: a) low temperature $POCl_3$ diffusions, b) metallization of back and front ohmic contacts, c) mask design and fabrication, and d) sintering in inert and H_2 atmospheres. These processing steps were varied in accordance with JPL's instructions. The device evaluation was performed at U.C.L.A. and JPL. The results of these measurements were correlated, and they included such tests as: a) dark current vs. voltage and log I vs. voltage, b) light current vs. voltage at AM1 and AM0, c) capacitance vs. voltage, and d) spectral response. The measurements were then interpolated and reduced to determine the material properties such as minority carrier lifetimes (t_n) and diffusion lengths (L_n). The diffusion length determination was accomplished by spectral response measurements at U.C.L.A. Similar measurements of various devices were done by S.P.V. (Surface Photo Voltage method) at JPL.

TITLE: Final Report. Investigation of Proposed Process Sequence for the AAA Task Phase II.

AUTHOR: Nick Mardesich

CORPORATE AUTH: Spectrolab, Inc.

CONTRACT NO: 954853

DATE: June 1980

REPORT NO: DOE/JPL-954853-80/10

ABSTRACT: A selected process sequence for the low cost fabrication of photovoltaic modules was defined during this contract. Each part of the process sequence was looked at regarding its contribution to the overall dollars per watt cost. During the course of the research done, some of the initially included processes were dropped due to technological deficiencies. The printed dielectric diffusion mask, codiffusion of the n+ and p+ regions, wrap-around front contacts and retention of the diffusion oxide for use as an AR coating were all the processes that were removed for this reason. Other process steps were retained to achieve the desired overall cost and efficiency. Square wafers, a polymeric spin-on PX-10 diffusion source, a p+ back surface field and silver front contacts are all processes that have been recommended for use in this program. The printed silver solderable pad for making contact to the aluminum back was replaced by an ultrasonically applied tin-zinc pad. Also, the texturized front surface was dropped as inappropriate for the sheet sequence for module fabrication. A shift from bonding with a conformal coating to laminating with ethylene vinyl acetate and a glass superstrate is recommended for further module fabrication. The processes that were retained for the selected process sequence, spin-on diffusion, print and fire aluminum p+ back, clean, print and fire silver front contact and apply tin pad to aluminum back, were evaluated for their cost contribution. The finalized process sequence is shown schematically on page 1A and in Table 3.21-1, page 295. The process specifications for the finalized process sequence are shown in Appendix F. The format A's for SAMICS calculations of the finalized process are shown in Appendix G.

TITLE: Final Report. Process Development for Automated Solar Cell and Module Production. Task 4: Automated Array Assembly

CORPORATE AUTH: MBAssociates

CONTRACT NO: 954882

DATE: June 1980

REPORT NO: DOE/JPL 954882-80/21

ABSTRACT: The scope of work under this contract involves specifying a process sequence which can be used in conjunction with automated equipment for the mass production of solar cell modules for terrestrial use. This process sequence is then critically analyzed from a technical and economic standpoint to determine the technological readiness of each process step for implementation. The process steps are ranked according to the degree of development effort required and according to their significance to the overall process. Under this contract the steps receiving analysis were: back contact metallization, automated cell array layup/interconnect, and module edge sealing. For automated layup/interconnect both hard automation and programmable automation (using an industrial robot) were studied. The programmable automation system was then selected for actual hardware development.

This work has been done to improve the performance of solar modules and to lower the cost through process development and large scale automa' on. The guidelines used in this effort has been to work toward a process sequence which will provide a 500 megawatt/year production capacity in the industry by the year 1986.

TITLE: Final Report. Development of High Efficiency (14%) Solar Cell Array Module

AUTHOR: P. A. Iles, etal

CORPORATE AUTH: Optical Coating Laboratory, Inc.

CONTRACT NO: 955217

DATE: June 1980

REPORT NO: DOE/JPL 955217-80/5

ABSTRACT: Most effort was concentrated on development of procedures to provide large area (3" diameter) high efficiency (16.5%, AM1, 28°C) P+NN+ solar cells. Intensive tests with 3" slices gave consistently lower efficiency (13.5%). The problems were identified as incomplete formation of an optimum back surface field (BSF), and interaction of the BSF process and the shallow P+ junction. Towards the end of the contract, a promising process sequence was identified, to meet the original goals and tests of this sequence are continuing outside of this program.

TITLE: Final Report. Gaseous Melt Replenishment System.

AUTHOR: D. N. Jewett, H. E. Bates and D. M. Hill

CORPORATE AUTH: Energy Materials Corporation

CONTRACT NO: 955269

DATE: August 1980

REPORT NO: DOE/JPL-955269-80/6

ABSTRACT: The objective of this program was to demonstrate the operation of a novel, efficient silicon production technique. The essentials of the method comprised chemical vapor deposition of silicon, by hydrogen reduction of chlorosilanes, on the inside of a quartz reaction vessel having large internal surface area. The system was designed to allow sucessive deposition-melting cycles, with silicon removal being accomplished by discharging the molten silicon. The liquid product would be suitable for transfer to a crystal growth process, casting into solid form, or production of shots. Successful, sequential operation of the reverse U-bend trap seal ("U-tube") was also demonstrated. This feature, acting as a 1400°C valve, permits successive deposition-meltout cycles in the reactor. Problems remaining to be solved with the system include: (1) Plugging of the reactor outlet tube by silicon halide polymers and by silicon monoxide generated during the melt-down. (2) Maximization of regenerative heat exchange between reactants and products, thus improving conversion levels.

TITLE: Final Report. Automated Solar Module Assembly Line.

AUTHOR: Max Bycer

CORPORATE AUTH: Kulicke & Soffa Industries, Inc.

CONTRACT NO: 955287

DATE: August 1980

REPORT NO: DOE/JPL-955287-80/6

ABSTRACT: The solar module assembly machine which Kulicke and Soffa delivered under this contract is a cell tabbing and stringing machine, flexible in design, and capable of handling a variety of cells and assembling strings up to 4 feet in a series or parallel arrangement, and in a straight or interdigitated array format. The machine cycle is 5 seconds per solar cell. This machine is primarily adapted to 3 inch diameter round cells with two tabs between cells. Pulsed heat is used as the bond technique for solar cell interconnects. The solar module assembly machine unloads solar cells from a cassette, automatically orients them, applies flux and solders interconnect ribbons onto the cells. It then inverts the tabbed cells, connects them into cell strings, and delivers them into a module array format using a track mounted vacuum lance, from which they are taken to test and cleaning benches prior to final encapsulation into finished solar modules. Throughout the machine the solar cell is handled very carefully, and any contact with the collector side of the cell is avoided or minimized. A lamp simulator has been used to test bonded solar cells to determine if the bonding operation had any degrading effect on the cell. I-V profile curves taken of these sample cells, before and after the bonding operation indicate no apparent effect on the electrical characteristics of the solar cell by the bonding operation.

TITLE:	Final Report. Low Cost Czochralski Crystal Growing Technology Near Term Implementation of the Flat Plate Photovoltaic Cost Reduction of the LSA Project.
CORPORATE AUTH:	Kayex Corporation
CONTRACT NO:	955270
DATE:	September 1980
REPORT NO:	DOE/JPL-955270-80/6

ABSTRACT: One of the primary requirements of the DOE/JPL silicon sheet task is to develop a process capable of producing low cost silicon. This silicon must be capable of being processed into solar cells which will yield a solar cell efficiency of 14% AM1. The technology generated under this contract was aimed at developing process improvement concepts for lowering the costs of the meltdown and crystal growth functions. A program aimed at improving process automation for increased yield and reduced labor requirement was also undertaken. The development of the various equipment designs that enable high volume, continuous Czochralski production to be achieved should be directly transferable to industry. The objectives of the process technology phase was to develop and demonstrate continuous Czochraslski crystal growth. Continuous Czochralski growth was defined as a throughput of 150 kg of silicon crystals of 15 cm diameter, utilizing one common crucible with melt replenishment. The conclusions and technology status of the contract as applicable to the objectives of the contract are reported. Cost projections and actual cost achievements have been developed using SAMICS/IPEG formula and are also reported. No investigation and evaluation of the variations of the effects of the physical form of silicon feed material on the crystal growth process and impurity build-up in the ultimate crystal produced was undertaken.

TITLE:	Final Report. Anti-Reflection Coatings on Large Area Glass Sheets.
AUTHOR:	E. Pastirik
CORPORATE AUTH:	Motorola Inc. Semiconductor Group.
CONTRACT NO:	955339
DATE:	September 1980
REPORT NO:	DOE/JPL-955339-80/4

ABSTRACT: Antireflective coatings which may be suitable for use on the covers of photovoltaic solar modules can be easily produced by a dipping process. The coatings are applied to glass by drawing sheets of glass vertically out of dilute aqueous sodium silicate solutions at a constant speed, allowing the adherent liquid film to dry, then exposing the dried film to concentrated sulfuric acid, followed by a water rinse and dry. The process produces coatings of good optical performance (96.7% peak transmission at 0.540 μM wavelength) combined with excellent stain and soil resistance, and good resistance to abrasion. The process is reproducible and easily controlled.

TITLE: Final Report. Development of Megasonic Cleaning for Silicon Wafers.

AUTHOR: A. Mayer

CORPORATE AUTH: RCA Corporation

CONTRACT NO: 955342

DATE: September 1980

REPORT NO: DOE/JPL-955342-79/5

ABSTRACT: The major contract goals to develop a cleaning and drying system for processing at least 2500 three-in.-diameter wafers per hour and to reduce the process cost were achieved. The new system consists of an ammonia-hydrogen peroxide bath in which both surfaces of 3/32-in.-spaced, ion-implanted wafers are cleaned in quartz carriers moved on a belt past two pairs of Megasonic transducers. The wafers are dried in the novel room-temperature, high-velocity air dryer in the same carriers used for annealing. A new laser scanner was used effectively to monitor the cleaning ability on a sampling basis.

TITLE: Final Report. Automated Array Assembly, Phase II.

AUTHOR: R. V. D'Aiello

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 954868

DATE: October 1980

REPORT NO: DOE/JPL-954868-80/9

ABSTRACT: Fiqure 1 is a schematic representation of the work of the first year. The philosophy of this plan was to establish an experimental process line starting with 3-in.-diam silicon wafers and consisting of junction formation using $POCL_3$ gaseous diffusion, screen-printed thick-film metallization, reflow solder interconnect, and double-glass lamination panel assembly. This experimental production line produced a sufficient number of solar cells to demonstrate the technological readiness of each of those process steps. Variations (of each process) were made to set limits on the usable range of each process step and to determine the interraction with adjoining steps. Inspection measurements, and tests were included to determin he output requirement characteristics of each step, obtair tatistical variations, and evaluate the performance of the olar cells and panels. A description of this work, which as conducted from October 1977 through December 1978, is given in Sections III and IV. This was followed by an 18-month study in which three manufacturing sequences synthesized from the above work and from studies conducted by other participants in the LSA program were exercised. The objectives were to assess the compatibility between process steps for each sequence, to generate sufficient data for comparative SAMICS cost analysis, and to make recommendations of the suitability of one or more of these sequences for the large-scale automated production of solar cells within the cost goal of \$0.70/pW. The detailed experimental results of this study are described in Section V, followed by SAMICS cost analysis, recommendations, and conclusions given in Sections VI and VII.

TITLE:	Final Report. The Establishment of a Production-Ready Manufacturing Process Utilizing Thin Silicon Substrates for Solar Cells.
AUTHOR:	R. A. Pryor
CORPORATE AUTH:	Motorola Inc. Semiconductor Group.
CONTRACT NO:	955328
DATE:	October 1980
REPORT NO:	DOE/JPL-955328-80/4

ABSTRACT: Three inch diameter Czochralski silicon substrates sliced directly to 5 mil, 8 mil, and 27 mil thicknesses with wire saw techniques were procured. Processing sequences incorporating either diffusion or ion implantation technologies were employed to produce n+p or n+pp+ solar cell structures. These cells were evaluated for performance, ease of fabrication, and cost effectiveness. It was determined that the use of 7 mil or even 4 mil wafers would provide near term cost reductions for solar cell manufacturers.

TITLE: Final Report. Phase 2 of the AAA Task for the LSA Project.

AUTHOR: Raymond C. Petersen

CORPORATE AUTH: Solarex Corp.

CONTRACT NO: 954854

DATE: November 1980

REPORT NO: DOE/JPL-954854-80/8

ABSTRACT: Studies were conducted on several fundamental aspects of electroless nickel/solder metallization for silicon solar cells. A process proposed by Motorola, which precedes the electroless nickel plating with several steps of palladium plating and heat treatment, was compared directly with single step electroless nickel plating. Work was directed toward answering specific questions concerning the effect of silicon surface oxide on nickel plating, effects of thermal stresses on the metallization, sintering of nickel plated on silicon, and effects of exposure to the plating solution on solar cell characteristics. The Motorola process was compared with simple electroless nickel plating in a series of parallel experiments. It was demonstrated by ellipsometry measurements that the electroless nickel plating solution dissolves silicon dioxide. Measurements of tab pull strengths and electrical characteristics of cells show that the presence of the oxide has no effect on cell properties. Removal of the oxide by the plating solution obviously does require some time, but the delay in onset of nickel plating caused by the presence of a normal atmospheric oxide on silicon is very short. It was also shown, by sheet resistance measurements and gravimetric measurements, that phenomenon dictates that special care be taken during the diffusion process to assure that the p-n junction is deep enough to survive the silicon dissolution. Brief sintering at relatively low temperatures after nickel plating sometimes increases otherwise poor adhesion. It has been shown by leakage current and electron microprobe measurements that sintering can safely be conducted for long times at 300°C, but it has also been shown that excellent adhesion can be obtained without sintering. Cells with electroless nickel/solder metallization have been shown to survive perfectly for over 1,000 hours under bias-temperature-humidity stresses of -.45 volt forward bias at 95°C and 85% relative humidity. This metallization also survies 763 hours at 100°C and 25 cycles of thermal

shock from $-40^{o}C$ to $+100^{o}C$, while temperature extremes of $-65^{o}C$ and $+150^{o}C$ are too severe. The Motorola process was found to be extremely lengthy and cumbersome, and was also found to produce a product virtually identical to that produced by single step electroless nickel plating, as shown by adhesion tests and electrical characteristics of cells under illumination.

