"This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy.

"The JPL Low-cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays."
ENERGY RESEARCH AND DEVELOPMENT AGENCY
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA

PROCEEDINGS
OF THE
SECOND PROJECT INTEGRATION
MEETING
APRIL 1976

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
INTRODUCTION

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.
SUMMARY

The Second Project Integration Meeting (PIM) permitted the exchange of information formally and informally between contractors and government representatives. The following six pages summarizes the results of the meeting and the concerns expressed.

A. General

1) Many of the contractors have been under contract long enough (approximately one-half year) so that their progress and specific technical activities could be discussed. It is intended that the scope of these technical discussions will increase in future meetings.

2) The meeting participants feel that a better understanding of the long range non-technical factors, such as institutional problems is required; and some think that these factors could become the dominant influence in the Project's future.

3) There is an uncertainty about the future resulting partially from a lack of understanding, that has been expressed as follows:
   a) The Program/Project participants are aware of many diverse and conflicting interests involved in the stimulation of an evolving industry and are seeking the best methods of attaining the Program objectives.
   b) The contractors feel uncertainties in working for the government in this field and are interested in how they can insure their participation in future Program/Project activities.

4) There is a need and a mutual desire for continuing discussions between Program/Project and Industry/University representatives so that the intentions and probable levels of participation in future
photovoltaic activities can be better understood. The areas of interest cover:

a) Technical progress and feasibility of the on-going activities.

b) Potential solar array cost reduction factors, timing, and resulting economic implications to photovoltaic systems.

c) Nature and size of the future photovoltaic power system market.

d) Extent and timing of future activities and funding in support of photovoltaics (both governmental and private).

e) Non-technical factors such as institutional attitudes, policies, laws, etc.

5) In general, participants thought that the meeting was well organized and run, although there were a number of suggestions on how to improve future integration meetings.

6) The planning and implementation of good Project Integration Meetings require continuing efforts because of the diversity of types of organizations, their methods of functioning, and their technical interests and capabilities. Consequently, the Project attempts to be receptive to the ideas of the participants, so that it can serve the interests of the majority as well as its sponsor, ERDA.

B. Technical

1) Interface requirements within the Project with due dates should be distributed to Project participants.

2) The Project requires a universal cost analysis methodology which provides for standardized cost values and financial parameters for use throughout the Project and preferably throughout the ERDA Photovoltaic Program.
3) The minimum efficiency solar cells that could be used for economically viable photovoltaic power systems should be determined. These minimum efficiency cells might vary for specific types of applications.

4) The suggestion was made that the Project should go metric.

5) Contractors desire to know more about JPL LSSA in-house, technical activities.

6) Experimental data from Battelle Memorial Institute (BMI) indicates that the production of semiconductor grade silicon from a Zn/SiCl₄ process is technically feasible. A BMI cost estimate for the production of silicon by the Zn/SiCl₄ process is $9.12/Kgm.

7) Preliminary evidence has been obtained showing that specific impurities in silicon enhance, degrade, or essentially destroy solar cell performance.

8) The effects of crystal growth rates on the concentration of impurities as well as the interplay of processing and impurity effects needs to be investigated.

9) The diagnosis of solar cell performance is an important tool for characterizing the silicon sheet material.

10) Structural analysis of the silicon sheet material is important because most crystal growth problems are structure related.

11) Sheet growth contractors are concerned about batch processes versus continuous processes. It is surmised that there is a distinct learning curve for each process.

12) What bounding conditions and/or characteristics are imposed upon module design by the encapsulant?

13) Discussions were held about difficulties, problems, available approaches, and the role of statistics in accelerated/abbreviated testing of encapsulants.
14) The automated assembly task will perform manufacturing process studies on a parametric basis until specific parameters are determined or tentatively determined. In order to focus their effort the task desires to receive timely estimates of bounding values from the other tasks, especially task 2.

15) The module manufacturers stated that the voltage requirements that have been specified for modules to be procured, are not consistent with commercial practice. Their comments and suggestions about voltage specifications will be solicited by a letter from the Project.

16) How is module performance data that is gathered by JPL/LeRC to be fed back to the module manufacturer?

17) Reports regarding 46 KW module failure modes and analysis were requested by Task 4 and 5 contractors.

18) Details about module requirements, specifications, and standards will be discussed during the next integration meeting; these could not be discussed during the 2nd PIM because the 130 KW proposals were being evaluated at the time.

C. Non-Technical

1) Contractors are concerned about the lack of definition of the photovoltaic market, both short and long term, and the government's role.

2) How are technology development contractor activities going to be continued after the existing contracts are completed? The government's concern is how to maximize the achievement of Program goals per dollar invested. The contractors desire information that will permit them to plan their future photovoltaic activities.

3) What will be the government's position in regard to capitalization funds when expensive pilot plants are required?
4) For example, a rough estimate of $25 to 30M capitalization might be required for crystal growth machines. If the 1985 goal is to be met a decision would be required during the early 1980's.

5) The module manufacturers desire additional information about how the automated assembly activities will eventually interact with their manufacturing activities.

6) The module manufacturers desire that the deliveries for future procurements be spread out over a longer time interval. Prices could be reduced if their production rates were constant.

7) Methods of how module manufacturers can introduce new ideas into the Project were discussed.

8) There is a need to improve the planning, scheduling, coordination of reports covering the Program/Project.

9) There is a need to circulate reports from other ERDA sponsored photovoltaic activities, such as from Sandia and LeRC.

D. Future Project Integration Meetings

1) Suggestion was made that the Project/Program presentations should include only the changes that have occurred since the previous meeting.

2) There should be more intertask discussion between contractors.

3) There should be more small sessions to discuss specific items in a less formal manner.

4) Task managers should solicit their contractors to be ready to discuss specific issues at the next PIM.

5) It was suggested that a contractor(s) can lead the discussion of specific subject matter in the intra and/or intertask sessions.

6) The silicon material contractors desire to have more technical progress presentations given in the intratask sessions such as given by Battelle and Union Carbide during the 2nd PIM.
7) Short workshop type sessions could be beneficial if incorporated into the PIM's such as a Lifetime Measurement Workshop for silicon material participants.

8) Concern was expressed about the cost/benefits of quarterly PIM versus less frequent PIM's.

9) The handout available at the start of the PIM was good.
ERDA PROGRAM SUMMARY

Dr. Leonard M. Magid, ERDA Program Manager for the LSSA Project, gave a brief summary of the current state and configuration of the ERDA Photovoltaic Program, condensed from his paper, "The U.S. Photovoltaic Conversion Program," presented at the International Colloquium on Solar Electricity in France in March 1976. This paper is reprinted in full as Appendix A of these proceedings.
CONCLUSIONS/RECOMMENDATIONS

From the 2nd Project Integration Meeting some definite conclusions and recommendations can be drawn.

A) Future Intra Task meetings should concentrate on discussions between Contractors, focusing on a one-to-one relationship between specific disciplines, e.g., physicist to physicist, chemist to chemist, etc. The agenda and format of these discussions should be mutually understood by all contractors in advance of the Intra-Task Meeting so that each can be prepared to address the problems and concerns of the other.

B) Future Inter-Task Meetings should be limited to interface between not more than two Tasks at one time, with a prearranged agenda, well understood in advance by contractors of both Tasks. One approach to a constructive meeting might be to extract a list of four or five key issues from each contractor that he would like to discuss. These issues would be collected from the contractors and compiled by the respective Task Manager, then submitted to the appropriate interface Task Manager. Each Task Manager would, in turn, forward these issues to his contractors for review and preparation of the oral discussion on each issue. Under this approach, issues raised by other tasks would be addressed by all three Contractors of Task 4, offering a range of insight to whatever these issues might be.

C) It is exceedingly more obvious that a standardized cost accounting system for reporting purposes be developed. Each Contractor is concerned that when results are published, it might be easy for the reader to draw an incorrect conclusion when comparing, on a one-to-one basis, different contractor reports.

D) Task 4 is concerned that results from Task 5 may not be reported in a timely fashion. Failure modes and corrective actions are of vital interest.
E) The Design and Test Requirements which result from activities at JPL/NASA/Sandia are of major interest to Task 4. This interest is not only critical from the panel/module physical and electrical needs, but also the environmental consideration.

F) In the absence of specific design and test requirements and lacking input data, particularly from Tasks 2 and 3, Task 4 will proceed on a parametric analysis basis and omit conclusions where it is clearly not possible to make conclusions until more data is available.

G) Task 4 is concerned that processes, used by contractors of Tasks 1 and 2, which yield solar cells of only 8.5% to 9.5% efficiencies, may lack the sensitivity to identify changes in cell performance due to silicon purity and mask the effects of impurities.

H) Project Integration Meetings should be held quarterly. If, however, a longer period between meetings is decided upon, they should be of longer duration if a format similar to A and B above is adopted.

I) The progress of Task 4 would be greatly enhanced if qualitative data could be supplied by Tasks 2 and 3, relative to what each has set as goals for their respective contractors. Some means of bounding each potential process of Task 2 would assist in narrowing down the almost endless matrix of variables which one might envision without bounds.

J) All Contractor quarterly reports must be issued and in the possession of the receiving agencies at least 2 weeks before these Project Integration Meetings take place.

K) The Project Integration Meetings should be less formal, even entering into after dinner discussion periods.

L) The Intra-Task Meetings should be a closed working meeting. People who are not directly concerned frequently disrupt the discussion to either gain information not relevant to the subject, or to vent a personal problem.
M) Omit the oral Task Manager summary reports and make them part of the printed hand-out. It was recommended that as part of the Task Managers Summary Report a Milestone Chart for each contract underway would be helpful to the contractors of Task 4 to relate their activities with those of the other Tasks.

N) Two minor critiques —

The badges were difficult to read — Contractor names and affiliation should be more bold.

Some viewgraphs were difficult to read; suggest they be of larger print and blacker.
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AGENDA
LOW-COST SILICON SOLAR ARRAY PROJECT
SECOND
PROJECT INTEGRATION MEETING

April 27-28, 1976

Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Presenter(s)</th>
<th>Minutes</th>
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<tr>
<td>8:15</td>
<td>Registration (Ramo Auditorium Lobby)</td>
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<tr>
<td>9:00</td>
<td>Welcome (Baxter Hall)</td>
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<tr>
<td>9:05</td>
<td>ERDA Program</td>
<td>Magid</td>
<td>15</td>
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<tr>
<td>9:20</td>
<td>LSSA Project</td>
<td>Forney</td>
<td>15</td>
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<td>9:35</td>
<td>Scope and Objectives of Meeting</td>
<td>Goldsmith</td>
<td>15</td>
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<td>9:50</td>
<td>Task 1 Status</td>
<td>Lutwack</td>
<td>20*</td>
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<tr>
<td>10:10</td>
<td>Task 2 Status</td>
<td>Zoutendyk</td>
<td>20*</td>
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<tr>
<td>10:45</td>
<td>Task 3 Status</td>
<td>Carroll</td>
<td>10*</td>
</tr>
<tr>
<td>10:55</td>
<td>Task 4 Status</td>
<td>Hasbach</td>
<td>10*</td>
</tr>
<tr>
<td>11:05</td>
<td>Task 5 Status</td>
<td>Sequeira</td>
<td>15*</td>
</tr>
<tr>
<td>11:20</td>
<td>Design and Test Status</td>
<td>Ross</td>
<td>15*</td>
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<tr>
<td>11:35</td>
<td>JPL Economics and Integration</td>
<td>Macomber</td>
<td>25*</td>
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<tr>
<td>12:00</td>
<td>-- Lunch --</td>
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<tr>
<td>1:15</td>
<td>Intra-Task Meetings:</td>
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<tr>
<td></td>
<td>Task 1 --- Room 242, Keck</td>
<td></td>
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<tr>
<td></td>
<td>Task 2 --- Room 168, Church</td>
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<td></td>
<td>Task 3 --- Room 254, Bridge</td>
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<td></td>
<td>Task 4 --- Room 351, Bridge</td>
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<tr>
<td></td>
<td>Task 5 --- Room 19, Baxter</td>
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</table>

NOTE: Coffee will be available from 2:15 - 3:15 at Ramo Auditorium Lobby

5:00   End of Day

* Allow one-third of time for discussion.

xxi
April 28

8:00 -- Coffee -- (Ramo Auditorium Lobby)

8:30 Inter-Task Meetings:
   Tasks 1 & 2 -- Room 142, Keck  Zoutendyk
   Tasks 3, 4 & 5 -- Baxter Hall  Hasbach

10:00 -- Coffee -- (Ramo Auditorium Lobby)

10:15 Inter-Task Meetings:
   Tasks 1, 2 & 4 -- Baxter Hall  Lutwack
   Tasks 3 & 5, and Design & Test -- Room 142, Keck  Carroll

11:45 Intra-Task Meetings to Discuss Results of the Above Sessions
   Task 1 --- Room 130, Keck
   Task 2 --- Room 168, Church
   Task 3 --- Room 254, Bridge
   Task 4 --- Room 351, Bridge
   Task 5 --- Room 19, Baxter

12:30 -- Lunch --

Task Managers prepare Task Summary Notes for their afternoon presentations -- Room 19, Baxter

For Contractors, free time for informal discussion with other attendees

2:00 Reconvene Entire Group (Baxter Hall)

2:00 Sandia -- Photovoltaic Power Systems  Marshall  30*
2:30 NASA/LeRC -- Test and Demonstration  Easter  30*

3:00 -- Coffee -- (Baxter Hall Lobby)

3:15 Task 1 Summary  Lutwack  15*
3:30 Task 2 Summary  Zoutendyk  15*
3:45 Task 3 Summary  Carroll  15*
4:00 Task 4 Summary  Hasbach  15*
4:15 Task 5 Summary  Sequeira  15*
4:30 Open Discussion  15
4:45 ERDA Comments  Magid  10
4:55 Summary  Forney  10
5:05 End of Meeting

* Allow one-third of time for discussion.
LOW-COST SILICON SOLAR ARRAY PROJECT

SECOND PROJECT INTEGRATION MEETING

APRIL 27-28, 1976

R. G. FORNEY, PROJECT MANAGER
LOW-COST SILICON SOLAR ARRAY PROJECT
(LSSA)

PROJECT DESCRIPTION

The Photovoltaic Conversion Program of ERDA and JPL's Project, LSSA, a part of the ERDA Program, have been established with the goal of driving the cost of solar arrays down by improving the technology and by increasing the production volume. The Federal Government will buy annually increasing quantities of solar arrays from industry for tests and demonstrations, which will stimulate the purchase of solar arrays by non-Government organizations and in turn further reduce costs. How fast can costs be reduced, and how quickly will their use expand? The answers to these questions will provide the guidelines for conducting the ERDA and JPL efforts. Primary long-range considerations of the Program will be the provision of economic benefits to the public, with a minimization in the impact on natural resources and the environment. The ten-year ERDA Program objectives are:

1. To develop low-cost photovoltaic systems
2. To stimulate industry to produce and distribute systems for widespread residential and commercial use

The ten-year JPL Project objectives are:

1. To sponsor silicon solar array manufacturing technology development
2. To foster industrial solar array production

Project goals for 1985 are:

1. To change today's solar array prices of $20,000 to $25,000 per kilowatt in annual quantities of 100 kW to less than $500 per kilowatt in annual quantities of 500,000 kilowatts.

The LSSA Project, managed by JPL as part of the ERDA Program, will be accomplished principally by industries and universities. The development of the technology necessary to produce large volumes of low-cost arrays requires four tasks:

1. Production of silicon suitable for low-cost mass production of solar arrays
2. Economical production of silicon in large-area sheets suitable for use in solar cells
3. Development of economical encapsulation materials, and techniques for array lifetimes greater than twenty years

Periodic purchase of increasing quantities of solar arrays for system tests and demonstrations will also be made. These tests will be sponsored by ERDA and performed under diverse conditions by various organizations.
Twenty-seven technology development contracts have been awarded. Six more are being negotiated. Five companies were awarded contracts to produce 46KW of solar arrays. Proposals are being evaluated now for the procurement of an additional 130KW of solar arrays. The technology development contracted activities are proceeding as planned. The initial experimental results will be discussed during this Project Integration Meeting. Modules from the 46KW procurement are being delivered.
LOW-COST SILICON SOLAR ARRAY PROJECT

OBJECTIVES

- REDUCE COSTS OF PHOTOVOLTAIC SOLAR ARRAYS
- DEVELOP SOLAR PHOTOVOLTAIC TECHNOLOGIES FOR COMMERCIAL PRACTICE
- FOSTER EXPANSION OF INDUSTRY FOR PHOTOVOLTAIC PRODUCTION
- SUPPORT MARKET GROWTH
- 1985-86

- PRICE < $500 /KW
- PRODUCTION > 500 MW /YR
- LIFETIME > 20 YRS
- CONVERSION EFFICIENCY > 10%

RGF
4/27/76
LOW-COST SILICON SOLAR ARRAY PROJECT

PROJECT APPROACH

PROJECT ANALYSIS & INTEGRATION

SILICON MATERIAL TASK

SILICON SHEET TASK

ENCAPSIATION TASK

AUTOMATED ASSEMBLY TASK

LARGE SCALE PROD. TASK

ERDA PROGRAM INTERFACES

1985-86
LOW COST $500/KW
PRODUCTION CAPABILITY
- 500 MW/YR

* MULTIPLE CONTRACTOR ACTIVITY

40 130 150 270 510 kW kW kW kW kW

1 2 3 4 MW MW MW MW

RGF
4/27/76
LOW-COST SILICON SOLAR ARRAY PROJECT
STATUS

• 15 MONTHS INTO PROGRAM

• TECHNOLOGY DEVELOPMENT
  
  − CONTRACTS UNDERWAY ................. 32
  PENDING .................................. 6

• LARGE-SCALE PROCUReMENTS
  
  − 46KW BLOCK .................................. 5 CONTRACTS
    DELIVERY UNDERWAY
    TESTING CONTINUES
  
  − 130KW BLOCK
    EVALUATION IN FINAL REVIEW / APPROVAL
    SELECTION ----- EARLY MAY

RGF
4/27/76
LOW-COST SILICON SOLAR ARRAY PROJECT

LSSA PROJECT ANALYSIS AND INTEGRATION
PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION

H.L. Macomber
27 April 1976
The responsibility of the Project Analysis and Integration (PA&I) Task area is to support the planning, integration, and decision-making activities of the Project. This responsibility is being carried out by an approach that includes these elements:

- Providing assessment of Project goals and of progress toward their achievement,
- Evaluating the consequences, in terms of both performance and economics, of alternative Project plans,
- Establishing standards for economic comparisons,
- Developing the interface requirements between the array technology development and production Tasks,
- Supporting the establishment of interface requirements between the Project and other Program activities,
- Developing plans and procedures for integrating the Tasks within the Project and between the Project activities and other elements of the Program, and
- Developing the analytical capabilities required to support the activities delineated above.

The Project approach of conducting parallel efforts within each of the five major Task areas will provide for examination of alternative approaches in order to obtain the most cost-effective methods for achieving individual Task objectives. It is also necessary, however, to seek to optimize the achievement of the overall Project objectives. Thus, adequate consideration of trade-offs between the Tasks is necessary to obtain the most cost-effective integration of the Tasks. For example, the decision to establish a certain allocation of resources among the various Tasks in order to provide for a level of priority consistent with the desired goal is typical. Preparation for such a decision will require examination of the cost and performance potential of the various technologies being considered, the expected production-demand relationships, and the degree of commercial risk and investment policies for incorporating the various technologies under development. These considerations will depend upon close interaction with the efforts being carried out by each of the Task areas as well as with the other activities of the ERDA Program. Thus, procedures and relationships must be established for obtaining and coordinating the information being generated within the Task areas and the ERDA Program activities.

Specific planned and on-going PA&I activities in FY-76 include:

- Developing and documenting initial versions of the Project Implementation Plan containing interface requirements, integration procedures, and detailed Task plans.
• Publishing initial versions of Project environmental and test requirements,

• Developing, coordinating, and publishing baseline techniques for economic analysis,

• Performing first-phase economic and operational trade-off studies,

• Establishing communication paths for the essential feedback from industrial participants, and

• Participating in Project planning and integration activities.
### Table 1

**TECHNOLOGY DEVELOPMENT CONTRACTORS**

#### SILICON MATERIAL, TASK 1 (11)

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Location</th>
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<tbody>
<tr>
<td>Battelle, Columbus Labs, Columbus OH</td>
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<tr>
<td>Motorola, Inc., Phoenix, AZ</td>
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<tr>
<td>Union Carbide Corp., Sistersville, WV</td>
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<td>Monsanto, St. Louis, MO</td>
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<tr>
<td>Westinghouse, Pittsburgh, PA</td>
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<tr>
<td>*Dow Corning, Hemlock, MI</td>
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<tr>
<td>Stanford Research Inc., Menlo Park, CA</td>
<td></td>
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<tr>
<td>Texas Instruments Inc., Dallas, TX</td>
<td></td>
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<tr>
<td>*Aero-Chem, Inc., Princeton, NJ</td>
<td></td>
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<tr>
<td>Lamar University, Beaumont, TX</td>
<td></td>
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<tr>
<td>*Westinghouse, Pittsburgh, PA</td>
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#### LARGE-AREA SILICON SHEET, TASK 2 (11)

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<tr>
<td>Mobil-Tyco, Waltham, MA</td>
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<tr>
<td>Motorola, Phoenix, AZ</td>
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<tr>
<td>RCA, Princeton, NJ</td>
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<tr>
<td>University of South Carolina, Columbia, SC</td>
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<td>GE, Schenectady, NY</td>
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<tr>
<td>Honeywell, Bloomington, MN</td>
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<tr>
<td>Rockwell International, Anaheim, CA</td>
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<tr>
<td>Crystal Systems, Inc., Salem, ME</td>
<td></td>
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<tr>
<td>Varian, Lexington, MA</td>
<td></td>
</tr>
<tr>
<td>*University of Pennsylvania, Philadelphia, PA</td>
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</tbody>
</table>

#### Semiconductor Grade Processes
- Produce silicon from SiCl₄ or SiF₄
- Produce silicon from SiF₄
- Produce silicon from SiH₄

#### Solar Cell Grade Definition
- Solar cell performance vs impurities
- Solar cell performance vs impurities

#### Solar Cell Grade Processes
- Silicon from metgrade Si and other processes
- Silicon from SiF₄
- Silicon from metgrade Si or SiO₂
- Nonequilibrium plasma jet processes
- Commercial practicality of processes
- Reduction of SiCl₄ using arc heater

#### Ribbon Growth
- Edge-defined film fed growth
- Edge-defined film fed growth
- Laser zone ribbon growth
- Inverted Stepanov
- Web-dendrite

#### Sheet Growth
- Floating substrate (chemical vapor deposition on liquid)
- Dip-coating (on low-cost substrates)
- Chemical vapor deposition (on low-cost substrates)

#### Ingot Growth and Cutting
- Heat-exchanger ingot-casting and multiple wire sawing

#### Ingot Cutting
- Breadknife sawing
- Hot-forming of silicon
Table 1

TECHNOLOGY DEVELOPMENT CONTRACTORS

**ENCAPSULATION, TASK 3 (4)**

- Battelle, Columbus Labs, Columbus, OH
- Battelle, Columbus Labs, Columbus, OH
- Rockwell International, Anaheim, CA
- *Simulation Physics, Burlington, MA*
- *DeBell and Richardson, Enfield, CN*

Encapsulant experience and definition of environment
Encapsulant test methods and capabilities
Accelerated/abbreviated testing
Bonded integral glass covers
Polymeric properties and Aging studies

**AUTOMATED SOLAR ARRAY FABRICATION, TASK 4 (7)**

- Motorola, Inc., Phoenix, AZ
- RCA, Princeton, NJ
- Texas Instruments Inc., Dallas, TX
- Simulation Physics, Burlington, MA
- Mitre Corp., McLean, VA
- Texas Instruments Inc., Dallas, TX
- Solarex Corp., Rockville, MD

Manufacturing Processes Assessment
Manufacturing Processes Assessment
Manufacturing Processes Assessment
Electron beam solar cell fabrication
Array test evaluation
Czochralski growth and wafering improvements
Array test evaluation

* NOTE: Asterisk indicates contracts to be awarded in Spring of 1976.

