Proceedings: 9th Project Integration Meeting
April 11-12, 1978
The JPL Low-cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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LSA
LOW-COST SOLAR ARRAY
PROJECT

PROCEEDINGS:
9th
PROJECT
INTEGRATION
MEETING
APRIL 11-12, 1978
## CONTENTS

I. INTRODUCTION AND SUMMARY ............................................ 1-1  
II. PROJECT ANALYSIS AND INTEGRATION ................................. 2-1  
III. TECHNOLOGY DEVELOPMENT AREA .................................... 3-1  
  A. SILICON MATERIAL TASK ................................................. 3-1  
  B. LARGE AREA SILICON SHEET TASK ................................... 3-64  
  C. ENCAPSULATION TASK ................................................... 3-160  
IV. PRODUCTION PROCESS AND EQUIPMENT AREA ......................... 4-1  
V. ENGINEERING AREA ....................................................... 5-1  
VI. OPERATIONS AREA ....................................................... 6-1  
APPENDIXES  
  A. AGENDA ................................................................. A-1  
  B. ATTENDEES .............................................................. B-1
SECTION I

INTRODUCTION AND SUMMARY

The 9th LSA Project Integration Meeting (PIM) was held April 11-12, 1978, on the campus of the California Institute of Technology. Invitation-controlled attendance included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the Photovoltaic Program.

Technical Highlights of the Project Integration Meeting:

1. Modules fabricated from encapsulation materials costing from 2.5¢ to 10¢/watt have passed the standard JPL module design qualification tests. Eighteen types of small modules (each with nine solar cells) were tested during a three-month period.

2. Based upon studies and the above tests it appears that several module encapsulation systems can meet the encapsulation materials price allocation of $.06/watt for $.50/watt module prices. These encapsulation systems also have the potential for meeting the lifetime requirements of 20 years.

3. Encapsulation activities that will continue to be emphasized:
   a. Development of module designs incorporating tested materials and low-cost assembly techniques.
   b. Development of inexpensive materials modified specifically for photovoltaic applications.
   c. Evaluation of current and future module encapsulation systems.
   d. Development of life prediction techniques and the application of these analyses and tests to commercial and experimental modules.

4. Economic analyses of new polysilicon production processes for solar cells have resulted in the following preliminary production cost estimates in annual quantities as shown ( ):

<table>
<thead>
<tr>
<th>CONTRACTOR</th>
<th>ESTIMATED $/Kg (1975 $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Union Carbide</td>
<td>$6.45 (1000 MT/yr)</td>
</tr>
<tr>
<td>Battelle Memorial Institute</td>
<td>$9.21/9.60 (1000 MT/yr)</td>
</tr>
<tr>
<td>Westinghouse</td>
<td>$8.98 (3000 MT/yr)</td>
</tr>
<tr>
<td>SRI International</td>
<td>$6.20 (1000 MT/yr)</td>
</tr>
<tr>
<td>Motorola</td>
<td>$7.50 (1000 MT/yr)</td>
</tr>
<tr>
<td>Dow Corning</td>
<td>$7.37 (3000 MT/yr)</td>
</tr>
</tbody>
</table>

1-1
The low production costs of these new processes relative to contemporary silicon processes are in general attributed to smaller plant capitalization requirements, large reductions in energy consumption, and reduced labor requirements.

These estimates will continue to be updated as results are received from the operation of experimental equipment and as the economic analyses mature. Of the above processes the top two processes are the most advanced and consequently these cost estimates are the most definitive.

5. Four different, experimental, multiple-ingot, Czochralski growth machines are under development. Multiple ingots have now been grown from the same container.

6. The general consensus was established that wafering will continue to control the viability of ingot technology.

7. The latest assessment continues to indicate that the silicon sheet interim price goals allocations for $2/watt modules can be met with ingot technology.

8. Good progress continues to be reported in the non-ingot technologies by the achievement of better quality sheets at faster growth rates. Meeting the sheet goal allocations of $.13/watt for $.50/watt modules appears to be paced by sheet area growth rates. Preliminary criteria for the desired growth rates and other factors has been established by use of SAMICS.

9. Presentations by SPIRE included information on:
   a. Ion-implanted 3-inch cells fabricated by SPIRE with a measured efficiency of 16% AM1.
   b. A new ion implanter system designed for processing 300 solar cells per hour that is now in operation.
   c. The design of a new implanter system that could process 100 W per year.

10. Presentations on metallization were given ranging from analytical to empirical approaches for thick-film metallization. One contractor described a wet chemical process. In all of the metallization approaches discussed, expensive materials were required to achieve high reliability. Low-cost material processes capable of meeting the $0.50/watt goal, have not demonstrated acceptable reliability.
11. Nearly 10% of the Block I (early production) modules in JPL field tests have failed, primarily from broken interconnects and corrosion of lead wires. Later Block I modules were much better. As yet no Block II modules have failed at JPL.

12. Block II modules show superior performance, compared to Block I modules, during JPL environmental tests.

13. Varying degrees of delamination resulting from field operations observed in all types of Block I modules encapsulated with silicone rubber were reported by LeRC and DOD. Silicone rubber adhesion to epoxy-fiberglass substrates has been particularly poor.

14. During the first nine months of operation of the Nebraska irrigation project, electrical failures have been insignificant (eight out of approximately 2200 modules). Concern has been voiced regarding safety where electrically live elements have been exposed through the silicone rubber.

15. Output power reductions caused by six months of dirt, soot, and other accumulations on glassed modules were about half of the 5% to 28% reduction for modules with silicone rubber top surfaces. Reductions were site-dependent.

16. Two non-destructive diagnostic tests were successfully used by JPL:

   a. Shorted/defective cells in a module were detected by shadowing individual cells. This technique can be used to directly measure cell shunt resistance.

   b. Solar cell cracks have been detected and imaged by use of a laser scanning system which measures cell output as the laser beam scans the cell.

17. Presentation of a seminar on the SAMICS computer code was given to familiarize industry users.
A. SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION (SAMIS) TUTORIAL

The SAMIS price estimation and industry simulation computer program was available by the time of this PIM. Therefore, a SAMIS III tutorial was conducted on the second afternoon of the meeting. The topics covered were: How to use SAMIS III; what SAMIS III does; what reports are produced; and how this methodology is being validated. The viewgraphs used to illustrate these topics appear on the following pages.

SAMIS III COMPUTER PROGRAM TUTORIAL

- HOW TO USE SAMIS III
- WHAT SAMIS III DOES
- WHAT GOES ON INSIDE THE PROGRAM
- YOUR ROLE IN VALIDATION

SAMIS III RESULTS
- REPORT CHOICES
- QUANTITY & PRICE
- COMPANY SUMMARIES
- PROCESS SUMMARIES
- DIRECT & INDIRECT REQUIREMENTS

VALIDATION
- METHODOLOGY
- COMPUTER PROGRAM
- ECONOMIC PARAMETERS
- PROCESS DESCRIPTIONS
- PRICES VS QUANTITIES
- INDIRECT REQUIREMENTS
- EXPERIENCED JUDGEMENT & COMMON SENSE

SAMIS III COMPUTER PROGRAM TUTORIAL
HOW TO USE SAMIS III

ESTABLISH AN ACCOUNT WITH NATIONAL CSS, INC
(203) 853-7200 CONN
(303) 534-2720 COLO
(408) 739-6271 CALIF
TO GET # OF LOCAL OFFICE

OR

OBTAIN A TAPE COPY OF THE SOURCE CODE FROM PAUL J. FERNETT OF JPL
(213) 354-4670 OR 6108

THEN

COMPILE, USING SIMSCRIPT 11.5

ALSO OBTAIN STANDARD DATA, THE TEST CASE, AND THE USER’S GUIDE

RUN THE TEST CASE AND FAMILIARIZE YOURSELF WITH THE PROGRAM OPERATION

PREPARE PROCESS DESCRIPTIONS, COMPANY DESCRIPTIONS, & INDUSTRY DESCRIPTIONS ACCORDING TO JPL DOCUMENT 5101-44

USE SAMIS III

USE OF SAMIS III

DEFINE RUN CONTROL CONDITIONS
INDUSTRY SIZE RANGE VECTOR
INTEGRAL MACHINES FLAG
STEADY STATE FLAG
PROMPT LEVEL
MAX NUMBER OF ITERATIONS
EPSILON
REPORTS
• FILE OR TERMINAL
• LINE LENGTH
• CHOICES

ENTER THE DATA
GREAT PAINS HAVE BEEN TAKEN TO MAKE THIS EASY
"CREATE" "HELP"
"SAVE" "DISPLAY"
"FIND" "EXPLAIN"
"CHANGE" WARNING: INPUT DATA IS NOT YET CHECKED FOR CONSISTENCY OR REASONABLENESS

LOGOUT PRINT THE OUTPUT FILE CHANGE SOME DATA AND RUN AGAIN OR "STOP"

ENTERT "SIMULATE"
SAMIS III REPORTS

You can control:
- Amount of detail
  (number of pages)
- Output unit
  (terminal or printer)
- Line length

Prices of all products
Quantities of everything
Ratios
Energy payback times, profits, markups

Expense summaries
and details
for each process step

Costs and amounts
of direct and indirect requirements

SAMIS III REPORT STRUCTURE

* Industry configuration
  Loop through industry size range vector
* Industry summary
  Loop through all companies
* Company summary
  Loop through all process steps
* Process summary (direct & indirect expenses)
  * List all direct & indirect requirements, with costs
  Repeat for the next process step
* List all company direct & indirect requirements
  Repeat for the next company
Repeat for the next industry size
* Cost account catalog
* Process steps
* Company descriptions
* Standards
* Run control parameters

Background reports
WHAT DOES SAMIS III DO?

START
INITIALIZE
"WELCOME TO SAMIS"
GET USER'S COMMAND

USER HELPS
"EXPLAIN" WHAT DOES SAMIS III DO?
"PROMPT" START INITIALIZATION

INITIALIZE "WELCOME TO SAMI S"

GET USER'S COMMAND

USER HELPS
"PROMPT" INITIALIZATION

ENTITY MANAGEMENT
"QUERY" "SAVE" "CREATE" "FIND"

"SIMULATE" STRUCTURE AND VERIFY

"STOP" 

LOOP OVER SIZES

QUANTITIES

PRICES

REPORTS

MANIPULATE COMMAND
"QUERY" "SAVE" "CREATE" "FIND"

"DISPLAY" "CHANGE" "DELETE"

"STOP"

SAMIS TOP-LEVEL ACTIONS

INITIALIZE: GET MACHINE SPECS, DIRECTORIES, DEFAULTS
PRINT "WELCOME TO SAMIS III"

RESPOND TO USER'S COMMANDS... UNTIL "STOP":

"?' LIST AVAILABLE COMMANDS
"EXPLAIN" GIVE SYNTAX OF COMMAND OR EXPLAIN TERM
"PROMPT" "FULL", "MID", "BRIEF", OR "OFF"
"QUERY" LIST ENTITIES ALREADY DEFINED
"CREATE" MAKE A NEW ENTITY - THEN MANIPULATE
"SAVE" AUGMENT THE DATA FILES (REWRITE)
"FIND" LOCATE AN OLD ENTITY - THEN MANIPULATE
"SIMULATE" CALCULATE QUANTITIES & PRICES - REPORTS
"STOP" CLOSE FILES, PRINT "GOODBYE"

MANIPULATION LEVEL

AFTER A TOP-LEVEL "CREATE" OR "FIND" THE ENTITY
(PROCESS, COMPANY, INDUSTRY, STANDARD, RUN, CONTROL, OR EXPENSE, ITEM)
CAN BE MANIPULATED

RESPOND TO USER'S COMMANDS... UNTIL "DONE"

"?' LIST AVAILABLE COMMANDS
"EXPLAIN" GIVE SYNTAX OF COMMAND
"DISPLAY" PRINT VALUES OF ATTRIBUTES
"CHANGE" CHANGE VALUE OF AN ATTRIBUTE
"DELETE" REMOVE THE ENTITY FROM CORE
"DONE" RETURN TO TOP-LEVEL
STRUCTURE AND VERIFY

MAKE SURE INDUSTRY, RUN, CONTROL, STANDARD ARE IN CORE
LOAD EVERY EXPENSE ITEM (AND THEIR INDIRECT REQUIREMENTS)
USE THE INDUSTRY MAKERS LIST TO START STRUCTURING
BUILD THE INDUSTRY STRUCTURE

USING COMPANY PURCHASED PRODUCT SUPPLIER LISTS
BRING IN (FROM THE FILE) ANY NEEDED COMPANIES
CORRESPONDING TO EACH COMPANY, MAKE A FIRM
(A "COMPANY" IS A TEMPLATE, A "FIRM" HOLDS RESULTS)
STRUCTURE THE FIRMS PRODUCTION AREA
USE THE COMPANY PROCESS LIST
BRING IN ANY NEEDED PROCESS
MAKE A WORK STATION FOR EACH PROCESS
STRATEGICALLY FILE WORK STATIONS IN PRODUCTION AREA
STRATEGICALLY FILE FIRMS IN INDUSTRY STRUCTURE

MAKE SURE AT LEAST ONE REPORT IS SPECIFIED
IF ANY PROBLEM, TELL THE USER AND SET AN ABORT FLAG.
CALCULATE QUANTITIES

FIRM'S PRODUCT QUANTITY

NUMBER OF MACHINES

PROCESS DESCRIPTION

REQUIRED PRODUCT

SUPPLIERS LISTS

ADD TO OTHER FIRM'S PRODUCT QUANTITIES

INDIRECT REQUIREMENTS (ALLOCATED BACK TO WORK STATIONS)

QUANTITY CALCULATIONS

INDUSTRY FINAL PRODUCT QUANTITY

+ INDUSTRY SIZE/HARDWARE PERFORMANCE

OBLITERATE PREVIOUS QUANTITIES

ASSIGN INDUSTRY PRODUCTION TO MAKERS OF FINAL PRODUCT

SEQUENCE THROUGH THE FIRMS IN THE INDUSTRY STRUCTURE

SEQUENCE THROUGH WORK STATIONS IN PRODUCTION AREA

ASSIGN FIRM'S PRODUCTION TO WORK STATION

CALCULATE MACHINES REQUIREMENTS

CALCULATE DIRECT NEEDS (& AUGMENT FIRM'S LIST)

CALCULATE AND ASSIGN PRODUCT NEEDS

INFERENCE THE FIRM'S INDIRECT NEEDS

ALLOCATE INDIRECTS BACK TO THE WORK STATIONS
INFERRING THE INDIRECT NEEDS

BASIC CONCEPTS

- TOTAL • DIRECT + INDIRECT
- INDIRECT = Σ FUNCTION (TOTAL)

CALCULATE THE INDIRECT NEEDS

DIRECT NEEDS SUFFICE TO OPERATE PROCESS...

BUT "INDIRECT NEEDS" ARE ALSO REQ'D TO RUN A COMPANY

ASSUMPTIONS:

- ALL INDIRECTS CAN BE INFERRED FROM DIRECTS
- THERE ARE FEW CROSS ECONOMIES OF SCALE (THAT IS, THE INDIRECT NEED FOR X IS THE SUM OF THE INDIRECT NEED FOR X FROM Y AND THAT FROM Z)

WHY IS ITERATION NECESSARY?

- BECAUSE THE INDIRECT REQUIREMENT RELATIONSHIPS GIVE INDIRECTS IN TERMS OF TOTAL REQUIREMENTS...

AT FIRST, ONLY THE DIRECTS ARE KNOWN
ECONOMY OF SCALE ALGORITHMS

"FAST" ALGORITHM: ALTER THE TOTAL REQUIREMENTS ONE AT A TIME UNTIL THE DIRECT PLUS THE INDIRECT IMPLIED BY THAT TOTAL EQUALS THAT TOTAL

\[
N_X + D_X = T_X \text{ AS FUNCTION OF } T_Y
\]

\[
N_Y + D_Y = T_Y \text{ AS FUNCTION OF } T_X
\]

"SLOW" ALGORITHM: SOLVE LEONTIEF EQUATION

\[
N = A + B \cdot (T - C) \quad \text{(PIECE-WISE LINEAR)}
\]

\[
T = D + N
\]

\[
- (T - B)^{-1} \cdot (D + A - B \cdot C)
\]

ALLOCATE FIRM'S INDIRECTS TO WORK STATIONS

FIRM'S INDIRECTS TAKE ADVANTAGE OF ECONOMIES OF SCALE

WORK STATIONS' INDIRECTS COULD BE CALCULATED THE SAME WAY, BUT WHAT ABOUT THE NON-LINEARITIES OF SCALE?

SOLUTION:

FILL THE INDIRECT REQUIREMENTS MATRIX, \( R \), WITH THE AMOUNT OF THE REQUIRED ITEM PER UNIT OF REQUIRING ITEM

THEN,

\[
N_{\text{FIRM}} \cdot R \cdot T_{\text{FIRM}} = T_{\text{FIRM}} \cdot (I - R)^{-1} \cdot D_{\text{FIRM}}
\]

\[
T_{\text{FIRM}} = \sum_{\text{WORK STATIONS}} T_{\text{FIRM}} \cdot \sum_{\text{WORK STATIONS}} D_{\text{FIRM}} + \sum_{\text{WORK STATIONS}} N_{\text{FIRM}} \cdot N_{\text{WS}}
\]

CALCULATE \( T_{\text{WS}} = (I - R)^{-1} \cdot D_{\text{WS}} \)

FINALLY:

\[
N_{\text{WS}} \cdot T_{\text{WS}} = D_{\text{WS}}
\]
PRICE CALCULATION

ALL EXPENSES ARE EXPRESSED IN MANUFACTURING YEAR DOLLARS
(PRODUCT PRICES ARE DEFLATED TO THE STANDARD PRICE YEAR - IN THE REPORTS)
AFTER THE FIRM'S TOTAL EXPENSES ARE FOUND, THEY ARE ALLOCATED BACK TO THE WORK STATIONS:

WORK STATION EXPENSES + THOSE ATTRIBUTABLE TO THE WORK STATION
PLUS
SHARE OF THE FIRM'S NON-ATTRIBUTABLE EXPENSES

THE VALUE-ADDED AND A PRODUCT PRICE IS ASSIGNED TO EACH WORK STATION
PROFITS, MARKUPS, AND ENERGY PAY-BACK TIMES ARE CALCULATED FOR WORK STATIONS AND FOR FIRMS
VALIDATION

VALIDATION — CONTINUED

• PROCESS DESCRIPTIONS
  YOU MUST PUT IN VALID, COMPLETE DESCRIPTIONS
  BASELINE PROCESSES WILL BE GENERATED FOR STANDARDIZATION
  WE WILL RELY ON THE JPL TECHNOLOGY DEVELOPMENT TASKS

• INDIRECT REQUIREMENTS
  GENERATED BY A FACILITIES ENGINEERING CONTRACTOR
  WILL BE COMPARED WITH 3 CONVENTIONALLY DESIGNED FACTORIES
  PLEASE USE YOUR EXPERIENCED JUDGMENT TO ASSESS RESULTS

• PRICE VS QUANTITY RELATIONSHIPS
  COMPILED FOR STANDARDIZATION
  YOUR EXPERIENCE IS ESPECIALLY VALUABLE HERE
  FORTUNATELY, PRODUCT PRICES ARE INSENSITIVE TO SMALL ERRORS

THE BOTTOM LINE ON VALIDITY IS THE REASONABLENESS OF RESULTS: PLEASE LET US KNOW OF ANY ABSURDITIES YOU FIND - OR, QUESTIONS, COMMENTS, ETC.:

ROBERT G. (ROB) CHAMBERLAIN
(213) 577-9273 OR FTS: 792-9273
JET PROPULSION LABORATORY
4800 OAK GROVE DRIVE
PASADENA, CA 91103

VALIDATION & VERIFICATION OF SAMIS III

ENSURING VALIDITY HAS BEEN A MAJOR CONSIDERATION THROUGHOUT THE DEVELOPMENT.

• METHODOLOGY
  REVIEW LITERATURE - IN AND OUT OF LSA PROJECT
  HIRE AN OUTSIDE FIRM TO CRITIQUE
  SEEK SOLAR ARRAY INDUSTRY REVIEW

• COMPUTER PROGRAM
  MODERN PROGRAMMING METHODS
  CHECK SUB-MODEL CALCULATIONS
  COMPARE WITH RESULTS OF MANUAL METHOD (SAMICS/PEG)

• ECONOMIC PARAMETERS
  OBTAIN JPL ECONOMISTS’ BLESSING
  USE STANDARD DATA SOURCES FOR SIMILAR INDUSTRIES
  USE "REALISTIC" VALUES WHERE "ACCURACY" IS MEANINGLESS

2-19
B. PRICE ALLOCATION GUIDELINES

The LSA Project's Price Allocation Guidelines (PAG) were presented on the first day of the PIM. The PAG is a working tool of LSA Project management. It provides meaningful and consistent long range targets for various Project elements.

PAG does not represent a project commitment to a specific technology or manufacturing technique. In fact, the current guidelines describe three general approaches to the Project's 1986 goals: Ingot technology, non-ingot technology, and types of non-ingot technology which are likely to produce relatively lower cell efficiencies.

Even though three types of technology are dealt with, there is consistency in the assigned guidelines for four of the Technology Development Area tasks. Guidelines for silicon price (in dollars per kilogram) and the value added by cell fabrication, encapsulation materials, and module manufacturing (in dollars per square meter of product) are generally consistent. However, each type of technology uses a different form of sheet and will exhibit different cell and cell packing efficiencies. Therefore, the sheet goals and cell efficiencies are developed to make each technology consistent with the objectives of the LSA Project.

These guidelines are revised and updated from time to time, as new information is developed. Several changes have occurred in the current allocation. First, the name has changed from the Price Goal Allocation (PGA) to the Price Allocation Guidelines (PAG). The 1986 targets are considered to be the most important project goals. The interim targets of PAG, from the 1978 to 1984, should be considered guidelines which indicate progress toward the 1986 goals.

The following viewgraphs were displayed at the PIM. However, one subsequent modification is shown on the following page, where the 1986 ingot goals are affected. The original assumption was that these cells would be squared off to obtain maximum module packing efficiency, but it is more cost effective to trim these cells into a modified hexagonal shape. This provides a reduced packing factor but also an improved silicon yield. The result is a slight reduction in the cell efficiency required to meet the ingot technology goals, from 17.5% to 16.9%.
## PRICE ALLOCATION GUIDELINES

### INGOT TECHNOLOGY

<table>
<thead>
<tr>
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<td>13</td>
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<tr>
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<th>EST</th>
<th>GUIDELINES</th>
<th>GOALS</th>
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<tbody>
<tr>
<td>$/Kg</td>
<td>65</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>$/Wpk</td>
<td>1,42</td>
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<th>$/Wpk</th>
<th>$/m^2 CELL</th>
<th>$/Wpk</th>
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<th>$/Wpk</th>
<th>$/m^2 MODULE</th>
<th>$/Wpk</th>
<th>$/m^2 MODULE</th>
<th>$/Wpk</th>
<th>$/m^2 MODULE</th>
<th>$/Wpk</th>
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<td>214</td>
<td>214</td>
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<td>129</td>
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<td>0.25</td>
<td>50</td>
<td>0.49</td>
<td>25</td>
<td>0.13</td>
<td>0.08</td>
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<td>90</td>
<td>90</td>
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<td>54</td>
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<td>20</td>
<td>0.15</td>
<td>15.5</td>
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| TOTALS            | $/Wpk | 7.00  | 4.00  | 2.00  | 1.00  | 0.50  |
## PRICE ALLOCATION GUIDELINES

**NON-INGOT TECHNOLOGY**

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<td><strong>GOALS</strong></td>
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<tr>
<td><strong>SILICON</strong></td>
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<tr>
<td>$/Kg</td>
<td>65</td>
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<tr>
<td>$/Wpk</td>
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<td>0.07</td>
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<td>98</td>
<td>55</td>
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<tr>
<td>$/m² CELL</td>
<td>200</td>
<td>120</td>
<td>52</td>
<td>30</td>
<td>22</td>
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<tr>
<td>$/Wpk</td>
<td>1.09</td>
<td>0.43</td>
<td>0.23</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>ENCAPSULATION MATERIALS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/m² MODULE</td>
<td>30</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>$/Wpk</td>
<td>0.25</td>
<td>0.14</td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>MODULE (VALUE ADDED)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/m² MODULE</td>
<td>100</td>
<td>50</td>
<td>34</td>
<td>20</td>
<td>15.5</td>
</tr>
<tr>
<td>$/Wpk</td>
<td>0.51</td>
<td>0.32</td>
<td>0.17</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>7.00</td>
<td>4.00</td>
<td>2.00</td>
<td>1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>
## PRICE ALLOCATION GUIDELINES

### LOWER EFFICIENCY

<table>
<thead>
<tr>
<th></th>
<th>ENC CELL</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULE</td>
<td>8.1</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### NON-INGOT TECHNOLOGY

<table>
<thead>
<tr>
<th></th>
<th>EST</th>
<th>GUIDELINES</th>
<th>GOALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILICON</td>
<td>65</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/Kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/Wpk</td>
<td>0.49</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>SHEET (VALUE ADDED)</td>
<td>90</td>
<td>62</td>
<td>36</td>
</tr>
<tr>
<td>$/m² SHEET</td>
<td>1.25</td>
<td>0.69</td>
<td>0.34</td>
</tr>
<tr>
<td>$/Wpk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CELLS (VALUE ADDED)</td>
<td>200</td>
<td>120</td>
<td>52</td>
</tr>
<tr>
<td>$/m² CELL</td>
<td>1.33</td>
<td>0.52</td>
<td>0.27</td>
</tr>
<tr>
<td>$/Wpk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENCAPSULATION MATERIALS</td>
<td>30</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>$/m² MODULE</td>
<td>0.31</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>$/Wpk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODULE (VALUE ADDED)</td>
<td>100</td>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>$/m² MODULE</td>
<td>0.62</td>
<td>0.38</td>
<td>0.20</td>
</tr>
<tr>
<td>$/Wpk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTALS</td>
<td>7.00</td>
<td>4.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>
A. SILICON MATERIAL TASK

The Silicon Material Task held contract progress reviews and participated in intertask sessions on "Crystal Growth Silicon Replenishment and Refractory Material Developments" and "Composition Analysis of Silicon". A summary of the first session is presented elsewhere. In the second session there were presentations describing experience in making composition analyses using spark source mass spectroscopy (SSMS) and neutron activation analysis (NAA), problem areas, and progress in the current contract programs at NBS and Livermore. The basis of the measurement and the procedures for NAA were detailed as well as the importance of blanks and the sensitive handling of samples. Both NBS and Dow Corning cited the elements of concern to the Si program which are not presently measureable to the ppba level using the usual techniques; NBS and Livermore have programs to extend the measurement ranges in these cases. The importance of accurate composition measurements was emphasized in a brief summary of the program by Westinghouse to determine the effects of impurities on solar cell measurement in which it was pointed out that in some cases impurity levels far below the ppba level markedly affect the performance of solar cells.

Progress reviews were given for all of the process developments. Unfortunately, not enough time had been allocated to allow for sufficiently long discussion periods. The following are brief descriptions of these reports: (1) The non-equilibrium plasma jet apparatus (AeroChem) is being used to investigate the process for depositing amorphous and polycrystalline films on various substrates. Since the pressure used is much higher than has been reported in the literature, a much greater deposition rate can be achieved than for the other procedures. (2) Experiments with a new electric arc furnace (Dow Corning) have begun. The major problem to be overcome to obtain a suitably pure product is to reduce the B and P concentrations in the C-reductant. A preliminary cost estimate, based on a 3000 MT/year plant, $38,000K capital investment, and no profit, gave $7.37/kg for this process. (3) Experimental runs at greater than 25 g/hr for 1 and 2 hr have been made in the SiF$_2$ transport process (Motorola). A flow chart with mass and energy balances was described. (4) A preliminary economic analysis of the Na/SiF$_4$ process (SRI International) showed that, if credit is taken for the manufacture and scale of cryolite as a byproduct, a total product cost of $6.20/kg Si for a 1000 MT/year plant is obtained. The analysis was based on the sample scale-up of the laboratory apparatus and a fixed capital investment of $1000K. A cost sensitivity graph was also shown. The effect of plant scale is that the cost becomes $5.30 for a 3000 MT/year plant and $5.00 for 5000 MT/year. (5) Experiments with the Na/SiCl$_4$ system were described (AeroChem). The kinetics and nucleation are very rapid; a powdery mixture of Si and NaCl is formed. All of the halosilane-alkali metals have been shown to be fast burning, self-igniting, and highly luminescent. (6) The process for the 50 MT/year Process System Development Facility (PSDF) (Battelle) was described. Two chemical
process design companies were subcontractors. Continued experiments with the fluidized bed reactor (FBR), Zn vaporizer, and ZnCl₂ electrolysis cell were reported. The configuration of the FBR for the PSDF was determined from the analysis of a full scale mockup. The operation of a Process Development Unit (PDA) (Union Carbide), which contains redistribution reactors, distillation columns, and a hydrogenation reactor, was routinely successful in producing SiH₄. Efforts continued to devise procedures for the consolidation of the Si powder produced in the free space reactor (FSR). The process design of a 100 MT/year PSDF is proceeding. Economic analyses for a 1000 MT/year plant were performed using several bases for calculating the market price. For example, for a 15 year straight line depreciation and 100% government funding the price is $4.96/kg Si; for the same depreciation method, 100% equity funding, and 25% return on investment the price is $8.08/kg Si (1978). The analyses of the problem of product collection in the Na/SiCl₄ arc heater process (Westinghouse) were described. The conclusions given: separation by condensation is feasible; a 5 meter reactor length will yield 80% efficient separation; the present basic reactor design is equivalent to the design obtained in Phase I of the contract; a higher temperature (up to 3500°K) and thus more energy input is required; and the final Si collector will be a closed crucible. A cost estimate of $8.98/kg Si was given for a 3000 MT/year plant.

IRRADIATION FACILITIES

Livermore Pool Type Reactor is a Research Reactor.

Three of the access tubes are used for activation analysis.

<table>
<thead>
<tr>
<th>Position</th>
<th>Thermal Flux</th>
<th>Epithermal Flux</th>
<th>Irradiation Flux</th>
<th>Container</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-2</td>
<td>.5 x 10¹³</td>
<td>.022</td>
<td>(POLY) 6.35</td>
<td>13.03</td>
</tr>
<tr>
<td>E-1</td>
<td>2.5 x 10¹³</td>
<td>.042</td>
<td>(AL) 1.88</td>
<td>4.27</td>
</tr>
<tr>
<td>A-4 (RABBIT)</td>
<td>2.0 x 10¹³</td>
<td>.045</td>
<td>(POLY) 2.38</td>
<td>6.99</td>
</tr>
</tbody>
</table>
COUNTING FACILITIES

Environmental Sciences Division
6 Systems - Manual

Nuclear Chemistry Division
5 Systems - Automatic Changers

All systems are large detectors (~ 60 cm³) and are calibrated to measure absolute photon emission rates.

Output of each analysis is 4096 Channel Spectra recorded on magnetic tape.

DATA PROCESSING I

Magnetic tapes are read into CDC-7600 computers and analyzed by a computer code - CAMANAL.

Based on a library of half-lives and photon emission probabilities, the spectral contributors are identified and absolute disintegration rates are computed. If limits are required, they must be requested by nuclide at time of GAMANAL run.
DATA PROCESSING II

Input Data

Experimental Data:

\[ A = \text{DPM at count time for each nuclide} \]
\[ \tau = \text{Time duration of irradiation} \]
\[ \gamma = \text{Time from end of irradiation to start of count} \]
\[ c = \text{Real time duration of count} \]
\[ \phi_0 = \text{Thermal neutron flux} \]
\[ \phi_1 = \text{Epithermal neutron flux} \]
\[ W = \text{Weight of irradiated sample} \]
\[ B = \text{Amount of material used to hold sample for irradiation if included in counting} \]
\[ b = \text{Concentration of element in mounting material} \]

Natural Constants:

\[ \sigma_0 = \text{Thermal neutron capture cross-section} \]
\[ \text{RI} = \text{Resonance integral (epithermal cross-section)} \]
\[ G = \text{Atomic abundance of target nuclide} \]
\[ M = \text{Atomic mass of target element} \]
\[ T = \text{Half-life of product nuclide} \]

DATA PROCESSING III

Output from GAMANAL and other experimental data are input to a second computer code, NADA, which combines experimental data and natural constants in appropriate equations to compute net micrograms of element per gram of sample.

This method can be termed "Absolute INAA". The accuracy of the method has been verified by analyzing appropriate SRM materials.
### JPL Nuclide List by Half-Life

<table>
<thead>
<tr>
<th>Element</th>
<th>Nuclide</th>
<th>Rate</th>
<th>Half-Life</th>
<th>$E_y$</th>
<th>$P_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>$^{28}$Al</td>
<td>$3.2 \times 10^6$</td>
<td>2.3M</td>
<td>1778.85</td>
<td>1.000</td>
</tr>
<tr>
<td>V</td>
<td>$^{52}$V</td>
<td>$3.5 \times 10^7$</td>
<td>3.8M</td>
<td>1434.19</td>
<td>1.000</td>
</tr>
<tr>
<td>Cu</td>
<td>$^{66}$Cu</td>
<td>$4.1 \times 10^6$</td>
<td>5.1M</td>
<td>1039.00</td>
<td>0.900</td>
</tr>
<tr>
<td>Ti</td>
<td>$^{51}$Ti</td>
<td>$7.4 \times 10^4$</td>
<td>5.8M</td>
<td>320.10</td>
<td>0.950</td>
</tr>
<tr>
<td>Mg</td>
<td>$^{27}$Mg</td>
<td>$6.5 \times 10^4$</td>
<td>9.5M</td>
<td>843.76</td>
<td>0.720</td>
</tr>
<tr>
<td>Mo</td>
<td>$^{101}$Mo</td>
<td>$1.2 \times 10^5$</td>
<td>14.6M</td>
<td>598.91</td>
<td>0.200</td>
</tr>
<tr>
<td>Ni</td>
<td>$^{65}$Ni</td>
<td>$1.1 \times 10^6$</td>
<td>2.56H</td>
<td>1481.90</td>
<td>0.257</td>
</tr>
<tr>
<td>Mn</td>
<td>$^{56}$Mn</td>
<td>$9.6 \times 10^7$</td>
<td>2.58H</td>
<td>846.60</td>
<td>0.990</td>
</tr>
<tr>
<td>Si</td>
<td>$^{31}$Si</td>
<td>$5.2 \times 10^4$</td>
<td>2.62H</td>
<td>1266.20</td>
<td>0.0007</td>
</tr>
<tr>
<td>Cu</td>
<td>$^{64}$Cu</td>
<td>$1.8 \times 10^7$</td>
<td>12.8H</td>
<td>1345.76</td>
<td>0.0048</td>
</tr>
<tr>
<td>Zn</td>
<td>$^{69}$ZnM</td>
<td>$8.2 \times 10^6$</td>
<td>13.8H</td>
<td>439.00</td>
<td>0.957</td>
</tr>
<tr>
<td>Zr</td>
<td>$^{97}$Zr</td>
<td>$2.6 \times 10^4$</td>
<td>17.0H</td>
<td>743.37</td>
<td>0.940</td>
</tr>
<tr>
<td>W</td>
<td>$^{187}$W</td>
<td>$3.0 \times 10^7$</td>
<td>23.9H</td>
<td>685.70</td>
<td>0.320</td>
</tr>
<tr>
<td>Mo</td>
<td>$^{99}$Mo</td>
<td>$4.2 \times 10^5$</td>
<td>66.7H</td>
<td>140.51</td>
<td>0.805</td>
</tr>
<tr>
<td>Cr</td>
<td>$^{51}$Cr</td>
<td>$5.2 \times 10^6$</td>
<td>27.8D</td>
<td>320.10</td>
<td>0.098</td>
</tr>
<tr>
<td>Fe</td>
<td>$^{59}$Fe</td>
<td>$2.5 \times 10^4$</td>
<td>45D</td>
<td>1099.32</td>
<td>0.562</td>
</tr>
<tr>
<td>Zr</td>
<td>$^{95}$Zr</td>
<td>$4.7 \times 10^4$</td>
<td>65D</td>
<td>756.72</td>
<td>0.546</td>
</tr>
<tr>
<td>(N, p) Ni</td>
<td>$^{58}$Co</td>
<td>$8.0 \times 10^4$</td>
<td>71.3D</td>
<td>810.79</td>
<td>0.995</td>
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<tr>
<td>Zn</td>
<td>$^{65}$Zn</td>
<td>$2.2 \times 10^6$</td>
<td>245D</td>
<td>1115.52</td>
<td>0.490</td>
</tr>
</tbody>
</table>
$^{31}\text{Si}$ ACTIVITY - 2.62 HOUR HALF-LIFE

<table>
<thead>
<tr>
<th>COOLING TIME (Hours)</th>
<th>DPM/GM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$4 \times 10^{10}$</td>
</tr>
<tr>
<td>24</td>
<td>$7 \times 10^{7}$</td>
</tr>
<tr>
<td>36</td>
<td>$5 \times 10^{6}$</td>
</tr>
<tr>
<td>48</td>
<td>$1 \times 10^{5}$</td>
</tr>
<tr>
<td>60</td>
<td>5300</td>
</tr>
<tr>
<td>72</td>
<td>220</td>
</tr>
</tbody>
</table>

**GROUP 1 ELEMENTS:** REQUIRE PRE-IRRADIATION SEPARATION FROM SILICON

**GROUP 2 ELEMENTS:**

<table>
<thead>
<tr>
<th>IRRADIATE</th>
<th>Cool</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1</td>
<td>72 MIN</td>
<td>400 MIN</td>
</tr>
<tr>
<td>S-2</td>
<td>6 HOURS</td>
<td>400 MIN</td>
</tr>
</tbody>
</table>

DETECTOR SYSTEM BACKGROUND SPECTRA USED TO FIND DETECTION LIMITS - GROUP 2 ELEMENTS

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>NUCLIDE</th>
<th>NANOGRAMS/GRAM (PPB) $^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>$^{64}\text{Cu}$</td>
<td>8</td>
</tr>
<tr>
<td>Zn</td>
<td>$^{69}\text{Zn}$</td>
<td>7</td>
</tr>
<tr>
<td>Zr</td>
<td>$^{97}\text{Zr}$</td>
<td>10 (50)$^{**}$</td>
</tr>
<tr>
<td>W</td>
<td>$^{187}\text{W}$</td>
<td>0.01</td>
</tr>
<tr>
<td>Mo</td>
<td>$^{99}\text{Mo}$</td>
<td>2</td>
</tr>
<tr>
<td>Cr</td>
<td>$^{51}\text{Cr}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Fe</td>
<td>$^{59}\text{Fe}$</td>
<td>77</td>
</tr>
<tr>
<td>Zr</td>
<td>$^{95}\text{Zr}$</td>
<td>56</td>
</tr>
<tr>
<td>Ni</td>
<td>$^{58}\text{Co}$</td>
<td>20 (200)$^{**}$</td>
</tr>
<tr>
<td>Zn</td>
<td>$^{65}\text{Zn}$</td>
<td>6</td>
</tr>
</tbody>
</table>

$^*$5 GM SAMPLE - DIVIDE LIMITS BY 5
$^{**}$S-2 VALUES

3-6
DETECTION LIMITS - GROUP 1 ELEMENTS

10M IRRADIATION, 10M COOL, 10M COUNT

<table>
<thead>
<tr>
<th>Element</th>
<th>DPM(BG)</th>
<th>DPM/Nanogram</th>
<th>Det. Lim. Nanograms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}$Al</td>
<td>5.1</td>
<td>94</td>
<td>.06</td>
</tr>
<tr>
<td>$^{27}$Mg</td>
<td>10.0</td>
<td>22</td>
<td>.45</td>
</tr>
<tr>
<td>$^{51}$Ti</td>
<td>3.5</td>
<td>18</td>
<td>.19</td>
</tr>
<tr>
<td>$^{52}$V</td>
<td>4.9</td>
<td>4400</td>
<td>.001</td>
</tr>
<tr>
<td>$^{56}$Mn</td>
<td>4.3</td>
<td>7900</td>
<td>.00005</td>
</tr>
<tr>
<td>$^{65}$Ni</td>
<td>16.0</td>
<td>8</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{66}$Cu</td>
<td>51.9</td>
<td>860</td>
<td>.061</td>
</tr>
</tbody>
</table>

PROCEDURES

GROUP 2 ELEMENTS - IRRADIATE PACKAGE AS RECEIVED
Transfer from package for counting
Suggestion: Double bag and label outer bag only

GROUP 1 ELEMENTS - Procedure under development

1.) 1 GM Si + 10 mL conc. HNO$_3$ + 10 mL 50% HF + .8 mg Tm tracer
2.) Heat to drive off SiF$_4$ in teflon beaker in hood
3.) Evaporate to dryness
4.) Recover TmF$_3$ - poly bag? Kemfol disc?
5.) Irradiate 10 min. Start count within 10 min. 10, 20, 40 and 80? min. Consecutive counts.
GROUP 1 ELEMENT - REAGENT BLANK DATA

Nanograms Blank/Gr SI (Reported Values)*

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>ULTREX UCO₂</th>
<th>ULTREX HE</th>
<th>SPECTRUM IND TM</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>30</td>
<td>20</td>
<td>N.L.</td>
<td>50+</td>
</tr>
<tr>
<td>V</td>
<td>N.L.</td>
<td>N.L.</td>
<td>N.L.</td>
<td>—</td>
</tr>
<tr>
<td>Cu</td>
<td>10</td>
<td>2</td>
<td>1 - 4</td>
<td>13-17</td>
</tr>
<tr>
<td>Ti</td>
<td>10</td>
<td>30</td>
<td>N.L.</td>
<td>40+</td>
</tr>
<tr>
<td>Mg</td>
<td>3</td>
<td>7</td>
<td>1 - 4</td>
<td>11-15</td>
</tr>
<tr>
<td>Mo</td>
<td>N.L.</td>
<td>N.L.</td>
<td>N.L.</td>
<td>—</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt;10</td>
<td>-10</td>
<td>N.L.</td>
<td>—</td>
</tr>
<tr>
<td>Mn</td>
<td>1</td>
<td>8</td>
<td>N.L.</td>
<td>9+</td>
</tr>
</tbody>
</table>

*In actual procedure blanks would be measured relative to thulium tracer.

THULIUM TRACER

Assume 1 procedure blank per 10 samples.

\[
\text{Net Nanograms Al} = \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Sample}} - \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Blank}}
\]

\[
= \frac{(\text{Nanograms Al})_{\text{Sample}} - (\text{Nanograms Al})_{\text{Blank}}}{\text{Gr SI}}
\]

\[
= \frac{(\text{Nanograms Al})_{\text{Sample}}}{\text{Gr SI}} - \frac{(\text{Nanograms Al})_{\text{Blank}}}{\text{Gr SI}}
\]

\[
= \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Sample}} - \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Blank}}
\]

\[
= \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Sample}} - \left( \frac{\text{Nanograms Al}}{\text{Gr SI}} \right)_{\text{Blank}}
\]

3-8
ENGINEERING DESIGN

CONSIDERATIONS

- CFR reduces specific Capital investment ($/kilo) with high throughput.
- CFR reduces Energy cost with gas fired reactor and Energy investment with high throughput of large A/V substrate.

PROPOSED CHANGES FROM EXTANT COMMERCIAL PROCESSES

Replace - SiCl-H System With Si-Br-H System

Replace - CVD Reactor With CFR* Reactor

* Continuous Flow Reduction

PROCESS CHARACTERISTICS

REQUIRED TO MEET JPL GOAL

<table>
<thead>
<tr>
<th>Existing Plants</th>
<th>Desired Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>$20,000,000/500 MTY</td>
</tr>
<tr>
<td>Raw Materials</td>
<td>$4.50/KgSi</td>
</tr>
<tr>
<td>Labor Related</td>
<td>$10.71/KgSi</td>
</tr>
<tr>
<td>Utilities</td>
<td>$3.50/KgSi</td>
</tr>
<tr>
<td>Capital Related</td>
<td>$8.10/KgSi</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$0.69</td>
</tr>
<tr>
<td>Total</td>
<td>$27.50</td>
</tr>
</tbody>
</table>
KINETIC ANALYSIS

\[
\text{SiBr}_4 + H_2(T_i) \rightarrow U_\infty \rightarrow U_p
\]

\[
\delta \rightarrow \text{Si}(R)
\]

CALCULATE \( V = \frac{\dot{R}}{R} \) (\( R, U_\infty, T_i, \Delta T_i, \text{Br}/\text{H} \))

- Account for heat loss due to deposition and convection
- Ignore "wall effects"

MATTER TRANSPORT

\[
V = 2 \cdot \Omega \cdot \text{No}_{i} \cdot \text{D}_{i}^{2/3} \cdot U_{\infty}^{1/3} \cdot R^{-2/3}
\]

With matter flux integrated over the particle

\( \Delta n = \) Atomic Volume Solid Si
\( \text{No}_{i} = \) Conc. \( i \)th species at outer boundary layer
\( \text{D}_{i} = \) Diffusion Coefficient \( i \)th species in boundary layer

HEAT TRANSPORT

- Assume particle small so that thermal diffusion maintains \( T_p(R) = \) Constant

Then

\[
\dot{\Delta T} = \frac{3 \cdot (\Delta H_d \cdot V)}{C_p \cdot R} \quad \text{due to deposition}
\]

\( \Delta H_d = \) Heat of deposition/unit volume

and

\[
\dot{\Delta T} = \frac{3 \cdot k^* \cdot \Delta T_i}{C_p \cdot R \cdot \delta_T} \quad \text{due to convection}
\]

- \( k^* = \) Thermal conductivity of gaseous species
- \( \delta_T = \) Thermal boundary layer

THERMODYNAMIC CONTRIBUTIONS

- \( \text{SiBr}_4 \rightarrow \text{Si} \) \( \rightarrow \) deposition
- \( \text{Si} \rightarrow \text{SiHBr}_3, \text{SiH}_2\text{Br}_2, \text{SiBr}_2 \) \( \rightarrow \) etching

Assume interface equilibrium so that

\[
K_j = \exp \left( -\frac{\Delta F_{T_j}}{R \cdot T} \right) \quad R^* = \text{gas constant}
\]

- Calculate \( \Delta F_{T_j} \) from Hunt & Sirtl Data
- Calculate \( D_j \) from gas dynamics where

\[
D_j = \frac{1}{3} \frac{k_j}{V_j}
\]

with \( l_j = \) mean free path

\( V_j = \) average particle velocity

- Calculate \( k^* = C_p \nu \) B for \( j \)th species

INITIAL RESULTS

\[
\Delta T(d) = 2.7 \cdot 10^3 \frac{V}{H} \quad \text{C/sec} = 27 \text{C/sec}
\]

at \( V = 1.4 \nu \) sec & \( R = 100 \nu \)

\[
\Delta T(c) = 4 \cdot 10^{-4} \cdot \frac{\Delta T_i}{R^2} = 4 \frac{\Delta T_i \nu \text{C}}{\text{sec}}
\]

(1) Thus \( \Delta T(c) \) \( \bar{\nu}(d) \) and \( \Delta T_i = 0 \) at \( t = .25 \) sec

(2) \( V = 1.4 \nu \) sec at 1100°C

3-10
\[ \text{SiH}_x\text{Br}_{4-x} + (2-x) H_2 = \text{Si} + (4-x) \text{HBr} \]

\[ \text{SiH}_x\text{Br}_{4-x} \rightarrow \text{SiH}_x\text{Br}_{4-x} \]

T-20-25°C T-1000°- 1200°C

\[ H_2 \rightarrow H_2 \]

T-20-25°C T-1000°- 1200°C

\[ \text{Si} \rightarrow \text{Si} \]

T-20-25°C T-1000°- 1200°C

**Products Isolated:**

a) \( \text{Si}_2\text{Br}_6 \)

b) \( \text{HBr} \)

c) Lower Homologs of \( \text{SiH}_x\text{Br}_{4-x} \) Series

d) Silicon
   1. Wall Deposition
   2. Finely Divided Powder
   3. Some Growth on Particles

I. Energy From Gas Streams

II. Energy From Gas Streams and Heated Particles

III. Energy From Gas Streams and an External Source

IV. Energy From Gas Streams, Heated Particles and an External Source

3-11
Figure 1. Reaction System Schematic

Silicon # 030 - Cr/Cu

<table>
<thead>
<tr>
<th></th>
<th>Cr Conc.</th>
<th>Cr Conc.</th>
<th>Previous Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr Conc.</td>
<td>29.6</td>
<td>0.80 ± 0.05</td>
<td>1.0</td>
</tr>
<tr>
<td>Cu Conc.</td>
<td>58.4</td>
<td>1.29 ± 0.08</td>
<td>1.0</td>
</tr>
</tbody>
</table>
## Silicon # 030 - Cr/Cu

<table>
<thead>
<tr>
<th>Analytical Method</th>
<th>Cr Conc.</th>
<th>Cr Conc.</th>
<th>Previous Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAA</td>
<td>29.6</td>
<td>0.80 ± 0.05</td>
<td>1.0</td>
</tr>
<tr>
<td>IDSSMS</td>
<td>30.</td>
<td>0.8 ± 0.4</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analytical Method</th>
<th>Cu Conc.</th>
<th>Cu Conc.</th>
<th>Previous Best Estimate</th>
</tr>
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<tbody>
<tr>
<td>NAA</td>
<td>58.4</td>
<td>1.29 ± 0.08</td>
<td>1.0</td>
</tr>
<tr>
<td>IDSSMS</td>
<td>60.</td>
<td>1.3 ± 0.5</td>
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</table>

## Silicon # 041 Ni/Cr/Cu

<table>
<thead>
<tr>
<th>Ni Conc.</th>
<th>Ni Conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ng/g</td>
<td>ATOMS/cc x 10^{15}</td>
</tr>
<tr>
<td>57</td>
<td>1.4 ± 0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cr Conc.</th>
<th>Cr Conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ng/g</td>
<td>ATOMS/cc x 10^{15}</td>
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<tr>
<td>16.5</td>
<td>0.44 ± 0.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cu Conc.</th>
<th>Cu Conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ng/g</td>
<td>ATOMS/cc x 10^{15}</td>
</tr>
<tr>
<td>0.22</td>
<td>0.005 ± 0.002</td>
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</tbody>
</table>

## Silicon # 039 - Ni

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<tr>
<th>Ni Conc.</th>
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<tbody>
<tr>
<td>ng/g</td>
<td>ATOMS/cc x 10^{15}</td>
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<tr>
<td>2640</td>
<td>63.0 ± 3.0</td>
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</table>

## Silicon # M4BS

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<tbody>
<tr>
<td>ng/g</td>
<td>ATOMS/cc x 10^{15}</td>
</tr>
<tr>
<td>620</td>
<td>14.8 ± 0.9</td>
</tr>
</tbody>
</table>
### SINGLE ELEMENT ANALYSIS OF DOPED SILICON

#### MANGANESE

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>TARGET CONCENTRATION ATOMS/cc x 10^{15}</th>
<th>MEASURED CONCENTRATION ATOMS/cc x 10^{15}</th>
</tr>
</thead>
<tbody>
<tr>
<td>005</td>
<td>1</td>
<td>0.96 ± 0.04</td>
</tr>
<tr>
<td>027</td>
<td>1</td>
<td>0.89 ± 0.18</td>
</tr>
<tr>
<td>031</td>
<td>1</td>
<td>1.55 ± 0.06</td>
</tr>
<tr>
<td>013</td>
<td>0.3</td>
<td>0.26 ± 0.04</td>
</tr>
<tr>
<td>026</td>
<td>0.01</td>
<td>0.008 ± 0.002</td>
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<tr>
<td>M11</td>
<td>0.7</td>
<td>0.09 ± 0.02</td>
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<tr>
<td>C5B</td>
<td>12</td>
<td>0.64 ± 0.04</td>
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<tr>
<td>M5B</td>
<td>1.5</td>
<td>0.021 ± 0.006</td>
</tr>
<tr>
<td>003</td>
<td>BLANK</td>
<td>0.122 ± 0.005</td>
</tr>
<tr>
<td>M1B</td>
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<td>0.0024 ± 0.0002</td>
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</tbody>
</table>

#### COPPER

<table>
<thead>
<tr>
<th>SAMPLE #</th>
<th>NEUTRON ACTIVATION</th>
<th>TARGET CONCENTRATION ATOMS/cc x 10^{15}</th>
<th>FOUND CONCENTRATION ATOMS/cc x 10^{15}</th>
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</thead>
<tbody>
<tr>
<td>056</td>
<td>017</td>
<td>25</td>
<td>45.3 ± 0.8</td>
</tr>
<tr>
<td>017</td>
<td>027</td>
<td>20</td>
<td>11.2 ± 0.5</td>
</tr>
<tr>
<td>017</td>
<td>027</td>
<td>20</td>
<td>10.9 ± 0.5</td>
</tr>
<tr>
<td>055</td>
<td>055</td>
<td>2</td>
<td>1.23 ± 0.08</td>
</tr>
<tr>
<td>019</td>
<td>019</td>
<td>2</td>
<td>1.29 ± 0.08</td>
</tr>
<tr>
<td>055</td>
<td>055</td>
<td>2</td>
<td>1.24 ± 0.08</td>
</tr>
<tr>
<td>007</td>
<td>007</td>
<td>2</td>
<td>0.050 ± 0.01</td>
</tr>
<tr>
<td>007</td>
<td>007</td>
<td>2</td>
<td>0.065 ± 0.01</td>
</tr>
<tr>
<td>041</td>
<td>041</td>
<td>2</td>
<td>0.005 ± 0.002</td>
</tr>
<tr>
<td>051</td>
<td>051</td>
<td>2</td>
<td>0.002 ± 0.002</td>
</tr>
<tr>
<td>020-00</td>
<td>BLANK</td>
<td>0.007 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>002-00</td>
<td>BLANK</td>
<td>0.006 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>ID SSMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>056</td>
<td>056</td>
<td>25</td>
<td>45.0 ± 1.3</td>
</tr>
</tbody>
</table>

3-14
OPERATION OF THE SISTERSVILLE SILANE
PROCESS DEVELOPMENT UNIT (PDU)

- Operation of the process development unit is being carried out in order to demonstrate silane manufacture via the hydrogenation and reformation of chlorosilanes.