TITLE: Final Report. Automated Array Assembly Task Development of Low-Cost Polysilicon Solar Cells

CORPORATE AUTH: Photowatt International, Inc.

CONTRACT NO: 955265

DATE: November 1980

REPORT NO: DOE/JPL 955265-80/3

ABSTRACT: Development of low-cost, large area polysilicon solar cells was conducted in this program. Three types of polysilicon material were investigated. Included in the study was the Wacker cast polysilicon, Crystal Systems HEM material, and Exotic Materials FAST-CZ polysilicon.

The influence of crystal grains on solar cell efficiency was studied. A theoretical and experimental comparison between single crystal silicon and polysilicon solar cell efficiency was performed.

The feasibility of applying an anisotropic sodium hydroxide etching process to polysilicon wafers was investigated. The texture etching rate, time and solution concentration were evaluated.

Several optional low-cost solar cell processes were investigated. They included $POCl_3$ gettering, spray-on n^+ polymer dopants, and printed aluminum. It was demonstrated that 10% efficient polysilicon solar cells can be produced with spray-on n^+ dopants. This result fulfills an important goal of this project, which is the production of batch quantity of 10% efficient polysilicon solar cells.

TITLE: Fi al Report. The Development of a Method of Producing Etch Resistant Wax Patterns of Solar Cells.

AUTHOR: E. Pastirik

CORPORATE AUTH: Motorola Inc. Semiconductor Group.

CONTRACT NO: 955324

DATE: November 1980

REPORT NO: DOE/JPL-95532- -80/4

ABSTRACT: A potentially attractive technique for wax masking of solar cells prior to etching processes was studied. This technique made use of a reuseable wax composition which was applied to the solar cell in patterned form by means of a letterpress printing method. After standard wet etching was performed, wax removal by means of hot water was investigated. Application of the letterpress wax printing process to silicon was met with a number of difficulties. The most serious shortcoming of the process was its inability to produce consistently well-defined printed patterns on the hard silicon cell surface.

TITLE:	Second Quarterly Report. Silicon Dendritic Web Material Process Development.
AUTHOR:	R. E. Stapleton, D. L. Meier, L. Sienkiewicz, R. B. Campbell, and P. Rai-Choudhury
CORPORATE AUTH:	Westinghouse R&D Center
CONTRACT NO:	955624
DATE:	November 1980
REPORT NO:	DOE/JPL 955624/80-2
ABSTRACT:	The properties of the cells to be used in the first 30 cm by 60 cm module are given. The average efficiency was 12.4±0.8%. The highest efficiency measured was 14.2%. A satisfactory lamination has been made with polyvinyl butyral replacing ethylene vinyl acetate.

TITLE: Final Report. Phase II AAA Task LSA Project.

AUTHOR: C. Olson

CORPORATE AUTH: Sensor Technology Inc.

CONTRACT NO: 954865

DATE: December 1980

REPORT NO: DOE/JPL-954865-80/9

ABSTRACT: The information presented in this Final Report provides a summary of the work performed from September 20, 1977 through June 20, 1980 by Sensor Technology, Inc., in Chatsworth, California and Photowatt International, Inc. in Tempe, Arizona.

The initial contract was a Phase II Process Development for a process sequence, but with concentration on two particular process steps: laserscribing and spray-on junction formation. The balance of the process, although important, was to be a subordinate level of effort to support these two major tasks.

The add-on portion of the contract was to further develop these tasks, to incorporate spray-on of AR Coating and aluminum and to study the application of microwave energy to solar cell fabrication.

The overall process cost projection is 97.918¢/Wp. The major contributor to this excess cost is the module encapsulation materials cost. The frame and encapsulation materials alone total 25.634¢/Wp. Since this was not an area of major effort on the contract, the approach was to automate what was available, not to develop new technologies and, as a result, less effort was devoted to this task.

During the span of this contract the study of microwave application to solar cell fabrication produced the ability to apply this technique to any requirement of 600°C or less. Above this temperature, non-uniformity caused the processing to be unreliable. It became evident that fundamental development efforts were required and these are being pursued through another contract.

TITLE: Final Report. Development of Simplified Process For Environmentally Resistant Cells.

AUTHOR: W. J. King

CORPORATE AUTH: Kinetic Coatings Incorporated

CONTRACT NO: 955079

DATE: December 1980

REPORT NO: DOE/JPL-955079-80/1

ABSTRACT: This report describes a program to develop a simple, foolproof, all-vacuum solar cell manufacturing process which can be completely automated and which results in medium efficiency cells which are inherently environmentally resistant. All components of the completed cells are integrated into a monolithic structure with no material interfaces. The exposed materials (Si, Al_2O_3, Al, Ni) are all resistant to atmospheric attack and the junction, per se, is passivated to prevent long term degradation. Such cells are intended to be incorporated into a simple module consisting basically of a press-formed metallic superstructure with a separated glass cover for missile, etc., protection. A 5 cm x 5 cm test cell configuration was designed in which the various efficiency loss factors were adjusted to yield a 10% AMI cell. Each of the cell elements was individually optimized for combination with the others. The basic cell consists of alloyed front (Al) and back (Ag plus Ni) contacts, a multi-purpose (AR, hermetic seal, implantation oxide) front surface coating of Al_2O_3, and an implanted front junction. Implantation damage annealing and contact alloying are carried out in a simple one step thermal treatment at 870°C using a resistance heated furnace in vacuum. Times at temperature as short as 15-20 seconds for complete cell activation were demonstrated in a related proprietary program. The use of non-analyzed and semi-analyzed beams for fabricating these cells was developed by KCI for use on this contract. A final lot of 50 cells made using the semi-analyzed beam method had an average efficiency of 10.4% at AMI (28 $\pm$ 1°C). An economic analysis predicts a manufacturing cost of \$.45/peak-watt for these cells using a one machine automatic method.

TITLE:	Final Report. High Resolution, Low Cost Solar Cell Contact Development.
AUTHOR:	N. Mardesich
CORPORATE AUTH:	Spectrolab, Inc.
CONTRACT NO:	955298
DATE:	December 1980
REPORT NO:	DOE/JPL-955298-80/2

ABSTRACT: Experimental work demonstrating the feasibility of the MIDFILM process as a low-cost means of applying solar cell collector metallization was completed during this contract. Cell efficiencies of above 14% (AMI, 28°C) were achieved with fritted silver metallization. Environmental tests suggest that the metallization is slightly humidity sensitive and degradation is observed on cells with high series resistance. The major yield loss in the fabrication of cells was due to discontinuous grid lines, resulting in high series resistance. Standard lead-tin solder plated interconnections do not appear compatible with the MIDFILM contact. Copper, nickel and molybdenum base powder were investigated as low-cost metallization systems. The copper based powder degraded the cell response. The nickel and molybdenum base powders oxidized then sintered in the oxidizing atmosphere necessary to ash the photoresin.

TITLE: Final Report. Cost Effective Flat Plate Photovoltaic Modules Using Light Trapping

AUTHOR: C. N. Bain, B. A. Gordon, T. M. Knasel, R. L. Malinowski

CORPORATE AUTH: Science Applications, Inc.

CONTRACT NO: 955787

DATE: April 1981

REPORT NO: DOE/JPL 955787-81/1

ABSTRACT: This report and Appendix A give the results of the study. The Final Report details the analyses and calculations performed to arrive at the design guidelines, and Appendix A is an Optical Design Guide which contains rules and guidelines for the practicing photovoltaic design engineer.

Science Applications is extending prior in-house work in optical trapping in "thick films" to form a design guide for photovoltaic engineering.

The Design Guide shows the reader how to construct photovoltaic modules to use and even to exploit this concept. By SAI calculations up to 20% improvements in standard module performance can be expected. Even larger improvements can be received in special modules constructed to exploit these thick film effects as discussed in the Final Report.

TITLE: Final Report. Processing Experiments on Non-Czochralski Silicon Sheet (MEPSDU Support Contract)

AUTHOR: R. A. Pryor, L. A. Grenon, N. G. Sakiotis, E. M. Pastirik, T. O. Sparks, and R. N. Legge

CORPORATE AUTH: Motorola Inc. Semiconductor Group

CONTRACT NO: 955844

DATE: April 1981

REPORT NO: DOE/JPL 955844-81/2

ABSTRACT: A program of six months duration was performed to support and promote the further development of processing techniques which may be successfully and cost-effectively applied to low-cost non-Czochralski silicon sheet for solar cell fabrication. Results are reported in the areas of process technology, cell design, cell metallization, and production cost simulation.

TITLE: Final Report. Automated Solar Panel Assembly Line.

AUTHOR: Howard Somberg

CORPORATE AUTH: ARCO Solar, Inc.

CONTRACT NO: 955278

DATE: May 1981

REPORT NO: DOE/JPL-955278-81/5

ABSTRACT: This report contains the results of a two-year effort to design, develop and operate automated equipment for the interconnection of solar cells and lamination of cell circuits into modules. The overall objective was to effect near-term reduction of silicon solar cell array costs so as to achieve the 1985 goal of $0.70/W*.

The program consisted of four sections: 1) design of a module that lends itself to automated assembly, 2) design and development of prototype equipment for the interconnection and lamination of solar cells into a completed module, 3) the operation of a pilot production line using the equipment developed in this program, and 4) perform a cost analysis of the production run.

This program was originally proposed as a 12 month effort. However, because of the complexity of the soldering equipment task the program was extended to 27 months. In late 1979, a prototype element of the soldering machine was implemented into the module production operation. This section of the machine consisted of a roller transport mechanism integrated with an electromagnetic induction coil** for soldering continuous ribbon interconnects to the front of solar cells. In a fashion, it was the first step in the mechanization of soldering or "tabbing" solar cells, and this simple mechanism has reliably tabbed about 1.8 million solar cells to date.

In mid-1980, the lamination system began operation in ARCO Solar's automated solar panel facility in Camarillo, California. This prototype system has produced PV modules

* All costs in this report are given in 1980 dollars.

** The automated soldering machine was subsequently redesigned to use an infrared heat source.

representing in excess of one megawatt. The pilot production line operation integrating the completed soldering and lamination equipment was successfully conducted in April 1981.

The following achievements were made on this program:

- a lamination system capable of producing 20 modules/hour
- a soldering machine capable of interconnecting 900 cells/hour
- a cost reduction of approximately 40% in module materials and labor.

TITLE	Final Report. Laser Annealing of Ion Implanted Silicon for Solar Cell Junction Formation
CORPORATE AUTH:	Lockheed Missiles and Space Company, Inc.
CONTRACT NO:	955696
DATE:	June 1981
REPORT NO:	DOE/JPL 955696-81/4

ABSTRACT:

An investigation was conducted which evaluated the merits of large spot size pulsed laser annealing of phosphorus implanted, Czochralski grown silicon for junction formation of solar cells. The feasibility and requirements were also determined to scale-up a laser system to anneal 7.62 cm diameter wafers at a rate of 1 wafer/second.

Laser parameters were developed for optimized performance. These parameters were substantiated by surface analysis, including SIMS, TEM and RBS techniques, followed by fabrication of 2 x 2 cm, 2 x 4 cm and 7.62 cm dia. functional cells to verify acceptability.

Results show that laser annealing yields active, defect free, shallow junction devices.

Experiments showed that texture etched surfaces are not compatible with pulsed laser annealing due to the surface melting caused by the laser energy. When compared with furnace annealed cells, the laser annealed cells generally exhibited conversion efficiencies which were equal to or better than those furnace annealed. In addition, laser annealing has greater throughput potential, which is mandatory for the LSA Project.

A high throughput pulsed laser system to accommodate single pulse annealing of 7.62 cm diameter wafers at a rate of one wafer per second is feasible.

TITLE:	Quarterly Report No. 3. Development of an All-Metal Thick Film Cost Effective Metallization System for Solar Cells
AUTHOR:	Bernd Ross
CORPORATE AUTH:	Bernd Ross Associates
CONTRACT NO:	955688
DATE:	September 1981
REPORT NO:	DOE/JPL 955688-80/3

ABSTRACT:

Experiments were conducted with variations in paste parameters, firing conditions, including gas ambients, furnace furniture, silicon surface and others.

The Photovoltaic Solar Energy Conference was attended and a paper was presented. Semiconductor and solar cell research activities in Munich were visited and activities of mutual interest were discussed.

A liquid medium, intended to provide transport during the carbon fluoride decomposition was incorporated in the paste with promising results.

TITLE: Quarterly Progress Report No. 7. Development and Fabrication of a Solar Cell Junction Processing System

CORPORATE AUTH: Spire Corporation

CONTRACT NO: 955640

DATE: October 1981

REPORT NO: DOE/JPL 955640-81/7

ABSTRACT: This quarterly report covers work performed during the period between 1 July through 30 September 1981 on Tasks 1 to 3 of the contract for the development and fabrication of a solar cell junction processing system. Assembly and system testing has continued on the Task 1 phase to develop a pulsed electron beam for the 4-inch wafers. Wafers have been successfully pulsed and solar cells fabricated. Assembly of the transport locks has now been completed. The transport has been operated successfully but not yet with sufficient reproducibility. An experimental test facility to examine potential scaleup problems associated with the proposed ion implanter design has been constructed and operated. Cells have been implanted and found to have efficiency identical to the normal Spire implant process.

TITLE: Quarterly Report. Development of Technique for AR Coating and Nickel and Copper Metallization of Solar Cells FPS Project Product Development.

AUTHOR: C. G. Rominger

CORPORATE AUTH: Photowatt International, Inc.

CONTRACT NO: 955986

DATE: October 1981

REPORT NO: DOE/JPL-955986-81/1

ABSTRACT: Solar cells were fabricated using the Photowatt International, Inc., production process. One hundred 3" cells with 800°A of silicon nitride over N+/P junction, and evaporated aluminum metal (on the back side) were delivered to ESL for nickel printing. Initially two nickel pastes were defined by ESL as lot 1051-21A and Lot 1051-21B; each lot had a different type of borosilicate frit. After application of nickel paste these solar cells were sent to Vanguard Pacific for brush copper plating. Electrical and mechanical data taken from Lot 1051-21A and Lot 1051-21B indicated a need to increase borosilicate frit and silver fluoride (AgF). Three more pastes were formulated by ESL. Electrical, mechanical and visual data were recorded for three groups of nickel pastes using various fire-in temperatures and time cycles. Quarter cells of each nickel group are being evaluated using techniques such as SEMS, SIMS and Beta-scan.