Table 2

**46KW SOLAR ARRAY PROCUREMENT CONTRACTORS**

**LARGE-SCALE PRODUCTION, TASK 5**

- M7 International, Arlington Heights, IL
- Sensor Technology, Chatsworth, CA
- Solar Power Corp., Wakefield, MA
- Solarex Corp., Rockville, MD
- SpectroLab Inc., Sylmar, CA

Solar array procurement -- 3KW
Solar array procurement -- 8KW
Solar array procurement -- 15KW
Solar array procurement -- 10KW
Solar array procurement -- 10KW
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION

OVERVIEW

- PROBLEM
- SOME CONSIDERATIONS
- APPROACH
- STATUS
  - INDUSTRY ASSESSMENT AND FEEDBACK
  - ECONOMIC STANDARDS
  - SAMIS (SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION)
  - COST GOAL ALLOCATIONS
  - INTEGRATION ACTIVITIES

THE PROBLEM

- NEED TO PROVIDE RELIABLE ASSESSMENTS OF:
  - PROGRESS TOWARD ACHIEVING PROJECT GOALS
  - BALANCE BETWEEN GOVERNMENT AND INDUSTRY INVOLVEMENTS
  - REQUIRED STRATEGIES FOR INTEGRATING
    - TASKS WITHIN PROJECT
    - PROJECT WITHIN PROGRAM
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION
SOME CONSIDERATIONS – SHORT/LONG TERM

• COST-EFFECTIVE PROCESSES
  • INDIVIDUAL vs INTEGRATED/SYSTEM REQUIREMENTS
• PROJECT RESOURCE ALLOCATIONS
  • COST DRIVERS vs BIGGEST PAYOFF AREAS/LIMITS
• INDUSTRY PROBLEMS AND EFFECTS
  • MARKET: SIZE ($, QUANTITY), TYPE
  • INVESTMENT: RISK, AVAILABILITY OF CAPITAL
  • PRODUCTION: IMPROVEMENTS, TOOLING NEEDS/LIMITS
  • GOVERNMENT INVOLVEMENT IMPACTS
• LEGAL, REGULATORY, INSTITUTIONAL REQUIREMENTS AND EFFECTS
  • PATENT POLICIES
  • ANTI-TRUST
  • SMALL BUSINESS
• MARKET NEEDS AND EFFECTS
  • USER TYPE: UTILITY, NON-UTILITY PRIVATE, GOVERNMENT
  • APPLICATION: SMALL/LARGE, REMOTE, ON-SITE, CENTRAL

APPROACH

• SUPPORT INDUSTRY PROCESS DEVELOPMENT AND EVALUATIONS (TASKS)
• ESTABLISH INTEGRATION PROCEDURES AND ACTIVITIES
  • TASKS/PROJECT/PROGRAM
• DEVELOP ASSESSMENT FACTORS AND PROCEDURES
  • GENERAL STRUCTURE/SPECIFIC PROBLEMS
• DEVELOP (OR USE EXISTING) ANALYTICAL METHODS AND MODELS
• GATHER DATA - CURRENT, PREDICTIONS (INDUSTRY INVOLVEMENT)
• IDENTIFY AND DEVELOP STANDARDS FOR COMPARISON
  • ECONOMIC AND PERFORMANCE STANDARDS
• COMPARE AND EVALUATE TASK APPROACHES
• PERFORM SENSITIVITY ANALYSES
• TEST AND VERIFY WITH INDUSTRY
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION
INTEGRATION ACTIVITIES

• PROJECT/PROGRAM
  • INTERFACE MEETINGS
  • MODULE DESIGN REQUIREMENTS
  • SYSTEM DESIGN REVIEW AND EVALUATIONS
  • PROGRAM PLANNING WORKING GROUPS

• TASK/PROJECT
  • TASK INTERFACE DEVELOPMENT
  • DESIGN AND TEST ACTIVITIES
  • PROJECT PLANNING WORKING GROUPS
  • PROJECT INTEGRATION MEETINGS
    • 1st - INTRATASK INTEGRATION
    • 2nd - INTRA/INTERTASK INTEGRATION

• PROJECT IMPLEMENTATION PLAN
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION

ECONOMIC STANDARDS

- DEVELOPED UTILITY REQUIRED REVENUE METHOD FOR ERDA/EPRI EVALUATIONS
- EXAMINING NEED FOR STANDARD LSSA MANUFACTURING COST EVALUATION METHOD

STRUCTURE OF MODEL

-input data
- utility description data (UDDD)
  - miscellaneous cost rates \( b_1, b_2 \)
  - system lifetime (from SDD) \( N \)
  - effective income tax rate \( \tau \)
  - capital structure \( \frac{D}{C} = \frac{P}{V} = \frac{V_c}{V} = \frac{V_r}{V} \)
  - rates of return \( k_D, k_E, k_P \)
  - general economic conditions
    - escalation rates \( g \)

-system description data
  - start of commercial operation \( Y_{co} \)
  - cash flows
    - capital investment \( C_I \)
    - operating costs \( O_P \)
    - maintenance costs \( MNT \)
    - fuel costs \( F_L \)
    - system lifetime \( N \)

-system energy output \( MWh_A \)

-computations
  - compute present values of cash flows
    - present value of capital investment Eq. (8.38)
    - present values of recurrent costs Eq. (8.39)
  - compute capital recovery factor Eq. (8.36)
  - compute annualized fixed charge rate Eq. (8.21)

-output
  - compute annualized system - resultant cost Eq. (8.20)
  - compute levelized busbar energy cost Eq. (8.22)
  - AC
  - BBEC

HLR
3/23/76
### Low Cost Silicon Solar Array Project
#### Project Cost Goal Allocation

All costs are in 1975 dollars.

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<td>50</td>
<td>40</td>
<td>15</td>
<td>10</td>
<td>7</td>
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<td>Processing Value Added $/W</td>
<td>4.8</td>
<td>2.1</td>
<td>1.6</td>
<td>1.9</td>
<td>0.52</td>
<td>0.14</td>
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<td>Wafer Material $/W</td>
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<td>3.2</td>
<td>2.2</td>
<td>2.0</td>
<td>0.57</td>
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<td>Wafers $/W</td>
<td>10.4</td>
<td>3.8</td>
<td>2.7</td>
<td>2.0</td>
<td>0.57</td>
<td>0.17</td>
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<tr>
<td>Add'l Materials $/W (Contacts, Etc.)</td>
<td>0.8</td>
<td>0.4</td>
<td>0.35</td>
<td>0.20</td>
<td>0.08</td>
<td>0.07</td>
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<td>0.85</td>
<td>0.25</td>
<td>0.09</td>
<td>0.06</td>
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<td>Cells $/W</td>
<td>15.5</td>
<td>5.4</td>
<td>3.9</td>
<td>7.45</td>
<td>0.77</td>
<td>0.30</td>
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<td>Add'l Materials $/W (Encapsulation, Framing, Etc.)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.10</td>
<td>0.06</td>
<td>0.08</td>
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<tr>
<td>Processing Value Added $/W</td>
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<td>1.1</td>
<td>0.8</td>
<td>0.45</td>
<td>0.18</td>
<td>0.12</td>
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<td>Array Price $/W</td>
<td>20</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0.50</td>
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Silicon Used in Final Project: 72% 30% 38% 78% 87% 91%
Total Processing Value Added: 84% 71% 55% 87% 73% 64%
Watts/Wg of Si: 374 47 62 162 187 202
Cell Efficiency (AM1): 11% 11.5% 12% 12.5% 13% 13.5%
Cell Thickness Mil: 15 12 12 10 10 10

HLM
3/23/76
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION

SAMIS IS A PLANNING TOOL FOR THE LSSA PROJECT

• PROGRESS TOWARD PROJECT GOALS
• INTER-TASK COST-EFFECTIVENESS
• IMPACT OF GOV'TAL POLICIES
• EFFECTS OF IMPROVED PROCESSES
• EFFECT OF SIZE OF MARKET
• ADDRESS INVESTMENT CONCERNS

TECHNOLOGY DEVELOPMENT ACTIVITIES

LSSA PROCUREMENTS

CURRENT MANUFACTURERS

MISSION/SYSTEM STUDIES

MANUFACTURING PROCESSES

COST DATA

FINANCIAL PARAMETERS

DEMAND RANGES

SENSITIVITY STUDIES

SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION COMPUTER PROGRAM

PRICE ESTIMATES

ENERGY USED

QUANTITY ESTIMATES

LSSA PROJECT OFFICE

HLM-6
4/28/76
LOW-COST SILICON SOLAR ARRAY PROJECT
LSSA PROJECT ASSESSMENT, ECONOMICS, AND COMMERCIALIZATION
TYPICAL SAMIS COST BREAKDOWN OF ARRAY PRICE

THIS CASE:
CZOCHRALSKI SILICON
10% CELL EFFICIENCY
8% INVESTMENT TAX CREDIT
1975 TECHNOLOGY
$7.84 PER WATT

HLM-7
4/28/76
LOW-COST SILICON SOLAR ARRAY PROJECT

TERRESTRIAL SOLAR ARRAY
PRICE GOALS

- ARRAY FABRICATION
- CELL MANUFACTURE
- SLICING
- INGOT/SHEET GROWTH
- SILICON MATERIAL

DOLLARS PER WATT

CALENDAR YEAR

CZORHALSKI INGOT TECHNOLOGY
SHEET TECHNOLOGY WITH AUTOMATION
LOW-COST SILICON SOLAR ARRAY PROJECT

TERRESTRIAL SOLAR ARRAY
PRICE HISTORY

KEY TO MANUFACTURERS' BIDS
- SOLAR POWER CORP.
- SENSOR TECHNOLOGY
- SPECTROLAB
- M7 INTERNATIONAL
- SOLAREX

LSSA PROJECT COST GOAL

CZOTRASLSKI INGOT TECHNOLOGY WITH AUTOMATION

AVERAGE $2.55/W

DOLLARS PER WATT

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 20 25 30


CALENDAR YEAR
LOW-COST SILICON SOLAR ARRAY PROJECT
THE PROJECT ANALYSIS AND INTEGRATION TASK IS
"EXAMINING THE NEED FOR STANDARD LSSA
MANUFACTURING COST EVALUATION METHODOLOGY"

IMPLICATIONS:

- UNIFORM ACCOUNTING STRUCTURE
- STANDARDIZED FRAMEWORK FOR ANALYSIS
  - e.g.: ERDA/EPRI METHODOLOGY FOR EVALUATION OF
    UTILITY-OWNED SOLAR ELECTRIC SYSTEMS
  - POSSIBLE STARTING POINT: SAMIS
    (SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION)

- NEED BASELINE VALUES OF FINANCIAL PARAMETERS
  - TO ALLOW COMPARISON OF TECHNOLOGIES RATHER
    THAN ECONOMIC ASSUMPTIONS
LOW-COST SILICON SOLAR ARRAY PROJECT
LSAA PROJECT ASSESSMENT, ECONOMICS AND COMMERCIALIZATION
THE SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION

• THE SUPPLY PRICE OF SOLAR PHOTOVOLTAIC POWER CAPABILITY DEPENDS ON
  • TECHNOLOGICAL PROCESSES
  • COSTS OF REQUIRED MATERIALS AND SERVICES
  • MANUFACTURING FINANCES (CAPITAL EXPENSES, OVERHEAD, PROFITS, ...)
  • GOVERNMENTAL INTERVENTION (TAXES, SUBSIDIES, LOANS, ...)
  • PRODUCTION QUANTITY
• SAMIS IS A MODEL OF THE RELATIONSHIPS AMONG THESE FACTORS.
• HENCE, IT CAN ASSESS THE POTENTIAL BENEFITS OF
  • PROCESS RESEARCH
  • MATERIALS RESEARCH
  • MANUFACTURING MANAGEMENT POLICIES
  • GOVERNMENTAL ACTIONS
• (THE SOLAR ARRAY MARKET COULD BE ANALYZED BY USING SAMIS IN
  CONJUNCTION WITH A DEMAND PRICE MODEL.)
SAMIS
(SOLAR ARRAY MANUFACTURING
INDUSTRY SIMULATION MODEL)
VERSIONS 1 & 2

ATTRIBUTES EQUATION CAN INFLUENCE
CAPITAL SUBSIDY
INTEREST RATE ON CORPORATE BONDS
CORPORATE INCOME TAX RATE
PROPERTY TAX RATE
MINIMUM DEPRECIATION LIFETIME
POLLUTION CONTROL REQUIREMENTS

FINANCIAL ATTRIBUTES OF THE FIRM
PROFIT (RETURN ON EQUITY)
OVERHEAD FRACTION (O & M)
CAPITAL (ADJUSTED FOR SCALE ECONOMIES)
DEBT TO EQUITY RATIO
REAL LIFETIME OF PLANT & EQUIPMENT

UNIT PRICE IS A FUNCTION OF QUANTITY
UNIT PRICE IS A FUNCTION OF QUANTITY
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UNIT PRICE IS A FUNCTION OF QUANTITY
UNIT PRICE IS A FUNCTION OF QUANTITY

TECHNOLOGY MODEL

P - FUNCTION OF COSTS, EXPENSES, TAXES, CAPITAL, PROFIT, QUANTITIES, POLLUTION CONTROL COSTS, LIFETIMES, INTEREST RATES, MANAGEMENT POLICIES
LOW-COST SILICON SOLAR ARRAY PROJECT
THE SAMIS FINANCIAL MODEL OF A MANUFACTURING PLANT

\[
p = \frac{5}{Q(1-x)} + \frac{(C+V)p(1-t)+f+(r-i)(1-t)p(1-b)(1+p)}{Q(1-x)(1-t)} + \frac{u}{1-x} \frac{tH}{Q(1-x)(1-t)}
\]
DESIGN AND TEST

DR. R. G. ROSS

April 27, 1976
LOW-COST SILICON SOLAR ARRAY PROJECT
DESIGN AND TEST
OBJECTIVES

- PROVIDE FOCAL POINT FOR SOLAR ARRAY DESIGN AND TEST REQUIREMENTS
  - PERFORMANCE REQ.
  - INTERFACE REQ.
  - DESIGN REQ.
  - ENVIRONMENTAL REQ.
- PROVIDE FOCAL POINT FOR MODULE/ARRAY INTERFACE ENGINEERING
  - MECHANICAL INTERFACES
  - TEMPERATURE CONTROL
  - STRUCTURAL DESIGN
  - ELECTRICAL TERMINATIONS
  - ELECTRICAL DESIGN
    - VOLTAGE LEVELS
    - SERIES/PARALLEL CONSIDERATIONS
  - RELIABILITY/REDUNDANCY

RR-2
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
DESIGN AND TEST
APPROACH

- Iterate toward balanced requirements and interface designs on the basis of:
  - Current user (demonstration) needs
  - Projected user (systems) needs
  - Module/array design factors & sensitivities
  - Current module/array state-of-the-art
  - Manufacturers experience/concerns
  - Users experience/concerns
  - Experience in related industries
LOW-COST SILICON SOLAR ARRAY PROJECT

DESIGN AND TEST INTERFACES

SANDIA
(System Req.)

LeRC/DoD
(Demo. Req.)

TEST RESULTS

AEROSPACE
(MISSION ANAL.)

MANUFACTURERS
(Experience Concerns)

DESIGN AND TEST
(Design Req. and Interface Engin.)

USERS
(Experience Concerns)

TASK 3
(Encapsulation)

TASK 5
(Large Production)

TASK 4
(Automated Array)

RR-4
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
DESIGN AND TEST
ENGINEERING STUDIES

- MODULE/ARRAY CONFIGURATION TRADES
  - ARRAY COST vs. MODULE SIZE/SHAPE
  - ELECTRICAL OUTPUT vs. MODULE AND CELL SIZE
- THERMAL ANALYSIS AND TESTING
  - THERMAL PERFORMANCE TESTING
  - THERMAL MODEL DEVELOPMENT
  - PARAMETER SENSITIVITY ANALYSIS
- STRUCTURAL ANALYSIS AND TESTING
  - AERODYNAMIC LOADING ANALYSIS
  - CYCLIC LOAD TESTING
  - MODULE/ARRAY STRUCTURAL ANALYSIS
- ELECTRICAL TERMINAL EVALUATION
  - IDENTIFICATION OF CONCEPTS
  - ENVIRONMENTAL TESTING AND EVALUATION
  - FIELD TESTING
- ELECTRICAL DESIGN STUDIES
  - SERIES/PARALLEL CONSIDERATIONS
  - LIGHTNING PROTECTION REQUIREMENTS
LOW-COST SILICON SOLAR ARRAY PROJECT
DESIGN AND TEST
1976 SCHEDULE

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RR-6
4-27-76
PHOTOVOLTAIC SYSTEMS DEFINITION PROJECT OF THE
ERDA NATIONAL SOLAR PHOTOVOLTAIC PROGRAM

Billy W. Marshall
Sandia Laboratory
Albuquerque, New Mexico

ABSTRACT

The ERDA Photovoltaic Branch has structured the
National Solar Photovoltaic Program into several inter­
related projects which address major segments of the overall
program. The responsibility to conduct the Systems Defini­
tion Project has been assigned to Sandia Laboratory. This
project is concerned with developing conceptual system de­
signs, evolving preferred system configurations, identifying
subsystem performance and technology requirements, and pro­
viding detailed system designs and specifications for a wide
range of photovoltaic applications having potential national
significance. Information developed through this project will
provide systems-related guidance to the other projects of the
program as well as input for future program planning. Spe­
cific objectives of the Systems Definition Project are to:

a) Aid the Test and Demonstration Project by pro­
viding systems definition support for the design
and implementation of demonstration projects.

b) Provide solar array design requirements and
performance specifications to the Low-Cost
Silicon Solar Array Project.

c) Conduct detailed system analysis and design
tradeoff studies of candidate photovoltaic
system applications to provide information on
system economics, net energy assessment and the
impact of design constraints imposed by legal,
environmental, and institutional factors.

d) Determine the specific performance requirements
for power conditioning and energy storage sub­
systems and identify the discrepancies between
these requirements and the existing technology.

e) Conduct experimental component and subsystem
breadboarding and testing as necessary to
establish the validity of analytical models
and confirm predicted performance.

An additional project responsibility is the development
and evaluation of photovoltaic arrays which incorporate sun­
light concentration as a means of significantly reducing
system cost. In this area, attention will be given to con­
centrator technology evaluation, high intensity solar cell
development, experimental performance evaluation of prototype
concentrator subsystems, application studies, and overall
system design tradeoffs.
ERDA PHOTOVOLTAIC SYSTEMS DEFINITION PROJECT

- PHOTOVOLTAIC SYSTEM CONCEPTS AND DESIGN DEFINITION
- SUBSYSTEM REQUIREMENTS AND TECHNOLOGY STATUS
- SYSTEM INTEGRATION EXPERIMENTS
- PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT
SANDIA LABORATORIES
SYSTEMS DEFINITION AND ANALYSIS TASK

• SYSTEMS DESIGN AND ANALYSIS
  INPUT DESIGN DATA
  CONCEPTUAL SYSTEMS DESIGN STUDIES
  SYSTEMS SPECIFICATIONS STUDIES

• SUBSYSTEMS REQUIREMENTS AND TECHNOLOGY EVALUATION
  POWER CONDITIONING
  STORAGE
  ARRAY CONFIGURATIONS

• SUBSYSTEMS INTERFACING AND INTEGRATION
  SYSTEM CONTROLS
  PROTOTYPE EXPERIMENTS
SYSTEMS DEFINITION PROJECT

CONCEPTUAL DESIGNS

- STAND-ALONE PV
- STORAGE -vs- BACKUP
- FLAT PLATE -vs- CONCENTRATOR
- DC -vs- AC -vs- SPECIALIZED
- PV ONLY -vs- HYBRID COLLECTORS

SYSTEMS DEFINITION PROJECT

POTENTIAL APPLICATIONS

- REMOTE
- ON-SITE RESIDENTIAL
- RESIDENTIAL COMMUNITY
- COMMERCIAL LOAD-CENTER
- INDUSTRIAL LOAD-CENTER
- CENTRAL STATION
PRESENT ACTIVITIES
SYSTEMS DESIGN AND ANALYSIS SUBTASK

- CONCEPTUAL DESIGN STUDIES
  GE, SPECTROLAB, WESTINGHOUSE

- SOLAR AND WEATHER DATA
  MAPPING OF SOLAR AVAILABILITY OVER U.S.
  HOURLY SOLAR AND WEATHER DATA FOR 1962-63 FOR EIGHT LOCATIONS
  AEROSPACE CONTRACT

- IN-HOUSE STUDIES;
  ELECTRIC/ THERMAL COMPARISON STUDIES
  SOLSYS UPDATE

PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT

OBJECTIVE -

- IMPLEMENT COST REDUCTION BY REPLACING SOLAR CELL
  AREA WITH LOWER COST REFLECTIVE OR REFRACTIVE MATERIALS

APPROACH -

- HIGH INTENSITY CELL TECHNOLOGY
- SUNLIGHT CONCENTRATORS
- SYSTEMS STUDIES

SLA 328
PHOTOVOLTAIC SYSTEMS DEFINITION PROJECT

SANDIA'S ROLE -

• PROVIDE OVERALL PROJECT MANAGEMENT IN CLOSE COORDINATION WITH THE ERDA PHOTOVOLTAICS BRANCH

• SUPPORT THE PROJECT WITH SELECTED IN-HOUSE TECHNICAL WORK

• COORDINATE PROJECT ACTIVITIES AND SCHEDULES WITH OTHER PROJECTS OF THE NATIONAL PHOTOVOLTAICS PROGRAM

PHOTOVOLTAIC SYSTEM DESIGN CONSTRAINTS

• ECONOMICS

• FUEL DISPLACEMENT

• CAPACITY DISPLACEMENT

• TECHNOLOGY REQUIREMENTS
  • SOLAR CELLS
  • ENERGY STORAGE
  • POWER CONDITIONING

• ENVIRONMENTAL

• LEGAL, SOCIETAL, REGULATORY
SANDIA LABORATORIES

1 kW<sub>E</sub> PHOTOVOLTAIC CONCENTRATOR SUBSYSTEM
- DESIGN SPECIFICATIONS -

ELECTRICAL

PEAK ELECTRICAL POWER 1000 W
NUMBER CELLS (SERIES CONNECTED) 135
CELL EFFICIENCY, \( \eta_c \)
   \( \text{AT 27°C} \) 0.140
   \( \text{At 100°C} \) 0.118
PEAK POWER PER CELL 7.4 W
CELL AREA 15.2 cm<sup>2</sup>

OPTICAL SYSTEM

SQUARE FRESNEL LENS CONCENTRATORS
30.5 cm FOCAL LENGTH (f 1.0) POINT FOCUSING
GEOMETRIC CONCENTRATION RATIO 60 X
ESTIMATED OPTICAL EFFICIENCY, \( \eta_0 \) 0.80
ACTUAL CONCENTRATION RATIO 48 X

MECHANICAL

DIMENSIONS 2.95 x 4.98 x 0.46 m
COLLECTOR AREA 14.7 m<sup>2</sup>
LENS PACKING EFFICIENCY, \( \eta_p \) 0.86

COOLING OPTIONS

PASSIVE (INCLUDING EXTENDED SURFACES)
FORCED AIR
WATER LOOP

ARRAY EFFICIENCY

ELECTRICAL, \( \eta_A = \eta_p \eta_0 \eta_c \)
   \( \text{AT 27°C} \) 0.096
   \( \text{AT 70°C} \) 0.090

THERMAL (COMBINED SYSTEM), \( \eta_T \)
   AVE T = 70°C, 1 GLAZING 0.40
   2 GLAZINGS 0.49

SLA 328
CONCEPT OF 1-kW<sub>E</sub> CONCENTRATOR SYSTEM USING FRESNEL LENS
SANDIA LABORATORIES
EFFICIENCY VS ILLUMINATION FOR SILICON CELLS AT MULTI-SUN EXPOSURE

SILICON CELL DESIGN FOR MULTI-SUN EXPOSURE

SLA 328
SANDIA LABORATORIES
FRESNEL CONCENTRATOR
WITH PHOTOVOLTAICS CELL
SOLAR ARRAY
37 STRINGS, 3 PARALLEL X 500 SERIES CELLS PER STRING

*LOCATED IN HOT WATER HEATER

Point Design Power System Functional Block Diagram

INVERTER COST VERSUS POWER

SLA 328
### SANDIA LABORATORIES

#### SCHEDULE FOR SYSTEM'S DEFINITION AND ANALYSIS TASK

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<th>FY 76</th>
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<th>FY 78</th>
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<td>5. ALTERNATIVE SYSTEM STUDIES</td>
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<td>6. SOLAR AND WEATHER DATA</td>
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<td>7. SOLSYS STUDIES</td>
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### SANDIA LABORATORIES

#### PLANNING SCHEDULE AND MILESTONES: CONCENTRATOR SUBSYSTEM DEVELOPMENT

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**NOTES:**

(1) PROTOTYPE CONCENTRATORS AVAILABLE  
(2) MODIFIED Si CELLS AVAILABLE  
(3) GALLIUM ARSENIDE CELLS AVAILABLE  
(4) INITIAL OPERATION  
(5) EVALUATION COMPLETE  
(6) ADDITIONAL PRODUCTION  

SLA 328
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<td>DON SCHUELER</td>
<td>PROJECT MANAGER</td>
<td>(FTS) 475-4041</td>
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<td>BILL MARSHALL</td>
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<td>JERRY FOSSUM</td>
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1 kWp PHOTOVOLTAIC

CONCEPT OF 1-kW<sub>e</sub> CONCENTRATOR SYSTEM

USING FRESNEL LENS

SLA 328
SANDIA LABORATORIES
PARABOLIC CONCENTRATION
WITH PHOTOVOLTAIC
CELLS ON TUBE

SLA 328
SANDIA LABORATORIES
FRESNEL CONCENTRATOR
WITH PHOTOVOLTAICS CELL

SLA 328
ERDA PHOTOVOLTAIC PROGRAM ELEMENTS (FY'76)

MISSION ANALYSIS PROJECT -- AEROSPACE CORPORATION

SYSTEMS DEFINITION PROJECT -- SANDIA LABS (ALBUQUERQUE, N. M.)

TEST AND DEMONSTRATION PROJECT -- NASA LEWIS RESEARCH CENTER

DOD APPLICATIONS PROJECT -- MERDC (FT. BELVOIR, VIRGINIA)

LOW COST SILICON SOLAR ARRAY PROJECT -- NASA JPL

CONCENTRATOR SYSTEMS PROJECT -- SANDIA LABS (ALBUQUERQUE, N. M.)

OTHER MATERIALS AND DEVICES -- ERDA PHOTOVOLTAIC BRANCH, (WASH, D.C.)

OVERALL MANAGEMENT -- ERDA PHOTOVOLTAIC BRANCH (WASHINGTON, D.C.)
PHOTOVOLTAIC TEST
AND DEMONSTRATION PROJECT
ELEMENTS (FY’76)

• APPLICATIONS SUBPROJECT
• DEVICE PERFORMANCE AND DIAGNOSTICS SUBPROJECT
• ENDURANCE TESTING SUBPROJECT
• PROJECT MANAGEMENT
TEST AND DEMONSTRATION PROJECT

DEVICE PERFORMANCE AND DIAGNOSTICS

SUBPROJECT ELEMENTS

• WORKSHOP AND PROCEDURES MANUAL TASK

OBJECTIVE: TO REFINE CURRENT STANDARD CONDITIONS AND PROCEDURES FOR MEASUREMENT OF SOLAR CELLS AND ARRAYS, AND TO PUBLISH AND DISTRIBUTE MANUALS DETAILING THESE CONDITIONS AND PROCEDURES

• STANDARD REFERENCE CONDITIONS AND METHODOLOGY TASK

OBJECTIVE: TO EVALUATE AND ESTABLISH REFERENCE CONDITION AND MEASUREMENT METHODS REPRESENTATIVE OF THOSE IN THE TERRESTRIAL ENVIRONMENT
TEST AND DEMONSTRATION PROJECT

DEVICE PERFORMANCE AND DIAGNOSTICS

SUBPROJECT ELEMENTS (CONT.)