- The data obtained so far indicate that PDU is performing as designed.

- Using only metallurgical grade silicon and hydrogen as feed materials, silane has been made in the PDU at a rate of up to .2 lbs/hour and a silicon efficiency of about 18%. 

3-15
SILANE PYROLYSIS

\[ \text{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2 \]

- 5"/hr FREE SPACE REACTOR
- 0.1-2.0 MICRONS SPHERES
- 50 MICRONS
- 1/2" HOLE
- 1-2"/hr MELTER
- 1/8" PELLET (CANTLE)
- VACUUM CAST
- PRODUCT SLO SOLUTION REFRACTIVE INDEX 2.028

SILANE

\[ \text{SiH}_4 \]

100 SCF/CM
FIG. 1. FLUIDIZATION BEHAVIOR OF -35/+60 MESH SILICON PARTICLES
PROCESS HIGHLIGHTS

1. HYDROGENATION

Metallurgical grade silicon is hydrogenated via a copper catalyzed reaction which proceeds rapidly to equilibrium in a fluidized bed reactor:

\[ \text{Si} + 2\text{H}_2 + 3\text{SiCl}_4 \rightarrow 4\text{HSiCl}_3 \]

Impurities in the metallurgical grade silicon are converted to metal chlorides, metal hydrides, and metal chloride complexes such as AlCl₃, FeCl₃, PCl₃, LiCl, MgCl₂, Al-Te-Cl and Al-P-Cl complexes.

Reaction has an endothermic heat of 8 Kcal/gm-mole.

Equilibrium yield is maximized by high pressure, excess hydrogen and excess silicon tetrachloride.

2. REDISTRIBUTION/DISTILLATION

Chlorosilanes form an equilibrium mixture when passed over a catalyst, which is a function only of chlorine/silicon ratio. The chlorine/silicon ratio may be advanced toward zero by removing silicon tetrachloride from the equilibrium mixture. A two step process is used.

\[ 4\text{HSiCl}_3 \rightarrow 2\text{HSiCl}_2 + 2\text{SiCl}_4 \]
\[ 2\text{HSiCl}_2 \rightarrow \text{SiH}_4 + \text{SiCl}_4 \]

Redistribution reactions have no measurable reaction heats.

Methane, nitrogen, hydrogen chloride and any gases lighter than dichlorosilane (HSiCl₃) are removed from the process by distillation before any redistribution of trichlorosilane (HSiCl₃).

Two redistribution reactors are separated by three distillation columns, the last producing a high purity silicon distillate. Advancing is taken of the fact that except for methane, no stable chloride or hydride compound exists that boils lower than silane.

3. PYROLYSIS

Silane is vaporized and injected into an oven vessel operating at 750°C. Decomposition to silicon starts at 500°C and is essentially complete by 750°C. Silicon is formed as a fine powder, with a typical particle of micron size.

\[ \text{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2 \]

Reaction has exothermic heat of 8 Kcal/gm-mole. This heat is used to heat up the silane to reaction temperature.

4. WASTE DISPOSAL

Solid wastes from the hydrogenation reaction are neutralized with lime, reacting metal chlorides to their hydrates.

\[ 2\text{ZnCl}_2 + \text{Ca(OH)}_2 \rightarrow 2\text{Zn(OH)}_2 + 2\text{Cl}_2 \]

Chlorosilanes lost with the metal chlorides are also neutralized to yield hydrated silicas, hydrogen and calcium chlorides.

Gaseous vents are passed through a flame and the combustion products scrubbed free of acid components with lime.

All plant wastes leave as a filter cake.
UCC SILICONE/SILICON PROCESS
 FOR 1000 MT/yr LOW COST SOLAR GRADE SILICON

Work performed under JPL/DOD Contract 954334
Plant Size: 1000 Metric Tons/Year
Estimated Stream Factor: 85%
Product Quality: 100 ohm-cm, as molten silicon
Plant Area (as shown): 240' x 170'
Estimated Plant Cost (1978 Dollars): $6,000,000

COSTS

<table>
<thead>
<tr>
<th>Raw Materials:</th>
<th>$/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallurgical-grade silicon</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
</tr>
<tr>
<td>Technical-grade silicon tetrachloride</td>
<td></td>
</tr>
<tr>
<td>Copper Cement Catalyst</td>
<td></td>
</tr>
<tr>
<td>Lime</td>
<td>2.03</td>
</tr>
</tbody>
</table>

| Labor: |
|--------|------|
| 4 Operators/shift | |
| 1 Laborer/shift | |
| 1 Foreman/shift | |
| 6 Maintenance men/shift | 0.79 |

| Utilities: |
|------------|------|
| 20 MMBtu/hr cooling water | |
| 15 MMBtu/hr Steam | |
| 4 MMBtu/hr direct heat | |
| 1310 KW Electricity | 0.75 |

| Maintenance: |
|--------------|------|
| Estimated @ 7% Plant Cost | 0.42 |

| Property Tax: |
|---------------|------|
| Estimated @ 0.5% Plant Cost | 0.03 |

| Insurance: |
|------------|------|
| Estimated @ 1.0% Plant Cost | 0.06 |

| Operating Cost, excluding depreciation | $4.08 |
| Capital Charges* | $3.72 |
| Product Cost | $7.80 |

* (15 year project life, 10 year SYD depreciation, 48% federal income tax, 100% equity financing, 2 years construction time, 7% CCR rate).

SENSITIVITY ANALYSIS FOR 1000 MT/yr SILICON PLANT

Product Cost vs DCF for 50% Plant Cost

<table>
<thead>
<tr>
<th>DCF Rate</th>
<th>$/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>6.18</td>
</tr>
<tr>
<td>20%</td>
<td>6.95</td>
</tr>
<tr>
<td>25%</td>
<td>7.83</td>
</tr>
<tr>
<td>30%</td>
<td>8.77</td>
</tr>
</tbody>
</table>

Product Cost vs Plant Cost @ 0.15% and 2% DCF Rate

<table>
<thead>
<tr>
<th>Plant Cost, $/y</th>
<th>0.15% DCF</th>
<th>2% DCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>$6.18</td>
<td>$7.20</td>
</tr>
<tr>
<td>7.0</td>
<td>6.48</td>
<td>8.33</td>
</tr>
<tr>
<td>8.0</td>
<td>6.76</td>
<td>8.83</td>
</tr>
</tbody>
</table>

3-19
The purpose of the present investigation is to convert metalurgical grade silicon (mg Si) into semiconductor grade silicon (sg Si) via a 3 step SiF$_2$ polymer transport purification process. The first step$^1$ involves the reaction of SiF$_4$ with mg Si to yield gaseous SiF$_2$:

$$\text{SiF}_4 + \text{Si} \rightarrow 1360^\circ \text{C} \rightarrow \text{SiF}_2$$

Step 1

This is followed by a polymer formation step.$^2$

$$x\text{SiF}_2 \rightarrow 48^\circ \text{C} \rightarrow 100^\circ \text{C} \rightarrow (\text{SiF}_2)_x$$

Step 2

The polymer is then converted into high purity silicon, SiF$_4$ and higher homologues.$^3$

$$(\text{SiF}_2)_x \rightarrow 360-850^\circ \text{C} \rightarrow \text{Si} + \text{SiF}_4 + x\text{SiF}_2$$

Step 3

The mg Si undergoes purification in all three steps of the above transport processes.
(SiF₄)₉ Polymer Condensation Experiments. These experiments are directed towards obtaining the parameters for efficient polymer formation. It was demonstrated that packed beds could restrict SiF₂ flow resulting in high back pressures which ultimately lead to low SiF₄ to SiF₂ conversion in step 1.

Experiments Involving SiF₂ Homologue Conversion Chemical Vapor Deposition. Results from these experiments clearly demonstrate the conversion efficiency is directly proportional to the bed length with other factors constant. Increasing the bed temperature from 500°C to 850°C also increases efficiency.

Modifications Made to the Near-Continuous Apparatus. A number of modifications have been made to the reaction apparatus to facilitate long runs (2 hrs) at high throughput (30-60 gm/hr). The reactor bed has been made vertical, the baffle area will now be heated during SiF₂ formation. The polymer will be heated in small units. The mass of the SiF₄ introduced into the reactor will be monitored by weighing the storage cylinder.

Silicon Product Analysis. Further work on establishing reliability and accuracy of SSMS analysis clearly demonstrate that the grinding procedure introduces contaminants into the silicon irrespective of the mortar and pestle construction material.

**FIGURE 1.** Condenser used for Conversion Efficiency Experiments.
Figure 3. (Run 4b) Substrate Temperature and Condenser Pressure as a Function of Run Time.

Figure 5. % Conversion based on Si$_x$F$_y$ Input to Bed.
Figure 7. Depicted above is the near-continuous apparatus as modified for silicon purification experiments to start in March. The apparatus includes a vertical reaction furnace, rechargable CVD SiF₄ disproportionation bed and unitized SiF₂ polymer condensation/liberation coil.

**Basis of Mass Balance**

1. Inlet Metallurgical Grade (96) Silicon is 98.6% Si, 0.7% Fe, 0.4% Al, 0.3% OTHER, by weight.

2. Unused slag consists of 80% Si.

3. 80% of the SiF₄ reacts with Si at 1350°C to form SiF₂.

4. 1% of SiF₂ prepolymerizes in baffle for impurity removal.

5. 80% of (SiF₂)ₖ polymer is converted to 86 Si and SiF₄ in the harvester with the remaining 20% being recycled (at 80% harvester conversion) after a polymerization/depolymerization step.

6. 4% of recycled SiF₄ is lost.
OVERALL REACTION SEQUENCE

\[ \Delta H \text{ (25°C)} \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Equation</th>
<th>( \Delta H ) (kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>React</td>
<td>( Si(s) + SiF_4(g) \rightarrow 2 SiF_2(g) )</td>
<td>88</td>
</tr>
<tr>
<td>Polymerize</td>
<td>( 2 SiF_2(g) \rightarrow 2 (SiF_2)_x(s) ) ( 2(-37.3) = -74.6 )</td>
<td></td>
</tr>
<tr>
<td>Depolymerize</td>
<td>( 2 (SiF_2)_x(s) \rightarrow 2(SiF_2)_x(g) = SiF_4(g) ) ( 2(3.7) = 7.4 )</td>
<td></td>
</tr>
<tr>
<td>Harvest</td>
<td>( SiF_4(g) = 2(SiF_2)_x(g) \rightarrow Si(s) + SiF_4(g) ) ( -20.8 )</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta H_1 = 88 - 74.6 + 7.4 - 20.8 = 0 \]
## ENERGY BALANCE SUMMARY PER KG Si

<table>
<thead>
<tr>
<th></th>
<th>Heating</th>
<th>Refrigeration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>Energy kcal/kg Si</td>
</tr>
<tr>
<td>Reactor</td>
<td>1400</td>
<td>6110</td>
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<tr>
<td>Main Polymerization</td>
<td>40</td>
<td>1040</td>
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<tr>
<td>Recycle Polymerization</td>
<td>-90</td>
<td>560</td>
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<tr>
<td>Main Depolymerize</td>
<td>270</td>
<td>(680)</td>
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<tr>
<td>Recycle *</td>
<td>270</td>
<td>130</td>
</tr>
<tr>
<td>Harvester</td>
<td>800</td>
<td>(-687)</td>
</tr>
<tr>
<td>SiF$_4$ Condensers</td>
<td>-180</td>
<td>390</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>6240</td>
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<tr>
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</tr>
</tbody>
</table>

## REACTOR SIZING

**SMALL SCALE** 50 GM/HR  1" x 24"  29 KCM/SEC  (8 to 3.5 TORR)

**LARGE SCALE** 12.2 KG/HR  16" x 43"  32 KCM/SEC  (20 to 1 TORR)

11 REACTORS x 12.2 KG/HR = 134.2 KG Si/HR

1000 M TONS/YEAR

1410°C

<table>
<thead>
<tr>
<th>1200</th>
<th>1300</th>
<th>1350°C</th>
</tr>
</thead>
</table>

\[ Q_{\text{rad. in}} = (31.6 + 18.1 + 20.7) \times 10^3 = 70,400 \text{ KCal/hr} \]

\[ Q_{\text{needed}} = 57,970 \text{ KCal/hr}. \]
WESTINGHOUSE ELECTRIC CORPORATION
P.C.B. DIVISION
ARC HEATER PRODUCTION OF SILICON

SCHEMATIC FLOW OF WESTINGHOUSE PROCESS FOR CONTINUOUS SILICON PRODUCTION

NaCl MAKE-UP

ELECTROLYSIS UNIT

LIQUID CL₂ STORAGE

CHLORINATION UNIT

CRUDE SiCl₄ STORAGE

SiCl₄ PURIFICATION UNIT

Ar

LIQUID Na STORAGE

ARC HEATER(S)

Na Pump

Reactor Chamber

SICl₄ COLLECTOR

GAS & SALT VAPOR

VENTURI SCRUBBER

BRINE SLURRY

BRINE CLARIFIER

COOLING BRINE

Si CASTER

Si TO STORAGE

NaCl DRYER

GAS COMPRESSOR

GAS COOLER & DRYER

H₂
Task II Objectives

- Conduct analysis and design to provide an effective means of silicon product removal after the reduction of silicon tetrachloride.

- Analyze Homogeneous Systems
  - Condensation of silicon vapor
  - Nucleation onto silicon seed particles, followed by inertial separation
  - Translate analysis results to design

- Analyze Heterogeneous Systems
  - Surface reaction on seed particles
  - Surface reaction on sodium droplets, followed by thermal treatment
  - Translate results to design, including inertial separation

- Review results with JPL. Select the route of highest potential for successful operation.

Silicon Production Separation

Initial Design Basis:

\[
\text{Na}(z) + \text{SiCl}_4 \longrightarrow \text{Si}(ssv) + \text{NaCl}(v)
\]

\[
\text{Si}(v) \longrightarrow \text{Si}(z)_{\text{Nuclei}} + \text{Si}(v)
\]

\[
\text{Si}(v) + \text{Si}(z)_{\text{Nuclei}} \longrightarrow \text{Si}(z)_{\text{Droplets for D > 5 microns}}
\]

Problem:

Inadequate Coagulation Rate

A) Brownian motion (0.2 to 0.3 micron in 0.1 seconds)

B) Turbulent coagulation: insufficient
SILICON REACTOR SYSTEM

POWER

ARC HEATER

GAS

VAPORIZATION

VAPOR

REACTION

SiCl₄

SILICON CONDENSER SEPARATOR

EFFLUENT GAS

SILICON(+) COLLECTOR

Basic Condensation Model
STREAM RELATIONS

ENERGY

\[ \frac{d(hh)}{dz} = -Qv - \tau_{st} \frac{h_{st}}{h_{my}} \]

MASS

\[ \frac{d\tilde{m}}{dz} = -\tau_{st} \]

COMBINED

\[ \frac{dh}{dz} = \frac{1}{\beta} \left[ -Qv + \tau_{st} \left( h - h_{st,m} \right) \right] \]

TRANSFER

\[ Qv = N_{h_{st}} (T_{h} - T_{w}) + Q_{r} \]

\[ \tau_{st} = N_{h_{st}} \rho_{h_{st}} \pi c (\xi_{h} - \xi_{h_{st,m}}) \]

BOUNDARY LAYER CONSIDERATIONS FOR CONDENSATION

HEAT TRANSFER

\[ q = c_c \left[ \frac{1}{\beta_{Pr}} + c \right] \frac{dT}{dy} \]

MASS TRANSFER

\[ \frac{1}{\beta} \left[ \frac{y'}{\beta} + c \right] c \frac{d\tilde{m}}{dy} \]

FULLY DEVELOPED UNIVERSAL VELOCITY PROFILE

\[ u = \frac{1}{\nu} \sqrt{\frac{y}{y^+}} \]

\[ y^+ = \frac{y}{\nu} \sqrt{\frac{C_f}{\rho}} \]

\[ \nu = \epsilon \left( y^+ \right) \]

3-29
**Saturation Conditions**

\[ u = \frac{M}{\eta_T} \frac{P_{sat}}{\rho} \]

**Sublayer (Saturated)**

\[ T_1 - T_u = 5 \Pr \, q_u^+ (1 + A_j) - \frac{1}{C_p} \frac{Pr}{Sc} (W_1 - W_u) \]

**Buffer Layer (Saturated)**

\[ T_2 - T_1 = 5q_u^+ (1 + A_j) \ln (1 + 5Pr) - \frac{1}{C_p} (w_2 - w_1) \]

**Turbulent Core**

\[ T^* - T_2 = 2.5 \, q_u^+ (1 + A_j) \ln \left[ \frac{(1 + Pr y_u^*)^{2.5} - Pr}{(1 + 11 \Pr)^{2.5/3}} \right] - \frac{1}{C_p} \, \left( w^{*} - w_2 \right) \]

\[ q_u^* = q_u^+ (1 + A_j) - \frac{1}{C_p} \, j_s^* \]

J and Q are constant for \( y^* > y^* \)

\[ T^* - T_2 = 2.5 \, (q u^* (1 + A_j - 1 + j_s^*)) \ln \left[ \frac{Pr y^*}{1 + Pr (2.5) - Pr} \right] \]

\[ u^*_w = 2.5 \, j_s^* \ln \left[ \frac{1 + y^*_w \text{Sc} - \text{Sc}}{3.5} \right] \]

\[ \frac{1 + y^*_w \text{Sc} - \text{Sc}}{3.5} \]
\[ T_s - T_w = q_w^+ \left[ 1 + A_w \right] \left[ 5 \Pr + 5 \ln \left( 1 + 5 \Pr \right) + 2.5 \ln \left( \frac{1 + Pr \gamma^+}{2.5} - Pr \right) \right] \]

\[ = \frac{1}{C_p} \left[ \frac{Pr}{Sc} - 1 \right] W_i - Pr \cdot \frac{W_s}{Sc} + W^* + \left( W_a - W_d \right) \left( \ln \left( \frac{1 + Pr \gamma^+ - Pr}{2.5} \right) \right) \]

\[ \left( \ln \left( \frac{1 + Sc \gamma^* - Sc}{2.5} \right) \right) \]

\[ \left( \ln \left( \frac{1 + Pr \gamma^* - Pr}{2.5} \right) \right) \]

\[ W_i, W_s \ll W_o \quad \text{AND RATIO OF LOGS} \ll 1 \]

\[ q_w^+ (1 + A_w) = \frac{T_s - T_w + \frac{1}{C_p} w}{F(y_o^+)} \]

WHERE

\[ F(y_o^+) = Pr + 5 \ln(1 + 5 \Pr) + 2.5 \ln \left( \frac{1 + Pr \gamma^+ - Pr}{2.5} \right) \]

TRANSITION

\[ q_a^+ = q_w^+ (1 + A_w) - \frac{1}{C_p} j^+ \]

\[ \frac{w_o - v^+}{T_s - T_w} = \frac{j^+}{q_a} \ln \left[ \frac{1 + Sc \gamma^* - Sc}{2.5} \right] \]

\[ \left( \ln \left( \frac{1 + Pr \gamma^* - Pr}{2.5} \right) \right) \]

\[ \left( \ln \left( \frac{1 + Pr \gamma^* - Pr}{2.5} \right) \right) \]

BY THE SAME APPROXIMATION

\[ j^+ = \frac{w_o - v^+}{q_a \cdot T_s - T_o^*} \]
FOR $v^+ \geq v^+_e$

$$L^+_e = \left( \frac{-1}{\kappa_e} + \frac{v^+_e}{\nu_s} - 1 \right) \left[ \frac{\nu_s}{\kappa_e} \right] \left[ \frac{\nu_p}{\kappa_e} \right].$$

$$a^+_e = \left( \frac{-1}{\kappa_e} + \frac{v^+_e}{\nu_s} - 1 \right) \frac{\nu_p}{\kappa_e}.$$

THUS,

$$\frac{v^+_s - v^+_e}{T_e - T_s} = \frac{\nu_p}{\kappa_e}.$$

$$v^+_s - v^+_e \exp \left[ \frac{(T_e - T_s) \left[ 1 + \frac{1}{\nu_p} \left( \frac{\nu_p}{\kappa_e} \right) \nu_p v^+_e \right]}{2.5 \left( T_e - T_s + \frac{1}{\nu_p} \nu_p v^+_e \right)} \right]$$

**Mass Transfer Enhancement (Relative to No Condensation in Boundary Layer)**

$$\frac{J_e}{J_b} = \frac{\nu_p}{\kappa_e} \frac{(T_e - T_s) \left[ 1 + \frac{1}{\nu_p} \left( \frac{\nu_p}{\kappa_e} \right) \nu_p v^+_e \right]}{2.5 \left( T_e - T_s + \frac{1}{\nu_p} \nu_p v^+_e \right)} \left[ \nu_p v^+_e \right].$$

**Heat Transfer Enhancement (Relative to No Mass Transfer)**

$$R_0 = 1 + \frac{W_s}{\kappa_e} \left[ \frac{\nu_p}{\kappa_e} \right].$$

3-32
GAS PROPERTIES

$\rho$, $C_p$, $Pr_F$, $Pr$, $K_F$, $K$, $Sc$, $D_{S1-M}$

FOR A) $3.31 H_2$  
0.83 Ar  
4.0 Na  
4.0 Cl  
1.0 Si

B) $3.31 H_2$
0.83 Ar  
2.0 Na  
2.0 Cl  
0.5 Si

*Two Dimensional B, T Representation/Interpolation

Fig. 3 - Local Nusselt number ratio vs. distance ratio obtained from Boelter & Coworkers' measurements on a circular tube with right angle bend entrance
Fig. 2—Local Nusselt number ratio vs distance ratio in swirl flow for different initial swirl intensities

**NUMERICAL PROCEDURE**

1) **Determine influence of condensation upon heat and mass transfer for fully developed turbulent flow with constant properties**

   i.e., \( \text{Re}_D, \text{Nu}_D \)

   and location of saturation/superheat transition

2) **Numerical Integration**

   \( f(x), T_g(x), Y_{\text{star}}(x), X_{\text{star}}(x), X_{\text{si}}(x), V_g(x), \)

   \( \text{Re}(x), \text{Nu}(x), \text{Nu}^*(x), V_{\text{tan}}(x) \)
Bias, Y Star & QW - See Figure 1

Figure 4
WATER VAPOR CONDENSATION

![Condensing Section Diagram]

**Condensing Section**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Gases</th>
<th>$T_1$(°K)</th>
<th>$T_e$(°K)</th>
<th>$X_1$(H$_2$O)</th>
<th>$\eta$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H$_2$ + O$_2$</td>
<td>2692</td>
<td></td>
<td>0.391</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>H$_2$ + Air</td>
<td>1711</td>
<td>853</td>
<td>0.215</td>
<td>75</td>
</tr>
</tbody>
</table>

\[
\frac{dX_{H_2O}}{dz} = \frac{4 \text{Nu} CD_{D_2} (X_{H_2O} - X_{H_2O,M})}{Uo \text{Co} D^2} \quad \text{TREF} = 790^\circ \text{K}
\]

\[\dot{m} = 4.18 \times 10^{-3} \text{kg/s} = 3.6 \times 10^{-5} \text{ Pa-s, } \eta = 0.0127 \text{m} \]

\[\text{Re} = 11544, \quad 30 < \text{Nu} < 40 \]

\[\lambda = 0.44 \text{m} \quad \eta_{\text{THEOR}} = \left(1 - e^{-2/\lambda}\right) 100\% \]

**SUMMARY OF CONDENSATION ANALYSIS**

1) Condensation product separation requires 1.5 MW arc heater power input for 100 lbm/hr. silicon flow rate. *Phase II facility is compatible for 100 lbm/hr. silicon flow rate.*

2) Analysis does not include cyclone path length.

3) Analysis indicated 80% separation efficiencies.

4) Thermal conductivity (equil. vs. frozen) "frozen" improves product separation.

5) Water vapor experiment demonstrates effective removal of low mole fraction condensable species.

6) Basic reactor configuration is equivalent to that of Phase I.
### TRANSLATION OF ANALYSIS TO DESIGN

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Homogeneous</th>
<th>Heterogeneous</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical System</strong></td>
<td>SiCl₄/Na</td>
<td>SiCl₄/Na</td>
</tr>
<tr>
<td><strong>Arc Heated Gas</strong></td>
<td>H₂/Ar</td>
<td>H₂/Ar</td>
</tr>
<tr>
<td><strong>Streaming Product</strong></td>
<td>Si(ν)</td>
<td>Si(L)</td>
</tr>
<tr>
<td><strong>Gaseous Coproduct</strong></td>
<td>NaCl/H₂/Ar</td>
<td>NaCl/H₂/Ar</td>
</tr>
<tr>
<td><strong>Max. Temp. (°K)</strong></td>
<td>3500</td>
<td>2200</td>
</tr>
<tr>
<td><strong>Wall Flux (w/cm²)</strong></td>
<td>40-100</td>
<td>20-50</td>
</tr>
<tr>
<td><strong>Required Duct Length (m)</strong></td>
<td>~5.</td>
<td>~1.</td>
</tr>
<tr>
<td><strong>Required Duct Diameter (cm)</strong></td>
<td>~15.</td>
<td>~10-15.</td>
</tr>
<tr>
<td><strong>Required Collector</strong></td>
<td>Closed Crucible</td>
<td>Cyclone</td>
</tr>
</tbody>
</table>

### ADDITIONAL CONSIDERATIONS

- **Minimize effect on project schedule.**
- **Minimize effect on completed subsystem design.**
- **Single geometry is preferable for both routes.**
  - **Improved probability of success.**
  - **Minimize design effort.**
  - **Minimize expense.**
### ESTIMATION OF SILICON PRODUCT COST ($/KgSi)

#### Cost Item

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Production Capacity (MT/yr)</th>
<th>500 MT&lt;sup&gt;1&lt;/sup&gt;</th>
<th>500 MT&lt;sup&gt;2&lt;/sup&gt;</th>
<th>3000 MT&lt;sup&gt;3&lt;/sup&gt;</th>
<th>3000 MT&lt;sup&gt;4&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch</td>
<td>Batch</td>
<td>Recycle</td>
<td>Recycle</td>
<td></td>
</tr>
<tr>
<td>Direct Manuf.</td>
<td></td>
<td>$13.84</td>
<td>$10.19</td>
<td>$5.67</td>
<td>$4.41</td>
</tr>
<tr>
<td>Indirect Manuf.</td>
<td></td>
<td>1.51</td>
<td>1.09</td>
<td>1.54</td>
<td>1.31</td>
</tr>
<tr>
<td>Plant Overhead</td>
<td></td>
<td>0.64</td>
<td>0.53</td>
<td>0.59</td>
<td>0.53</td>
</tr>
<tr>
<td>Total Manuf. Cost</td>
<td></td>
<td>15.99</td>
<td>11.81</td>
<td>7.80</td>
<td>6.25</td>
</tr>
<tr>
<td>General Expense</td>
<td></td>
<td>2.40</td>
<td>1.78</td>
<td>1.18</td>
<td>0.95</td>
</tr>
<tr>
<td>Total Product Cost&lt;sup&gt;4&lt;/sup&gt; ($/KgSi)</td>
<td></td>
<td>18.39</td>
<td>13.59</td>
<td>8.98</td>
<td>7.20</td>
</tr>
</tbody>
</table>

#### Fixed Capital<sup>4</sup> (K$)

|           | 3,582 | 2,720 | 22,035 | 19,073 |

### NOTES:

1. Homogeneous Reaction (condensation), assumes 80% yield on batch
2. Heterogeneous Reaction, assumes 100% yield on batch and recycle
3. Homogeneous Reaction (condensation), assumes 100% yield on recycle
4. 1975 Dollars
ARC HEATER/REACTOR SYSTEM

- REACTOR DESIGN (90% COMPLETE)

- REFRATORY SPECIFICATION

- DETAILED DRAWINGS (50% COMPLETE)

- PROCUREMENT

  (ALL ORDERS ENTERED IN MAY)

SILICON COLLECTOR

- DETAILED DESIGN COMPLETED

- DRAWINGS ARE UNDERWAY

- PROCUREMENT INITIATED
\textbf{SiCl\textsubscript{4} STORAGE AND INJECTION SYSTEM}

- STORAGE TANK SPECIFICATIONS
- FILLING
- EMERGENCY LOOP SHUTDOWN PROCEDURES
- I&C INTERFACING
- FINALIZE SiCl\textsubscript{4} SYSTEM SPECIFICATION

\textbf{NA STORAGE AND FEED SYSTEM}

- DETAILED DESIGN OF PIPING FOR Na AND NaK NEAR COMPLETE
- REVISED FLOW SYSTEM SCHEMATIC
- PROCUREMENT IS UNDERWAY

\textbf{Figure 5.5 - SiCl\textsubscript{4} Flow System Schematic}
Figure 5.6 – Sodium Supply System Schematic

KINETICS EXPERIMENT

DESIGN (COMPLETE)
FABRICATION (UNDERWAY)
LASER VAPOR MEASUREMENT EVALUATED

INJECTION TECHNIQUE

SODIUM TEST CHAMBER ASSEMBLY (90% COMPLETE)
PRELIMINARY NOZZLE CHARACTERIZATION
PARTICLE MEASUREMENT TECHNIQUES ESTABLISHED

Na – SiCl₄ REACTION DEMONSTRATION

DESIGN (COMPLETE)
FABRICATION (UNDERWAY)

3-42
Figure 8.1 - Assembly Drawing of Test Apparatus

Figure 9.1 - Water Testing Shroud
Figure 9.2 - Soncore Nozzle Performance For Water Spray Tests

Figure 8.1 - Schematic Of The Reaction Demonstration (Task 10) Apparatus
Figure 10.2 - Schematic Of The SiCl₄ System

Figure 10.3 - Schematic Of The Sodium System
EXPERIMENTAL VERIFICATION PROJECT SUMMARY

TEST SYSTEM

DETAILED DESIGN AND DRAWINGS (NEAR COMPLETION)

PROCUREMENT INITIATED (ORDER PLACEMENT COMPLETED IN MAY)

RESEARCH PROGRAMS

"EXPERIMENTAL EFFORT" (UNDERWAY)

PROCUREMENT AND FABRICATION (UNDERWAY)

PRODUCT SEPARATION

CONDENSATION MODE

SILICON HALIDE-ALKALI METAL FLAMES AS A SOURCE
OF SOLAR GRADE SILICON

CONTRACT NO. 954777

AeroChem Research Laboratories, Inc.

HIGH TEMPERATURE, SELF SUSTAINING DIFFUSION FLAMES

\[
\begin{align*}
4K + SiCl_4 & \to Si(s) + 4KCl(s) & \Delta H &= -344.3 \text{ kcal} \\
4Na + SiCl_4 & \to Si(s) + 4NaCl(s) & \Delta H &= -337.6 \text{ kcal} \\
3K + SiHCl_3 & \to Si(s) + 3KCl(s) + 1/2H_2 & \Delta H &= -258.4 \text{ kcal} \\
3Na + SiHCl_3 & \to Si(s) + 3NaCl(s) + 1/2H_2 & \Delta H &= -253.4 \text{ kcal} \\
CH_4 + 2O_2 & \to CO_2 + 2H_2O & \Delta H &= -212.8 \text{ kcal}
\end{align*}
\]
The diagram shows the relationship between temperature (K) and pressure (atm) for different compounds: SiCl₄, SiHCl₃, and SiF₄. The graph indicates that as pressure increases, the temperature increases for each compound. The flow diagram includes a particle filter, a Pyrex pipe 210 mm i.d., a silica or Pyrex tube 64 mm i.d., and a connection to a vacuum pump.
**THERMOCHEMICAL PARAMETERS**

### AEROCHEM SIMULATION REACTOR

<table>
<thead>
<tr>
<th>REACTANT</th>
<th>MOLE FRACTION</th>
<th>STATE</th>
<th>T(K)</th>
<th>ΔH(KCAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂/Ar</td>
<td>0.333</td>
<td>gas</td>
<td>1300</td>
<td>2.24</td>
</tr>
<tr>
<td>Na</td>
<td>0.533</td>
<td>gas</td>
<td>1200</td>
<td>16.12</td>
</tr>
<tr>
<td>SiCl₄</td>
<td>0.134</td>
<td>gas</td>
<td>600</td>
<td>-20.28</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td>-1.92</td>
</tr>
</tbody>
</table>

### WESTINGHOUSE ARC-JET REACTOR

<table>
<thead>
<tr>
<th>REACTANT</th>
<th>MOLE FRACTION</th>
<th>STATE</th>
<th>T(K)</th>
<th>ΔH(KCAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂/Ar</td>
<td>0.333</td>
<td>gas</td>
<td>3600</td>
<td>19.18</td>
</tr>
<tr>
<td>Na</td>
<td>0.533</td>
<td>liquid</td>
<td>500</td>
<td>1.12</td>
</tr>
<tr>
<td>SiCl₄</td>
<td>0.134</td>
<td>liquid</td>
<td>298</td>
<td>-22.18</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td>-1.88</td>
</tr>
</tbody>
</table>

3-48
AMORPHOUS vs CRYSTALLINE

ADVANTAGES
- Low cost
- Thin film, μm
- Purity apparently not as important
- Absorption greater

DISADVANTAGES
- New art
- Low efficiencies to date

NON-EQUILIBRIUM PLASMA JET
vs GLOW DISCHARGE

- Higher operating pressure
- Another approach
• STRONGLY ADHERING FILMS FROM:
  SiCl₄ technical and semiconductor grade
  SiHCl₃

• STRONGLY ADHERING FILMS ON:
  Pyrex
  Vycor
  Aluminum
  Carbon

• STABLE AT HIGH TEMPERATURES
  820K for 22 hrs
  1200 K for 2.5 hrs—cracking

• BY X-RAY DIFFRACTION
  Most films amorphous
  Some polycrystalline
  Some polycrystalline with preferred growth

• BY INFRARED ABSORPTION
  Adhering Films
    no Si-O-Si, Si-OH, Si-H
  Non-Adhering Films
    Si-O-Si, Si-OH, Si-H

• BY PIXE
  Cl < 1%
  Cu ~ 0.1% (electrode sputtering)
  Other metals < 10 ppm
SOME PROBLEMS

- Analysis for impurities
- Electrode sputtering
- Failure to obtain good films with substrate perpendicular to flow axis

PLANS

1. Dope films with B(BCl₃) and P(PH₃).
2. Extend resistivity measurements leading to preparation Schottky Cell.
3. Continue study variation synthesis parameters.
PRESENTATION
FOR
LSSA PIM No. 9

DOW CORNING PROCESS SILICON

LOW-COST SILICON SOLAR ARRAY PROJECT
SILICON MATERIAL TASK
PART III

CONTRACT No. 954559

PREPARED BY
Lee P. Hunt, Principal Investigator
Dow Corning Corporation
Solid-State Research and Development Laboratory
Hemlock, Michigan 48626

APRIL, 1978

SEMICONDUCTOR PRODUCTS PLANT • DOW CORNING CORPORATION
Hemlock, Michigan 48626 • Telephone 517-642-5201
PROGRAM TASKS

A. Quartz and Carbon Raw Materials

B. Silicon Production via the Reaction $\text{SiO}_2 + 2\text{C} \rightarrow \text{Si} + 2\text{CO}$

C. Unidirectional Solidification of Silicon

Figure 1. Schematic Diagram of the Dow Corning Process for Producing SoC-Si

PAST ACCOMPLISHMENTS

RAW MATERIALS

Quartz

- Identified Suitable Sources
- More Extensive Investigation Needed in Future

Carbon

- Concentrated on Charcoal
- 2000°C-Purified Gave 99.96-% Silicon
- 2500°C-Purified Was Highly Pure; Did Not React Well
PAST ACCOMPLISHMENTS

DIRECT ARC REACTOR

- Used 40-kVA Unit In Norway
- Developed High Purity Techniques
- Silicon produced was >10x purer than commercial
- Boron & Phosphorus are problems

<table>
<thead>
<tr>
<th>IMPURITY (ppmw)</th>
<th>MG-Si</th>
<th>DAR-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>1300</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Fe</td>
<td>4200</td>
<td>250</td>
</tr>
<tr>
<td>P</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>Ti</td>
<td>500</td>
<td>40</td>
</tr>
<tr>
<td>V</td>
<td>230</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Zr</td>
<td>30</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

PAST ACCOMPLISHMENTS

DCP - SILICON (AFTER UNIDIRECTIONAL SOLIDIFICATION)

- Used CZO Technology
  - Poly ingot had < 1 ppba impurities
  - B & P =10 ppma
  - 60% Yield

- Cells from FZ single were 11-% efficient (90% of baseline)

COST ANALYSIS

$7.37/kg with $38 M Capital
- 3000 Mt/y
- January 1375 $'s
- No profit

3-55
FIGURE 3. SCHEMATIC DIAGRAM OF CARBON MATERIAL EVALUATION AND SELECTION
DAR BASELINE EXPERIMENTS

$\text{SiO}_2$: ARKANSAS QUARTZ
$C^\circ$: UNPURIFIED CHARCOAL (75 % C)

<table>
<thead>
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<th>Run No.</th>
<th>$C/\text{SiO}_2$</th>
<th>$S_{i}(\text{kg})$</th>
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<th>$E$ (kWh/kg)</th>
<th>$\tau$ (h)</th>
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<tr>
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<td>30*</td>
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<td>3</td>
<td>99</td>
<td>110</td>
<td>2.6**</td>
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* Unscheduled Shut Down
  ** -25 Mt/y Rate

CAST 10-cm-DIAMETER x 65-cm, CRACK-FREE INGOT (12 kg)
CAST 15-cm-DIAMETER x 30-cm, INGOT (NOT CALCULATED)
UNIDIRECTIONAL SOLIDIFICATION

- Only evaluating DAR-Si on small scale

- Recommend co-development program
  - 20 to 30 cm diameter ingots
  - Melt replenishment
    - Continuous
    - Semicontinuous

PLANS

RAW MATERIALS

Prepare, analyze, & test carbon reductants

DAR

Establish baseline
Evaluate purified carbon reductants
200-kVA operates much better than 40-kVA
- Re-evaluate past reductants

UNIDIRECTIONAL SOLIDIFICATION

Evaluate DAR-Si
B. LARGE AREA SILICON SHEET TASK

On April 11, 1978 the LASS Task conducted a session on Critical Review of Technology for the development of Large Area Silicon Sheet. The primary objectives of this session were the following:

1. Review the technology progress to date.
2. Identify the features of the technology required to achieve the LSA Project goals.
3. Provide opportunity for contractors to critique each others’ analysis. It was an all-day session and was very well attended.

A considerable amount of progress has been made in non-ingot sheet growth processes. Figures 1 and 2 summarize the technical status of these processes.

Currently the ingot technology development effort in the LASS Task is dominated by advanced Czochralski growth and wafering processes. At the time of this review the Cz contracts were in their second quarter of development and hence were not ready for technical review on the same basis as other processes. Figures 3 and 4 summarize the technical status of various ingot growth and wafering efforts.

A significant amount of time in the session was allotted for the discussions of price projections. The presentations included the SAMICS analysis of add-on sheet prices. Figure 5 shows the add-on price for silicon sheet for non-ingot technologies. It also lists in the last column the throughput criteria required for achieving the projected prices. It is worth noting that the requirements are not out of reach.

Figure 6 shows the similar add-on price projections for ingot technology option based on two different wafering approaches i.e., multiblade (MBS) and multiwire (MWS) sawing.

The general consensus that emerged out of the discussion of ingot technology was that wafering will continue to control the viability of ingot technology. It was evident, however, that the technology can meet the interim goals of $2/W_{pk}$ rather easily.

The individual presentations appear in the following pages.
SILICON SHEET TECHNOLOGY
TECHNICAL STATUS

EF6 PROCESS
- PILOT OPERATION ROUTINELY PRODUCES 1" WIDE X 4" LONG EF6 RIBBON CELLS
- AVERAGE EFFICIENCY IS 11.36% SOME EXCEEDING 12%.
- MULTIPLE RIBBON GROWTH HAS BEEN DEMONSTRATED 5 RIBBONS OF 5 CM WIDTH AT 3 CM/MIN.
- MELT REPLENISHMENT HAS BEEN DEMONSTRATED
- 7.5 CM WIDE RIBBONS ARE ROUTINELY GROWN AT 4.3 CM/MIN (5%).

WEB PROCESS
- 4 CM WIDE RIBBON GROWTH ACHIEVED
- 10 CM/MIN MAXIMUM GROWTH RATE HAS BEEN ACHIEVED.
- AREA GROWTH RATE OF 8 CM²/MIN IS ROUTINE
- EFFICIENCY 14.5%.

Figure 1.
SILICON SHEET TECHNOLOGY

RTR PROCESS

- Maximum width of 7.5 cm achieved
- Maximum growth rate of 12.5 cm/min demonstrated
- Area growth rate of 25 cm²/min is routine
- Demonstrated multiple ribbon growth (2 ribbons of 2.5 cm width)
- Efficiency: 10%

SOC PROCESS

- Solar cell quality silicon coating has been demonstrated
- 1 cm² active area cells fabricated
- 9.5% cell efficiency
- Area growth rate of 15 cm²/min is routine for solar cell quality layers

KK
4/13/78

Figure 2.
INGOT TECHNOLOGY
TECHNICAL STATUS

GROWTH

HAMCO
. HOT FILL METHOD DEMONSTRATED - 14 KG/HR MELT BACK RATE
. TWO 10 KG INGOTS GROWN WITH MELT REPLENISHMENT
. AVERAGE GROWTH RATE OF 9.2 CM/HR FOR 10 CM DIA. INGOT ACHIEVED

SILTEC
. MACHINE DESIGN COMPLETED
. LEAD ITEMS ARE ON ORDER

T.I.
. DESIGN COMPLETED
. LABORATORY EXPERIMENTS ON LIQUID SILICON TRANSFER ARE UNDERWAY

VARIAN
. RECHARGE SIMULATION OF SIX MELT & PULL CYCLES OF 106 KG TOTAL HAS BEEN DEMONSTRATED.
. 7KG, 18KG INGOTS GROWN WITH MELT REPLENISHMENT

CSI
. DEVELOPMENT OF GRADED CRUCIBLES
. CRACK FREE->3 KG INGOT CASTING

Figure 3.
WAFFERING

**VARIAN (MBS)**
- Ingot conversion of 0.80 m²/kg with 95% yield routine (20 slices of 12.5 cm dia/cm)
- Large capacity prototype saw (1000 blade capacity) nearing completion (May '78)
- Laboratory test saw completed
- Water-based slurry configuration show promise for cost reduction and recycling

**CSI (MWS)**
- Ingot conversion of 1.0 m²/kg with 95% yield (25 slices of 4 cm x 4 cm) demonstrated
- Surface damage 3-5 μM.

Figure 4.
SILICON SHEET TECHNOLOGY
1986 ADD-ON PRICE ($/m²)

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<th>Manufacturer</th>
<th>Price</th>
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<tr>
<td>MOBIL-TYCO (EFG)</td>
<td>16.57</td>
<td>5 ribbons; 75 mm wide at 75 mm/min</td>
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<tr>
<td>WESTINGHOUSE (WEB)</td>
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<td>MOTOROLA (RTR)</td>
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<tr>
<td>HONEYWELL (SOC)</td>
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Figure 5.
INGOT TECHNOLOGY

PROJECT ADD-ON WAFER PRICE ($/M²)

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<tr>
<th></th>
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Figure 6.
I. HISTORICAL INTRODUCTION

It seems appropriate to preface this presentation with a short historical introduction. The EFG method was invented in 1965 when efforts were made to prepare alumina fibers for the reinforcement of metal matrices. This work was quickly extended into preparing a variety of shapes and also a variety of materials which appeared to have utility in shaped form. At Tyco, the "Saphikon" division was established to fabricate and market sapphire shapes for a variety of purposes. The most popular of these shapes were however discovered to be fairly simple ones such as tubes and ribbons. The tubes were found to be suitable competitors in the high pressure sodium arc lamp market which was then solely based on the translucent "Lucalox" ceramic. The process for this purpose was, therefore, licensed to Corning Glass Works, which intended to compete in this market using multiple EFG sapphire tubes for which they set up a production facility.

It was also recognized early that EFG ribbons would compete in the substrate market for silicon on sapphire devices with Czochralski grown, sliced, and polished sapphire boules, and the process was subsequently licensed to Kyoto Ceramic, RCA and Allied Chemical for this purpose.

It is quite obvious, then, that since the early 1970's the process as such has been well recognized as an industrially suitable competitive process for fabricating sapphire shapes.