TITLE: Final Report. High Resolution, Low Cost Solar Cell Contact Development

AUTHOR: N. Mardesich

CORPORATE AUTH: Spectrolab, Inc.

CONTRACT NO: 955725

DATE: November 1981

REPORT NO: DOE/JPL 955725-81/1

ABSTRACT: MIDFILM cell fabrication and encapsulation have been demonstrated as a means of applying low-cost solar cell collector metallization. The average cell efficiency of 12.0% (AM1, 28°C) was achieved with fritted silver metallization with a demonstration run of 500 starting wafers. A 98% mechanical yield and 80% electrical yield were achieved through the MIDFILM process. High series resistance was responsible for over 90% of the electrical failures and was the major factor causing the low average cell efficiency. Environmental evaluations suggest that the MIDFILM cells do not degrade. A slight degradation in power was experienced in the MIDFILM minimodules when the AMP Solarlok connector delaminated during environmental testing.

Molybdenum-tin-titanium hydride has been identified as a metallization for producing non-noble MIDFILM contacts. Efficiencies of 9 to 10% have been achieved for non-AR coated cells. The low efficiencies of the non-noble MIDFILM contacted cells is attributed totally to the series resistance associated with the grid line configuration.

TITLE: Final Program Summary Report. Evaluation and Verification of Epitaxial Process Sequence for Silicon Solar-Cell Production

AUTHOR: D. Redfield

CORPORATE AUTH: RCA Laboratories

CONTRACT NO: 955825

DATE: November 1981

REPORT NO: DOE/JPL 955825-81/3

ABSTRACT: To achieve the program goals, 28 minimodules were to have been fabricated and tested, using 600 cells made from three-inch-diameter wafers processed by the sequence chosen for this purpose. Of these 600 cells, half were to be made from epitaxially grown layers on potentially low-cost substrates. The other half were to be made from commercial semiconductor-grade (SG), single-crystal silicon wafers that served as controls. Cell processing was normally performed on mixed lots containing significant numbers of each of these two types of wafers. After evaluation of the performance of all cells, they were separated by types for incorporation into modules that were to be tested for electrical performance and response to environmental stress. A simplified flow chart displaying this scheme, for quantities representing half of the planned total to be processed, is presented.

Documentation of the specifications and procedures of all process steps chosen for this program, and detailed SAMICS cost analyses have been provided in separate reports bearing those titles. As with all R&D projects, however, there are unavoidable differences between some of the laboratory processes used to fabricate cells and modules for the present evaluations and the analogous processes as they would take place in a factory at high production rates. In all cases where uncertainties may exist in specific process steps, the materials or procedures used were consistent with developments occurring under either the LSA Program or the Exploratory Development (ED) contract that RCA was conducting for SERI. In this report, some information is provided on relevant work under the ED Program.

TITLE: Quarterly Report No. 4. A Module Experimental Process System Development Unit (MEPSDU)

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 955902

DATE: November 1981

REPORT NO: DOE/JPL 955902-81/4

ABSTRACT: The purpose of this program is to demonstrate the technical readiness of a cost-effective process sequence that has the potential for the production of flat plate photovoltaic modules which meet the price goal in 1986 of 70¢ or less per Watt peak.

The major accomplishments of the program to date have been the development of an improved AR coating technique, the development of sand blast back clean-up to reduce clean up costs and to allow much of the Al paste to serve as a back conductor, and finally the development of wave soldering for use with solar cells.

During the quarter, program efforts included:

Suspension of all module processing efforts per JPL's orders.

Redefining the program budget, schedule and program plan to reflect the reduced funding level and scope of work.

Processing of control and test material via a controlled process sequence to determine the material capability.

Experimentation with diffusion barrier materials.

Cell processing to evaluate different process steps.

Preparation of a Cell and Minimodule Test Plan.

Collecting data for preliminary SAMICS cost analysis.

TITLE: Quarterly Report. A Module Experimental Process System Development Unit (MEPSDU).

CORPORATE AUTH: Westinghouse Electric Corporation

CONTRACT NO: 955909

DATE: November 1981

REPORT NO: DOE/JPL-955909-81/4

ABSTRACT: Work on the Westinghouse MEPSDU contract was initiated on November 26, 1980. This report describes work performed during the fourth three-month period of the contract (September 1, 1981 through November 30, 1981) and outlines plans for the next quarter. Module design work during the past quarter resulted in the identification of surface treatment to the module glass superstrate which improves module efficiencies by approximately .5% (absolute). This improvement has been verified by testing conducted at Westinghouse. This is an important breakthrough which could reduce production costs by as much as 2.5¢/watt. The final module environmental test, a simulated hailstone impact test, was conducted on full size module superstrates at Westinghouse during this quarter. The objective of the test was to verify that the module's tempered glass superstrate can withstand specified hailstone impacts near the corners and edges of the module. Process sequence design work continued throughout the quarter on the metallization process selection, liquid dopant investigation, dry processing, and anti-reflective/photoresists application technique tasks. An optimum Ti/Pd thickness has been established. Work on the identification of commercial grade dopants which could allow simultaneous front and back junction diffusions has led to promising results. An experiment has been performed to identify a noncontact cleaning method for raw web cleaning. In addition, a vendor has agreed to apply antireflective and photoresist coatings to dendritic web strips using a meniscus coating technique to allow a qualification of this improved process. Work on the Kulicke and Soffa task to design an automated cell interconnect station for the Westinghouse MEPSDU continued this quarter. SAMIS economic analyses were updated during this quarter and have reaffirmed that the Westinghouse MEPSDU process sequence can meet the DOE/JPL cost goals of $.70 per peak watt (in 1980$).

TITLE: Final Report. LSA Large Area Silicon Sheet Task Enhanced ID Slicing Technology for Silicon Ingots.

CORPORATE AUTH: Siltec Corporation

CONTRACT NO: 955282

DATE: December 1981

REPORT NO: DOE/JPL-955282-81/8

ABSTRACT: To bring I.D. slicing technology to a higher performance level by demonstrating a significant increase in the number of usable slices per centimeter over industry practice through the reduction of both blade and slice thickness, a combination of three key technologies was investigated: ingot rotation with minimum exposed blade area, dynamic cutting edge control, and the use of prefabicated blade inserts. Prefabricated blade inserts promise great potential for increasing the blade lifetime while decreasing kerf. Results have been encouraging, however, more fundamental work in the materials area of the bond is required before these blades become an effective production tool. An alternative solution of etched core construction permitted low kerf slicing, but further refinement for greater lifetime is necessary. Economic modeling of the enhanced I.D. slicing process utilized the IPEG II option of SAMICS. A comparison of slicing with ingot rotation and plunge cutting has shown that simultaneous multiple ingot feed will improve the present cost picture of I.D. slicing significantly.

TITLE: Final Report. Equipment Development for Automated Assembly of Solar Modules

CORPORATE AUTH: Tracor MBA (MBA Associates)

CONTRACT NO: 955699

DATE: January 1982

REPORT NO: DOE/JPL 955699-81/05

ABSTRACT: Prototype equipment was developed which allows for totally automated assembly in the three major areas of module manufacture: cell stringing, encapsulant layup and cure and edge sealing.

The equipment is designed to be used in conjunction with a standard Unimate 2000B industrial robot although the design is adaptable to other transport systems.

TITLE:	Quarterly Report. Silicon Production Process Evaluations.
CORPORATE AUTH:	Texas Research and Engineering Institute, Inc.
CONTRACT NO:	956045
DATE:	February 1982
REPORT NO:	DOE/JPL-956045-82/3

ABSTRACT: Chemical engineering analysis was continued for the HSC process (Hemlock Semiconductor Corporation) in which solar cell silicon is produced in a 1,000 MT/yr plant. Progress and status are reported for the primary engineering activities involved in the preliminary process engineering design of the plant: base case conditions (96%), reaction chemistry (96%), process flow diagram (85%), material balance (85%), energy balance (60%), property data (60%), equipment design (40%), major equipment list (30%) and labor requirements (10%). Engineering design of the second distillation column (D-02, TCS column) in the process was completed. The design is based on a 97% recovery of the light key (TCS, trichlorosilane) in the distillate and a 97% recovery of the heavy key (TET, silicon tetrachloride) in the bottoms. At a reflux ratio of 23, the specified recovery of TCS and TET is achieved with 20 trays (equilibrium stages, N=20). Respective feed tray locations are 9, 12 and 15 (NF_1 = 9, NF_2 = 12, and NF_3 = 15). A total condenser is used for the distillation which is conducted at a pressure of 90 psia.

TITLE: Final Report. Silicon Dendritic Web Material Process Development.

AUTHOR: D. L. Meier, R. B. Campbell, L. J. Steinkiewicz, and P. Rai-Choudhury

CORPORATE AUTH: Westinghouse R&D Center

CONTRACT NO: 955624

DATE: March 1982

REPORT NO: DOE/JPL-955624-82/3

ABSTRACT: The purpose of this program was to develop a low-cost contact system for solar cells and to integrate techniques for fabricating, interconnecting, and encapsulating solar cells in order to produce several demonstration modules. Two experimental contact systems were examined and compared to a baseline contact system consisting of evaporated layers of titanium, palladium, and silver and an electroplated layer of copper. The first experimental contact system consisted of evaporated layers of titanium, nickel, and copper and an electroplated layer of copper. This system performed at least as well as the baseline system in all respects, including its response to temperature stress tests, to a humidity test, and to an accelerated aging test. In addition, the cost of this system is estimated to be only 43% of the cost of the baseline system at a production level of 25 MW/year.

The second experimental contact system consisted of evaporated layers of nickel and copper and an electroplated layer of copper. Auger electron spectroscopy was used to show that the evaporated-nickel layer is not an adequate barrier to copper diffusion at temperatures at least as low as 250°C. This fact brings into question the long-term reliability of this contact system. This system was further afflicted with problems of adherence between the silicon and the evaporated nickel, and for these reasons is not viewed as a promising contact system.

Three modules were fabricated using cells made from dendritic web silicon. Ultrasonic seam bonding was used to interconnect the cells into strings, and ethylene vinyl acetate was used to encapsulate these cell strings. The first two modules were of nominal (30 X 60) cm size and the third module was of nominal (36 x 118) cm size. The efficiency of the third module was measured in natural sunlight to be 10.6%.

Engineering
(Engineering Sciences)
JPL - In-House Abstract

TITLE: Cyclic Pressure Load Developmental Testing of Solar Panels.

AUTHOR: D. Moore

CORPORATE AUTH: Jet Propulsion Laboratory

CONTRACT NO: 00757

DATE: November 1976

REPORT NO: 5101-19

ABSTRACT: 9 solar panels of 5 different designs were subjected to a 50 lb/ft^2 uniform load which was alternately applied to the front and back sides of the panel. The loading was intended to simulate periodic recurrence of wind loading over the lifetime of a solar panel. Each of the 5 designs was subjected to at least 10,000 pressure cycles. No gross structural failures occurred. One of the designs failed regularly at the cell interconnects. Another design shorted out one or more cells upon panel flexure. Both problems are readily explained in terms of design deficiencies in the cell interconnects, and therefore appear to be easily remedied in future designs. The cyclic pressure loading apparatus developed as part of this effort performed more than 130,000 cycles to the various panels tested.

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TITLE: Availability of Ultraviolet Radiation Data (For Encapsulation System Design).

AUTHOR: C. Gonzalez

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1977

REPORT NO: 5101-13

ABSTRACT: The purpose of this report is to review the literature in order to determine the avilability and adequacy of ultraviolet (UV) data which is required to predict the effects of solar UV radiation (less than 4000 A° magnitude and spectral distribution) on terrestrial solar cell encapsulants. In addition, the characteristics of UV radiation which affect the amount reaching the Earth's surface will be considered. The parameters and relationships reviewed include: the ratio of the UV (selected bands) intensity to the total surface incident horizontal solar radiation; seasonal and diurnal UV variation; atmospheric conditions-haze, turbidity, smog, ozone; UV variation with solar altitude; UV variation with receiving plane orientation; ground reflectance; ratio of direct-to-diffuse radiation; and anisotropy of sky UV.

Investigators (References 1-1 and 1-2) have found that the degradation of polymers is related to the UV spectrum when outdoor weathering tests are performed, but not to the total solar spectrum. It has also been shown that degradation proceeds faster in summer than in winter. This could be due in part to higher temperatures, but is also probably related to the higher UV which is measured in summer. In any case, the consideration of UV radiation is extremely important in materials testing.

Although numerous measurements have been made of selected UV bands between 2900-4000 A° (UV below 2900 is absorbed by Earth's atmosphere) the actual amount of data usable for the purpose of predicting encapsulant degradation are limited. The difficulty arises when one attempts to correlate these measurements over different spectral ranges made at different times and locations, under various atmospheric conditions, and using different instruments. Attempts to estimate UV radiation will result in large uncertainties. The amount of UV, both absolute and relative, reaching the surface is a function of the time of day, time of year, cloud or haze cover, and air pollution levels. Therefore, measurements made at one location may not correlate with those made at another.

The approach used by the Battelle Columbus Laboratories (Reference 1-3) in performing the analysis for the Low-Cost Silicon Solar Array (LSSA) Module Encapsulation Task was to obtain the percentage of the total solar radiation attributed to UV. This was based on measurements by the Smithsonian Radiation Biology Laboratory for Washington, D. C., and Rockville, Maryland (Reference 1-4). The data for Washington were considered to represent an urban area, and those for Rockville a suburban (or non-urban area).

The objective of the Battelle approach is to predict long-term (20-year) UV Exposure. Therefore, the difficulties which are encountered when attempting to estimate UV exposure over a short time period become less important. They cannot be eliminated from consideration completely, however. An average value of the ratio of UV percentage of total solar radiation determined in one location may be different from that at another location. For example, two locations may have the same total insolation levels, but may experience different weather patterns in terms of cloudiness such that the total amount of UV received would be different. It is also possible for two locations to have the same total UV radiation (less than 4000° A°), but different spectral distributions. Such differences will also be introduced by differences in air pollution levels.

Another consideration, when making estimates of the UV radiation, is that the response of various bands of the UV spectrum to ozone, pollution and atmospheric scattering are different. Also, different polymers respond to different bands in the UV spectrum. This report discusses some of the measurements taken in the past in order to identify the characteristics of UV radiation which are required for developing the methodology needed for predicting the UV exposure at a particular site.