• STANDARD CELL MEASUREMENT FACILITY TASK

  OBJECTIVE: TO ESTABLISH AND OPERATE A STANDARD
  CELL MEASUREMENT FACILITY WHOSE SERVICES
  ARE AVAILABLE TO ALL RESEARCHERS IN THE
  PHOTOVOLTAIC COMMUNITY

• CALIBRATED REFERENCE CELLS TASK

  OBJECTIVE: TO CALIBRATE AND DISTRIBUTE REFERENCE
  CELLS, IN APPROPRIATE HOLDERS, TO
  PHOTOVOLTAIC INVESTIGATORS
TEST AND DEMONSTRATION PROJECT

DEVICE PERFORMANCE AND DIAGNOSTICS

SUBPROJECT ELEMENTS (CONT.)

• MODULE MEASUREMENT FACILITY TASK

OBJECTIVE: TO ESTABLISH AND OPERATE A FACILITY FOR MEASURING THE PERFORMANCE OF SOLAR CELL MODULES

• DEVICE ELECTRICAL DIAGNOSTICS FACILITY TASK

OBJECTIVE: TO MAINTAIN A FACILITY FOR MAKING AND INTERPRETING A VARIETY OF ELECTRICAL MEASUREMENTS AIMED AT DIAGNOSING SPECIAL SOLAR CELL PROBLEMS

• INSOLATION MEASUREMENTS TASK

OBJECTIVE: TO ACQUIRE INSOLATION DATA, USING SOLAR CELLS AS DETECTORS, FOR SELECTED GEOGRAPHICAL LOCATIONS RELATED TO THE TEST SITES OF THE ERDA-DOD AND ERDA-NASA TEST AND DEMONSTRATION PROJECTS

NASA/LcRC/02/25/76
TEST AND DEMONSTRATION

PROJECT

ENDURANCE TESTING SUBPROJECT ELEMENTS

- REAL TIME EXPOSURE TESTING TASK

  OBJECTIVE: TO OBTAIN REAL TIME EXPOSURE DATA ON
  ARRAYS, MODULES AND COMPONENT MATERIALS
  IN A VARIETY OF GEOGRAPHIC AND CLIMATOLOGICAL CONDITIONS

- ACCELERATED ENVIRONMENTAL TESTS

  OBJECTIVE: TO OBTAIN ACCELERATED EXPOSURE DATA ON
  ARRAYS, MODULES AND COMPONENT MATERIALS
Figure 2 - PHOTOVOLTAIC TEST AND DEMONSTRATION PROJECT

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<tr>
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<th>T FY 77</th>
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1 CONVENE WORKSHOP
2 DISTRIBUTE INTERIM MANUAL
3 DISTRIBUTE UPDATED MANUAL
4 EVALUATE REFERENCE COND. & METHODS
5 FACILITY OPERATIONAL
6 FACILITY IMPROVEMENTS OPERATIONAL
7 DISTRIBUTE INTERIM REF. CELLS
8 DISTRIBUTE UPDATED REF. CELLS
9 INITIAL INSTRUMENTS AVAILABLE
10 FACILITIES AVAILABLE FOR NAT'L. EVAL.
11 ANNUAL REVIEW

NASA-LR, 12/20/75

59
APPLICATIONS

IDENTIFICATION

ALL PROJECTS
(MeRC-NEAR TERM)
MERADCOM - DoD

• BRAINSTORMING
• OTHER ENERGY SOURCES
• SOLICITATION

EVALUATION

ALL PROJECTS

• TECHNICAL FEASIBILITY
• ECONOMICS
• MARKET SITUATION

TEST AND DEMONSTRATION

LeRC
(MERADCOM - DoD)

• STRATEGY DEPENDS ON EVALUATION
• USER INVOLVEMENT
• VISIBILITY (DEMONSTRATIONS)
• COMMERCIAL MARKET STIMULATION

ADOPTION

• COMMERCIAL SUPPLIERS

NASA/LeRC/04/28/76
TEST AND DEMONSTRATION PROJECT

APPLICATIONS SUBPROJECT ELEMENTS

• PHOTOVOLTAIC SYSTEM TEST FACILITY TASK

OBJECTIVE: TO ESTABLISH A FLEXIBLE BREADBOARD TEST
FACILITY TO EVALUATE DESIGN METHODS, SYSTEM
OPERATING CHARACTERISTICS AND SYSTEM PERFORM-
ANCE OF OPERATING PHOTOVOLTAIC POWER SYSTEMS
OF UP TO 100 KW

• RESIDENTIAL APPLICATIONS TASK

OBJECTIVE: TO ACQUIRE, THROUGH A SERIES OF SUITABLY
CONFIGURED SYSTEMS EXPERIMENTS, THE OPERA-
TIONAL EXPERIENCE AND INFORMATION NEEDED TO
FULLY ASSESS THE TECHNICAL FEASIBILITY AND
RANGE OF USE OF RESIDENTIAL PHOTOVOLTAIC
APPLICATIONS
TEST AND DEMONSTRATION PROJECT

APPLICATIONS SUBPROJECT ELEMENTS (CONT.)

• DOD APPLICATIONS SUPPORT

OBJECTIVE: TO SUPPORT THE IMPLEMENTATION OF PHOTOVOLTAIC POWER SYSTEMS FOR DOD APPLICATIONS

• SPECIAL AND GOVERNMENTAL APPLICATIONS

OBJECTIVE: TO IDENTIFY, EVALUATE, AND DEVELOP DEMONSTRATIONS OF SELECTED SPECIAL AND GOVERNMENTAL PHOTOVOLTAIC SYSTEMS APPLICATIONS
### APPLICATIONS SCHEDULE -- PHOTOVOLTAIC TEST AND DEMONSTRATION PROJECT

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- S • START OF TESTING

**NASA-LEWIS 3-30-76**
TEST AND DEMONSTRATION PROJECT

CONTACTS AT LERC

OVERALL PROJECT AND APPLICATIONS SUBPROJECT

JIM DEYO OR BOB EASTER

216 - 433-4000, EXT. 6840

DEVICE PERFORMANCE AND DIAGNOSTICS SUBPROJECT

HENRY BRANDHORST

216 - 433-4000, EXT. 309

ENDURANCE TESTING SUBPROJECT

MOE FORESTIERI

216 - 433-4000, EXT. 786

NASA/LERC/04/28/76
TASK 1
SILICON MATERIAL
LOW-COST SILICON SOLAR ARRAY PROJECT
SILICON MATERIAL TASK
AGENDA TASK 1 MEETING

• DISCUSSIONS OF CONTRACT RESULTS
  
  • BATTELLE
  
  • UNION CARBIDE
  
  • WESTINGHOUSE
  
  • MONSANTO
  
  • LAMAR

• DISCUSSION OF MEASUREMENTS

• DISCUSSION OF INFORMATION REQUIREMENTS
LOW-COST SILICON SOLAR ARRAY PROJECT
SILICON MATERIAL TASK

OBJECTIVE

• ESTABLISH Si PRODUCTION CAPABILITY

• SUITABLE FOR SOLAR CELLS

• PRODUCTION RATE

  • EQUIVALENT TO 500 PEAK MW/YEAR

• PRICE

  • $10 / KGM

R. L.
4/28, 76
LOW-COST SILICON SOLAR ARRAY PROJECT
SILICON MATERIAL TASK

- PHASE I
  - PART I  SEMICONDUCTOR GRADE Si PROCESS
  - PART II  SOLAR CELL GRADE Si DEFINITION
  - PART III  SOLAR CELL GRADE Si PROCESS

- NEXT PHASE - SCALE-UP STUDIES

R. L.
4/28/76
LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS

• BATTELLE
  • Si I₄ Process
  • Zn/Si Cl₄ Process

• UNION CARBIDE
  • Redistribution Reaction
  • Direct Synthesis of Si H₂ Cl₂
  • Conversion of Si Cl₄
  • Mini-Plant

• WESTINGHOUSE
  • Ingot Preparation
  • Measurements of Blanks
  • Measurements of Solar Cells
  • Preliminary Conclusions

• MONSANTO
  • Ingot Preparation
  • Measurements of Blanks
  • Measurements of Solar Cells
  • Preliminary Conclusions

• LAMAR
• TEXAS INSTRUMENTS
• MOTOROLA
• STANFORD RESEARCH INSTITUTE
• CONTRACTS BEING NEGOTIATED
# Low-Cost Silicon Solar Array Project
## Silicon Material Task
### Phase I Contracts

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R.L.
4/28/76
SILICON MATERIAL TASK

INTRATASK MEETING

• PRESENTATION BY BATTELLE
  • METHODS, DATA BASE, CALCULATIONS LEADING TO
    CONCLUSION: Si\textsubscript{14}/SiCl\textsubscript{4}
  • CONSIDERABLE DISCUSSION OF EXPERIMENTS
    • FLUIDIZED BED IN PARTICULAR
  • Δ\textsubscript{G} MINIMIZATION FOR THERMO ANALYSES
  • INFORMATION: PROPRIETARY + SIMILAR ANALYSES + LITERATURE
  • CONCLUSIONS: SiCl\textsubscript{4}/Zn
    \textsubscript{Si}4
SILICON MATERIAL TASK

- PRESENTATION BY UNION CARBIDE

- DETAILS OF REACTIONS
  - REDISTRIBUTION
  - $\text{SiH}_2\text{Cl}_2$ DIRECT SYNTHESIS
  - $\text{SiCl}_4 \rightarrow \text{SiHCl}_3$
  - DESCRIPTION MINI PLANT DESIGN

WESTINGHOUSE

- GENERAL STATUS/CONCLUSIONS
- SEGREGATION COEFFICIENTS
- CONSIDERATIONS
  - PROCESSING/IMPURITY EFFECTS
  - LIFETIME MEASUREMENTS
  - CONCENTRATION/PRECIPITATION
  - LONG TIME STABILITY

SILICON MATERIAL TASK

- MONSANTO

- GENERAL STATUS/CONCLUSIONS
- SEGREGATION COEFFICIENTS
- RESISTIVITY SPREAD
- DEFECTS IN DOPED INGOTS

RL - 2
4/21/76

RL - 3
4/21/76

73
The objective of these studies by Battelle is to analyze for potential utility, two basic processes whose products are known to be of good quality, but which were not fully developed in the early stages of the semiconductor silicon industry. These processes are (1) the zinc reduction of silicon tetrachloride, and (2) several modifications of the iodide process using either thermal decomposition or hydrogen reduction of SiI₄. A fluidized bed approach is being used in the zinc reduction process and both heated filament and fluidized bed techniques are being evaluated in the iodide process.

The major effort during the second quarter of this program has been the estimation of plant construction and manufacturing costs for the zinc process and seven options of the iodide process. In addition, experimental work was done for verification of the assumptions and reaction rate data used in the process evaluation, and thermodynamic calculations were made on the iodination of SiO₂/C mixtures.

For purposes of this economic evaluation, it was assumed that the overall requirement of 3000 metric tons per year of solar grade silicon would be produced at three sites with a capacity of 1000 metric tons per year each. The cost estimation method used in the present program is that of Peters and Timmerhaus(*).

Based on a conservative approach in costing of individual process units and in assigning manpower loads, the estimated cost of the zinc reduction process, $9.12 Kg⁻¹ Si, is within the target of $10.00 Kg⁻¹; however, none of the modifications of the iodide processes yielded costs below $20 Kg⁻¹ Si. Although optimization of one of the iodide process modifications should bring the cost to below $20 Kg⁻¹ Si, it would not be possible to reduce the cost to below that of the zinc reduction product. In view of the conservative approach adopted in this initial analysis, the product cost of the zinc reduction process might be considerably less than the preliminary estimate.

Energy consumption data for the zinc reduction process and each of the iodide process options appear to be acceptable from the standpoint of energy pay back (<10.6 mo). The zinc reduction process is the lowest in terms of energy burden with a payback time of only 2.2 months.

The results of the additional experimental work performed this quarter in the zinc reduction of SiCl₄ and the electrolytic recovery of zinc from ZnCl₂ have continued to support the initial assumption as to the technical feasibility of producing semiconductor-grade silicon by this process. The results of a more thorough thermodynamic evaluation of the iodination of silicon oxide/carbon mixtures explained apparent inconsistencies in an earlier cursory examination of this system.

In the light of the results of the economic analysis, it is recommended that no further work be done at this time with the iodide process(es), and that the effort be concentrated on building and operating a "miniplant" based on the fluidized bed zinc reduction of SiCl₄ to verify process operability and product quality and to obtain further engineering information to permit a more accurate product cost estimate.

LOW COST, HIGH VOLUME PRODUCTION OF SILANE

D. L. Bailey, W. C. Breneman, J. Y. P. Mui

Activity for First Quarter of 1976

During the first quarter of 1976, the laboratory scale redistribution reactor was used to determine the rate of redistribution of dichlorosilane as catalyzed by a tertiary amine ion exchange resin, Rohm & Haas Amberlyst A-21. An on-line gas chromatograph was designed and constructed to permit accurate determination of product compositions. Initial results show that approximately 12-15 mole-% SiH₄ is formed with 5 seconds contact time at 60°C. More precise data will result when recent chromatograms are evaluated. The direct synthesis of dichlorosilane from reaction of HCl with copper catalyzed silicon failed to fully reproduce earlier results – yields of only 2% H₂SiCl₂ were obtained. The hydrogenation of SiCl₄ by reaction with H₂ at 500-600°C in the presence of copper catalyzed metalurgical silicon was shown to yield 21-22 mole-% HSiCl₃ with 5.7 seconds contact time in a fluidized bed reactor.

The design of a 10 lbs/day silane from H₂SiCl₂ plant has been successfully completed; procurement of major items initiated and site preparation begun. The design and initiation of procurement for major items for a dichlorosilane synthesis plant has also been completed. A proposal has been made to modify the program to suspend installation of the dichlorosilane synthesis plant while instead substituting a pilot scale unit to study further the hydrogenation of SiCl₄ and expand laboratory studies on the fundamental chemistry under girding the redistribution, direct synthesis and hydrogenation processes. Areas of work planned for the next quarter include completing the evaluation of the data obtained from the laboratory redistribution reactor, installation of the silane from H₂SiCl₂ "mini"-plant, additional laboratory studies on the hydrogenation reaction and the initial planning and design of a hydrogenation pilot plant pending acceptance of the program modification.
The objective of this program, Part 2 of the Silicon Materials Task, is to develop and define purity requirements for Solar Cell Grade silicon material by evaluating the effects of metal impurities and impurity concentration on the performance of silicon solar cells.

During this quarter the growth of all first generation doubly-doped Czochralski ingots was completed (baseline boron + Cr, Mn, Cu, Ni, Fe, Ti, V, Mg, Zn, and Zr), as were 90% of the second generation ingots, several third generation ingots, and three multiply-doped (B + Cu/Mn, Cu/Cr, Mn/Cr) ingots. Qualitative mass spec analysis is complete for most of these ingots and semiquantitative results have been obtained for the Mn, Cu, Cr, and Ni-doped, first generation crystals. In general, ingot analyses are consistent with the target impurity levels except for Ti and V, which are about 30% below the expected values, Zr which is low by a factor of two, and Mg and Zn where rapid evaporation from the melt reduces the crystal impurity content significantly.

All wafers processed to solar cells show relatively low dislocation densities, typically $<10^3$ and often below $10^2$. Uniform ingot doping is indicated by flat radial spreading resistance profiles. PCD lifetime measurements are complete on all first generation (save Mg) and most second generation ingots. The lifetime of the baseline (3 Ωcm) boron-doped material decreases during junction formation at 825°C (as widely reported in the literature) while the lifetime of silicon doped with metal impurities generally rises during the phosphorus diffusion. Gettering and/or precipitation are potential mechanisms for the lifetime improvement.

Solar cells have been fabricated and tested on most first generation and several second generation ingot wafers. The metal impurities tend to fall into groups: those causing little (Cu, Ni, Zr), modest (Cr, Mn, Fe), and severe (Ti, V) cell degradation. The relative solar cell efficiencies ($\eta$) for cells made from wafers metal-doped to near $10^{15}$ cm$^{-3}$ are: Cu - 1.0, Ni - 0.9, Zr - 1.0, Cr - 0.75, Mn - 0.71, Fe - 0.53, V - 0.39, and Ti - 0.25. For the baseline material, $\eta \approx 9.4$-9.5% for cells without AR coating at AM1 illumination.
Solar device fabrication and evaluation are the key elements of this contract. Test devices from sixteen experimental crystals have been processed to date. A 12-chip LED, specifically developed for this project, provides now ten times more light than the standard lamp and allows meaningful measurements of the minority carrier lifetime in the substrate before processing. A clear relationship between $\tau$ and solar cell efficiency $\eta$ is indicated. Certain trends are beginning to crystallize. For example, oxygen seems to be an undesirable secondary impurity. All Low-Oxygen i.e. Fz crystals investigated in this contract not only have better $\tau$ values before and after processing but also make a more efficient solar cell. It also seems that nickel, manganese, magnesium and even carbon may actually enhance solar cell performance.

To be sure the above mentioned trends require confirmation through additional experimentation. One element, however, literally kills solar cell performance: Titanium.

In Cz-crystal growth thirteen acceptable single crystals resulted from 23 runs. The most difficult dopants were Cr and Zr. Cr-doping caused persistent slag formation; Zr-doping so far has not given any useable single crystal. The presence of C, Fe, Cr, Mn, Ni, V, Al and oxygen in their respective matrices was confirmed by mass spec. Mg and Ti were not detected in the first two crystals so doped and second generation crystals were grown with larger amounts of these impurities. A detailed study to confirm or correct the available data for solubility and segregation is underway.

All but one of the originally scheduled Fz-crystals have been grown, also two second-generation crystals. The missing crystal will contain a combination of compatible secondary impurities. So far we have found four "compatible" elements: C, Mn, Ni, and Mg. What if a synergistic effect could be found! Compared to equivalent devices fabricated on Cz-material, nearly all solar cells on Fz-crystal are about 22% more efficient.

All material prepared has been characterized by Quality Assurance and has been found to deviate considerably from semiconductor silicon standards: 1. Typically 95% of a given series of standard P-type crystals targeted for 0.5 ohm cm would read 0.42 - 0.58. The experimental crystals had resistivity readings ranging from 0.14 - 0.94. 2. All experimental crystals had minority carrier lifetimes under 20 microseconds, well below standards. 3. The structure of the contract samples also deviated from standard. Although Zero-D crystal growth was achieved in all crystals, most metallographic tests showed unfamiliar etchpit formations and distributions.

The analytical technique used to date for the phys. chem. analysis is mass spectroscopy which has a superb sensitivity for nearly all elements. Only titanium and magnesium have not been detected in the first series of samples analyzed. Emission spectroscopy is in progress now to complement the results of the mass spectroscopy. For the determination of C and O, I.R. absorption is used. Here the high carrier concentration in the "contaminated" silicon has resulted in zero transmittance in many samples. Thinner samples are now being used trading detection limits for visibility.
Major activities were devoted to process system properties, chemical engineering and economic analyses during this reporting period.

In Task 1, preliminary data collection is very near completion for the silicon source materials - silane (SiH₄), silicon tetrachloride (SiCl₄) and silicon tetraiodide (SiI₄) - which are associated with the silane, Zn/SiCl₄ and H₂/SiI₄ processes under consideration. Major effort was initiated on the silicon source materials - silicon tetrafluoride (SiF₄) and silicon difluoride (SiF₂) - for the transport process.

In addition, preliminary results for the critical constants and physical properties of silane (SiH₄) were tabulated. The sole data source is based on work performed approximately sixty-five years ago in 1911. The fraction boiling at -116°C was used. Since the boiling point of silane is generally accepted as -112°C, the values for critical temperature (Tₐ) and pressure (Pₐ) are subject to question. Data for the remaining critical constants-volume (Vₐ), compressibility factor (Zₐ) and density (ρₐ) - are apparently not available.

For Task 2, initial background technical information exchange was accomplished on the following processes in the task integration meeting and subsequent discussions: Zn/SiCl₄ (Battelle); H₂/SiI₄ (Battelle); silane (Union Carbide); transport (Motorola); induction plasma (Texas Instruments); arc furnace (Dow Corning) and SiF₄ reduction (Stanford).

Several base case conditions including a plant size of 1000 metric tons/yr. were tentatively suggested and selected. Three such plants would provide the required 3000 metric tons/yr. of solar cell grade silicon.

In Task 3, procurement of data sources for numerous equipment types was accomplished for use in economic analysis. A review of methods for estimating capital investment was also initiated. Three methods were identified: (1) Ratio Factor Method, (2) Lang Factor Method and (3) Turnover Ratio Method. The Ratio Factor Method appears best suited for application to the solar cell grade silicon processes. The method is based on capital investment (fixed, working and total) as a percentage of the cost of major process equipment associated with the process under consideration.
{SiF$_2$)$_x$ Polymer Transport Purification Process

This investigation has been undertaken to examine the potential for a three step SiF$_2$ polymer transport purification process. Low cost m.g. silicon is reacted with SiF$_4$ to yield SiF$_2$ gas. The gas is condensed to form a polymer. When heated above 500°C the polymer decomposes to yield silicon, SiF$_4$ and higher SiF homologues.

The first phase of the project was to interface a mass spectrometer directly to the silicon purification unit for direct monitoring of the gaseous species for on line analysis. This interfacing is now complete.

The initial experiments have been directed toward reducing impurity levels in the silicon being prepared and at increasing the rate of transport. These experiments are proceeding as scheduled. It is interesting to note that when the {SiF$_2$)$_x$ polymer is formed at higher temperatures (e.g. -78°C), it forms a continuous clear sheet which when heated to 500°C converts to continuous silicon sheet.

In addition high temperature experiments (>1420°C) have been initiated and are proceeding as planned. Preliminary results indicate a rate increase with temperature. Further work to determine the magnitude of this increase is underway.
SUMMARY OF ACCOMPLISHMENTS

This period's activity centered about developing criteria for evaluation of progress, putting together the baseline cost estimate and milestone chart for the program, and in initiating experiments for preparation of the raw material (silica and carbon) mixture. Emission spectrographic analysis was used for comparison of the commercial grade carbon and silica which is currently available. Other physical, e.g., particle size, and chemical attributes were also considered both in selection and preparation of the raw materials for use in the reduction reaction. Experiments in preparation of the raw materials for the plasma reaction were aimed at optimizing the procedure for achieving maximum intimacy of particle contact and homogeneity of mixing while maintaining low levels of contamination during the preparation process.