In June 1971, we started our first small exploratory effort under the sponsorship of the U.S. Navy on growing Si ribbon, and in December of that year we published a report documenting that it was indeed possible to grow single crystal EFG ribbon from graphite dies (1). Simultaneously, an in-house effort was started to demonstrate that this ribbon possessed properties which made it a suitable vehicle for the preparation of electronic devices in general and, somewhat later, for solar cells in particular. Starting in 1972/73, the Jet Propulsion Laboratory and the National Science Foundation sponsored further efforts with the aim of making such a ribbon an economic vehicle for the preparation of solar cells (2,3).

In 1974, recognizing the potential of photovoltaics in terrestrial solar energy conversion as well as the potential of the EFG
ribbon technology in this field, Mobil Oil Corporation committed itself to expend $30 million in order to develop the technique toward that end and Mobil Tyco Solar Energy Corporation was formed as a vehicle to accomplish this task. This, at that time, was surely the most significant commitment of private funds toward the development of any technique for photovoltaic solar energy conversion, and I much suspect it is even yet one of the largest of such commitments. Therefore, our present JPL sponsored effort is only one part of a large integrated facility devoted to decreasing the cost of all steps in the silicon solar power supply sequence from crystal growth to cell making and array fabrication. Recently, our process has also been licensed to a Japanese consortium which considered it the major contender for economical silicon sheet fabrication. It is clear, therefore, that a variety of groups consider EFG a viable industrial technology for several areas, including silicon sheet growth towards terrestrial power generation.

During our NSF-RANN contract (April 1973 - February 1975 (2)), we developed our first somewhat detailed analysis on the economics of the EFG process as it applies to the preparation of silicon solar cells at a cost of 50c/watt. The results then achieved were summarized as follows:

"...The EFG process seems eminently capable of being developed to a point where it can be used in the production of silicon solar cells for sale at less than $500/kw (peak). The development areas which must be addressed to attain the full potential of the technique include:

1. The growth of wider and thinner ribbon.
2. Multiple ribbon growth.
5. Low cost polycrystalline silicon.
6. Low cost ribbon to cell processing techniques.

In addition, low cost techniques for "panelizing" the cells must be developed, possibly using solar concentrators. Finally, there is a great deal of upside potential from increased efficiency cells, say, 15% instead of 10%.

Based on these guidelines, we started evolving concepts and machinery to meet these various goals with a particular emphasis on the first four since these were by and large the "EFG-specific" ones and we could not hope to get any help towards solving the problems inherent therein by any general progress towards low cost silicon solar cells.

From that time on, then, concepts for our present multiple furnace evolved, and its operation, recently demonstrated in a five ribbon run over a 12 hour day, provided us with the necessary inputs to carry out a detailed cost analysis based on the SAMICS-IPEG model.
II. **ECONOMIC ANALYSIS USING SAMICS-IPEG**

To get a realistic price from these guidelines does indeed require some significant detail of knowledge about the process. For instance, the space requirements of the machines should be reasonably well known. One should also be able to clearly distinguish which parts of the machine will in fact last through the depreciation cycle assumed in IPEG and which will not, and thus what can be counted as equipment and what is material. Also realistic duty cycle projections are essential or the IPEG denominator may be significantly off. Operating a real model of the equipment we will in fact use, backed by parts tests from single ribbon machines which are run on a three-shift pilot production basis, has therefore enabled us to make a fairly detailed analysis of the process. Since most of you have heard the analysis described at the last PIM and have also probably had a chance to study it in our last quarterly report (4), I will only highlight those parts here which I feel are particularly significant.

Table I shows the input data for the analysis. The end of 1978 figures are essentially costs as they are incurred at present (1977 dollars), costs for the "single production unit" are based on the concept of a twin five-ribbon machine operated by one crystal grower where each of the ten ribbons growing is 7.5 cm wide and grows 7.5 cm/min. The arrows indicate where changes occur between "now" and "then". As you can see, the projected changes are rather modest, except to assume that silicon will indeed be available for $10/kg. Under these circumstances, the price picture drawn in Table II results. It can be seen that even one such unit would come much closer to meeting the 1986 JPL goal which is $20.8/m² inflation adjusted from 1975 into 1977 dollars. Note that the silicon has been burdened here by 30% since we assume that we will purchase it from an outside vendor.

If one now makes some reasonable projections of costs to procure very many of these items to build 100 of these production units and run them for a year (i.e., one procures for instance 52000 dies/year), one arrives at the cost reductions shown in Table III. With these, a final product cost of $22.63/m² is realized (Table IV). Such a 100 production unit plant would have an annual output of over 1.1 x 10⁶ m², which represents about 25% of the total estimated 1986 wafer market. This is a reasonable plant size then, not too large so that it must claim 100% of the market and not so small as to be entirely insignificant.

Based on these data, a variety of sensitivity analyses can now be performed and we have reported a number of them in our last quarterly report. For instance, it could be shown that multiple growth is always preferable to single growth, that argon cost and the cartridge cost are significant variables, and that, depending on the yield of material, provision of polysilicon at $10 - $15/kg is absolutely essential to achieving the price goal. However, in terms of discussing technology readiness, perhaps the most significant of the analyses is depicted in Fig. 1. It shows that there is a considerable range in the trade-offs between yield of material, and
duty cycle for a machine which clearly indicates that one is not rigidly tied to solving each and every small problem the technology may have.

III. STATUS OF TECHNOLOGY

This topic can be best discussed in two parts, namely (a) is EFG ribbon generally of sufficient quality to prepare solar cells with reasonable efficiency? and (b) what is the status of the multiple, fast, wide effort which will bring the cost to the levels needed to achieve the 1986 goals? To address myself to the first question, I am happy to report that solar cells from EFG ribbons grown in single ribbon machines at 2.5 cm width and ~2.5 cm/min now are routinely expected to produce 11% cells (Table V). Those of you who attended the last PIM have seen me project a similar sheet in which I proudly announced an average 10% efficiency from such a lot of cells. This type of progress is occurring through general improvements in Mobil Tyco's "pilot" three-shift crystal growth operation, and in adjustments in the cell making procedures to better cope with the idiosyncracies of the material. Using these kinds of cells, over 10% panel efficiencies have recently been achieved.

Obviously then, one must come to the conclusion that in spite of its defect structure, EFG material per se has indeed excellent potential for the preparation of solar cells with the kinds of efficiencies that are demanded by the terrestrial photovoltaic power program. To assess the status of the multiple effort is somewhat more difficult, though.

Let me therefore simply state first where the various parts of it stand at this time as they relate to the ultimate goal of building the twin five-ribbon production unit on which the economic analysis is based.

1. Multiple Growth of 5 Ribbons, 5 cm Wide

This was demonstrated during a continuous 12 hour run (5) on January 26/27, 1978 with the following outcome:

- Cartridge No. 1 grew ~9 m of 2.5 - 4 cm wide ribbon;
- Cartridge No. 2 grew ~12 m of largely 5 cm wide ribbon;
- Cartridge No. 3 grew 2 m of 2.5 - 4 cm wide ribbon;
- Cartridge No. 4 grew ~13 m of largely 5 cm wide ribbon;
- Cartridge No. 5 grew ~9 m of largely 5 cm wide ribbon.

(The average growth speed for all cartridges was ~3 cm/min). Several problems were discovered here aside from the significant achievement that most of the many parts required worked quite reliably together for the 12 hour run. Cartridge No. 1 which is located next to the melt replenisher could never be brought up to full width; the thermal interaction between it and the melt replenisher made that impossible. In Cartridge No. 3, a short circuit developed in the electrical system shortly after the run started, and we decided not
to attempt to withdraw and repair it during this critical run.

Otherwise, the most general problem discovered was that we know too little about the phenomena which influence spreading of ribbons to full width. The spreading phase takes too long at present and requires the full attention of the operator. It is, however, a transient phase; as soon as the ribbon is spread to the "bulbous ends" of the die, it is anchored there. The phenomenon which then interferes with growth is the "freeze", a condition in which the liquid film collapses and the ribbon attaches to the die. If a "freeze" occurs, the ribbon must be "unfrozen" by increasing the die temperature and reseeding the ribbon and spreading it again. It is obvious then that frequent "freezes" in multiple growth are quite intolerable.

2. Wide (7.5 cm), Fast (7.5 cm/min) Growth

Towards the end of 1977, after several design changes had been made in the original cartridge, considerable improvements in the growth conditions were realized.

Nearly 25 m of ribbon were grown in eight of the runs. The width was up to 7.0 cm and speeds up to 6.3 cm/min were realized. The 7.5 cm belt puller has been routinely used in these experiments; in one run continuous growth of ribbon over a 1 3/4 hour period was achieved.

These experiments permitted important observations with respect to thermal stress in fast and wide ribbon growth. These problems include: (i) high residual stresses in the ribbon which shows up in problems of cutting it into solar cell blanks, or (ii) generation of buckles in the ribbon during growth, which makes the ribbon useless for cell fabrication because it is not flat (4,5).

It was found that residual stress in the ribbon could be avoided by running the afterheater > 1100°C. However, there are still unsolved problems since it is difficult to keep the afterheater temperature this high if one has to use helium to cool the interface region. The helium then has a tendency to carry too much heat away from the afterheater. This will have to be solved by redesign of the cold shoe-heat shield-afterheater combination.

The most pressing problem at this time is the persistent presence of buckles in almost all ribbon. The reasons for this are not clear and the buckles have occasionally disappeared for no obvious reasons during a run. Under low speed growth conditions (< 4 cm/min) the ribbon is essentially always flat for widths > 2.5 cm in width, using present afterheater designs.

3. Materials Quality

Three significant pieces of information were derived here:

(a) Chemical analysis efforts on many ribbons have now fairly conclusively shown that the main culprit which influences the quality
of ribbons grown from resistance heated machines is the stainless steel used in the construction of various hot parts (4). A program to redesign these parts using other materials will now be undertaken.

(b) As a back-up to these efforts, it has been demonstrated experimentally and theoretically that fluid flow effects in the ribbon strongly affect the impurity distribution. By using a center capillary only, to transport liquid to the top of the die, the impurity distribution in a "dirty" 5 cm wide ribbon was manipulated such that the center 2.5 cm width could be used to prepare solar cells of up to 10.6% efficiency (4). These effects will now be vigorously explored to see whether their use is indeed practicable, i.e., can we concentrate impurities into the very edge of the ribbon so that removal of the dirty part does not consume too much silicon.

(c) Ribbons grown at higher speeds (> 4 cm/min) have shown a deterioration of the grain structure through the ribbon thickness. It was feared that this might negatively impact solar cell efficiency. It has now been rather conclusively demonstrated that this structure in itself is not the cause of any cell degradation (4).

The "demonstration" phase of our current contract which ended on January 31, 1978 has thus functionally proven all the basic elements for multiple EFG growth at high speed (Table VI) and has uncovered no intrinsic physical limitations to prevent the achievement of the cost goals.

IV. WHERE DO WE GO FROM HERE?

Having now identified all the basic elements, the normal next step would be to integrate them all into one true prototype machine. Before attempting to prepare such a design, however, there are three basic areas in which progress must be made:

1. Select construction materials for the multiple furnace so that contamination is avoided and 10+% cells result.
2. Produce an improved cartridge design that allows consistent stress-free growth of 7.5 cm wide ribbon at 7.5 cm/min.
3. Improve growth stability by understanding, avoiding or automatically controlling "freezes".

This, in fact, is our basic program for 1978, in order of importance. If indeed at the end of this year either the multiple furnace or the single cartridge furnace produce 9 - 11% cells fairly consistently, one may be quite confident that the quality goal can be achieved. This has to be done by judicious selection of the construction materials for the hot areas of these furnaces. As an example, currently the hot zone enclosure of this furnace is constructed using several square feet of stainless steel sheet. At present we are experimenting with both a molybdenum enclosure and a
more rigid carbon insulation which is bakeable and needs no structural reinforcement. So far, scant attention has been paid to this kind of problem because a demonstration that the present concepts could indeed achieve the required volume output had to be provided first.

High speed wide ribbon growth at present is impeded by stress generation and "buckling". These problems are known to be related to the temperature gradients the ribbon sees on cooling and they can thus be addressed in principle by manipulation of these gradients.

This has to be, in practice, accomplished by a variety of design iterations in the thermal control parts of the growth cartridges (5).

Firstly, to achieve heat transfer of a sufficient magnitude to allow growth at 7.5 cm/min requires convectively aided radiative heat transfer, which is provided by arranging water-cooled heat removal elements which also contain channels for helium introduction within a fraction of a mm above the solid-liquid interface. Thus, ~2 mm above the solid-liquid interface, the ribbon is cooled from its melting point - 1415°C to 1200°C in a very steep temperature gradient. However, below that temperature where Si is no longer able to relieve the thermal stresses (on the time scale of the growth) caused by contraction in a nonuniform gradient, the cooling must proceed in a uniform thermal gradient in order not to generate such stresses. To achieve this, linear cooling plates powered by an afterheater which operates at about 1100°C are provided, along with heat shields which minimize thermal communication between the 1100°C operating temperature of the afterheater and the 500 to 600°C operating temperature of the heat removal element. Hence, the design and the geometrical relationships of the heat removal element-heat shield-afterheater combination determine the rate of growth which can be achieved along with the properties (stress/buckling) of the resulting ribbon which do, to a large extent, determine its utility for solar cell fabrication. The detail in the arrangement of parts a few millimeters above the die top is exceedingly important and must be arrived at largely by empirical methods. An important feature of the modular (cartridge) approach to growth system design is that these critical parts can be developed in small experimental furnaces and then transferred to the multiple machine where they will perform similarly. From the changes we are now making, we conclude that this is a tractable problem. Although progress in this area may not be very fast, we hope that during 1978 a sufficient number of gradient measurements and design iterations can be executed to arrive at a design for the production of straight, flat and reasonably stress-free ribbon (at 7.5 cm/min).

Finally, progress has to be made this year in understanding and controlling "freezes". They are a significant nuisance in multiple growth, and our electro-optical automatic width control system is completely defeated by their occurrence. To reiterate, a "freeze" is a condition where the liquid on the die top ceases to
exist and thus the ribbon attaches to the die, which brings growth to a halt until it is restarted by the operator, which usually occasions loss of the full-width condition; thus respreading is required. Freezes have a long history in EFG growth and they are not a special feature of multiple or fast growth. However, in a situation where there is only one operator for 10 ribbons, they are more detrimental since "unfreezing" and "reseeding" ribbons can consume a significant fraction of the operator's attention.

Although the phenomenon is well known, its origin is not. There is, however, a general correlation of the kind that the time between freezes has increased in our 2.5 cm pilot machines with time (the present record is set by a run where no freeze occurred for 28 hours), concurrent with improvements in operating procedure, accuracy of machine parts, placement of temperature control elements, and the like. Also, a large percentage of "freezes" is preceded by optical phenomena which are of sufficient magnitude and occur early enough so that a skilled operator can take corrective action. This indicates that an optical freeze sensing device with a suitable feedback control could probably be devised.

In any event, study of this problem has high priority in our 1978 program and we expect to have enough information on it to know of some ways to cope with it by the end of this year.

In summary, then, in the work during 1977 we clearly demonstrated that fast, wide, and multiple growth of EFG ribbons is indeed possible using realistic engineering concepts. We also discovered some phenomena which, using present parts and machine designs, interfere with stable multiple growth and high speed growth. These problems seem basically tractable ones, but they do require more delineation in order to devise the most effective solutions to them.

However at the present time there do not appear to be any outstanding fundamental problems which would seem to prevent multiple EFG growth from reaching the 1986 goals of the JPL program.

April 11, 1978

F.V. Wald, Program Manager
REFERENCES


Fig. 1
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<td>Melt replenishment materials ($/furnace/run)</td>
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<td>40.00</td>
</tr>
<tr>
<td>Die ($/ribbon)</td>
<td>15.00</td>
<td>10.00 +</td>
</tr>
<tr>
<td>Die lifetime (runs)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cartridge materials ($/ribbon/run)</td>
<td>40.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Argon ($/100 cu ft)</td>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>Helium ($/100 cu ft)</td>
<td>8.48</td>
<td>8.48</td>
</tr>
<tr>
<td>Electricity ($/kwh)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Furnace argon flow rate (ft³/hr/furnace)*</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Cartridge argon flow rate (ft³/hr/ribbon)*</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Cartridge helium flow rate (ft³/hr/ribbon)*</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Furnace power consumption (kw/furnace)*</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Cartridge power consumption (kw/ribbon)*</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

*Modes of time-dependent variables.
PRICE BREAKDOWN FOR MULTIPLE RIBBON GROWTH BY EFG

EQUIPMENT
FURNACE LIFETIME SUBSYSTEMS ($/SQ M) 2.622
CARTRIDGE LIFETIME SUBSYSTEMS 3.933
CONTROL EQUIPMENT 1.311
MELT REPLENISHMENT SUBSYSTEMS 0.787
TOTAL EQUIPMENT 8.652

FLOOR SPACE
AREA FOR ONE PRODUCTION UNIT 1.427

DIRECT LABOR
DIRECT LABOR PAY RATE 5.453
TOTAL LABOR 5.453

MATERIALS
FURNACE INSULATION 0.464
HEATING ELEMENTS 0.232
CRUCIBLE 0.965
MELT REPLENISHMENT MATERIALS 0.482
DIE 0.603
CARTRIDGE MATERIALS 2.411
FURNACE ARGON 0.315
CARTRIDGE ARGON 0.774
CARTRIDGE HELIUM 1.104
TOTAL MATERIAL 7.349

UTILITIES
FURNACE POWER 1.352
CARTRIDGE AND MR POWER 0.859
TOTAL UTILITIES 2.211

QUANTITY
OUTPUT FROM ONE RUN (SQ M/RUN) 215.643
TOTAL QUANTITY (SQ M/YR) 11213.425

PRICE1 = 8.652 + 1.427 + 5.453 + 7.349 + 2.211
= $ 25.09/SQ M

PRICE2 = PRICE1 + 1.3(POLY COST) = PRICE1 + 1.3($ 4.88/SQ M)
= $ 31.44/SQ M

Table II
<table>
<thead>
<tr>
<th></th>
<th>CONSERVATIVE TECHNOLOGY PROJECTION</th>
<th>CONSERVATIVE TECHNOLOGY PROJECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SINGLE PRODUCTION UNIT</td>
<td>100 PRODUCTION UNITS</td>
</tr>
<tr>
<td>Ribbon width (in.)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Growth rate (in./min)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Run length (hours)</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>Number of runs per year</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Number of ribbons per furnace</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Number of furnaces per production unit</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of operators per production unit*</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Yield (mass ribbon wafers/mass poly)</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Duty rate</td>
<td>0.67</td>
<td>0.67</td>
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<tr>
<td>Polysilicon ($/kg)</td>
<td>10.0</td>
<td>10.0</td>
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<tr>
<td>Dopant ($ dopant/$ poly)</td>
<td>0.1</td>
<td>0.05</td>
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<tr>
<td>Thickness (in.)</td>
<td>0.006</td>
<td>0.006</td>
</tr>
<tr>
<td>Furnace lifetime subsystems ($/furnace)</td>
<td>30000</td>
<td>20000</td>
</tr>
<tr>
<td>Cartridge lifetime subsystems ($/ribbon)</td>
<td>9000</td>
<td>4500</td>
</tr>
<tr>
<td>Melt replenishment subsystems ($/furnace)</td>
<td>9000</td>
<td>4500</td>
</tr>
<tr>
<td>Electro-optical controls ($/ribbon)</td>
<td>3000</td>
<td>1300</td>
</tr>
<tr>
<td>Area for one production (sq ft)</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Labor pay rate ($/hr)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Furnace insulation ($/furnace)</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Insulation lifetime (runs)</td>
<td>52.0</td>
<td>52.0</td>
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<tr>
<td>Heating elements ($/furnace)</td>
<td>500</td>
<td>250</td>
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<tr>
<td>Heating elements lifetime (runs)</td>
<td>26.0</td>
<td>26.0</td>
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<tr>
<td>Crucible ($/furnace)</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Crucible lifetime (runs)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Melt replenishment materials ($/furnace/run)</td>
<td>40.00</td>
<td>20.00</td>
</tr>
<tr>
<td>Die ($/ribbon)</td>
<td>10.0</td>
<td>2.00</td>
</tr>
<tr>
<td>Die lifetime (runs)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cartridge materials ($/ribbon/run)</td>
<td>40.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Argon ($/100 cu ft)</td>
<td>2.35</td>
<td>2.12</td>
</tr>
<tr>
<td>Helium ($/100 cu ft)</td>
<td>8.48</td>
<td>6.36</td>
</tr>
<tr>
<td>Electricity ($/kwh)</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Furnace argon flow rate (ft³/hr/furnace)*</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Cartridge argon flow rate (ft³/hr/ribbon)*</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Cartridge helium flow rate (ft³/hr/ribbon)*</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Furnace power consumption (kw/furnace)*</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Cartridge power consumption (kw/ribbon)*</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

*Indicates time-dependent variables.
PRICE BREAKDOWN FOR MULTIPLE RIBBON GROWTH BY EFG

EQUIPMENT

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost ($/SQ M)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Lifetime Subsystems</td>
<td>1.748</td>
<td></td>
</tr>
<tr>
<td>Cartridge Lifetime Subsystems</td>
<td>1.966</td>
<td></td>
</tr>
<tr>
<td>Control Equipment</td>
<td>0.655</td>
<td></td>
</tr>
<tr>
<td>Melt Replenishment Subsystems</td>
<td>0.393</td>
<td></td>
</tr>
<tr>
<td>Total Equipment</td>
<td>4.763</td>
<td></td>
</tr>
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</table>

FLOOR SPACE

<table>
<thead>
<tr>
<th>Area for One Production Unit</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.427</td>
</tr>
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</table>

DIRECT LABOR

<table>
<thead>
<tr>
<th>Direct Labor Pay Rate</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.453</td>
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</tbody>
</table>

MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Insulation</td>
<td>0.232</td>
</tr>
<tr>
<td>Heating Elements</td>
<td>0.116</td>
</tr>
<tr>
<td>Crucible</td>
<td>0.482</td>
</tr>
<tr>
<td>Melt Replenishment Materials</td>
<td>0.241</td>
</tr>
<tr>
<td>Die</td>
<td>0.121</td>
</tr>
<tr>
<td>Cartridge Materials</td>
<td>0.603</td>
</tr>
<tr>
<td>Furnace Argon</td>
<td>0.284</td>
</tr>
<tr>
<td>Cartridge Argon</td>
<td>0.698</td>
</tr>
<tr>
<td>Cartridge Helium</td>
<td>0.828</td>
</tr>
<tr>
<td>Total Material</td>
<td>3.604</td>
</tr>
</tbody>
</table>

UTILITIES

<table>
<thead>
<tr>
<th>Utility</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Power</td>
<td>0.811</td>
</tr>
<tr>
<td>Cartridge and MR Power</td>
<td>0.516</td>
</tr>
<tr>
<td>Total Utilities</td>
<td>1.327</td>
</tr>
</tbody>
</table>

QUANTITY

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output from One Run (SQ M/RUN)</td>
<td>215.643</td>
</tr>
<tr>
<td>Total Quantity (SQ M/YR)</td>
<td>11213.425</td>
</tr>
</tbody>
</table>

PRICE1 = 4.763 + 1.427 + 5.453 + 3.604 + 1.327
       = $16.57/SQ M

PRICE2 = PRICE1 + 1.3(POLY COST) = PRICE1 + 1.3($4.66/SQ M)
       = $22.63/SQ M ($21.23/sq m if poly cost not burdened by 30%)

CONSERVATIVE TECHNOLOGY PROJECTION
100 PRODUCTION UNITS

Table IV
Table V. Recent production run of solar cells from RF heated furnace. Ribbons are 2.5 cm wide, grown at 2.5 cm/min.
Table VI

BASIC ELEMENTS FOR MULTIPLE HIGH SPEED EFG GROWTH

1. We have a 5 ribbon furnace.

2. We have a 7.5 cm/7.5 cm cartridge.

3. Melt replenishment has been demonstrated.

4. A form of automatic control has been demonstrated.

5. A few > 10% solar cells have been made from material grown in the multiple furnace, and a lot has been learned about impurities and their actions in these furnaces.
ASSESSMENT OF SILICON WEB FOR LOW COST SOLAR CELLS

1. Can Web be economically competitive?

2. What technical objectives must be met to fulfill the economic projections?

3. What is the status of Web development relative to these objectives?

4. What technical obstacles remain to be overcome?

5. Can the required technical solutions be implemented in a timely fashion?
ASSUMPTIONS FOR COST ANALYSIS

- Analysis Uses the SAMICS Interim Price Estimation Guidelines and the IPEG Equation

- Heat-Up, Start of Growth and Shutdown of Growth will be a Manual Operation. Growth will be Fully Automatic

- Area Growth Rate Costs are Computed for Assumed Values of 4, 8, 16, 25 and 50 Square Centimeters Per Minute

- Growth Cycle Costs are Computed for Periods of One to Six Days. Operation is for 24 Hours Daily and Seven Days Per Week

- Automatic Melt Replenishment will be Used

- 15% Cell Efficiency is Assumed
POLYSILICON COST FOR SILICON WEB PROCESS

Dollars Per Peak Watt vs Polysilicon Price

- 6 mils thick
- 4 mils thick
- JPL 1986 Polysilicon Cost Goal

Polysilicon Price, $/Kg

Dollars Per Peak Watt
SILICON WEB COMBINED POLYSILICON AND WAFER COST

Dollars Per Peak Watt vs Area Rate of Growth
For Assumed Polysilicon Prices of $10, $25 and $60/Kg
Three Day Growth Cycle

Combined Goal $10/Kg

JPL 1986 Combined Goal For Polysilicon and Wafer Cost

Present Growth Rate Technology for Silicon Web

Area Rate of Growth, Cm²/minute
SILICON WEB VALUE ADDED WAFER COST

Dollars Per Peak Watt vs Area Rate of Growth
Three Day Growth Cycle

Present Growth Rate Technology

12% Cell Efficiency

JPL 1986 Goal

Area Rate of Growth, cm²/minute
# SILICON WEB
TECHNICAL REQUIREMENTS FOR ECONOMIC GROWTH (1986)

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Feasibility Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Utilize &quot;cheap&quot; Silicon</td>
<td>Tolerate Impurities</td>
<td>✓</td>
</tr>
<tr>
<td>2. Silicon Conservative</td>
<td>Thickness &lt; 6 Mil</td>
<td>✓</td>
</tr>
<tr>
<td>3. Low-cost, Low-maintenance System</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>4. Efficient Cell Performance</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>5. Continuous Growth Melt Replenishment Closed-Loop Control</td>
<td>40 Hrs.</td>
<td></td>
</tr>
<tr>
<td>6. Adequate Throughput Area Rate</td>
<td>25 cm$^2$/min.</td>
<td></td>
</tr>
</tbody>
</table>
## SILICON WEB DEVELOPMENT STATUS

<table>
<thead>
<tr>
<th>Item</th>
<th>Performance Average</th>
<th>State-of-Art</th>
<th>Technical Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contract Start</td>
<td>Present</td>
<td></td>
</tr>
<tr>
<td>1. Throughput</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width (cm)</td>
<td>1.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Speed (cm/ min)</td>
<td>1.5</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>Area Rate (cm²/min)</td>
<td>2.3</td>
<td>6.3</td>
<td>8</td>
</tr>
<tr>
<td>2. AM1 Solar Cell Efficienc (%)</td>
<td>—</td>
<td>12.5</td>
<td>14.5</td>
</tr>
<tr>
<td>3. Silicon Usage (Thickness, Mils)</td>
<td>—</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>4. Impurity Tolerance</td>
<td>—</td>
<td>Feedstock- Up to 40 PPM Fe, Cr, Ni, Mn, Ti or V Utilize Cheap Si</td>
<td></td>
</tr>
</tbody>
</table>

### SILICON WEB CRITICAL TECHNICAL DEVELOPMENTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Technical Obstacle</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Increased Throughput</td>
<td>Primarily Width Limited</td>
<td>Implement After-Heater System (1978)</td>
</tr>
<tr>
<td>Area Rate</td>
<td>Web Deformation</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Continuous Growth</td>
<td>Feed System</td>
<td>Design and Implement System (1978)</td>
</tr>
<tr>
<td>Melt Replenishment</td>
<td>Control Loop</td>
<td>Design and Implement System</td>
</tr>
</tbody>
</table>
SILICON WEB
SUMMARY

- TECHNICAL REQUIREMENTS CAN BE MET

- ECONOMIC GOALS CAN BE MET OR EXCEEDED

- POTENTIAL FOR LESS THAN 50¢ PER WATT MODULES
ECONOMIC ANALYSIS OF A RIBBON-TO-RIBBON (RTR) CRYSTAL GROWTH PROCESS, USING POLycRYSTALLine FEEDSTOCK PRODUCED EITHER BY A CONVENTIONAL CVD PROCESS OR A PLASMA DEPOSITION PROCESS.
SUMMARY

An initial economic analysis of the RTR growth process has been performed. This analysis is based upon an extrapolation of our present growth rates to a number of high-speed, wide ribbon growth stations.

We have also analyzed two candidate processes for producing the polyribbon feedstock needed for RTR growth. The "near term" process uses conventional CVD with trichlorosilane as the source gas. The analysis assumes the present cost of trichlorosilane, $7/Kg-silicon. Using deposition rates already achieved in the lab, this ribbon could be produced at a price of $9/M^2 in a 500 MW facility.

The "long term" approach uses a plasma deposition process with silane as the source gas. The cost of the silane used for this analysis is the $5/Kg-silicon cost projected by Union-Carbide min. This process could produce polyribbon at a cost of $5/M^2 in a 500MW facility.

Thus silicon ribbon produced by the RTR process could be sold at $0.25/watt using conventional CVD poly, or $0.18/watt using a plasma deposited silicon ribbon.
ECONOMIC DATA BASE

**Direct Labor Cost (including fringe benefits):** $5.96/hr.

**Overhead on Labor:** 40%

**Factory Cost - Production Space:** $80/sq. ft.

**Support Space:** $30/sq. ft.

**Total Factory Cost:** 115/sq. ft. of production space.

**Factory Overhead:** $6.30/sq. ft.

**Interest Rate:** 9%

**Depreciation - Capital Equipment:** 7 years, straight line

**Depreciation - Factory Building:** 40 years, straight line

**Electricity:** $219/kW year
SAMICS MODEL

PRICE = 0.49 (EQPT) + 96.9 (SQFT) + 2.1 LABOR
       + 1.3 UTILITY + 1.3 MATERIAL

OPERATOR: $5.00/HOUR

TECHNICIAN: $7.00/HOUR
**TECHNICAL DATA - POLYCRYSTALLINE RIBBON**

<table>
<thead>
<tr>
<th>Factory Capacity</th>
<th>500MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace</td>
<td>$10,000/meter</td>
</tr>
<tr>
<td>Belt System</td>
<td>$12,500</td>
</tr>
<tr>
<td>Area</td>
<td>250 sq. ft.</td>
</tr>
<tr>
<td>Automation</td>
<td>$5,000</td>
</tr>
<tr>
<td>Cleaning</td>
<td>$5,000</td>
</tr>
<tr>
<td>Equipment Utilization</td>
<td>80%</td>
</tr>
<tr>
<td>Machines/Operator (3 shifts)</td>
<td>3</td>
</tr>
<tr>
<td>Machines/Technician (1 shift)</td>
<td>3</td>
</tr>
<tr>
<td>Substrate</td>
<td>Mo belt, 125 μm thick, re-cycled 200 times.</td>
</tr>
</tbody>
</table>
CHEMICAL VAPOR DEPOSITION

Source Gas: SiHCl₃ at $7.00/Kg-Si
Gas Recycling Plant (500MW) $20 million

PLASMA DEPOSITION

Source Gas: SiH₄ at $5.00/Kg-Si
Plasma Unit (10KW): $25,000

FURTHER ASSUMPTIONS

Solar Cell Efficiency: 12%
Poly Ribbon Plant Cost includes yield of RTR process.
CVD: SAMICS
SOURCE GAS: SiHCl₃
DEPOSITION RATES

--- 3 µm/min.

----- 5 µm/min.

- - - 8 µm/min.

- - - - - - 12 µm/min.

Growth Rate (cm²/min.)
PLASMA DEPOSITION: SiH₄

- SAMICS PRICE MODEL
- MOTOROLA PRICE MODEL

MATERIAL COST: $2.61/M²

--- MATERIAL COST: $2.61/M²

CVD: SiHCl₃

- SAMICS PRICE MODEL
- MOTOROLA PRICE MODEL

Material Cost: $4.2/M²

--- MATERIAL COST: $4.2/M²
CONCLUSIONS

- USING CONVENTIONAL CVD TO PRODUCE THE POLYCRYSTALLINE FEEDSTOCK, A RTR RIBBON COULD BE SOLD FOR LESS THAN $30/M² OR $0.25/WATT, ASSUMING A GROWTH RATE OF 100 cm²/MIN.

- USING PLASMA DEPOSITION, RTR RIBBON COULD BE SOLD FOR $20/M² OR 0.18/WATT, ASSUMING A GROWTH RATE OF 150 cm²/MIN.
STATUS

- HIGHER GROWTH RATE: 12.5 CM/MIN
- MAXIMUM WIDTH: 5 CM
- TYPICAL SOLAR CELL PERFORMANCE
  \[ V_{OC} = 0.500 - 0.520 \]
  \[ I_{SC} = 27-30 \text{ MA/cm}^2 \]
  \[ n = 9-10\% \]
- LIMITED STROKE APPARATUS
- DEMONSTRATED MULTIPLE RIBBON GROWTH
GOALS FOR '78-'79

- FABRICATE SOLAR CELLS ON RIBBON GROWN FROM CVD FEEDSTOCK
- BUILD AND OPERATE FACILITY FOR THE SEMI-CONTINUOUS GROWTH OF CVD FEEDSTOCK
- IMPROVE SOLAR CELL PERFORMANCE
MANAGEMENT COMMITMENT

. SUPPORTED DEVELOPMENT OF CVD POLYCRYSTALLINE RIBBON

. RTR '78-'79 ONLY PARTIALLY SUPPORTED BY JPL/DOE

. BROAD COMMITMENT TO PHOTOVOLTAICS INCLUDING PRODUCTION AND MARKETING IN ADDITION TO R&D
LARGE AREA SILICON SHEET TASK
HAMCO
ADVANCED CZOCHRALSKI INGOT GROWTH

CI GROWTH METHODS

<table>
<thead>
<tr>
<th>CONDITIONS:</th>
<th>BATCH #1</th>
<th>BATCH #2</th>
<th>CONTINUOUS #1</th>
<th>CONTINUOUS #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRUCIBLE SIZE (in)</td>
<td>12 x 9 h</td>
<td>12 x 9 h</td>
<td>12 x 9 h</td>
<td>14 x 10½ h</td>
</tr>
<tr>
<td>CRYSTAL DIAMETER (cm)</td>
<td>10</td>
<td>12.5</td>
<td>10</td>
<td>12.5</td>
</tr>
<tr>
<td>GROWTH RATE (cm/hr)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL POLY MELTED (kg)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>110</td>
</tr>
<tr>
<td>TOTAL CRYSTAL PULLED (kg)</td>
<td>14.4</td>
<td>14.4</td>
<td>100</td>
<td>101</td>
</tr>
<tr>
<td>PULLED YIELD (%)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>92</td>
</tr>
<tr>
<td>USEABLE AFTER GRINDING (kg)</td>
<td>12.6</td>
<td>12.6</td>
<td>87.5</td>
<td>88.3</td>
</tr>
<tr>
<td>GROUND CRYSTAL YIELD (%)</td>
<td>70</td>
<td>70</td>
<td>83</td>
<td>80</td>
</tr>
<tr>
<td>No. CRYSTALS/Crucible</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

IFEG PRICE CALCULATION (PER MACHINE-YEAR) (1910 DOLLARS)

<table>
<thead>
<tr>
<th></th>
<th>BATCH #1</th>
<th>CONTINUOUS #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIRECT EQUIPMENT INITIAL COST</td>
<td>$100,000</td>
<td>$150,000</td>
</tr>
<tr>
<td>DIRECT MANUFACTURING FLOOR SPACE</td>
<td>100 sq.ft</td>
<td>100 sq.ft</td>
</tr>
<tr>
<td>ANNUAL DIRECT LABOR SALARIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROD'N OPERATOR (8 $19.20)</td>
<td>$4,752</td>
<td>$4,752</td>
</tr>
<tr>
<td>ELECT TECH (8 $370.40)</td>
<td>763</td>
<td>763</td>
</tr>
<tr>
<td>INSPECTOR (8 $19.20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLAP</td>
<td>$16,927</td>
<td>$16,927</td>
</tr>
<tr>
<td>DIRECTLY USED MATERIALS &amp; SUPPLIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRUCIBLES</td>
<td>10,400</td>
<td>17,900</td>
</tr>
<tr>
<td>SEEDS</td>
<td>2,700</td>
<td>4,498</td>
</tr>
<tr>
<td>DOFANT</td>
<td>9,916</td>
<td>14,576</td>
</tr>
<tr>
<td>ARGON</td>
<td>79,273</td>
<td>49,894</td>
</tr>
<tr>
<td>MISCELLANEOUS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL MATERIALS LESS POLY</td>
<td>$743,393</td>
<td>$511,197</td>
</tr>
<tr>
<td>DIRECT UTILITIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELECTRICITY (G1032 K)</td>
<td>8,960</td>
<td>10,806</td>
</tr>
<tr>
<td>COOLING WATER (G112PD)</td>
<td>2,066</td>
<td>2,561</td>
</tr>
<tr>
<td>UTIL</td>
<td>$10,926</td>
<td>$13,167</td>
</tr>
<tr>
<td>POLYSILICON USED</td>
<td>9996 lb</td>
<td>10,446 lb</td>
</tr>
<tr>
<td>POLYSTYRICAC YIELDED</td>
<td>6755 lb</td>
<td>8708 lb</td>
</tr>
</tbody>
</table>
### IPEG PRICE CALCULATION (1978 DOLLARS)

<table>
<thead>
<tr>
<th></th>
<th>BATCH #1</th>
<th>CONTINUOUS #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁ x EQPT</td>
<td>$63,900</td>
<td>$78,500</td>
</tr>
<tr>
<td>C₂ x SQFT</td>
<td>9,100</td>
<td>9,100</td>
</tr>
<tr>
<td>C₃ x DLAB</td>
<td>35,357</td>
<td>35,357</td>
</tr>
<tr>
<td>C₄ x MATS-2</td>
<td>185,944</td>
<td>64,419</td>
</tr>
<tr>
<td>C₅ x UTIL</td>
<td>14,864</td>
<td>17,117</td>
</tr>
<tr>
<td>TOTAL</td>
<td>299,487</td>
<td>202,153</td>
</tr>
</tbody>
</table>

IPEG PRICE IN $/kg = TOTAL QUAN

$49.00

$29.22

**NOTE:** IPEG PRICES ARE FOR ADD-ON CE COSTS EXCLUDING POLYSICILICON AND ITS OVERHEAD MULTIPLIER.

### EFFECT OF GROWTH RATE ON 1978 COSTS (CONTINUOUS CE #1)

<table>
<thead>
<tr>
<th>GROWTH RATE</th>
<th>8 cm/hr</th>
<th>10 cm/hr</th>
<th>12 cm/hr</th>
<th>20 cm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 CYCLE TIME, HR.</td>
<td>85.8</td>
<td>74.4</td>
<td>67.7</td>
<td>63.1</td>
</tr>
<tr>
<td>THROUGHPUT, kg/hr</td>
<td>1.02</td>
<td>1.17</td>
<td>1.29</td>
<td>1.64</td>
</tr>
<tr>
<td>.49 x EQPT</td>
<td>75,900</td>
<td>73,900</td>
<td>73,900</td>
<td>79,500</td>
</tr>
<tr>
<td>91 x SQFT</td>
<td>9,100</td>
<td>9,100</td>
<td>9,100</td>
<td>7,700</td>
</tr>
<tr>
<td>2.1 x DLAB</td>
<td>55,337</td>
<td>55,337</td>
<td>55,337</td>
<td>55,337</td>
</tr>
<tr>
<td>1.3 x MATS-2</td>
<td>63,175</td>
<td>63,175</td>
<td>63,175</td>
<td>63,175</td>
</tr>
<tr>
<td>1.3 x UTIL</td>
<td>17,300</td>
<td>17,117</td>
<td>17,000</td>
<td>16,819</td>
</tr>
<tr>
<td>IPEG (EXC. POLY) QUAN - kg/hr</td>
<td>7,600</td>
<td>7,600</td>
<td>7,600</td>
<td>7,600</td>
</tr>
<tr>
<td>CE PRICE (ADD-ON) $/kg</td>
<td>26.17</td>
<td>23.22</td>
<td>21.29</td>
<td>17.34</td>
</tr>
<tr>
<td>CHANGE FROM 10 cm/hr BASE 9% CHANGE</td>
<td>+22.1%</td>
<td>0</td>
<td>-1.9%</td>
<td>-5.8%</td>
</tr>
<tr>
<td>POLY @ .72 x 1.3 + YIELD TOTAL IPEG PRICE</td>
<td>$123.92</td>
<td>$112.32</td>
<td>$112.32</td>
<td>$112.32</td>
</tr>
<tr>
<td>TOTAL</td>
<td>133.44</td>
<td>133.54</td>
<td>133.60</td>
<td>124.66</td>
</tr>
<tr>
<td>CHANGE FROM BASE 9% CHANGE</td>
<td>2.95</td>
<td>0</td>
<td>-1.9%</td>
<td>-5.8%</td>
</tr>
</tbody>
</table>

3-104
ECONOMIC PROJECTIONS

1. ADD-ON COST OF CONTINUOUS CE #1 OF $23.22/kq
   MAY BE REDUCED BY PERHAPS 20-25% TO APPROX. $18.00

2. MOST PROBABLE IMPROVEMENTS:
   CAPITAL (-20%)  
   PULL SPEED 10-12 m/hr  
   CRUCIBLE (-50%)  
   ARGON (-50%)  

3 SENSITIVE ITEMS IN IPEG CALCULATION:

\[
\begin{array}{ccc}
C_1 \times \text{EQUIP} & = & 73,500 \\
C_2 \times \text{QRT} & = & 9,100 \\
C_3 \times \text{DILAG} & = & 35,337 \\
C_4 \times \text{NETS} & = & 66,494 \\
C_5 \times \text{UTIL} & = & 17,119 \\
\text{ Tot. } & = & 202,133
\end{array}
\]

\[36.4\% \quad 4.5\% \quad 17.6\% \quad 32.4\% \quad 8.5\% \quad 100.0\%\]

4. CONTINUOUS CE #2 - PROJECTED ADD-ON COST OF $18.26
   25% REDUCTION TO 13.70 ??

5. 1978 - GOOD MARGIN - WILL MEET GOALS  
    1982 - LITTLE MARGIN - MAY MEET GOALS  
    1986 - CE DOESN'T CUT IT!
**LARGE AREA SILICON SHEET TASK (TASK-II)**

**SILTEC ADVANCED CZ INGOT GROWTH**

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>1978</th>
<th>1982</th>
<th>1986</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. POLYSILICON*</td>
<td>$/Kg</td>
<td>60.00</td>
<td>25.00</td>
<td>10.00</td>
</tr>
<tr>
<td>B. SILICON INGOT (4&quot; DIA.), AS GROWN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CONVENTIONAL CZ (CURRENT TECHNOLOGY)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SILICON MATERIAL (Yielded)</td>
<td>$/Kg</td>
<td>65.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- VALUE ADDED</td>
<td>$/Kg</td>
<td>50.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>116.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. PROTOTYPE C.L.F.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SILICON MATERIAL (Yielded)</td>
<td>$/Kg</td>
<td>65.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- VALUE ADDED</td>
<td>$/Kg</td>
<td>29.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>95.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. OPTIMUM C.L.F.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SILICON MATERIAL (Yielded)</td>
<td>$/Kg</td>
<td>27.30</td>
<td>10.96</td>
<td></td>
</tr>
<tr>
<td>- VALUE ADDED</td>
<td>$/Kg</td>
<td>9.26</td>
<td>6.38</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>36.66</td>
<td>19.29</td>
<td></td>
</tr>
<tr>
<td>C. INGOT PROCESSING</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CONVENTIONAL CZ VALUE ADDED</td>
<td>$/Kg</td>
<td>31.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. PROTOTYPE C.L.F. VALUE ADDED</td>
<td>$/Kg</td>
<td>70.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. OPTIMUM C.L.F. VALUE ADDED</td>
<td>$/Kg</td>
<td>31.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. TOTAL INGOT COSTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CONVENTIONAL CZ</td>
<td>$/Kg</td>
<td>227.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. PROTOTYPE C.L.F.</td>
<td>$/Kg</td>
<td>161.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. OPTIMUM C.L.F.</td>
<td>$/Kg</td>
<td>68.62</td>
<td>36.11</td>
<td></td>
</tr>
<tr>
<td>E. SLICE CONVERSION (YIELDED AS-CUT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CURRENT (12 Mils Thick/12 Mils Kert)</td>
<td>$/SLICE</td>
<td>2.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Conventional CZ Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. CURRENT (12 Mils Thick/12 Mils Kert)</td>
<td>$/SLICE</td>
<td>2.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Prototype C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. PLANNED (10 Mils Thick/8 Mils Kert)</td>
<td>$/SLICE</td>
<td>.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Optimum C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. PLANNED (8 Mils Thick/7 Mils. Kert)</td>
<td>$/SLICE</td>
<td>.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Optimum C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F. TOTAL WAFFER COST (CONVERTED TO $/IN$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CURRENT (12 Mils Thick/12 Mils Kert)</td>
<td>$/IN$</td>
<td>367.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Conventional CZ Cost)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. CURRENT (12 Mils Thick/12 Mils Kert)</td>
<td>$/IN$</td>
<td>261.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Prototype C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. PLANNED (10 Mils Thick/8 Mils Kert)</td>
<td>$/IN$</td>
<td>83.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Optimum C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. PLANNED (8 Mils Thick/7 Mils Kert)</td>
<td>$/IN$</td>
<td>37.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Using Optimum C.L.F. Data)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G. TOTAL WAFER PRICE (GOAL)*</td>
<td>$/IN$</td>
<td>301</td>
<td>120</td>
<td>10</td>
</tr>
</tbody>
</table>

*See next page for details.*
## C.L.F. Furnace Operating Costs

(Dollars per kilogram)

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional CZochralski (1)</th>
<th>C.L.F. Prototype</th>
<th>C.L.F. Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power(2)</td>
<td>1.52</td>
<td>.83</td>
<td>.70</td>
</tr>
<tr>
<td>Argon</td>
<td>6.49</td>
<td>2.95</td>
<td>.79(3)</td>
</tr>
<tr>
<td>Crucibles(6)</td>
<td>7.50</td>
<td>1.40</td>
<td>.70</td>
</tr>
<tr>
<td>Graphite</td>
<td>1.40</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Labor(4)</td>
<td>1.50</td>
<td>1.50(5)</td>
<td>.66(6)</td>
</tr>
<tr>
<td>Total</td>
<td>18.40</td>
<td>7.48</td>
<td>3.35</td>
</tr>
</tbody>
</table>

(1) Based on 12 kg. charge size
(2) Based on $.035/KVA-hour
(3) Assuming partial pressure growth and recirculation
(4) Based on 3 furnaces/operator and $5.00/hour direct labor
(5) Based on conventional CZ labor cost
(6) Based on 4 optimized furnaces/operator

SILTEC: 4-11-78
LARGE AREA SILICON SHEET TASK
TEXAS INSTRUMENTS
ADVANCED CZochralski PROCESS DEVELOPMENT

GOAL: DEVELOP A CONTINUOUS CRYSTAL GROWTH MACHINE HAVING:

1. LIQUID SILICON FEED

2. 100 KG CRYSTAL OUTPUT PER RUN

3. 10-CM DIAMETER CRYSTAL

4. 10-CM/H GROWTH RATE

5. CAPABILITY TO HANDLE VARIOUS POLYSILICON FORMS
FIGURE I. CONTINUOUS CZOCHRALSKI SILICON FURNACE
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

BASIC ASSUMPTIONS

1. 100-kg furnace runs
2. 10-cm diameter crystal pulled at 10 cm/h
3. Equipment cost is $121,000
4. Equipment utilization is 83%
5. Furnace floor space is 150 ft²
6. Two pullers per operator
7. Direct labor cost is $5.00/hour
8. Operating supplies are $516/furnace run
9. Utilities costs are $114/furnace run
10. 100% yield output/run is 85.77 m² in slice equivalent area based on 20 slices/cm crystal
11. Multiblade slicing cost is $27/m² at 95% saw yield
### CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

#### CYCLE TIME

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cleanup</td>
<td>0.5 h</td>
</tr>
<tr>
<td>2. Load and Melt (12 kg)</td>
<td>1.5</td>
</tr>
<tr>
<td>3. Seed and Top</td>
<td>1.0</td>
</tr>
<tr>
<td>4. Growth (14.34 kg)</td>
<td>7.8</td>
</tr>
<tr>
<td>5. Taper (10.6 kg)</td>
<td>1.0</td>
</tr>
<tr>
<td>6. Unload</td>
<td>1.0</td>
</tr>
<tr>
<td>7. Repeat - 6 Crystals</td>
<td>64.8</td>
</tr>
<tr>
<td>8. Cooldown and Unload</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Totals:**

- 78.6 h
- 546 cm

**Polysilicon Charged:** 104.6 kg

**Power Consumption:** 3800 kW-h
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

CRYSTAL GROWTH EQUIPMENT COST

1. Basic Furnace $100,000
2. Auxiliary Melter/Power Supply 3,000
3. Silicon Hopper/Feed System 4,000
4. Melt Level Control 5,000
5. Vacuum Valve 4,000
6. Contingency 5,000

Total $121,000
## CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

### CRYSTAL GROWTH OPERATING SUPPLIES COSTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost/Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crucible Shaft</td>
<td>$18.00</td>
</tr>
<tr>
<td>2. Graphite Crucible</td>
<td>32.00</td>
</tr>
<tr>
<td>3. Quartz Liner</td>
<td>100.00</td>
</tr>
<tr>
<td>4. Graphite Shaft Parts</td>
<td>9.00</td>
</tr>
<tr>
<td>5. Graphite Heater</td>
<td>16.67</td>
</tr>
<tr>
<td>6. Misc. Graphite Heater Parts</td>
<td>3.75</td>
</tr>
<tr>
<td>7. Graphite Heat Shield</td>
<td>20.00</td>
</tr>
<tr>
<td>8. Graphite Felt Insulation</td>
<td>3.00</td>
</tr>
<tr>
<td>9. Outer Stainless Heat Shield</td>
<td>4.00</td>
</tr>
<tr>
<td>10. Misc. Heat Shield Parts</td>
<td>6.00</td>
</tr>
<tr>
<td>11. Shaft Seals</td>
<td>1.00</td>
</tr>
<tr>
<td>12. Auxiliary Heater</td>
<td>12.50</td>
</tr>
<tr>
<td>13. Auxiliary Crucible</td>
<td>10.00</td>
</tr>
<tr>
<td>14. Crystal Seeds</td>
<td>35.00</td>
</tr>
<tr>
<td>15. Vacuum Pump Filter</td>
<td>9.00</td>
</tr>
<tr>
<td>16. Vacuum Pump Oil</td>
<td>3.00</td>
</tr>
<tr>
<td>17. Argon</td>
<td>233.00</td>
</tr>
</tbody>
</table>

**Total** $515.92/run
Figure 5. SAMICS/IPEG Continuous Czochralski Crystal Cost Expressed in Equivalent Slice Area
Figure 6. SAMICS/IPEG Cost Projections of a Continuous Czochralski Wafer Process
1975 Dollars
10-cm Diameter
$25/kg Polysilicon
80% Crystal Yield
95% Saw Yield

Figure 7. SAMICS/IPEG Cost Breakdown of a Continuous Czochralski Wafer Process
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

1PEG WaFER COST BREAKDOWN

1975 DOLLARS
80% CRYSTAL YIELD
95% SAW YIELD

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>$15.00/m²</td>
<td>29.3%</td>
</tr>
<tr>
<td>Space</td>
<td>6.50</td>
<td>12.7%</td>
</tr>
<tr>
<td>Labor</td>
<td>11.08</td>
<td>21.6%</td>
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<tr>
<td>Material</td>
<td>16.84</td>
<td>32.9%</td>
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<tr>
<td>Utilities</td>
<td>1.79</td>
<td>3.5%</td>
</tr>
<tr>
<td>Totals</td>
<td>$51.21/m²</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

IPEG CRYSTAL GROWTH COST BREAKDOWN

1975 DOLLARS

100% YIELD

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>$6.21/m^2</td>
<td>31.6%</td>
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<tr>
<td>Space</td>
<td>1.52</td>
<td>7.7</td>
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<tr>
<td>Labor</td>
<td>4.00</td>
<td>20.3</td>
</tr>
<tr>
<td>Materials</td>
<td>6.60</td>
<td>33.1</td>
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<tr>
<td>Utilities</td>
<td>1.43</td>
<td>7.3</td>
</tr>
<tr>
<td>Totals</td>
<td>$19.66/m^2</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

EQUIPMENT REQUIREMENTS

Crystal Output: 6354 m²/yr/Furnace at 80% yield

Slicing Output: 1406 m²/yr/Saw at 95% yield

<table>
<thead>
<tr>
<th>IPEG QUANTITY / COMPANY</th>
<th>1982</th>
<th>1986</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Furnaces</td>
<td>11</td>
<td>209</td>
</tr>
<tr>
<td>Furnace Capital (1978 $)</td>
<td>$1.33 M</td>
<td>$25.3 M</td>
</tr>
<tr>
<td>No. Saws</td>
<td>48</td>
<td>946</td>
</tr>
<tr>
<td>Saw Capital (1978 $)</td>
<td>$1.20 M</td>
<td>$23.7 M</td>
</tr>
<tr>
<td>Support Capital (1978 $)</td>
<td>$0.25 M</td>
<td>$4.9 M</td>
</tr>
<tr>
<td>Total Capital</td>
<td>$2.78 M</td>
<td>$53.9 M</td>
</tr>
</tbody>
</table>
CONTINUOUS CZOCHRALSKI ECONOMIC MODEL

COST REDUCTION OPPORTUNITIES

1. Larger Diameter Crystal
   • 15 cm vs. 10 cm improves productivity 40%
   • Output per furnace run greater than 100 kg
   • Would require larger furnace
   • Add-on cost reduction potential up to 50%

2. Cheaper Furnaces

   Large production run should effect significant price reduction. An $85 K vs. $121 K furnace could reduce crystal cost by 8%.