TITLE:	Test Program on Low-Cost Connector For Solar-Array Modules.
AUTHOR:	A. H. Cantu
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	February 1977
REPORT NO:	5101-20

ABSTRACT:

A recently-developed low-cost electrical connector (the ITT Cannon Sure-Seal) was selected for and subjected to a qualification test series related to terrestrial solar-array applications. Ninety-four mated pairs were subjected to an environmental test program to determine whether this connector could be used in this application. The solar panel interconnect requirement for voltages in the 220-250 Vdc range apears to be adequately met by this connector.

The connector was originally designed for automotive use at a 12Vdc working voltage level. The simplicity of its design and its low cost made it an attractive candidate for this test. The connector body is made by injecting a Nitrile rubber and PVC compound into separate male and female molds. The contacts are a stamped copper-alloy tin-lead plate. The cost of a 4-contact mated-pair connector is approximately $1.25 in quantities.

The results indicate that the present production configuration while performing better than expected under environmental exposure still has some problems. The Nitrile rubber, PVC compound connectors were attacked harshly by the ozone and UV environments. The Ethylene Propylene Diene Monomer (EPDM) connectors are not in production; however, a few samples were available for test. In general, they performed better than the Nitrile rubber PVC. The ozone and UV did not significantly affect them. The contact resistance seemed to increase more than the Nitrile rubber PVC connectors when exposed to moisture. A new configuration with a longer wire entry barrel will provide added protection. The insulation resistance of the EPDM was outstanding. EPDM connectors are not as resilient as the other connectors, as evidenced by some elongation of the wire entry holes, but this condition can be alleviated by prudent wire routing.

TITLE: Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight.

AUTHOR: J. W. Stultz and L. C. Wen

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: July 1977

REPORT NO: 5101-31

ABSTRACT: The electrical power output of photovoltaic solar cell modules is dependent upon the operating temperature of the cells, and decreases at a rate of approximately 0.5%/°C with increasing cell temperature. Because of this temperature sensitivity, it is important to understand the thermal characteristics of modules so that modules and their supporting structures can be designed to reduce cell temperature to the extent that it is cost-effective. An understanding of module operating temperature characteristics is also necessary to allow accurate prediction of module power output under field operating conditions, and to allow accurate comparison of the field electrical performance of alternate module designs.

The activity described in this report was conducted throughout 1976 as a part of the Engineering Area of the JPL Low-cost Silicon Solar Array (LSSA) Project. At the start of the investigation, available data was limited on several key parameters necessary to design, predict, and compare the thermal-electrical performance of terrestrial flat-plate solar cell modules. In particular, the thermal performance of current commercially available modules was unknown and the thermal significance of the key environmental and module thermal parameters was not well understood. As a result, a combined study was undertaken to characterize types and, simultaneously, to develop a basic understanding of the important thermal properties (environmental and module-related) that could guide future module developments.

TITLE:	Module Efficiency Definitions, Characteristics and Examples
AUTHOR:	R. Grippi
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	October 1977
REPORT NO:	5101-43

ABSTRACT: With the current trend toward lower module dollar-per-watt cost, present system studies are placing greater emphasis on module efficiency since area-related costs become a greater portion of the system costs. The increased emphasis on module efficiency provides the need for establishing a standard method for specifying, comparing and discussing module efficiency. This report presents the definition of module efficiency and discusses the factors that comprise module efficiency. In addition, numerous examples of module efficiency factors are presented and discussed based on existing JPL large-scale procurements and research and development modules. Conclusions are drawn as to the maximum module efficiency possible with current technology.

TITLE: Environmental Hail Model For Assessing Risk to Solar Collectors

EDITOR: Gonzalez, C.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1977

REPORT NO: N-78-26541 and 5101-45

ABSTRACT: The probability of solar arrays being struck by hailstones of various sizes as a function of geographic location and service life was assessed. The study complements parallel studies of solar array sensitivity to hail damage, the final objective being an estimate of the most cost effective level for solar array hail protection.

TITLE: Photovoltaic Module Design, Qualification, and Testing Specification

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1978

REPORT NO: DOE/JPL/1012-78/7A and 5101-65

ABSTRACT: This specification establishes minimum design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in photovoltaic array applications in the 20 kW to 500 kW range, such as defined by Department of Energy PRDA EM-D-04-0038. Both mandatory and recommended requirement levels for selected performance criteria have been specified for modules within these arrays. As applicable, the manufacturer/contractor shall be responsible for generation and selection of appropriate design or test levels within the scope of these criteria. Specification of any additional requirements as necessary to satisfy the particular array or system application shall be the responsibility of the manufacturer/contractor. Environmental requirements imposed by this specification are considered to be the minimum level acceptable to DOE. Test procedures are detailed.

TITLE: Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight

AUTHOR: J. W. Stultz

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: July 1978

REPORT NO: DOE/JPL-1012-78/9 - 5101-76

ABSTRACT: The electrical power output of photovoltaic solar cell modules is dependent upon the operating temperature of the cells, and decreases at a rate of approximately 0.5% per ^{o}C with increasing cell temperature. Because of this temperature sensitivity, it is important to understand the thermal characteristics of modules so that modules and their supporting structures can be designed to reduce cell temperature to the extent that it is cost-effective. An understanding of module operating temperature characteristics is also necessary to allow accurate prediction of module power output under field operating conditions, and to allow accurate comparison of the field electrical performance of different module designs.

The activity described in this report was conducted throughout 1977 and during the first half of 1978, as a part of the Engineering Area of the JPL Low-Cost Solar Array (LSA) Project. This report is a follow-up of the first thermal report (5101-31) and covers all the thermal activity in this interim period. The bulk of the testing has been the characterization of twenty-nine modules according to their nominal operating cell temperature (NOCT) and the effect on NOCT of changes in module design, various residential roof mounting configurations, and dirt accumulation.

Other tests, often performed parallel with the NOCT measurements, evaluated the improvement in electrical performance by cooling the modules with water and by channeling the waste heat into a phase change material (wax). Electrical degradation resulting from the natural marriage of photovoltaic and solar water heating modules was also demonstrated. Cost effectiveness of each of these techniques are evaluated in light of the LSA cost goal of $0.50 per watt.

TITLE: Photovoltaic Solar Panel Resistance to Simulated Hail.

EDITOR: Moore, D.; Wilson, A.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1978

REPORT NO: DOE/JPL--1012-78/6 and 5101-62

ABSTRACT: As part of the Jet Propulsion Laboratory's Low-Cost Solar Array Project, Test Methods have been evaluated and procedures developed for testing Photovoltaic Flat-Plate Solar Cell Modules for resistance to impact by hailstones. Testing has included the use of simulated hailstones (frozen ice spheres projected at terminal velocity), steel balls, and other projectile types applied with three loading methods: Pneumatic gun, gravity drop, and static loading. Results are presented that compare the advantages and disadvantages of the three test methods. Dropped-steel-ball tests are shown to exhibit little correlation with high-velocity ice-ball tests, whereas statically-loaded steel balls show a somewhat better correlation with ice-ball tests. Results are presented on the hail impact strength of 16 Flat-Plate Photovoltaic Modules. The module designs tested have been shown to be capable of withstanding as large as 1-1/2-inch diameter and not capable of withstanding as small as 1/2-inch diameter simulated hail. The top surface material of the modules has a dominant influence on the hail impact resistance of the modules. In order of increasing impact strength for a given thickness, the top surface materials encountered in the modules tested were: Clear silicone rubber, annealed glass, tempered glass, and acrylic sheet. The critical failure mechanism of each module type is explored and means for improving the hail resistance of future modules are described.

TITLE: Bias-Humidity Testing of Solar Cell Modules

AUTHOR: A. R. Hoffman and E. L. Miller

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: October 1978

REPORT NO: DOE/JPL-1012-78/11 - 5101-84

ABSTRACT: Humidity-related degradation of solar cells and modules is well known from both space and terrestrial experience. Current humidity cycling tests being applied to flat plate modules (References 1, 2) are "survival" tests, i.e., the modules are not operating -- no illumination, no voltage, terminals short-circuited. A standard environmental test in the semiconductor industry is to subject devices to 85°C, 85% relative humidity while imposing a voltage bias across the device (Reference 3). A TV manufacturer in Japan found a positive correlation between mean time between failures (MTBF) from an accelerated life test (TV set operating) at high temperature and high humidity and MTBF from field conditions (Reference 4). The results indicated that for each hour of operation at 35°C and 95% relative humidity, the manufacturer expected about 16.8 hours of operation under field conditions. Also, experienced people at JPL noted that with an applied voltage-humidity combination using a ground plane the resulting electrolysis would accelerate the deterioration of the insulating material. Furthermore, if a voltage gradient from cell to cell were applied, metal migration may be accelerated. For these reasons, the feasibility and value for solar cell modules of a humidity test combined with a voltage bias was an appropriate subject for research and development.

The objectives of the bias-humidity efforts were:

Develop testing procedures combining voltage biasing with a humidity cycle for the purpose of accelerating failure mechanisms which may occur in long term field use.

Define the bias-humidity tolerance of current photovoltaic module designs.

Define design changes associated with improving bias-humidity tolerance.

Determine value of bias-humidity testing as a mandatory qualification test.

This report describes the results associated with these efforts.

TITLE: Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1978

REPORT NO: DOE/JPL-1012-78/10, 5101-16, Rev. A

ABSTRACT: This document establishes requirements for performance of terresterial solar cell modules intended for use in various test applications typically characterized as Intermediate Load Centers. During the 1979-80 time period, such applications are expected to be in the 20 kilowatt to 500 kilowatt size range. In general, modules satisfying these requirements will have the following design features and characteristics:

1. 15.0 Vdc nominal operating voltage
2. Ability to be series connected to operating voltages of 500 Vdc.
3. Nominal length of 1.2 m
4. Width from 0.2 m to 1.2 m in 20-mm increments
5. Output power rated at the Standard Operating Conditions
6. Flat plate configuration (non-concentrating)

In addition to module design and performance requirements, a series of characterization and qualification tests necessary to certify the module design for production, and the necessary performance tests for acceptance of modules are also specified.

Applicable Documents

The following documentation is applicable to the extent specified:

1. Military: MIL-STD-810 C, Environmental Test Methods, March 10, 1975

2. Energy Research and Development Administration: TM 73702, ERDA/NASA/1022-77/16 "Terrestrial Photovoltaic Measurement Prodeaures," June 1977, Lewis Research Center, Cleveland, Ohio, 44135.

TITLE:	Block IV Solar Cell Module Design and Test Specification for Residential Applications.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	November 1978
REPORT NO:	5101-83
ABSTRACT:	This specification provides near-term design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in photovoltaic power sources (2 kW to 10 kW) applied to single family residential installations. Requirement levels and recommended design limits for selected performance criteria have been specified for modules intended principally for rooftop installations. Modules satisfying the requirements of this specification fall into one of two categories, residential panel or residential shingle, both meeting general performance requirements plus additional category peculiar constraints.

TITLE: Low Cost Solar Array Project. The Zero Depth Concentrator Phenomenon.

AUTHOR: J. G. Mark and C. H. Volk

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: August 6, 1979

REPORT NO: 5101-136

ABSTRACTS The zero depth concentrator phenomenon, discovered by the General Electric Company, refers to the enhancement of the solar cell electrical output due to internally reflected light from the white background of a glass covered solar cell array. We have undertaken to describe this enhancement effect in terms of a series of basic models which yield an intuitive understanding of the mechanisms and allow trade-off considerations of some design parameters.

TITLE: '82 Technical Readiness Module Design and Test Specification - Intermediate Load Applications.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1980

REPORT NO: DOE/JPL-1012-36 and 5101-138

ABSTRACT: This document establishes the requirements for the design and test of terrestrial solar cell modules for one phase of DOE's Low-Cost Solar Array Project. Modules designed to meet this specification are intended to show that technology needed to meet the overall project goals for 1986 can be demonstrated in 1982 for intermediate load applications.

TITLE: Proposed Method for Determining the Thickness of Glass in Solar Collector Panels.

AUTHOR: D. M. Moore

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1980

REPORT NO: DOE/JPL-1012-41 and 5101-148

ABSTRACT: As part of the Jet Propulsion Laboratory's Low-cost Solar Array Project, an analytical method has been developed for determining the minimum thickness for simply supported, rectangular glass plates subjected to uniform normal pressure environmental loads such as wind, earthquake, snow, and deadweight. The method consists of comparing an analytical prediction of the stress in the glass panel to a glass breakage stress determined from fracture mechanics considerations. Based on extensive analysis using the nonlinear finite element structural analysis program ARGUS, design curves for the structural analysis of simply supported rectangular plates have been developed. These curves yield the center deflection, center stress and corner stress as a function of a dimensionless parameter describing the load intensity. Results are included for plates having length-to-width ratios of 1, 1.5, 2, 3 and 4. The load range considered extends to 1000 times the load at which the behavior of the plate becomes significantly nonlinear. Over the load range analyzed, the analysis shows that the ratio of center deflection to plate thickness for a plate of length-to-width ratio of 4 is less than 70 to 1, whereas linear theory would predict a center deflection about 1200 times the plate thickness. The stress is also markedly lower than would be predicted by linear theory. These analytical results show good agreement with the analytical and experimental work of others.

A method of estimating the glass breakage stress as a function of a specified failure rate, degree of glass temper, design life, load duration time, and panel size is presented. Development of this method consisted largely of collecting and/or adapting, in convenient form, the best available information from the literature. To establish the glass breakage stress versus probability of failure, the experimental data of other investigators has been reanalyzed to obtain a "best-fit" Weibull statistical distribution. This state-of-the-art analysis yields the glass breakage strength as a function of failure probability.

TITLE: Flat-Plate Photovo:*a*c Module and Array Circuit Design Optimization Worksh(› Proceedings. Engineering Area.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: May 1980

REPORT NO: 5101-170

ABSTRACT: This document contains the proceedings of the Flat-Plate Photovoltaic Module and Array Circuit design Optimization Workshop held at JPL during May of 1980. The workshop was held to discuss the problem of optimizing terrestrial photovoltaic array cell and circuit reliability and the methods of resolving this problem.

Certain faults are present in terrestrial photovoltaic modules, both at the beginning of life and throughout field experience. These faults occur as a result of mismatch of photovoltaic cell characteristics, both initial mismatch and mismatch caused by field environmental stresses and maintenance procedures. They include open-circuit cell interconnects, cracked cells and cell shadowing.