Results of initial tests run at the TAFA facility using a 10 kw DC plasma torch and a powder feed system were inconclusive. Little reaction occurred between the carbon and silica due to insufficient residence time in the plasma flame. It was estimated that the residence time in the small torch was of the order 0.2 msec, whereas calculated time for 200 micron diameter particles to reach a plasma temperature of 40000K was approximately 30 msec. Tests using a pressed pellet of silica-carbon mixture in a 40 kw DC unit in which the plasma flame impinged on the compact and product was collected downstream as condensate gave more positive results. Silicon was identified by x-ray diffraction in the reaction products. A large scale (30 kg) evaluation of the powder feed plasma technique using TAPA's lonarc furnace, a 350 kw DC modified plasma reactor, has been planned. The large reactor should provide for particle residence times approximately 100 times greater than the small torch and allow closer control of the quenching atmosphere. Preparation (milling, pelletizing) of raw materials for this test has been scheduled to be done at the J. M. Huber Corporation at Borger, Texas. The test run at TAPA is scheduled for April 12.
TASK 2
LARGE-AREA
SILICON SHEET
LOW-COST SILICON SOLAR ARRAY PROJECT

LARGE AREA SILICON SHEET TASK

DR. J. ZOUTENDYK, TASK MANAGER

APRIL 27, 1976
LOW-COST SILICON SOLAR ARRAY PROJECT

OBJECTIVES

1980

- DEMONSTRATE BOTH TECHNICAL AND ECONOMIC FEASIBILITY OF SHEET GROWTH METHODS

1985

- DEMONSTRATE PRODUCTION CAPABILITY
  - LARGE AREA SILICON SHEET VALUE ADDED COST OF < $18/SQ METER
  - SILICON SHEETS CAPABLE OF ARRAY FABRICATION WITH > 10% CONVERSION EFFICIENCY
  - AUTOMATED SHEET PRODUCTION CAPABILITY OF > 5 MILLION SQ METERS PER YEAR

JZ-2
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
CONTRACT SUMMARY

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°ANTECEDENT START DATE 1 MAY 1976
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
ORGANIZATIONAL CHART

LASS TASK 2
J. ZOUTENYK, MANAGER

SILICON GROWTH DEVELOPMENT CONTRACTS
- CRYSTAL SYSTEMS (T. DIGGES)
- GE (G. CUMMING)
- HONEYWELL (M. LEIPOLD)
- IBM (M. LEIPOLD)
- MOBIL-TYCO (M. LEIPOLD)
- MOTOROLA (K. KOLIWAD)
- RCA (K. KOLIWAD)
- ROCKWELL (G. TURNER)
- U. SO. CAROLINA (T. DIGGES)
- U. PENNSYLVANIA (T. DIGGES)
- VARIAN ASSOC (G. CUMMING)

SILICON MATERIAL CHARACTERIZATION

REFRACTORY MATERIALS STUDIES
M. LEIPOLD

CRYSTAL GROWTH STUDIES
T. DIGGES

THERMAL ANALYSIS OF LIQUID-SOLID GROWTH
F. WOLF

STRUCTURAL CHARACTERIZATION
- M. LEIPOLD
- M. HAGAN

ELECTRICAL CHARACTERIZATION
- G. CUMMING
- K. KOLIWAD
- G. TURNER
- J. COLLIER

DEVICE FABRICATION
L. KUDRAVY

JZ-4
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
MAJOR PROGRESS
RIBBON

- CAPILLARY DIE (EFG, CAST)
  - GROWTH RATE OF 7 cm/minute OBSERVED
  - PREFERRED EQUILIBRIUM GROWTH ORIENTATION ESTABLISHED
  - THERMAL CONTROL STUDIES IN PROGRESS

- NON-WETTING DIE (1ST)
  - INVESTIGATION OF SiO₂ DIE IN PROGRESS
  - SEARCH FOR NON-DOPING DIE MATERIALS IN PROGRESS

- WEB-DENDRITIC GROWTH
  - DENDRITE AND WEB GROWTH STUDIES IN PROGRESS

- LASER-ZONE CRYSTALLIZATION (RTR)
  - AUXILIARY HEATING UNDER INVESTIGATION
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
MAJOR PROGRESS SHEET

• DIP-COATING
  • CONTINUOUS COATING OF 20 cm² CARBON-COATED MULLITE SUBSTRATES ACHIEVED
  • CRYSTALLITES 1 mm WIDE BY 1-2 cm LONG OBTAINED

• FLOATING SUBSTRATE
  • SUPERCOOLING OF TIN-SILICON MELTS MEASURED
  • PLANAR GROWTH AT SUPERCOOLED SURFACE OBSERVED

• CHEMICAL VAPOR DEPOSITION
  • MODIFICATION OF CVD SYSTEM COMPLETE
  • PRELIMINARY RUNS ON GLASS, CERAMIC AND SAPPHIRE (CONTROL) SUBSTRATES PERFORMED
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
MAJOR PROGRESS
INGOT GROWTH/SLICING

- INGOT CASTING (HEM)
  - VACUUM GROWTH SYSTEM COMPLETE
  - INITIAL SEEDED GROWTH RUNS PERFORMED

- INGOT SLICING
  - MULTIPLE WIRE AND BLADE MACHINE MODIFICATION AND FABRICATION COMPLETE
  - MULTIPLE WIRE STRETCHING SYSTEM COMPLETE
  - MULTIPLE BLADE CUTTING TESTS SHOW INCREASED CUTTING RATE FOR THIN BLADES
LOW-COST SILICON SOLAR ARRAY PROJECT
LASS TASK 2
INTRATASK MEETING
27 APRIL 1976

TIME | SUBJECT | DISCUSSION LEADER
--- | --- | ---
1:15 pm | TASK REVIEW | J. ZOUTENDYK
3:00 | MATERIAL CHARACTERIZATION
- MINORITY CARRIER DIFFUSION LENGTH AND LIFETIME MEASUREMENTS
- SHEET RESISTANCE, SPREADING RESISTANCE
- CARRIER CONCENTRATION, RESISTIVITY, HALL MOBILITY
- EBIC (SEM)
- IMPURITIES | K. KOLIWAD
4:00 | SOLAR CELL TESTING
- "STANDARD" CELL DESIGN
- "STANDARD" CELL PROCESSING
- TERRESTRIAL SECONDARY STANDARD CELLS
- TEST CONDITIONS | G. CUMMING

JZ - 8
4-27-76
During the past three months the work on this project has progressed along several fronts. Preliminary growth rate experiments were conducted and growth speeds approaching 3"/minute (the program goal) were attained for short periods of time. Such ribbons have, however, been found to exhibit a high degree of strain. Theoretical analysis of thermal stresses in ribbons is being utilized in the program. One of the principal predictions of the theory is that if the steady-state temperature along the ribbon varies linearly with a set of rectangular Cartesian space coordinates, then all the stress components throughout the solid are identically zero.

In the area of equipment design and construction, the furnace being used for the growth of thin, fast ribbons is completely operational and is in regular use. The new furnace (for the growth of 3" wide ribbons) is in the design stage and some of the main components have already been procured.

Studies relating to the seed orientation have been completed this quarter. It has been determined that (a) there exists an "equilibrium defect" structure in EFG ribbons consisting of parallel boundaries parallel to the edges of (110) [112] oriented ribbons; (b) the orientation of the seed does not influence the ultimate attainment of the equilibrium structure on orientation in the growing ribbon and (c) the use of a (110) [112] single crystal seed or of a "defect structure" ribbon seed allows initiation of the equilibrium structure immediately at the seed/crystal interface.
CAPILLARY ACTION SHAPING TECHNIQUE

IBM

Summary

- Ribbons 25 mm wide and 0.5 m long were grown from silicon carbide dies.
- Thermal modifiers were studied, and systems were developed that reduce frozen in stress in silicon ribbons and improve thickness uniformity.
- Spreading-resistance measurements indicate that resistivity variations of up to 200% are caused by grain boundaries. Twin boundaries give no indication of similar fluctuations in resistivity.
- Electron channeling patterns are applied to analyze surface orientations of ribbons grown with carbon dies.
- Surface orientation of ribbon sections grown under steady-state conditions approaches the <011> direction.
- Single and double-tilt misalignment off the <011> directions occurs.
- Best ribbons grown show 5 to 8 degrees single tilt in surface orientation off <011> and twin lines in the <112> growth direction.
- Seed orientation has no influence on final surface orientation.
- Technology projection and sensitivity analysis indicate that single-ribbon growth systems—as opposed to multi-ribbon systems—offer the best potential for achieving low-cost silicon sheet material within the shortest period of time.
- Processing technology improvements are the key elements for reducing costs of silicon sheets.
- Significant reductions in sheet material cost are achievable in the near future by increasing ribbon width to 5 cm.
INVERTED STEPANOV TECHNIQUE FOR
SILICON SHEET GROWTH

RCA Laboratories
Princeton, New Jersey

G. W. Cullen/K. M. Kim/S. Berkman/A. E. Bell

ABSTRACT

A new susceptor and die geometry has been designed in which flat plates which constitute the die are positioned in the susceptor. In cross section, the plates are in a "V" shaped geometry. This setup was adopted to facilitate the use of SiO₂ as the shaping guide in the inverted configuration. In preliminary IST silicon ribbon growth attempts employing a flat SiO₂ die with a rectangular slot (0.05 x 2.0 cm and 0.1 cm thick), the slot was not filled with the liquid silicon. When the slot was tapered, flow of the silicon into the slot was enhanced, but did not flow completely to the bottom edge of the die.

With the new design, the SiO₂ capillary slot (0.05 x 2.5 cm and 0.3 cm long) is filled with the molten silicon completely to the end. Efforts are being made to achieve a reproducible and stable ribbon growth. With the "V" shape configuration, a very high vertical thermal gradient can be achieved. We are in the process of optimizing the vertical as well as the horizontal temperature gradient at the solid/liquid growth interface.

In the new configuration, the die package can readily be fitted with other die materials. In initial attempts to grow thinner ribbons, pyrolytic BN is employed as the die material. In early attempts to grow 250 μm thick ribbon with the flat die, the ribbon width decreased continuously as the growth proceeded. Since the adjustments of thermal gradients did not alleviate this behavior, it is concluded that tapering of the width was not due to an unsatisfactory isotherm, but more likely was due to the lack of sufficient replenishing of the liquid to the growth interface.

The first stage in the thermal analysis of the Inverted Stepanov Technique for silicon ribbon growth will be a one-dimensional steady state analysis of the temperature profile down the single crystal ribbon. A computer program is now being written which will allow us to investigate the dependence of the height of the molten region in contact with the die surface as a function of the die temperature, the temperature profile which exists in the environment of the ribbon, and the dimensions of the ribbon itself. The sensitivity of the height of the molten zone to variations in the temperature of the die surface will dictate the degree of stability which will be required in the temperature of the die in order to maintain uniform growth conditions.
WEB-DENDRITIC GROWTH

University of South Carolina

ABSTRACT

Very early in this quarter attempts were made to pull webs. The initial pulls resulted in "third dendrite" webs (the term third dendrite actually refers to webs that have one dendrite in the web portion between the two edge dendrites; however, it is often used to refer to web with more than one dendrite in the web portion). Improvement in technique, and a change in the diameter of the reel drive wheel resulted in true three dendrite web and finally good web.

The following parameters were varied to see their effect on the growth of the webs. This was done not only to gain information required in the thermal analysis task but also to improve the width of the webs: 1) position of the susceptor in the R.F. coil; 2) thicker heat shield; 3) shape of the susceptor; 4) size and shape of the opening in the heat shield; 5) pull rate.

X and y micrometer motions were added to the coil holder to give better control over the center of thermal symmetry.

Measurement of the twin spacing showed the total spacing to be three micrometers and the spacing of the widest lamella to be two micrometers. It is felt that this may be too narrow. Attempts are being made to build up a supply of different twin spacings.

The thermal analysis of the web growth is being performed at present in two parts. The web and meniscus is being modeled assuming 1-dimensional convection and conduction. A separate model is being used for the crucible, susceptor, etc. Computer programs that will be used to obtain solutions to the thermal models are CSMP (for the 1-dimensional model) and lion-4 (for the susceptor, etc.).

A special holder was built to examine web cross-section in the sem. Sem examination is necessary to measure the narrow twin spacings presently found.

The following electrical characterization facilities have been completed and tested: 1) van de pauw; 2) 4-point probe; 3) hot probe; 4) mos minority carrier lifetime. The facility for determining dark and illuminated I-V characteristics of solar cells have also been completed and tested.
MODIFICATIONS TO THE EXISTING RTR APPARATUS ARE NEARLY COMPLETE. MECHANICAL TRANSLATION PROBLEMS WHICH HAVE CAUSED DIFFICULTIES PREVIOUSLY, HAVE ESSENTIALLY BEEN SOLVED. WHEN OPERATING WITH INDEPENDENTLY DRIVEN CHUCKS, SHORT TERM CHUCK SPACING VARIATIONS OF LESS THAN ±1 MIL ARE OBTAINED. LONG TERM VARIATIONS OF AS MUCH AS ±7 MILS OCCUR, BUT THESE WILL NOT AFFECT THE RTR PROCESS BECAUSE THE MELT CAN ACCOMMODATE SLOW VARIATIONS WITH A NEGLECTIBLE THICKNESS VARIATION.

A NEW CCTV REMOTE VIEWING SYSTEM HAS BEEN COMPLETED. OBSERVATION OF BOTH SIDES OF A RIBBON MAY BE PERFORMED SIMULTANEOUSLY WITH TWO CAMERAS, EACH OF WHICH HAS REMOTE FOCUS, IRIS AND ZOOM CONTROLS. WITH VARIOUS AVAILABLE MAGNIFICATIONS, AND THROUGH THE USE OF REMOTELY CONTROLLED MIRRORS, ANY REGION MAY BE OBSERVED AT HIGH OR LOW MAGNIFICATIONS. A VIDEO SWITCHING CONSOLE ALLOWS VIDEO TAPPING OF A SELECTED VIDEO SIGNAL AND/OR THE SIGNAL MAY BE SENT TO A VIDEO ANALYZER SYSTEM WHICH DISPLAYS INTENSITY VARIATIONS IN BOTH A "FALSE-COLOR" MODE ON A COLOR MONITOR AND A PSEUDO-THREE DIMENSIONAL FORM ON AN XYZ MONITOR.

IN ADDITION TO THE CCTV SYSTEM, THE SAME MIRROR SYSTEM ALLOWS AN OPTICAL PYROMETER TO MEASURE THE TEMPERATURE OF A SELECTED REGION. THE SPATIAL RESOLUTION OF THIS SYSTEM IS ONLY APPROXIMATELY 0.1" BUT THIS ALLOWS CORRELATION OF VIDEO INTENSITIES WITH TEMPERATURE.

THE PHOTON SOURCES, CO₂ LASER HAS BEEN CHARACTERIZED IN VARIOUS WAYS. BY UTILIZATION ON AN OSCILLATING MIRROR SYSTEM AND A HIGH SPEED PYROELECTRIC DETECTOR, THE OUTPUT BEAM PROFILE HAS BEEN MEASURED AND OPTIMIZED THROUGH GAS FLOW CONTROLS. THE OPTIMIZED BEAM APPEARS TO BE ESSENTIALLY GAUSSIAN UNDER MOST CONDITIONS. A LOBED MODE CAN EASILY RESULT AT LOW POWERS IF GAS COMPOSITIONS ARE WRONG. GAS COMPOSITIONS HAVE ALSO BEEN OPTIMIZED TO YIELD THE MAXIMUM POWER; RECOMMENDED FLOW CONDITIONS WERE FOUND TO BE ONLY APPROXIMATELY CORRECT.

AUXILIARY HEATING TECHNIQUES ARE UNDER INVESTIGATION FOR THERMAL PROFILE CONTROL AND AS SUPPLEMENTARY POWER TO THE LASER. AT PRESENT, "REMOTE" HEATING TECHNIQUES ARE OF PRIMARY INTEREST. RADIANT HEATING REMAINS A PROMISING CANDIDATE AND VENDORS ARE PERFORMING EXPERIMENTS FOR US. THE "ENERGY BEAM" ALSO APPEARS VERY INTERESTING AS AN EFFICIENT,
remote heating device. Some difficulties in heat zone shape need to be resolved. Direct electrical heating of the ribbon will be utilized for certain experiments, and a fixture has been completed and demonstrated which can be incorporated directly into the RTR growth apparatus. Ribbons have been heated close to the melting point with very uniform thermal gradients.

Plans for the next phases involve a few more check-out procedures for the optical system and growth chamber and then ribbon melting and regrowth studies will begin. Thermal profile measurement, auxiliary heating effects and initial growth studies will soon begin.
DIP-COATING PROCESS

Honeywell, Inc.
Corporate Research Center
Bloomington, Minnesota 55420

ABSTRACT

In the past three months, our experimental dip-coating facility was completed, tested and placed into service. Using this facility several 6.5 x 5.0 x 0.1 cm carbon-coated mullite substrates have been successfully dip-coated with 0.5 to 3.0 ohm-cm p-type polycrystalline silicon. These coatings were ~20 cm² in area and had a controlled thickness ranging from 12 to 50 µ meters.

As previously demonstrated, crystallization and layer thickness responds to and can be controlled by at least two growth parameters; namely, pulling rate and melt temperature. The crystalline grains are dendritic in nature and many times larger than the layer thickness. The thicker (~50 µ meter) coatings have dendrite-like crystallites of the order of 1 mm wide and 1 to 2 cm long. Their axes were aligned along the direction of pulling indicating that the growth continues to occur from previously grown silicon.

A 95% alumina substrate was also uniformly coated with a smooth, thick (~100 µ meter) layer of silicon, but it shattered upon cooling, presumably due to the thermal expansion mismatch.

Honeywell's Ceramic Center has purchased or prepared by various methods a variety of ceramic substrates including mullite, alumina, zircon, cordierite, silica, calcium aluminate and "Fiberfrax". The silicon-coated mullite substrates were prepared by rolling, drying and firing a plastic extrudable composition.

A diffusion furnace has been placed into service and 5 ohm-cm, p-type single crystal silicon wafers have been given an n-type phosphorus diffusion in preparation for use as control samples when the polycrystalline coatings are diffused.

Preliminary substrate carbonization by pyrolysis produced extremely thin carbon coatings.

To date, no rigorous characterization of the electrical of physical properties of the coatings has been performed.
Laboratory apparatus has been designed, built, and put into operation to study the supercooling of silicon-tin melts and the incorporation of silicon into tin from silanes. Values of supercooling of Sn-Si melts as high as 78°C at 1100°C and 39°C at 1200°C have been observed. These results are limited by nucleation caused by foreign material on the surface of the melt.

Two types of impurity have been observed. One, initially a thin film covering the tin surface, gathers into a thin disc as the temperature is raised above 1100°C. It is seen with quartz, BN, and alumina crucibles. The second, a fluffy material, is seen only with quartz crucibles and consists of SiO₂ with particles of metallic tin. It is due to SiO₂ dissolved by the hot tin forming upon the surface of the melt as it is cooled. While these impurities will cause no difficulty in a steady-state sheet apparatus, they have limited our supercooling results. Nevertheless, the results to date are encouraging. They show that substantial supercooling (within the range assumed in the preliminary analysis of surface growth in our proposal) can be achieved even in the presence of surface contamination.

On two occasions spontaneously nucleated planar growth has been observed at the supercooled tin-silicon surface. Crystals grew in size to approximately 8mm. x 2mm. in about 90 seconds.

Homogeneous nucleation of silane decomposition was studied at 1015°C and 1135°C. The flow rates of BCl required to suppress gas phase decomposition has been determined for SiH₄ flow rates up to 4.5 x 10⁻³ mole/min. Initial silicon uptake experiments have shown that at least 20% of the incoming silicon contained in a flowing SiH₄ gas stream can be incorporated into liquid tin at 1040°C.
CHEMICAL VAPOR DEPOSITION

Rockwell International

ABSTRACT

An existing laboratory-type CVD reactor system with a vertical deposition chamber has been used for growth of the Si films studied to date. Extensive modifications of this system, involving mass flow controllers and automatic timing of reactant gas flow by means of solenoid-activated air-operated bellows valves, have now been completed, and the Design and Performance Review was held on April 15, 1976.

Several potential suppliers of candidate substrate materials have been contacted. Numerous samples of materials have been received for consideration, some of which have been evaluated experimentally as substrates for CVD of Si by pyrolysis of SiH4 in H2 or He carrier gases. Materials of three main classes - glasses, glass-ceramics, and polycrystalline ceramics are being investigated.

Preliminary deposition experiments with two of the available glasses have not been encouraging because of adverse physical and/or chemical effects on the glass in the CVD process, even at relatively low temperatures. Moderately encouraging results, however, have been obtained with fired polycrystalline alumina substrates, which have been used for Si deposition at temperatures above 1000°C. These materials exhibit some preferred orientation in their polycrystalline structures, and the films grown on these are also preferentially oriented, although no crystallographic correlations have yet been made.

The surfaces of both the substrates and the films have been characterized by x-ray diffraction, reflection electron diffraction, scanning electron microscope, optical microscopy, and surface profilometric techniques. Some evidence of improved surface grain size has been found in some aluminas subjected to high-temperature firing cycles beyond those normally used, and the polishing of some alumina wafers to produce better surfaces for Si film deposition and grain growth has begun.

A variety of CVD experiments has been carried out to establish baseline performance data for the reactor system, including temperature distributions on the sample pedestal, effects of carrier gas flow rate on temperature, effects of carrier gas flow rate on film thickness uniformity in H2 and in He (with H2 producing more uniform results), and Si film growth rate by SiH4 pyrolysis as a function of temperature for H2 and He. An activation energy for the deposition process in the temperature range up to 850-900°C of ~1.8 eV was found for either carrier gas. Above that temperature range the growth rate still increases with temperature in H2 but with a much lower activation energy (~0.14 eV). For He the rate passes through a maximum at 850-900°C, decreasing rapidly.
for further increases in temperature, indicating a difference in the deposition process at high temperatures ( > 850°C) in the two gases. Generally, better looking Si films have been achieved to date by deposition in H₂ than He.

X-Ray diffraction methods have been used to obtain preliminary information on the amount of preferred orientation and the grain size in CVD Si films deposited on polycrystalline alumina at several different temperatures. Methods of SEM Analysis and classical metallography combined with etching procedures have been used to provide evidence of vertical or columnar growth in some of the Si films on alumina. Only limited electrical measurements have been made, primarily because of the emphasis on structural properties of the films to date and the fact that only undoped films have been prepared; experiments with doped films will be initiated early in the second quarter.

Several samples have been sent to OCLI for experimental processing into solar cell structures. Preliminary results obtained on the first group of four to be processed were not encouraging. The films were thin and undoped, and considerable difficulty was encountered in processing them by standard solar cell fabrication techniques.
A graphite resistance furnace with a 14” diameter by 14” tall heat zone has been adopted to grow silicon. The furnace has been instrumented so that the furnace temperature should be controlled on the basis of power or temperature, and the heat exchanger temperature could be controlled by the heat exchanger temperature or the helium flow rate.

It has been demonstrated that silicon could be melted and solidified in a 0.1 Torr pressure (mechanical pump vacuum) in an open quartz crucible. The actual rate of crucible decomposition $\text{Si} + \text{SiO}_2 \rightarrow 2 \text{SiO}$ is 20,000 times slower than theory predicted. The boundary layer between the crucible and the molten silicon is not broken down due to convection; therefore, it remains highly concentrated with SiO which may chemically suppress crucible decomposition.

Processing in vacuum has a big cost advantage over processing in an inert atmosphere. In addition, it is easier to control heat flow, possible to refine the molten silicon and achieve a lower equilibrium oxygen solubility at the lower pressures.

It has been demonstrated that the silicon seed bonds to the quartz crucible bottom, preventing it from floating to the surface when the silicon charge melts. Partial seeding has been accomplished on the top edge where the molten silicon melted into it. This resulted in a single crystal growth to the top surface of the ingot, indicating that the growth parameters were sufficient for single crystal growth.

For crystal slicing, a multi-blade wafering technique will be used. Equipment had to be developed to upgrade the current state of the art. This involved designing and fabricating a responsive feed mechanism, slurry-recovery system and wire-stretching system. The machine is now completed and capable of slicing silicon with wire.

The feed mechanism has the following features:

1. The feed force can be controlled and resolved to within .01 lb/wire (4.5 g/wire) for 25 wires or .0025 lb/wire (1.1 g/wire) for 100 wires.

2. Motion of the workpiece is incorporated in the feed mechanism so the workpiece motion can be coordinated with the motion of the blade carriage.
3. An efficient coolant/slurry recovery system is incorporated into the feed mechanism. The catch pans are designed so there will be virtually no spillage or entrapment of slurry. This allows use of expensive diamond slurries since there will be almost complete recovery. The pan system is made out of stainless steel; this will allow use of corrosive chemicals for chemical/mechanical slicing.

The wire-stretching system has been completed and tested. Any size and number of wires can be easily strung to a consistent tension with the wire-stretching system.
SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates
M. H. Hablanian

ABSTRACT

A modified Varian model 686 multiblade wafering saw was set up to perform tests for the slurry sawing of silicon. Standard operating procedures and data collection schemes were established. A thickness characterization technique was established to measure wafer accuracy.

Silicon was ordered to meet specifications as solar cell grade material. Both \( <111> \) and \( <100> \) material was purchased to allow determination of any differences in cutting due to anisotropy of hardness. The silicon was fabricated into various block sizes to suit the first stage of cutting tests. A reference flat was specified to allow reorganization of wafers in their as-sawn configuration.

A dynamometer was built and tested to measure cutting forces. It will be installed on the saw at a convenient stopping point in the cutting program, in order to avoid unnecessary delays.

The first stage of cutting tests is approximately one-half complete. Under standard conditions of slurry application, load, kerf length, and size have been varied. Cutting rates are linearly proportional to load, and are inversely proportional to kerf length. Thin blades give higher cutting rates due to lower kerf width.