3. Sawing Advances
   • 25 slices/cm = 1.06 m²/kg of 15 cm
   • Multiple crystals sawed simultaneously
   • Capital cost under $20 K/saw
   • Reduce blade and slurry costs

4. Reduce Crystal Materials Costs
   • Argon consumption excessive
   • Cheaper crucible liners
   • Need inexpensive, expendable auxiliary melter
Semicontinuous
$10/kg Polysilicon
80% Crystal Yield
5 mm/h Saw Rate

Crystal Diameter:
7.6 cm
10
12
15

SLICE + KERF, K, mm
Czochralski Silicon Sheet Cost

(ADD-ON COST) x (SAW YIELD), $/m²
Czochralski Silicon Sheet Cost Exclusive of Polysilicon
LARGE AREA SILICON SHEET TASK
VARIAN
CONTINUOUS CZOCHRALSKI GROWTH
BASIS FOR COST EVALUATION

1978 - CURRENT EQUIPMENT
- ONE CRYSTAL FROM 12 INCH DIAMETER CRUCIBLE
- 55 PER CENT AFTER-GRIND YIELD
- CURRENT PROCESS AND OPERATION
- CURRENT CYCLE TIME

1980 - CURRENT EQUIPMENT MODIFIED FOR RECHARGING
- FIVE CRYSTALS FROM ONE 12 INCH DIAMETER CRUCIBLE
- 55 PER CENT AFTER-GRIND YIELD
- CURRENT PROCESS AND OPERATION
- CURRENT CYCLE TIME EXTRAPOLATED

1982 - NEW RECHARGEABLE, HIGH-YIELD EQUIPMENT
- FIVE CRYSTALS FROM ONE 12 INCH DIAMETER CRUCIBLE
- 70 PER CENT AFTER-GRIND YIELD
- CURRENT PROCESS AND OPERATION
- CURRENT CYCLE TIME EXTRAPOLATED AS FOR 1980
### Continuous Czochralski Growth

#### Cycle Time

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crystal 1:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean Furnace</td>
<td>0.5 hr</td>
<td>0.50 hr</td>
</tr>
<tr>
<td>Load and Melt Charge</td>
<td>2.5 hr (20 kg)</td>
<td>2.50 hr (20 kg)</td>
</tr>
<tr>
<td>Seed; Grow Neck, Crown &amp; Shoulder</td>
<td>1.0 hr</td>
<td>1.00 hr</td>
</tr>
<tr>
<td>Grow Body of Crystal</td>
<td>9.0 hr (18 kg)</td>
<td>7.50 hr (15 kg)</td>
</tr>
<tr>
<td>Grow Taper</td>
<td>0.5 hr (1 kg)</td>
<td>0.50 hr</td>
</tr>
<tr>
<td>Cool &amp; Remove Crystal</td>
<td>1.5 hr</td>
<td>-</td>
</tr>
<tr>
<td>Maintain &amp; Repair Furnace</td>
<td>2.5 hr</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.5 hr</td>
</tr>
<tr>
<td><strong>Crystal 2:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>(21.5 kg) 1.50 hr</td>
<td></td>
</tr>
<tr>
<td>Seed; Grow Neck, Crown &amp; Shoulder</td>
<td>1.00 hr</td>
<td></td>
</tr>
<tr>
<td>Grow Body of Crystal</td>
<td>(20.5 kg) 10.25 hr</td>
<td></td>
</tr>
<tr>
<td>Grow Taper</td>
<td>(1 kg) 0.50 hr</td>
<td></td>
</tr>
<tr>
<td>Cool &amp; Remove Crystal during Recharge</td>
<td>- -</td>
<td></td>
</tr>
<tr>
<td><strong>Crystal 3:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same as Crystal 2</td>
<td></td>
<td>13.25 hr</td>
</tr>
<tr>
<td><strong>Crystal 4:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same as Crystal 3</td>
<td></td>
<td>13.25 hr</td>
</tr>
<tr>
<td><strong>Crystal 5:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>(21.5 kg) 1.50 hr</td>
<td></td>
</tr>
<tr>
<td>Seed; Grow Neck, Crown &amp; Shoulder</td>
<td>1.00 hr</td>
<td></td>
</tr>
<tr>
<td>Grow Body of Crystal</td>
<td>(23.5 kg) 11.75 hr</td>
<td></td>
</tr>
<tr>
<td>Grow Taper</td>
<td>(1 kg) 0.50 hr</td>
<td></td>
</tr>
<tr>
<td>Cool &amp; Remove Crystal</td>
<td>1.50 hr</td>
<td></td>
</tr>
<tr>
<td>Maintain &amp; Repair Furnace</td>
<td>12.00 hr</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.00 hr</td>
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</table>
CONTINUOUS CZOCHRALSKI GROWTH
1978 COST SUMMARY (INFLATED $)

ONE CRYSTAL GROWN FROM A 12 INCH DIAMETER CRUCIBLE AT 55% AFTER-GRIND YIELD

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>AMOUNT</th>
<th>UNIT COST</th>
<th>DIRECT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT CONVENTIONAL FURNACE</td>
<td>1</td>
<td>$115,000</td>
<td>$115,000 x C1 = $56,350</td>
</tr>
<tr>
<td>SOFT FLOOR SPACE</td>
<td>80 FT²</td>
<td>-</td>
<td>- x C2 = $7,760</td>
</tr>
<tr>
<td>DLAB OPERATOR</td>
<td>0.92 PRSN YR</td>
<td>$12,247</td>
<td>$11,305</td>
</tr>
<tr>
<td>DLAB FOREMAN</td>
<td>0.31 PRSN YR</td>
<td>$16,330</td>
<td>$5,025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$16,330 x C3 = $34,293</td>
</tr>
<tr>
<td>MATS POLY CRUCIBLE</td>
<td>9,460 KG</td>
<td>$54.50</td>
<td>$515,570</td>
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<tr>
<td>MATS ARGON</td>
<td>473</td>
<td>$210</td>
<td>$99,330</td>
</tr>
<tr>
<td>MATS MISCELLANEOUS</td>
<td>255,420 FT³</td>
<td>$0.0494</td>
<td>$12,618</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$11,825</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$639,343 x C4 = $831,146</td>
</tr>
<tr>
<td>UTIL ELECTRICITY</td>
<td>345,750 KW-HR</td>
<td>$0.03187</td>
<td>$11,306 x C5 = $14,698</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$944,247</td>
</tr>
<tr>
<td>QUAN 5,203 KG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPEG PRICE</td>
<td></td>
<td>$182 PER KG</td>
<td></td>
</tr>
</tbody>
</table>

3-124
### CONTINUOUS CZOCHRALSKI GROWTH

#### 1980 COST SUMMARY (INFLATED $)

**FIVE CRYSTALS GROWN FROM ONE 12 INCH DIAMETER CRUCIBLE AT 55% AFTER-GRIND YIELD**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>AMOUNT</th>
<th>UNIT COST</th>
<th>DIRECT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EQPT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODIFIED FURNACE</td>
<td>1</td>
<td>$147,600</td>
<td>$147,600 x C₁ = $72,324</td>
</tr>
<tr>
<td><strong>SGFT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOOR SPACE</td>
<td>100 FT²</td>
<td>-</td>
<td>- x C₂ = $9,700</td>
</tr>
<tr>
<td><strong>DLAB</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPERATOR</td>
<td>0.92 PRSN YR</td>
<td>$14,285</td>
<td>$13,186</td>
</tr>
<tr>
<td>FOREMAN</td>
<td>0.31 PRSN YR</td>
<td>$19,047</td>
<td>$5,861</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$19,047 x C₃ = $39,999</td>
</tr>
<tr>
<td><strong>MATS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POLY</td>
<td>10,971 KG</td>
<td>$61</td>
<td>$669,231</td>
</tr>
<tr>
<td>CRUCIBLE</td>
<td>103.5</td>
<td>$245</td>
<td>$25,358</td>
</tr>
<tr>
<td>ARGON</td>
<td>412,965 FT³</td>
<td>$0.0576</td>
<td>$23,787</td>
</tr>
<tr>
<td>MISCELLANEOUS</td>
<td>-</td>
<td>-</td>
<td>$15,043</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$733,419 x C₄ = $953,445</td>
</tr>
<tr>
<td><strong>UTIL</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ELECTRICITY</td>
<td>419,175 KW-HR</td>
<td>$0.0400</td>
<td>$16,767 x C₅ = $21,797</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1,097,265</td>
</tr>
</tbody>
</table>

**QUAN 6,034 KG**

**IPEG PRICE $182 PER KG**
CONTINUOUS CZOCHRALSKI GROWTH
1982 COST SUMMARY (INFLATED $)

FIVE CRYSTALS GROWN FROM ONE 12 INCH DIAMETER CRUCIBLE AT 70% AFTER-GRIND YIELD

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>AMOUNT</th>
<th>UNIT COST</th>
<th>DIRECT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>NEW, HIGH-YIELD FURNACE</td>
<td>1</td>
<td>$229,000</td>
</tr>
<tr>
<td></td>
<td>FLOOR SPACE</td>
<td>100 FT²</td>
<td>- -</td>
</tr>
<tr>
<td>DLAB</td>
<td>OPERATOR</td>
<td>0.92 PRSN YR</td>
<td>$16,662</td>
</tr>
<tr>
<td></td>
<td>FOREMAN</td>
<td>0.31 PRSN YR</td>
<td>$22,217</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>MATS</td>
<td>POLY</td>
<td>10,971 KG</td>
<td>$ 38</td>
</tr>
<tr>
<td></td>
<td>CRUCIBLE</td>
<td>103.5</td>
<td>$ 286</td>
</tr>
<tr>
<td></td>
<td>ARGON</td>
<td>412,965 FT³</td>
<td>$0.0672</td>
</tr>
<tr>
<td></td>
<td>MISCELLANEOUS</td>
<td>- -</td>
<td>- -</td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UTIL</td>
<td>ELECTRICITY</td>
<td>419,175 KW-HR</td>
<td>$0.0501</td>
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</table>

QUAN 7,680 KG
IPEG PRICE $ 109 PER KG
CONTINUOUS CZOCHRALSKI GROWTH
IPEG PRICE ESTIMATES vs. IPEG STANDARDS

<table>
<thead>
<tr>
<th></th>
<th>CURRENT 1978</th>
<th>+RECHARGE 1980</th>
<th>+RECHARGE +HIGH-YIELD 1982</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPEG PRICE, INFLATED $ PER KG</td>
<td>182</td>
<td>182</td>
<td>109</td>
</tr>
<tr>
<td>IPEG PRICE, 1975 $ PER KG</td>
<td>151</td>
<td>135</td>
<td>71.6</td>
</tr>
<tr>
<td>- DIRECT POLY COST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>82.3</td>
<td>81.9</td>
<td>35.7</td>
</tr>
<tr>
<td>- GROWTH ADD-ON COST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>68.9</td>
<td>52.6</td>
<td>35.9</td>
</tr>
<tr>
<td>INGOT CONVERSION FACTOR, m² PER KG</td>
<td>0.669</td>
<td>0.803</td>
<td>0.892</td>
</tr>
<tr>
<td>IPEG PRICE GOAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALLOCATION, PWAFERS, 1975 $ PER m²</td>
<td>381</td>
<td>245</td>
<td>128</td>
</tr>
<tr>
<td>- DIRECT POLY COST</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>123</td>
<td>102</td>
<td>40.0</td>
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<tr>
<td>- GROWTH ADD-ON COST</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>65.5</td>
<td>40.3</td>
</tr>
<tr>
<td>MARGIN AVAILABLE FOR WAferING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD-ON COST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>155</td>
<td>77.5</td>
<td>47.7</td>
</tr>
</tbody>
</table>
LARGE AREA SILICON SHEET TASK
CRYSTAL SYSTEMS INC.
SILICON INGOT CASTING BY HEM

3-128
SCHEMATIC OF CRYSTAL CASTING FURNACE

CRYSTAL SYSTEMS
Advantages - Technical

1. Simple directional solidification process
   a. Process based on heat flow
   b. No moving parts
   c. Post solidification anneal
   d. Scale up

2. Growth from bottom to top
   a. Minimum convection
   b. No rotation required

3. Interface surrounded by liquid
   a. Impurities float to surface
   b. Vibration damped out

4. Interface stability
HEAT EXCHANGER METHOD (HEM)

Advantages - Economic

1. Low capital investment
2. Low energy cost
3. Low labor cost
4. Shaped ingot
5. High growth rates

HEAT EXCHANGER METHOD (HEM)

Problems and Solutions

Cracking of ingot - Graded crucibles
SiC impurities - Graphite retainers
Heat flow - Heat exchanger insulation
- Low superheat
Low conductivity of silica - Graphite plug
Shaped ingots - ?
TABLE II. I-V Parameters under AM1 conditions for AR coated (Ta₂O₅) solar cells fabricated from run 2-021-C using Xenon and Tungsten source illumination.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>I&lt;sub&gt;sc&lt;/sub&gt; (mA)</th>
<th>V&lt;sub&gt;oc&lt;/sub&gt; (mV)</th>
<th>CFF</th>
<th>P&lt;sub&gt;max&lt;/sub&gt; (mW)</th>
<th>η  (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Xenon Source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>114.2</td>
<td>609</td>
<td>0.771</td>
<td>53.6</td>
<td>13.3</td>
</tr>
<tr>
<td>2</td>
<td>116.8</td>
<td>612</td>
<td>0.764</td>
<td>54.6</td>
<td>13.6</td>
</tr>
<tr>
<td>3</td>
<td>114.5</td>
<td>610</td>
<td>0.784</td>
<td>54.8</td>
<td>13.6</td>
</tr>
<tr>
<td>4</td>
<td>117.2</td>
<td>615</td>
<td>0.782</td>
<td>56.4</td>
<td>14.0</td>
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<tr>
<td>5</td>
<td>116.2</td>
<td>613</td>
<td>0.784</td>
<td>55.9</td>
<td>13.9</td>
</tr>
<tr>
<td>6</td>
<td>113.3</td>
<td>612</td>
<td>0.792</td>
<td>54.9</td>
<td>13.7</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>115.4</td>
<td>612</td>
<td>0.780</td>
<td>55.0</td>
<td>13.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample #</th>
<th>I&lt;sub&gt;sc&lt;/sub&gt; (mA)</th>
<th>V&lt;sub&gt;oc&lt;/sub&gt; (mV)</th>
<th>CFF</th>
<th>P&lt;sub&gt;max&lt;/sub&gt; (mW)</th>
<th>η  (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tungsten Source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>95.9</td>
<td>598</td>
<td>0.771</td>
<td>44.2</td>
<td>11.0</td>
</tr>
<tr>
<td>2</td>
<td>99.0</td>
<td>602</td>
<td>0.770</td>
<td>45.9</td>
<td>11.4</td>
</tr>
<tr>
<td>3</td>
<td>95.5</td>
<td>599</td>
<td>0.787</td>
<td>45.0</td>
<td>11.2</td>
</tr>
<tr>
<td>4</td>
<td>100.2</td>
<td>605</td>
<td>0.784</td>
<td>47.6</td>
<td>11.8</td>
</tr>
<tr>
<td>5</td>
<td>98.0</td>
<td>602</td>
<td>0.789</td>
<td>46.6</td>
<td>11.6</td>
</tr>
<tr>
<td>6</td>
<td>97.0</td>
<td>602</td>
<td>0.788</td>
<td>46.0</td>
<td>11.4</td>
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<tr>
<td><strong>Mean</strong></td>
<td>97.6</td>
<td>601</td>
<td>0.782</td>
<td>45.9</td>
<td>11.4</td>
</tr>
</tbody>
</table>
ECONOMIC ANALYSIS - SHORT TERM GOALS

Process - HEM crystal casting and FAM slicing
Production - 67,000 square meter silicon wafers
Utilization - 95%

<table>
<thead>
<tr>
<th></th>
<th>HEM</th>
<th>SECTION</th>
<th>FAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment cost, $</td>
<td>45,000</td>
<td>35,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Floor space, sq.ft.</td>
<td>60</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Labor, units/operator</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Expendables/run, $</td>
<td>95</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Boule size</td>
<td>$20 \times 20 \times 20 \text{ cm}^3$</td>
<td>$4(20 \times 10 \times 10 \text{ cm}^3)$ sections</td>
<td>25 wafers/cm</td>
</tr>
</tbody>
</table>
## ECONOMIC ANALYSIS - SHORT TERM GOALS

**HEM Casting**

Value added costs, $/m²

<table>
<thead>
<tr>
<th>Growth Rate (kg/hr)</th>
<th>Expendables/run</th>
<th>$ 95</th>
<th>$ 190</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>14.99</td>
<td>21.78</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>13.33</td>
<td>20.11</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>13.09</td>
<td>20.18</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>12.50</td>
<td>19.54</td>
<td></td>
</tr>
</tbody>
</table>

**FAM Slicing**

Value added costs, $/m²

<table>
<thead>
<tr>
<th>Slicing Rate (mm/min)</th>
<th>Labor, units/operator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>0.05</td>
<td>16.57</td>
</tr>
<tr>
<td>0.10</td>
<td>9.23</td>
</tr>
<tr>
<td>0.15</td>
<td>7.17</td>
</tr>
<tr>
<td>0.20</td>
<td>5.59</td>
</tr>
<tr>
<td>0.25</td>
<td>4.44</td>
</tr>
</tbody>
</table>
ECONOMIC ANALYSIS - SHORT TERM GOALS

HEM Casting
Sectioning: $3.33/m²
FAM Slicing

Value added costs, $/m²

<table>
<thead>
<tr>
<th>HEM Casting</th>
<th>Growth Rate, kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAM Slicing</td>
<td>1.0</td>
</tr>
<tr>
<td>0.05</td>
<td>34.89</td>
</tr>
<tr>
<td>0.10</td>
<td>27.55</td>
</tr>
<tr>
<td>0.15</td>
<td>25.49</td>
</tr>
<tr>
<td>0.20</td>
<td>23.91</td>
</tr>
<tr>
<td>0.25</td>
<td>22.76</td>
</tr>
</tbody>
</table>

Wafer price (based on $25/kg polysilicon), $/m²

<table>
<thead>
<tr>
<th>HEM Casting</th>
<th>Growth Rate, kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAM Slicing</td>
<td>1.0</td>
</tr>
<tr>
<td>0.05</td>
<td>64.98</td>
</tr>
<tr>
<td>0.10</td>
<td>57.64</td>
</tr>
<tr>
<td>0.15</td>
<td>55.58</td>
</tr>
<tr>
<td>0.20</td>
<td>54.00</td>
</tr>
<tr>
<td>0.25</td>
<td>52.85</td>
</tr>
</tbody>
</table>
ECONOMIC ANALYSIS - LONG TERM GOALS

Process - HEM Crystal Casting and FAM Slicing
Production - 1,330,000 square meter silicon wafers
(Firm market in 1986)
Utilization - 95%

<table>
<thead>
<tr>
<th></th>
<th>HEM</th>
<th>Sectioning</th>
<th>FAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment cost, $</td>
<td>30,000</td>
<td>25,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Floor space, sq.ft.</td>
<td>60</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Labor, units/ operator</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Expendables/ run, $</td>
<td>95</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Cycle time, hrs.</td>
<td>48</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Boule size</td>
<td>30cm x 30cm x 30cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth rate</td>
<td>2.4 kg/hr</td>
<td>9(30x10x10cm$^3$) sections</td>
<td></td>
</tr>
<tr>
<td>Slicing rate</td>
<td></td>
<td>25 wafers/cm</td>
<td>25 wafers/cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1 mm/min</td>
<td></td>
</tr>
</tbody>
</table>
## ECONOMIC ANALYSIS - LONG TERM GOALS

### Value added price, $/m²

<table>
<thead>
<tr>
<th></th>
<th>HEM</th>
<th>Section</th>
<th>FAM</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>1.77</td>
<td>0.18</td>
<td>1.32</td>
<td>3.26</td>
</tr>
<tr>
<td>SQFT</td>
<td>1.12</td>
<td>0.12</td>
<td>0.52</td>
<td>1.78</td>
</tr>
<tr>
<td>SLAB</td>
<td>1.14</td>
<td>1.19</td>
<td>0.76</td>
<td>3.08</td>
</tr>
<tr>
<td>MATS + UTIL</td>
<td>0.43</td>
<td>0.04</td>
<td>2.04</td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>4.46</td>
<td>1.53</td>
<td>4.63</td>
<td>10.62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polysilicon $/kg</th>
<th>Wafer price $/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>22.64</td>
</tr>
<tr>
<td>17</td>
<td>31.06</td>
</tr>
<tr>
<td>25</td>
<td>40.67</td>
</tr>
<tr>
<td>50</td>
<td>70.73</td>
</tr>
</tbody>
</table>
Fixed Abrasive Multiple-wire Slicing (FAM)

Advantages

1. Low expendable materials cost
2. High material utilization
   a. thin slices
   b. low kerf
   c. low surface damage
3. Low labor costs

Fixed Abrasive Multiple-wire Slicing (FAM)

Progress

1. Machine Development
   a. Feed mechanism
   b. Support rollers
   c. Rocking of workpiece
2. Blade Development
   a. Plated wires
   b. Impregnated wires
   c. Impregnation in cutting edge
   d. Diamond pull-out
3. Testing and Characterization
   a. 4 cm x 4 cm workpiece
   b. 7.6 cm diameter workpiece
   c. 64 slices/in.; 25/cm
   d. Surface damage: 3-5 µm

3-138
INGOT SLICING

Cost of Expendable Material

A cost analysis of diamond and wire for wire slicing was made using current operation data to determine the cost of expendable materials per square meter of silicon material sliced. Five mil core material is plated and charged with diamond to 100 concentration.

Data: 100 Concentration of diamond = 72 carats/in³ of bond (NBS Standard)

Cost of diamond - $2.25/carat

Cost of 5 mil wire = $40/lb or $0.0035 per wire blade

8" stroke of machine, 9" abrasive length

5 mil, 0.125 mm wire core

0.75 mil, 18 µm plating thickness

1.2 mil, 30 µm diamond

Volume of bond per wire

\[ \text{Volume of bond per wire} = \frac{\pi}{4} (D^2 - d^2) \]

\[ = \frac{\pi}{4} \left( (7 \times 10^{-3})^2 - (5 \times 10^{-3})^2 \right) \]

\[ = 0.170 \times 10^{-3} \text{ in}^3 \]

Carats of diamond per wire

\[ = 72 \times 0.170 \times 10^{-3} \]

\[ = 12.24 \times 10^{-3} \text{ carats} \]

Cost of diamond per wire

\[ = 2.25 \times 12.24 \times 10^{-3} \]

\[ = $0.0275 \]

In commercially impregnated wire, the diamonds are uniformly impregnated over the diameter. Crystal Systems has developed a process whereby diamonds are impregnated only in the cutting
edge, thereby reducing the diamond costs by half.

<table>
<thead>
<tr>
<th></th>
<th>Commercial Process</th>
<th>CSI Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of diamond/wire</td>
<td>$ 0.0275</td>
<td>$ 0.0138</td>
</tr>
<tr>
<td>Cost of wire</td>
<td>$ 0.0035</td>
<td>$ 0.0035</td>
</tr>
<tr>
<td>Cost of diamonds + wire/blade</td>
<td>$ 0.0310</td>
<td>$ 0.0173</td>
</tr>
</tbody>
</table>

Assuming each wire cuts 0.1 square meter of silicon, cost of expendable material/square meter of wafer,

For commercial process = $ 0.310
For CSI process = $ 0.173
MULTIBLADE SLURRY WAFERING

FEATURES FOR PROCESS COST EVALUATION

1978 - CURRENT EQUIPMENT
- PURCHASED BLADE PACKAGES
- EXISTING PROCESS TECHNOLOGY
- CONSERVATIVE SLICE THICKNESS

1980 - CURRENT EQUIPMENT
- IN-PLANT BLADE PACKAGE FABRICATION
- LOW COST SLURRY VEHICLE
- INTERMEDIATE SLICE THICKNESS

1982 - LARGE CAPACITY EQUIPMENT
- PARTIAL SLURRY RECLAMATION
- IMPROVED SLICE THICKNESS

1984 - LARGE CAPACITY EQUIPMENT
- LOW COST BLADE STOCK
- WATER BASED SLURRY VEHICLE
- RECLAIMED ABRasive
- MINIMUM SLICE THICKNESS
1978 WAFFERING FACTORY

TOTAL OUTPUT: $5.3 \times 10^3$ m$^2$/yr

MACHINE OUTPUT: 10 cm Diamter Silicon Ingot
300 Slices/Batch
30 HR Cycle
95% Product Yield
95% Equipment Utilization

FACTORY SPECIFICATIONS: 9 Saws
1 Operator
550 SQ. FT.
$5,000$ Misc. Equipment
2368 Production Cycles

ANNUAL REQUIREMENTS: 2368 Blade Packages
4736 Gallons Vehicle
14,208 Lbs. Abrasive
$11,472$ Supplies
$75 \times 10^3$ KW-HR Electricity
### 1978 COST SUMMARY (1978 $)

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
<th>AMOUNT</th>
<th>COST</th>
<th>TOTAL PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>SAWS</td>
<td>9</td>
<td>$20,000</td>
<td>$90,650 (.18)</td>
</tr>
<tr>
<td></td>
<td>MISC. EQPT</td>
<td>(1)</td>
<td>$  5,000</td>
<td></td>
</tr>
<tr>
<td>SQFT</td>
<td>FLOOR AREA</td>
<td>550 SQ.FT.</td>
<td>$116.69</td>
<td>$ 64,179 (.13)</td>
</tr>
<tr>
<td>DLAB</td>
<td>MACHINE OPERATOR</td>
<td>4.0 PRSN YRS</td>
<td>$10,694</td>
<td>$ 92,097 (.18)</td>
</tr>
<tr>
<td>MATS</td>
<td>BLADE PACKS</td>
<td>2368</td>
<td>$  63.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VEHICLE</td>
<td>4736 GAL</td>
<td>$    2.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ABRASIVE</td>
<td>14,208 LB.</td>
<td>$    1.70</td>
<td>$258,108 (.51)</td>
</tr>
<tr>
<td></td>
<td>MISC. SUPPLIES</td>
<td>(1)</td>
<td>$ 11,472</td>
<td></td>
</tr>
<tr>
<td>UTIL</td>
<td>ELECTRICITY</td>
<td>$75 \times 10^3$ KW-HR</td>
<td>$.036</td>
<td>$ 3,510 (.01)</td>
</tr>
</tbody>
</table>

TOTAL PRICE $505,365

QUAN = $5.3 \times 10^3$ m²

PRICE (1978 $) $95.95

\$/m² (1975 $) $79.75
1980 Wafering Factory

Total Output: \(20 \times 10^3 \text{m}^2/\text{yr}\)

Machine Output:
- 10 cm diameter silicon ingot
- 300 slices/batch
- 30 hr cycle
- 95% production yield
- 95% equipment utilization

Factory Specifications:
- 34 saws
- 2 machine operators
- 0.5 assemblers
- 1760 sq. ft.
- $55,000 misc. equipment
- 8935 production cycles/yr.

Annual Requirements:
- 25,997 lbs. steel
- 17,870 gallons vehicle
- 53,610 lbs. abrasive
- $16,000 supplies (1978 $)
- \(2 \times 10^5\) kw-hr electricity
## 1980 Cost Summary (1980 $)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Amount</th>
<th>Cost</th>
<th>Total Price</th>
<th>Factors Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>Saws</td>
<td>34</td>
<td>$22,898</td>
<td>$412,336 (.32)</td>
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<tr>
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<td>Misc. EQPT</td>
<td>(1)</td>
<td>$62,970</td>
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</tr>
<tr>
<td>SQFT</td>
<td>Floor Area</td>
<td>1760 SQ.FT.</td>
<td>$131.14</td>
<td>$230,806 (.18)</td>
<td></td>
</tr>
<tr>
<td>DLAB</td>
<td>Machine Operator</td>
<td>8.0 PRSN YR</td>
<td>$12,789</td>
<td>$261,139 (.20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assembler</td>
<td>2.0 PRSN YR</td>
<td>$11,020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATS</td>
<td>Steel</td>
<td>25,997 LB</td>
<td>$ 5.83</td>
<td>$ 386,464 (.30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vehicle</td>
<td>17,870 GAL</td>
<td>$ 1.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrasive</td>
<td>53,610 LB</td>
<td>$ 1.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misc. Supplies</td>
<td>(1)</td>
<td>$18,662</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UTIL</td>
<td>Electricity</td>
<td>$2 \times 10^5$ KW HR</td>
<td>$0.0045</td>
<td>$ 11,700 (.01)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total Price</strong></td>
<td><strong>$1,302,445</strong></td>
</tr>
</tbody>
</table>

**QUAN = 20 \times 10^3 m^2**

**Price (1980 $)** $65.12

**$/m^2 (1975 $)** $48.17
1982 Wafering Factory

Total Output: \[6 \times 10^5 \text{ m}^2/\text{yr}\]

Machine Specifications: 10 cm diameter silicon ingot
900 slices/batch
30 HR cycle
95% production yield
95% equipment utilization

\[6.72 \text{ m}^2/\text{cycle}\]

Factory Specifications: 38 machines
2.0 machine operators
0.75 assemblers
2350 sq. ft.
$80,000 (1978 $) miscellaneous equipment
9978 cycles/years

Annual Requirements: 82,820 lbs. steel
59,868 gallons vehicle
119,736 lbs. abrasive
$40,000 (1978 $) supplies
5 \times 10^5 \text{ kw-hr} electricity
<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
<th>AMOUNT</th>
<th>COST</th>
<th>TOTAL PRICE FACTORS APPLIED</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>SAWS</td>
<td>38</td>
<td>$52,432</td>
<td>$1,027,667 (.34)</td>
</tr>
<tr>
<td>EQPT</td>
<td>MISC. EQPT</td>
<td>(1)</td>
<td>$104,864</td>
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</tr>
<tr>
<td>SQFT</td>
<td>FLOOR AREA</td>
<td>2350 SQ.FT.</td>
<td>$147.34</td>
<td>$346,249 (.12)</td>
</tr>
<tr>
<td>DLAB</td>
<td>MACHINE OPERATORS</td>
<td>8.0 PRSN YR</td>
<td>$14,917</td>
<td>$331,586 (.11)</td>
</tr>
<tr>
<td>DLAB</td>
<td>ASSEMBLERS</td>
<td>3.0 PRSN YR</td>
<td>$12,854</td>
<td></td>
</tr>
<tr>
<td>MATS</td>
<td>STEEL</td>
<td>82,820 LB</td>
<td>$6.80</td>
<td>$1,268,289 (.42)</td>
</tr>
<tr>
<td>MATS</td>
<td>VEHICLE</td>
<td>59,868 GAL</td>
<td>$1.36</td>
<td></td>
</tr>
<tr>
<td>MATS</td>
<td>ABRASIVE</td>
<td>119,736 LB</td>
<td>$2.31</td>
<td></td>
</tr>
<tr>
<td>MATS</td>
<td>MISC. SUPPLIES</td>
<td>(1)</td>
<td>$54,420</td>
<td></td>
</tr>
<tr>
<td>UTIL</td>
<td>ELECTRICITY</td>
<td>$5 \times 10^5$ KW HR</td>
<td>$0.0056</td>
<td>$36,400 (.01)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTAL PRICE</td>
</tr>
</tbody>
</table>

QUAN = $67 \times 10^3 m^2$

PRICE (1982 $) $44.93
$/m^2$ (1975 $) $29.58
1984 WAFERING FACTORY

TOTAL OUTPUT: 

\[ 353 \times 10^3 \text{m}^2/\text{yr} \]

MACHINE SPECIFICATIONS: 

- 10 cm DIAMETER SILICON INGOT
- 1000 SLICES/BATCH
- 30 HR CYCLE
- 95% PRODUCTION YIELD
- 95% EQUIPMENT UTILIZATION

\[ 7.46 \text{ m}^2/\text{cycle} \]

FACTORY SPECIFICATIONS: 

- 180 MACHINES
- 10.0 MACHINE OPERATORS
- 1.0 ASSEMBLERS
- 10,000 SQ. FT.
- $170,000 (1978 $) MISC. EQUIPMENT
- 47,311 CYCLES/yr.

ANNUAL REQUIREMENTS: 

- 413,806 LBS. STEEL
- 283,866 GALLONS VEHICLE
- 283,866 LBS. ABRASIVE
- $190,000 (1978 $) MISC. SUPPLIES
- \( 2.5 \times 10^6 \text{ kw-hr} \) ELECTRICITY
### 1984 Cost Summary (1984 $)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Amount</th>
<th>Cost</th>
<th>Total Price</th>
<th>Factors Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQPT</td>
<td>Saws</td>
<td>180</td>
<td>$60,030</td>
<td>$5,419,657</td>
<td>(.44)</td>
</tr>
<tr>
<td></td>
<td>Misc. EQPT</td>
<td>(1)</td>
<td>$255,125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SQFT</td>
<td>Floor Area</td>
<td>10,000</td>
<td>$165.58</td>
<td>$1,655,800</td>
<td>(.14)</td>
</tr>
<tr>
<td>DLAB</td>
<td>Machine Operators</td>
<td>40.0</td>
<td>$17,399</td>
<td>$1,587,457</td>
<td>(.13)</td>
</tr>
<tr>
<td></td>
<td>Assemblers</td>
<td>4.0</td>
<td>$14,993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATS</td>
<td>Steel</td>
<td>413,806</td>
<td>$3.17</td>
<td>$3,300,276</td>
<td>(.27)</td>
</tr>
<tr>
<td></td>
<td>Vehicle</td>
<td>283,866</td>
<td>.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abrasive</td>
<td>283,866</td>
<td>$2.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misc. Supplies</td>
<td>(1)</td>
<td>$301,506</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UTIL</td>
<td>Electricity</td>
<td>2.5 x 10^6</td>
<td>.071</td>
<td>$230,750</td>
<td>(.02)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Price</td>
<td>$12,193,940</td>
</tr>
</tbody>
</table>

**QUAN = 353 x 10^3 m^2**

**PRICE (1984 $) $34.54/m^2**

$20.23/m^2 (1975 $)
SUMMARY OF SLICING COSTS AND MAJOR FEATURES FOR REDUCTION

(1975 $)

<table>
<thead>
<tr>
<th>YEAR</th>
<th>PRICE (1975 $/m²)</th>
<th>IMPORTANT COST REDUCTION FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>$79.76</td>
<td>- IN-HOUSE BLADE PACKAGE FAB.</td>
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<tr>
<td></td>
<td></td>
<td>(IMPROVED CONVERSION RATE)</td>
</tr>
<tr>
<td>1980</td>
<td>$48.17</td>
<td>- INCREASED MACHINE/LABOR PRODUCTIVITY</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- EXPENDIBLE MATERIALS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IMPROVED CONVERSION RATE)</td>
</tr>
<tr>
<td>1982</td>
<td>$29.58</td>
<td>- EXPENDIBLE MATERIALS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- MACHINE PRODUCTIVITY</td>
</tr>
<tr>
<td>1984</td>
<td>$20.23</td>
<td>- MACHINE PRODUCTIVITY</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(OR COSTING STANDARDS)</td>
</tr>
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</table>

INGOT CONVERSION FACTORS

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SLICE &amp; KERF (INCHES)</th>
<th>SLICES/CM</th>
<th>YIELD</th>
<th>CONVERSION RATE (m²/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1978)</td>
<td>0.024</td>
<td>16.4</td>
<td>95</td>
<td>0.669</td>
</tr>
<tr>
<td>(1980)</td>
<td>0.020</td>
<td>19.7</td>
<td>95</td>
<td>0.803</td>
</tr>
<tr>
<td>(1982)</td>
<td>0.018</td>
<td>21.9</td>
<td>95</td>
<td>0.892</td>
</tr>
<tr>
<td>(1984)</td>
<td>0.016</td>
<td>24.6</td>
<td>95</td>
<td>1.003</td>
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</table>
### COMBINED COST SUMMARY FOR WAFCO

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SLICING PRICE ($/m²)</th>
<th>INGOT PRICE ($/kg)</th>
<th>INGOT PRICE ($/m²)</th>
<th>TOTAL PRICE ($/m²)</th>
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</thead>
<tbody>
<tr>
<td>1978</td>
<td>$ 79.76</td>
<td>$ 151.00</td>
<td>$ 225.71</td>
<td>$ 305.47</td>
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<td>1980</td>
<td>$ 48.17</td>
<td>$ 135.00</td>
<td>$ 168.12</td>
<td>$ 216.29</td>
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<tr>
<td>1982</td>
<td>$ 29.58</td>
<td>$ 71.60</td>
<td>$ 80.27</td>
<td>$ 109.85</td>
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<tr>
<td>1984</td>
<td>$ 20.23</td>
<td></td>
<td></td>
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(1975 $)

### WAFER PRICE ESTIMATES vs. IPEG STANDARDS

<table>
<thead>
<tr>
<th>YEAR</th>
<th>WAFER PRICE $/m²</th>
<th>IPEG ALLOCATION $/m²</th>
<th>ADVANTAGE %</th>
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</thead>
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<tr>
<td>1978</td>
<td>$ 305.47</td>
<td>381</td>
<td>19.8%</td>
</tr>
<tr>
<td>1980</td>
<td>$ 216.29</td>
<td>245</td>
<td>13.3%</td>
</tr>
<tr>
<td>1982</td>
<td>$ 109.85</td>
<td>128</td>
<td>14.2%</td>
</tr>
<tr>
<td>1984</td>
<td></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td></td>
<td>18.2</td>
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</tr>
</tbody>
</table>

(1975 $)
MULTIBLADE SLURRY WAFFERING

TECHNOLOGY DEVELOPMENT OBJECTIVES

NEAR 100% YIELD

IMPROVED INGOT CONVERSION

MACHINE PRODUCTIVITY INCREASE

REDUCE EXPENDABLE MATERIALS

BASIC ABRASION RESEARCH
NEAR 100% YIELD

CHARACTERIZATION

- RUNS SHOW 0-20% OR 70-100% YIELD
- NO CORRELATION WITH PROCESS PARAMETERS
- SLICE BREAKAGE WHILE CLEANING
- EDGE CRACKS

THEORY

- MACHINE ACTION CAUSES CHIPPING
- RANDOM PERTURBATIONS CAUSE FRACTURE

EXPERIMENTATION

- MEASURED BLADEHEAD ACCELERATION
- BOUNCE FIXTURE
- BLADE ALIGNMENT
IMPROVED INGOT CONVERSION

- LIMITS OF EXISTING EQUIPMENT DEFINED
- #600 SiC ABRASIVE BEST KERF-CONTROL TRADEOFF
- THINNER BLADES SHOW FATIGUE PROBLEMS
- THINNEST WAFER POSSIBLE NOW IS .25 MM

MACHINE PRODUCTIVITY

- BASIC APPROACH IS 1000 BLADE SAW
- INCORPORATES PROCESS IMPROVEMENTS
- PROGRAMMED OPERATION WILL BE CONSIDERED
REDUCE EXPENDABLE MATERIALS

FLUID COST

- SPECIFICATIONS UNCERTAIN
- OIL BLENDING UNSUCCESSFUL
- PRELIMINARY SUCCESS WITH WATER BASE

ABRASIVE COST

- MICROGRAPHS OF ABRASIVE INDICATE RECYCLABILITY
- RECLAMATION SYSTEM DEFINED AND TO BE TESTED

BLADE COST

- LOWER ACCURACY STOCK WAS NOT SUCCESSFUL IN FIRST TEST
BASIC ABRASION RESEARCH

- INSUFFICIENT EVIDENCE TO CHOOSE A MODEL
- LAB SAW WILL ALLOW GREATER PROCESS VARIATION

### SUMMARY OF TECHNOLOGY DEVELOPMENT

<table>
<thead>
<tr>
<th>OBJECTIVE</th>
<th>APPROACHES</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH YIELD</td>
<td>REDUCE SHOCK</td>
<td>DEMONSTRATED</td>
</tr>
<tr>
<td></td>
<td>BLADE ALIGNMENT</td>
<td>INCOMPLETE; MINOR IMPACT</td>
</tr>
<tr>
<td>IMPROVED INGOT CONVERSION</td>
<td>DEFINE CURRENT LIMITS</td>
<td>COMPLETE</td>
</tr>
<tr>
<td></td>
<td>OPTIMIZE ABRASIVE</td>
<td>COMPLETE</td>
</tr>
<tr>
<td></td>
<td>USE THINNER BLADES</td>
<td>TESTED; FATIGUE FAILURE</td>
</tr>
<tr>
<td>IMPROVE MACHINE PRODUCTIVITY</td>
<td>1000 BLADE SAW PROGRAMMED</td>
<td>MAY 1978</td>
</tr>
<tr>
<td></td>
<td>OPERATION</td>
<td>NO ACTION</td>
</tr>
<tr>
<td>REDUCE EXPENDABLE MATERIALS</td>
<td>LOW COST FLUID</td>
<td>ONGOING</td>
</tr>
<tr>
<td></td>
<td>RECYCLE ABRASIVE</td>
<td>SYSTEM TEST SOON</td>
</tr>
<tr>
<td></td>
<td>LOW COST BLADES</td>
<td>INITIAL FAILURE</td>
</tr>
<tr>
<td>BASIC ABRASION RESEARCH</td>
<td>LAB SAW (PROCESS VARIATIONS)</td>
<td>AVAILABLE</td>
</tr>
</tbody>
</table>
The meeting began with a discussion of the available forms of silicon to be expected from the processes being developed under Task I. This was presented by Ralph Lutwack. The most mature processes, Battelle and Union Carbide, will be most likely producing a granular silicon 1 to 1.5 mm in diameter as the output of a fluidized bed. It is possible that a free space reactor could be used which would result in a finer powder which would be most likely compacted. The Westinghouse process would yield a liquid capable of being cast into any reasonable required shape. Silane gas would be available from the Dow process which when converted would yield a fine powder. Other processes, while less mature and definitive, would appear to yield product within this general framework.

Considerable discussion centered around the potential problem of oxide and scum formation on top of silicon baths produced from relatively fine particulate material. The magnitude of this problem has not been evaluated with the Task I products. This should be done in the near future. The question was also raised as to whether the solar grade silicon would be doped. The response was that it would not. Consideration of providing doped material was urged. This was based on the cost of adding dopant to material in Task II and the difficulties in removing dopant species from the Task I product.

Next, a discussion of experience with transport or injection systems was held. Mobil Tyco summarized their experience, using a rod injector and stated that no particular problems were experienced although the design was based on high probability of success and not cost effectiveness. Hamco showed poly silicon
rod melt back into a Czochralski crucible as a successful means of replenishment and maximizing crucible fill. Westinghouse stated that pellets of silicon have been dropped into a dendritic web furnace during growth without perturbing growth. In general, it appears that the direct experience with melt replenishment was rather meager but that what little experience existed did not portend serious problems.

Next, presentations by the Task II Materials Development Activities were given. In general, results were preliminary without hard conclusions as a result of the limited activity to date. Battelle gave data for vapor species resulting from silicon in contact with several potential refractory materials. They also described the systems being developed for compatibility studies. Coors described success in providing large size substrates for the dip coating process and the development of a modified mullite whose thermal expansion is identical to that of silicon. Eagle-Picher described substrate and coating samples produced primarily of silicon carbide and silicon nitride which will be shortly investigated for compatibility with silicon under controlled atmosphere conditions. RCA reported results on silicon nitride and silicon oxynitride produced by CVD methods. Preliminary findings suggest improved stability if the silicon nitride is in the beta form. Tylan Corporation described glassy carbon coatings which have been produced on carbon and mullite and suggested that these coatings show unique character in the silicon carbide film produced in contact with molten silicon.

The user requirements on the part of the Task II crystal growers were next discussed and the greatest preference was indicated for pelletized material in the 1 to 5 mm size range. One or two indicated preference for rod material, although in most cases pellets would be acceptable. The Motorola process specifically requires either gas or thin sheet silicon as its source of material.
If silicon is provided in a gas form to the crystal grower, concern was expressed about the cost effectiveness of the by-product gas produced upon decomposition. In general, this gas could be recycled into the silicon production system but shipping costs would probably require that the crystal growth and silicon production operations be placed close to each other.