The objective of the workshop was to investigate the effectiveness of certain circuit-design strategies in ameliorating the effects of faults on module and array-system performance. A set of guidelines was presented for use in developing module and array-system circuit design strategies that maximize reliability through use of fault-tolerant circuiting. For simplicity, the open-circuit cell interconnect failure mode was emphasized in the workshop.

Cost and efficiency values presented in the proceedings are values accepted at the time of the workshop. All costs are in 1975 dollars.

TITLE: Photovoltaic Module Soiling Studies May 1978 - October 1980.

AUTHOR: A. R. Hoffman and C. R. Maag

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1980

REPORT NO: DOE/JPL-1012-49 and 5101-131

ABSTRACT: The retention of particulate contamination on the surface of flat-plate photovoltaic devices is adversely affecting electrical performance of outdoor-exposed modules. This report describes the results of an experimental study being performed by the Jet Propulsion Laboratory's Low-Cost Solar Array Project to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate photovoltaic modules and cover materials.

Comparative electrical and optical performance data from photovoltaic modules and materials subjected to outdoor exposure at field test sites throughout the United States have been collected and examined. The results show significant time- and site-dependence. During periods when natural removal processes do not dominate, the rate of particulate contamination accumulation appears to be largely material-dependent. Glass and acrylic top-cover materials retain fewer particles than silicone rubber does. Side-by-side outdoor exposure testing for long duration is presently the most effective means of evaluating soiling differences between materials. Changes in spectral transmission as a function of time and location and limited scattering data are presented.

TITLE: Low Cost Solar Array Project. Determining Terrestrial Solar Cell Reliability. Proceeding of Workshop.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 1980

REPORT NO: 5101-163

ABSTRACTS This document is an outgrowth of a workshop on "Determining Terrestrial Solar Cell Reliability," which was held May 1-2, 1980, at Clemson University, Clemson, South Carolina. The workshop was organized jointly by the Jet Propulsion Laboratory (JPL) and Clemson University, and was sponsored by the Low-Cost Solar Array Project (LSA) of the U.S. Department of Energy.

The purpose of the workshop was the critical review of silicon solar cell test results from a reliability testing program being carried out by Clemson University under contract to the Engineering Area of JPL/LSA. Since 1977 Clemson has conducted experimental reliability investigations on more than 1000 unencapsulated solar cells procured from seven photovoltaic industry manufacturers.

A total of 33 persons attended the workshop, representing fourteen organizations including private industry, national laboratories, and universities. This group of basic scientists, design engineers, and personnel involved in quality assurance and module/array field reliability participated actively in two days of workshop activities which included technical sessions, a tour of the test facilities, review of reliability test methods for solar cells, critique of test results, and moderated discussion sessions. The workshop provided a forum for productive discussion of various aspects of solar cell reliability by a broad spectrum of photovoltaic industry personnel. Much valuable information was exchanged, and recommendations were made regarding the validity of reliability data obtained to date and the direction in which future work should be channeled.

Preparation of this document was a collaborative effort by the Engineering Area of the Low-Cost Solar Array Project, Jet Propulsion Laboratory, and the Department of Electrical and Computer Engineering, Clemson University. Included are reproductions of graphic presentation materials and highlights of discussions related to solar cell reliability test methods.

Inquiries regarding details of the contents or requests for additional information should be directed to Mr. E. L. Royal of JPL or Professor J. W. Lathrop of Clemson University.

TITLE: Low-Cost Solar Array Project. Block V Solar Cell Module Design and Test Specification for Intermediate Load Applications 1981. LSA Engineering Area.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 20, 1981

REPORT NO: 5101-161

ABSTRACTS

This document establishes the requirements for the design and test of terrestrial solar cell modules for one phase of DOE's Low-Cost Solar Array Project. Intermediate-load modules designed to meet this specification will generally have the following design features and characteristics:

1. Nominal Operating Voltage (V_{no}) between 5 Vdc and 20 Vdc.

2. Ability to be series-connected to worst-case open-circuit voltages of 1000 Vdc.

3. Dimensions not exceeding 1.22 m x 2.44 m (4 ft x 8 ft).

4. Flat-Plate configuration (non-concentrating).

5. Output power referenced to nominal operating conditions (NOC) and V_{no}.

In addition to module design and performance requirements, a series of characterization and qualification test are also specified.

TITLE:	Block V Solar Cell Module Design and Test Specification for Residential Applications - 1981.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	February 1981
REPORT NO:	5101-162

ABSTRACT:

This specification provides near-term design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in photovoltaic power sources (2 kW to 10kW) applied to single-family residential installations. Requirement levels and recommended design limits for selected performance criteria have been specified for modules intended principally for rooftop installations. Modules satisfying the requirements of this specification fall into one of two categories, residential panel or residential shingle, both meeting general performance requirements plus additional category peculiar constraints. Residential modules designed to meet this specification will generally have the following design features and characteristics:

(1). Nominal Operating Voltage (V_{no}) between 5 Vdc and 20 Vdc.

(2). Ability to be series-connected to worst-case open-circuit voltages of 300 Vdc.

(3). Mounting arrangement compatible with new or existing residences.

(4). Flat-plate configuration (non-concentrating).

(5). Output power referenced to Nominal Operating Conditions (NOC) and V_{no}.

In addition to module design and performance requirements, a series of characterization and qualification tests are also specified.

TITLE: Low Cost Solar Array Project. Interim Standard for Safety: Flat-Plate Photovoltaic Modules and Panels. Volume I: Construction Requirements.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 20, 1981

REPORT NO: 5101-164, Vol. I

ABSTRACTS Underwriters Laboratories, Inc., under contract to the Jet Propulsion Laboratory (JPL), has conducted a study of present photovoltaic module array designs and configurations likely to be used in residential, commercial, and industrial applications. That investigation of engineering safety requirements has resulted in the development of this Interim Standard for Safety.

This document, primarily written by Underwriters Laboratories, Inc. (UL), is published in two volumes. Volume I, Construction Requirements, contains safety requirements for flat-plate photovoltaic modules and panels. Volume II, Performance Requirements, contains test procedures and methods to verify compliance with the safety requirements set forth in Volume I.

The purpose of this documents is to offer to the flat-plate photovoltaics community, for trial use, this Interim Standard for Safety as part of JPL's Low-Cost Solar Array (LSA) Project.

Volume I is intended to be used on a trial basis with the latest Block V Module Procurement Specifications for Intermediate Load and Residential Applications, 5101-161 and 5101-162, respectively. This use will support such things as future module procurements and module development activities sponsored by the U.S. Department of Energy.

Volume II contains test methods currently defined within the above module specifications together with additional tests under consideration by Underwriters Laboratories, Inc. Volume II is not intended for immediate use, but is designed to serve as a focus for review and iteration of future tests.

The results of feedback on these volumes will be submitted to UL for further refinement and ultimately for publication as a standard containing basic requirements for products covered by UL under its Follow-Up Service.

TITLE: Low-Cost Solar Array Structure Development

AUTHOR: A. H. Wilson

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: June 1981

REPORT NO: DOE/JPL-1012-53 and 5101-165

ABSTRACT: Early studies of flat-plate arrays have project costs on the order of $50/m^2 for installed array support structures. This report describes an optimized low-cost frame-truss structure that is estimated to cost below $25/m^2, including all markups, shipping and installation. The structure utilizes a planar frame made of members formed from light-gauge galvanized steel sheet and is supported in the field by treated-wood trusses that are partially buried in trenches. The buried trusses use the overburden soil to carry uplift wind loads and thus to obviate reinforced-concrete foundations. Details of the concept, including design rationale, fabrication and assembly experience, structural testing and fabrication drawings are included.

TITLE: Flat-Plate Solar Array Project. Interconnect Fatigue Design for Terrestrial Photovoltaic Modules.

AUTHOR: G. R. Mon, D. M. Moore and R. G. Ross, Jr.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1, 1982

REPORT NO: 5101-173

ABSTRACTS

Fatigue of solar cell electrical interconnects due to thermal cycling has historically been a major failure mechanism in photovoltaic arrays; the results of a comprehensive investigation of interconnect fatigue that has led to the definition of useful reliability-design and life-prediction algorithms are presented. Experimental data gathered in this study indicate that the classical strain-cycle (fatigue) curve for the interconnect material is a good model of mean interconnect fatigue performance, but it fails to account for the broad statistical scatter, which is critical to reliability prediction. To fill this shortcoming the classical fatigue curve is combined with experimental cumulative interconnect failure rate data to yield statistical fatigue curves (having failure probability as a parameter) which enable (1) the prediction of cumulative interconnect failures during the design life of an array field, and (2) the unambiguous--i.e., quantitative--interpretation of data from field-service qualification (accelerated thermal cycling) tests.

Optimal interconnect cost-reliability design algorithms are derived based on minimizing the cost of energy over the design life of the array field. This procedure yields not only the minimum break-even cost of delivered energy, but also the required degree of interconnect redundancy and an estimate of array power degradation during the design life of the array field. The usefulness of the design algorithms is demonstrated with realistic examples of design optimization, prediction, and service qualification testing.

TITLE: Flat-Plate Solar Array Project. An Investigation of the Effect of Wind Cooling on Photovoltaic Arrays.

AUTHOR: L. Wen

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1982

REPORT NO: 5101-201

ABSTRACTS Convective cooling of photovoltaic modules is investigated for different wind conditions, including steady-state controlled testing in a solar simulator and natural test environments in a field. Analytical thermal models of different module designs were used to correlate experimental data. The results obtained in the controlled environment confirm the applicability of existing heat-transfer correlations. The result of long-term field testing at the Jet Propulsion Laboratory test site is not conclusive because wind conditions were measured at different heights than of the modules. Nevertheless, reasonable agreement can be obtained by applying a power-law wind profile.

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TITLE: Final Report. Engineering Study of the Module/Array Interface for Large Terrestrial Photovoltaic Arrays

CORPORATE AUTH: Bechtel National, Inc.

CONTRACT NO: 954698

DATE: July 1977

REPORT NO: ERDA/JPL 954698-77/1

ABSTRACT: Bechtel Corporation has conducted a study of several factors contributing to the design of photovoltaic panels and their interface with the array. The study's emphasis was on large arrays, with a 200 MW central station power plant used for the baseline. Three major areas--structural, electrical, and maintenance--were evaluated.

Efforts in the structural area included establishing acceptance criterial for materials and members, determining loading criteria, and analyzing glass modules in various framing system configurations. Array support structure design was addressed briefly. Electrical considerations included evaluation of module characteristics, intermodule connectors, array wiring, converters and lightning protection. Plant maintenance features such as array cleaning, failure detection, and module installation and replacement were addressed.

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TITLE: Final Report. Module/Array Interface Study.

CORPORATE AUTH: Bechtel National, Inc.

CONTRACT NO: 954698

DATE: August 1978

REPORT NO: DOE/JPL-954698-78/1A

ABSTRACT: Bechtel National, Inc. has conducted a study of alternate module, panel, and array designs for use in large scale applications such as central station photovoltaic power plants. The objective of the study is to identify design features that will lead to minimum plant costs. Several aspects of module design are evaluated, including glass superstrate and metal substrate module configurations, the potential for hail damage, light absorption in glass superstrates, the economics of glass selection, and electrical design. 3 alternate glass superstrate module configurations are evaluated by means of finite element computer analyses. 2 panel sizes, 1.2 by 2.4 m (4 by 8') and 2.4 by 4.8 m (8 by 16'), are used to support 3 module sizes, 0.6 by 1.2 m (2 by 4'), 1.2 by 1.2 m (4 by 4'), and 1.2. by 2.4 m (4 by 8'), for design loadings of about 1.7 kPa (35 psf), 2.4 kPa (50 psf), and 3.6 kPa (75 psf). Designs and cost estimates are presented for 20 panel types and 9 array configurations at each of the 3 design loadings. Structural cost sensitivities of combined array configurations and panel cases are presented.

TITLE: Phase I: Final Report. Feasibility Study of Solar Dome Encapsulation of Photovoltaic Arrays.

AUTHOR: Zimmerman, D. K.

CORPORATE AUTH: Boeing Engineering and Construction CO., Seattle, WA (USA)

CONTRACT NO: 954833

DATE: December 1978

REPORT NO: DOE/JPL/954833-78/1

ABSTRACT: This report describes a study which investigated the potential technical and economic advantages of using air-supported plastic enclosures to protect flat plate photovoltaic arrays. Conceptual designs for a fixed, latitude-tilt array and a fully tracking array were defined. Another program provided much of the design and supporting analyses for the tracking array. Detailed wind loads and strength analyses were performed for the fixed array. Detailed thermal and power output analyses provided array performance for typical seasonal and extreme temperature conditions. Costs of each design as used in a 200 MWE central power station were defined from manufacturing and material cost estimates. The capital cost and cost of energy for the enclosed fixed-tilt array were lower than for the enclosed tracking array. The enclosed fixed-tilt array capital investment was 38% less, and the levelized bus bar energy cost was 26% less than costs for a conventional, glass-encapsulated array design. The predicted energy cost for the enclosed fixed array was 79 mills/kw H for direct current delivered to the power conditioning units.

TITLE: Final Report. Residential Photovoltaic Module and Array Requirements Study

CORPORATE AUTH: Burt Hill Kosar Rittelmann Associates

CONTRACT NO: 955149

DATE: June 1979

REPORT NO: DOE/JPL 955149-79/1

ABSTRACT: Burt Hill Kosar Rittelmann Associates has conducted a study to identify design requirements for photovoltaic modules and arrays used in residential applications. Building codes and referenced standards were reviewed for their applicability to residential photovoltaic array installations. Four installation types were identified-integral (replaces roofing), direct (mounted on top of roofing), stand-off (mounted away from roofing), and rack (for flat or low slope roofs, or ground mounted). Installation costs were developed for these mounting types as a function of panel/module size. Cost drivers were identified. Studies were performed to identify optimum module shapes and sizes and operating voltage cost drivers. The general conclusion is that there are no perceived major obstacles to the use of photovoltaic modules in residential arrays. However, there is no applicable building code category for residential photovoltaic modules and arrays and early additional work is needed with standards writing organizations to develop residential module and array requirements.