A theory has been proposed to predict the cutting rate of multiblade slurry sawing. The agreement of results to date is excellent, and the process has been shown to be an effective form of two-body abrasion.
1. PURPOSE

TO DETERMINE THE COST EFFECTIVENESS OF A PROCESS
PRODUCING SINGLE CRYSTAL CZOCHRALSKI WAFERS
LOW-COST SILICON SOLAR ARRAY PROJECT
DEVELOPMENT AND EVALUATION OF SILICON CRYSTAL GROWTH AND WAFERING PROCESSES

2. OBJECTIVES

- CRYSTAL GROWTH (CZOCHRALSKI)
  - DIAMETER
  - GROWTH RATE
  - CRYSTAL WEIGHT
  - FURNACE LINER CAPABILITY
  - RESISTIVITY
  - USEABLE SINGLE CRYSTAL
  - OUTPUT PERFORMANCE PER FURNACE HEAT

- WAFER PROCESSING (SAWING)
  - 250 micron THICK 12 cm DIAMETER CRYSTALS

- WAFER SHAPING
  - LASER SCRIBING AT RATE OF 10 cm/sec

- CHARACTERIZATION
  - ANALYZE AND EVALUATE RELEVANT PROPERTIES OF ABOVE PROCESSES WHICH MAY AFFECT SOLAR CELL PERFORMANCE
### Tentative Melt Replenishment Procedure

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<tr>
<th>Process</th>
<th>Hrs</th>
<th>Charge</th>
<th>Output</th>
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<tr>
<td>Load and Melt Down</td>
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<td>12 kg</td>
<td></td>
</tr>
<tr>
<td>Seed and Top</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grow</td>
<td>2.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taper</td>
<td>1.0</td>
<td></td>
<td>9.0 kg</td>
</tr>
<tr>
<td>Reload, Melt</td>
<td>2.0</td>
<td>9 kg</td>
<td></td>
</tr>
<tr>
<td>Seed, Top</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grow</td>
<td>2.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taper</td>
<td>1.0</td>
<td></td>
<td>9.0 kg</td>
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<tr>
<td>Reload, Melt</td>
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<td>Seed, Top</td>
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</tr>
<tr>
<td>Grow</td>
<td>3.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taper</td>
<td>1.0</td>
<td></td>
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</tr>
<tr>
<td>Cool</td>
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<td>11.2 kg</td>
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<td><strong>Totals</strong></td>
<td>25.2 hr</td>
<td>30 kg</td>
<td>29.2 kg</td>
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LOW-COST SILICON SOLAR ARRAY PROJECT
DEVELOPMENT AND EVALUATION
OF SILICON CRYSTAL GROWTH
AND WAFERING PROCESSES

4. COST ANALYSIS - CRYSTAL GROWTH

<table>
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<tr>
<th>MATERIAL</th>
<th>$65/kg</th>
<th>$10/kg</th>
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<tr>
<td>POLYSILICON 30 kg</td>
<td>1950.00</td>
<td>300.00</td>
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<tr>
<td>OTHER - 3 SEEDS</td>
<td>15.00</td>
<td>30.00</td>
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<tr>
<td>1 LINER</td>
<td>30.00</td>
<td>30.00</td>
</tr>
<tr>
<td>MISC</td>
<td>45.00</td>
<td>45.00</td>
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SUBTOTAL MATERIAL: 2040.00

LABOR:

| CYCLE TIME 25.2 hr AT 12 cm/hr | 151.20 |
| GROWTH RATE AND 6.00/hr        | 151.20 |

TOTALS

| COST OF 3 CRYSTALS            | 2191.20 |
| GMS GOOD MTL 26, 100          | 541.00  |
| COST/GM OF GOOD MTL           | 0.0839  |

BDG-4
4-28-76

0. 0207
**LOW-COST SILICON SOLAR ARRAY PROJECT**

**DEVELOPMENT AND EVALUATION OF SILICON CRYSTAL GROWTH AND WAFERING PROCESSES**

(Contd)

4. (cont)

IF 5 XTALS PULLED FROM 1 LINER

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<th>HRS</th>
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<tr>
<td>5</td>
<td>10.53</td>
<td>9</td>
<td>11.2</td>
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**TOTALS**

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<th>HRS</th>
<th>CHARGE</th>
<th>OUTPUT</th>
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<tbody>
<tr>
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MTL COSTS AT $65/kg AT $10/kg

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<th>MATERIAL</th>
<th>WEIGHT (kg)</th>
<th>COST</th>
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<tr>
<td>POLYSILICON</td>
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<td>$3120</td>
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<tr>
<td>SEEDS</td>
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<td>$25</td>
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<tr>
<td>QUARTZ</td>
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<tr>
<td>MISC</td>
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<td>$75</td>
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LABOR COSTS

38.85 hr x $6.00 PER hr $233 $233

COST 5 CRYSTALS

$3483 $843

COST/GM

$0.0815 $0.0197

BDG-5 4-28-76
LOW-COST SILICON SOLAR ARRAY PROJECT
DEVELOPMENT AND EVALUATION
OF SILICON CRYSTAL GROWTH
AND WAFERING PROCESSES

4. (cont)

<table>
<thead>
<tr>
<th>NUMBER CRYSTALS</th>
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<th>BOTTOM kg</th>
<th>RESIDUE kg</th>
<th>OUTPUT kg</th>
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BDG-6
4-28-76
5. STATUS

NEW CONTRACT

PROGRAM PLAN DUE APRIL 30
TASK 3
ENCAPSULATION
LOW-COST SILICON SOLAR ARRAY PROJECT
PROJECT INTEGRATION MEETING

ENCAPSULATION TASK

W.F. CARROLL, TASK MANAGER

APRIL 27, 1976
LOW-COST SILICON SOLAR ARRAY PROJECT
ENCAPSULATION TASK
OVER-ALL OBJECTIVE-ENCAPSULATION SYSTEM

- 20 YEAR LIFETIME
- LOW COST
- DEMONSTRATED RELIABILITY
# LOW-COST SILICON SOLAR ARRAY PROJECT
## ENCAPSULATION TASK CONTRACTS

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>SUBJECT</th>
<th>PI</th>
<th>JPL TECH MGR</th>
<th>START</th>
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<tr>
<td>BATTELLE</td>
<td>-1 CANDIDATE MATLS.</td>
<td>G. GAINES*</td>
<td>H. MAXWELL</td>
<td>OCT '75</td>
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<td>-2 ENV. DEF./REQTS.</td>
<td>R. THOMAS*</td>
<td>H. MAXWELL</td>
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<td>-3 MATL. PROP &amp; TEST</td>
<td>G. GAINES*</td>
<td>H. MAXWELL</td>
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<td>-4 ACCEL/ABBREV. TEST</td>
<td>G. GAINES*</td>
<td>H. MAXWELL</td>
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<td>ROCKWELL</td>
<td>ACCEL/ABBREV. TEST</td>
<td>J. FARRAR</td>
<td>J. MOACANIN</td>
<td>MAR '76</td>
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<td>DeBELL &amp; RICHARDSON</td>
<td>MATL. PROP. &amp; TEST</td>
<td>B. BAUM</td>
<td>E. CUDDIH</td>
<td>MAY '76</td>
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<td>SIMUL. PHYS.</td>
<td>INTEG. GLASS COVERS</td>
<td>A. KIRKPATRICK</td>
<td>R. HOLTZE</td>
<td>MAY '76</td>
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*D.C. CARMICHAEL IS BATTELLE TECH. MGR.*
LOW-COST SILICON SOLAR ARRAY PROJECT
ENCAPSULATION TASK
STATUS

BATTELLE CONTRACT

STUDY - 1  CANDIDATE MATERIALS
   • REVIEW OF PUBLISHED AND UNPUBLISHED INFO. IN PROCESS
   • SUMMARY OF ARRAY EXPERIENCE - PUBLISHED

STUDY - 2  ENVIRONMENTAL ANALYSIS & DEFINITION
   • ANALYSIS OF CLIMATIC DATA COMPLETE
   • POLLUTION, ULTRAVIOLET, NORMAL INSOLATION IN PROCESS

STUDY - 3  MATERIALS PROPERTIES & TEST
   (STARTED THIS MONTH)

STUDY - 4  ACCEL/ABBREV TEST
   • SURVEY OF METHODS, EXPERIENCE & DATA

ROCKWELL-ACCELERATED/ABBREVIATED TEST
   • (STARTED LATE MARCH)
   • TEST SPECIMEN PRELIMINARY DESIGN COMPLETE
   • PROGRAM DETAIL PLAN - IN PROCESS

DE BELL & RICHARDSON - MATERIAL PROPERTIES & TEST
   • CONTRACT NEGOTIATED
   • START EARLY MAY

SIMULATION PHYSICS - INTEGRAL GLASS COVER
   • CONTRACT NEGOTIATED
   • START EARLY MAY
LOW-COST SILICON SOLAR ARRAY PROJECT
STUDY 2 - ENVIRONMENTAL DEFINITIONS AND REQUIREMENTS

DETRIMENTAL ENVIRONMENTAL CONDITIONS
(IN 20 YEAR ARRAY LIFETIME)

- FREQUENCY
- DURATION
- COMBINATIONS AND INTERACTIVE EFFECTS
- CANNOT USE ONLY
  - AVERAGES
  - INDIVIDUAL DISTRIBUTION OR EXTREMES
- ACTUAL RECORDED DATA FROM SELECTED SITES

WFC-8
1-20-76
LOW-COST SILICON SOLAR ARRAY PROJECT

STUDY 2 - ENVIRONMENTAL DEFINITIONS
AND REQUIREMENTS

SITE SELECTION

PRIMARY CRITERIA
○ U.S. COVERAGE
○ REPRESENTATIVE EXTREMES
○ AVAILABLE DATA

SELECTED SITES
○ PHOENIX - SEMI-ARID, HIGH INSOLATION, MOD. ALTITUDE, MATL. TEST DATA
○ ALBUQUERQUE - SEMI-ARID, HIGH INSOLATION, HIGH ALTITUDE
○ MIAMI - SEMI-TROPICAL, MARINE, HIGH HUMIDITY, HIGH AVER. TEMP.
○ BISMARCK - LOW WINTER TEMP, LG SEASONAL VARIATIONS
○ CLEVELAND - POLLUTION, HIGH HUMIDITY
○ LOS ANGELES/RIVERSIDE - POLLUTION, HIGH DIURNAL TEMP VARIATION
○ FAIRBANKS - LOW AVER TEMP, EXTREME LOW TEMP, LG SEASONAL VAR.
○ SAN ANTONIO/BROWNSVILLE - WARM, HIGH INSOLATION
○ BOSTON/BLUE HILL - MOD COLD MARINE
LOW-COST SILICON SOLAR ARRAY PROJECT
STUDY 2 - ENVIRONMENTAL DEFINITIONS
AND REQUIREMENTS
SCHEMATIC REPRESENTATION
OF APPROACH

FREQUENCY & DURATION

NO. OF OCCURRENCES
1 2 3 4 5
SEQUENTIAL OBSERVATIONS

RELATIVE HUMIDITY

TEMP

INSOLATION

ANALYSIS AND 20 YEAR FORECAST

MATERIAL EVALUATION CONDITIONS
MATERIAL QUALIFICATION CONDITIONS

TRANSIENTS

NEXT CELL
LOW-COST SILICON SOLAR ARRAY PROJECT

DESIGN REQUIREMENTS FOR

SOLAR ARRAY MODULES

Dr. R. G. Ross

28 April 1976
LOW-COST SILICON SOLAR ARRAY PROJECT

AGENDA

- DESIGN REQUIREMENT OBJECTIVES
- APPROACH TO REQUIREMENT GENERATION
- TYPES OF REQUIREMENTS
  - FUNCTIONAL
  - PERFORMANCE
  - INTERFACE
  - ENVIRONMENTAL
LOW-COST SILICON SOLAR ARRAY PROJECT

APPROACH TO REQUIREMENT GENERATION

PROGRAM WIDE EFFORT TO:

• UNDERSTAND USER/SYSTEM NEEDS
• UNDERSTAND MODULE/ARRAY DESIGN FACTORS AND SENSITIVITIES
• UNDERSTAND MANUFACTURING FACTORS
• UNDERSTAND MARKETING FACTORS

LOW-COST SILICON SOLAR ARRAY PROJECT

DESIGN REQUIREMENT OBJECTIVES

PROVIDE FOCUS FOR LARGE SCALE PROCUREMENTS AND ARRAY R&D EFFORTS

• STIMULATE PERFORMANCE IMPROVEMENT (COMMERCIAL VIABILITY)
  • PRICE
  • RELIABILITY/LIFETIME
  • SAFETY/CONVENIENCE
  • ELECTRICAL/MECHANICAL PERFORMANCE
  • INTERCHANGEABILITY/ADAPTABILITY
• ENCOURAGE NEW DESIGNS AND TECHNOLOGY
• MINIMIZE RISK OF DEMO FAILURES
• PROVIDE SMOOTH CONTINUITY FROM CURRENT DESIGNS
LOW-COST SILICON SOLAR ARRAY PROJECT

TYPES OF DESIGN REQUIREMENTS

- FUNCTIONAL
- PERFORMANCE
- INTERFACE
- ENVIRONMENTAL

LOW-COST SILICON SOLAR ARRAY PROJECT

ENVIRONMENTAL (LIFETIME) REQUIREMENTS

- MAXIMIZE LIFE EXPECTANCY BY IDENTIFYING AND ALLEVIATING IMPORTANT FAILURE/DEGRADATION MODES
- PHYSICAL PROPERTY DEGRADATION
  - THERMAL CYCLE STRESSING
  - MOISTURE AFFECTS
  - MECHANICAL STRESSING (WIND, FOUNDATION)
  - ATMOSPHERIC OXIDENTS
  - SOLAR EXPOSURE (UV)
  - CORROSION (INTERNAL/EXTERNAL)
  - IMPACT LOADING (HAIL, ICE, ETC)
  - TEMPERATURE AFFECTS
- OPTICAL PROPERTY DEGRADATION
  - SOLAR EXPOSURE (UV)
  - DIRT COLLECTION
  - MECHANICAL EROSION (SAND, HAIL)
  - SURFACE OXIDATION
LOW-COST SILICON SOLAR ARRAY PROJECT

MODULE FUNCTIONAL REQUIREMENTS

• ADAPTABLE TO WIDELY VARYING APPLICATIONS
  • DIFFERENT POWER/VOLTAGE LEVELS
  • SYSTEM MECHANICAL CONSTRUCTION VARIATIONS
  • OPERATING ENVIRONMENT VARIATIONS
• COMPATIBLE WITH SAFE OPERATION AND MAINTENANCE
• COMPATIBLE WITH MAINTENANCE REQUIREMENTS
  • INTERCHANGEABILITY BETWEEN MODULES OF GIVEN MANUFACTURER
  • INTERCHANGEABILITY BETWEEN MANUFACTURERS
• PROVIDE OTHER FUNCTIONS
  • AESTHETIC/ARCHITECTURAL FUNCTIONS
  • WATER BARRIER (ROOF)
  • SOLAR HEATING PANEL
LOW-COST SILICON SOLAR ARRAY PROJECT

MODULE PERFORMANCE REQUIREMENTS

• CURRENT-VOLTAGE LEVEL AS INFLUENCED BY:
  • SYSTEM VOLTAGE/POWER REQUIREMENTS
  • LOAD VOLTAGE/POWER NEEDS
  • POWER CONDITIONING TRADES
  • STORAGE BATTERY VOLTAGE CHARACTERISTICS
• CIRCUIT MODULARITY (SERIES/PARALLELING)
• ADAPTABILITY (BUILDING BLOCK NEEDS)
• HANDLING CONVENIENCE (O&M)
  • PHYSICAL SIZE/WEIGHT
  • REPLACEMENT COST
  • SAFETY (VOLTAGE LEVEL)
• MODULE DESIGN FACTORS (COST TRADES)
• OPERATING TEMPERATURES

• CURRENT-VOLTAGE TOLERANCES (BOL/EOL)
  • MODULE INTERCHANGEABILITY

• SYSTEM PERFORMANCE (MISMATCH LOSSES)

• MODULE/CELL DESIGN SENSITIVITIES
  (MANUFACTURING TOLERANCES)

• OPERATING TEMPERATURES
LOW-COST SILICON SOLAR ARRAY PROJECT
MODULE INTERFACE REQUIREMENTS

• CONFIGURATION (ENVELOPE CONSTRAINTS)

• MECHANICAL ATTACHMENT
  • DESIGN
  • LOCATION WITH TOLERANCES
  • ACCESS

• ELECTRICAL TERMINATION
  • DESIGN
  • LOCATION (ACCESS)
  • CURRENT/VOLTAGE RATING

• GROUNDING/ISOLATION FROM GROUND
LOW-COST SILICON SOLAR ARRAY PROJECT

TYPICAL MEASURED MODULE TEMPERATURES

<table>
<thead>
<tr>
<th>MODULE SIZE</th>
<th>TYPICAL POWER (5 W/ft²)</th>
<th>TYPICAL VOLTAGE (3' CELLS)</th>
<th>TYPICAL WEIGHT (2 lb/ft²)</th>
<th>TYPICAL COST</th>
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<tbody>
<tr>
<td>FEET</td>
<td>WATTS</td>
<td>VOLTS</td>
<td>POUNDS</td>
<td>10$/W</td>
</tr>
<tr>
<td>2 x 2</td>
<td>20</td>
<td>17</td>
<td>8</td>
<td>200</td>
</tr>
<tr>
<td>2 x 4</td>
<td>40</td>
<td>34</td>
<td>16</td>
<td>400</td>
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<tr>
<td>4 x 4</td>
<td>80</td>
<td>68</td>
<td>32</td>
<td>800</td>
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<tr>
<td>4 x 8</td>
<td>160</td>
<td>136</td>
<td>64</td>
<td>1600</td>
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</table>
TASK 4
ARRAY
AUTOMATED ASSEMBLY
LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATED
ASSEMBLY TASK

TASK INTEGRATION MEETING

APRIL 27 and 28, 1976

W.A. HASBACH, TASK MANAGER
LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATED ASSEMBLY TASK

OBJECTIVES

• ESTABLISH AN ANNUAL PRODUCTION CAPABILITY
  > 500 MW/yr

• < $500/ KW

SOLAR ARRAY AUTOMATED ASSEMBLY TASK
PARTICIPATING ORGANIZATIONS

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>CONTRACT</th>
<th>PRINCIPLE INVESTIGATOR</th>
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<tbody>
<tr>
<td>PHASE I - TECHNOLOGY ASSESSMENT</td>
<td></td>
<td></td>
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<tr>
<td>• MOTOROLA CORP</td>
<td>#954363</td>
<td>DR. MICHAEL COLEMAN</td>
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<tr>
<td>• RCA LABORATORIES</td>
<td>#954352</td>
<td>DR. BROWN WILLIAMS</td>
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<tr>
<td>• TEXAS INSTRUMENTS</td>
<td>#954405</td>
<td>DR. BERNARD CARBAJAL</td>
</tr>
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<td>DEVELOPMENT AND EVALUATION OF SILICON CRYSTAL GROWTH AND WAFER PROCESSING</td>
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<tr>
<td>• TEXAS INSTRUMENTS</td>
<td>#954475</td>
<td>DR. SAM REA</td>
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<tr>
<td>HIGH RATE-LOW ENERGY CONSUMPTION PROCESSING OF SOLAR CELLS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• SIMULATION PHYSICS</td>
<td>#954289</td>
<td>ALLEN KIRKPATRICK</td>
</tr>
</tbody>
</table>
TECHNOLOGY ASSESSMENT - PHASE I

THREE PARALLEL CONTRACT EFFORTS HAVE BEEN INITIATED TO OBTAIN A RANGE OF CONCLUSIONS AND RECOMMENDATIONS

OBJECTIVES

- IDENTIFY THE MOST PROBABLE COST EFFECTIVE PROCESSES AND TECHNOLOGIES AVAILABLE FOR MASS-PRODUCTION OF SOLAR CELLS/MODULES
- DEFINE THOSE PROCESSES AND TECHNOLOGIES WHICH REQUIRE MODIFICATION AND/OR DEVELOPMENT
- PERFORM DETAILED COST ANALYSES TO SUPPORT THE TECHNICAL ASSESSMENT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK
MOTOROLA, TEXAS INSTRUMENT AND RCA

PHASE I - TECHNOLOGY ASSESSMENT

CONTRACT INVOLVE:

- ANALYSES OF SEMICONDUCTOR TECHNOLOGY AND MANUFACTURING PROCESSES
- IDENTIFICATION OF SPECIFIC REQUIRED TECHNOLOGY DEVELOPMENT
- DETAILED COST ANALYSES OF EACH POTENTIAL COST EFFECTIVE PROCESS
- CONCEPTUAL APPROACHES FOR MASS-PRODUCTION OF SOLAR CELLS AND MODULES

CURRENT STATUS

- IDENTIFICATION AND CATALOGING OF SEMICONDUCTOR PROCESSES WHICH COULD BE AMMENABLE TO LOW-COST, LARGE-VOLUME PRODUCTION HAS BEGUN
- COST MODELS BY WHICH EACH PROCESS WILL BE EVALUATED ARE BEING DEVELOPED BY THE CONTRACTORS
SOLAR ARRAY AUTOMATED ASSEMBLY TASK
DEVELOP AND EVALUATION OF SILICON CRYSTAL GROWTH AND WAFER PROCESSING
TEXAS INSTRUMENTS, INC.

CONTRACT INCLUDES:

A. DEVELOP COST EFFECTIVE METHODS FOR THE PRODUCTION OF LARGE DIAMETER WAFERS

B. WAFERS ARE TO BE SLICED FROM SILICON CRYSTALS GROWN BY A MELT-REPLENISHMENT PROCESS
   • CRYSTAL DIAMETER 12 CENTIMETERS
   • CRYSTAL GROWTH RATE 12 CENTIMETERS PER HOUR
   • CRYSTAL WEIGHT 9 KILOGRAMS
   • USABLE SINGLE CRYSTAL YIELD 60% OF POLYCRYSTALLINE INPUT
   • OUTPUT PERFORMANCE PER FURNACE HEAT 3 SINGLE CRYSTALS (INGOTS)

C. INVESTIGATE THE EFFECTS ON WAFER QUALITY AND COST THAT FOLLOW FROM A RANGE OF CRYSTAL SAWING PARAMETERS.

D. DEVELOP AN ECONOMIC MODEL THAT WILL REFLECT THE IMPACT, ON SOLAR CELL COST AND QUALITY, BY VARIATIONS IN THE CRYSTAL GROWTH AND WAFFERING PROCESSES

CURRENT STATUS

PROGRAM PLAN IS BEING PREPARED FOR REVIEW APRIL 30TH
SOLAR ARRAY AUTOMATION ASSEMBLY TASK
SIMULATION PHYSICS

HIGH RATE, LOW ENERGY CONSUMPTION PROCESSING OF SOLAR CELLS

CONTRACT INCLUDES:

• ION-IMPLANTED JUNCTION FORMATION
• LOW ENERGY ELECTRON BEAM ANNEAL OF ION-IMPLANTED JUNCTION AND OHMIC CONTACT SINTERING
• DEMONSTRATE TOTAL PROCESSING TIME (EXCLUDING HANDLING AND TRANSFER OPERATIONS) TO BE LESS THAN 30 SECONDS PER cm² OF CELL AREA
• DEMONSTRATE DIRECT PROCESSING ENERGY OF ALL FORMS INCIDENT UPON THE CELL BEING PROCESSED AS LESS THAN 58 WATT HOURS/METER² OF CELL AREA

CURRENT STATUS

• CELLS OF 9.5% AMO EFFICIENCY HAVE BEEN MANUFACTURED (CONTRACT GOAL IS 11% AMO)
• CELL PROCESS OPERATING TIME FOR N⁺ P P⁺ CELL
  - FURNACE PROCESSING, MEASURED TIME 5732 SECONDS
  - PULSED ELECTRON BEAM PROCESSING, MEASURED TIME 1968 SECONDS
• OPTIMIZATION STUDIES ARE CONTINUING
## LOW-COST SILICON SOLAR ARRAY PROJECT
### TASK 4 - AUTOMATED ASSEMBLY OF ARRAYS
#### TASK PLAN

<table>
<thead>
<tr>
<th>START</th>
<th>1st yr</th>
<th>3rd yr</th>
<th>5th yr</th>
<th>8th yr</th>
<th>10th yr</th>
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</thead>
<tbody>
<tr>
<td>COMPLETE TECHNOLOGY ASSESSMENT</td>
<td>COMPLETE PROCESS DEVELOPMENT</td>
<td>COMPLETE DESIGN AND DEVLPMT OF FACILITY(S) AND EQUIPMENT</td>
<td>DEMONSTRATE TECHNOLOGICAL READINESS</td>
<td>FULFILL PROJECT GOALS*</td>
<td></td>
</tr>
<tr>
<td>ESTABLISH REQUIREMENT FOR PRODUCTION</td>
<td></td>
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</table>

* GOALS
- INDUSTRY CAPABILITY OF 500 mW PER YEAR
- PRICE OF $500 PER KW

DBB-1
4-28-76
PHASE 1  ASSESS TECHNOLOGY

a) TECHNOLOGY ASSESSMENT PLAN
b) ANALYZE EXISTING TECHNOLOGIES
c) EVALUATE COST EFFECTIVE OPTIONS
d) IDENTIFY COST/TECHNOLOGY OBSTACLES
e) CONCEPTUAL SOLUTIONS TO OBSTACLES
f) DEMONSTRATE COST EFFECTIVE TRADE-OFFS OF SOLUTIONS
g) DEFINE THE MOST COST EFFECTIVE ARRAY FABRICATION/ASSEMBLY PROCESS

PHASE 2  DEVELOP TECHNOLOGY
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 4 INTERFACES

LEGEND:
△ TASK 1
□ TASK 2
▽ TASK 3
○ TASK 4

DB8-3
4-28-76
LOW-COST SILICON SOLAR ARRAY PROJECT
A METHOD FOR HANDLING INTERFACES

• List decisions required for selection of most cost effective manufacturing method

• List influences upon each decision

• Analyze each influence regarding costs
  
  If influence depends upon a decision known to be unavailable, analyze change of cost as a function of the variable(s) most probable from the pending decision

LOW-COST SILICON SOLAR ARRAY PROJECT
ADVANTAGES TO METHOD OF EVALUATING IN TERMS OF VARIABLES

• Work proceeds without waiting for resolution of prerequisites

• Keeps processes ready for technological breakthroughs

• Allows evaluation of alternative processing methods
LOW-COST SILICON SOLAR ARRAY PROJECT

HYPOTHETICAL COST INFLUENCE PLOT

COST (PER GIVEN CELL SIZE)

EVAPORATE METAL

- - - - -

SILK SCREEN

ENCAPSULATE

ANTI-REFL COAT

ELECTROLESS NICKEL

DIFFUSION

ROUGHNESS, in microns

0.1 1 10 100 1000 10,000

DB3-6
4-28-76
LOW-COST SILICON SOLAR ARRAY PROJECT
TYPICAL DECISION OPTION

UNRESOLVED DECISION: SILICON WITH OR WITHOUT SUBSTRATE
OPTIONS TO BE COSTED IF SILICON IS ON SUBSTRATE; (SEQUENCES)

• DIFFUSION
  DIFFUSE
  PHOTOMASK (BACK)
  ETCH TO BACK
  PHOTOMASK (FRONT AND BACK)
  ETCH FRONT OXIDE
  METALLIZE

• GETTERING DIFFUSION
  DIFFUSE
  REMOVE OXIDE
  PHOTOMASK (BACK)
  ETCH TO BACK
  PHOTOMASK (FRONT AND BACK)
  METALLIZE
  A-R COAT

• ION IMPLANT
  ION IMPLANT
  ANNEAL
  PHOTOMASK (BACK)
  ETCH TO BACK
  PHOTOMASK (FRONT AND BACK)
  METALLIZE
  A-R COAT

DBB-7
4-28-76
TASK 5
LARGE-SCALE PRODUCTION
LOW-COST SILICON SOLAR ARRAY PROJECT
LARGE SCALE PRODUCTION TASK

TASK INTEGRATION MEETING

E.A. SEQUEIRA, TASK MANAGER

APRIL 27, 1976
LOW-COST SILICON SOLAR ARRAY PROJECT
LARGE SCALE PRODUCTION TASK
OBJECTIVES

OVERALL OBJECTIVES:

• PROVIDE ERDA (LeRC) WITH 11.11 MEGAWATTS OF SOLAR CELL MODULES OVER THE NEXT 10 YEARS

• ADVANCE STATE-OF-THE-ART TECHNOLOGY AND EFFECT A PRICE REDUCTION IN THE PROCUREMENT OF SOLAR CELL MODULES

• UTILIZE THE EXPERIENCE ACQUIRED TO ASSIST IN THE TECHNOLOGY DEVELOPMENT OF OTHER LSSA TASKS

1975 - 1976 OBJECTIVE

• PROVIDE ERDA (LeRC) WITH 170 KW OF SOLAR CELL MODULES
LOW-COST SILICON SOLAR ARRAY PROJECT
CURRENT STATUS

- THE CONTRACTORS DELIVERED A TOTAL OF 0.89 KW OF SOLAR CELL MODULES TO JPL
- DELIVERED A TOTAL OF 2.8 KW OF SOLAR CELL MODULES TO LeRC
- COMPLETED MOST OF ENVIRONMENTAL TESTS; 100 THERMAL CYCLES PLUS 168 HOURS OF HUMIDITY
- COMPLETED INSPECTION SYSTEM PLAN
- COMPLETED & DELIVERED A SET OF SOLAR CELL MODULE DRAWINGS
- DELIVERED 20 SOLAR CELLS TO BE USED FOR STANDARDS & FOR TEMPERATURE COEFFICIENT MEASUREMENTS
- ASSEMBLED & DELIVERED SOLAR CELLS MOUNTED ON COPPER SUBSTRATE TO BE USED FOR SPECIAL TEST

INCORPORATED MODULE DESIGN CHANGES REQUESTED BY JPL TO EASE MODULE MOUNTING ON FRAMES FOR DEMONSTRATION TESTS
LOW-COST SILICON SOLAR ARRAY PROJECT
CURRENT STATUS

CONTRACT ACTIVITIES

SOLAR POWER CORP.
TOTAL POWER 15 kW
MODULE RATING 14.47W, 9.2V MIN.