Consideration was next given to the available properties of molten silicon to be used in the design of melt replenishment systems. M. Leipold presented a list of some available properties and offered to summarize information and requirements in such a list for the use of the people involved. Numerous additional suggestions as to the additional properties required were given and some additional data was given. This compilation will be made over the next several months.

The meeting concluded with several minutes of open discussion concerning technical and economic aspects of materials for use with molten silicon, for example, the statement was made that there has been no demonstrated growth of Czochralski crystals from other than SiO crucibles. No contradictory evidence was offered. Further, some types of silicon crucibles using naturally occurring amorphous silica and solid state processing are becoming available as growth crucibles. These are apparently significantly cheaper as a result of both reduced raw material costs and processing costs.

In summary, it may be concluded that no major problems exist concerning the Task I - Task II interface with respect to form of silicon. Significant questions exist concerning oxide layers and scums on particulate silicon and the question of doping should be addressed. With respect to melt replenishment experience is meager but promising. Data is being developed on refractory materials which should be capable of defining suitable and unsuitable materials.
C. ENCAPSULATION TASK

A major emphasis of this quarter's Project Integration Meeting was an assessment of the adequacy of existing encapsulation materials and processes to meet the 1986 performance and cost goals. The expanded Encapsulation Task activities at this PIM included a full day intratask meeting of the Encapsulation Task contractors on Tuesday, April 11. At the PIM itself, there was a lobby display of the hardware and results of an assessment of some 18 low-cost solar cell encapsulant systems which were experimentally evaluated as nine-cell minimodules during the previous three-month period.

During the first morning session of the PIM a comprehensive two-hour report was presented of the objectives, scope, status, and plans of the LSA Project Encapsulation Task.

The major conclusions from this encapsulation assessment effort and from the discussion of the results at the PIN were as follows:

1. Encapsulation systems costing from 2.5c - 10c/Watt are feasible and appear to be cost effective and have long life potential.

2. Optimum encapsulation systems are not obvious yet and will require cost and performance trade-off specific to proposed applications, locations, and life requirements.

3. Life prediction test techniques and supporting analysis methodologies still need to be developed.

4. The life-limiting (long-term wear-out) failure modes of currently installed, and of proposed candidate encapsulation systems, have not been determined by current qualification and field testing approaches.

A summary of the contractor programs status and the PIM presentation are given by a selection of the viewgraphs and data which are appended without specific reference in the following text.

The Encapsulation Task has been working in two general areas, (a) materials and processes and (b) life prediction. The nine contractors supporting technology development on specific items in these two areas are shown in one of the attached charts entitled Task Breakdown. In-house work at JPL has included research on photodegradation and failure mechanisms in candidate encapsulant materials plus minimodule fabrication and experimental evaluation of failure mechanisms in candidate 1986 low-cost encapsulant systems.

A spectrum of existing solar module encapsulation material systems and processes were defined representing potential candidates for meeting the LSA 1986 encapsulation cost and performance goals. Sixty-four nine-cell modules of 18 design concepts were fabricated by several
groups including Battelle, Springborn, Lockheed, OCLI, JPL and SPIRE. Material costs for the encapsulant/substrate/superstrate systems ranged from $0.25 to $1.50 per square foot of module (or 2.5-15¢/watt). Material candidates included glass and metals as well as low-cost thermoplastics, paper honeycomb, and wood particle board.

The minmodules were subjected to the JPL Thermal Cycle Test (-40 to 90°C) and the Humidity Cycle Test. Examination of the physical and electrical performance changes showed several low-cost systems were viable long-life material candidates, including the use of UV screening films, ethylene vinyl acetate pottant, and particle board substrates. Results are summarized in the attached charts.

JPL and supporting contractors will continue to evaluate these and other low-cost systems to provide data for life prediction and will develop and demonstrate improved materials and processes.

**OBJECTIVES:**

1. DEFINE, DEVELOP, DEMONSTRATE ENCAPSULATION SYSTEMS, MATERIALS, AND PROCESSES TO MEET THE LSA PROJECT LIFE, COST, AND PERFORMANCE GOALS

2. DEVELOP AND VALIDATE A MODULE LIFE PREDICTION METHODOLOGY BASED ON MODELING LIFE-LIMITING FAILURE MODES AND ON CONDUCTING AND ANALYZING ACCELERATED AGING TESTS
SCOPE

1. SURVEY, SCREEN, EVALUATE, AND RANK EXISTING MATERIALS AND SYSTEMS

2. DEFINE THE ENVIRONMENTAL STRESSES AND THEIR EFFECTS ON SOLAR MODULE COMPONENTS AND ENCAPSULANTS

3. IDENTIFY POTENTIAL LOW-COST SYSTEMS AND PROCESSES AND THE DEVELOPMENT REQUIREMENTS TO ACHIEVE TECHNOLOGY READINESS

4. DEVELOP AND DEMONSTRATE IMPROVED MATERIALS AND SYSTEMS

5. DEVELOP AND DEMONSTRATE NOVEL AND IMPROVED ENCAPSULATION PROCESSES AND FABRICATION CONCEPTS

6. DEVELOP AND IMPLEMENT A LIFE PREDICTION TEST PROGRAM

7. DEVELOP A LIFE PREDICTION MODEL AND METHODOLOGY

8. DEVELOP AND DEMONSTRATE APPROPRIATE TEST METHODS, FACILITIES, AND INSTRUMENTATION

9. DEFINE AND CHARACTERIZE POLYMER AGING AND PHOTODEGRADATION

ENCAPSULATION SYSTEM GOALS

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<thead>
<tr>
<th></th>
<th>1982</th>
<th>1986</th>
</tr>
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<tbody>
<tr>
<td>ENCAPSULATION MAT'L PRICES (PER WATT)</td>
<td>$11.00/m²</td>
<td>$3.30/m²</td>
</tr>
<tr>
<td>OPTICAL TRANSMISSION</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>20 year Δτ</td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td>ELECTRICAL PERFORMANCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BREAKDOWN VOLTAGE</td>
<td>3000 VDC</td>
<td>3000 VDC</td>
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<tr>
<td>STRUCTURAL PERFORMANCE</td>
<td>NO FAILURE</td>
<td>NO FAILURE</td>
</tr>
<tr>
<td>HANDLING &amp; WEATHER</td>
<td>SEMI- AUTOMATED</td>
<td>AUTOMATED</td>
</tr>
<tr>
<td>PROCESSING</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ENCAPSULATION INTERFACES

ENVIRONMENTAL DEFINITION
- TEMPERATURE
- UV, WIND, HAIL
- MOISTURE, DIRT, ETC.

FUTURE REQUIREMENTS
- ECONOMIC & TECHNICAL
- 1978 → 1986

ARRAY STRUCTURE
& POWER CONNECTORS
- DESIGN

FAB.
- AUTOMATED MODULE ASSEMBLY

ARRAY LIFE REQUIREMENTS
- DEGRADATION MECHANISMS
- VALIDATION TESTING

ENCAPSULATION TECHNOLOGY

SILICON CELLS
- METALLIZATION
- OPTICAL COUPLING

CURRENT TECHNOLOGY

SILICONE
- ELECTRONIC PACKAGING
- WEATHERABLE
- PROCESSABLE
- PROBLEMS: COST, DIRT, DELAMINATION

GLASS
- GLAZING (>50 yr)
- WEATHERABLE
- MOISTURE TIGHT
- PROBLEMS: BRITTLE

POLYVINYL BUTYRAL
- SAFETY GLASS
- PROCESSABLE
- MODERATE COST
- PROBLEMS: WATER SENSITIVE

PMMA ACRYLIC
- GLAZING (>17 yr)
- WEATHERABLE
- PROPERTY RANGE
- PROBLEMS: THERMAL MISMATCH

FLUOROCARBON
- ELECTRICAL, CHEMICAL
- WEATHERABLE
- CHEMICAL & TEMPERATURE STABLE
- PROBLEMS: COST, PROCESSING
### SUPERSTRATE/SUBSTRATE DESIGN

**PRINTED CIRCUIT BOARD (PCB)**
- **SUPERSTRATE**
- **Pottendant**
- **SUBSTRATE**
- **TOP COVER**
- **ELECTRICAL ISOLATOR**
- **CELLS**

<table>
<thead>
<tr>
<th>VARIATION</th>
<th>MATERIAL</th>
<th>FUNCTION</th>
<th>THICKNESS, in.</th>
<th>COST, $/ft²</th>
<th>TOTAL COST, $/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED RTV SILICONE RUBBER FIBERGLASS/PVC SCREEN ALUMINUM</td>
<td>SUPERSTRATE POTTANT ELEC. ISOLATOR SUBSTRATE</td>
<td>0.125 0.075 0.008 0.150</td>
<td>0.70 3.00 0.05 2.00</td>
<td>5.75</td>
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<tr>
<td>2</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED RTV SILICONE RUBBER MYLAR FILM ALUMINUM</td>
<td>SUPERSTRATE POTTANT BOTTOM COVER SUBSTRATE</td>
<td>0.187 0.60 0.006 0.060</td>
<td>0.80 2.40 0.10 0.80</td>
<td>4.10</td>
</tr>
<tr>
<td>3</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED SILICONE GEL EPOXY/GLASS/COPPER ALUMINUM</td>
<td>SUPERSTRATE POT TANT PCB SUBSTRATE</td>
<td>0.093 0.60 0.060 0.062</td>
<td>0.65 1.00 1.50 0.80</td>
<td>3.95</td>
</tr>
<tr>
<td>4</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED SILICONE GEL POLYIMIDE/GLASS/COPPER GLASS CLOTH STAINLESS STEEL</td>
<td>SUPERSTRATE POT TANT PCB ELEC. ISOLATOR SUBSTRATE</td>
<td>0.125 0.60 0.018</td>
<td>0.70 1.00 0.35 2.75</td>
<td></td>
</tr>
</tbody>
</table>

### SUBSTRATE TYPE ENCAPSULATION DESIGN

**POTTANT**
- **TOP COVER**
- **SUBSTRATE**
- **ELECTRICAL ISOLATOR**
- **CELLS**

<table>
<thead>
<tr>
<th>VARIATION</th>
<th>MATERIAL</th>
<th>FUNCTION</th>
<th>THICKNESS, in.</th>
<th>COST, $/ft²</th>
<th>TOTAL COST, $/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RTV SILICONE RUBBER ALUMINUM</td>
<td>POTTANT SUBSTRATE</td>
<td>0.075 0.060</td>
<td>3.00 3.80</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RTV SILICONE RUBBER FIBERGLASS/PVC SCREEN ALUMINUM</td>
<td>POTTANT ELEC. ISOLATOR SUBSTRATE</td>
<td>0.075 0.008 0.030</td>
<td>3.00 0.05 1.40</td>
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<tr>
<td>3</td>
<td>RTV SILICONE RUBBER EPOXY/GLASS IG-1D</td>
<td>POTTANT SUBSTRATE</td>
<td>0.075 0.060</td>
<td>3.00 1.50 4.50</td>
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<tr>
<td>4</td>
<td>R4-3117 SILICONE RTV SILICONE RUBBER EPOXY/GLASS IG-1D</td>
<td>TOP COVER POTTANT SUBSTRATE</td>
<td>0.006 0.075 0.060</td>
<td>0.70 1.00 1.50 4.70</td>
<td></td>
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<tr>
<td>5</td>
<td>RTV SILICONE RUBBER POLYESTER/GLASS</td>
<td>POTTANT SUBSTRATE</td>
<td>0.075 0.060</td>
<td>3.00 0.75 3.75</td>
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<tr>
<td>6</td>
<td>R4-3117 SILICONE RTV SILICONE RUBBER POLYESTER/GLASS</td>
<td>TOP COVER POTTANT SUBSTRATE</td>
<td>0.006 0.075 0.060</td>
<td>0.20 1.00 0.75 3.95</td>
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</tr>
<tr>
<td>7</td>
<td>SODA-LIME GLASS, ANNEALED RTV SILICONE RUBBER ALUMINUM</td>
<td>TOP COVER POTTANT SUBSTRATE</td>
<td>0.093 0.060</td>
<td>0.25 3.60 0.80 4.05</td>
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3-164
SUPERSTRATE TYPE ENCAPSULATION DESIGN

<table>
<thead>
<tr>
<th>VARIATION</th>
<th>MATERIAL</th>
<th>FUNCTION</th>
<th>THICKNESS, IN.</th>
<th>COST, $/m²</th>
<th>TOTAL COST, $/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SODA-LIME GLASS, TEMPERED SAFLEX PVB MYLAR FILM</td>
<td>SUPERSTRATE POTANT BOTTOM COVER</td>
<td>0.125 0.030 0.006</td>
<td>0.50 0.35 0.10</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED SAFLEX PVB MYLAR FILM</td>
<td>SUPERSTRATE POTANT BOTTOM COVER</td>
<td>0.125 0.030 0.006</td>
<td>0.70 0.35 0.10</td>
<td>1.15</td>
</tr>
<tr>
<td>3</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED SAFLEX PVB TELAR FILM</td>
<td>SUPERSTRATE POTANT BOTTOM COVER</td>
<td>0.125 0.030 0.002</td>
<td>0.70 0.35 0.10</td>
<td>1.15</td>
</tr>
<tr>
<td>4</td>
<td>SODA-LIME GLASS, LOW-IRON, TEMPERED SILICONE GEL SODA-LIME GLASS, ANNEALED</td>
<td>SUPERSTRATE POTANT BOTTOM COVER</td>
<td>0.125 0.060 0.093</td>
<td>0.70 1.00 0.25</td>
<td>1.95</td>
</tr>
<tr>
<td>5</td>
<td>SODA-LIME GLASS, ANNEALED RTV SILICONE RUBBER R4-31I7 SILICONE</td>
<td>SUPERSTRATE POTANT BOTTOM COVER</td>
<td>0.187 0.040 0.006</td>
<td>0.35 1.60 0.20</td>
<td>2.15</td>
</tr>
</tbody>
</table>

TASK BREAKDOWN:

MATERIALS AND PROCESSES
- SPRINGBORN - LOW-COST MATERIALS AND PROCESSES
- BATTELLE - MATERIALS AND SYSTEM EVALUATION
- DOW-CORNING - SILICONE-BASED OPTIMIZED SYSTEMS
- SPIRE - ELECTROSTATIC BONDING
- ENDUREX - ION PLATING
- JPL - MATERIALS TECHNOLOGY SEARCH AND ASSESSMENT

LIFE PREDICTION
- BATTELLE - ENVIRONMENT DEFINITION
- ACCELERATED TEST METHODS AND LIFE PREDICTION
- DIAGNOSTIC TECHNIQUES
- ROCKWELL (ANAHEIM) - ACCELERATED TEST AND ANALYSIS
- ROCKWELL (SCI CTR) - INTERFACE PHENOMENA
- CASE WESTERN - FRACTURE MECHANISMS
- JPL - PHOTODEGRADATION AND FAILURE MECHANISMS

3-165
DEVELOPMENT AREAS

1. NONSOLVENT ACRYLIC COATING FOR 20-YEAR LIFE

2. LOW-COST, WEATHERABLE, LOW-CREEP POTTANT

3. ELASTOMERIC ACRYLIC

4. LOW-COST, RIGID, WEATHERABLE SUBSTRATES

5. COST-EFFECTIVE ADHESIVES

6. AUTOMATABLE FABRICATION METHODS

LOW-COST PROCESSABLE TRANSPARENT POTTANTS

<table>
<thead>
<tr>
<th>MODULE SYSTEMS</th>
<th>MATERIALS COST ($/LB)</th>
<th>PROJECTED 1986 COST ($/FT²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>0.55</td>
<td>0.072</td>
</tr>
<tr>
<td>PVC PLASTISOL</td>
<td>0.39-3.43 (Ingredients)</td>
<td>0.076</td>
</tr>
<tr>
<td>IONOMER/EVA</td>
<td>1.05/0.55</td>
<td>0.083</td>
</tr>
<tr>
<td>ACRYLIC/POLYSTYRENE/EVA</td>
<td>1.40/0.28/0.55</td>
<td>0.098</td>
</tr>
<tr>
<td>ALIPHATIC URETHANE</td>
<td>1.24</td>
<td>-</td>
</tr>
<tr>
<td>EPR</td>
<td>0.49</td>
<td>-</td>
</tr>
<tr>
<td>PVC PLASTICIZED WITH EVA</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Substrate Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum Thickness Required (in.)</th>
<th>Cost ($/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Styrene-maleic copolymer</td>
<td>0.27</td>
<td>0.53</td>
</tr>
<tr>
<td>Rigid PVC</td>
<td>0.27</td>
<td>0.59</td>
</tr>
<tr>
<td>Galvanized steel</td>
<td>0.07</td>
<td>0.56</td>
</tr>
<tr>
<td>Glass-reinforced gypsum (coated)</td>
<td>1.00</td>
<td>0.30</td>
</tr>
<tr>
<td>Soda-lime glass</td>
<td>0.10</td>
<td>0.29</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>Particle board, phenolic binder</td>
<td>0.27</td>
<td>0.12-0.14</td>
</tr>
<tr>
<td>Polyester/glass</td>
<td>0.18</td>
<td>1.08</td>
</tr>
<tr>
<td>Epoxy/glass (NEMA G-10)</td>
<td>0.14</td>
<td>4.08</td>
</tr>
</tbody>
</table>

(1) Substrate costs per required thickness based on deflection calculations for 15" x 45" module under 50 lb/ft² wind loading.

### Ultraviolet Absorbing Acrylic (1) Coating

**Material Properties**

- UV Absorbers
  - Tinuvin P 5 phr
  - Cyasorb UV-1084 1 phr
- Optical Transmission (2)
  - UV, 290-350 mµ 0
  - Visible, 350-800 mµ 82.1
- Cost, $/ft²/mil 0.0092

**Coating Property**

- Time of exposure without degradation to date (3) 16 weeks

(1) Acryloid B44
(2) Integrated on 1-mil film
(3) 1-mil film over polypropylene sheet exposed under the G.E. RS-4 sunlamp

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3-167
ENCAPSULATION STUDIES

1. REVIEW WORLD EXPERIENCE
2. ACCELERATED TESTING—CHARACTERIZE SERVICE ENVIRONMENTS (TEST CONDITIONS)
3. EVALUATE PROPERTIES OF CANDIDATE MATERIALS
4. ACCELERATED TESTING—DEVELOP METHOD TO DESIGN ACCELERATED LIFE-PREDICTION TESTS
5. ACCELERATED TESTING—EVALUATE MEASUREMENT TECHNIQUES INSTRUMENTS FOR LIFE-PREDICTION TESTS
6. EVALUATE SELECTED ENCAPSULANTS—CONFORMAL COATINGS AND LAMINATES OF GLASS AND/OR POLYMERS
7. ACCELERATED TESTING—DEVELOP TEST PLAN FOR LIFE PREDICTION OF MEAD-NEBRASKA ARRAY

FLEXIGARD/SILGRIP/SILK-SCREENED Ag SILGRIP/FLEXIGARD

- CURVE 1: UNENCAPSULATED
- CURVE 2: ENCAPSULATED
- CURVE 3: AFTER 240-H TEMPERATURE CYCLING (-40 TO 90°C; 80 CYCLES) AND 1096 h AT 38°C AND 95% RELATIVE HUMIDITY

0: MAXIMUM POWER
SILICONE/SILK-SCREENED Ag/SILICONE

CURVE 1: UNENCAPSULATED
CURVE 2: ENCAPSULATED
CURVE 3: AFTER 336-h TEMPERATURE CYCLING (-40 TO 90°C; 84 CYCLES) AND 1000 h AT 38°C AND 95% RELATIVE HUMIDITY

MAXIMUM POWER

RECOMMENDATIONS

1. DEVELOP WATER-VAPOR BARRIER
2. DEVELOP ADHESIVES FOR ACRYLICS
3. TREAT AR COATING, METALLIZATION, ENCAPSULANT AS SUBUNIT (PERFORMANCE, COST, PROCESSING)
4. INVESTIGATE GLASSES SPECIFICALLY FOR ENCAPSULANTS

ELECTROSTATIC BONDING

- ADHESIVELESS BONDING OF GLASS TO INSULATORS, SEMICONDUCTORS OR CONDUCTORS
- ION TRANSFER/CHEMICAL BOND
- SIMPLE, REPRODUCIBLE PROCESS
- REQUIRE 450 - 600°C FOR 1 - 3 MINUTES
- GIVES STRONG, STABLE HERMETIC SEAL
ELECTROSTATIC BONDING PROCESS

H. V. Supply

Pressure

Chamber

Top Electrode/Heater

Cells

Glass

Bottom Electrode/Heater

Pressure

BOND #141 TEST MD-32a

P in PSI
V in VOLTS

TIME INTO BOND

1 minute

2 minute

3 minute

TEMP.

PRESSURE

VOLTAGE

Data display for a typical bond

3-170


PRACTICAL ESB MODULE CONFIGURATION

ADVANCED FULLY INTEGRAL ESB MODULE
ESB DEVELOPMENT PROGRAM

3. MODULE DEVELOPMENT

- DEVELOP MODULE COMPONENTS
  - NEW GLASSES
  - LOW COST METALLIZATION
  - MODULE EDGE SEALS
  - AR COATINGS
  - OUTPUT TERMINALS/INTERCONNECTIONS
  - CELL CONFIGURATIONS

- MODULE CONFIGURATIONS
  - DOUBLE SIDED GLASS MODULES
  - FRONT SIDE GLASS WITH ALTERNATE BACKINGS
  - PRE-SHAPED GLASS

ELECTROSTATIC BONDING - ECONOMICS

- DRIVEN BY COST OF GLASS

- CORNING PROJECTIONS FOR BOROSILICATE GLASS SHEET

<table>
<thead>
<tr>
<th>VOLUME</th>
<th>PRICE /SQUARE FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MILLION SQ. FT.</td>
<td>.45</td>
</tr>
<tr>
<td>100-200 MILLION SQ. FT.</td>
<td>.30</td>
</tr>
</tbody>
</table>
EVALUATION OF DIAGNOSTIC METHODS FOR USE IN PHOTOVOLTAIC-ARRAY SERVICE LIFE PROJECTIONS

OBJECTIVES

- IDENTIFY, EVALUATE, AND RECOMMEND TECHNIQUES AND INSTRUMENTS FOR MEASURING CHANGES IN PROPERTIES OF MATERIALS UNDERGOING ACCELERATED, LABORATORY-SIMULATED, OR NATURAL WEATHERING

- DETERMINE THE EXTENT TO WHICH EXISTING INSTRUMENTS ARE SATISFACTORY FOR USE IN DIAGNOSIS OF ARRAY DEGRADATION

- EVALUATE THE MERITS OF MODIFYING EXISTING INSTRUMENTS OR THE NEED FOR DESIGNING AND BUILDING NEW INSTRUMENTATION TO MEET ESSENTIAL DIAGNOSTIC REQUIREMENTS

EXAMPLES OF ACID-ETCHED AND SILICATE ANTI-REFLECTION PERFORMANCE. Transmission of Light Incident Perpendicular to Glass Surface.
MATERIALS APPROACH TO LIFE PREDICTION

EXAMPLES

A: PHOTO OXIDATION OF -CH₃ GROUPS TO GENERATE COOH OR OH GROUPS, LOSS OF -CO GROUPS, REDUCTION OF MOLECULAR WEIGHT

B: CHANGES IN MODULUS, SURFACE POLARITY, HARDNESS, TRANSMISSION

C: INCREASED DIRT RETENTION, REDUCED BOND STRENGTH LEADING TO DELAMINATION, EMBRITTLEMENT, DARKENING

APPROACH

DETERMINE CHANGE IN MOLECULAR STRUCTURE ON IRRADIATION OF SILICONES

CONDITIONS

SOURCE OF ULTRAVIOLET

- UNFILTERED MERCURY (≥ 245nm)
- UNFILTERED XENON (≥ 260nm)
- FILTERED MERCURY (≥ 295nm)

TEMPERATURE:

- 25 ± 3°C

ENVIRONMENT:

- AIR (~ 30% RH)
- DRY N₂
ABSORPTANCE SPECTRA FOR TRANSPARENT POLYMERS AND SOLAR IRRADIANCE AT AIRMASS ONE (AM-1)

RTV-615 PHOTODEGRADATION UNDER AM-1 AND SHORTER WAVELENGTHS

MERCURY LAMP (MEDIUM PRESSURE)

HIGH PRESSURE XENON ARC

TIME OF IRRADIATION, hr

0 4 8 12 16 20 24 28

ABSORBANCE AT 3400 cm⁻¹

0.5

0.4

0.3

0.2

0.1
PHOTODEGRADATION OF STABILIZED AND VIRGIN PMMA

2537 Å RADIATION, AIR, 25 °C

- - - - - PMMA

- - - - - PMMA +10 wt% 2 HB

EVAPORATION OF RESIDUAL SOLVENT

WT LOSS, %

TIME, hr
MECHANISM OF OPERATION OF A UV STABILIZER/SCREEN

2-HYDROXYBENZOPHENONE

\[ \text{PROCESS} \quad \text{SOLVENT} \quad \text{RATE} \]

- \[ k_1 \quad \text{ETHANOL} \quad \sim 1.3 \times 10^9 \]
- \[ \text{BENZENE} \quad >1 \times 10^{10} \]
- \[ \text{PMMA} \quad >1 \times 10^{10} \]

- \[ k_2 \quad \text{ETHANOL} \quad 2 \times 10^7 \]
- \[ \text{BENZENE} \quad 1.5 \times 10^7 \]
- \[ \text{PMMA} \quad 2 \times 10^6 \]

MOLECULAR WEIGHT DECREASE AS FUNCTION OF IRRADIATION PERIOD

POLYMETHYL METHACRYLATE, PMMA, "PLEXIGLAS"
UNFILTERED LIGHT FROM HIGH PRESSURE XENON ARC, RUN IN AIR, 25°C
ELECTRONIC SPECTRUM OF PMMA AS A FUNCTION OF IRRADIATION TIME

HELIUM ATMOSPHERE
MEDIUM PRESSURE Hg ARC.

ELECTRONIC ABSORPTION SPECTRUM OF PHOTOPRODUCT IN PMMA MEDIUM PRESSURE Hg ARC 5 min. IRRADIATION

3-179
RATE OF FORMATION OF PHOTOPRODUCT IN PMMA

ABSORBANCE AT 250 nm

TIME OF IRRADIATION, min

ABSORBANCE MONITORED AT 250 nm

WAVELENGTH RESPONSE OF JPL ACTIONOMETER

% TRANSMISSION

WAVELENGTH RESPONSE OF JPL ACTIONOMETER

3-180
USE OF UV INTEGRAL TO CORRELATE DEGRADATION RATES

SUMMARY
POTENTIAL FAILURE AND DEGRADATION RATES

ENVIRONMENTAL STRESSES (i.e., UV, TEMP, HUMIDITY) (SMOG, SALT, ETC.)

MODULE FAILURE RATE CLASSIFICATION

(INFANT MORTALITY)
MANUFACTURING PROCESS CONTROLS
- MATERIALS
- CONTAMINATION
- DIMENSIONS
- ASSEMBLY
- HANDLING

WEAR-OUT (AGING)
- MATERIAL PROPERTIES
- FATIGUE (CYCLING)
- WEAR (DIMENSIONAL)
- DAMAGE ACCUMULATION

FAILURE RATE

- RANDOM OVERSTRESS
- RANDOM FLAWS

TIME IN OPERATION

3-182
ACCELERATED ENVIRONMENTAL TESTING
DIFFERING TEST OBJECTIVES

I. OBJECTIVE: SYSTEM PERFORMANCE
DESIGN + STRESS = PERFORMANCE

II. OBJECTIVE: FAILURE MODE DEFINITION
DESIGN + STRESS = FAILURE

III. OBJECTIVE: AGING MECHANISMS LEADING TO FAILURE
DESIGN + STRESS + TIME = DEGRADATION RATE

IV. OBJECTIVE: ANALYTICAL MODEL TO PREDICT FAILURE
DESIGN VALUE + STRESS VALUE + ANALYSIS MODELS = FAILURE RATE OR PROBABILITY
(SHORT TIME TESTS)

VALIDATION TESTING

LSSA DELAMINATION STUDY

TEST CELL
SEALANT

INJECT: AIR
WATER

MEASURE: CHANGES IN IV CHARACTERISTICS

SEALANT: SYL GARD

CONTROL AND ENERGY CONVERSION DIVISION

3-183
POWER DEGRADATION OF SILICONE-ENCAPSULATED SOLAR CELLS

<table>
<thead>
<tr>
<th>CELL TEST</th>
<th>CELL CONFIGURATION</th>
<th>I-V EFFICIENCY</th>
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</thead>
<tbody>
<tr>
<td>24-1</td>
<td>BARE</td>
<td>11.3%</td>
</tr>
<tr>
<td>-2</td>
<td>ENCAPSULATED</td>
<td>9.5</td>
</tr>
<tr>
<td>-3</td>
<td>DELAMINATED 90%</td>
<td>8.5</td>
</tr>
<tr>
<td>-4</td>
<td>WATER ADDED</td>
<td>9.1</td>
</tr>
<tr>
<td>-5</td>
<td>AGED 45 DAYS</td>
<td>8.2</td>
</tr>
<tr>
<td>25-1</td>
<td>BARE</td>
<td>11.0</td>
</tr>
<tr>
<td>-2</td>
<td>ENCAPSULATED</td>
<td>9.8</td>
</tr>
<tr>
<td>-3</td>
<td>DELAMINATED 25%</td>
<td>8.7</td>
</tr>
<tr>
<td>-4</td>
<td>WATER ADDED</td>
<td>9.6</td>
</tr>
<tr>
<td>-5</td>
<td>AGED 45 DAYS</td>
<td>8.9</td>
</tr>
</tbody>
</table>

ACCOMPLISHMENTS - JPL CONTRACT NO. 954458

- DEVELOPED MULTICONDITION ACCELERATED TEST METHOD FOR ENCAPSULANTS. COMPARED THIS WITH 45°S OUTDOOR, EMA AND EMAQUA.
- SHOWED FEASIBILITY OF HYPERACCELERATED UV EXPOSURE (1000 SUNS).
- CLEARLY SHOWED RELATIVE EFFECTS OF SUNLIGHT, TEMPERATURE, AND HUMIDITY. DETERMINED FAILURE MODES. CORRELATED RATES OF DEGRADATION FOR SIMILAR PROPERTIES.
- ESTABLISHED DEGRADATION MODELS FOR 20-YEAR PREDICTIONS.
- DEMONSTRATED THAT SOLAR CELLS ARE RELIABLE AND RESISTANT TO MOISTURE AND ENCAPSULANT DEGRADATION PRODUCTS PROVIDING METALLIZATION REMAINS INTACT.
ENCAPSULANT SYSTEM #7 (NITROCELLULOSE LACQUER ENCAPSULANT, EPOXY SUBSTRATE) AFTER 61 DAYS ACCELERATED EXPOSURE

NOTE: FRACTION OF ORIGINAL POWER IS SHOWN FOR EACH CELL.
COST SENSITIVITY TO ENCAPSULANT PERFORMANCE

MODULE COST ENCAP COST = 45¢/watt
RELIABILITY OF UNENCAPSULATED SOLAR CELLS
ENGINEERING AREA STUDY ACTIVITIES
(CONTRACT TO CLEMSON UNIVERSITY)

OBJECTIVES

o IDENTIFY LIFE-LIMITING FAILURE MECHANISMS AND FAILURE MODES.

o DETERMINE RELIABILITY ATTRIBUTES AND TIME-TO-FAILURE DISTRIBUTIONS.

o PROVIDE SPECIFICATION FOR ACCELERATED STRESS TESTING OF UN ENCAPSULATED SILICON SOLAR CELLS.

OTHER USEFUL RESULTS EXPECTED

o DATA TO SUPPORT DEVELOPMENT OF INTERIM FAILURE DEFINITION/FAILURE CRITERIA FOR SOLAR CELLS.

o DATA TO IMPROVE APPORTIONMENT/ALLOCATIONS OF MODULE RELIABILITY.

o DATA TO SUPPORT WHAT ENCAPSULATION PROTECTION IS NEEDED—MINIMUM REQUIREMENT.

ENCAPSULATION MATERIAL TRENDS FOR 1986

AN ASSESSMENT OF MATERIALS AND MATERIALS TECHNOLOGY FOR FABRICATING A $.25/ft² ENCAPSULATION SYSTEM

E. F. CUDDIHY
APRIL 12, 1978

5101-61 Supplement A.

3-188
MODULE DESIGN CONCEPTS
ENCAPSULATION TASK

DESIGN OPTIONS

1) SUBSTRATE BONDED
2) SUPERSTRATE BONDED
3) LAMINATED
   A) RIGID, SELF-SUPPORTING
   B) FLEXIBLE
      i) SUBSTRATE SUPPORTED
      ii) SUPERSTRATE SUPPORTED

CONSTRUCTION ELEMENTS

1) TRANSPARENT OUTER COVERS
2) TRANSPARENT POTTANTS
3) ADHESIVES
4) SUBSTRATE
5) TRANSPARENT SUPERSTRATE
6) SUPERSTRATE BACKSIDE POTTANTS AND/OR BACK COVERS

FLAT MODULE DESIGN CLASSIFICATIONS
ENCAPSULATION TASK

1) SUBSTRATE BONDED

2) SUPERSTRATE BONDED

3) LAMINATED
   A) RIGID
   B) FLEXIBLE
      i) SUBSTRATE SUPPORTED
      ii) SUPERSTRATE SUPPORTED

OUTERCOVER

TRANSPARENT POTTANT

ADHESIVE

STRUCTURAL SUBSTRATE

TRANSPARENT STRUCTURAL SUPERSTRATE

ADHESIVE

BACKSIDE POTTANT

BACK COVER

TRANSPARENT LAMINATING MATERIAL

LAMINATED CELLS

ADHESIVES

STRUCTURAL SUBSTRATE

TRANSPARENT STRUCTURAL SUPERSTRATE

ADHESIVES

LAMINATED CELLS

3-189
KNOW WEATHERABLE AND
TRANSPARENT MATERIALS
ENCAPSULATION TASK

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GLASS</td>
<td>• SODA-LIME WINDOW GLASS</td>
</tr>
<tr>
<td>• ACRYLICS</td>
<td>• PLEXIGLAS, LUCITE</td>
</tr>
<tr>
<td>• SILICONES</td>
<td>• SYLGARD 184, RTV 615</td>
</tr>
<tr>
<td>• FLUOROCARBONS AND HALOCARBONS</td>
<td>• TEDLAR, FEP, KEL-F RESINS</td>
</tr>
</tbody>
</table>

ECONOMICS OF MODULE FABRICATION WITH KNOWN WEATHERABLE AND TRANSPARENT MATERIALS ENCAPSULATION TASK

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>AS TRANSPARENT STRUCTURAL SUPERSTRATES</th>
<th>AS POTANTS ADHESIVES OUTER COVERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLASS</td>
<td>$0.29 TO $1.00/ft²</td>
<td></td>
</tr>
<tr>
<td>ACRYLICS</td>
<td>$1.77/ft²</td>
<td>≤$.01/ft² - mil</td>
</tr>
<tr>
<td>SILICONES</td>
<td>$45.00/ft²</td>
<td>$.02-.05/ft² - mil</td>
</tr>
<tr>
<td>FLUOROCARBONS HALOCARBONS</td>
<td>$12-$23/ft²</td>
<td>&gt;$.05/ft² - mil</td>
</tr>
</tbody>
</table>

3-190
SUBSTRATES/SUPERSTRATES
ENCAPSULATION TASK

MATERIAL CLASSES BEING SURVEYED

EXAMPLES

INORGANICS
CEMENT BOARDS, TILES, BRICKS, ETC.

PAPER PRODUCTS
KRAFT PAPER HONEYCOMBS, PRESSED PAPERBOARD PANELS, ETC.

WOOD PRODUCTS
PLYWOOD, HARDBOARD, PARTICLE BOARDS, ETC.

GLASS
SODA LIME GLASS, BOROSILICATES, ETC.

METALS
STEEL, ALUMINUM, ETC.

PLASTICS
GLASS-REINFORCED POLYESTER, PHENOLICS, ETC.

SUBSTRATES/SUPERSTRATES
ENCAPSULATION TASK

MATERIALS AND COSTS

INORGANICS, SURVEYS IN PROGRESS

PAPER PRODUCTS

- PAN-L BOARD, MEAD PAPERBOARD PRODUCTS, INC.
  WEATHERPROOFED AND WATERPROOFED, 17 YEARS OUTDOOR EXPOSURE IN WISCONSIN,
  24¢/ft²

- KRAFT PAPER HONEYCOMB, HEXCEL CORPORATION,
  9¢/ft²

- HOMASOTE, INC., PAPER PANEL
  13.6¢/ft²

WOOD PRODUCTS

- PLYWOOD, CLASS C, PLUGGED
  COST PER ft²

- MASONITE EXTERIOR HARDBOARD
  CCB  COMMERICAL

- PARTICLE BOARDS
  i) WAFER BOARDS
  ii) STRAND BOARDS
  iii) FLAKE BOARDS

3-191
SUBSTRATES/SUPERSTRATES
ENCAPSULATION TASK

MATERIALS AND COSTS

- GLASS
  SODA LIME GLASS $0.29/ft^2
  OTHERS $0.42/ft^2

- METALS
  MILD STEEL $0.42/ft^2
  ALUMINUM $1.15/ft^2
  STAINLESS STEEL $3.16/ft^2

- PLASTICS
  STRUCTURAL POLYPROPYLENE $0.49/ft^2
  POLY VINYL CHLORIDE EXT. PANEL $0.59/ft^2
  OTHERS $0.72 TO $4.08/ft^2

- TRANSPARENT PLASTICS
  PLEXIGLAS, LUCITE (ACRYLICS) $1.77/ft^2
  LEXAN (POLYCARBONATE) $3.41/ft^2

SUBSTRATES/SUPERSTRATES
ENCAPSULATION TASK

TENTATIVE CONCLUSIONS

- WOOD PRODUCTS AND PAPER PRODUCTS LOWEST-COSTING STRUCTURAL SUBSTRATE MATERIALS, INDUSTRIAL TECHNIQUES FOR WATERPROOFING AND WEATHERPROOFING EXIST

- SUPERSTRATE DESIGN EMPLOYING TRANSPARENT PLASTICS IS ECONOMICALLY UNATTRACTIVE, OPTION WITH GLASS IS STILL OPEN

SUBSTRATES/SUPERSTRATES
ENCAPSULATION TASK

DEVELOPMENTAL NEEDS

- HIGH STRENGTH TO WEIGHT RATIO PANEL DESIGNS FOR LOWER-COST UTILIZATION OF STRUCTURAL MATERIALS

EXAMPLE: CENTER REINFORCEMENT OF SUBSTRATE PANEL LOWERS THICKNESS REQUIREMENT AND PANEL COST BY A FACTOR OF 2.47, PAN-L BOARD COST BECOMES 10¢/ft

- WATERPROOFING AND WEATHERPROOFING OF WOOD PRODUCTS

3-192
ADHESIVES
ENCAPSULATION TASK

COST COMPARISON BASIS: COST PER ft² PER 5 mil GLUE LINE

- **FLUOROCARBONS** > 9-10¢
- **SILICONES** 9-10¢
- **ACRYLICS** 4¢
- **EPOXIES** ≤ 4¢
- **OTHERS** < 4¢

PARTIAL REQUIREMENTS: 100% ADHESIVE MATERIAL, NO VOLATILE
SOLVENT OR WATER CARRIER, NO GAS
PRODUCTS RELEASED DURING SET OR
DURING OUTDOOR SERVICE

TRANSPARENT POLYMERIC POTTANTS
ENCAPSULATION TASK

- **COST COMPARISON BASIS:** COST PER ft² PER mil
- **MODES OF OUTDOOR WEATHERING DEGRADATION**
  1) THERMAL OXIDATION
  2) HYDROLYSIS (WATER REACTIONS)
  3) UV REACTIONS
     a) UV PHOTOLYSIS
     b) UV PHOTO-OXIDATION
     c) UV PHOTO-HYDROLYSIS

- **SURVEY FOR TRANSPARENT MATERIALS WHICH ARE INHERENTLY
  WEATHERABLE, AND THOSE WHICH ARE SUSCEPTIBLE TO DEGRADATION
  FROM UV REACTIONS ONLY (ASSUMES THE USE OF A UV-SCREENING
  OUTER COVER)**

3-193
## TRANSPARENT POLYMERIC POTTANTS
### ENCAPSULATION TASK

#### CANDIDATE MATERIALS

<table>
<thead>
<tr>
<th>Weatherable with UV Protection</th>
<th>Material Cost</th>
<th>Module Cost</th>
<th>Maximum Thickness at $0.06/ft², mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETHYLENE VINYL ACETATE</td>
<td>$0.50</td>
<td>0.17</td>
<td>35</td>
</tr>
<tr>
<td>ETHYLENE ETHYL ACRYLATE</td>
<td>$0.48</td>
<td>0.18</td>
<td>33</td>
</tr>
<tr>
<td>Ionomer</td>
<td>$0.64</td>
<td>0.30</td>
<td>20</td>
</tr>
<tr>
<td>POLY VINYL CHLORIDE PLASTISOL</td>
<td>$0.60</td>
<td>0.33</td>
<td>18</td>
</tr>
</tbody>
</table>

### WEATHERABLE

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost</th>
<th>Module Cost</th>
<th>Maximum Thickness at $0.06/ft², mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACRYLICS</td>
<td>$1.50</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>SILICONE GELS</td>
<td>$3.75</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>SILICONE ELASTOMERS</td>
<td>$9.00</td>
<td>5</td>
<td>≈ 1</td>
</tr>
<tr>
<td>FLUOROCARBONS AND HALOCARBONS</td>
<td>$6.75 TO &gt;$20</td>
<td>&gt; 5</td>
<td>≤ 1</td>
</tr>
</tbody>
</table>

## TRANSPARENT OUTER COVERS
### ENCAPSULATION TASK

**COST COMPARISON BASIS:** COST PER ft² PER mil

**REQUIREMENTS:**
- TRANSPARENT
- INHERENTLY WEATHERABLE
- SOIL RESISTANT (MODULUS > 20,000 psi)
- UV ABSORBING

**MATERIAL CANDIDATES:**
- GLASS ≈ 0.3¢
- ACRYLICS ≈ 1¢
- SILICONES ≈ 5¢
- FLUOROCARBONS AND HALOCARBONS ≥ 5¢
SUMMARY FOR CONSIDERATION OF $0.25/ft^2 MATERIALS COST
ENCAPSULATION TASK

• SUBSTRATE DESIGN

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost/ft^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mil UV-ABSORBING OUTER COVER</td>
<td>$0.01</td>
</tr>
<tr>
<td>TRANSPARENT POTTANT</td>
<td>$0.06</td>
</tr>
<tr>
<td>ADHESIVES</td>
<td>$0.04</td>
</tr>
<tr>
<td>WOOD OR PAPER PRODUCT SUBSTRATE</td>
<td>$0.14</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$0.25</td>
</tr>
</tbody>
</table>

• SUPERSTRATE DESIGN

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost/ft^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSPARENToplastics</td>
<td>&gt;$1.77</td>
</tr>
<tr>
<td>GLASS</td>
<td></td>
</tr>
<tr>
<td>BACKSIDE POTTANT</td>
<td>$0.06</td>
</tr>
<tr>
<td>ADHESIVES</td>
<td>$0.04</td>
</tr>
<tr>
<td>WINDOW GLASS</td>
<td>$0.29</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$0.39</td>
</tr>
</tbody>
</table>

EXPERIMENTAL ASSESSMENT OF 1986 ENCAPSULANTS

OBJECTIVE:
ASSESS EXISTING LOW-COST SYSTEMS FOR MEETING 1986 COST AND PERFORMANCE GOALS

APPROACH:
DESIGN, FABRICATE, AND TEST A SPECTRUM OF ENCAPSULATION SYSTEMS AND PRESENT RESULTS AT 9th PIM

SCOPE:
1. DURING DECEMBER '77 - APRIL '78 DEFINED AND FABRICATED 18 SYSTEMS, 64 MODULES (9 CELL)
2. MATERIALS: GLASS, POLYMERS, METAL, WOOD, PAPER
3. COST $0.25 - $2.00/ft^2 (2.5¢ - 20¢/watt)
4. TEMPERATURE CYCLE (-40 TO +90 C) + HUMIDITY
5. ASSESS PERFORMANCE AND FUTURE POTENTIAL OF SYSTEMS
6. CONTINUE TEST EVALUATION OF PROMISING SYSTEMS

3-195
INTERIM ASSESSMENT: 1986 CANDIDATES

SUPERSTRATE CONFIGURATIONS (STRUCTURAL TRANSPARENCY)

<table>
<thead>
<tr>
<th>GLASS SUPERSTRATE</th>
<th>ADHESIVE</th>
<th>POTANT</th>
<th>BACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BOROSILICATE</td>
<td>ELECTRO-STATIC BOND</td>
<td>PVB</td>
<td>SL GLASS</td>
</tr>
<tr>
<td>2. BOROSILICATE</td>
<td>ESB</td>
<td>EPoxy</td>
<td>AL FOIL</td>
</tr>
<tr>
<td>3. BOROSILICATE</td>
<td>ESB</td>
<td>BUTYL</td>
<td>AL FOIL</td>
</tr>
<tr>
<td>4. SUNADEX TEMPERED</td>
<td>PVB</td>
<td>PVB</td>
<td>SL GLASS</td>
</tr>
<tr>
<td>5. SUNADEX</td>
<td>PVB</td>
<td>PVB</td>
<td>MYLAR</td>
</tr>
</tbody>
</table>

SUBSTRATE CONFIGURATIONS (STRUCTURAL BACK)

<table>
<thead>
<tr>
<th>COVER</th>
<th>POTANT</th>
<th>ADHESIVE</th>
<th>SUBSTRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ACRYLIC</td>
<td>S1 LGrip</td>
<td>POLYESTER/PG</td>
<td>ALUMINUM</td>
</tr>
<tr>
<td>2. SPRAYLON (FLUOROCARBON)</td>
<td></td>
<td></td>
<td>STEEL</td>
</tr>
<tr>
<td>3. ACRYLIC UV-FILM</td>
<td>EVA</td>
<td></td>
<td>STEEL</td>
</tr>
<tr>
<td>4. ACR-UV-FILM</td>
<td>Ionomer</td>
<td></td>
<td>THERMOPLASTIC</td>
</tr>
<tr>
<td>5. ACR-UV-FILM</td>
<td>PVC</td>
<td></td>
<td>WOOD</td>
</tr>
<tr>
<td>6. ACR-UV-FILM</td>
<td>ACRYLIC</td>
<td></td>
<td>THERMOSET</td>
</tr>
<tr>
<td>7. EVA</td>
<td>EVA</td>
<td>ACRYLIC</td>
<td>PAPER</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HONEYCOMB</td>
</tr>
</tbody>
</table>

NOTE:
- PVB - POLYVINYL BUTYRAL
- EVA - ETHYLENE VINYL ACETATE
- SL - SODA LIME GLASS
- PVC - POLYVINYL CHLORIDE
- ACR-UV - ACRYLIC-UV SCREEN

MAXIMUM CYCLE TIME

<table>
<thead>
<tr>
<th>TIME (h)</th>
<th>CELL TEMPERATURE (DEGREES C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-60</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>-60</td>
</tr>
</tbody>
</table>

CONDITION

<table>
<thead>
<tr>
<th>TIME (h)</th>
<th>CELL TEMPERATURE (DEGREES C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>1</td>
<td>40.5</td>
</tr>
<tr>
<td>2</td>
<td>23.5</td>
</tr>
<tr>
<td>3</td>
<td>40.5</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>40.5</td>
</tr>
<tr>
<td>6</td>
<td>23.5</td>
</tr>
</tbody>
</table>

PRE-DRY 50% RH 90 TO 95% RH
<table>
<thead>
<tr>
<th>Ident.</th>
<th>Encapsulation System</th>
<th>Material Cost per Sq. Ft.</th>
<th>Thermal Cycle Test (Fig. 1)</th>
<th>Humidity Cycle Test (Fig. 1)</th>
<th>Post Test Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-001</td>
<td>Potting - Ethylene Vinyl Acetate Substrate - Hardboard (Masonite)</td>
<td>$0.62</td>
<td>50 Cycles</td>
<td>Potting softened and flowed from module but cells remained covered. 168 hrs</td>
<td>No change in appearance due to humidity test. I-V curves showed no significant changes.</td>
</tr>
<tr>
<td>AE-006</td>
<td>Potting - Ethylene Vinyl Acetate Substrate - Kraft Honeycomb</td>
<td>$0.49</td>
<td>50 Cycles</td>
<td>Potting softened and flowed from module but cells remained covered. 168 hrs</td>
<td>Slight curling of honeycomb edges occurred. No significant changes in I-V curves.</td>
</tr>
<tr>
<td>AE-007</td>
<td>Potting - Polyvinyl chloride plastic Substrate - Hardboard (Masonite)</td>
<td>$0.74</td>
<td>25 Cycles</td>
<td>Potting had extensive delamination and cracking. 168 hrs</td>
<td>No run</td>
</tr>
<tr>
<td>AE-010</td>
<td>Potting - Polyvinyl chloride plastic Substrate - Kraft honeycomb</td>
<td>$0.65</td>
<td>25 Cycles</td>
<td>Potting had extensive delamination and cracking. Substrate curled at edges. Not run</td>
<td>Erratic I-V curves.</td>
</tr>
<tr>
<td>BC-002</td>
<td>Top cover - Flexigard Laminating Adhesive - (Sigratop 9 31) Bottom cover - Flexigard</td>
<td>$0.60</td>
<td>25 Cycles</td>
<td>Flexigard became distorted and cracked. 168 hrs</td>
<td>Very little changes due to humidity. Module should have been supported during thermal testing. No I-V curves obtained due to cracked cells.</td>
</tr>
<tr>
<td>BE-007</td>
<td>Coating - Acrylic Substrate - Polyester impregnated fiberglass</td>
<td>$0.83</td>
<td>25 Cycles</td>
<td>No noticeable changes. 168 hrs</td>
<td>Slight delamination and lifting of coating in 3 cells. Large variations in P_MAX occurred among the cell strings during all tests.</td>
</tr>
<tr>
<td>BE-009</td>
<td>Coating - Acrylic Substrate - Spray coal painted with a white acrylic coating</td>
<td>$0.25</td>
<td>25 Cycles</td>
<td>Substrate was badly distorted. 168 hrs</td>
<td>Coating was excellent. Substrate distorted. One string showed 11.3% loss in P_MAX but other 2 strings showed no change in I-V tests.</td>
</tr>
<tr>
<td>BE-010</td>
<td>Coating - Acrylic Substrate - Styrene-Acrylonitrile painted with a white acrylic coating</td>
<td>$0.25</td>
<td>25 Cycles</td>
<td>Substrate was very slightly distorted. 168 hrs</td>
<td>Coating was excellent. One string showed 11.1% loss in P_MAX in humidity test but remaining 2 strings were excellent.</td>
</tr>
<tr>
<td>CE-001</td>
<td>Superstrate - Glass (Bunredo) Potting - Polyvinyl Butyral Back cover - Polyvinyl film (0.005&quot;)</td>
<td>$1.36</td>
<td>50 Cycles</td>
<td>No apparent changes. 168 hrs</td>
<td>Thermal and humidity tests caused no apparent changes in either appearance or I-V curves.</td>
</tr>
<tr>
<td>CE-006</td>
<td>Superstrate - Glass (Bunredo) Potting - Polyvinyl Butyral Substrate - Glass (K-light)</td>
<td>$1.59</td>
<td>50 Cycles</td>
<td>No apparent changes 168 hrs</td>
<td>Same results as shown above for CE-001 and 002.</td>
</tr>
<tr>
<td>DE-001</td>
<td>Cover Film - Acrylic (.0015&quot;) Potting - Polyvinyl chloride plastic Substrate - Water based</td>
<td>$0.51</td>
<td>25 Cycles</td>
<td>Film had slight brownish color. No other changes in appearance. 168 hrs</td>
<td>Very slight flow of potting under acrylic film. One string was run after thermal test and a second string was open after humidity test.</td>
</tr>
<tr>
<td>DE-003</td>
<td>Cover Film - Acrylic (.0015&quot;) Potting - Epoxy Primer Substrate - PVC panel board</td>
<td>$0.59</td>
<td>25 Cycles</td>
<td>Very bad distortion of substrate causing cracking of cells. Not run</td>
<td>I-V tests were not run due to extensive cracking of cells. Potting also delaminated from substrate.</td>
</tr>
<tr>
<td>DE-005</td>
<td>Cover Film - Acrylic (.0015&quot;) Potting - Acrylic compound Substrate - Phenol formal board</td>
<td>$0.70</td>
<td>25 Cycles</td>
<td>Potting flowed and became very sticky during thermal testing. 168 hrs</td>
<td>Potting was still sticky. I-V curves were very erratic as packing material had adhered to the potting and could not be removed.</td>
</tr>
<tr>
<td>DE-007</td>
<td>Cover Film - Acrylic (.0015&quot;) Potting - Epoxy Vinyl acetate Substrate - Galvanized steel</td>
<td>$0.75</td>
<td>25 Cycles</td>
<td>Potting turned slightly yellow and flowed under the acrylic film. 168 hrs</td>
<td>I-V curves showed no significant changes after the thermal and humidity tests.</td>
</tr>
<tr>
<td>JE-002</td>
<td>Superstrate - Borosilicate glass electronically bonded Potting - Butyl rubber Backing - Aluminum foil</td>
<td>$0.47</td>
<td>50 Cycles</td>
<td>No change in appearance or in I-V curves. 168 hrs</td>
<td>No change in appearance or in I-V curves.</td>
</tr>
<tr>
<td>SE-001</td>
<td>Superstrate and Substrate - Borosilicate glass electronically bonded to the cell.</td>
<td>$0.70</td>
<td>50 Cycles</td>
<td>No change in appearance or in I-V curves. 168 hrs</td>
<td>No change in appearance or in I-V curves.</td>
</tr>
<tr>
<td>SE-002</td>
<td>Superstrate - Borosilicate glass ESB to cells. Substrate - Soda-lime glass Potting - Polyvinyl butyral</td>
<td>$1.45</td>
<td>50 Cycles</td>
<td>No change in appearance or in I-V curves. 168 hrs</td>
<td>No change in appearance or in I-V curves.</td>
</tr>
<tr>
<td>TE-001</td>
<td>Coating - Spraylon Substrate - Aluminum</td>
<td>$2.67</td>
<td>50 Cycles</td>
<td>Extensive delamination of coating and cracking of cells. Coating adhered to the substrate. Not run</td>
<td>I-V curves could not be run due to cracking of cells.</td>
</tr>
</tbody>
</table>
# ACRYLIC/STYRENE-ACRYLONITRILE

<table>
<thead>
<tr>
<th>ORIGINAL VALUES</th>
<th>AFTER 50 THERMAL CYCLES</th>
<th>AFTER HUMIDITY TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{MAX}}$</td>
<td>$I_{\text{SC}}$</td>
<td>$V_{\text{OC}}$</td>
</tr>
<tr>
<td>BE-010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO. 1</td>
<td>1.50</td>
<td>1.151</td>
</tr>
<tr>
<td>NO. 2</td>
<td>1.48</td>
<td>1.143</td>
</tr>
<tr>
<td>NO. 3</td>
<td>1.53</td>
<td>1.159</td>
</tr>
</tbody>
</table>

**MODULE INFORMATION**

Module contained 3 strings of 3 cells each. Thermal and humidity tests had very little effect on the module.