TITLE: Final Report. Wind Loads on Flat Plate Photovoltaic Array Fields

AUTHOR: Ronald Miller

CORPORATE AUTH: Boeing Engineering and Construction Company

CONTRACT NO: 954833

DATE: September 1979

REPORT NO: DOE/JPL 954833-79/2

ABSTRACT: This report describes a theoretical study of the aerodynamic forces resulting from winds acting on flat plate photovoltaic arrays. Local pressure distributions and total aerodynamic forces on the arrays are shown. Design loads are presented to cover the conditions of array angles relative to the ground from 20^{o} to 60^{o}, variable array spacings, a ground clearance gap up to 1.1 m (4 ft) and array slant heights of 2.4 m (8 ft) and 4.8 m (16 ft). Several means of alleviating the wind loads on the arrays are detailed. The expected reduction of the steady state wind velocity with the use of fences as a load alleviation device are indicated to be in excess of a factor of three for some conditions. This yields steady state wind load reductions as much as a factor of ten compared to the load incurred if no fence is used to protect the arrays. This steady state wind load reduction is offset by the increase in turbulence due to the fence but still an overall load reduction of 2.5 can be realized. Other load alleviation devices suggested are the installation of air gaps in the arrays, blocking the flow under the arrays and rounding the edges of the array. Included is an outline of a wind tunnel test plan to supplement the theoretical study and to evaluate the load alleviation devices.

TITLE:	Final Report. Study of Curved Glass Photovoltaic Module and Module Electrical Isolation Design Requirements
CORPORATE AUTH:	Bechtel National, Inc.
CONTRACT NO:	954698
DATE:	June 1980
REPORT NO:	DOE/JPL 954698-80/2

ABSTRACT:

Bechtel National, Inc., has conducted a study to evaluate the technical feasibility and cost effectiveness of curved glass superstrate photovoltaic modules for use in large scale applications such as central station power plants. The study also evaluated electrical insulation and isolation design considerations with regard to module encapsulation systems.

The design of a 1.2 by 2.4 m (4 by 8 ft) curved glass superstrate and support clip assembly is presented, along with the results of finite element computer analyses and a glass industry survey conducted to assess the technical and economic feasibility of the concept. Installed costs for four curved glass module array configurations are estimated and compared with costs previously reported for comparable flat glass module configurations.

Electrical properties of candidate module encapsulation systems are evaluated along with present industry practice for the design and testing of electrical insulation systems. Electrical design requirements for module encapsulation systems are also discussed.

TITLE: Final Report. Photovoltaic Module Electrical Termination Design Requirement Study.

AUTHOR: F. J. Mosna, Jr. and J. Donlinger

CORPORATE AUTH: Motorola Inc.

CONTRACT NO: 955367

DATE: July 1980

REPORT NO: DOE/JPL-955367-80/1

ABSTRACT: The purpose of this document is to provide additional details and information to supplement the data provided in the Executive Summary. The document consists of Appendices 2.0, 3.0, and 4.0 which address the major tasks of the project (criteria development; ranking; and results/conclusions, respectively) and Appendix 5.0, a series of mini-appendices addressing specific topics complementing the major task areas.

TITLE:	Final Report. Operation and Maintenance Cost Data for Residential P/V Modules/Panels
CORPORATE AUTH:	Burt Hill Kosar Rittelmann Associates
CONTRACT NO:	955614
DATE:	July 1980
REPORT NO:	DOE/JPL-955614-80/1

ABSTRACT: Burt Hill Kosar Rittelmann Associates has conducted a study to identify and estimate costs associated with the operation and maintenance of residential P/V modules and arrays. Six basic topics related to operation and maintenance to P/V arrays were investigated - General (Normal) Maintenance, Cleaning, Panel Replacement, Gasket Repair/Replacement, Wiring Repair/Replacement, and Termination Repair/Replacement. The effects of the mounting types - Rack Mount, Stand-Off Mount, Direct Mount, and Integral Mount - and the installation/replacement type - Sequential, Partial Interruption, and Independent - have been identified and described. Recommendation on methods of reducing maintenance costs have been made.

TITLE: Quarterly Report. A Program to Develop Elements of a Reliability Design Guidebook for Flat Plate Photovoltaic Modules/Arrays

CORPORATE AUTH: IIT Research Institute

CONTRACT NO: 955720

DATE: October 1980

REPORT NO: DOE/JPL 955720-80/1

ABSTRACT: The objective of the overall IITRI support study is to provide and/or develop engineering-oriented reliability data, guidelines, procedures and techniques to serve as elements of a reliability design guidebook on terrestrial, low-cost, photovoltaic (PV) modules/arrays. The approach being used in this support study is to first initiate an on-going reliability engineering data base and then develop and validate design guidelines that can be used by the photovoltaic industry to build reliability into their products most cost effectively.

Meeting the objective will involve accomplishment of at least the following five sub-tasks:

Sub-Task 1) - Analyze available flat plate photovoltaic field and test data (P/FRs) to obtain an initial reliability engineering data base.

Sub-Task 2) - Formulate guidelines for appropriate reliability analysis methodologies (for example, reliability allocation generation and validation, etc.)

Sub-Task 3) - Develop methods to establish failure rates for PV modules

Sub-Task 4) - Develop methods to establish material and module component failure rates

Sub-Task 5) - Develop methods to determine and assign failure rate and degradation modifying factors and formulate an analysis tool for assessing the reliability/life potential of photovoltaic module

TITLE: Final Report. Safety and Liability Considerations for Photovoltaic Modules/Panels

AUTHOR: Meeker, D. G. and Weinstein, A. S.

CORPORATE AUTH: Carnegie-Mellon University

CONTRACT NO: 955846

DATE: January 1981

REPORT NO: DOE/JPL 955846-81/1

ABSTRACT: The concept of product liability implies that a manufacturer is responsible to the consumer for products that are not reasonably safe. Recently, consumers have become more aware that manufacturers could be liable for harm incurred by a consumer while using their products. Evidence of this awareness can be seen by the increase in product liability suits and sizes of awards in recent years. Clearly this presents a problem for the manufacturer. Not only must the product be reliable and safe for its intended purpose, but it must also be safe for foreseeable misuse.

This preliminary report explores product safety and product liability consideraions for photovoltaic module/array devices. The purpose of this study is twofold--first to give an overview of legal issues as they apply to design, manufacture and use; second, to suggest a methodology to be used during design of a photovoltaic module/array to minimize or eliminate perceived hazards. This study does not attempt to answer any of these questions in detail, but only to pose them so as to stimulate consideration of this area. The questions raised in this study can only be answered through future efforts in concert with the manufacturers.

TITLE:	Annual Report. Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells
AUTHOR:	J. L. Prince and J. W. Lathrop
CORPORATE AUTH:	Clemson University
CONTRACT NO:	954929
DATE:	January 1981
REPORT NO:	DOE/JPL 954929-81/8
ABSTRACT:	Work covered in this report represents a portion of the third year's effort of a continuing program to determine the reliability attributes of terrestrial solar cells. Major effort during this reporting period was devoted to two tasks: 1) improvement of the electrical measurement instrumentation through the design and construction of a microcomputer controlled short interval tester, and 2) better understanding of second quadrant behavior by developing a mathematical model relating cell temperature to electrical characteristics. In addition some preliminary work is reported on an investigation into color changes observed after stressing. While the accelerated stressing of various cell types is continuing, no new results of this activity are presented in this report and reader is referred to earlier reports for the latest available documenttion.

TITLE: Final Report. Wind Loads on Flat Plate Photovoltaic Array Fields

AUTHOR: Ronald Miller

CORPORATE AUTH: Boeing Engineering and Construction Company

CONTRACT NO: 954833

DATE: April 1981

REPORT NO: DOE/JPL 954833-81/3

ABSTRACT: This report presents the results of an experimental analysis (boundary layer wind tunnel test) of the aerodynamic forces resulting from winds acting on flat plate photovoltaic arrays. Local pressure coefficient distributions and normal force coefficients on the arrays are shown and compared to theoretical results. Parameters that were varied when determining the aerodynamic forces included tilt angle, array separation, ground clearance, protective wind barriers, and the effect of the wind velocity profile. Recommended design wind forces and pressures are presented, which envelop the test results for winds perpendicular to the array's longitudinal axis.

TITLE:	Quarterly Report No. 1. Integrated Residential Photovoltaic Array Development
CORPORATE AUTH:	AIA Research Corporation
CONTRACT NO:	955893
DATE:	April 1981
REPORT NO:	DOE/JPL 955893-81/1

ABSTRACT:

This first quarterly report on a contract to develop an optimal integrated residential photovoltaic array describes sixteen conceptual designs produced by eight teams. Each design concept was evaluated by an industry advisory panel using a comprehensive set of technical, economic and institutional criteria. Key electrical and mechanical concerns that affect further array sub-system development are also discussed.

Three integrated array design concepts were selected by the advisory panel for further optimization and development. From these concepts a single one will be selected for detailed analysis and prototype fabrication. The three concepts selected are the following:

An array of frameless panels/modules sealed in a "T" shaped zipperlocking neoprene gasket grid pressure fitted into an extruded aluminum channel grid fastened across the rafters.

An array of frameless modules pressure fitted in a series of zipperlocking EPDM rubber extrusions adhesively bonded to the roof. Series string voltage is developed using a set of integral tongue connectors and positioning blocks.

An array of frameless modules sealed by a silicone adhesive in a prefabricated grid of rigid tape and sheet metal attached to the roof.

TITLE: Phase IV: Final Report. Wind Loads on Flat Plate Photovoltaic Array Fields. (Nonsteady Winds)

AUTHOR: Ronald Miller, Donald K. Zimmerman

CORPORATE AUTH: Boeing Engineering and Construction Company

CONTRACT NO: 954833

DATE: August 1981

REPORT NO: DOE/JPL-954833-81/4

ABSTRACT: This report presents the results of a combined experimental (wind tunnel test results) and theoretical analysis utilizing random harmonic analysis tecniques to predict the dynamic response and the structural dynamic loads of flat plate photovoltaic arrays due to wind turbulence. Guidelines for use in predicting the turbulent portion of the wind loading on future similar arrays using the results of this study are presented.

TITLE: Final Report. Commercial/Industrial Photovoltaic Module and Array Requirement Study

CORPORATE AUTH: Burt Hill Kosar Rittelmann Associates

CONTRACT NO: 955698

DATE: December 1981

REPORT NO: DOE/JPL 955698-81/1

ABSTRACT: Burt Hill Kosar Rittelmann Associates has conducted a study to identify design requirements for photovoltaic modules and arrays used in commercial and industrial applications.

Building codes and referenced standards were reviewed for their applicability to commercial and industrial photovoltaic array installation. Four general installation types were identified - integral (replaces roofing), direct (mounted on top of roofing), stand-off (mounted away from roofing), and rack (for flat or low slope roofs, or ground mounted). Each of the generic mounting types can be used in vertical wall mounting systems. Installation costs were developed for these mounting types as a function of panel/module size. Cost drivers were identified. Studies were performed to identify optimum module shapes and sizes and operating voltage cost drivers.

As some obstacles could make PV extremely costly, this report makes recommendations to the PV industry which will facilitate a more successful product entrance into the building industry.

TITLE: Final Report. Integrated Residential Photovoltaic Array Development.

CORPORATE AUTH: General Electric

CONTRACT NO: 955894

DATE: December 1981

REPORT NO: DOE/JPL-955894-4

ABSTRACT: An advanced, universally-mountable, integrated residential photovoltaic array concept has been defined based upon an in-depth formulation and evaluation of three candidate approaches which were synthesized from existing or proposed residential array concepts.

Past residential photovotaic array concepts emphasized the module as given. This study addresses the next level of detail by considering the impact of module circuitry and process sequence, and by identifying technology gaps and performance drivers associated with residential photovoltaic array concepts. The actual learning experience gained from the comparison of the problem areas of the hexagonal shingle design with the rectangular module design has led to what is considered an advanced array concept. Building the laboratory mockup provided actual experience and the opportunity to uncover additional technology gaps.

TITLE:	Final Report. Bypass Diode Integration
CORPORATE AUTH:	General Electric
CONTRACT NO:	955894
DATE:	December 1981
REPORT NO:	DOE/JPL 955894-5

ABSTRACT: This report summarizes the results of a bypass diode integration study which was conducted as part of the "Integrated Residential Photovoltaic Array Development" effort. The study involved research into protective bypass diodes and mounting configurations which are applicable for use with photovoltaic modules having power dissipation requirements in the 5 to 50 watt range. Using PN silicon and Schottky diode characterization data on packaged diodes and diode chips, typical diodes were selected as representative for each range of current carrying capacity, an appropriate heat dissipating mounting concept along with its environmental enclosure was defined, and a thermal analysis relating junction temperature as a function of power dissipation was performed. In addition the heat dissipating mounting device dimensions were varied to determine the effect on junction temperature. The results of the analysis are presented as a set of curves indicating junction temperature as a function of power dissipation for each diode package.

Operations
(Module Performance and Failure Analysis)
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TITLE: Low Cost Silicon Solar Array Project Operations Task. Solar Cell Module Performance, Environmental Test, Handling, Storage and Inspection Procedure.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: July 27, 1976

REPORT NO: 5101-6

ABSTRACTS This document covers the procedures for performance evaluation, environmental testing, handling, storage and inspection of sample solar cell modules form the 40 KW procurement.

The tests to be conducted are shown on Fig. 1. There are four sets of tests to be performed, each on a different set of modules, designated Sets A, B, C, and D. Set A modules will be subjected to the same environments that the contractor will perform--thermal cycling and humidity. Electrical performance measurements will be made before and after each environmental exposure. Set B will subject a different set of modules to other terrestrial environments--humidity/freezing, rain/heat, and salt fog. Set C modules will be subjected to an environment favorable to fungus growth to determine suitability for use in certain moist, tropical areas. Set D modules will undergo a field test at a local site for various time periods interrupted by performance evaluations.

Set A tests, thermal cycling and humidity, will be performed in Building 144. Test flow and test durations for Set A modules are shown in Fig. 6.

This document contains test procedures for only set A tests at this time. Procedures for Set B, Set C, and Set D tests will be generated in the near future.

TITLE:	Summary Results of Block I (46 kW) Module Testing
AUTHOR:	J. S. Griffith and S. G. Sollock
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	May 1977
REPORT NO:	5101-27
ABSTRACTS:	This report documents the test procedure and the results of testing the modules procured by JPL under Block I. Included are tabulations of module features and performance data, descriptions of the variety of exploratory tests, a summary of the analysis of problems and failures and a summary of conclusions and recommendations.