M7 INTERNATIONAL
TOTAL POWER 3 kW
MODULE RATING 5W, 9.2-10.0V

SENSOR TECHNOLOGY
TOTAL POWER 8 kW
MODULE RATING 5W, 9.2-10.0V

EAS-3
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
CURRENT STATUS (contd)

CONTRACT ACTIVITIES

SPECTROLAB
TOTAL POWER 10 kW
MODULE RATING 5W, 9.2-10.0V

SOLAREX
TOTAL POWER 10 kW
MODULE RATING 9.2W, 7.0V

DRAWINGS DEPICT MODULE OUTSIDE
DIMENSIONS ONLY

EAS-4
4-27-76
# Low-Cost Silicon Solar Array Project Schedule

<table>
<thead>
<tr>
<th>Module Power</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
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<tbody>
<tr>
<td>Solar Power Corp. (15 kW)</td>
<td>14.5W</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>260</td>
<td>320</td>
<td>320</td>
<td>97</td>
<td></td>
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<tr>
<td>M7 International, Inc. (3 kW)</td>
<td>5W</td>
<td>5</td>
<td>15</td>
<td>200</td>
<td>200</td>
<td>180</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sensor Technology, Inc. (8 kW)</td>
<td>5W</td>
<td>95</td>
<td>350</td>
<td>480</td>
<td>480</td>
<td>195</td>
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<tr>
<td>Spectrolab (10 kW)</td>
<td>5W</td>
<td>10</td>
<td>110</td>
<td>450</td>
<td>500</td>
<td>250</td>
<td>180</td>
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<tr>
<td>Solarex (10 kW)</td>
<td>9.2W</td>
<td>10</td>
<td>120</td>
<td>210</td>
<td>340</td>
<td>240</td>
<td>156</td>
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<tr>
<td><strong>Total Power Delivered (kW)</strong></td>
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<td>0.24</td>
<td>1.56</td>
<td>4.9</td>
<td>16.8</td>
<td>29.6</td>
<td>41.5</td>
<td>45.1</td>
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EAS-5
4-27-76
LOW-COST SILICON SOLAR ARRAY PROJECT
INTRA TASK MEETING

• SCHEDULED THIS AFTERNOON AT 1:15 IN BAXTER HALL
• DISCUSSIONS RELATING TO ADMINISTRATIVE ITEMS SUCH AS:
  • REPORTS; REQUIREMENTS, VOLUME, CONTENTS, FREQUENCY,
  • ADEQUACY
  • PROBLEMS RELATING TO COMMUNICATION OF INFORMATION
• DISCUSSIONS RELATING TO THE TECHNICAL ASPECT OF THE PROGRAM
  FOCUSING ON:
  • COMMON INDUSTRY PROBLEMS
  • DISCUSSIONS RELATING TO CELL AND MODULE ELECTRICAL
    MEASUREMENTS
• DISCUSSIONS RELATING TO ENVIRONMENTAL TEST REQUIREMENTS
• DISCUSSIONS RELATING TO QUALITY CONTROL REQUIREMENTS AND
  PROCEDURES
• DISCUSSIONS AND SUGGESTIONS REGARDING OTHER ITEMS YOU
  MAY BRING UP TO ASSIST IN MEETING THE OBJECTIVES OF THE
  TASK

EAS-7
4-27-76
INTERTASK AND INTRATASK MEETINGS
# LOW-COST SILICON SOLAR ARRAY PROJECT
## TASK 1 & 2 INTERFACE MEETING
### 28 APRIL 1976
#### AGENDA

<table>
<thead>
<tr>
<th>TIME</th>
<th>SPEAKER</th>
<th>SUBJECT</th>
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<tbody>
<tr>
<td>8:30 am</td>
<td>J. ZOUTENDYK, CHAIRMAN</td>
<td>OBJECTIVES OF INTERFACE MEETING</td>
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<tr>
<td>8:50</td>
<td>T. DIGGES, LEADER</td>
<td>PRESENTATION OF INTERFACE SUBJECTS</td>
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<tr>
<td>9:50</td>
<td>J. ZOUTENDYK</td>
<td>DISCUSSION OF KEY INTERFACE TOPICS</td>
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<td>• CHARACTERIZATION</td>
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<tr>
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<td>• IMPURITIES</td>
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<tr>
<td></td>
<td></td>
<td>• FORM OF Si MATERIAL</td>
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<tr>
<td></td>
<td></td>
<td>• Si MATERIAL SAMPLES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• STATE-OF-THE-ART INFORMATION</td>
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<td>10:00</td>
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JZ-9
4-27-76
INTERTASK MEETING TASKS 1 + 2

- NEED FOR SEGREGATION COEFFICIENT DATA
  - LITERATURE INCORRECT
  - DEPENDENCE ON RATE

- IMPURITY EFFECTS
  - PROCESS DEPENDENCE ON TASK 1 INFORMATION

- TASK 1
  - ENLARGE MATRIX
  - CONCENTRATION LIMITS
  - CONTINUING DETN EFFECTS IMPURITIES/PROCESSING
  - DEFECT INTERACTIONS

- TASK 2
  - INFO ON IMPURITIES IN MTL
  - EFFECTS GROWTH RATE/Mechanism

RL-4
4/2/76
GENERAL NOTES

• TECHNICAL PRESENTATIONS
  • TOO LITTLE TIME
  • INTER TASK -- SELECTED SUBJECTS
  • INTRA TASK -- AVOID REPETITION

• GENERAL PROJECT MEETING
  • WHAT'S NEW?
    • PROGRAM - PROJECT/ERDA
    • BUDGET - PROJECT/ERDA
    • LESS FREQUENT

• OTHER MEETINGS
  • SMALLER GROUP AT INTEGRATION MTG.
  • WORKSHOP - LIFETIME MEASUREMENTS

• PROBLEMS
  • MATERIAL AVAILABILITY FROM TASK 1
  • IMPURITY/PROCESSING/LAS INFO. LOOPS

RL-5 4/20/76
LASS TASK 2

SUMMARY OF TASK 1 - 2 INTERFACES

- Delineation of impurity-related growth anomalies by:
  - Early identification of most likely impurities resulting from each purification process being investigated (qualitative or quantitative)
  - Providing samples of Si material to sheet growth contractor as soon as possible

- Solar cell and material properties due to impurities may be vastly different in CZO/FZ material as compared with ribbon/sheet/ingot forms under investigation

- Impurity analysis service needed from a centralized laboratory (for both CZO/FZ and ribbon/sheet/ingot)

JZ
4/21/74
SUMMARY OF TASK 1-2 INTERFACES

• FORM OF SILICON MATERIAL DESIRED
  
  • EFG, CAST, IST, HEM (MT, IBM, RCA, CSI)
    • PELLETS 1 - 10 mm DIAMETER
  
  • WEB-DENTRITIC (USC, WEST.)
    • HOCKEY PUCKS/RODS
  
  • DIP-COATING (HON.)
    • ROCKS
  
  • CVD (GE, RI)
    • HIGH PURITY SILANE (IN CLEAN CONTAINERS)
  
  • RTR (MOT.)
    • RIBBON
  
  • HOT-FORMING (UP)
    • SOLID SLABS/CYLINDERS
      (FOR <1 m WIDE ROLLERS)
SILICON MATERIAL TASK — INTERTASK MEETING TASKS 1, 2, AND 4

In the intertask meeting involving Tasks 1, 2, and 4 there were two extended presentations: An Overview of The Common Interfaces and Decisions by Don Bickler of JPL and a Description of SAMIS by Bob Chamberlain of JPL.

An outline of the decisions and interfaces dealing with the areas of impurities, base dopant type, substrates for solar cells, and solar cell thickness and surface roughness was discussed by Don Bickler of JPL. The complexity of the tradeoffs and the involvements of the programs of the various tasks of the project were apparent. The questions and the responses emphasized these factors.

The description of SAMIS, a procedure for cost analysis using a computer program and model simulations, was given by Bob Chamberlain of JPL. The analyses using SAMIS will be made available through JPL publications, such as conference proceedings and other periodic reports. The operation of SAMIS through the 1990 era by incorporating new technologies was stated to illustrate the projected utility of this procedure.
LOW-COST SILICON SOLAR ARRAY PROJECT
DECISIONS INTERFACING TASKS 1, 2 AND 4

• SILICON IMPURITIES
• N ON P vs P ON N
• SILICON, ON SUBSTRATE OR NOT
• SILICON THICKNESS
• GRAIN SIZE
• SURFACE ROUGHNESS
LOW-COST SILICON SOLAR ARRAY PROJECT
Task 1, 2 And 4
Silicon Impurities Decision

Primary Influences:

- Cost of Raw Materials
- Cost of Processing

Synergistic Influences:

- Ease of Processing into Sheets
- Cost ($/Watt) of Processing into Solar Cells
  - N On P vs P On N
  - Junction Formation
  - Back Contact System
  - Impurity Gettering
  - Deposition of Pure Material over Impure Material
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 1, 2 AND 4
N on P vs P on N DECISION

FEASIBILITY INFLUENCE

• DOPING IMPURITIES IN SILICON MATERIAL

COST INFLUENCES:

• JUNCTION FORMATION
• BACK SURFACE
• BACK CONTACT
• FRONT CONTACT
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 1, 2 AND 4
SILICON SUBSTRATE DECISION

FEASIBILITY

• PROCESSES UNDER STUDY BY TASK 2

COST INFLUENCES:

• CELL ELECTRICAL EFFICIENCY
• BACK CONTACT METHOD
• ENVIRONMENTAL STABILITY
• STRUCTURAL ADVANTAGE
• RAW MATERIAL REQUIREMENTS

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LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 1, 2 AND 4
SILICON IMPURITIES DECISION

COST INFLUENCES:

• CELL ELECTRICAL EFFICIENCY

• SHEET FABRICATION METHOD

• RAW MATERIAL COST
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 1, 2 AND 4 GRAIN SIZE DECISION

FEASIBILITY

• CAN MULTI GRAIN SILICON BE USED?

COST INFLUENCES:

• SILICON THICKNESS
• CONDUCTING GRID REQUIREMENT
• JUNCTION FORMATION
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 1, 2 AND 4
SURFACE ROUGHNESS DECISION

COST INFLUENCES:

• METALLIZATION REQUIREMENTS
• OPTICAL COATING REQUIREMENTS
• MECHANICAL STRENGTH
• CLEANING DIFFICULTIES
• SURFACE APPLIED CHEMICALS
  • PHOTO RESIST
  • PAINT ON DIFFUSANTS
  • ENCAPSULANTS/SEALANTS
INTER-TASK MEETING
TASKS 1 + 2 + 4

- JPL ANALYSES AND ACTIVITIES - QUARTERLY
  AND OTHER REPORTS

- $500/KW
  - DERIVED CHERRY HILL WORKSHOP
  - 1985 INTERMEDIATE GOAL
  - NATIONAL ENERGY NEED/PROGRAM UNDER
    CONTINUAL EVALUATION

- SAMIS
  - USABLE FOR TECHNOLOGY UNDER DEVELOPMENT
  - INPUTS FROM CURRENT TECH/GOALS
  - WILL BE PUBLISHED

RL - C
4/23/76
SUMMARY OF TASK 2 - 4 INTERFACES

• **TASK 4 SHOULD NOT LIMIT THEIR AUTOMATION STUDIES TO "CZO-LIKE" PROCESSING**

• **INFORMATION REGARDING CHARACTERISTICS OF VARIOUS RIBBON/SHEET/WAFER WILL BE AVAILABLE AS GROWTH WORK PROCEEDS**

• **COST PROJECTIONS OF SILICON AREA SHOULD BE DONE ON AN ITERATIVE BASIS BY THE INDIVIDUAL GROWTH CONTRACTORS (TO 1985).**
LOW-COST SILICON SOLAR ARRAY PROJECT
DECISIONS INTERFACING TASKS 3, 4 AND 5

- SILICON ON SUBSTRATE OR NOT
- SILICON THICKNESS
- SILICON SURFACE ROUGHNESS
- ANTI-REFLECTIVE COATING
- ENCAPSULANT
- MODULE SUBSTRATE
- CELL INTERCONNECTOR
- METALLIZATION
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
SILICON SUBSTRATE DECISION

FEASIBILITY

• PROCESSES UNDER STUDY BY TASK 2

COST INFLUENCES:

• CELL ELECTRICAL EFFICIENCY
• BACK CONTACT METHOD
• ENVIRONMENTAL STABILITY
• STRUCTURAL ADVANTAGE
• RAW MATERIAL REQUIREMENTS

LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
SILICON THICKNESS DECISION

COST INFLUENCES:

• CELL ELECTRICAL EFFICIENCY
• SHEET FABRICATION METHOD
• RAW MATERIAL COST
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
SURFACE ROUGHNESS DECISION

COST INFLUENCES:

- METALLIZATION REQUIREMENTS
- OPTICAL COATING REQUIREMENTS
- MECHANICAL STRENGTH
- CLEANING DIFFICULTIES
- SURFACE APPLIED CHEMICALS
  - PHOTO RESIST
  - PAINT ON DIFFUSANTS
  - ENCAPSULANTS/SEALANTS

LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
ANTI-REFLECTIVE COATING DECISION

COST INFLUENCES:

- JUNCTION FORMATION OXIDE
- SURFACE ROUGHNESS
- ENCAPSULANT
- APPLICATION METHOD
ENCAPSULANT DECISION

DESIGN INFLUENCES:
- GLASS COVER OPTION
- BACK PLATE OPTION

COST INFLUENCES:
- CONTACT VULNERABILITY
- SURFACE REFLECTIONS
- INTERCONNECTOR DESIGN

MODULE SUBSTRATE DECISION

DESIGN INFLUENCES:
- MODULE SIZE
- STRUCTURAL REQUIREMENT
- THERMAL EXPANSION

COST INFLUENCES:
- INTERCONNECTOR FLEXIBILITY
- SILICON CELL STRUCTURE
- DIELECTRIC REQUIREMENT
- ENCAPSULANT
  - FLEXIBILITY
  - DURABILITY
  - STRUCTURAL CONTRIBUTION
LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
CELL INTERCONNECTOR DECISION

COST INFLUENCES:

• CELL METALLIZATION
• SUBSTRATE THERMAL EXPANSION
• CELL SIZE
• ELECTRICAL RESISTANCE
• ENCAPSULANT FLEXIBILITY
• CELL ASSEMBLY METHOD

LOW-COST SILICON SOLAR ARRAY PROJECT
TASK 3, 4 AND 5
CELL METALLIZATION DECISION

DESIGN COST INFLUENCES:

• METHOD OF APPLICATION
  • EVAPORATION
  • SILK SCREEN
  • ELECTRO PLATE
  • ELECTRO LESS PLATE
  • STAMP

• METAL CHOICE
  • SINGLE LAYER
  • MULTI LAYER
  • SOLDER COATED

PROCESS COST INFLUENCES:

• N LAYER OR P LAYER
• JUNCTION PENETRATION
• GRID LINE DEFINITION
• SURFACE ROUGHNESS
• INTERCONNECTOR STRESSES
• BACK SURFACE TREATMENT
PROJECT INTEGRATION MEETING
INTRA-TASK MEETING

ACCELERATED/ABBREVIATED TESTING

- NECESSITY
- DIFFICULTIES
  - COMPLEXITY
  - INTERACTIONS
- APPROACHES
  - SOME KEY TOOLS AVAILABLE
- STATISTICAL SIGNIFICANCE

"THE THINGS THAT WILL DESTROY
THE SOLAR CELLS WILL BE THOSE
WHICH NOBODY ANTICIPATED" ----
INTEGRATION MEETING

CLARIFICATIONS

• RECOGNITION OF ENCAPSULATION SYSTEM -- NOT JUST TRANSPARENT COVER

• OUTPUT OF STUDY 2 -- ENV. ANAL. & DEF.
  USE FOR MATERIAL TEST
  BASE FOR JPL TO DEVELOP MODULE REQMTS.

INTEGRATION MEETING

ENCAPSULATION TASK NEEDS

• DESIGN IMPLEMENTATION FOR MODULES

• INFO ON OBSERVED FAILURES

• FOCUS ON REQTS, HAZARDS, ETC -- TO DEFINE ENCAP REQTS

• COST EFFECT FACTORS
INTEGRATION MEETING

CURRENT AND ANTICIPATED DEGRADATION RATES ARE TOO HIGH -- NEED TO REDUCE TO ACCEPTABLE LEVELS

FOR EXAMPLE:
- DELAMINATION
- CORROSION
- SHORTED JUNCTION
- MECHANICAL EFFECTS
- CHANGE MECH PROP
- OPTICAL
  - DARKENING
  - SURFACE EFFECTS
  - DIRT ACCUMULATION

APPROACH & SOLUTION TO EACH REQUIRES TECHNICAL/COST INTERFACES WITH OTHER PROJECT ELEMENTS

WFC-6

INTEGRATION MEETING

KEY ISSUES

- EFFECTIVE INTERACTION WITH MANUFACTURERS

FAILURES & FAILURE ANALYSIS
  TO MFG OF FAILED PARTS
  TO OTHER MFG'S
  TO POTENTIAL MFG'S

MATERIALS & PROCESSES INFO -- TIMELY

- IMAGE -- EMPHASIS ON "FAILURES"

EFFORT
PUBLICATION
PUBLICITY

WFC-7
LSSA PROJECT
INTER-TASK MEETING - 3, 5, D&T

AGENDA

INTRODUCTION
CARROLL
SEQUIERA

DESIGN REQTs FOR SOLAR ARRAY MODULES
ROSS

ENV. ANALYSIS & DEFINITION
CARROLL

DISCUSSION
ALL

LSSA PROJECT
INTER-TASK MEETING 3, 5 D&T

OBJECTIVES

- IDENTIFY & ESTABLISH INTERFACES
- DESCRIBE RELATED PROJECT ACTIVITIES
- IDENTIFY INTERFACE PROBLEMS
ENCAPSULATION TASK CONTRACTORS

BATTELLE

D. CARMICHAEL
G. GAINES
R. THOMAS
J. SLIEMERS
C. KISTLER

PROGRAM MANAGER
PI STUDIES 1, 3, 4
PI STUDY 2; STAT ANAL., STUDY 4
POLYMERIC MATERIALS - STUDY 1
INORGANIC MATERIALS - STUDY 1

ROCKWELL

J. FARRAR
J. KOLYER
N. MANN

PROGRAM MANAGER
PI
STAT ANALYST

DeBELL & RICHARDSON

B. BAUM

PROGRAM MANAGER

SIMULATION PHYSICS

A. KIRKPATRICK

PROGRAM MANAGER

PROF. CHARLES ROGERS

CONSULTANT, CASE WESTERN
LSSA PROJECT
DESIGN & TEST
JPL TECHNICAL TEAM

RON ROSS D & T MANAGER
DICK GRIFFI MECHANICAL CONFIGURATION
DON MOORE STRUCTURAL ANALYSIS
AL WEN THERMAL ANALYSIS
ABE CANTU ELECTRICAL TERMINATION/CABLING
JIM ARNETT USER SURVEYS
ERNY COSTAGUE ELECTRICAL DESIGN
GIL HERRERA FIELD TESTING
PETE JAFFE FIELD TEST LEADER

LSSA PROJECT
ENCAPSULATION TASK
JPL TECHNICAL TEAM

W. CARROLL MATL ENGR/TASK MANAGER
H. MAXWELL MATL ENGR/TECH MGR - BATTELLE CONTRACT
J. MOACANIN POLYMER SCI/TECH MGR - ROCKWELL CONTRACT
E. CUDDIHY POLYMER SCI/TECH MGR - DE BELL & RICHARDSON CONT.
R. HOLTZE MATL ENGR/TECH MGR - SIMULATION PHYS CONTRACT
C. GONZALEZ ENV ANAL & DEF/ENV REQTS
M. SALAMA STR & DYN ANAL/STAT ANAL
H. PATTERSON CONTRACTS NEGOTIATOR
TASK SUMMARIES
SILICON MATERIAL TASK

SUMMARY

The first phase of the program for the Silicon Material Task is comprised of Part I for the Development of Semiconductor Grade Si Processes, Part II for the Definition of Solar Cell Grade Si, and Part III for the Development of Solar Cell grade Si Processes. The major efforts of the program are being performed under contract. A JPL in house program supports some elements of the contracts.

The contracts with Battelle, Union Carbide, Westinghouse Electric, Monsanto, and Lamar University have been underway about six months. The programs of each of these contracts permits considerable data and information together with preliminary analyses and conclusions to be presented at this meeting. The contracts with Texas Instruments, Motorola, and Stanford Research Institute are not yet at this stage.

In the contract with Battelle Memorial Institute, a conservative approach has led to cost estimations of $9.12/Kgm of Si for the Zn/SiCl_4 process and to greater than $20/Kgm of Si for each modification of the SiI_4 process considered. The optimization of these processes would reduce these values but would not result in changing the relative economic positions. Calculations of energy-uses have yielded energy pay back values of 2.2 months for the Zn/SiCl_4 process and less than 10.6 months for one of the SiI_4 process alternatives. Experimental data support the contention that both processes are technically feasible for producing semiconductor grade Si. On the basis of the economic analysis, BMI has recommended that no further work be done on the SiI_4 process and that a SiCl_4 process miniplant, based on the use of fluidized bed reactors, be used to obtain process operation information.

In the contract with Union Carbide for the development of a redistribution process for producing SiH_4 experimental investigations of several of the reactions involved have been carried out. Initial results using a laboratory scale redistribution reactor have shown that 12-15 mole % of SiH_4 is produced under conditions of a 5 second contact time at 60°C. Investigations to develop processes for producing chlorinated silanes to be used as a feed for the redistribution reactors have provided preliminary results that the Cu catalyzed
hydrogenation of SiCl$_4$ and reaction with metallurgical grade Si yields 21-22 mole % of SiHCl$_3$ with 5.7 second contact time in a fluidized bed; the early results for the direct synthesis of SiH$_2$Cl$_2$ could not be reproduced. Studies of these reactions to obtain data for process decisions are continuing. Concurrently, the design of a miniplant for the production of 10 lb. of SiH$_4$ per day has been completed.

In the contracts with Westinghouse and Monsanto the effects of impurities on the properties of Si material and solar cells are being determined in efforts to define solar cell grade Si. Some preliminary conclusions have been derived in each contract.

In the contract with Monsanto the data, which were obtained during the preparation of Czochralski ingots, are being used to calculate solubility and segregation constants. All of the single impurity Float Zone ingots have been prepared, and it has been shown that C, Mn, Ni, and Mg are compatible elements. The cells fabricated from FZ ingots are generally about 22% more efficient than those from Cz. Other preliminary conclusions are: the presence of O$_2$ is detrimental to lifetimes and to cell efficiencies; Ni, Mn, Mg, and C seem to increase cell performance; Ti destroys cell performance; and most metallographic tests show unusual etchpit formations and distributions.

In the contract with Westinghouse all first generation, 90% of the second generation, and several third generation ingots have been completed. Ingots containing Cu/Mn, Cu/Cr, and Mn/Cr doping have also been prepared. The composition analyses are consistent with the impurity level targets with the exceptions of Ti and V, which were 30% low; Zr, which was low by a factor of two; and Mg and Zn. All wafers, which were subsequently processed into cells, exhibited low dislocation densities of <10$^3$, and sometimes <10$^2$. Data for cells from ingots doped to about 10$^{15}$ atoms/cc have shown relative cell efficiencies, compared to cells from baseline material doped only with B, of: Cu-1.0, Ni-0.9, Zr-1.0, Cr-0.75, Mn-0.71, Fe-0.53, V-0.39, and Ti-0.25.