**NOTES**

1. $I_{\text{SC}}$ is in milliamperes. $V_{\text{OC}}$ is in millivolts.
2. Percent changes after thermal and humidity testing are from original values.

# POLYVINYL CHLORIDE/PARTICLE BOARD

<table>
<thead>
<tr>
<th>ORIGINAL VALUES</th>
<th>AFTER 50 THERMAL CYCLES</th>
<th>AFTER HUMIDITY TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{MAX}}$</td>
<td>$I_{\text{SC}}$</td>
<td>$V_{\text{OC}}$</td>
</tr>
<tr>
<td>DE-001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO. 1</td>
<td>1.74</td>
<td>1.587</td>
</tr>
<tr>
<td>NO. 2</td>
<td>1.85</td>
<td>1.573</td>
</tr>
<tr>
<td>NO. 3</td>
<td>1.77</td>
<td>1.595</td>
</tr>
<tr>
<td>DE-002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO. 1</td>
<td>1.76</td>
<td>1.592</td>
</tr>
<tr>
<td>NO. 2</td>
<td>1.79</td>
<td>1.601</td>
</tr>
<tr>
<td>NO. 3</td>
<td>1.75</td>
<td>1.541</td>
</tr>
</tbody>
</table>

**MODULE INFORMATION**

Module contained 3 strings of 3 cells each.

**NOTES**

1. $I_{\text{SC}}$ is in milliamperes. $V_{\text{OC}}$ is in millivolts.
2. Percent changes after thermal and humidity testing are from original values.
## GLASS/POLYVINYL BUTYRAL/MYLAR

<table>
<thead>
<tr>
<th>Original Values</th>
<th>After 50 Thermal Cycles</th>
<th>After Humidity Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{MAX}}$</td>
<td>$I_{\text{SC}}$</td>
<td>$V_{\text{OC}}$</td>
</tr>
<tr>
<td>CE-001</td>
<td>3.73</td>
<td>3.44</td>
</tr>
<tr>
<td>CE-002</td>
<td>3.75</td>
<td>3.48</td>
</tr>
</tbody>
</table>

### Module Information

No apparent physical deterioration occurred as a result of the thermal and humidity tests.

### Notes

1. $I_{\text{SC}}$ is in milliamps. $V_{\text{OC}}$ is in millivolts.
2. Percent changes after thermal and humidity testing are from original values.

## ETHYLENE VINYL ACETATE/KRAFTHONEYCOMB

<table>
<thead>
<tr>
<th>Original Values</th>
<th>After 50 Thermal Cycles</th>
<th>After Humidity Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{MAX}}$</td>
<td>$I_{\text{SC}}$</td>
<td>$V_{\text{OC}}$</td>
</tr>
<tr>
<td>AE-006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>1.29</td>
<td>1.213</td>
</tr>
<tr>
<td>No. 2</td>
<td>1.42</td>
<td>1.219</td>
</tr>
<tr>
<td>No. 3</td>
<td>OPEN CIRCUIT</td>
<td>-</td>
</tr>
</tbody>
</table>

### Module Information

Module contained 3 strings of 3 cells each.

### Notes

1. $I_{\text{SC}}$ is in milliamps. $V_{\text{OC}}$ is in millivolts.
2. Percent changes after thermal and humidity testing are from original values.
POLYVINYL CHLORIDE PLASTISOL/HARDBOARD

ORIGINAL VALUES

<table>
<thead>
<tr>
<th>MODULE</th>
<th>( P_{\text{MAX}} )</th>
<th>( I_{\text{SC}} )</th>
<th>( V_{\text{OC}} )</th>
<th>( P_{\text{MAX}} )</th>
<th>( P_{\text{MAX}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-007</td>
<td>1.45</td>
<td>1.138</td>
<td>1.80</td>
<td>0.08</td>
<td>-25.5%</td>
</tr>
<tr>
<td>NO. 1</td>
<td>1.34</td>
<td>1.038</td>
<td>1.76</td>
<td>1.03</td>
<td>-23.1%</td>
</tr>
<tr>
<td>NO. 2</td>
<td>1.46</td>
<td>1.141</td>
<td>1.81</td>
<td>OPEN CIRCUIT</td>
<td></td>
</tr>
<tr>
<td>NO. 3</td>
<td>1.47</td>
<td>1.13</td>
<td>1.83</td>
<td>1.16</td>
<td>-24.1%</td>
</tr>
</tbody>
</table>

NOMINAL VALUES AFTER 50 THERMAL CYCLES AFTER HUMIDITY TEST

NOTES

1. \( I_{\text{SC}} \) IS IN MILLIAMPS. \( V_{\text{OC}} \) IS IN MILLIVOLTS.
2. PERCENT CHANGES AFTER THERMAL AND HUMIDITY TESTING ARE FROM ORIGINAL VALUES.

ELECTROSTATIC BONDING/BUTYL RUBBER/ALUM. FOIL

ORIGINAL VALUES

<table>
<thead>
<tr>
<th>MODULE</th>
<th>( P_{\text{MAX}} )</th>
<th>( I_{\text{SC}} )</th>
<th>( V_{\text{OC}} )</th>
<th>( P_{\text{MAX}} )</th>
<th>( P_{\text{MAX}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>JE-003</td>
<td>0.987</td>
<td>0.635</td>
<td>2.23</td>
<td>1.00</td>
<td>+1.3%</td>
</tr>
</tbody>
</table>

NOMINAL VALUES AFTER 50 THERMAL CYCLES AFTER HUMIDITY TEST

NOTES

1. \( I_{\text{SC}} \) IS IN MILLIAMPS. \( V_{\text{OC}} \) IS IN MILLIVOLTS.
2. PERCENT CHANGES AFTER THERMAL AND HUMIDITY TESTING ARE FROM ORIGINAL VALUES.
ENCAPSULATION ASSESSMENT
ETHYLENE VINYL ACETATE / KRAFT HONEYCOMB

Before Test...

Encapsulation System

- Plant: Ethylene Vinyl Acetate
- Cell Adhesive: Acrylic film contact adhesive
- Substrate: Waterproof Kraft honeycomb

Fabrication Method: Contact adhesive is applied to honeycomb. Cells are pressed into place. EVA pillars are melted over the cells at 365°F in vacuum oven.

Post-Test Evaluation

- Determination: None
- Appearance: Excellent. Slight curving of honeycomb edges
- Effect on cells: Interconnects exposed on some cells due to flow of coating
- I.V. Results: One string of cells was open circuit when received and remained that way
- Miscellaneous Effects: Plant melted and flowed during thermal test

After Temperature Cycling and Humidity Test...

Thermal Cycle Test... Humidity Cycle Test

AE-006

AE-006

Before and After
ENCAPSULATION ASSESSMENT
POLYVINYL CHLORIDE PLASTISOL / WAfer BOARD

Before Test . . .

Encapsulation System

Cover Film — Acrylic (.005 in.)
Potent — Polyvinyl chloride plastisol
Cell Adhesive — PVC
Substrate — Wafer board

Fabrication Method — Cells are adhered to board and coated with PVC plastisol. Potent is cured in vacuum oven at 300 F for one hour. Potent is coated and acrylic film applied over it.

After Temperature Cycling and Humidity Test . . .

Post-Test Evaluation

Delamination — None
Appearance — Film has slight brownish color
Effect on cells — None
I.R. Results — One string was open circuit after thermal test and a second string was open after humidity test
Miscellaneous Effects — Very slight flow of potent under acrylic film

Before and After

Thermal Cycle Test . . . Humidity Cycle Test . . .
TASK STATUS

MATERIALS AND PROCESS PROBLEMS
- UNKNOWN PERFORMANCE
- HIGH COST
- AUTOMATED PROCESSING
- UNKNOWN EFFECT OF MOISTURE, UV, ETC.

LIFE TESTING & MODELING PROBLEMS
- LIFE DEFINITION
- UNKNOWN FAILURE MODES
- UNKNOWN AGING RATES
- TEST METHODS NOT DEFINED
- INSTRUMENTATION NOT DEVELOPED
- ANALYSIS METHODOLOGY NOT AVAILABLE

76 77 78 79 80
SCREEN AND RANK MATERIALS IDENTIFY CANDIDATES
NOVEL PROCESS DEMO (ESB, ION PLATE)
CANDIDATE PROCESSES IDENTIFIED
TEST AND ANALYSIS METHOD EVALUATION
ACCELERATED TEST METHODS RANKED
AGING MECHANISMS DEFINED
AGING RATES FOR ACRYLICS AND SILICONES
LIFE PREDICTION METHOD

ANTICIPATED STATUS - September 1978

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MATERIALS AND PROCESSES
- PERFORMANCE OF LOW-COST: 2.5x - 10x with prototype systems
- ELECTROSTATIC BONDING: ECONOMIC VIABILITY
- ION-PLATING PROCESS EVALUATION
- NEW SILICONE MATERIAL SYSTEMS: EVALUATION
- PRODUCTION PROCESSES IDENTIFIED FOR FURTHER DEVELOPMENT

LIFE PREDICTION
- NEBRASKA ARRAY LIFE TEST PLAN IMPLEMENTED
- EFFECTIVENESS OF UV AGENTS EVALUATED
- MOST PROMISING INSTRUMENTATION AND TECHNIQUES APPLICABLE TO MODULE WILL BE DEMONSTRATED
- PHOTODEGRADATION RATES FOR SELECTED MATERIALS (SILICONES, ACRYLICS, PVB)
- COMPLETED INITIAL ASSESSMENT: MODULE PERFORMANCE RELATED TO AGING MECHANISMS.
ENCAPSULATION HIGHLIGHTS

1. REPORTS AVAILABLE - CONTRACTOR AND LSA/JPL
2. LOW COST SYSTEMS 2.5¢ - 10¢/watt IDENTIFIED
3. PHOTODEGRADATION PROCESSES AND FAILURES CHARACTERIZED
4. ACCELERATED TESTING CRITERIA DEVELOPED
5. ELECTROSTATIC BONDING PROCESS EQUIPMENT DEVELOPED
6. ELECTROSTATIC BONDED MODULES PASS RUGGEDNESS TESTS
7. NOVEL MATERIALS AND PROCESSES IDENTIFIED; BEING ASSESSED
8. DIAGNOSTIC METHODS IDENTIFIED AND ASSESSED
9. EXPERIMENTAL ASSESSMENT OF 1986 CANDIDATES
10. ECONOMICS OF LOW-COST SYSTEMS

IN CONCLUSION

1. 2.5¢ - 10¢ ENCAPSULATION SYSTEMS ARE FEASIBLE AND COST EFFECTIVE
2. OPTIMUM DESIGN APPROACHES NOT OBVIOUS YET
3. MULTIPLE MATERIAL SYSTEM CONCEPTS WILL FILL SPECIFIC SITE REQUIREMENTS
4. LIFE LIMITING FAILURE MODES AND RATES WILL BE PREDICTED

1. TAILORED MATERIALS AND PROCESSES
2. MULTI-MATERIAL LOW-COST ENCAPSULANT SYSTEMS
3. PROGRAMMED ACCELERATED LIFE TESTING AND DIAGNOSTICS
4. PHOTO DEGRADATION RATE STUDIES
5. LIFE PREDICTION MODEL
D. AUTOMATED ARRAY ASSEMBLY TASK

An Ion Implantation discussion for solar cell production was presented at the Project Integration Meeting by SPIRE Corporation on Wednesday, April 12. Discussed at the symposium were the theory of ion implantation, the advantages of ion implantation in solar cell junction formation, the advantages of pulsed energy processes for post implant anneal, the performance of ion implanted cells and the design of commercially available equipment and equipment design for mass volume production lines.

Best results to date for post implant wafer anneal has been in a conventional furnace at 550°C for two hours, followed by 15 minutes at 850°C and two hours at 550°C. However, pulsed energy anneals (laser, electron beam) were considered potentially superior because of better epitaxial regrowth, and shorter anneal times that were more compatible with automation. The electron beam anneal pulse duration is just a fraction of a microsecond, but needs more development to increase its diameter from 2.5 inches, and to improve its repetition rate. Scan problems still limited the use of lasers.

SPIRE process specifications were distributed for the manufacture of the 76mm diameter cells that measured 16% AM1 efficiency at JPL. The ion implanted N+P+P+ cells had the 4 1/4 hour furnace anneal and had a newly designed Starburst grid pattern with Cr Au Ag metallization. Glass photolithographic masks for the grid pattern were also distributed.

A new ion implanter system manufactured solely for processing solar cells is now in operation. The system has continuous feed with a 300 wafer per hour throughput. Wafers are rotated during the five second implant dose interval (31p+) to accommodate texturized surfaces. High current levels at low energy levels permit the formation of shallow junctions (e.g., 4.2 mA of 31p+ at 10 keV). The system has a capability of processing (10)^6 peak watts annually.

The design of an implanter system that could process (10)^8 peak watts annually also was described. A minimum ion beam current of 100 mA at 31p+ at 10-30 keV would accommodate a variety of materials within 20 x 20 cm platens to ion implant at a rate of 500 cm^2/sec.

Also described were cells tested at 10% AM1 efficiency that didn't have conventional grid patterns or metallization. Silver screen mesh that was placed between a solar cell wafer and borosilicate glass, before electrostatic bond of glass-to-wafer, served both as the cell grid and metallization. A conceptual automated production line was discussed that would ion implant junctions, electron beam anneal the implant, and electrostatically bond cells into assembled modules.

Solar Cell Metallization was discussed by four Task IV contractors: Motorola, RCA, Solarex, and Spectrolab. Thick film printing systems developed for use on ceramics use binders which require oxidizing atmosphere, have copper thick films which suffer from an oxidizing atmosphere, and require high temperatures to give best results. Solar cells require
ohmic contact with shallow junction shunting unique to solar cells. The most promising results will probably come from dopant type frits (antimony). Many variables are involved:

1. Metal transferred by going into solution with molten frit.
2. Metal particle size and shape.
3. Proportion of frit to metal.
4. Firing time and temperature.

The costs still need reduction. The cost is presently 3¢ per watt to 6¢ per watt for one side of a wafer.

In the electroless plating of nickel, firing is required in order to bond to silicon. The firing of the nickel threatens the junction. Palladium, however, forms a barrier layer which is stable over a reasonably wide temperature range, but palladium is expensive (approximately 7¢ per watt). The masking of the solar cell surface during electroless nickel plating requires a durable coating.

Solder coating is necessary to reduce series resistance, with an attendant solder cost of 2¢ to 3¢ per watt.

The following pages are copies of the viewgraphs used in the presentations.
PHASE 2 - ARRAY AUTOMATED ASSEMBLY TASK
LSA - PROJECT

SOLAREX PROCESS SEQUENCE SUGGESTED FOR AUTOMATION.

STARTING MATERIAL
SURFACE PREPARATION
△ JUNCTION FORMATION

ETCH CLEAN
△ METALLIZATION

EDGE REMOVAL
WAFER TESTING
△ INTERCONNECTION & ENCAPSULATION

4" CZ WAFFER, (100)
CHEMICAL ETCHING AND TEXTURING
DOPANT DIP, DIFFUSE, ETC
OFF GLASS, DOPANT SPRAY, ALLOY
BUFFERED HF,
NEGATIVE SILKSCREEN
ELECTROLESS NICKEL PLATING
SOLDER DIPPING
MECHANICAL, LASER SCRIBING
TAB WELDING, SOLDER REFLUXING,
ACRYLIC ENCAPSULATION, BACK PROTECTION
METALLIZATION STEP

INNOVATIVE TECHNOLOGY REQUIRED TO PRODUCE THE FRONT ELECTRODES IN AN AUTOMATED PROCESS.

AMONGST ALL METALLIZATION TECHNIQUES LISTED IN PHASE 1 WE CONSIDER A SILKSCREENING PROCESS MOST VIALBE AND ECONOMIC FOR FUTURE AUTOMATION.

HOWEVER, CONVENTIONAL INKS RATHER EXPENSIVE AS A RESULT OF THEIR COMPLEXITY AND THE FACT THAT THEY CONTAIN PRECIOUS METALS SUCH AS SILVER.

ALSO, CONVENTIONAL INKS NEED TO BE FIRED AT HIGH TEMPERATURE AFTER SCREENING.

IN VIEW OF THESE SITUATIONS, SOLAREX PROPOSES A VARIATION OF THE CONVENTIONAL SILKSCREENING PROCESS AND ADDITIONAL TECHNOLOGIES FOR ELECTRODE PATTERN FORMATION.
METALLIZATION STEP

CONSISTING OF:

- NEGATIVE SILKSCREEN FOR PATTERN PREPARATION
- ELECTROLESS NICKEL PLATING FOR PATTERN FORMATION
- SOLDER DIPPING FOR PATTERN ENFORCEMENT

INPUT TO METALLIZATION STEP:

4" CZ WAFERS, CLEAN SURFACES, DRY

FRONT SURFACE IS TEXTURED

BACK SURFACE IS ALUMINIZED.
NEGATIVE SILKSCREENING

ART OF SILKSCREENING

• BASICALLY AN EXTRUSION PROCESS WHEREBY INK IS FORCE THROUGH A FINE MESH SCREEN USING A RUBBER SQUEEgee.

• SCREEN IS POSITIONED SLIGHTLY ABOVE SUBSTRATE SO THAT IT ONLY CONTACTS SUBSTRATE WHEN SQUEEgee PASSES OVER.

• SCREEN MATERIAL IS NOW EITHER SYNTHETIC FIBER WAS STAINLESS STEEL.

• PATTERN IS GENERATED ON SCREEN IN PROCESS SIMILAR TO PHOTOLITHOGRAPHY USING PHOTOSENSITIVE LIQUID WHICH SOLIDIFIES, LIGHT-EXPOSED AREAS AFTER DEVELOPING CAN BE WASHED CLEAR ON SCREEN.

• LINE DEFINITION CONTROLLED BY:

  SCREEN MESH SIZE
  INK VISCOSITY
  SHARPNESS OF SCREEN PATTERN

• PRINTING IS FASTEST WHEN DONE WITH A THIXOTROPIC INK, I.E., INK WHICH LIQUEFIES UNDER EXTERNAL FORCE BUT HARDENS WHEN SCREEN SEPARATES FROM THE SUBSTRATE.

• STROKE OF SQUEEgee IMPORTANT WITH RESPECT TO BLADE ANGLE, PRESSURE AND SPEED.
NEGATIVE SILKSCREENING:

- Those wafer areas which are not supposed to be metallized are covered with a low cost masking ink by means of a silkscreen process.

- Screens are currently made from polyester fiber, 100 mesh, stainless steel, 400 mesh, on order.

- Emulsion, which forms pattern on screen is soluble only to water: PVA polyvinylacetate.

- Standard SOLAREX 4" chevron pattern, smallest line width 3 mil.

- Spacing between screen and wafer: 1/16".

- Inks: Inexpensive, water resistant, soluble in organic agents, must be able to withstand solution with pH 8-9 at 95°C for 10 minutes.
INKS TRIED:

1. **CROWN 6004, KLEER ROTE (ACRYLIC) DOES NOT HOLD UP WELL TO TEMP OF Ni-SOLUTION BATH.**

2. **KRYLON 1505, HIGH HEAT WHITE, CONTAINS TiO₂, Mg - SILICATE ETC., HOLDS UP IN Ni-SOLUTION, SCREENS WITH GOOD ACUITY, DOES NOT CONTAMINATE Ni-SOLUTION.**

   HOWEVER, DRIES TOO QUICKLY, CLOSES THE SCREEN, VISCOSITY PROBLEM, CARRIER MIGRATES ON WAFER.

3. **KRYLON 1501, STANDARD SPRAY PAINT FROM HARDWARE STORE, DOES NOT HOLD UP IN Ni-SOLUTION.**

4. **PACTRA SM60D, HOBBY PAINT, STANDS UP TO PLATING SOLUTION, DOES NOT SCREEN WELL, CARRIER MIGRATION PROBLEM.**

5. **NAZ-DAR, SILK SCREEN INK, CONTAINS PETROLEUM DISTILLATES, MINERAL SPIRITS, SOFTENS BADLY IN Ni-SOLUTION.**

6. **EPOXY INK, 2 PART INK, NOT RIGHT VISCOSITY, NO RESISTANCE TO Ni-SOLUTION.**
**7. URETHANE VARNISH - WORKS WELL**

ADDED TiO₂ FOR HIGHER VISCOSITY, MAKES INK PRACTICALLY
THIXOTROPIC, STANDS UP TO Ni-SOLUTION AND HIGH TEMPERATURE, CAN BE STRIPPED BY ORGANIC SOLVENTS. APPEARS TO
BE THE LEAST EXPENSIVE INK FOR NEGATIVE SILKSCREENING.

**AFTER THE SCREENING PROCESS THE WAFER IS HEATED TO
90°C FOR ABOUT 10 MINUTES TO DRY THE INK AND HARDEN
IT. THIS IS FOLLOWED BY A SHORT HF DIP (1:20 HF, 10
SECONDS, AMBIENT TEMPERATURE) TO OPEN UP ALL RESIDUES
AND CLEAN THE EXPOSED Si-SURFACES FOR THE FOLLOWING
Ni-PLATING STEP.**
ELECTROLESS NICKEL PLATING

To form the electrode pattern on the exposed silicon surface a thin film of nickel is deposited.

Nickel is contained in specifically formulated solution.

Plating of the nickel to the bare silicon surface occurs at elevated temperatures without the use of electrical plating equipment.

Wafer is simply dipped into solution for a specified length of time.

Solutions tried are:

Sel-Rex Electroless #11250
J. E. Halma Co. #139-500011-71
SIL-REX was tried at the full range of recommended temperatures (85°C - 95°C) and pH-levels (5.5 - 6.0). Plating occurred only when the silicon surface was made cathodic with an electric current. This means that the plating process depends on the current density distribution on the silicon surface, an unacceptable restraint for future automation.

Very good results are achieved with: J.E. HAMMA Co., plating solution #139-500011-71. Plating occurred as soon as the clean wafers were immersed.

The commercial solution is heated to 90°C - 95°C and its pH adjusted to 8 by means of ammonium hydroxide. When the solution reaches 93°C - 95°C additional heat input does not increase the temperature but causes evolution of ammonia vapor which can subsequently be condensed and returned to the bath.

Under operating conditions:

Plating time is 5 minutes
Film thickness .6µ

Film thickness control critical, nickel is stiff and strong.

Thick layers do not adhere well.
THIN LAYERS MAY BE LOST IN SUBSEQUENT OXYDATION PROCESSES.

NICKEL PLATING PROCESS SENSITIVE TO ORGANIC RESIDUES. PLATING PROCESS WORKS BUT LEADS TO DISCOLORATION AND REDUCED SOLDER ADHESION.

AFTER PLATING WAFER IS RINSED IN TAP WATER TO RINSE THE NICKEL SOLUTION OFF. THIS RINSE-OFF SHOULD BECOME RECYCLED IN LARGE SCALE PRODUCTION ENVIRONMENTS.

ORGANIC MASK IS THEN WASHED OFF IN ORGANIC SOLVENTS (MINERAL SPIRITS, ETHANOL), AND SINTERED IN INERT (N₂) ATMOSPHERE AT 500°C FOR 1.7 - 2 MINUTES. BEST CONDITIONS TO INSURE ADHESION AND MINIMIZE OXIDE BUILD-UP.

20 MINUTE SOAK IN STRAIGHT AMMONIUM HYDROXIDE TO TAKE OFF ANY NiO₂.

AMMONIUM HYDROXIDE ACTS ALSO AS FLUX FOR SUBSEQUENT SOLDER DIPPING.
SOLDER DIPPING

USED TO ENFORCE THE GRID PATTERN CONSISTING OF THIN NICKEL FILM.

SOLDER DIPPING WIDELY USED IN MANUFACTURE OF CIRCUIT BOARDS, ESTABLISHED TECHNOLOGY.

HOWEVER, WE STILL HAVE PROBLEMS WITH OUR LABORATORY SET-UP.

SO FAR WE USED 60 Sn - 40 Pb SOLDER ONLY AT 200°C.

THE THICK OXIDE LAYER ON TOP OF THE MOLTEN SOLDER IS TROUBLESOME. THE OXIDE IS THE FIRST MATERIAL TO CONTACT THE NICKEL AND PREVENTS THE SOLDER TO COAT EVENLY.

WE THINK WE CAN SOLVE THE PROBLEMS BY USING THE RIGHT FLUX.

SO FAR WE TRIED THE FOLLOWING FLUXES WITH ONLY MODERATE SUCCESS:
- HALMA CLEANER LC 139-50168513
- HARRIS Ag SOLDER FLUX 1:0  
  1:10
- CRAFTSMAN FLUX ZINC & AMMONIUM CHLORIDE
- KESTER FLUX FORMULA 415
- HCl, AMBIENT TEMPERATURE
- HCl, HOT

WE ARE ALSO LOOKING INTO THE EFFECT OF FLOW SOLDERING MACHINES AND WAVE SOLDERING MACHINES.

IN ADDITION, OXIDE LAYER ON NICKEL FILM FORMED DURING SINTERING AND IF PHOSPHOROUS CONTENT OF NICKEL BATH IS TOO HIGH SOLDIER STICKS LESS WELL TO THE NICKEL FILM.

ALSO, ROOM TEMPERATURE WAFER CRACK OCCASIONALLY WHEN SUDDENLY DIPPED INTO 200°C NICKEL BATH.

WAFER PREHEAT AVOIDS THIS PROBLEM.
ECONOMIC ANALYSIS (PRELIMINARY)

SILK SCREENING

AUTOMATIC SILKSCREEN MACHINE $10 K - $20 K

ADDITIONAL COST FOR WAFER HANDLING EQUIPMENT, THUS

ENTIRE COST ABOUT $50 K, @ 3 YEAR OPERATING LIFE

AT 120 WAFERS/MINUTE IMPLIES

EQUIPMENT: 0.03¢ PER WAFER

STAINLESS STEEL SCREEN $25.00

SCREEN LASTS 5 FIVE MASK CYCLES, 1000 PRINTINGS

PER MASK CYCLE, 12 WAFERS EACH PRINTING.

MASK REMAKING 0.125¢/WAFER

SCREEN 0.042¢/WAFER

0.167¢/WAFER

INK, URETHANE VARNISH, $8.00 PER LITER, GOOD FOR

100 WAFERS,

THUS 0.8¢/WAFER
MUSCLE PLATING

COST OF EQUIPMENT $100 K/FIVE YEARS OF OPERATING LIFE.

THROUGHPUT: 120 WAFERS PER MINUTE

RESIDENT TIME: 10 - 15 MINUTES MAXIMUM

EQUIPMENT COST: 0.04¢/WAFER

PLATING SOLUTION COSTS $1.20/LITER

1 LITER PLATES 500 4" DIAMETER WAFERS

THUS: PLATING SOLUTION 0.24¢/WAFER

ACETONE FOR INK REMOVAL 0.1¢/WAFER

INSTEAD OF ACETONE ANOTHER CLEANING FLUID WHICH CAN BE RECYCLED, SUCH AS CHLOROETHANE COULD BE USED.
SOLDER DIPPING

EQUIPMENT ESTIMATED  $50 K
WAFER COST LOADING ESTIMATED  0.04¢/WAFER
SOLDER COSTS  18¢/cm³, GOOD FOR 6 WAFERS
THUS SOLDER COST IS  3.0¢/WAFER

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<td><strong>TOTAL</strong></td>
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EFFECT OF PASTE FIRING TIME ON I-E CURVE
SCHEMATIC

EFFECT OF PASTE FIRING TIME ON SOLAR CELL MODEL PARAMETERS
SCHEMATIC

MATERIAL: COMMERCIAL SILVER PASTES WITH MODIFICATIONS

SOLAR CELL MADE WITH SCREEN PRINTED AC PASTE
FIRED APPROXIMATELY EIGHT MINUTES
AT 650°C

LOT 1100-02-75
2" DIA.
NO AIR

EFFECT OF FIRING TIME AT 650°C ON CURVE SHAPE, PASTE B

VOLTAGE (VOLTS)

I-V CURVE SCHEMATIC

TIME

T1

T2

T3

SHUNT RESISTANCE

TIME

SERIES RESISTANCE

4-19
EVALUATION MATRIX, FRONT CONTACT METALLIZATION

PASTE: DuPONT 7095
I@50 - mA

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COMMERCIAL AG PASTES EVALUATED FOR USE AS COLLECTOR METALLIZATION

AVX .............................. 6080
CERMALLOY .......................... 4450
DUPONT ........................... 7095*
................................. 7713
................................. 8032
ELECTROMATERIALS ................. AG-6058-1
................................... AG-92*
ELECTROSCIENCE LAB ............... 590*
ENGLERHARD ......................... E-439-A/B^o/C
................................... A2735
................................... A2921 (MOD. 025)*
................................... A3233
METHODE DEV. CO ................... 3521
................................... 3522
PLESSEY .......................... L15-1260-T1
THICK FILM SYSTEMS ............... A250 (FRITLESS)
................................... A256*
................................... A268
................................... A3330
TRANSENE ........................ 100
................................... 200
IMPROVEMENT OF CURVE SHAPE
BY REDUCING FRIT CONTENT
OF PASTE

- 40 CERAMALLOY 4450
- 60 TFS A250

CERAMALLOY 4450
PROCESS REQUIREMENTS

- CLASS A MFG. SPACE
- NO OILY OR GREASY CONTAMINATION
- CONTROL OF PASTE COMPOSITION

METALLIZATION SYSTEM CHARACTERISTICS

- SHEET $\rho$ : 0.0025 ohm/square
- THICKNESS : 0.5-1.0 mils
- WIDTH : 6 mils min.
- HUMIDITY : 168 hours 70°C 100% RH
- ADHERENCE : 800-1400 gms (solder pull)
- JUNCTION DEPTH : ~0.25 $\mu$m
\[ P_r = (0.49 \cdot \text{EQPT} + 97 \cdot \text{SQFT} + 2.1 \cdot \text{DLAB} + 1.3 \cdot \text{MATS} + 2.3 \cdot \text{UTIL})/\text{QUAN}. \]

\[ \text{EQPT} = 67,500 + 6750 - 1250 = 73,000 \]

\[ \text{SQFT} = 320 \]

\[ \text{DLAB} = 0.2 \text{ PSN.YRS.} \times 4.7 \times 8,100 \]
\[ + 0.1 \text{ PSN.YRS.} \times 4.7 \times 11,000 = 12,784/\text{YR} \]

\[ \text{MATS} = (0.077 \text{ gm Ag PASTE} \times 0.17/\text{gm} \]
\[ + 0.00003 \text{ #3 SOLVENT} \times 0.55/# \]
\[ + 0.00005 \text{ SCREENS} \times 5 \text{ EA} \times 11,300,000 \text{ CELLS/YR} \]
\[ + 150,930/\text{YR} \]

\[ \text{UTIL} = 0.0009 \text{ kWh/CELL} \times 11,300,000 \text{ CELLS/YR} \]
\[ = 10,170/\text{YR} \]

\[ \text{QUAN} = 1500 \text{ CELLS/HR} \times 0.91 \times 8280 \text{ HR/YR} \times \]
\[ = 11,300,000 \text{ CELLS/YR} \]

\[ P_r = (3,577 + 31,040 + 26,846 + 196,209 + 13,221)/11,300,000 \]
\[ = 0.02397/\text{CELL} \]

IF \( \eta_m = 0.13 \)

\[ \text{POWER/CELL} = 10.16^2 \text{ cm}^2 \times 0.1 \times 0.13 \]
\[ = 1.342 \text{ WATTS/CELL} \]

\[ P_r = 0.02786/\text{WATT} \]

ASSUMING NO YIELD LOSS.
PALLADIUM/NICKEL COMPARISON

PALLADIUM
- Rapid silicide formation at 200°C and above
- Forms primarily Pd$_2$Si
- Pd$_2$Si grows epitaxially on <111> silicon
- Atomic diffusion shared by palladium and silicon
- Stable

NICKEL
- Three primary silicide phases
  - Ni$_2$Si: 200°C to 350°C
  - NiSi: 350°C to 750°C
  - NiS$_2$: 750°C and above
- Atomic diffusion almost exclusively nickel
NICKEL-PALLADIUM METALLIZATION SYSTEM
SCHEMATIC DIAGRAM

CELL FRONT

PB-Sn SOLDER

Ni

Pd

Pd2Si

N+ JUNCTION

P SUBSTRATE

P+ BACK

SAME AS FRONT

CELL BACK
NICKEL-PALLADIUM METALLIZATION SYSTEM
PROCESS SEQUENCE OUTLINE

1. IMMERSION PALLADIUM
2. SINTER
3. SCRUB
4. ELECTROLESS PALLADIUM
5. SINTER
6. ELECTROLESS NICKEL
7. SOLDER

NICKEL-PALLADIUM METALLIZATION SYSTEM
PRESENT BASELINE PROCESS

1. 10 SEC 10:1 H₂O:HF DIP
   DIH₂O RINSE
   2 MIN IMMERSION PALLADIUM COAT
   DIH₂O RINSE
   SPIN DRY

2. 30 MIN SINTER AT 600°C IN N₂

3. HIGH PRESSURE HYDROLIC SCRUB (BOTH SIDES)

4. DIH₂O DIP
   5 SEC 10:1 H₂O:HF DIP
   15 IMMERSION PALLADIUM DIP
   DIH₂O RINSE
   95 SEC ELECTROLESS PALLADIUM PLATE
   DIH₂O RINSE
   SPIN DRY
BASELINE PROCESS (CONTINUED)

5. 30 MIN. SINTER AT 600°C IN N₂

6. D₁H₂O DIP
   5 SEC 10:1 H₂O:HF DIP
   D₁H₂O RINSE
   5 MIN. ELECTROLESS NICKEL PLATE
   D₁H₂O RINSE
   SPIN DRY

7. SOLDER

IMMERSION PALLADIUM SOLUTION

<table>
<thead>
<tr>
<th>CONSTITUENT</th>
<th>AMOUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td>H₂O</td>
</tr>
<tr>
<td>FLUOBORIC ACID</td>
<td>HBF₄</td>
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<tr>
<td>HYDROCHLORIC ACID</td>
<td>HCL (38%)</td>
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<tr>
<td>PALLADIUM CHLORIDE</td>
<td>PdCl₂</td>
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### ELECTROLESS PALLADIUM SOLUTION

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<td>WATER</td>
<td>$\text{H}_2\text{O}$</td>
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<tr>
<td>HYDROCHLORIC ACID</td>
<td>$\text{HCL} (38%)$</td>
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<tr>
<td>PALLADIUM CHLORIDE</td>
<td>$\text{PdCl}_2$</td>
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<tr>
<td>AMMONIUM CHLORIDE</td>
<td>$\text{NH}_4\text{Cl}$</td>
</tr>
<tr>
<td>SODIUM HYPOPHOSPHITE</td>
<td>$\text{NaH}_2\text{PO}_2 \cdot 2\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>AMMONIUM HYDROXIDE</td>
<td>$\text{NH}_4\text{OH} (58%)$</td>
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(a) textured front surface
(b) flat back surface

FIGURE 7: Electroless plated palladium layers
### ELECTROLESS NICKEL SOLUTION

<table>
<thead>
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<th>Constituent</th>
<th>Amount</th>
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<td>WAFER</td>
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<td>NICKEL CHLORIDE</td>
<td>NiCl₂·6H₂O 30 g</td>
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<td>AMMONIUM CHLORIDE</td>
<td>NH₄Cl 50 g</td>
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<td>SODIUM CITRATE</td>
<td>Na₃C₆H₅O₇·2H₂O 84 g</td>
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<td>AMMONIUM HYDROXIDE</td>
<td>NH₄OH (58%) 125 mL</td>
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### IPEG PRICE ANALYSIS

**ASSUMPTIONS**

1. EQUIPMENT AND LABOR ARE **NOT** INTEGRIZED

2. PRICES ARE IN 1975 DOLLARS (INFLATION RATES FROM COST ACCOUNT CATALOG)

3. PROCESS YIELD IS 100%

4. WORK YEAR IS 8280 HOURS (8 x 3 x 345)

5. CELLS ARE MADE ON 12 cm DIAMETER WAFERS

6. CELL THROUGHPUT IS 76 CELLS/HOUR
POWER OUTPUT VS. EFFICIENCY AT THROUGHPUT OF 76 CELLS/HOUR

AT 14% EFFICIENCY
QUAN = 996,378 WATTS
INTERIM PRICE ESTIMATION GUIDELINES
JPL IPEG PRICE EQUATION

PRICE =

\[ 0.489 \text{EQPT} + 96.9 \text{SQFT} + 2.133 \text{DLAB} + 1.255 \text{MATS} + 1.255 \text{UTIL} \]

WHERE

\begin{align*}
\text{EQPT} & = \text{DIRECT EQUIPMENT CAPITAL COST} \\
\text{DLAB} & = \text{ANNUAL DIRECT LABOR SALARIES} \\
\text{MATS} & = \text{COST OF DIRECT MATERIALS AND SUPPLIES} \\
\text{UTIL} & = \text{COST OF DIRECT PROCESS UTILITIES} \\
\text{SQFT} & = \text{DIRECT MANUFACTURING FLOOR SPACE}
\end{align*}

DIRECT COSTS AND FLOOR SPACE

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<thead>
<tr>
<th>STEP</th>
<th>EQPT</th>
<th>SQFT</th>
<th>DLAB</th>
<th>MATS</th>
<th>UTIL</th>
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<td>10.133</td>
<td>2177.07</td>
<td>2027.08 (752.75)</td>
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<td>748.02</td>
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<tr>
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<td>42.87</td>
<td>11142.54</td>
<td>77044.20 (19434.10)</td>
<td>3602.35</td>
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4-32
IPEG PRICES IN CENTS/WATT

<table>
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<tr>
<th>STEP</th>
<th>0.489 SQF</th>
<th>96.9 SQF</th>
<th>2.133 DLAR</th>
<th>1.255 MALS</th>
<th>2.255 UTIL</th>
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<td>(.77)</td>
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<td>(2.45)</td>
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TYPICAL I-V CHARACTERISTIC CURVES
FOR 3 INCH NON-TEXTURED
SOLAR CELL

![Graph of I-V Characteristic Curves](image-url)
SOLAR CELL METALLIZATION TOPICS

1. REVIEW METALLIZATION CANDIDATES
2. DESCRIBE SCREEN PRINTING PARAMETERS
3. REVIEW SINTERING THEORY
4. DISCUSS RCA METALLIZATIONS
5. DESCRIBE SOME COMMERCIAL METALLIZATIONS
6. EXAMINE ONE Cu METALLIZATION
7. EXPLORE FUTURE WORK
SUBSTRATE SEQUENCE

WEIGHT OF INK (mg)

COEFFICIENT OF VARIATION (%)
METALLIZATION PROCESS

I. CLEANING
   a. H$_2$SO$_4$ - H$_2$O$_2$
   b. HF (10%) RINSE

II. SCREEN PRINTING (0-5 6105 Ag)
   a. PARAMETER SELECTION
   b. CRACKING WAFERS (?)

III. DRYING - FORCED AIR 125°C - 15min.

IV. FIRING - air, tube furnace
    500°C - 2 min.
    + 675°C - 10 min.

\[ \begin{align*}
3.25 \text{ mils} & \quad \text{V} \\
10 \text{ mils wire} & \quad 5^\circ \\
10 \text{ mils cellulose} & \quad \text{X}
\end{align*} \]
FORCE, lbs vs SQUEEGEE COMPRESSION, mils

THERMAL SHOCK -196°C to +200°C, 5 cycles
All OK, if no original cracks

PARTICLE SIZE DISTRIBUTION
Glas spreading and metal sintering begins at time (min) 16. The temperature range is from 25°C to 800°C. The graph shows the temporal progression of these processes.

Diagram:
- Two circles representing glass and metal.
- Radius (r) denoting distance between the centers.
- Distance (2h) indicating the spatial overlap.
- Parameter (ρ) symbolizing a specific condition or measurement.

4-39
**RCA METALLIZATION CONSTITUENTS**

<table>
<thead>
<tr>
<th>Ag Metal Powders</th>
<th>Surface Area m²/g</th>
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<tbody>
<tr>
<td>METZ K-ISO</td>
<td>3.40</td>
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<tr>
<td>FS Type C</td>
<td>0.98</td>
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<tr>
<td>U.S. Met Ref. 72-2</td>
<td>0.24</td>
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</table>

## Frits (wt%)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Surface Area m²/g</th>
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<tbody>
<tr>
<td>80 PbO-10B₂O₃-10SiO₂</td>
<td>0.45</td>
</tr>
<tr>
<td>70 PbO-10P₂O₅-10B₂O₃-10SiO₂</td>
<td>0.52</td>
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</table>

*Ag₃PO₄ (meta) m.p. = 492°C
Ag₃PO₄ (pyro) m.p. = 585°C
Ag₃PO₄ (ortho) m.p. = 849°C

*AgNO₃ + H₂PO₂ (H₃PO₄) → Ag₃PO₄ + NO₂ (H₂O)

**Organic Vehicle**

Butyl carbitol with 6-9% ethyl cellulose (N-300)
**CONTACT ANGLE COMPARISON**

*(500°C - 2 min.)*

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle (°)</th>
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<tbody>
<tr>
<td>m-Si</td>
<td>5</td>
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<tr>
<td>Ag foil</td>
<td>13.5</td>
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<tr>
<td>80 PbO-10B₂O₃-10SiO₂</td>
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</tr>
<tr>
<td>70 PbO-10ZnO-10B₂O₃-10SiO₂</td>
<td>42.5</td>
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<tr>
<td>Ag PO₃ (?)</td>
<td>18</td>
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<tr>
<td></td>
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</tbody>
</table>

**Graph:**

- **Sheet Resistance (mΩ/Square)**
  - 0
  - 5
  - 10
  - 15

- **Time (s)**
  - 30
  - 60
  - 90
  - 120

- **Temperature (°C)**
  - 300
  - 600
  - 900
  - 1200
  - 1500

**Ag (U.S. METALS REFINING)**
% OF DULL CONDUCTIVITY
METZ K-150 Ag VS. GLASS CONTENT

5 v/o (80 PbO - 10 B₂O₃ - 10 SiO₂)

<table>
<thead>
<tr>
<th>℃</th>
<th>500</th>
<th>600</th>
<th>700</th>
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10 v/o

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% of Bulk Conductivity

\( Ag (TFS 3347) \)

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<th>500</th>
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\( Ag (TFS A-250) \) No Frit

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% of Bulk Conductivity

Ag (Eng. E-Y22-C)

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Ag (Eng. E-Y22-E)

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## % of Intercal Conduction

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<td>38</td>
<td>9</td>
</tr>
<tr>
<td>60</td>
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<tr>
<td>90</td>
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<td>39</td>
<td>9</td>
</tr>
<tr>
<td>120</td>
<td>38</td>
<td>39</td>
<td>7</td>
</tr>
<tr>
<td>600</td>
<td>38</td>
<td>39</td>
<td>7</td>
</tr>
</tbody>
</table>
% of Bulk Conductivity

Firing Time - 600 sec

<table>
<thead>
<tr>
<th>Metal</th>
<th>Temp, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>Ag-TFS 3347</td>
<td>53</td>
</tr>
<tr>
<td>&quot; A 250</td>
<td>51</td>
</tr>
<tr>
<td>Eng E-422-E</td>
<td>46</td>
</tr>
<tr>
<td>&quot; E-422-C</td>
<td>61</td>
</tr>
<tr>
<td>Ag-AR</td>
<td></td>
</tr>
<tr>
<td>Eng 422-D</td>
<td>46</td>
</tr>
<tr>
<td>422-F</td>
<td>38</td>
</tr>
</tbody>
</table>
Specific contact res. a.-cm

°C
(time: 10 min at temp.)