TITLE: LSSA Field Test Activity System Description

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: August 1977

REPORT NO: 5101-39

ABSTRACT: The purpose of this memorandum is to provide details of the current status and plans of the Field Testing Activity. An attempt has been made to incorporate into these plans the capability of being responsive to the changing needs of the Project. This has, hopefully, been accomplished by not only recognizing near-term requirements but also by providing imbedded flexibility in the structure of the Activity.

The objectives of the Activity are to:

1. Obtain high quality continuous performance field data on a limited quantity of modules.

2. Track module degradation to provide a base for the development of endurance projection techniques.

3. Develop improved in-situ diagnostic testing tools and analytical techniques.

4. Provide confirmation data for qualification testing.

5. Provide real-time/real-weather facilities for general Project use.

TITLE: Humidity and Temperature Cycling Tests of Spectrolab Solar Cells

AUTHOR: J. S. Griffith

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1977

REPORT NO: 5101-42

ABSTRACTS: Seventy-two new Spectrolab evaporated contact solar cells and eight older Process A printed contact cells were tested at JPL to determine if the former would be a suitable replacement for the older type in production solar modules. Cells were divided into three lots: one lot received humidity exposure, the second lot humidity and temperature cycling, and the third lot was held out for control. Results indicate that the newer evaporated contact cells are much superior to the older cells based on electrical tests and mechanical tab pull tests. Pull tests of soldered tabs on the contacts were inconclusive. This can be attributed in the case of the evaporated contacts to difficulties in soldering tabs to the cells.

TITLE:	User Handbook for Block II Silicon Solar Cell Modules
AUTHOR:	M. I. Smokler
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	October 1977
REPORT NO:	5101-36

ABSTRACT:

The program of the Low-Cost Silicon Solar Array (LSSA) Project includes a series of competitive procurements of production quantities of solar cell modules. The objectives of this procurement effort are to stimulate reduction in manufacturing cost and to provide modules for test of solar cell arrays in practical applications.

The first in this series of procurements, designated Block I, included the purchase from five contractors of a quantity of modules having a total nominal power output of about 58 kilowatts. These Modules were procured to the contractor's specifications as a means of ascertainting the state-of-the-art of terrestrial solar cell modules and of providing modules for early test and applications programs.

Block II, the second in the series of procurements, involved purchase of 123 kilowatts of total power capacity from four contractors. Block II introduced a degree of standardization by defining the module design specifications and by providing for a design qualification test program.

The purpose of this User Handbook is to supply engineering data necessary for planning or investigating application programs utilizing the Block II modules. Anyone requiring additional technical information should direct his request to Mr. Larry N. Dumas, LSSA Project Operations Manager, at the JPL.

TITLE:	LSSA Project Task Report. Interface Management Plan for Block III Solar Cell Modules in Field Test and Applications.
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	December 2, 1977
REPORT NO:	5101-48

ABSTRACTS

This plan is intended to provide clarification for the user regarding responsibilities and interfaces of JPL and Block III module users. Questions regarding the interpretation or utilization of these guidelines should be referred to the LSSA Operations Manager or Project Office. The provisions herein apply to modules procured by the Jet Propulsion Laboratory (JPL) for the Department of Energy (DOE) during 1978 in the following quantities, hereafter referred to as Block III.

ARCO Solar, Inc.	35 kW
Motorola, Inc.	50 kW
Sensor Technology, Inc.	40 kW
Solar Power, Inc.	40 kW
Solarex, Inc.	30 kW

The Block III Modules are being procured by the Large-Scale Production Task of the Low-Cost Silicon Solar Array (LSSA) Project. The Block III procurement supports the project objective to increase manufacturing capacity and reduce the price of solar cell modules and to provide modules for test and application projects sponsored by the Department of Energy.

TITLE: Measurment of Solar and Simulator Ultraviolet Spectral Irradiance.

AUTHOR: R. S. Estey

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1978

REPORT NO: 5101-58

ABSTRACT: This report presents in summary form the intensity and spectral characteristics of the sun and various engineering sources of radiation relevent to the operation and testing of photovoltaic cell arrays and presents a description of the characteristics and operation of a spectroradiometer system developed to measure and document the radiation from the source of interest. Sun and other source measurements support durability studies of external surfaces exposed to sun and weather. These studies are a part of the LSSA program to develop low cost and long life solar cells.

This report discusses the characteristics of sun and sky radiation, the ultraviolet from the solar simulators, the details of the ultraviolet spectroradiometer system and field measurements.

In the selection of terminology and of units, this report follows the latest practice and uses System International (SI) units and the preferred choice of decimal multipliers (Ref. 1-1). For the purpose of this report we are primarily concerned with the radiant flux incident on a surface or passing through the location which such a surface represents. The flux density, i.e., flux/unit area, is termed irradiance with the symbol, E, and the units milliwatts centimeter^{-2}. When the spectral irradiance is measured, the wavelength unit, nanometer, and symbol, E (λ), are used. The spectral irradiance at wavelength, λ , is symbolized as E (λ) with the units (as customarily abbreviated), mW cm^{-2} nm^{-1}. The above choice of units and symbols conforms to the SI system and represents the best current practice.

TITLE: LSA Field Test Annual Report, August 1977--August 1978

AUTHOR: Jaffe, P.

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1978

REPORT NO: DOE/JPL/1012-78/12 and 5101-85

ABSTRACTS: The status of field testing of photovoltaic modules at sites operated by JPL is updated. This includes a description of the fields and the modules deployed therein at JPL, Table Mountain, Goldstone and Point Vicente, all in California. The hardware and software in the data acquisition system are discussed as well as the testing procedures. The effects of electrical degradation, physical change and dirt accumulation on modules at the JPL site are reviewed, and a summary of the experience at the remote sites is recounted.

TITLE: Acceptance/Rejection Criteria for JPL/LSA Modules.

AUTHOR: W. E. Bishop and K. J. Anhalt

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: November 3, 1978

REPORT NO: 5101-21, Rev B.

ABSTRACT: The objective of this document is to establish the basis for the workmanship inspection criteria which are to be written and made a part of the Inspection System Plan used in the production of solar cell modules procured for the JPL Low-Cost Solar Array Project. The criteria, terminology, and illustrations are derived from the details of specific module designs. It is understood that the criteria presented herein may not be applicable to certain module designs, and that other module designs will contain features which require criteria not presented in this document, but which must be included in the operational Inspection System Plan.

TITLE: Low Cost Solar Array Project. Quality System Requirements for Flat Plate Solar Photovoltaic Systems: General Specification.

AUTHOR: G. Inskeep and K. Anhalt

CORPORATE AUTH: Jet Propulsion Laboratory

REPORT NO: 5101-97

ABSTRACTS This specification covers the quality system requirements for flat plate solar photovoltaic systems. It includes a definitive outline of quality-oriented activities to be pursued by the contractor to assure the physical and operational quality of delivered hardware. To the greatest extent possible, the contractor's existing quality and inspection programs shall be used to minimize changes to an acceptable operating quality system.

TITLE: Solar Cell Module Problem/Failure Reporting Procedure

AUTHOR: Operations Area

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: January 1979

REPORT NO: 5101-26 REV A

ABSTRACTS: The problem/failure reporting system is described, and detailed instructions are provided for the initiation, review and closeout of Problem/Failure Reports (P/FRs).

TITLE: Environmental Testing of Block II Solar Cell Modules

EDITOR: Griffith, J. S.

CORPORATE AUTHOR: Jet Propulsion Laboratory

DATE: January 1979

REPORT NO: DOE/JPL/1012-79/1 and 5101-98

ABSTRACT: The results of environmental tests of Block II solar modules are described. Block II was the second large scale procurement of silicon solar cell modules made by the JPL Low-Cost Solar Array Project with deliveries in 1977 and early 1978. The results of testing showed that the Block II modules were greatly improved over Block I modules. In several cases it was shown that design improvements were needed to reduce environmental test degradation. These improvements were incorporated during this production run.

TITLE: User Handbook for Block III Silicon Solar Cell Modules.

AUTHOR: M. I. Smokler

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: February 1979

REPORT NO: DOE/JPL-1012-79/6 - 5101-82

ABSTRACT: The program of the Low-Cost Solar Array (LSA) Project has included a series of competitive procurements of production quantities of solar cell modules. The objectives of this procurement effort were to stimulate reduction in manufacturing cost and to provide modules for test of solar cell arrays in practical applications.

The first in this series of procurements, designated Block I, included the purchase from five contractors of a quantity of modules having a total nominal power output of approximately 58 kW. These modules were procured to the contractors' specifications as a means of ascertaining the state-or-the-art of terrestrial solar cell modules and of providing modules for early test and applications programs.

Block II, the second in the series of procurements, involved purchase of 123 kW of total power capacity from four contractors. Block II introduced a degree of standardization by defining the module design specifications and by providing for a design qualification test program. The Block II modules are described in JPL document 5101-36, "User Handbook for Block II Silicon Solar Cell Modules."

Block III, the third in the series, consisted of procurement of a nominal 205 kW of total power capacity from five contractors. The design specifications were essentially the same as for Block II. As no design or development was permitted under the contracts, only designs which previously had been qualified by JPL were eligible for Block III contracts.

TITLE: Module Performance Assessment: Laboratory and Field Environment

AUTHOR: P. Tsou and D. Schwartz

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: March 1979

REPORT NO: DOE/JPL-1012-23 and 5101-96

ABSTRACT: This report examines several methods that can be used to assess the performance of solar modules in a terrestrial environment. The report presents results that are derived from extensive laboratory and field measurements on four Solarex Energizer modules. The major thrusts of this study are 1) an analysis of the I-V curve translation model that is currently being used to correct field and laboratory measurements for temperature and solar insolation variations, and 2) a characterization of module performance parameters as functions of solar insolation and temperature. Applications of the above techniques to the assessment of performance degradation due to dust in the field environment are reported.

TITLE: Environmental Testing of Block III Solar Cell Modules. Part I: Qualification Testing of Standard Production Modules.

AUTHOR: John S. Griffith

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: September 1979

REPORT NO: DOE/JPL-1012-30 and 5101-134

ABSTRACT: This report describes the results of qualification tests of Block III solar modules. Block III was the third large-scale procurement of silicon solar cell modules made by the JPL Low-cost Solar Array Project; the qualification modules were delivered in 1978. Block III modules continue to show improvements over Block I and Block II modules. Cell cracking and delamination are less prevalent, and interconnect problems and electrical degradation from environmental testing are now rare.

TITLE: LSA Field Test Annual Report August 1978-August 1979.

AUTHOR: P. Jaffe

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1979

REPORT NO: DOE/JPL-1012-38 and 5101-141

ABSTRACT: In the course of three years of testing no evidence has resulted to suggest that the twenty-year-life goal for photovoltaic modules will not be met. Results of studies of more than 600 modules under test show that they are generally enduring well both electrically and physically, particularly those from more recent procurements. Degradation tests performed at JPL indicate that electrical degradation is not a slow monotonically increasing phenomenon as originally thought but occurs abruptly as the result of some traumatic event. This finding has led to a change in the test philosophy. The report includes a discussion of this change, a summary of degradation and failure data from all the sites, results from a variety of special tests, and a description of new instrumentation for in-field measurements. The field testing activity was expanded by the addition of twelve remote sites located as for away as Alaska and the Canal Zone. A description of the new sites is also included.

TITLE:	Insolation at Goldstone - 1976
AUTHOR:	Roger S. Estey
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	May 1980
REPORT NO:	5101-153
ABSTRACTS:	Radiometer data for 1976 have been extracted from ongoing measurements made at the Goldstone Tracking Station and are presented in Tables and Graphs displaying values of direct and global solar energy.

TITLE: LSA Field Test Annual Report August 1979-August 1980

AUTHOR: Peter Jaffe

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1980

REPORT NO: DOE/JPL-1012-52 and 5101-166

ABSTRACT: After almost four years of endurance testing of photovoltaic modules, no fundamental life-limiting mechanisms have been identified that could prevent the twenty-year life goal from being met. The endurance data show a continual decline in the failure rate with each new large-scale procurement. Cracked cells and broken interconnects continue to be the principal causes of failure. Although the modules are more adversely affected physically by hot, humid environments than by cool or dry environments, there are insufficient data to correlate failures with environment. There is little connection between the outward physical condition of a module and changes in its electrical performance. Electrical degradation is a transient condition that is generally intermittent and is present before a module destined to fail finally fails. Analysis of year-long electrical performance data indicates that the fill factor is insensitive to most measurement problems and remains the best diagnostic tool for determining module degradation. Investigations at the JPL site reveal that shadowing the indirect component of irradiance can reduce the electrical output of modules and result in anomalous performance data. Extrapolating this result to arrays suggests that a loss of power can result if indirect shadowing is not considered in the array layout. The introduction of the Portable I-V Data Logger was a success. About 1200 high quality I-V curves were obtained during a tour of the 15 remote sites. Next year a major reorganization in the inventory of test modules is planned. A significant portion of the older modules will be removed and replaced with modules from the upcoming Block IV large-scale procurement.

TITLE:	The Correction for Spectral Mismatch Effects on the Calibration of a Solar Cell When Using a Solar Simulator.
AUTHOR:	Clay H. Seaman
CORPORATE AUTH:	Jet Propulsion Laboratory
DATE:	January 1981
REPORT NO:	DOE/JPL-1012-50 and 5101-169
ABSTRACT:	A general expression has been derived to enable calculation of the calibration error resulting from simulator-solar AMX spectral mismatch and from reference cell-test cell spectral mismatch. The information required includes the relative spectral response of the reference cell, the relative spectral response of the cell under test, and the relative spectral irradiance of the simulator (over the spectral range defined by cell response). The spectral irradiance of the solar AMX is assumed to be known.

TITLE: FSA Field Test Annual Report - August 1980 - August 1981

AUTHOR: Peter Jaffe, Robert W. Weaver and Robert H. Lee

CORPORATE AUTH: Jet Propulsion Laboratory

DATE: December 1981

REPORT NO: DOE/JPL-1012-59 and 5101-197

ABSTRACTS: A complete restructuring of Flat-Plate Solar Array Project field-test activity was done during the past year; its major element was redirecting emphasis away from collecting endurance data and toward the early identification and analysis of fundamental module problems. To support this shift and to accommodate an expected reduction in resources: (1) the 12 Continental Remote Sites have been decommissioned; (2) testing has been consolidated into a five-site network consiting of the four Southern California sites and a new Florida site; (3) 16 kW of new state-of-the-art modules are being deployed at the five sites; (4) testing of the old modules is continuing at the Goldstone site but as a low-priority item; (5) the major thrust of the new emphasis--early problem detection--will be accomplished by array testing of modules at the JPL site; (6) additional new testing capabilities are being added to the JPL site, which will elevate its operations to those of a field test laboratory for the simulation and investigation of real-use problems and the development of improved testing techniques; (7) a new key instrument is being fabricated, a versatile battery-powered array data logger, which will permit in-field diagnoses of arrays as large as 40 amperes and 400 volts. Restructuring is progressing on schedule.