In the contract with Lamar University preliminary data collection for the Si-source materials in the SiH$_4$, Zn/SiCl$_4$, and SiI$_4$ processes is nearly complete; efforts for the SiF$_4$ processes have started. Data for the critical
constants and physical properties of SiH₄ have been tabulated; several critical constants are missing. Economic analyses have proceeded with the procurement of data sources for equipment, and capital investment estimation methods have been examined.

Contracts are underway with Texas Instruments for an Investigation of the Use of a Plasma Heater for the C-Reduction of SiO₂, with Motorola for an Investigation of the SiF₄ Transfer Process, and with Stanford Research Institute for an Investigation of a Duplex Process for the Na Reduction of SiF₄.
The interfaces of Tasks 1 and 2 were discussed in a presentation by Dr. Tom Digges of JPL. The interrelationships of impurities, large area sheet processing, and material and cell properties were stressed.

The main discussion dealt with concerns about the differences in the ranges of concentrations of impurities and rates of crystallization being investigated in Part II of Task 1 and those of direct, special interest to the sheet process developers of Task 2. Particular cases were cited, and it was apparent that extreme conditions of concentrations and rates were not covered in Task 1. However, the objective of Part II of the Task is to determine the effects of impurities on the characteristics of Si single crystal material and of solar cells, as well as the concomitant effects of certain processes on impurity concentrations, and to provide this information as a basis for trade-off analyses for Si material process developments and LSSA. Therefore, the information applicable to special crystallization process conditions can only be obtained by making provisions for separate studies wither in Task 1 or in Task 2. Several contractors of Task 2 expounded on their need for such data.

Some Task 2 contractors also declared that the specific impurities in the Si products resulting from the chemical process developments of Task 1 need to be specified so that proper investigations of the crystallization processes could be conducted. The need for this information seemed to be universal among the Task 2 contractors, and everyone was in agreement that the mechanisms of the various crystallization processes under development would be affected to some degree by impurities. In response it was pointed out that this information would not be available until the Si material developments had reached the stage of demonstrating technical feasibility, a time which varied for different contracts and would be attained by some at the end of 1976.

The mutual requirements for data and information of Tasks 1 and 2 were repeatedly made obvious by the questions and comments. It is apparent that a combined Task 1 and Task 2 technical session in which progress reports and extended technical discussions were scheduled would be valuable and would complement similar, but not repetitious, sessions for each Task.
SILICON MATERIAL TASK INTRATASK MEETINGS

In the first of two Intratask Meeting technical sessions, presentations were made that described the data, analyses, and conclusions obtained so far. These presentations were made by M. F. Browning of Battelle, W. C. Breneman of Union Carbide, R. H. Hopkins of Westinghouse, D. E. Hill of Monsanto, and C. L. Yaws of Lamar University. Summaries of these progress reports are given in pages 74 through 80 of these proceedings. Progress summaries on the Motorola and TI Contract efforts were also submitted, though not presented orally.

In the second Intratask Meeting the discussions dealt with subjects and problems, which had been introduced at the intertask meetings with Task II and with Tasks II and IV, as well as with suggestions for the next project integration meeting. The investigations of the effects of the interplay of processing and impurities on material and cell characteristics were of particular concern. The involvement of those participating in Task I was generalized as being in three areas: (1) impurities in the Si produced in the processes under development; (2) the performance of solar cells as a function of impurities (and the effects of cell fabrication processes on impurities), and the adventitious introduction of impurities during large area sheet and cell processing. Although the program of Part II of Task I includes studies of this interplay and an extensive information base for trade-off analyses will be obtained, data for some extreme conditions will have to be secured separately to meet particular needs of the large area sheet processes. As an example, the investigations being conducted in Part II include the determination of the segregation coefficients of some impurities under conditions of limited ranges of concentrations as well as rates and means of crystallization; separate studies would be required to secure segregation coefficient data for the extreme conditions of concentrations and rates and methods of crystallization of the processes being developed in Task II.

The group advocated that the Task I intratask session at the next project integration meeting be extended in time, utilizing the same format of detailed technical presentations and full discussions and that selected technical subjects of mutual interest be treated in a similar manner in intertask sessions. The subsequent interface discussions should then be of more value and pertinence.
LARGE-AREA SILICON SHEET

John A. Zoutendyk

SUMMARY

The Large Area Silicon Sheet Task is designed to aid in the development of silicon growth techniques which will eventually result in low-cost, high efficiency solar arrays. The present activity within the task is centered around research and development of specific growth methods which are considered as viable candidates for the stated application.

There are now in progress ten, R&D contractural efforts pursuant to the study of unique growth technologies. Brief summaries written by each contractor regarding progress mode during the last quarter (January-March, 1976) are contained in the following pages of this document. The overall contract work is proceeding according to the individual program plans. As anticipated at the first TIM, growth and/or slicing machine construction have all been completed on all contracts and silicon growth and/or slicing activity is in progress.

In addition to the work being done under contract, there is complimentary work being performed at JPL in the form of silicon material characterization, crystal growth studies, refractory materials studies and thermal analyses of liquid-solid crystal growth. Work in these areas has commenced during the last quarter.

Activity during the three months prior to this Project Integration Meeting has yielded significant progress toward demonstrating technical feasibility in the areas of ribbon growth, sheet growth, and ingot growth and cutting. The following paragraphs summarize the highlights of major accomplishments.

Shaped ribbon growth has been observed at 7 cm/minute pull speed under non-equilibrium (thermal) conditions but with meniscus stability. A preferred equilibrium growth orientation has been observed by two laboratories (Mobil-Tyco and IBM). Thermal control for optimization of growth velocity and minimization of residual stress within the ribbon structures is a key problem and is being addressed in the form of thermal analyses and heat shield design.

Sheet growth from a silicon melt (dip-coating) has resulted in the growth of silicon layers containing large (1 mm wide by 1-2 cm long) crystallites. Continuous growth areas of 20 cm² have been achieved on carbon-covered mullite substrates.

Quasi-static ingot growth by directional solidification has been done using silicon for the first time. Present results are very preliminary, but seeded crystal growth has been observed in its primary stage (i.e., at the seed-melt interface). Multiple-blade ingot cutting experiments have shown that increased cutting rates can be achieved by decreasing blade thickness (i.e., lower kerf loss is accompanied by higher cutting rates).
LASS TASK 2

SUMMARY OF INTRA-TASK MEETING

• MATERIAL CHARACTERIZATION
  
  • BULK MATERIAL CHARACTERIZATION SHOULD BE USED TO DIAGNOSE SPECIFIC GROWTH-RELATED PROPERTIES (E.G., RECOMBINATION AT GRAIN BOUNDARIES)
  
  • SOLAR CELL EVALUATION AN IMPORTANT TOOL FOR MATERIAL DIAGNOSIS
  
  • STRUCTURAL ANALYSES VERY IMPORTANT SINCE MOST GROWTH PROBLEMS ARE STRUCTURE RELATED

• SOLAR CELL TESTING
  
  • OUTDOOR SUNLIGHT TESTING PREFERRED
  
  • JPL WILL SUPPLY SECONDARY TERRESTRIAL STANDARD CELLS
  
  • NO "STANDARD" SOLAR CELL PROCESSING -- VARIOUS CONTRACTORS ESTABLISHING PROCESSES
LASS TASK 2

SUMMARY OF INTRA-TASK MEETING

- CONTRACT REVIEW
  
  - THERMAL STRESSES IN HIGH SPEED RIBBON A MAJOR CONCERN

  - SPREADING RESISTANCE INCREASE AT GRAIN BOUNDARIES OBSERVED BY IBM (NOT AT TWINS)

  - "V"-SHAPED DIE FOR STAPANOV PROCESS (RCA) HAS MULTIPLE APPLICATIONS (E.G., VARIATION OF SLOT WIDTH)

  - GOOD BONDING AND LARGE GRAINS DEMONSTRATED BY DIP-COATING PROCESS

  - HIGH PURITY CARRIER (AND REACTANT) GAS IMPORTANT FOR CVD (E.G., CLEAN TANKS)

  - NASA WEB-DENTRITIC PROGRAM DISCUSSED.
LASS TASK 2

• NEXT QUARTER'S ACTIVITY
  • OPERATION OF CONTRACTOR GROWTH FACILITIES FOR STUDY OF GROWTH TECHNIQUES ACCORDING TO PROGRAM PLANS
  • MATERIAL, CHARACTERIZATION, REFRACTORY MATERIAL STUDIES, CRYSTAL GROWTH STUDIES, THERMAL ANALYSES (LIQUID-SOLID GROWTH) AT JPL ACCORDING TO TASK PLAN.

RECOMMENDED ACTIONS
  • UPDATING OF SI MATERIAL IMPURITY INFORMATION FROM TASK 1 (JPL)
  • ESTABLISH BASELINE COST MODELS AND PREDICTIONS FOR VARIOUS GROWTH TECHNIQUES (CONTRACTORS/JPL)
LSSA PROJECT
ENCAPSULATION TASK
QUARTERLY SUMMARY

CONTRACTS

During the Quarter, three additional contracts have been negotiated, in accordance with the technical plans developed last summer. The contracts are:

1) Rockwell International. To experimentally evaluate accelerated and abbreviated test methods. This will compliment the more analytically oriented effort at Battelle. Contract started 4th week in March. Preliminary design of test specimen is completed and detail program plan is being prepared.

2) DeBell and Richardson. To study properties, processing and aging of polymeric encapsulant materials and to use high-stress testing to evaluate encapsulation systems utilizing these materials. Contract expected to start early May.

3) Simulation Physics. To examine the feasibility of utilizing electrostatically bonded integral glass covers as the transparent part of the encapsulation system. Contract expected to start early May.

Progress at Battelle during the Quarter is summarized in the attached.

INTERFACES

A preliminary list of interfaces, developed during the last Quarter of CY'75, was presented and discussed at the Encapsulation Task session of the January Integration meeting. Based on that discussion and subsequent evaluation, the list has been expanded and definition improved.

ENVIRONMENTAL ANALYSIS

Analysis capability, based on Battelle methodology development, is being established at JPL. This capability will be used for environmental analysis of additional sites if required as well as to perform special analyses in support of project requirements.
Four studies of the Encapsulation Task of the LSSA Project are assigned to Battelle-Columbus Laboratories. Three of the studies were in progress during the first quarter of 1976; the remaining study is being initiated in the second quarter. Progress in each of the active studies is summarized separately.

**Study 1. Evaluation of World Experience and Properties of Materials for Encapsulation of Terrestrial Photovoltaic Arrays**

World experience in solar-array encapsulation is being drawn from the published literature, material suppliers, solar-array fabricators, array users, and from site visits. In addition to a summary of world experience, the program is to provide a list of candidate materials and processes for the total encapsulant system, the selection being based upon such criteria as present and projected availability, known and potentially achievable properties, suitability for automated production, and cost.

In the information collection and analysis portion of the study, emphasis this quarter was placed on the experience of related applications with encapsulation material and processes. Data-bank interrogation was expanded substantially to include glass and polymeric protective systems for such applications as integrated circuits, photo devices, reflectors, lenses, transparent structural components, pottants, and coatings. Additionally, emphasis was placed on obtaining nonpublished information through site visits to array fabricators and users. The experience collected to date was summarized. A tentative selection was made of candidate materials for specific encapsulant functions, such as protective covers, adhesives, and coatings.

**Study 2. Definition of Encapsulant Service Environments and Test Conditions**

Climatic, insolation, and air pollution data were processed for the following geographic locations: Albuquerque, New Mexico; Bismarck, North Dakota; Boston, Massachusetts; Brownsville, Texas; Cleveland, Ohio; Fairbanks, Alaska; Los Angeles, California; Miami, Florida; and Phoenix, Arizona. The data analyses consist of several parts. The descriptive statistics include the means, standard deviations, maximums, and minimums for available climatic, insolation, and air pollution measurements by hour of day at 3-hour intervals, by month, for the years 1965-1974. The weather events consist of counts of the total number of occurrences.
of fog, drizzle, rain, thunderstorms, etc., over the same 10-year period. The frequency-and-duration analyses consist of determining how often a particular environmental condition occurred, how long it lasted, and what condition occurred next. The conditions analyzed to date include several combinations of variables, one such combination being temperature, relative humidity, wind speed, and insolation. The expected number of occurrences for specific conditions over a 20-year period was also estimated, together with approximate 95 percent confidence limits. Preliminary efforts were made to identify those environmental conditions which should be considered as part of the test conditions suitable for abbreviated and accelerated tests for encapsulant materials.

Study 3. Evaluation of Test Methods and Determination of Properties of Candidate Encapsulation Materials

Study 3 is being initiated in the second quarter of 1976.


Study 4 constitutes the initial efforts toward the development of accelerated/abbreviated tests for the eventual encapsulant system, or systems, of solar arrays. The specific objectives of Study 4 are (1) to review and evaluate current practices and methodology for accelerated/abbreviated testing and to identify available aging data for polymeric and glass materials that may be appropriate for present conceptions of the eventual systems and (2) to develop and demonstrate, on the basis of statistical analyses of existing aging data, accelerated/abbreviated test methods to predict the performance and aging characteristics of encapsulant systems over a 20-year life under environmental conditions set forth in Study 2.

In this initial quarter of the study, emphasis was placed on early identification and retrieval of relevant documents on methodology, aging data, and weathering tests. Based on an extensive search for relevant documents, approximately 500 are marked for collection and review; about 100 have been received. In addition, a critical review was made of weathering tests in both natural and artificial weathering environments, and those factors which are expected to control sensitively aging performance.
TASK 4 PRESENTATIONS

The automated assembly task participants discussed the merits of presenting cost data for manufacturing processes in a parametric manner. This method has the advantage of permitting processes analyses by Task 4 contractors to continue until specific detailed data is available from the other tasks of the Project.

The discussion focused about the interfacing diagram (viewgraph number DBB-3). The circles are presented as decisions which Task 4 needs to resolve before any given design of solar cells can be automated. (More than one design is being pursued.) Decisions involving other tasks have the appropriate symbols superimposed upon the circles of Task 4. The lines connecting the decisions are considered lines of influence and are intended to show the interdependence of the decisions.

Some of the viewgraphs shown under the automated assembly task were used in more than one session. Don Bickler gave three presentations in three separate sessions in which different combinations of viewgraphs were used. To save space three complete sets are not included in this document. The viewgraphs used for the three sessions are numbered as follows:

Auto Assembly intratask session — DBB 1 through 7;
Tasks 3, 4, and 5 intertask session — DBB 3 through 7 plus DBB B1 through B9;
Tasks 1, 2, and 4 intertask session — DBB 3 through 7 plus DBB A1 through A7
INTRODUCTION

The primary objectives to be accomplished during the first year, Technology Assessment Phase, include the identification of the most cost effective processes and technologies which are available today; within the semiconductor industry, that could be applicable to the mass production of solar cells and solar cell module manufacturing. From this study of available processing know how and present state-of-the-art technology, certain areas of limited manufacturing expertise and technology related to photovoltaics will become visible. These areas of limited understanding or experience will be identified, and potential solutions described for development during later Phases of this Task, or other Tasks of the LCSSA Project. Underlying the entire importance of the Technology Assessment Phase is the requirement for detailed cost analyses, which will identify the extent to which each process under evaluation can contribute to meeting the goals set forth by the Project. If the Project cost or mass production goals cannot be achieved, then the technology must be evaluated to determine the extent to which developments must take place to meet the Project goals.

WORK DEFINITION

Five Contractors are directly involved in evaluating various technologies to contribute to achieving high-volume, low-cost production of solar cells/array modules as part of Task 4. Three Contractors (Motorola, Texas Instruments and RCA), are working under contracts of "Common Statements of Objectives," to assess current technology, and evaluate its potential for meeting the Project goals.

A second contract issued to Texas Instruments deals with a considerable advancement in the present state-of-the-art crystal growth technology, known as the Czochralski method; as well as development of improved slicing of Czochralski ingots into wafers.

Simulation Physics conceived processing techniques by which it is anticipated that 11% AMO solar cell processing costs can be reduced toward $10.00 per peak kilowatt and energy expenditure in processing to approx. 3 Kilowatt-hrs per peak Kilowatt of solar panel capacity.

CURRENT STATUS

The current status of each contract under the technical supervision of Task 4 is shown in the following attachments:

I. Motorola - Contract No. 954363
II. Texas Instruments - Contract No. 954405
III. RCA Corporation - Contract No. 954352
IV. Texas Instruments - Contract No. 954475
V. Simulation Physics - Contract No. 954289
Attachment I - Motorola Corp.

**ABSTRACT**

Design criteria for efficient solar cells were investigated, emphasis being given to front metal surface pattern and texture etched front surfaces. This work on solar cell design has pointed to the desirability of multiple contacts on a solar cell for improved performance. The use of a textured surface can have a large effect on optical absorption; in addition, it interacts with other parameters to affect the internal cell design for optimal performance.

A generalized processing matrix, containing competing methods for solar cell manufacturing steps, was set up as an aid to the continuing technology assessment study. The steps in this processing matrix are discussed and characterized according to immediate and potential usefulness. Representative steps have been chosen for empirical evaluation. A group of eight processes has been selected for initial process adaptation study. These processes are texture etching, photolithography, silicon nitride, diffusion, ion implantation, electroless nickel plating, solder coating, and phosphorus gettering.
LOW-COST SILICON SOLAR ARRAY PROJECT
AUTOMATED SOLAR ARRAY ASSEMBLY TASK
PHASE I - FIRST QUARTER 1976
CONTRACT NO. 954405

SUMMARY

First quarter effort focused on preparing baseline cost estimates for current solar cell processing technologies, preparing an initial design-to-cost goal breakdown, designing and initiating construction of an experimental solar cell module, and initiating the various activities that make up this task. A standard set of cost assumptions have been defined for use in baseline cost estimation. Each candidate process element will be evaluated using this standard set of cost assumptions. The baseline cost estimates show that current solar cell fabrication technology is about an order of magnitude too expensive as compared to the design-to-cost goals.

The design-to-cost concept is used to measure the overall effectiveness of low-cost silicon solar cell module improvements. The design-to-cost goal is $500 per peak kilowatt in 1985 with an annual production output of 500 megawatts peak power. The key to the LSSA Project is the ability to meet this integrated cost goal. The Automated Solar Array Assembly Task is the obvious focal point for assessing the overall success of the program.
ABSTRACT

We have begun our study for the Automated Array Assembly Task by simultaneously evaluating present manufacturing techniques using expenses based on experience and studying basic cost factors for each step to evaluate expenses from a first-principles point of view. We have developed a formal cost accounting procedure which will be used throughout the study for cost comparisons. The first test of this procedure was a comparison of its predicted costs for array module manufacturing with costs from a study we performed which was based on experience factors. In that study we estimated a manufacturing cost for array modules of $10/W, based on present day manufacturing techniques, expenses, and materials costs. Our first principles cost estimate based on existing manufacturing techniques will be described. The array module configuration which was costed out will be given.

In every area of array module fabrication, the materials cost and capital and labor requirements are being accumulated to provide the basis of a variational approach to establishing the lowest cost process using existing technology.
LOW-COST SILICON SOLAR ARRAY PROJECT

Second Task Integration Meeting

Large Area Czochralski Silicon
Texas Instruments Incorporated
Contract No. 954475

Technical Accomplishments

The effective date of this contract was 30 March 1976. This contract is to demonstrate rapid growth, slicing, and shaping of Czochralski crystal, thereby providing low cost wafers for subsequent solar cell fabrication.

The primary goals of this program are:

Crystal: 12 cm diameter grown at 12 cm/hour from a 12 kg crucible with an overall 60% yield.

Sawing: Utilize a multiblade slurry saw and optimize parameters to produce 250 micron thick wafers from 12 cm diameter crystal.

Shaping: Investigate laser shaping of 12 cm wafers and define requirements for scribing at an edge rate of 10 cm/s.

Characterization: Analyze and evaluate relevant properties of the crystal and slices which may affect solar cell performance.

Economics: Develop a baseline economic model of the Czochralski wafering process and update periodically to demonstrate cost effectiveness of the overall process.

Due to the recent start date of this program, technical progress to date is nil. Efforts have concentrated on establishing the detailed program plan, baseline cost estimate, personnel assignments, and equipment acquisition. Extrapolations of pull rate, melt size, and sawing speed, assuming successful completion of this program and $10/kg polysilicon, indicate that a Czochralski wafering process can provide an acceptable, low cost product for cell fabrication.
Attachment V - Simulation Physics

STATUS REVIEW - APRIL 1976
HIGH RATE, LOW ENERGY EXPENDITURE
FABRICATION OF SILICON SOLAR CELLS

Simulation Physics, Inc.
Burlington, Mass. 01803

ABSTRACT

Program effort during the past three months has involved development of individual process steps of the simplified all vacuum sequence for cell fabrication. Included have been the following:

(i) Investigation of phosphorus ion implantation parameters for junction formation.

(ii) Identification of satisfactory boron ion implantation parameters for P⁺ layer at back contact interface.

(iii) Examination of large area electron pulse conditions for anneal of damage associated with above implants.

(iv) Evaluation of all aluminum contacts using pulse sintering.

Cells fabricated under the room temperature processing sequence continue to be characterized by satisfactory currents and curve factors but open circuit voltages remain at least 30 mV lower than those obtained by conventional processing of similar ion implanted cell structures.

Program study to minimize processing time required for cell fabrication has been initiated. Cells prepared by room temperature procedures now require less than 10 percent of the processing operation duration associated with more conventional procedures. The goal of 120 seconds for fabrication of a 2 x 2 cm cell is being approached.
LARGE-SCALE PRODUCTION

TASK 5 SUMMARY

The overall objectives of Task 5 are to provide ERDA (LeRC) with 11.11 megawatts of solar cell modules over the next ten-year period and to advance the state-of-the-art technology to effect a price reduction in the cost of solar cell modules. In addition, the experience acquired in these activities will be utilized to assist in the technology development of other LSSA tasks. The 1976 objective is to provide ERDA (LeRC) with approximately 170 KW of solar cell modules.

The approach used to accomplish the objectives was to initiate a series of procurements with each consecutive procurement reflecting increased module quantities. The first procurement was for a total of 46 KW and is underway with module deliveries contracted with the following companies:

- Solar Power Corporation 15 KW
- Solarex Corporation 10 KW
- M7 International 3 KW
- Spectrolab, Inc. 10 KW
- Sensor Technology, Inc. 8 KW

A similar multiple-contracts approach will be used to procure a second block of modules totaling 130 KW with the exception that a two-month period will be devoted to design and development.

The Task 5 status shows that qualification modules have been received from all contractors, environmental tests have been conducted at contractors facilities and at JPL, and 2 KW of solar cell modules have been delivered to LeRC for the ERDA Demonstration Program. Proposal review for the 130 KW procurement is in the final stages with contractor selection anticipated in early May 1976.
The Intra-Task Meeting proceeded in accordance with the agenda outlined in Vugraph EAS-1. Summary of the discussion that took place during the meeting is presented in the attached vugraphs, two through five. Vugraph 6 shows a summary of the work planned to be accomplished by Task 5 in the immediate future.
AUTOMATED ASSEMBLY TASK

TOPICS DISCUSSED INCLUDED:

• NEED FOR A COMMON ECONOMIC MODEL
• PARAMETRIC COST VS. VARIABLES
• NEED FOR CIRCULATION OF REPORTS FROM OTHER ERDA SPONSORED PROGRAMS (LEWIS AND SANDIA)
• FUTURE TASK INTEGRATION MEETINGS
• DESIGN AND TEST REQUIREMENTS INTERFACE
• JPL IN-HOUSE ACTIVITIES & RESULTING REPORTS

AREAS OF SPECIAL INTERESTS THAT WERE SURFACED:

• CONCERN OVER THE LACK OF MARKET DEFINITION
  • SHORT-TERM
  • LONG-TERM

• STATE-OF-THE-ART MODULE FAILURE MODES AND ANALYSES
AREAS OF UNCERTAINTY RESOLVED:

• PROCESS RANKING WILL BE BY PARAMETRIC COST PRESENTATION WHEN SPECIFIC SELECTION IS LACKING.

PROBLEMS & LIMITATIONS

• NEED FOR CORRELATION & COEFFICIENTS IN THE ECONOMIC MODEL TO ACCOMMODATE SYNERGISTIC EFFECTS

• HOW DETAILED OR DESCRIPTIVE CAN A PROCESS DEFINITION BECOME BEFORE INPUT PARAMETERS ARE ESTABLISHED?
AREAS OF UNCERTAINTY LEFT UNRESOLVED

- MODULE DESIGN
- STANDARDIZED COST SYSTEM
- ENVIRONMENTAL REQUIREMENTS

ACTIONS RECOMMENDED
FOR THE NEXT TASK INTEGRATION MEETING:

- CONTRACTOR QUARTERLY REPORTS
- CONTRACTORS SHOULD BE SOLICITED TO RESPOND TO SPECIFIC ISSUES
- MORE INTER-TASK CROSSTALK BETWEEN CONTRACTORS
TASK 5 SUMMARY

- REPORTING REQUIREMENTS AND COMMUNICATION OF INFORMATION
  - NO CONCERN EXPRESSED ASSOCIATED WITH TASK REQUIREMENTS
  - NO CONCERN EXPRESSED RELATING TO TECHNOLOGY INFORMATION FROM OTHER TASKS
  - EXPRESSED NEED TO KNOW ABOUT THE APPLICATION OF THE MODULES IN THE LeRC TEST AND DEMONSTRATION PROGRAM
  - EXPRESSED NEED TO KNOW ABOUT PERFORMANCE OF MODULES IN THE FIELD AS SOON AS AVAILABLE.