CERMALLOY Cu 7029-5
(low temp.)

2 RC

cm

4-54
SUMMARY

(1) THICK-FILM AG METALLIZATION IS STILL PREFERRED CHOICE FOR SOLAR CELLS.

(2) HOWEVER, RISING AG PRICE MAY FORCE RECONSIDERATION OF OTHERS,
    e.g. Cu, Al, Ni.
\[ N(x) \text{ (cm}^{-3}\text{)} \]

\[ p^{31+} \text{ IMPLANTS INTO SILICON} \]

\[ \text{DEPTH (MICRON)} \]

\[ V/cm \]

\[ 10^4 \]

\[ 10^2 \]

\[ 10^{-2} \]

\[ 10^{-4} \]
### COMPARISON OF ION IMPLANTATION EQUIPMENT FOR SOLAR JUNCTION IMPLANTS

<table>
<thead>
<tr>
<th></th>
<th>CONVENTIONAL HIGH CURRENT IMPLANTER</th>
<th>SOLAR CELL PROCESS IMPLANTER</th>
<th>HIGH VOLUME SOLAR CELL PRODUCTION IMPLANTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>PURCHASE PRICE $</td>
<td>$350K</td>
<td>$315K</td>
<td>$1000K</td>
</tr>
<tr>
<td>PROCESS MODE</td>
<td>Batch</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>TYPE OF MATERIAL PROCESSED</td>
<td>Wafers</td>
<td>Wafers</td>
<td>Wafers, Sheet, Ribbon, etc.</td>
</tr>
<tr>
<td>P&lt;sub&gt;31&lt;/sub&gt; BEAM CURRENT</td>
<td>2 mA @ 25 keV</td>
<td>4 mA @ 10 keV</td>
<td>100 mA @ 10 keV</td>
</tr>
<tr>
<td>BEAM UTILIZATION EFFICIENCY</td>
<td>3%</td>
<td>15%</td>
<td>83%</td>
</tr>
<tr>
<td>THROUGHPUT PER HOUR (SOLAR CELL JUNCTION IMPLANTS)</td>
<td>30 3-inch Wafers (0.14 m²)</td>
<td>300 3-inch Wafers (1.4 m²)</td>
<td>180 m²</td>
</tr>
<tr>
<td>ESTIMATED UP TIME/DOWN TIME</td>
<td>0.85</td>
<td>0.85</td>
<td>&gt;0.90</td>
</tr>
<tr>
<td>SOLAR CELL PRODUCT THROUGHPUT PER YEAR - MAXIMUM OPERATION</td>
<td>100 kW&lt;sub&gt;E&lt;/sub&gt;</td>
<td>1 MW&lt;sub&gt;E&lt;/sub&gt;</td>
<td>&gt;100 MW&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>OPERATORS/TECHNICIAN REQUIRED</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>ELECTRICITY CONSUMPTION</td>
<td>25 kW</td>
<td>25 kW</td>
<td>200 kW</td>
</tr>
</tbody>
</table>

---

4-59
ESTIMATED OPERATING COSTS OF
HIGH VOLUME SOLAR CELL IMPLANTER

DIRECT LABOR

1. SUPERVISION, OPERATION AND ROUTINE
   MAINTENANCE $30

2. SPECIAL MAINTENANCE 3

OPERATIONAL MATERIALS

ELECTRICITY, SOURCE GAS, NITROGEN
MISC. 32

MAINTENANCE MATERIALS

SOURCE PARTS, CONVEYOR SYSTEM COMPONENTS
CARRIERS, VACUUM COMPONENTS, PUMP OILS,
MISC. 10

TOTAL 75

SOLAR CELL PRODUCT THROUGHPUT ~180 M²/HR
>18,000 PWₑ

DIRECT OPERATING COSTS (~0.004 $/PWₑ)
(JUNCTION IMPLANT)

CONVENTIONAL ION IMPLANTATION EQUIPMENT

- HIGH ION ENERGIES 25 - 200 + keV
- LOW BEAM CURRENTS OR INEFFECTIVE BEAM UTILIZATION AT
  HIGH CURRENTS
- EXCELLENT UNIFORMITY
- SHADOWED AREAS ON WAFERS FROM HOLDERS
- NO WAFER ROTATION
- BATCH PROCESS AT HIGH CURRENTS
- LOW THROUGHPUTS AT SOLAR CELL REQUIREMENT LEVELS
5 x 10^{15} \text{ cm}^{-2} \text{ P}^{31+} \text{ implants into silicon through native oxide}

Oxygen atoms per cm$^2$

- 50 keV
- 100 keV
- 150 keV

Depth (Å) →

Helium ion backscattering

(100) Silicon wafer
Implanted: phosphorus 3 x 10^{15} \text{ cm}^{-2} 100 keV

Counts

No anneal
Furnace anneal
Phos. diff. anneal

4-62
DIRECTED ENERGY PULSE ANNEALING

0 PULSED ELECTRON BEAM
0 Q-SWITCHED LASER

\( <10^{-6} \) SECOND

FLUENCE = 0.2 CAL/CM\(^2\)
PULSE LENGTH = 0.1 \( \mu \)SEC
ELECTRON BEAM

TEMPERATURE RISE (°C)

T = 0 AFTER PULSE
T = 0.5 \( \mu \)SEC
T = 1.0 \( \mu \)SEC
T = 4.6 \( \mu \)SEC

DEPTH (\( \mu \)M)
INTERMEDIATE DOSE IMPLANTS

DOUBLE STEP ANNEAL
EFFECT OF IMPLANT DOSE ON ANNEALING REQUIREMENTS

LOW DOSE - DISTRIBUTED DEFECTS

- EFFECTIVE ANNEALING AT LOW TEMPERATURE

HEAVY DOSE - AMORPHOUS LAYER FORMATION

- EPITAXIAL REGROWTH AT 500-850°C
- COMPLICATIONS IF WAFER TEMPERATURE RISES DURING IMPLANT

INTERMEDIATE DOSE - LOCALIZED NUCLEATION SITES REMAINING WITHIN HEAVILY DAMAGED LAYER

- COMPETITION BETWEEN LOCAL AND EPITAXIAL REGROWTH
- POLYCRYSTALLITE FORMATION BY SIMPLE 500-850°C ANNEAL
- ADDITIONAL COMPLICATIONS IF WAFER TEMPERATURE RISES DURING IMPLANT

SILICON SOLAR CELL JUNCTION AND BACK LAYER IMPLANTS

\[ \begin{align*}
\text{P}^{31+} & \quad 5-25 \text{ KEV} \quad \sim \quad 10^{15} \text{ IONS/CM}^2 \\
\text{B}^{11+} &
\end{align*} \]

- INTERMEDIATE SITUATION
- PROBABLY NOT COMPLICATED BY WAFER HEATING
POST IMPLANT ANNEALING

IONS CAUSE RADIATION DAMAGE TO CRYSTAL LATTICE
  • ANNEALING NECESSARY FOR REGROWTH

IMPLANTED DOPANT ATOMS ARE INTERSTITIAL
  • ANNEALING NECESSARY FOR ELECTRICAL ACTIVATION

METHODS
  • CONVENTIONAL PROCESS - FURNACE
  • ADVANCED TECHNOLOGY - DIRECTED ENERGY PULSING

REQUIRED CONDITIONS DEPEND UPON:
  • ION
  • DOSE
  • SUBSTRATE ORIENTATION
  • SUBSTRATE TEMPERATURE DURING IMPLANT
  • ?
$p^{31+}$ IMPLANTED AT $10^0$

ACTUAL PROFILE

CHANNELED COMPONENT

IDEAL STOPPING

LOG $N(x)$

DEPTH
$N(x)$

$\text{(cm}^{-3})$

$\mathbf{P}^{31+} \text{ IMPLANTS INTO SILICON}$

$\text{COMPOSITE}$

$5 \times 10^{14}$

$2 \times 10^{14}$

$3 \times 10^{13}$

$10 \text{ KEV}$

$25 \text{ KEV}$

$50 \text{ KEV}$

$\text{DEPTH (MICRON)}$

$\text{FIELD}$

$\text{v/CM}$

$10^4$

$10^2$

$0$

$-10^2$

$-10^4$
ANALYZING MAGNET

BEAM SCANNER

END STATION FOR WAFER PROCESSING

ACCELERATION OR DECELERATION POTENTIAL

ACCELERATION POTENTIAL

ION SOURCE

SOURCE GAS

SHEET RESISTANCE MAP

© SIGNETICS CORP 01-MAR-1978 23:30
U3163 SPIRES PHOS. IMPLANT 25 KEV 3x10^15 WAFER # 1009-3

PARAMETERS:
C.F. = 4.450
FPP SPACING = 0.025
CURRENT = 2100.0
CONTOUR INT. = 1.0000 %
UNPAIRED DATA

48.34 OHM/SQ. ± 4.38 %
ADVANTAGES OF ION IMPLANTATION FOR SOLAR CELL PRODUCTION

• PROCESS SIMPLICITY
  - SINGLE SURFACE
  - LINE OF SIGHT
  - NO RESIDUES
  - REDUCTION OF SUBSEQUENT STEPS
  - CONTINUOUS MODE

• VERSATILITY

• REPRODUCIBILITY, UNIFORMITY, CONTROL

• PURITY

• RATE

• LOW ENERGY CONSUMPTION

• EASE OF AUTOMATION

• EASE OF SCALE-UP

• ENVIRONMENTAL IMPACT

• COST
CONCENTRATION

10^20
10^19
10^18
10^17
10^16

0  R_P  0.1  0.2  \mu M

DEAD LAYER
REVERSE FIELD REGION

HEAVY RECOIL DENSITY LAYER
SURFACE COATING
RECOIL ATOMS

ION

4-75
ESTIMATED MANUFACTURING COST OF
HIGH VOLUME SOLAR CELL IMPLANTER

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>PRODUCTION UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PROTOTYPE UNIT</td>
<td></td>
</tr>
<tr>
<td>ENGINEERING</td>
<td>$360,000</td>
<td>$36,000</td>
</tr>
<tr>
<td>DOCUMENTATION (over 10 units)</td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td>MATERIAL AND SUB ASSEMBLY LABOR</td>
<td>590,000</td>
<td>400,000</td>
</tr>
<tr>
<td>OTHER MANUFACTURING COSTS</td>
<td>59,000</td>
<td>40,000</td>
</tr>
<tr>
<td>ASSEMBLY ON SITE</td>
<td>32,000</td>
<td>20,000</td>
</tr>
<tr>
<td>TEST AND QUALIFICATION</td>
<td>40,000</td>
<td>20,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$1,081,000</strong></td>
<td><strong>$528,000</strong></td>
</tr>
</tbody>
</table>

![Graph showing concentration vs. depth](4-76)
SOLAR CELL PROCESS IMPLANTER

- LOW ION ENERGIES 5 - 90 keV
- HIGH CURRENTS OF MASS ANALYZED ION BEAM
  EFFICIENTLY UTILIZED ON WAFER

<table>
<thead>
<tr>
<th>ION</th>
<th>DEMONSTRATED BEAM CURRENT ON WAFER AT 10 KEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>p³¹+</td>
<td>4.2 mA</td>
</tr>
<tr>
<td>As⁷⁵+</td>
<td>2.5 mA</td>
</tr>
<tr>
<td>B¹¹+</td>
<td>0.9 mA</td>
</tr>
</tbody>
</table>

- MODERATE DOSE UNIFORMITY
- WAFER ROTATION DURING IMPLANT
  - NO SURFACE SHADOWING
  - CAPABILITY FOR TEXTURIZED MATERIALS
- CONTINUOUS PROCESS
- HIGH THROUGHPUT
  - \(10^{15} \text{ cm}^{-2}\) \(\text{p}^{31+}\) JUNCTION
    IMPLANTS INTO >300 3-INCH
    OR 4-INCH WAFERS PER HOUR.
TECHNICAL CONSIDERATIONS - ION IMPLANTATION
FOR SOLAR CELLS

SILICON FORM:
- PROBABLY ANY

SURFACE CONDITION:
- POLISHED, ETCHED, TEXTURIZED, AS-GROWN

IMPLANT PARAMETERS:
- ION, ENERGY, DOSE, BEAM/WAFER ORIENTATIONS
- JUNCTION PROFILE IMPORTANT (SHALLOW, MINIMIZED REVERSE FIELD REGION)

LINE OF SIGHT PROBLEMS:
- WAFER HOLDING
- DIRT, CONTAMINATION
- SURFACE FEATURES
- EDGES

ANNEALING:
- FURNACE ANNEAL SCHEDULES
- DIRECTED ENERGY
PROJECTED STOPPING DISTANCE

\[ N(x) = \frac{Q}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x-R_p)^2}{2\sigma^2}\right) \]
1. Implant both sides

2. Electron pulse both sides

3. Evaporate thin film contacts

4. Electron flow both sides

5. Front and back contacts
SAMICS ANALYSIS  
FRONT LAYER IMPLANTATION  
COST TO DO PROCESS  
IN GOAL YEAR $'s

<table>
<thead>
<tr>
<th>MACHINE</th>
<th>NO OF MACHINES</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 - 20 A</td>
<td>7</td>
<td>$2.93</td>
</tr>
<tr>
<td>200 - 100 WF</td>
<td>1</td>
<td>.98</td>
</tr>
<tr>
<td>DEDICATED</td>
<td>1</td>
<td>1.07*</td>
</tr>
</tbody>
</table>

*RUNS FOR 35 HR.

<table>
<thead>
<tr>
<th>MACHINE</th>
<th>NO OF MACHINES</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATED PRODUCTION</td>
<td>2**</td>
<td>$0.09***</td>
</tr>
</tbody>
</table>

**1.27 MACHINES NEEDED  
***$0.05 IN 1975 DOLLARS
\textbf{ATOMIC MASS UNITS}

\begin{align*}
\text{PH}_3 \text{ GAS IN DD-50 SOURCE}
\end{align*}
SYSTEM PERFORMANCE SPECIFICATION

- **ION SPECIES**
  - $p^{3+}$, $As^{75+}$, $B^{11+}$ (Single machine may be dedicated to only one ion)

- **ION ENERGY**
  - Fixed range 10-30 keV

- **BEAM CURRENT**
  - Min. 100 mA $p^{3+}$

- **ANALYZED BEAM PURITY**
  - Resolution of 0.5 AMU at mass 31

- **BEAM UNIFORMITY/REPRODUCIBILITY**
  - Not worse than $\pm 10\%$ over all material area processed

- **SUBSTRATE THROUGHPUT**
  - Variable - min. of 500 cm$^2$/sec at $1 \times 10^{15}$ ions/cm$^2$

- **MATERIALS TO BE HANDLED**
  - 20 x 20 cm max dimensions
  - Silicon wafers, ribbon, sheet, etc.

- **SURFACES TO BE IMPLANTED**
  - Plain and texturized

- **PROCESSING MODE**
  - Continuous flow

- **OPERATIONAL MODE**
  - Continuous throughout routine with predictable component maintenance
BASIC DESIGN PHILOSOPHY

- CONSERVATIVE DESIGN - FACTORY OPERATION
- RELIABILITY - MULTIPLE ION SOURCES
- ANALYSIS REQUIRED
- CONTINUOUS FEED - SUBSTRATE
- IMPLANT SUBSTRATES - ANY SIZE UP TO 20 x 20 cm
- ACCOMMODATE VARIETY OF MATERIALS
- REDUCED ENERGY USE
MAJOR SYSTEM COMPONENTS

- ION SOURCE AND POWER SUPPLIES
- EXTRACTION SYSTEM
- ANALYZER SYSTEM
- BEAM SCANNING SYSTEM
- DOSE CONTROL SYSTEM
- VACUUM SYSTEM
- SUBSTRATE CARRIER SYSTEM
- CONTROL ASSEMBLY
BEAM REQUIREMENT

\[
\text{DOSE} \propto \frac{I(\text{mA})}{\Lambda (\text{cm}^2/\text{sec})} \times 10^{13} \text{ions/cm}^2
\]

\[10^{15} \text{ions/cm}^2 \text{ requires 100 mA}\]

BEAM POWER 3 KW at 30 KeV
TOTAL WEIGHT: 23.5 Tons (21,000 Kg)
MAGNET WEIGHT: 10 Tons (9070 Kg)

FACILITY REQUIREMENTS:
* POWER - 200 kVA max., 3-phase
  4 wire, plus ground
* WATER - 75 psig (5 kg/cm²) max.
  40 psig (2-8 kg/cm²) min.
  differential between inlet and outlet 9 gpm (110 Gpd)
  60-80°F (16-27°C) max.
  inlet temperature
* COMPRESSED AIR - 60-100 psig (42-7 kg/cm²) for pneumatic valves
* HYDROGEN - 4.0 cfm (565 SCF/sec) at entrance and exit
* VENTILATION - 1200 cfm (565 SCF/sec) exhaust

SCHEMATIC OF SOLAR CELL IMPLANTER

ENTRANCE +

ION BEAMS

PUMP

ION BEAMS

PROCESS CHAMBER

PUMP

EXIT +

PROCESS CHAMBER

PUMP

110F

120 FT.

(4.1m)

37 FT.

(1.1m)

41 FT.

(12.5m)

4-90
ANALYZED BEAM AS A FUNCTION OF SLIT AREA

ESTIMATED SOURCE ARC CURRENT vs ANALYZED BEAM CURRENT
CROSS-SECTION, SOLAR IMPLANTER

ION SOURCE

ANALYZING MAGNET

SCANNER

SUBSTRATE

PROCESS CHAMBER
TWO LEVEL ENTRANCE LOCKS

\[ P_0 \rightarrow P_1 \rightarrow P_2 \]

\[ P_1 \text{ torr} \]

TIME (seconds)
<table>
<thead>
<tr>
<th>PRODUCTION SCHEDULE</th>
<th>YEAR ONE</th>
<th>YEAR TWO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENGINEERING</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MANUFACTURING</td>
<td></td>
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</tr>
<tr>
<td>ASSEMBLY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INSTALLATION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUALIFICATION</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## System Performance Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
<td>$\text{p}^{31+}, \text{As}^{75+}, \text{B}^{11+}$ (single machine may be dedicated to only one ion)</td>
</tr>
<tr>
<td>Ion Energy</td>
<td>Fixed range 10-30 keV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>Min. 100 mA $\text{p}^{31+}$</td>
</tr>
<tr>
<td>Analyzed Beam Purity</td>
<td>Resolution of 0.5 AMU at mass 31</td>
</tr>
<tr>
<td>Beam Uniformity/</td>
<td>Not worse than ± 10% over all material area processed</td>
</tr>
<tr>
<td>Reproducibility</td>
<td></td>
</tr>
<tr>
<td>Substrate Throughput</td>
<td>VARIABLE-MIN of 500 cm²/sec at $1 \times 10^{15}$ ions/cm²</td>
</tr>
<tr>
<td>Materials to be handled</td>
<td>20 x 20 cm max dimensions silicon wafers, ribbon, sheet, etc</td>
</tr>
<tr>
<td>Surfaces to be handled</td>
<td>Planar and texturized</td>
</tr>
<tr>
<td>Processing Mode</td>
<td>Continuous flow</td>
</tr>
<tr>
<td>Operational Mode</td>
<td>Continuous throughout routine and predictable component maintenance</td>
</tr>
</tbody>
</table>

4-97
BASIC DESIGN PHILOSOPHY

- CONSERVATIVE DESIGN - FACTORY OPERATION
- RELIABILITY - MULTIPLE ION SOURCES
- ANALYSIS REQUIRED
- CONTINUOUS FEED - SUBSTRATE
- IMPLANT SUBSTRATES - ANY SIZE UP TO 20 x 20 CM
- ACCOMMODATE VARIETY OF MATERIALS
- REDUCED ENERGY USE

BEAM REQUIREMENT

\[
\text{DOSE} = \frac{I(\text{mA})}{A(\text{cm}^2/\text{sec})} \times 6 \times 10^{15} \text{ IONS/cm}^2
\]

\[10^{15} \text{ IONS/cm}^2 \text{ REQUIRES 100 mA}\]

BEAM POWER 3 KW AT 30 KEV
MAJOR SYSTEM COMPONENTS

- Ion Source and Power Supplies
- Extraction System
- Analyzer System
- Beam Scanning System
- Dose Control System
- Vacuum System
- Substrate Carrier System
- Control Assembly

CHARACTERISTICS OF ANNEALING ENERGY SOURCE

<table>
<thead>
<tr>
<th>HEATING SOURCE</th>
<th>PULSE WIDTH</th>
<th>ENERGY DEPOSITION IN SILICON</th>
<th>BEAM SIZE</th>
<th>ENERGY EFFICIENCY</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace</td>
<td>HRS</td>
<td>3-D Bulk</td>
<td>Very Large</td>
<td>Poor</td>
<td>Long Anneal Times</td>
</tr>
<tr>
<td>Radiant Heater</td>
<td>HRS</td>
<td>2-D Bulk</td>
<td>Very Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lasers: CO₂</td>
<td>0.1 µSEC-1 MSEC</td>
<td>2-D Surface</td>
<td>Very Small</td>
<td>Moderate</td>
<td>Must be Scanned or Stepped</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruby</td>
<td>0.1 µSEC 1 MSEC</td>
<td>2-D Surface</td>
<td>Very Small</td>
<td></td>
<td>Overlap Problems</td>
</tr>
<tr>
<td>Electron Beam:</td>
<td>10 KEV</td>
<td>2-D Surface</td>
<td>2.5 cm</td>
<td>Good</td>
<td></td>
</tr>
</tbody>
</table>

4-99
## PERFORMANCE COMPARISON OF PARALLEL CELL PROCESSES

<table>
<thead>
<tr>
<th>CELL PROCESS</th>
<th>AMO EFFICIENCY (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>σ</td>
<td>PEAK</td>
</tr>
<tr>
<td>DIFFUSED</td>
<td>12.1</td>
<td>0.4</td>
<td>12.9</td>
</tr>
<tr>
<td>IMPLANTED JUNCTION</td>
<td>11.5</td>
<td>0.6</td>
<td>12.5</td>
</tr>
<tr>
<td>FURNACE ANNEAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMPLANTED JUNCTION</td>
<td>11.0</td>
<td>0.8</td>
<td>12.3</td>
</tr>
<tr>
<td>PULSE ANNEAL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**OCLI PROCESSING:** CONTACTS, MULTIPLE LAYER AR AND AMO PERFORMANCE

**SILICON:** 1 Ω-cm <100> CZ BRIGHT ETCHED-surfaces
IMPLANTED LAYER

\[ T_{\text{MELT}} \]

RECRYSTALLIZATION

SILICON SUBSTRATE

AT END OF PULSE

DEPTH

AT START OF RECRYSTALLIZATION OF IMPLANT LAYER

IMPLANT LAYER FULLY RECRYSTALLIZED
CONTACT DESIGN FOR IMPLANTED JUNCTIONS

○ CONTACT DEPENDENT CELL POWER LOSSES
  ○ AREA SHADOWING
  ○ RESISTIVE LOSS WITHIN CONTACT LINE
  ○ RESISTIVE LOSS WITHIN JUNCTION LAYER
  ○ SEMICONDUCTOR - METAL CONTACT LOSS

○ CRITICAL PARAMETERS
  ○ JUNCTION SHEET RESISTANCE
  ○ MINIMUM PRACTICAL LINE WIDTH

\[
\frac{\text{LINE WIDTH}}{\text{LINE HEIGHT}} \quad \text{RATIO}
\]

○ SINTERING PROPERTIES

○ DESIGN APPROACH
  ○ OPTIMIZED NO. OF OUTPUT TERMINALS AT 4
  ○ 1.4 MIL LINE WIDTH SELECTED
  ○ CHROMIUM, GOLD, SILVER SYSTEM (ALUMINUM, SILVER)
  ○ OPTIMIZE LINE SPACING
POWER LOSS AGAINST FINGER WIDTH for concentric pattern for varied numbers of output terminals.

PERCENT OF TOTAL CELL POWER LOST BY RESISTANCE AND SHADOWING VS. LINE WIDTH FOR SEVERAL SHEET RESISTANCES.

7.6 CM DIAMETER CELL.
PROCESS SPECIFICATION

HIGH EFFICIENCY IMPLANTED 3" DIAMETER CELLS

Silicon Material
10 ohm-cm <100> CZ p-type
Surfaces: Front - Polished
Back - Bright Etched

Process Sequence

Implant:
Front - $2 \times 10^{15}$ $31p^{+}$/cm$^2$, 5 keV, 100, 250°C
Back - $5 \times 10^{13}$ $115^{+}$/cm$^2$, 25 keV, 100, 250°C

Anneal:
Simultaneous phosphorus and boron implant anneal in nitrogen
550°C - 2 hours
850°C - 15 minutes
550°C - 2 hours

Clean:
Buffered HF
DI rinse

Front Metallization:
Evaporate 400 Å Cr + 400 Å Au
Define Spire Starburst pattern with standard Kodak KTFR process
Electroplate 12 μm Ag
Clean:
Buffered HF
DI rinse

Back Metallization:
Evaporate 400 Å Al + 1 μm Ag

AR Coating:
Evaporate 700 Å TiO$_2$

Sinter:
400°C - 10 minutes in nitrogen

Test:
AMO I-V
SPIRE NO. 10052-2
"STARBURST"

OPTIMIZED FRONT CONTACT METALLIZATION PATTERN 7.6 CM (3 INCH) CELLS

Figure 1.
DIRECTED ENERGY SOURCES FOR PULSE ANNEALING

- REQUIRED CHARACTERISTICS OF A SOURCE
  - SURFACE ENERGY DEPOSITION
    WITHIN 1-10 μM
  - SHORT PULSE DURATION
    LESS THAN 1 μSEC
  - LARGE AREA
    3-4" DIAMETER WAFERS
  - OTHERS
    REP RATE, ENERGY EFFICIENCY, BEAM PURITY
    UNIFORMITY AND REPRODUCIBILITY

- PRESENTLY UNDER DEVELOPMENT
  - PULSED
    LOW ENERGY ELECTRONS 10 keV
    Nd:YAG LASER 1.06 μM
    RUBY LASER 0.69 μM
  - SCANNED
    LOW ENERGY ELECTRONS
    ARGON LASER 0.49 μM
TEMPERATURE PROFILES IN SILICON FOLLOWING ELECTRON BEAM PULSE ANNEAL
MECHANISM OF PULSE ANNEALING

BASIS FOR MODEL
- 3 YEARS LASER/PULSED ELECTRON BEAM ANNEALING EXPERIENCE AT SPIRE
- EXISTING LITERATURE USSR, AND USA DESCRIBING LASER ANNEALING
- MEASUREMENTS OF STRUCTURE AND ELECTRONIC PROPERTIES OF IMPLANTED/PULSE ANNEALED DEVICES

KEY ELEMENTS OF MODEL
- ENERGY ADDED DURING IMPLANT RESULTS IN CRYSTAL TO GLASS (AMORPHOUS) TRANSITION
- ABSENCE OF A HEAT OF FUSION FOR AMORPHOUS MATERIALS
- FAST EPITAXIAL REGROWTH RATE (10^8 Å/SEC)
- MAJOR REDISTRIBUTION OF IMPLANTED PHOSPHOUS OR ARSENIC BASED ON DIFFUSION IN A MELT
Measured arsenic impurity profiles for As-implanted and after pulse electron beam annealing.

- As implanted
- After pulse anneal

75 $^{+}_{\text{As}} \rightarrow \text{Si} <100>$
25 keV
$5 \times 10^{15}$/cm

Depth (Å)
REGROWTH RATES FOR α-SI TO RECRYSTALLIZE WITH AND WITHOUT SINGLE CRYSTAL SUBSTRATE
DIFFUSION COEFFICIENTS FOR ARSENIC AND PHOSPHORUS IN SOLID AND LIQUID SILICON
ADVANTAGES OF PULSE PROCESSING OF ION IMPLANTED DEVICES

- TECHNICAL ADVANTAGES
  - POTENTIAL FOR HIGH CELL EFFICIENCIES
    - FEWER DEFECTS
    - BETTER DOPANT PROFILE
    - BULK SILICON LIFETIME PRESERVATION/ENHANCEMENT
  - EASILY CONTROLLED PROCESS
    - TIGHTER CELL PERFORMANCE DISTRIBUTION
  - CAN ACCOMMODATE ADVANCED MATERIALS
    - POLYCRYSTALLINE SHEET, RIBBON
    - ABSENCE OF GRAIN BOUNDARY DIFFUSION
  - REDUCED CLEANING REQUIREMENTS
    - NO WET PROCESSING
    - NO ACID WASTE DISPOSAL
  - AUTOMATABLE
    - EASILY INTEGRATED WITH ION IMPLANTATION
    - RAPID ANNEALING RATES
SOLAR CELL IMPLANT ANNEALING

- REQUIREMENTS
  - RESTORATION OF CRYSTAL LATTICE
  - EPITAXIAL REGROWTH OF AMORPHOUS SILICON
  - ACTIVATION OF IMPLANTED, INTERSTITIAL IONS
  - MAINTAIN SHALLOW DOPANT PROFILE
  - PRESERVATION OR ENHANCEMENT OF SILICON LIFETIME

- RESULTING SCHEDULES FOR FURNACE ANNEALING
  - MULTIPLE STEP
    1. 450 - 600°C  PRE-ANNEAL EPITAXIAL REGROWTH
    2. 850°C  SUBSTITUTION OF DOPANT INTO LATTICE
    3. 450 - 600°C  LIFETIME RECOVERY BY COMPLEXING RESIDUAL DEFECTS

- DRY NITROGEN ATMOSPHERE
BACK SURFACE IMPLANT LAYER PARAMETER SELECTION

\[ \text{N}^+ \text{ P P}^+ \text{ CELL STRUCTURE} \]

**Example No. 1**
- Energy (keV) = 35
- Dose (ions/cm\(^2\)) = 5 \times 10^{15}
- Activity ratio = 7.12 \times 10^{-21}

---

**Active Dopant (N/cm\(^2\))**

\[ \begin{align*}
1 \times 10^{21} \\
1 \times 10^{20} \\
1 \times 10^{19} \\
1 \times 10^{18} \\
1 \times 10^{17}
\end{align*} \]

- Deeper implant
- Higher concentration
- B\(^+\), BF\(_2\)^+ or Al\(^+\)

---

**Depth (Microns)**

\[ \begin{align*}
.25 \\
.18 \\
.15 \\
.22 \\
.25 \\
.30
\end{align*} \]
SOLAR CELL
PROCESS COMPARISONS

• MATERIAL SPECIFICATIONS
  • CZ, 1 Ω-cm, <100>
  • BRIGHT ETCHED SURFACES

• PARALLEL CELL PROCESSES
  • DIFFUSION
    JUNCTION: PH₃, 825 - 850°C
    BACK SURFACE LAYER: ALUMINUM ALLOY
  • IMPLANT/FURNACE ANNEAL
    JUNCTION: PHOSPHORUS IMPLANT
    BACK SURFACE LAYER: ALUMINUM ALLOY
    ANNEAL: 850°C
  • IMPLANT/PULSE ANNEAL
    JUNCTION: PHOSPHORUS IMPLANT
    BACK SURFACE LAYER: ALUMINUM ALLOY
    ANNEAL: SINGLE PULSED ELECTRON BEAM
SPIRE AUTOMATED PRODUCTION CONCEPT
MEASURED MINORITY CARRIER LIFETIMES FOR SILICON LIFETIMES IN MICROSECONDS

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<th>Orientation</th>
<th>Growth</th>
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<th>II (550°C - 2 hrs) + (850°C + 1 hr)</th>
<th>III (I + II)</th>
<th>IV (550°C - 4 hrs.)</th>
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<td>6.2</td>
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<td>FZ</td>
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<td>FZ (0 EPD)</td>
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<td>5.5</td>
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<td>(1-0-0)</td>
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<td>3.1</td>
<td>4.3</td>
<td>2.7</td>
<td>3.7</td>
</tr>
<tr>
<td>10.0</td>
<td>(1-0-0)</td>
<td>FZ</td>
<td>3.6</td>
<td>9.4</td>
<td>3.1</td>
<td>2.7</td>
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<tr>
<td>1.0 OCLI</td>
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<td>7.3</td>
<td>18.7</td>
<td>22.3</td>
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<tr>
<td>5.0 SILSO</td>
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<td>CAST</td>
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</tbody>
</table>

I (550°C - 2 hrs)
II (550°C - 2 hrs) + (850°C + 1 hr)
III (I + II)
IV (550°C - 4 hrs.)
ION IMPLANTED SOLAR CELL DESIGN FACTORS

CELL PARAMETERS

- $R_{\text{sheet}}$
- CONTACT DESIGN
- BSF
- LIFETIME
- MATERIAL

PROCESS PARAMETERS

- IMPLANT
  - DOSE
  - ENERGY
  - THROUGHPUT
- ANNEAL
  - TIME
  - TEMPERATURE
  - RATE

STARTING REQUIREMENTS FOR ION IMPLANTED SILICON SOLAR CELLS

- MATERIALS
  - SINGLE CRYSTAL WAFER OR SHEET
  - POLYCRYSTALLINE SHEET
  - DENDRITIC WEB
  - OTHER

- SURFACE PREPARATION
  - AS-GROWN ON SHEET AND RIBBON
  - POLISHED
  - BRIGHT ETCHED
  - TEXTURIZED
  - NOT AS-SAWN

- SURFACE CLEANING
  - FREE OF PARTICULATES
QUALITATIVE MAP OF DIRECTED ENERGY SOURCE EFFECTS IN THE ABSORPTION DEPTH - PULSE WIDTH PLANE

REGION | DOMINANT EFFECT
---|---
1 | THERMOMECHANICAL SHOCK DAMAGE
2 | SURFACE BLOW-OFF DAMAGE
3 | FEASIBLE FOR RADIATION DAMAGE ANNEALING
4 | CONDUCTIVE LOSS TO SUPPORT STRUCTURE
5 | INSUFFICIENT ENERGY INPUT
6 | INEFFICIENT ENERGY UTILIZATION

RELATIVE EXPOSURE TIME

RELATIVE ABSORPTION DEPTH

FISHEYE | CONCENTRIC | BRANCHED | STARBURST
JUNCTION IMPLANT PARAMETER SELECTION
N⁺ P P⁺ CELL STRUCTURE

EXAMPLE NO. 7
ENERGY (KEV) 10
DOSE (IONE/CM²) 3.2 × 10¹⁵
ACTIVITY RATIO 4.25 × 10⁻¹¹

ACTIVE DOPANT (N/CM³)

SHALLOW JUNCTION 0.1-0.3 µM
PHOSPHOROUS OR ARSENIC
SHEET RESISTANCE COMPATIBLE
WITH CONTACT DESIGN
MINIMIZED CHANNELING
PROFILE PEAK AT SURFACE

DEPTH (MICRONS)

4-120
AMO 25°C
2 x 2 cm
MULTI-LAYER AR
1 Ω cm <100> CZ
N⁺: 2.5 x 10¹⁵ 31p⁺ 5 keV → Si
P⁺: Al ALLOY
# METALLIZATION MASK SUMMARY

<table>
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<th>MASK DESIGN</th>
<th>FRACTIONAL POWER OUTPUT LOSSES (%)</th>
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<td>SHADOW LOSS</td>
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<td>SPIRE BRANCHED PATTERN-4 SECTOR</td>
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<tr>
<td>SPIRE STARBURST PATTERN-4 SECTOR</td>
<td>2.6</td>
</tr>
<tr>
<td>CONCENTRIC &amp; RADIAL - 8 SECTOR</td>
<td>3.8</td>
</tr>
</tbody>
</table>
IMPLANTED SOLAR CELL STRUCTURE SELECTION

CONTACT

0.1-0.3 μm

SHALLOW JUNCTION

300 μm

~ 0.3 μm

BACK SURFACE FIELD

BACK CONTACT
\[ \text{IMPLANT} \quad 2.5 \times 10^{15} \text{ Si}^+ \quad 5 \text{KEV} \rightarrow <100> \text{ Si} \]

\[ \begin{align*}
\triangle & \quad \text{SINGLE STEP - 30 MIN} \\
\square & \quad \text{TWO STEP-450 - 1 HOUR PREANNEAL} \\
\bigcirc & \quad \text{TWO STEP-550 - 1 HOUR PREANNEAL} \\
\end{align*} \]

\[ \begin{align*}
R_{SH} \quad (\Omega/\square) \\
\begin{array}{ccccccc}
450 & 500 & 550 & 600 & 650 & 700 & 750 & 800 & 850 \\
\end{array} \\
\end{align*} \]

\[ \text{T (°C)} \]

ISOCHRONAL ANNEALING (10 Ω- CM CZ)
SECTION V
ENGINEERING AREA

A. Summary

During this meeting the principal objective of the Engineering Area was to provide a forum for discussion of recent progress in three areas of interest: Module Structural Design Requirement Studies, Module Reliability Studies, and Module Testing. The intertask session held on Wednesday afternoon addressed each of these areas.

B. Module Structural Design Studies

Investigations currently in progress include two study contracts. Boeing Engineering is performing module cost trade-offs based on the direct reduction of module structure and support structure. This reduction is obtained by placing the module/array inside air-supported enclosures. Bechtel has investigated the influence of module sizing and structural mounting interfaces on basic module structural costs. Current status of each of these studies is presented in the following paragraphs.

1. Module Designs for Transparent Enclosures
   D. K. Zimmerman, Boeing Engineering and Construction

   a. Abstract

   The objective of this study is to assess the potential technical and economic benefits obtained when photovoltaic modules are protected by transparent air-supported enclosures. The study plan and current status of the contract were described (Figure 1). The two basic concepts, a fully tracking array and a fixed array, being evaluated were described (Figure 2). The size of the arrays depends on the limitations on enclosure size. Some of the design assumptions for the enclosure were given in Figure 3. The resulting enclosure design for the fixed array was described in Figure 4. Figure 5 was presented to indicate the impact of the higher strength polyester on allowable size, and the large margin of safety for the selected 15 foot radius and 7 mil thickness. The transmittance of new and weathered polyester was shown in Figure 6. Because array temperatures are increased by the enclosures, various methods of cooling the solar cells were analyzed. Figure 7 was presented to show that power for an active cooling system exceeded the increase in array output. Results of the cooling study were summarized in Figure 8. The module design for the fixed array was described (Figures 9, 10 and 11), and its temperature and power output summarized in Figure 12. Two configurations of the tracking array being evaluated to determine the design to be costed were presented in Figures 13 and 14. Remaining work (Figure 15) included completion of the tracking array design and its thermal analysis and completion of the cost analyses.

   b. Graphic Presentation
Feasibility Study of 'Solar Dome' Protection of Photovoltaic Arrays
JPL Contract No. 954833

Objective: Assess technical and economic benefits of protecting photovoltaic arrays with air supported enclosures

Study Plan:

- Establish System Requirements
  - Application
  - Loads & Environment

- Define System Concepts
  - Tracking
  - Non-Tracking

- Establish Cell Parameters
  - Efficiency
  - Environmental Effects

- Evaluate Cooling Concepts
- Prepare Preliminary Designs
- Determine Life Cycle Costs

---

**Solar Dome Concepts**

- Weather-proof encapsulation on cells not required
- UV screening by dome increases cell coating choice
- Module support structure protected from wind, snow loads
- Cell temperature increase

---

Spherical Enclosure
- Lightweight, fully-tracking array

Cylindrical Enclosure
- Low-cost array structure - gravity loads only
- Simple module replacement
- Weather protection for power buss

---

Figure 5-1.
Figure 5-2.
Cylindrical Enclosure Design Assumptions

- Use existing materials and fabrication methods
- Design to Phoenix, Arizona environment
  - 80 MPH wind
  - 5 psf snow load
  - 116°F max. ambient temperature
  - Seismic zone 2 (zone 3 used)
  - 1½ inch dia. hailstones
- Size compatible with material limits, installation and servicing convenience
- Wind loading is reduced by protective fence on boundary

Figure 5-3.

Overview of Enclosure Configuration
Fixed Tilt Array

Figure 5-4.
Cylindrical Enclosure Sizing

Enclosure Membrane Load LB/IN

Allowable loads
Tedlar

Phoenix, AZ
80 MPH wind, 116°F
5 PSF snow load, ps/Pi = .75

Factors of safety
yield: 1.0
ultimate: 3.0

Weatherized polyester

Figure 5-5.
Transmission of New and Weathered Polyester Film
Martin UV-X Weatherable Polyester
Martin Processing, Inc.

Figure 5-6.
Cooling System Evaluation Conclusions

Active cooling system

- Parasitic power exceeds benefit

Passive cooling systems

- No apparent cost savings
- Additional complexity
- Modest cooling capability

Conclusion: Design array without additional cooling provisions
Selected Circuit Arrangement

[Diagram of circuit arrangement with labels for Left-oriented module (LOM) and Right-oriented module (ROM), showing submodule and polarity connections.]

Submodule

Same submodule except inverted

Figure 5-9.
Overall Module Geometry

3 photovoltaic modules
6 submodules per module
Field replace modules, shop repair/replace submodules
Module upper attachment

Main bus/module bus interconnect

Module bus/module bus interconnect

0.75 in. (typ.)

24 ft structural bay

94.5 in. (typ.)

Module lower attachment

View A-A

Figure 5-10.
Submodule Configuration

Material available for end bead:
1.97 in.

94.5 in. 50 x 3 = 150 cells in series

48.0 in. (stock width)

8 cells in parallel

Output interconnect & blocking diode

0.50 in. lap joint area

By-pass diodes:
- None required for normal array shadows
- Diodes (or operational procedures) required for irregular shadows

Substrate - weatherized oriented polyester film - 7 mils thick fire retardants added

Figure 5-11.

5-9
Thermal/Performance Analyses
Latitude Tilt Array

Figure 5-12.
Large-module Tracking Array

- +600V

- 31.8 ft diameter spherical enclosure

- 691 ft² (64 m²) array

- 6 in. diameter aluminum tube-ring & support arms

Figure 5-13.

Small-module Tracking Array

- 31.8 ft diameter spherical enclosure

- 576 ft² (53.5 m²) array

- Lightweight frame attaches to support arms at 4-6 points

- Rhombic cell shape for maximum packing density

- Submodule glass reinforced polyester substrate (rigid)

Figure 5-14.
Remaining Work

• Finalize tracking design
  Thermal/performance analysis
• Complete costing
• Prepare report

Figure 5-15.
2. Module/Array Interface Study
W. J. Stolte, Bechtel National, Inc.

a. Abstract

The objective of this study is to assist in determining optimum module designs by evaluating various design features from the viewpoint of an architect engineer and constructor of large photovoltaic power plants.

System voltage is a variable (Figure 1) and affects module design by imposing a voltage stress across the module encapsulant system (Figure 2). This stress imposes thickness requirements on the encapsulant materials (Figure 3) and thereby affects module costs (Figure 4). Module leakage current is also affected by the types of encapsulant material used (Figure 5).

A nonlinear computer analysis was conducted for three glass-superstrate module designs; picture frame, segmentally supported and curved, segmentally support designs (Figure 6). Good agreement was obtained between the computer analysis and available data for the picture frame design (Figures 7 and 8).

Eight similar array designs and variations were completed for 35, 50 and 70 psf loading (Figures 9 and 10). Estimates show cost to be a stronger function of loading than the variations in design considered (Figure 11).

b. Graphic Presentation
Figure 5-16.
MAXIMUM PERMISSIBLE VOLTAGE STRESS, IN A UNIFORM FIELD, SET AT 200 VOLTS/MIL

MODULE VOLTAGE GRADIENT AND STRESS DISTRIBUTION

Figure 5-17.
Figure 5-18.
MATERIAL COSTS (1975 $)
SYLGARD 184 - $0.043/FT²/MIL
MYLAR - $0.01/FT²/MIL
TEDLAR - $0.036/FT²/MIL
PVB (SAFLEX - PT10) - $0.022/FT²/MIL

MODULE ENCAPSULATION PARTIAL COST VERSUS VOLTAGE

Figure 5-19.
## TYPICAL MODULE CONFIGURATIONS

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<th>COVER TYPE</th>
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### Figure 5-20.

**4 FOOT BY 8 FOOT MODULE OPERATING AT 1000 VOLTS WITH RESPECT TO GROUND**

**MODULE LEAKAGE CURRENT**

5-18
GLASS SUPERSTRATE MODULE CONCEPTS

Figure 5-21.
Figure 5-22.
Figure 5-23.
Figure 5-25.
Figure 5-26.
C. Module Reliability Studies

In the area of module reliability, a recently-initiated contract with Clemson University to study several aspects of cell reliability was discussed.

A computer program is under development at JPL for analysis of cell and module series/parallel circuit configurations under various cell and circuit failures or anomalies.

1. Reliability Attributes and Accelerated Stress Factors of Terrestrial Solar Cells
J. L. Prince and J. W. Lathrop, Clemson University

a. Abstract

Results of the first quarter of work on the program "Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells" include (1) design of a two-phase accelerated stress test plan for terrestrial solar cells, (2) establishment of a stress testing facility and cell handling and storage procedures, and jigging and fixturing for high temperature, high humidity stress testing, and (3) establishment of an electrical measurement procedure in consultation with cognizant NASA Lewis Research Center personnel, and partial establishment of a final electrical measurement capability. The first phase of accelerated stress testing was begun. Physical evidence of such things as changes in metallization, electro-plating and attack of the antireflective coating was obtained for three cell types after bias-temperature-humidity stress testing.

b. Graphic Presentation

INVESTIGATION OF RELIABILITY ATTRIBUTES AND ACCELERATED STRESS FACTORS OF TERRESTRIAL SOLAR CELLS

ENGINEERING AREA

J. L. PRINCE AND J. W. LATHROP
CLEMSON UNIVERSITY
12 APRIL 1978

Figure 5-27.
PERSONNEL

- DR. J. L. Prince, Reliability and Failure Analysis, Co-Principal Investigator
- DR. J. W. Lathrop, Measurements, Co-Principal Investigator
- DR. F. W. Morgan, Statistical Analysis
- Graduate Students - 4 M.S. Level, 1 Ph.D. Level

Figure 2-28.

OBJECTIVE

- Investigate factors involved in the reliability of individual unencapsulated terrestrial solar cells
  - Degradation ("Failure") modes and mechanisms
  - "Time-to-Failure" distributions
  - Parametric degradation rates
  - Technology problem identification

- Develop specifications for a cell qualification test based on accelerated stress testing

Figure 5-29.
SCOPE

- CELLS FROM FOUR MANUFACTURERS
- PHASE I CELL QUANTITIES APPROXIMATELY 50 PER TYPE
- PHASE II CELL QUANTITIES APPROXIMATELY 400 PER TYPE

Figure 5-30.

APPROACH

- TWO STRESS TESTING PHASES
  - PHASE I: SMALL CELL QUANTITIES, TRUNCATED TESTS. "A QUICK LOOK" TO PROVIDE INFORMATION FOR FINAL ITERATION OF PHASE II
  - PHASE II: LARGER CELL QUANTITIES, LONGER DURATION TESTS. STATISTICALLY SIGNIFICANT RESULTS.
  - STRESS TESTS BASED ON MIL-STD-883 TECHNIQUES
  - "FAILURE" ANALYSIS IN PARALLEL WITH TESTING
  - DEVELOPMENT OF MEASUREMENT PROCEDURES AND FACILITY IN PARALLEL WITH PHASE I
  - QUALIFICATION TEST SCHEDULE SYNTHESIS AFTER EXPERIMENTAL RESULTS HAVE BEEN OBTAINED
  - LIAISON WITH CELL MANUFACTURERS DURING PROGRAM

Figure 5-31.
STRESS TEST DESIGN

PROJECTED DEGRADATION MECHANISMS

- Primarily metalization/contact related: corrosion, electroplating, electromigration, metal delamination and cracking, junction punch-through
- Secondarily cell fracture or cracking

ASSUMPTIONS IN STRESS TEST DESIGN

- Observation of minimum 15 "failures" desirable for statistics
- All strictly temperature-dependent degradation modes have 1 eV activation energy
- $10^4$ acceleration factor for 85°/85% R.H. testing
- Catastrophic failure rate > 1% in 20 years

Figure 5-32.
STRESS TEST FACILITIES AND PROCEDURES

FACILITIES

- 1000 SQ. FT. LABORATORY WITH SEPARATED AREAS FOR STRESS TESTING, ELECTRICAL MEASUREMENT, AND CELL STORAGE, INSPECTION AND PHOTOGRAPHY
- 8 TEMPERATURE CHAMBERS, PRESSURE COOKER WITH FEEDTHROUGH; THERMAL CYCLE AND TEMP-HUMIDITY CHAMBERS (1 MAY)
- DRY NATURAL CELL STORAGE, LAMINAR FLOW BENCHES FOR HANDLING
- SEPARATE FAILURE ANALYSIS LABORATORY

PROCEDURE

- INITIAL INSPECTION, SERIALIZATION AND PHOTOGRAPHY
- INITIAL ELECTRICAL MEASUREMENTS
- STORAGE
- STRESS TEST
- INTERIM MEASUREMENTS AT DOWNTIMES
  - ELECTRICAL
  - VISUAL INSPECTION (AND PHOTOGRAPHY IF NECESSARY)

Figure 5-33.
Stress Test Schedule: Phase I

1. Bias/Temperature/Humidity (5V Reverse Voltage, 1A-2A Forward Current)
   - 121°C, 15 PSIG Steam: 10 units/type, 50 HRS.
   - 85°C/85% R.H.: 10 units/type, 500 HRS.