A final set of failure and degradation data was obtained from the modules at the Southern California sites before they were relocated at Goldstone. The mean composite failure rate for all the modules (Blocks I, II and III) over the past five years is 2.0 percent per year. Considering the final two years only, the rate is 4.4 percent, suggesting a significant upward trend with age.

Operations
(Module Performance and Failure Analysis)
Contract Abstracts

TITLE:	Final Report. Failure and Degradation Analyses. MITRE Solar Energy Test System Evaluation.
CORPORATE AUTH:	Solarex Corporation
CONTRACT NO:	954341
DATE:	April 1976
REPORT NO:	ERDA/JPL-954341

ABSTRACT: As part of JPL Contract No. 954341 "Mitre Solar Energy Test System Evaluation", the Solarex Corporation is to perform Failure and Degradation Analyses on not more than three of the 136 Solarex Unipanels (TM) in Mitre's 859 Watt (peak) solar array. This report details the observations and experiments performed on the two such Unipanels already in Solarex's possession.

Individual Unipanels are the basic "building blocks" in the assembly of the 50 Watt (peak) modules that comprise the Mitre array. These panels were rated by Solarex to deliver a minimum of 6 Watts (peak) and were so arranged in groups of eight to deliver 50 Watts (peak) per module.

The two Unipanels that are the subject of this report were received from the Mitre Corporation in August 1975. These two panels subsequently labeled "Mitre A_1" and Mitre A_2", were described by Mitre officials at that time as "operational" (A_1) and "open" (A_2).

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TITLE: Final Report. Fabrication, Test, and Delivery of 8 kw of Solar Power Modules. Large Scale Production Task.

CORPORATE AUTH: Sensor Technology, Inc.

CONTRACT NO: 954387

DATE: 15 October 1976

REPORT NO: ERDA/JPL/954387-76/1

ABSTRACT: Through this contract, and the cooperative program resulting from the JPL-ERDA-NASA Low Cost Silicon Solar Array Project, Sensor Technology has produced modules at the rate of 3.5 kw per month with a power output of 83.2 watts per 4' x 4' array. These modules were produced at a cost of $19.07 per watt. The production techniques of this program make it easily possible to expand this to the 10 to 15 kw per month range and methods were developed by which future costs may be reduced by 15 to 30%. Two inch diameter cells were used on this project, however, facilities now exist to process 3 inch, 3.56 inch and 4 inch diameter wafers. The module design, performance, cost factors, problem areas, efficiency, encapsulation, and humidity and temperature test results are reported.

TITLE: Final Report. Large Scale Production Task of the Low Cost Silicon Solar Array Project.

CORPORATE AUTH: Spectrolab, Inc.

CONTRACT NO: BQ-649005

DATE: December 1976

REPORT NO: ERDA/JPL-BQ-649005-76/1

ABSTRACT: 2000 solar power modules capable of producing over 10 kW of peak power were delivered. These modules have good structural and thermal dissipation characteristics, but difficulties were encountered with respect to delamination of the encapsulant material, low electrical breakdown resistance and humidity sensitivity. Design modifications that have been recommended to improve reliability and reduce cost, include the elimination of metal substrate, replacement of silicone with a more suitable encapsulant, larger module size and use of series-parallel circuit configurations.

TITLE: Final Technical Report. Large Scale Production Task.

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: BQ-649006

DATE: December 1976

REPORT NO: DOE/JPL-BQ-649006-76/1

ABSTRACT: Twenty production modules, representing the state-of-the-art, were produced for qualification testing and for installation of the thermal cycling and temperature humidity chambers. The first 10 modules completed the required thermal cycling and program without electrical, mechanical, structural or optical degradation. After temperature-humidity testing significant electrical degradation was observed. Early indications were that production error was the cause in that the silicone rubber used in those panels was not properly dehydrated. It was also learned that the freshly cured silicone rubber is quite permeable to water. To correct the problem palladium was added to the contact metallization. This completely eliminated any electrical degradation problems for the remainder of the delivery.

TITLE: Final Report. Silicon Solar Cells With Total Power Capacity of 30 Kilowatts.

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 954577

DATE: October 1977

REPORT NO: DOE/JPL-954577-77/1

ABSTRACT: There are two phases of the contract effort to design, develop, manufacture, test and deliver a quantity of solar cell modules capable of providing 30 kilowatts of power. The first phase consists of module design, pre-production module fabrication, inspection and test. Phase two consists of production, test and delivery.

TITLE: Final Technical Report. 40 kw of Solar Cell Modules for the Large Scale Production Task.

AUTHOR : Jones, G. T.

CORPORATE AUTH: Sensor Technology, Inc., Chatswarth, Calif. (USA)

CONTRACT NO: 954565

DATE: December 1977

REPORT NO: DOE/JPL/954565-77/1

ABSTRACT: Forty kilowatts of solar cell modules was produced in this program. This is equivalent to 4123 modules. The average power output per module was 9.7 watts at 16.5 volts, 60°C and 100 MW/CM^2. The peak production rate was 200 modules per week which is equal to 1.9 kw per week. This rate was sustained for over four and one-half months and is equivalent to 100 kw per year. The solar cell module design, electrical and power performance, module preproduction environmental test results, production and shipping schedule, program summary, and delivery. A cost analysis section is written. Particular emphasis on the percentage of labor and material utilized in constructing a solar cell module is presented. Also included are cost reduction recommendations. It was concluded from this program that volume production on the order of hundreds of kilowatts per year per company as a minimum is required to significantly reduce the price per watt for solar cell modules. Sensor Technology more than doubled its solar cell module manufacturing facilities since the completion of the JPL Block II procurement. Plans are being made for large scale expansion of our facilitites to meet growing JPL/DOE procurements.

TITLE: Final Technical Report. Large Scale Production Task

CORPORATE AUTHOR: Spectrolab, Inc., Sylmar, CA (USA)

CONTRACT NO: 954587

DATE: September 1978

REPORT NO: DOE/JPL/954587-1

ABSTRACT: Several design concepts were evaluated and compared with respect to potential for low cost and automation, protection against weathering, potential for array efficiency as a function of weight and area, potential for design flexibility and exposure to electrical breakdown or leakage to ground. This evaluation program narrowed attention to design concepts involving glass as the primary structural and weather resistant component of the module. The leading specific design structure consisted of the solar cell circuit embedded in polyvinyl butyrate by lamination between a glass front surface and a polyester film rear surface. Preliminary evaluation of this structure in high humidity and thermal cycle was promising, and extensive field experience with similar structures in architectural and automotive applications was favorable. The specific design proposed was comprised of 120 two-inch diameter cells in a series-parallel configuration. The laminate was mounted in an aluminum frame with a neoprene gasket providing the requisite mechanical strength with flexibility. The resulting module size of 15 by 46 inches permits three modules to be neatly fitted into the 46 inch square subarray specified by JPL. The design as modified to accommodate subsequent experience is shown. Performance and environmental test results are presented and discussed.

TITLE: Final Report. Design, Fabrication, Test, Qualification and Price Analysis of "Third-Generation" Design Solar Cell Modules.

AUTHOR: Shepard, N. F.

CORPORATE AUTH: General Electric Company

CONTRACT NO: 955401

DATE: March 1980

REPORT NO: DOE/JPL-955401-80/1

ABSTRACT: This design, development, fabrication and qualification testing of a "third-generation" solar cell module for residential applications is reported. This Block IV shingle-type module makes it possible to apply a photovoltaic array to the sloping roof of a residential building by simply nailing the overlapping hexagon-shaped shingles to the plywood roof sheathing. This "third-generation" shingle module design consists of nineteen series-connected 100 mm diameter solar cells which are arranged in a closely packed hexagon configuration. The solar cells are individually bonded to the embossed underside of a 4.4 mm thick thermally-tempered piece of ASG Sunadex glass. An experimental GE silicone pottant, which is identified by the number 534-044, was used as the transparent bonding adhesive between the cells and glass. The encapsulant between the underside of the glass superstrate and a rear protective sheet of Mead Pan-L board is GE Silglaze SCS 2402. The semi-flexible portion of each shingle module is a composite laminate construction consisting of an outer layer of B. F. Goodrich FLEXSEAL bonded to an inner core of closed cell polyethylene foam. Uniroyal Silaprene M6338 is used as the substrate lamination adhesive. The module design has satisfactorily survived the JPL-defined qualification testing program which includes 50 thermal cycles between -40 and +90°C, a seven day temperature-humidity exposure test and a wind resistance test per UL997.

TITLE:	Final Report. Third Generation Design Solar Cell Module LSA Task V, Large Scale Production.
AUTHOR:	Ling, K. S.
CORPORATE AUTH:	Applied Solar Energy Corporation
CONTRACT NO:	955409
DATE:	August 1980
REPORT NO:	DOE/JPL-955409-80/1
ABSTRACT:	During this contract solar cell modules were designed and built in accordance with the JPL Document No. 5101-16 Revision A, entitled "Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications." A total of twelve (12) preproduction modules were constructed, tested and delivered. A new concept to the frame assembly was designed and proven to be quite reliable. This frame design, as well as the rest of the assembly, was designed with future high volume production and the use of automated equipment in mind.

TITLE:	Final Report. Analysis of the Effects of Impurities in Silicon.
CORPORATE AUTH:	Solar Power Corporation
CONTRACT NO:	955403
DATE:	September 1980
REPORT NO:	DOE/JPL-955403-80/1
ABSTRACT:	This final design report for the Low Cost Solar Array Block IV Program has been prepared in response to the Contract Data Requirements List (CDRL) Item #6 DRD NO. SE-2. The report includes an updated program plan showing the task descriptions depicting the work, progress, achievements and the cause of any deviations from the original plan (SC-1), and how this impacted on the original schedule of the program. In addition there is an update documenting all design alterations made during the pre-production phase and a complete up to date set of Engineering and Manufacturing Documentation (CM-1). The purpose of this report is to document the work performed through the final design and the test results of the modules developed under this contract, and to use this documentation to further the understanding and evolution of solar cell module design.

TITLE:	Final Report. Design, Fabrication, Test, Qualification and Price Analysis of Third Generation Design Solar Cell Modules.
CORPORATE AUTH:	Spire Corporation
CONTRACT NO:	955405
DATE:	October 1980
REPORT NO:	DOE/JPL-955405-80/1

ABSTRACT: This report describes a one year program to design, develop and produce a high-efficiency Block IV Solar Module according to JPL requirements defined in document 5101-16 Revision A, "Block IV Solar Cell Module Design and Test Specifications for Intermediate Load Center Applications". The module design is described along with the rationale for each major component choice. Experiments performed during the development phase of the program are described. The Quality Assurance Plan is outlined. Both cell and module fabrication are described. Performance and yield data on modules are given. Testing, both to determine module characteristics and to establish JPL qualifications are discussed. Finally, the results of the SAMIS cost analysis are presented. The results of this program are that a JPL qualified module with a power density of 125 W/m^2 at 28°C has been developed and manufactured.

TITLE:	Final Report. Design, Fabrication, Test, Qualification And Price Analysis of "Third Generation" Design Solar Cell Modules.
AUTHOR:	E. Pastirik
CORPORATE AUTH:	Motorola Inc. Semiconductor Group.
CONTRACT NO:	955406
DATE:	January 1981
REPORT NO:	DOE/JPL-955406-81/1

ABSTRACT: Motorola entered into a contract with JPL on May 16, 1979, to design, fabricate, test, qualify, and deliver pre-production Block IV modules satisfying the requirements of JPL Document 5101-16, Revision A. The following report reviews the schedule of this effort as well as the basic module design and test results. Modifications to the design which occurred as a result of problems are also considered. Module qualification was achieved in December, 1980, and all documentation submissions were completed in January, 1981.

TITLE: Final Report. Design, Fabrication, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules. Part 1: Intermediate Load Module.

CORPORATE AUTH: ARCO Solar, Inc.

CONTRACT NO: 955402

DATE: September 1981

REPORT NO: DOE/JPL-955402-81/1

ABSTRACT: This final design report presents an updated program plan for the design, fabrication, test and qualification of the "third generation" design intermediate load solar cell module. This updated program plan and narrative reflects the design and development work done and progress made in establishing a viable design for these modules. Design alterations from the preproduction plan are discussed on experience gained during the preproduction phase of the program.

TITLE: Final Report. Design, Fabrication, Test, Qualification, and Price Analysis of "Third Generation" Design Solar Cell Modules.

CORPORATE AUTH: Solarex Corporation

CONTRACT NO: 955404

DATE: October 1981

REPORT NO: DOE/JPL-955404-81/1

ABSTRACT: Description of Program: The Solarex Block IV contract calls for the design, manufacture, and delivery of eighteen residential load modules and eighteen intermediate load modules. Common features of both modules include:

- 72 9.5 cm X 9.5 cm Semicrystalline Cells
- Cells - Ti-Pd-Ag front Metallization with n/p p+ junction
- Geometrically arranged in 6 X 12 matrix
- 3/16" Sunadex tempered glass superstrate
- Ethylene vinyl acetate as encapsulant with craneglas spacer
- White Tedlar moisture barrier
- Redundant Cell-Interconnect Design which has six pads per cell
- Wraparound Interconnect
- Circuit Board style interconnect with in-plane stress relief feature.
- Two pigtail connections per positive or negative outlet.

Features which are different are shown in Table I.

TITLE:	Final Report. Design, Fabrication and Testing of Block IV Design Solar Cell Modules Part II: Residential Module.
CORPORATE AUTH:	ARCO Solar, Inc.
CONTRACT NO:	955402
DATE:	April 1982
REPORT NO:	DOE/JPL-955402-82/2
ABSTRACT:	This final design report concludes work performed on the design, fabrication and test of the Block IV Residential Load Module by ARCO Solar, Inc. This report outlines design changes from the proposed module design through three iterations to the discontinuance of testing agreed upon by both JPL and ARCO Solar, Inc.

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