- DISCUSSIONS RELATING TO TECHNICAL ASPECTS OF PROGRAM
  - CONCERN EXPRESSED BY ALL THAT THE JPL VOLTAGE REQMT IS NOT CONSISTANT WITH COMMERCIAL REQUIREMENTS
  - CONTRACTORS TO SUBMIT VOLTAGE PREFERRED AND THE RATIONALE FOR THE SELECTION BY LETTER TO THE TASK 5 MANAGER
  - CONCERN EXPRESSED REGARDING ERDA SUPPLYING MODULES TO THE COAST GUARD AND THE FAA

- CONTRACTORS EXPRESSED POSSIBILITY THAT COST OF SILICON WILL INCREASE DUE TO INCREASED DEMAND.
- JPL SHOULD MAKE SILICON SUPPLIERS AWARE OF THE ERDA SOLAR ENERGY PROGRAM
- CONTRACTORS SUGGESTED THAT JPL INVESTIGATE THE CAPACITY OF SUPPLIERS TO PRODUCE POLY-SILICON, ENCAPSULANTS AND OTHER PERTINENT MATERIALS.
- DISCUSSION WAS CARRIED OUT ON THE IMPORTANCE OF RELATING LABORATORY ENVIRONMENTAL TESTS TO ACTUAL FIELD EXPERIENCE.
TASK 5 SUMMARY

DISCUSSIONS ON TOPICS NOT IDENTIFIED IN AGENDA

• CONTRACTORS EXPRESSED DESIRE TO WORK ON LONG-TERM PRODUCTION

• HOW DOES INDUSTRY FEEL ABOUT SUPPLYING MODULES TO DOD THROUGH JPL AS OPPOSED TO DEALING WITH DOD DIRECTLY. CONTRACTOR RESPONSE WAS THAT THEY PREFER TO WORK THROUGH JPL AT THE PRESENT TIME.

• GENE RALPH, SPECTROLAB, ASKED MANUFACTURERS INTEREST IN SETTING UP AN INDUSTRY ASSOCIATION OF SOLAR ARRAY MANUFACTURERS OR ELSE JOINING THE EXISTING SEIA (SOLAR ENERGY INDUSTRY ASSOCIATION) FOR THE PURPOSES OF ESTABLISHING STANDARDS, TERMS, AND DEFINITIONS.
  • JPL WILL FOLLOW UP ON THIS SUGGESTION.
TASK 5
INTER-TASK MEETING SUMMARY

- TASK 5 CONTRACTORS EXPRESSED CONCERN ABOUT THE APPROACH TASK 4 IS FOLLOWING IN ACHIEVING AUTOMATION. TASK 4 APPROACH APPEARS TO DETERMINE CELL MANUFACTURING TECHNIQUES AND DESIGN. THE ARRAY MANUFACTURER SHOULD SELECT HIS DESIGN AND MODE OF OPERATION BASED ON INFORMATION PROVIDED BY THE DEVELOPMENT PROGRAM.

- TASK 5 CONTRACTORS EXPRESSED NEED FOR IMMEDIATE REPORT OF FAILURES. FAILURE REPORT WILL BE MADE AVAILABLE TO EACH TASK 5 CONTRACTOR RELATING TO THEIR PRODUCT. OTHERS WILL BE INFORMED BY MEANS OF QUARTERLY REPORT PUBLICATION.
LOW-COST SILICON SOLAR ARRAY PROJECT
FUTURE PLANS

• CONTINUE MODULE DELIVERY ON THE 46 KW PROCUREMENT
• CONTINUE WORK TO ESTABLISH STANDARDS
  • CORRELATE STANDARD CELLS WITH LeRC
  • DEVELOP SECONDARY STANDARD CELLS
  • DETERMINE TEMPERATURE COEFFICIENTS
• INITIATE PROCUREMENT ON THE 130 KW
• CONTINUE IN-HOUSE TESTS
  • THERMAL CYCLING
  • HUMIDITY
  • FUNGUS
  • FIELD TEST
APPENDIX A

The U. S. Photovoltaic Conversion Program*

Leonard M. Magid
Division of Solar Energy
Energy Research and Development Administration
Washington, D. C. 20545

SUMMARY

The overall objective of the U. S. Photovoltaic Conversion Program within the Division of Solar Energy of the Energy Research and Development Administration (ERDA) is to develop low-cost reliable photovoltaic systems and to stimulate the creation of a viable industrial and commercial capability to produce and distribute these systems for widespread use in residential, commercial and governmental applications.

To assist in achieving this goal, this program has the following specific objectives: (1) conduct research, development and demonstrations to establish a factor of forty reduction in solar array prices (to $500/peak kWe) by 1986; (2) conduct a focused research and development effort on novel materials and devices to show the feasibility of a reduction in solar array prices of one hundred or greater (to $100 to $300/peak kWe) by 1986 and to establish the viability of this advanced technology by the year 2000; (3) develop concentration systems to demonstrate early low-cost electrical (and thermal) power generation systems; (4) continue systems and applications studies to further optimize the cost-effectiveness of photovoltaic energy conversion systems; and (5) conduct tests and demonstrations of governmental, residential, commercial, industrial and utility-type photovoltaic systems to establish their viability and stimulate their wide-scale acceptance. The program plan to achieve these objectives is described and the major ten-year planning milestones are identified.

*This paper was presented at the International Colloquium on Solar Electricity, Toulouse, France, March 1-5, 1976
INTRODUCTION

Solar Photovoltaic Conversion Systems (SPCS) are based on the direct conversion of the sun's energy to electricity through the use of photovoltaic or "solar" cells. The principles behind the operation of SPCS components are widely understood, basically through the experience gained with their use in the space program. With the development of new, less expensive means of producing components, SPCS have the potential of providing a significant source of clean and renewable energy.

The two major problems that must be overcome before the use of SPCS can be widespread are:

* High Cost—Terrestrial photovoltaic panels now sell for approximately $21,000 per peak kWe.

* Low Production—The terrestrial SPCS market in the U.S. for 1975 was estimated to be 100 peak kWe.

The National Photovoltaic Conversion Program intends to overcome these problems and to achieve significantly higher annual production rates of lower-cost SPCS. The major goals in this regard are the establishment of total plant capacity capable of producing at least:

* 500 peak MWe per year of solar array modules at a market price of less than $500 per peak kWe by FY 1986.

* 50,000 peak MWe per year of solar array modules at a market price of $100 to $300 per peak kWe by FY 2000.

The attainment of the second goal should lead to a total operating capacity of about 20,000 MWe of electricity, or approximately 3% of the estimated electrical power demand of the Nation in the year 2000. This, in turn, would account for a savings of nearly one million barrels of oil daily.*

*For SPCS with 10% overall efficiency, yearly peak to 24 hour average insolation ratio of five, total area to collector area ratio of two, and a peak insolation of 1 kW/m², this could be achieved with about 800 square miles of SPCS arrays.
OBJECTIVES OF THE PROGRAM

The general objective of the ERDA Photovoltaic Conversion Program is to develop low-cost reliable SPDS and to stimulate the creation of a viable industrial and commercial capability to produce and distribute these systems for widespread use in residential, commercial and governmental terrestrial applications. A program has been developed to achieve the following specific objectives:

- Conduct research, development and demonstrations to establish a factor of forty reduction in solar array prices (to $500 peak kWe) by 1986.
- Conduct a focused research and development effort on novel materials and devices to show the feasibility of a reduction in solar array prices on one hundred or greater (to $100 to $300 peak kWe) by 1986 and to establish the viability of this advanced technology by the year 2000.
- Develop concentration systems to demonstrate early low-cost electrical (and thermal) power generation systems.
- Continue systems and applications studies to further optimize the cost-effectiveness of photovoltaic energy conversion systems.
- Conduct experimental tests and demonstrations of photovoltaic power systems for a variety of governmental residential, commercial, industrial and utility-type applications to establish the viability of these systems and stimulate their wide-scale acceptance.

PROGRAM STRUCTURE

The structure of the ERDA Photovoltaic Conversion Program designed to implement these objectives is shown in Figure 1.

The principal programmatic emphasis at this time is on the research, development and demonstration of low-cost reliable silicon arrays. These are devices for which the technical feasibility for stable electric power systems has been well established both within the space program and by the existing terrestrial solar cell industry. The intent is to develop by 1986 the technological and industrial capability to produce silicon solar arrays at an annual rate of more than 500 peak MWe with an efficiency greater than 10% and a price of less than $500 per peak kWe.
A second and parallel program thrust is in the novel materials and device area. This element is aimed at developing lower-cost and/or more efficient alternatives to single crystal silicon devices. Current emphasis now is on obtaining a better understanding of a variety of thin-film photovoltaic materials, including: Silicon, Cadmium Sulfide/Copper Sulfide, Gallium Arsenide, Indium Phosphide and other II-VI and III-V semiconductor compounds. Studies on other novel photovoltaic systems such as Schottky-barrier, MIS and inversion devices are also within this element. As the viability of each new material and/or device is established, it will be blended into the testing and demonstration element of the program.

Studies will also be conducted on the use of optical concentrators to reduce the costs of photovoltaic power systems by reducing the number (or size) of solar cells required to provide electrical power or to provide combined electrical and thermal outputs in photovoltaic total energy systems.

The testing, evaluation and demonstration of the performance of photovoltaic systems, subsystems, materials and devices, as well as the collection of insolation data at sites throughout the country and the establishment of standards for solar cell performance, reliability and lifetimes are included in the test and demonstration element of the program.

The power conditioning and storage element of the program will identify specific requirements for solar cells when used in electric power systems, particularly with respect to the need for storage to compensate for the day-night solar cycle and effects that transient conditions such as cloud cover and bad weather impose on storage systems. In addition, this area must also analyze the constraints imposed upon the system design by utility-grid interfacing problems including the conversion of low voltage DC output to AC.

Finally, the structure and content of the SPCS program will be guided by continuing mission analysis studies aimed at evaluating alternative applications for photovoltaic systems and their major subsystems, identifying the most promising ones and establishing the pertinent cost and performance goals. System design and analysis studies will be conducted concurrently and will lead to conceptual designs for photovoltaic systems in three broad categories: (1) on-site residential systems (2 to 10 peak kW); (2) intermediate level systems (100 peak kW to 10 peak MW); and (3) central-station utility systems (50 to 1,000 peak MW). These studies should lead to the identification and resolution of critical subsystem interface problems. A series of studies to determine possible economic, environmental, social, or legal impacts (and associated constraints) resulting from large-scale deployment of photovoltaic power systems will also be undertaken.
PROGRAM PLAN

A program plan that addresses the technical and institutional problems of SPCS over the next ten years is presented in the planning milestones shown in Figure 2. This plan consists of the milestone schedules for seven major programs elements: Systems and Applications, Low-Cost Silicon Arrays, Concentrator Systems, Test and Demonstrations, Novel Materials and Devices, Storage and Power Conditioning and Assessment of Goals.

Primary emphasis is being placed initially on tasks to improve technical design, efficiency, reliability, lifetimes and energy payback times of photovoltaic solar arrays through silicon technology development. Particular stress will be placed on: production of low cost silicon material and large area silicon sheets; array encapsulation materials and techniques; improved cell and environmentally-satisfactory array design; and high-volume, cost-effective automated array assembly techniques. By FY 83 it is expected that pilot plants will be established with the capability for producing in excess of 5 million square meters per year of silicon sheet to be sold at less than $18 per square meter. By FY 84, industrial facilities with the capability for producing approximately 2000 metric tons per year of silicon material at a market price of less than $10 per kilogram are anticipated. By FY 86 a total plant capacity should be established capable of producing in excess of 500 MWe peak per year of encapsulated solar array modules at a market price of less than $500 per peak kWe. Figure 3 gives the projected price goals for this effort.

Concurrent with the silicon effort, emphasis will also be placed on the focused research and development of alternative photovoltaic materials, devices and concepts in the novel materials and device element that show promise of meeting the program's long-range goal of achieving 50,000 peak MWe/yr. of solar array modules at a market price of $100 to $300 per peak kWe by FY 2000. Studies will be conducted through FY 86 on improving the understanding and control of the basic growth and nucleation processes of a variety of promising thin-film materials and devices, including: polycrystalline silicon, cadmium sulfide/copper sulfide, gallium arsenide, indium phosphide and other interesting II-VI and III-V compounds. Studies on other novel photovoltaic systems such as Schottky-barrier, MIS and inversion devices are also within this element.
## 10-Year Planning Milestones

**Solar Photovoltaic Conversion Program**

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<td><strong>Large Scale Prod.</strong></td>
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<td>502 kW</td>
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**Legend:**
- ESTAB.: Established
- DEL.: Delivery
- INIT.: Initiation
- ACHEV.: Achieved
- DEVEL.: Development
- SCALE UP: Scale Up
- DECISION: Decision
LOW-COST SILICON SOLAR ARRAY PROJECT
TERRESTRIAL SOLAR ARRAY
PRICE GOALS

DOLLARS
PER WATT

CALANDAR YEAR

ARRAY FABRICATION
CELL MANUFACTURE
SLICING
INGOT/SHEET GROWTH
SILICON MATERIAL

CZECHRALSKI INGOT TECHNOLOGY
SHEET TECHNOLOGY WITH AUTOMATION

A-10
Heavy emphasis in these studies will be on the trade-offs with respect to conversion efficiency, reliability, stability, lifetime, utilization of natural resources, energy payback times and the overall economics of the most promising of the advanced photovoltaic technologies in a continual search for the best state-of-the-art candidates for reaching the program's long range goals.

By FY 80, one or more thin-film cells are expected to demonstrate 10% energy conversion efficiency, and by FY 86 the feasibility of achieving the $100 to $300 per peak kWe array price goal is expected to be demonstrated by one or more of these devices.

Studies and experiments will also be undertaken over the next ten years to examine the technology limitations and the design and cost trade-offs of photovoltaic concentrator systems. Emphasis will be placed on: high-temperature cell design; concentration, tracking and cooling techniques; the determination of optimal concentration ratios as functions of available insolation as well as cell and structure costs; and the added benefits gained by the combined electrical and heat energies generated in photovoltaic total energy systems.

The first generation of concentrating photovoltaic systems is expected to produce electricity at/or below $2,000 per peak kWe by FY 78. Subsequent price goals in this area are: $1,000 per peak kWe by FY 80, $500 per peak kWe by FY 82, and $250 per peak kWe by FY 86.

The testing and evaluation of the various photovoltaic materials, devices, systems and subsystems developed within the program was initiated in FY 75 and will continue throughout its duration. A standards laboratory has been established to perform exposure and life tests on arrays and materials, and establish failure mechanisms and accelerated endurance tests.

A major portion of the test and demonstration element of the program is dedicated to a series of federally-sponsored prototype tests and experimental demonstrations of a wide variety of photovoltaic conversion systems. The test and demonstration systems under current consideration within the program begin with a plan for 90 peak kWe of military applications (to be conducted in cooperation with the DOD) and an additional blend of special and governmental applications of semi-remote civilian power systems (to be conducted in cooperation with other Federal agencies and local municipalities), both to be initiated in FY 76. As the DOD and other agencies pick-up the sponsorship of the cost-effective elements of these tests, the ERDA testing will turn to the larger residential, commercial and central-station systems to be conducted in cooperation with utilities and private industry throughout the remainder of the 10-year program plan.
More specifically, the key elements of the current 10-year ERDA-sponsored test and demonstration plan are:

- A total of approximately 90 peak kWe of ERDA-supplied solar arrays will be applied to military applications during FY 76 and 77. This will include supplying electrical power to small battery charges, intrusion systems, a communications van, remote radar sites, a water purification system and a significant fraction of the grid power of a remote island military base.

- Special and governmental applications of photovoltaic systems will also begin in FY 76. Solar arrays will be applied to a variety of civilian electrical power systems that show promise both of early commercial cost-effectiveness and of stimulating otherwise untapped early photovoltaic markets.

- The initial phase of the photovoltaic system test facility will be in operation in FY 76, and will extend to its full capacity of 100 peak kWe through FY 79. This facility will continue to test new photovoltaic systems throughout the program's duration.

- A residential prototype system is scheduled to be initiated in FY 77, and to be followed in future years by a series of regional residential experimental systems and demonstrations.

- Individual load center tests and demonstrations beginning with a total of 200 peak kWe in FY 79 and ranging up to a cumulative total of 10 peak MWe by FY 84 will continue to be tested and evaluated throughout this period to FY 86.

Test and evaluation of energy storage and power processing systems will also be conducted throughout this time period. Studies will be conducted to resolve questions of ownership and liability of experimental system demonstration equipment and modifications of labor practices, building codes and architectural design guides needed to accommodate photovoltaic systems. Technology transfer will be accomplished through conferences, workshops, press releases, manuals, and technical and trade publications. Local industry and small business participation will be encouraged in this demonstration phase.

During the FY 76 to FY 79 period, research and development will be conducted to determine storage and power conditioning interface requirements. The performance, reliability, and cost of current storage and power conditioning subsystems will be evaluated and new designs will be specifically engineered for photovoltaic applications. Subsystem and interface engineering and tests necessary to adapt storage and power conditioning subsystems to solar photovoltaic applications will be completed by the early 80's, as will studies needed to determine environmental,
legal and safety impacts of storage and power conditioning subsystems and methods of removing or alleviating these impacts.

It is the intent of the above test and demonstration element of the program not only to establish the technical and economic feasibility of SPCS, but just as importantly, to serve to accelerate or amplify their wide-scale adoption in the private free-enterprise system. Based on discussions with many individuals from both the photovoltaic and semiconductor industries, a scenario for a planned growth in the rate of production of solar photovoltaic conversion systems in terms of the expected peak power produced annually has been developed, as shown in Fig. 4. It includes: (1) the planned ERDA purchases through FY 83; (2) the total expected governmental purchases, including those systems purchased by other agencies for cost-effective applications stimulated by the ERDA-funded demonstrations; (3) the accelerated free-market purchases (also stimulated by the ERDA program); and (4) the sum of these individual elements that gives the total annual production rate of SPCS. One can see that the production goals shown in Fig. 4 project an annual growth rate of slightly under a factor of 3X. The achievement of such a projected growth rate would, in fact, lead to the attainment of the program's 10-year goal of 500 peak MWe per year approximately one year early. For purposes of comparison, the output of a free-market growth curve of approximately 1.8X that has been projected in the absence of an ERDA Photovoltaic Conversion Program is also shown in Fig. 4.

Figure 5 shows the projected results of the 10-year program plan in the form of an industry learning curve. An aggressive research development and demonstration effort is expected to accomplish the breakthrough required to obtain the $2,000/peak kWe price point shown at an estimated production rate of about 2 peak MWe. From that point, the growth necessary to achieve the desired FY 86 goal is seen to be a reasonable 80% slope. Although entirely different technologies may be required and the uncertainties are far greater, it is interesting to note that only a 90% growth slope is required to go from the FY 86 goal to the program's long-range FY 2000 goal of widespread SPCS applications.

Finally, as indicated earlier, it is one of the objectives of the program to bring the photovoltaic industry to the point of technology readiness by FY 86. It is hoped that the major programmatic decision as to how to continue the National effort towards the program's long-range FY 2000 goal can then be soundly based on a variety of available technologies and a free-enterprise industrial system ready, willing and able to do its part in this job.
FIGURE 4

PHOTOVOLTAIC PRODUCTION GOALS

TOTAL ANNUAL PRODUCTION RATE
ACCELERATED FREE-MARKET PURCHASES
TOTAL GOVERNMENT PURCHASES
FREE MARKET (1.8x) (IN ERDA ABSENCE)
ERDA PURCHASES

1000 MW
100 MW
10 MW
1 MW
100 KW

ANNUAL PEAK POWER

75 76 77 78 79 80 81 82 83 84 85 FY

A-14
FIGURE 5

SOLAR PHOTOVOLTAIC ARRAY COST REDUCTION

[Graph showing the reduction in cost per unit of renewable energy over time, with various cost projections for different scenarios.]
MAJOR MILESTONES AND DECISIONS POINTS

Major planning milestones of the SPCS program are:

- FY 1976, initiate testing of the first 30 kWe (peak) of the military applications of SPCS in cooperation with the Department of Defense (DOD).
- FY 1976, initiate basic R&D awards in the novel materials and device area.
- FY 1976, specify interim measurement techniques for tests and standards and have photovoltaic test facility operational.
- FY 1976, initiate special and governmental applications of SPCS.
- FY 1976, complete the phase-zero conceptual designs and systems analyses of photovoltaic conversion systems.
- FY 1976, initiate R&D awards on photovoltaic concentrating devices and systems.
- FY 1977, initiate testing of the remaining 60 kWe (peak) of military applications of SPCS as part of a remote DOD island base grid.
- FY 1977, complete preliminary photovoltaic system design specification and define solar cell performance specifications.
- FY 1977, first concentrator production cells developed.
- FY 1977, first residential prototype SPCS in operation.
- FY 1978, SPCS encapsulation process defined.
- FY 1978, residential experimental systems demonstrations initiated.
- FY 1978, operate $2,000/peak kWe concentrator systems.
- FY 1979, specify post-1986 systems and subsystems.
- FY 1979, demonstrate operational solar arrays at $5,000/peak kWe.
- FY 1980, demonstrate operational concentrator systems at $1,000/peak kWe.
- FY 1980, demonstrate the feasibility of manufacturing and marketing solar arrays at a price of $500/peak kWe.

- FY 1980, demonstrate 10% efficiency for thin-film solar cells.

- FY 1980, reach determination of industry vs. government development and ownership of photovoltaic plants required to meet program's FY 1986 goals.

- FY 1986, establishment of total installed industrial production plant capacity for an annual 500 MWe (peak)/yr of solar arrays at a market price of less than $500/peak kWe.

- FY 1986, establish $250/peak kWe photovoltaic concentrator systems.

- FY 1986, demonstrate feasibility of thin-film solar arrays priced at $100 to $300/peak kWe.

- FY 1986, achieve technology readiness for the photovoltaic industry to move into the most promising avenues to provide the program's goal of 3% of the Nation's electrical power demand by the year 2000.

- FY 1986, reach decision on which of the competing photovoltaic conversion systems to develop further towards the program's FY 2000 objective of an annual production rate of 50,000 MWe (peak)/yr. at a market of $100 to $300 per peak kWe.
UTILIZATION PLAN

The ERDA role in the plan for utilization of SPC systems will be to undertake, coordinate and direct RD&D to improve performance-to-cost ratios, reduce techno-economic risks and uncertainties, verify the estimated operational characteristics of solar electric systems, and establish their economic viability. Early large-scale demonstrations will be undertaken to enhance public and user acceptance and accelerate industrial implementation of solar photovoltaic systems. A series of studies will be conducted to determine possible environmental, legal, societal, or institutional impacts, as well as means for removing these types of constraints on public and user acceptability. Studies will be conducted to address questions of ownership of commercial manufacturing facilities and operational power plants. Related programs of other Federal agencies include: 1) studies of the basic characteristics and properties of semiconductor and organic materials that exhibit photovoltaic energy conversion (NSF); 2) establishment of high efficiency silicon solar arrays for space applications (NASA); and 3) studies of market conditions and the use of Federal and local incentives (such as tax reductions) to induce solar cell development and use (FEA).

Various types of information and data on SPC systems will be compiled and entered into the Solar Energy Information Data Bank, including:

- Reports, Journal articles, dissertation, monographs, project descriptions, and other written materials pertaining to research, development and applications of solar photovoltaic conversion systems;
- Technical information on the design, construction, and maintenance of solar photovoltaic conversion systems;
- General information on solar photovoltaic conversion system applications disseminated to the public;
- Physical and chemical properties and possible environmental impacts of materials required for solar photovoltaic conversion systems activities and equipment; and
- Engineering performance data on equipment and devices utilizing solar photovoltaic energy conversion.

The data will also be supplied by ERDA as appropriate, to Federal, State and local government organizations, and their contractors; universities, colleges and not-for-profit organizations; and the private sector, including the public, industry, commercial organizations, etc.
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                             | Phoenix, AZ 85008                          | Ingle, W.*  
                             |                                              | Chaney, R.*  
                             |                                              | McGinnis, B.  
|                                 |                                              | IV          |
|                                 |                                              | II          |
|                                 |                                              | I           |
|                                 |                                              | I           |
|                                 | RCA Laboratories                            | Cullen, G.*  |
|                                 | David Sarnoff Research Center                | Richman, D.*  
                             | Princeton, NJ 08540                         | Shelpuk, B.*  
                             |                                              | Toner, J.  |
|                                 |                                              | I           |
|                                 |                                              | IV          |
|                                 |                                              | IV          |
|                                 | Rockwell International                      | Farrar, J.*  |
|                                 | Autonetics Division                         | Kolyer, J.M.*  
                             | 3370 Miraloma Avenue                       | Manasevit, H.*  
                             | Anaheim, CA 92803                          | Ruth, R. P.*  
                             |                                              | Mann, N.  
                             |                                              | Maxum, B.  
|                                 |                                              | III         |
|                                 |                                              | III         |
|                                 |                                              | II          |
|                                 |                                              | II          |
|                                 | Sensor Technology, Inc.                     | Rubin, I.*   |
|                                 | 21012 Lassen Street                         | Van Der Pool, K.*  
                             | Chatsworth, CA 91311                       | Wu, I.*  
|                                 |                                              | V           |
|                                 |                                              | V           |
|                                 | Simulation Physics, Inc.                    | Kirkpatrick, A.*  
                             | 41 "B" Street                              | Minnucci, J.*  
                             | Burlington, MA 01803                       | Little, R.*  
|                                 |                                              | IV          |
|                                 |                                              | IV          |
|                                 | Solar Power Corp.                           | Caruso, P.*  |
|                                 | 23 North Ave.                               | Addiss, R.*  |
|                                 | Wakefield, MA 01880                         | V           |
|                                 |                                              | V           |
|                                 | Solarex Corp.                               | Clifford, A.E.*  
                             | 1335 Piccard Drive                         | Lindmayer, J.*  
                             | Rockville, MD 20850                        | V           |
|                                 |                                              | V           |
|                                 | SpectroLab, Inc.                            | Ralph, E. L.*  
                             | 12500 Gladstone Ave.                       | Wrench, G.*  
<pre><code>                         | Sylmar, CA 93142                           | V           |
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