2. Bias/Temperature (5V Reverse Voltage, 1A-2A Forward Current)
   - Step stress, 75°C to 165°C, 150 HRS. per step
     - 16 units/type

3. Power Cycle (1A-2A Forward Current, 50% Duty Cycle)
   - 5 units/type, 35°C Ambient

4. Thermal Cycle
   - 5 units/type, -65°C/25°C/+150°C, MIL-STD-883 METHOD 1010.1

5. Thermal Shock
   - 5 units/type, -65/+150°C, MIL-STD-883 METHOD 1011.1

Figure 5-34.
### PLANNED STRESS TEST SCHEDULE: PHASE II

<table>
<thead>
<tr>
<th>STRESS TEST</th>
<th>CONDITIONS</th>
<th>TEST POPULATION (PER TYPE)</th>
<th>TEST DURATION</th>
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<tr>
<td>B-T-H</td>
<td>$T_{\text{AMB}} = 121^\circ\text{C}, 15$ PSIG STREAM</td>
<td>20</td>
<td>500$^+$ HOURS</td>
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<tr>
<td>B-T-H</td>
<td>$T_{\text{AMB}} = 85^\circ\text{C}/85% \text{ R.H.}$</td>
<td>25</td>
<td>1,999$^+$ HOURS</td>
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<td>B-T</td>
<td>$T_J = 75^\circ\text{C}, \text{ FORWARD BIAS}$</td>
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<td>4,999$^+$ HOURS</td>
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<tr>
<td>B-T</td>
<td>$T_J = 135^\circ\text{C}, \text{ FORWARD BIAS}$</td>
<td>60</td>
<td>4,999$^+$ HOURS</td>
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<tr>
<td>B-T</td>
<td>$T_J = 159^\circ\text{C}, \text{ FORWARD BIAS}$</td>
<td>40</td>
<td>3,000$^+$ HOURS</td>
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<tr>
<td>B-T</td>
<td>$T_J = 165^\circ\text{C}, \text{ FORWARD BIAS}$</td>
<td>40</td>
<td>1,500$^+$ HOURS</td>
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<tr>
<td>POWER CYCLING</td>
<td>$T_{\text{AMB}} = 35^\circ\text{C}, \text{ FORWARD BIAS}$</td>
<td>25</td>
<td>12,999$^+$ HOURS</td>
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<tr>
<td>THERMAL CYCLING</td>
<td>MIL-STD-883 A, METHOD 1010.1, CONDITION C</td>
<td>20</td>
<td>100$^+$ CYCLES</td>
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<tr>
<td>THERMAL SHOCK</td>
<td>MIL-STD-883 A, METHOD 1011.1, CONDITION C</td>
<td>10</td>
<td>25$^+$ CYCLES</td>
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<td>SEQUENCE TESTING</td>
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<td>TOTAL</td>
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Figure 5-35.
ELECTRICAL MEASUREMENTS

PARAMETERS MEASURED OR CALCULATED

- $V_{OC}$
- $I_{SC}$
- $V_M$
- $I_M$
- $P_M = I_M V_M$
- FILL FACTOR ($P_M / V_{OC} I_{SC}$)
- EFFICIENCY
- $R_S$
- $R_{SH}$

Figure 5-36.
ELECTRICAL MEASUREMENTS

CURRENT STATUS (PHASE I)

- Brass vacuumholding jig, no temperature control, cell temperature monitored
- 4-point (Kelvin) voltage measurements
- Single ELH lamp (uniformity problem)
- Light calibration by single JPL reference cell
- Some data (R_s, P_sh) taken off curve tracer

ADDITIONS FOR FINAL MEASUREMENT SYSTEM (PHASE II - DESIGNED AFTER CONSULTATION WITH NASA/LERC PERSONNEL)

- Jig temperature controlled at 20°C
- 4-lamp ELH light source and Schoeffel xenon arc solar simulator
- Light calibration for each cell type using JPL reference cells
- X-Y plotter substituted for curve tracer

Figure 5-37.

RESULTS TO DATE: PHASE I TESTING

- Electrical: no clear parametric degradation with bias-temperature-humidity stress

- Exception: one cell failed due to decreased shunt resistance (junction punch-through)

- Visual Analysis

- Definite effects observed after bias-temperature-humidity stress
  - "bubbles" in solder metalization (type A cells)
  - Dendritic growth (type B cells)
  - Attack of AR coating (type C cells)

Figure 5-38.
SUMMARY OF ACCOMPLISHMENTS

- Phase I Stress Testing Schedule Designed and Being Implemented
- Phase II Stress Testing Schedule Designed
- Final Measurement Procedure Established
  - After consultation with NASA/LERC personnel
  - Measurement capability in process of realization
- Cell handling, cell flow, and data management procedure established
- Facilitation nearly complete
  - Delivery of humidity and thermal cycle chambers 1 May

Figure 5-39.

PLANS

- Phase II measurement capability established mid-May
- Phase II testing started mid-May (longer tests)
- Phase I testing finished early June

Figure 5-40.
C. Module Reliability Studies (Cont'd)

2. Solar Cell and Module Circuit Analysis
   C. Gonzales, JPL

   a. Abstract

   Module/system performance characteristics are defined with respect to the effect of circuit anomalies on performance, the relationship of standalone performance and performance within the system, and the advantages of various circuit design features.

   b. Graphic Presentation

   **OBJECTIVE**

   • DEFINE EFFECT OF CIRCUIT ANOMALIES ON MODULE/SYSTEM PERFORMANCE
     • BROKEN CELLS
     • OPEN CIRCUITS
     • SHADOWS

   • DEFINE RELATIONSHIP BETWEEN MODULE STAND-ALONE PERFORMANCE AND PERFORMANCE WITHIN SYSTEM
     • MISMATCH LOSSES
     • HOT-SPOT CELL HEATING

   • DEFINE ADVANTAGES OF VARIOUS CIRCUIT DESIGN FEATURES TO MINIMIZE ABOVE POWER LOSSES
     • SERIES PARALLELING
     • BY-PASS DIODES
     • FAILURE DETECTION

   Figure 5-41.
APPROACH

• DEVELOP COMPUTER PROGRAM TO COMBINE CIRCUIT ELEMENTS

  • CALCULATES "SYSTEM" I-V CURVE

  • CALCULATES OPERATING POINT FOR EACH SYSTEM ELEMENT

• INTRODUCE CIRCUIT PERTURBATIONS AND ANOMALIES INTO VARIOUS CIRCUITS AND DETERMINE PERFORMANCE IMPACT

Figure 5-42.

COMPUTER ALGORITHM

• REPRESENT I-V CURVES BY \( I = f (I_{sc}, FF, V_{oc}, R_{SH}) \)

• FOR ELEMENTS IN SERIES ADD VOLTAGES ALONG CONSTANT CURRENT LINES

• FOR ELEMENTS IN PARALLEL ADD CURRENTS ALONG CONSTANT VOLTAGE LINES

Figure 5-43.
PRESENT ANALYSES

• ASSESSMENT OF RELATIVE IMPORTANCE OF VARIOUS MISMATCH VARIABLES ($I_{SC}$, $FF$)

• ASSESSMENT OF SERIES-PARALLELING ON MISMATCH LOSSES

• EFFECTS OF SERIES-PARALLELING ON SINGLE CELL FAILURE LOSSES

• EFFECTS OF DIODES ON SINGLE CELL FAILURE LOSSES

Figure 5-44.

MISMATCH LOSSES

• SIMULATED BY USING RANDOM DISTRIBUTION OF $I_{SC}$ AND $FF$

• $I_{SC}$

• MISMATCH EFFECTS MOST SEVERE WHERE COMBINING ALONG CONSTANT CURRENT LINES

• $FF$

• MISMATCH EFFECTS LESS SEVERE THAN THOSE DUE TO VARIATION IN $I_{SC}$

Figure 5-45.

5-37
MISMATCH LOSSES vs STANDARD DEVIATION
100 SERIES CELLS

VARIATION IN FILL FACTOR ONLY

VARIATION IN ISC ONLY

Figure 5-46.
SCHEMATIC OF SERIES-PARALLEL COMBINATIONS

- Using constant 48 cells

4 PARALLEL STRINGS

6 SERIES BLOCKS

4 SERIES BLOCKS

6 SERIES BLOCKS

4 SERIES BLOCKS

2 PARALLEL STRINGS

EFFECTS OF SERIES-PARALLELING ON MISMATCH LOSSES
ONE TO SIX PARALLEL STRINGS - 96 CELLS
(\(I_{sc}\) MISMATCH ONLY, \(\sigma/I_{sc} = 0.1\))

FIGURE 5-47.

FRACTIONAL POWER (\(P/P_{max}\))

SERIES BLOCKS

FIGURE 5-48.

5-39
1-V CURVES FOR 48-CELL MODULE WITH ONE FAILED CELL (4 PARALLEL STRINGS)

EXAMPLE:
4 PARALLEL CELLS

MODULE WITH NO FAILED CELLS

V/V_{OC}

I/I_{SC}

NUMBER OF SERIES BLOCKS

Figure 5-49.
POWER LOSS IN SERIES-PARALLEL CELL COMBINATIONS WITH ONE FAILED CELL - 48 CELLS TOTAL

Figure 5-50.

POWER LOSS IN SERIES-PARALLEL CELL COMBINATIONS WITH ONE CRACKED* CELL - 48 CELLS TOTAL

*CRACKED CELL IS ONE WHOSE $I_{sc} = 0.5 I_{sc}$ OF NORMAL CELL

Figure 5-51.
I-V CURVE FOR CASE OF ONE BAD CELL USING A BY-PASS DIODE

![Graph showing I-V curve for one bad cell using a by-pass diode.]

- **Combining at constant current**
- **With a by-pass diode**
- **Without a by-pass diode**
- **Max power point with a by-pass diode**
- **Max power point without a by-pass diode**

**Six series blocks**
**Two parallel strings**

Combining at constant voltage

Figure 5-52.
CONCLUSIONS

• USE OF SERIES-PARALLELING DOES NOT AFFECT MISMATCH LOSSES SIGNIFICANTLY

• CELL HEATING DUE TO FAILED CELL
  • INCREASED NUMBER OF PARALLEL STRINGS FOR A CONSTANT NUMBER OF SERIES BLOCKS REDUCES CELL HEATING
  • INCREASED NUMBER OF SERIES BLOCKS FOR A CONSTANT NUMBER OF PARALLEL STRINGS INCREASES CELL HEATING

• POWER OUTPUT WITH A FAILED CELL
  • USE OF A BY-PASS DIODE:
    • INCREASES POWER OUTPUT WHEN MODULES ARE CONNECTED IN SERIES
    • HAS NO EFFECT ON POWER OUTPUT WHEN MODULES ARE CONNECTED IN PARALLEL

Figure 5-53.
D. Module Testing Activities

JPL has initiated a series of exploratory tests investigating the influence of combined ultra-violet exposure and high relative humidity on module performance. Preliminary results were presented. The latest results of a continuation of module testing under conditions of bias-humidity exposure were described. A brief comparison test between the output power profiles for fixed tilt versus one-axis (tilted) tracing modules was made. A clock-driven mounting structure was fabricated, and simultaneous measurements of a pair of matched modules were made. The tracked array produced 42% more power. Presentations by Alec Garcia and Dr. R. G. Ross describing these testing activities are provided below.

LOW-COST SOLAR ARRAY PROJECT

UV HUMIDITY TESTING

Alec Garcia

April 12, 1978

Figure 5-54.
CONTENTS

• OBJECTIVES OF TESTS

• STANDARD WEATHEROMETER TEST

• TENSILE TEST EVALUATION

• RADIANT HEAT HUMIDITY TEST

• RED/BLUE RATIO RESULTS

• COMPARISON OF UV SOURCES

• POSSIBILITIES FOR FUTURE TESTS

Figure 5-55.
OBJECTIVES OF STUDIES

• QUALIFICATION TEST

• PRODUCE DELAMINATION

• STANDARD FACILITY

• UNDERSTAND FAILURE MECHANISMS

• PROFITABLE AREAS FOR FUTURE STUDIES

Figure 5-56.
SOLAR MODULE WEATHEROMETER TEST

EQUIPMENT

ATLAS TWIN ARC WEATHEROMETER (TRUESDAIL LABS)

SPECIMENS

ONE MINI-MODULE FROM EACH VENDOR

PRE- AND POST-TEST EVALUATION

VISUAL EXAMINATION
FLASH-GENERATED IV CURVE
RED/BLUE RATIO
REFLECTANCE MEASUREMENTS

TEST CONDITIONS

20 HOURS PER DAY
CONSTANT UV FROM TWIN CARBON ARC LAMPS
DISTILLED WATER SPRAY 5 min IN 40 min
TEMPERATURE CONSTANT 140°F

Figure 5-57.
Figure 5-58. Atlas Twin-arc UV Weatherometer with Block II Mini-module Samples in Place
RESULTS OF WEATHEROMETER TEST
PEAK WATTAGE

Figure 5-59.
TENSILE PULL TEST

LOAD APPLIED

NAIL HEAD BONDED TO OUTER SKIN
OUTER SECONDARY ADHESIVE
MATERIAL REMOVED FROM OUTSIDE CORE

OUTER SKIN
ENCAPSULANT
SUBSTRATE OR CELL

NEAT 5/8" CORE

Figure 5-60.
## TENSILE TEST DATA

<table>
<thead>
<tr>
<th>ZM 850 (CONTROL)</th>
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<td>LOCATION</td>
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<td>1</td>
<td>30.3</td>
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<table>
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<th>ZM 804 (500 HOURS)</th>
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<tbody>
<tr>
<td>LOCATION</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

Figure 5-61.
PLOT OF MODULE VM 009 TEMPERATURE DURING TEST CYCLE RADIANT HEAT HUMIDITY TEST

Figure 5-62.
Figure 5-63. Bemco Combined UV/Humidity Test Set-up with High-pressure Xenon Lamp Source; Block II Mini-module Samples in Place
RESULTS OF RADIANT HEAT HUMIDITY TEST
PEAK WATTAGE

Figure 5-64.
RESULTS OF RADIANT HEAT HUMIDITY TEST
RED/BLUE RATIO

Figure 5-65.
UV SOURCES

- CARBON ARC
  NO SHORT WAVE UV < 340 nm
  SOILING OF ENCLOSING GLASS

- HIGH PRESSURE XENON
  CAUSES HIGH TEMPERATURE
  SAFETY
  WAVELENGTH < 290 nm

Figure 5-66.
SPECTRAL IRRADIANCE OF ENCLOSED CARBON ARC

Figure 5-67.
SPECTRAL IRRADIANCE OF BEMCO SIMULATOR (XENON)

Figure 5-68.
CONCLUSIONS

- CARBON ARC DOES NOT ACCELERATE

- XENON CAUSES TOO MUCH HEAT

- MEDIUM PRESSURE MERCURY LAMP

Figure 5-69.
ENGINEERING AREA ACTIVITIES

MODULE REQUIREMENT GENERATION

- CENTRAL POWER REQUIREMENTS - BECHTEL
- TRANSPARENT ENCLOSURE REQUIREMENTS - BOEING
- RESIDENTIAL REQUIREMENTS RFP

MODULE ENGINEERING ACTIVITIES

- THERMAL ANALYSES OF COMBINED COLLECTORS
- MODULE GLASS STRUCTURAL ANALYSIS
- SERIES/PARALLEL MISMATCH ANALYSIS
- ENCAPSULANT OPTICAL TRANSMISSION EXPERIMENTS
- MODULE RELIABILITY STUDIES
- CELL RELIABILITY (CLEMSON UNIV) CONTRACT

ENVIRONMENTAL TESTING R&D

- HAIL ENVIRONMENTAL ASSESSMENT
- MODULE HAIL TESTING AND TEST DEVELOPMENT
- BIAS-HUMIDITY TESTING
- DIRT ADHERANCE TESTING
- UV - HUMIDITY (DELAMINATION) TESTING

Figure 5-70.
GLASS STRESS vs LOAD FOR FLAT PLATE MODULE

**Figure 5-71.**

- Linear Theory
- ANSYS Linear Solution
- ANSYS Non-Linear Solution (Bechtel)

**Experimental Data (PPG Reference 2):**
- ○ Center Stress
- ▲ Corner Stress
MISMATCH LOSSES vs STANDARD DEVIATION
100 SERIES CELLS

VARIATION IN FILL FACTOR ONLY

VARIATION IN $I_{SC}$ ONLY

Figure 5-72.
TYPICAL TEMPERATURE/INTENSITY PERFORMANCE CHARACTERISTICS

Figure 5-73.
POWER ENHANCEMENT vs REFLECTOR AREA FOR FLAT PLATE MODULES

Figure 5-74.
DAILY POWER PROFILE
FIXED TILT vs TRACKING

Figure 5-75.
BIAS - HUMIDITY TEST SETUP

Figure 5-76.
PHASE II BIAS-HUMIDITY TESTING

Figure 5-77.
SECTION VI
OPERATIONS AREA

Large-Scale Production Task and other Operations Area personnel attended many of the technology development sessions on the basis of individual interests. The Tuesday afternoon 1:15 - 3:15 p.m. session on Module Experience served to highlight both LSA and Applications Projects experience in module performance over the past four months.

In his introductory remarks, Larry Dumas (JPL) presented an overview of silicone rubber encapsulant field performance data as reported by Test and Applications Projects (DOD, LeRC) for Block I modules. Key findings were that varying degrees of delamination have been observed for all manufacturers' modules, but that adhesion to epoxy-fiberglass substrates has been particularly poor. Field reports of this type tend to be subjective and qualitative, and further efforts are needed to standardize and quantify such visually obtained data.

John Griffith (JPL) summarized recent environmental test results, which included the completion of the standard exploratory tests on Block II modules. These modules have continued to show superior performance when compared with their Block I counterparts, but occasional cracked cells and minor encapsulant delamination continue to occur. A combined environments chamber which permits cyclical variation of UV-rich irradiation and humidity has been developed, but early results on full-size modules have failed to replicate field-observed (Block I) encapsulant delamination. Further work on this test apparatus is planned, as Engineering Area and Encapsulation Task studies indicate that humidity and UV are the prime suspects in encapsulant delamination.

JPL field test results were presented by Peter Jaffe (JPL). The three operational sites at Pasadena, Goldstone, and Table Mountain were described, and the automated data acquisition system at the Pasadena site was reviewed. Results of a study comparing field performance measurements with corresponding laboratory (LAPSS) measurements have demonstrated that fill factors are a repeatable and reliable indicator of module health. Nearly 10% of the Block I modules originally placed under field test have failed, with broken interconnects and corrosion of lead wires the most prevalent problems. These data are not representative of other field results because of the large percentage of early production and previously tested modules which are under test. No Block II modules have failed, and physical degradation has been minimal.

Correction of in-situ I-V curves to standard test conditions using conventional (Standstrom) techniques shows a surprising amount of data scatter among curves taken under differing environmental conditions. Carefully structured tests are being performed to isolate variables and assess their individual effects in inducing errors.

Steve Sollock (JPL) presented an overview of problem/failure reporting (P/FR) and analysis activity for Block I and II modules. A total of
283 P/FR's have been processed to date, 207 of which have been closed. In comparing Block I and II modules, it was noted that Block II modules have generally shown improved performance. Interconnect problems have virtually disappeared, and encapsulation delamination observed to date has not been as severe. Cracked cells are being encountered with equal frequency, however. In addition to environmental stresses, cell edge chips and fissures are significant contributors to this problem. Encapsulant delamination has not received reliable coverage in the P/FR system, since there has been no correlation to date of electrical performance degradation with this type of physical degradation. Among the standard environmental tests, temperature cycling has produced the most cases of delamination - but not to the extent noted in field tests and applications.

Two non-destructive diagnostic tests have been successfully employed by the JPL Failure Analysis Lab. Shadowing of individual cells in a module has permitted detection of shortened or otherwise defective cells and yielded a direct measurement of cell shunt resistance. A laser scanning system has been used to map and image the output of a cell over its surface area. This scheme has been used to detect and image cell cracks, and it is hoped that with further refinement hairline cracks not otherwise visible can be imaged.

Steve Forman (MIT/LL) reported on the results of the MIT/Lincoln Laboratory program of module performance analysis. Problems and progress in on-site evaluation of module evaluation were described, and observations on the condition of the 2200 Block II modules at the Nebraska irrigation project were given. Over the first nine months of operation, the number of electrical failures has been insignificant. A serious concern was voiced with regard to safety, as 27 modules have been discovered which had interconnects or other live circuit elements exposed through the silicone rubber encapsulant. Other physical degradation noted includes encapsulant delamination and cracked cells. Dirt accumulation studies at three other locations show power output reduction to be site dependent; for silicone rubber encapsulated modules the effect after six months ranged from 5% to 28%. The reduction for a glassed module was about half that for silicone rubber encapsulated modules at the same site.

Henry Brandhorst (LeRC) reviewed the results of accelerated testing of Block II modules performed for Lewis Research Center by the Naval Weapons Support Center. Considerable damage occurred as a result of vacuum/steam/pressure tests, and fungus growth on modules on which nutrients had been placed was extensive.

Viewgraphs illustrating the above presentations appear on the following pages.
MODULE DELAMINATION
(BLOCK I)

• BASED ON FIELD EXPOSURE
• 9-18 MOS FIELD CONDITIONS
• INSTALLATIONS
  • LeRC STF (CLEVELAND)
  • MERADCOM (CHINA LAKE, FT BELVOIR, ETC)
• SILICONE RUBBER ENCAPSULANT
• METALLIC vs NON-METALLIC SUBSTRATE
• NUMERICAL RESULTS ESTIMATED

MODULE DELAMINATION
(BLOCK I)

METALLIC SUBSTRATE

• DATA BASE – 266 MODULES (MANUFACTURER V)
• MAJOR AREA – AROUND TERMINALS
  – MODULES AFFECTED – UNKNOWN (INSUFFICIENT DATA)
  – SEVERITY – ≈ 25% OF AREA
• OTHER AREAS – TO SUBSTRATE AND EDGES, TO AND AROUND CELLS, AROUND INTERCONNECTS
  – MODULES AFFECTED – UNKNOWN (INSUFFICIENT DATA)
  – SEVERITY – 5-10% OF AREA
MODULE DELAMINATION
(BLOCK I)

NON-METALLIC SUBSTRATE

- DATA BASE - 640 MODULES (MANUFACTURER Y)
- MAJOR AREA - EDGES AND SUBSTRATE
  - MODULES AFFECTED - 60-80% (EST)
  - SEVERITY - 25-75% OF AREA (EST)
- OTHER AREAS - TO AND AROUND CELLS, AROUND TERMINALS AND INTERCONNECTS
  - MODULES AFFECTED - UNKNOWN (INSUFFICIENT DATA)
  - SEVERITY - 5-40% OF AREA (EST)

- DATA BASE - 1302 MODULES (MANUFACTURER Z)
- MAJOR AREA - AROUND EDGES AND TERMINALS
  - MODULES AFFECTED - UNKNOWN (INSUFFICIENT DATA)
  - SEVERITY - 25-75% OF AREA (EST)
- OTHER AREAS - TO SUBSTRATE, TO AND AROUND CELLS, AROUND INTERCONNECTS
  - MODULES AFFECTED - UNKNOWN (INSUFFICIENT DATA)
  - SEVERITY - 3-35% OF AREA (EST)
MODULE DELAMINATION
(BLOCK I)

CONCLUSIONS

- MODULES W/METALLIC SUBSTRATE
  - GENERALLY BETTER

- MAJOR DELAMINATION
  MODULES WITH
  METALLIC SUBSTRATE —— AROUND TERMINALS
  NON-METALLIC SUBSTRATE —— SUBSTRATE, EDGES, AND TERMINALS

- DATA BASE NOT SOLID
  - NEED UNIFORM DATA
  - MORE DATA
  - MORE TIME HISTORY

LOW-COST SOLAR ARRAY PROJECT
OPERATIONS AREA

ENVIRONMENTAL TESTING

JOHN GRIFFITH

APRIL 12, 1978

5101-67

6–5
## TASK 4 MODULES
### QUALIFICATION-TYPE TESTING

<table>
<thead>
<tr>
<th>SUPPLIER</th>
<th>MODULES TESTED</th>
<th>CELL CRACKS</th>
<th>ELECTRICAL DEGRADATION</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>5, CONV. CONTACTS</td>
<td></td>
<td></td>
<td>●</td>
</tr>
</tbody>
</table>

## BLOCK 2 PRODUCTION SAMPLES (kW)
### QUALIFICATION-TYPE TESTS

<table>
<thead>
<tr>
<th>SUPPLIERS</th>
<th>CELL CRACKS</th>
<th>ELECTRICAL DEGRADATION</th>
<th>DELAMINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (EARLY)</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>V (LATER)</td>
<td>●</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>W</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Y</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Z</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

- ● TEMPERATURE CYCLING
- ● HUMIDITY CYCLING
- ● WIND SIMULATION
BLOCK 2 TESTS
OPERATIONS AREA

QUALIFICATION TESTING
• TEMPERATURE CYCLING  +90°C, -40°C, 100°C/hr, 50 TIMES
• HUMIDITY CYCLING  +40°C, +23°C, 90% R.H., 5 DAYS
• WIND SIMULATION  ±50 lb/ft², 100 TIMES

EXPLORATORY TESTING
• HUMIDITY - FREEZING
• SALT FOG
• HARD RAIN
• HEAT - RAIN
• HUMIDITY - HEAT

EVALUATION
• ELECTRICAL TEST
• PHYSICAL INSPECTION

SALT - FOG TEST PROCEDURE
OPERATIONS AREA

• MIL-STD-810C, METHOD 509.1

• SALT SPRAY; 35°C; 95% RELATIVE HUMIDITY

• 48 hr EXPOSURE
EFFECT OF SHADOWING ONE CELL OF A MODULE: I-V CURVES FROM FOUR DIFFERENT MODULES
HUMIDITY - FREEZING TEST PROCEDURE
OPERATIONS AREA

- MIL-STD-202E, METHOD 1060 (NO VIBRATION)
- 10 CYCLES

HARD RAIN TEST PROCEDURE
OPERATIONS AREA

- SIMULATION OF 40 mi/hr WIND-DRIVEN RAIN
- AVERAGE DROPLET SIZE OF 2 mm
- 42 liters/min (11 gal/min)
- MODULES ROTATED AT 5 RPM TO EXPOSE ALL SIDES
- 15 min DURATION
HEAT - RAIN TEST PROCEDURE
OPERATIONS AREA

• SIMULATION OF SUDDEN HARD RAIN ON WARM MODULES

• MODULE TEMPERATURE STABILIZED ON CLEAR WARM DAY

• HARD RAIN SIMULATED UNTIL MODULE TEMPERATURE STABILIZED AT 16-17°C (> 8 MINUTES)

• 5 CYCLES
HUMIDITY - HEAT TEST PROCEDURE
OPERATIONS AREA

- SIMULATION OF SUNLIGHT ON "WATER-LOGGED" MODULES

- PRECONDITIONED 6 hr AT 70°C, 95% RELATIVE HUMIDITY

- IRRADIATED AT MAXIMUM ENVIRONMENTAL LEVEL UNTIL TEMPERATURE STABILIZED

- 10 CYCLES
EXPLORATORY TESTING OF BLOCK 2 MODULES
OPERATIONS AREA

<table>
<thead>
<tr>
<th>SUPPLIER</th>
<th>HUMIDITY-FREEZING</th>
<th>SALT FOG</th>
<th>HEAT-RAIN</th>
<th>WIND-DRIVEN RAIN</th>
<th>HUMIDITY-HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>ELECTRICAL DEGRADATION</td>
<td>OXIDATION</td>
<td>ELECTRICAL DEGRADATION</td>
<td>PASS</td>
<td>CRACKED CELL</td>
</tr>
<tr>
<td>W</td>
<td>PASS</td>
<td>ELECTRICAL ISOLATION</td>
<td>CELL CRACKED</td>
<td>PASS</td>
<td>-</td>
</tr>
<tr>
<td>Y</td>
<td>DELAMINATION</td>
<td>CORROSION</td>
<td>PASS</td>
<td>PASS</td>
<td>PASS</td>
</tr>
<tr>
<td>Z</td>
<td>MINOR DELAMINATION</td>
<td>PASS</td>
<td>ELECT. DEGRAD. SPLIT ENCAP.</td>
<td>PASS</td>
<td>ELECTRICAL DEGRADATION</td>
</tr>
</tbody>
</table>

COMBINED ENVIRONMENTS TEST EQUIPMENT
OPERATIONS AREA

INCLUDES:
- TEMPERATURE CYCLING
- HUMIDITY CYCLING
- IRRADIATION - XENON LAMP
  - XENON LAMP, APPROX. 100 mW/cm²
  - UV RICH
  - POWER GENERATION FROM MODULE
SUMMARY

QUALIFICATION TESTING OF PRODUCTION SAMPLES, BLOCK 2

- CRACKED CELLS
- ELECTRICAL DEGRADATION
- DELAMINATION

EXPLORATORY TESTING

- ELECTRICAL DEGRADATION
- CRACKED CELLS
- DELAMINATION
- ELECTRICAL ISOLATION
- CORROSION

TASK 4 QUALIFICATION TESTING

- CRACKED CELLS
- VOIDS IN ENCAPSULANT GEL
- DELAMINATION

TRENDS

- BLOCK 2 AND TASK 4 MODULES SUPERIOR TO BLOCK 1
  - LESS DELAMINATION
  - HUMIDITY PROBLEMS GREATLY REDUCED
  - LESS ELECTRICAL DEGRADATION
  - FEW INTERCONNECT PROBLEMS
  - CELL CRACKING MORE PREVALENT
    - MOST SERIOUS EXAMPLE CORRECTED BY REDESIGN

- TEST DESIGN
  - WORK TOWARDS COMBINED ENVIRONMENTS
    - HIGH HUMIDITY, ULTRAVIOLET
  - MEASURE SUSCEPTIBILITY TO CRACKING
    - PREDICT FIELD RELIABILITY
LSA FIELD TEST SITE
GOLDSTONE VENUS SITE
BASIC DAILY DATA

WEATHER DATA (EVERY 15 min) → WEATHER DATA LISTING

RAIN FLAG YES/NO → I-V DATA (ONCE DAILY) → RAW I-V DATA LISTING → COMPARISON I-V DATA → ARCHIVED I-V DATA

INSOLATION DATA (EVERY 5 min) → INSOLATION DATA LISTING

FILL-FACTOR CORRELATION TABLE

<table>
<thead>
<tr>
<th>MODULE TYPE</th>
<th>LAPSS FILL-FACTOR</th>
<th>MEAN FIELD* FILL-FACTOR</th>
<th>DIFFERENCE (%)</th>
<th>FROM MEAN (%)</th>
<th>TREND WITH DECREASING INSOLATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>0.758</td>
<td>0.751</td>
<td>0.9</td>
<td>±1.5</td>
<td>LINEAR TO 50 mW/cm² THEN DECREASING</td>
</tr>
<tr>
<td>V</td>
<td>0.754</td>
<td>0.749</td>
<td>0.7</td>
<td>±1.2</td>
<td>LINEAR TO 50 mW/cm² THEN DECREASING</td>
</tr>
<tr>
<td>W</td>
<td>0.711</td>
<td>0.714</td>
<td>0.4</td>
<td>±1.8</td>
<td>INCREASING THEN LEVEL AFTER 60 mW/cm²</td>
</tr>
<tr>
<td>Y</td>
<td>0.628</td>
<td>0.621</td>
<td>1.1</td>
<td>±1.0</td>
<td>LINEAR TO 60 mW/cm² THEN DECREASING</td>
</tr>
<tr>
<td>Z</td>
<td>0.741</td>
<td>0.741</td>
<td>~0.0</td>
<td>±2.0</td>
<td>INCREASING THEN LEVEL AFTER 60 mW/cm²</td>
</tr>
</tbody>
</table>

*IN THE 60 TO 100 mW/cm² RANGE
## BLOCK 1 MODULE FAILURE DATA

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>SAMPLE</th>
<th>NUMBER FAILED AT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>JPL</td>
</tr>
<tr>
<td>V</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>W</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>54</td>
<td>3</td>
</tr>
<tr>
<td>Z</td>
<td>37</td>
<td>7</td>
</tr>
</tbody>
</table>

*NOT YET REPORTED IN PFR SYSTEM*

## PRINCIPAL REASONS FOR FAILURES

- BROKEN INTERCONNECTS
- CORROSION OF CONDUCTORS/CABLE WIRES
**FUTURE PLANNED ACTIVITIES**

- INSTALLATION OF LOAD RESISTORS
- DEVELOPMENT OF IMPROVED TEMPERATURE/INSOLATION CORRECTION EQUATIONS AND CONSTANTS
- INVESTIGATION OF REFERENCE CELL READINGS AS FUNCTIONS OF:
  - INSOLATION LEVEL
  - SKY CONDITION
  - INCIDENT ANGLE
- INVESTIGATION OF SHADOWING EFFECTS
- DEVELOPMENT OF NUMERICAL I-V CHARACTERIZATION AND CURVE FITTING TECHNIQUES

**PROBLEM/FAILURE REPORT P/FR STATUS**

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>MODULE TYPE</th>
<th>No. PFRs</th>
<th>No. CLOSED</th>
<th>PROBLEM/FAILURE ORIGIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ENVIRONMENTAL TEST</td>
</tr>
<tr>
<td>V</td>
<td>Block I</td>
<td>16</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>63</td>
<td>54</td>
<td>57</td>
</tr>
<tr>
<td>W</td>
<td>Block I</td>
<td>29</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>14</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Y</td>
<td>Block I</td>
<td>29</td>
<td>27</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>14</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Z</td>
<td>Block I</td>
<td>48</td>
<td>40</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Block II</td>
<td>27</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Devel. / Commer.</td>
<td></td>
<td>43</td>
<td>24</td>
<td>43</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>283</td>
<td>207</td>
<td>235</td>
</tr>
</tbody>
</table>

6-25
### PROBLEM/FAILURE MODE SUMMARY

<table>
<thead>
<tr>
<th>PROBLEM/FAILURE MODE</th>
<th>BLOCK I</th>
<th>BLOCK II</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRACKED CELLS</td>
<td>● ● ● ●</td>
<td>● ● ● ●</td>
</tr>
<tr>
<td>ENCAPSULATION DELAMINATION</td>
<td>◦ ◦ ◦ ◦</td>
<td>◦ ◦ ◦ ◦</td>
</tr>
<tr>
<td>BROKEN INTERCONNECTS</td>
<td>● ● ● ●</td>
<td>● ● ● ●</td>
</tr>
<tr>
<td>DEGRADED CELL CONTACTS</td>
<td>○ ● ● ●</td>
<td>○ ○ ○ ○</td>
</tr>
<tr>
<td>DIELECTRIC BREAKDOWN</td>
<td>● ◦ ◦</td>
<td>○ ○ ◦ ◦</td>
</tr>
<tr>
<td>PHOTON DEGRADATION</td>
<td></td>
<td>● ● ● ●</td>
</tr>
<tr>
<td>CORROSION OF CONDUCTORS</td>
<td>● ● ● ●</td>
<td>● ● ● ●</td>
</tr>
</tbody>
</table>

- ● DESIGN RELATED
- ◦ WORKMANSHP RELATED
- ○ BOTH

### TYPES OF CRACKED CELLS

- RADIAL CRACKS
- TERMINATED
- RIM-TO-RIM
- CIRCULAR CRACKS

### CONTRIBUTORY FACTORS FOR CRACKED CELLS

- CELL EDGE IMPERFECTIONS AS CHIPS/FISSURES
- EFFECT OF THERMAL STRESS ON CELL
- ENVIRONMENTAL STRESS: TEMP, HAIL, WIND, ETC
- ROUGH HANDLING DURING ASSEMBLY, PACKAGING, SHIPPING, UNPACKAGING

6-26
TYPES OF DELAMINATION

• AT PERIMETER
• BETWEEN SUBSTRATE AND CELL AREA
• SURFACE OF CELLS
• UNDER INTERCONNECTS
• BETWEEN LAYERS OF ENCAPSULATION

PROBABLE CAUSE FOR DELAMINATION

DESIGN:
• SELECTION OF MATERIALS
• POOR MODULE EDGE DESIGN
• MISSING STEPS IN PREPARATION OF MATERIALS

WORKMANSHIP:
• SURFACES NOT PREPARED PROPERLY
• CONTAMINANTS INTRODUCED DURING ENCAPSULATING
• IMPROPER USE OF MATERIALS
• ENTRAPPED AIR IN ENCAPSULANT OR UNDER CELLS

OPERATIONAL:
• CRACKED CELL/LOCAL HEATING
• EXPANSION/CONTRACTION OF MATERIALS
• MOISTURE PENETRATION/FREEZING
• EFFECTS OF MOISTURE/UV ON BOND PLANES
# Delamination History Noted in P/FR System

<table>
<thead>
<tr>
<th>Test</th>
<th>Vendor</th>
<th>V</th>
<th>W</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procurement</td>
<td>I</td>
<td>II</td>
<td>I</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>Temperature Cycle</td>
<td>2</td>
<td>9</td>
<td>8</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Humidity</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity Freeze</td>
<td>1</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity Heat</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>3</td>
<td>3</td>
<td></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>JPL Field Test</td>
<td>4</td>
<td></td>
<td>3</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

# Failure Analysis Technique Developments

- LASER SCAN SYSTEM
- CRACK DETECTION
- SURFACE VARIATIONS
- SHORTED CELLS
- SHADOW MASKING
- FRACTIONAL MEASUREMENT OF CELLS
- COMPARISON OF SHUNT RESISTANCE CELL-TO-CELL

6-28
MIT/LINCOLN LABORATORY MODULE
DEGRADATION ANALYSIS PROGRAM

1. Field inspection and location of electrically
defective modules.

2. In-house visual examination and analysis of modules
   returned from the field.

3. Soil accumulation studies of modules from Nebraska,
   Chicago, New York City, Cambridge and Lexington.

Schematic of a typical Sensor Tech string in Nebraska.

4 modules in parallel = 1 quad

9 quads in series = 1 string

6-29
LOCATING ELECTRICALLY DEFECTIVE
MODULES

1. Isolate string from ground and open-circuit
   the string in a test box. Measure the leakage-
   current to ground.

2. Measure the short-circuit current of each quad
   in the string.

3. If one open module exists, \( I_{SC} \) will be \( 3/4 \) of
   the normal short-circuit current.

LOCATING THE OPEN MODULE

1. Shadow each module in the defective quad and
   monitor short-circuit current.

2. Shadowing working modules will change the short-
   circuit current from \( 3/4 I_{SC} \) to \( 1/2 I_{SC} \).

3. Shadowing an open module will produce no meter
   response.
### Module Performance in Nebraska

#### From 7/15/77 to 4/1/78

<table>
<thead>
<tr>
<th></th>
<th>Front Row</th>
<th>Back Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Modules</td>
<td>728</td>
<td>1512</td>
</tr>
<tr>
<td>Electrical Failures</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Safety Hazard Due To</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed Interconnects,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cells or Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Elements</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

### Nebraska Field Inspection

#### Results 3/27/78 Through 3/30/78

<table>
<thead>
<tr>
<th></th>
<th>Front Row</th>
<th>Back Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules Observed</td>
<td>342</td>
<td>698</td>
</tr>
<tr>
<td>Exposed Interconnects</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Exposed Cell</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Exposed Ground Screw/Bus Bar</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Splits Down to Active Element</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Newly Cracked Cells</td>
<td>11</td>
<td>81</td>
</tr>
<tr>
<td>Multiple Cracked Cells</td>
<td>1</td>
<td>22</td>
</tr>
</tbody>
</table>

#### Delamination

<table>
<thead>
<tr>
<th></th>
<th>Front Row</th>
<th>Back Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Seal</td>
<td>ALL</td>
<td>175</td>
</tr>
<tr>
<td>Terminal Area</td>
<td>1</td>
<td>533</td>
</tr>
<tr>
<td>Cell (Over or Around)</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>Interconnect (Over or Around)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Mounting Boss</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Ground Screw</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>Encapsulant Torn Around</td>
<td>0</td>
<td>220</td>
</tr>
<tr>
<td>Mounting Boss</td>
<td></td>
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</tr>
</tbody>
</table>
## MIT/LINCOLN LABORATORY SOIL ACCUMULATION STUDIES

<table>
<thead>
<tr>
<th>Manufacturer (Cover)</th>
<th>Power Loss by Location (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIT (5 Mos.)</td>
</tr>
<tr>
<td>A - (Glass)</td>
<td>6</td>
</tr>
<tr>
<td>B - (RTV &amp; Hard Coat)</td>
<td>10.6</td>
</tr>
<tr>
<td>C - (RTV)</td>
<td>13.2</td>
</tr>
<tr>
<td>D - (RTV)</td>
<td>14.2</td>
</tr>
</tbody>
</table>

## MIT/LINCOLN LABORATORY SOIL ACCUMULATION STUDIES NEBRASKA FIELD SITE

<table>
<thead>
<tr>
<th>Manufacturer (Cover)</th>
<th>Power Loss % (Sample Size)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Mos.</td>
</tr>
<tr>
<td>C - (RTV)</td>
<td>–</td>
</tr>
<tr>
<td>D - (RTV)</td>
<td>1.2-7.2 (11)</td>
</tr>
</tbody>
</table>
"Characterization of Solar Cell Performance" was the subject of a tutorial lecture by Dr. Henry Brandhorst (LeRC). The viewgraphs that follow were presented during this lecture. For further information, readers are referred to ERDA, NASA 1022/76/8, NASA CP-2010, Technical Report III-1, "Introduction to Basic Solar Cell Measurements," by Henry W. Brandhorst, Jr.

**CHARACTERIZATION OF SOLAR CELL PERFORMANCE**

- LIGHT SOURCES
- I-V CURVE MEASUREMENT
- TEST CONDITIONS

**LIGHT SOURCES USED FOR PERFORMANCE MEASUREMENT**

- SUNLIGHT
- TUNGSTEN LAMPS
  - ELH LAMP (≈ AM2)
  - 3400°K LAMP PLUS WATER FILTER
- XENON ARC LAMPS
- PULSED XENON LAMPS
CONSIDERATIONS FOR SUNLIGHT MEASUREMENTS

- MONITOR ATMOSPHERIC COMPOSITION
  - $H_2O$ VAPOR
  - TURBIDITY
- REFERENCE CELL OR PYRANOMETER FOR IRRADIANCE MONITORING
- CONTROL TEST TEMPERATURE (FOR CELLS)
- CORRECT DATA TO SINGLE REFERENCE CONDITION (e.g. 100 mW/cm², 28°C)
- ORIENTATION

REQUIREMENTS FOR ARTIFICIAL LIGHT SOURCES

- UNIFORMITY ($\pm 2\%$)
- SPECTRAL DISTRIBUTION
- STABILITY
- REPRODUCIBILITY (USE OF REFERENCE CELLS)
Spectral distribution of terrestrial sunlight

Spectral distribution of xenon lamp simulator
Spectral distribution of ELH lamp simulator

Spectral distribution of tungsten lamp simulator

6-36
SPECTRAL DISTRIBUTION OF SOLAR SIMULATORS

RELATIVE RESPONSE/0.1 μm BANDWIDTH

CURRENT-VOLTAGE CURVES OF A Cu₂S-CdS CELL ILLUMINATED WITH RED AND WHITE LIGHT
MEASURED $I_{sc}$ FOR VARIOUS TERRESTRIAL CELLS USING Z-01 AS A STANDARD UNDER DIFFERENT SOLAR SIMULATORS

<table>
<thead>
<tr>
<th>CELL</th>
<th>SUNLIGHT</th>
<th>XENON</th>
<th>TUNGSTEN</th>
<th>ELH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{sc}$</td>
<td>%Δ</td>
<td>$I_{sc}$</td>
<td>%Δ</td>
</tr>
<tr>
<td>Z-01</td>
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<td>113.6</td>
<td>112.9</td>
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<td>Z-06</td>
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Comparison of spectral responses of cells Z-00 and Z-01
Comparison of spectral responses of cells Z-23 and Z-01

Comparison of spectral responses of cells Z-27 and Z-01
Comparison of spectral responses of cells Z-70 and Z-01

Transmission curves for broad-band filters
Comparison of Cell and Module Spectral Response

REFERENCE ATMOSPHERIC CONDITIONS

- AIR MASS: 1.5
- WATER VAPOR: 2.0 cm
- TURBIDITY: 0.12
- OZONE: 0.34 cm

NASA-LeRC, 5/7/77
Effect of water vapor on the calibration factor.

CIRCUIT DIAGRAM OF CURRENT-VOLTAGE CURVE PLOTTER
Comparison of calibration factor measured under collimated and uncollimated conditions

<table>
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<th>UNCOLLIMATED CAL. FACTOR*</th>
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<td>CELL Y-56</td>
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<td>SILICONE RESIN</td>
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</table>

\[ \text{MA} \quad \text{mW/cm}^2 \]

 CONDITIONS FOR CELL MEASUREMENTS

TEMPERATURE - 28 ± 2°C
LIGHT SOURCE - (FILTERED Xe - ELH PULSED Xe)
INTENSITY - (100 mW/cm²)
AREA - TOTAL CELL AREA
I_{SC} - ≤ 20 mV
V_{oc} - R_{meter} > 10^4 Ω/V
EFFICIENCY - \[ \frac{I_m \cdot V_m}{A} = 100 \text{ mW/cm}^2 \]
AIDS TO ACHIEVING REPRODUCIBLE PERFORMANCE MEASUREMENTS

- VACUUM HOLD-DOWN FOR CELL
- TEMPERATURE CONTROLLED TEST PLANE (28 ± 2 C)
- 4-WIRE ELECTRICAL CONNECTIONS
- ADJUST LIGHT LEVEL WITH CALIBRATED REFERENCE CELL

TYPES OF EQUIPMENT FOR I-V CURVE MEASUREMENTS

- FIXED LOAD RESISTOR BANK
- VARIABLE POWER SUPPLY (BATTERY ETC.)
- ELECTRONIC LOAD
- CALCULATOR-CONTROLLED ELECTRONIC LOAD AND DATA ACQUISITION AND REDUCTION SYSTEM

![Diagram of an intermediate reference cell](image)
BASIC DIAGNOSTIC INFORMATION

- **I-V CHARACTERISTIC**
  - SHUNT RESISTANCE
  - SERIES RESISTANCE
  - JUNCTION QUALITY

- **FORWARD DIODE CHARACTERISTIC**
  - DARK FORWARD
  - LIGHT FORWARD
  - \( V_{oc} \) \( I_{sc} \)
  - SATURATION CURRENT DENSITY

- **SPECTRAL RESPONSE**
  - MONOCHROMATIC
  - BIAS LIGHT

- **DIFFUSION LENGTH**

Solar cell current-voltage characteristics
(Current axis, vertical, voltage axis horizontal)

- **GOOD**
  - HIGH FILL FACTOR
  - a

- **POOR**
  - JUNCTION
  - b

- **LOW SHUNT RESISTANCE**
  - c

- **HIGH SERIES RESISTANCE**
  - d

- **NON-OHMIC CONTACT**
  - e

- **EXTREMELY HIGH SERIES RESISTANCE**
  - f

- **EXTREMELY LOW SHUNT RESISTANCE**
  - g

6-45
SERIES RESISTANCE MEASUREMENT TECHNIQUES

- TWO LIGHT LEVEL (WOLF AND RAUSCHENBACH)
- FAR FORWARD CHARACTERISTIC \( \Delta V \) 300-400 ma
- DARK FORWARD \( V_{oc} - I_{sc} \) SUBTRACTION
- LIGHT FORWARD \( V_{oc} - I_{sc} \) SUBTRACTION
- DIFFERENCE BETWEEN OBSERVED AND THEORETICAL SLOPE AT \( V_{oc} \)

Solar cell forward I-V characteristics measured by dark and illuminated methods
Quantum yield of a CdS solar cell
TECHNIQUES FOR DIFFUSION LENGTH/LIFETIME MEASUREMENT

OPTICAL
- PENEATING RADIATION
  - X-RAYS
  - 1 MeV ELECTRONS
  - INFRARED LIGHT (1.1 > λ > 0.9 µm)
- PHOTOCNDUCTIVE DECAY
- STEADY STATE PHOTOCONDUCTIVITY
- SURFACE PHOTOVOLTAGE

ELECTRICAL
- OPEN CIRCUIT VOLTAGE DECAY
- COLLECTION OF STORED CHARGE (CURRENT DECAY)
APPENDIX A

AGENDAS

Wednesday, April 12, 1978

7:45 - 8:30 Registration (Coffee Available) ......................... Baxter/Ramo Lobby
8:30 - 9:40 Announcements - M. Prince/L. Magid/R. Forney (30 min) .... Ramo Auditorium
DOE Environmental Research Program for PV - E. Frankel (20 min) .... Ramo Auditorium
SAMICS News & Price Goal Allocation Update - W. Callaghan (10 min) .... Ramo Auditorium
Late News (10 min) ......................................................... Ramo Auditorium

9:40 - 10:00 Coffee Break
10:00 - 12:15 Encapsulation Assessment: Meeting 1986 Goals - C. Coulbert .......... Ramo Auditorium
12:15 - 1:15 Lunch Break

1:15 - 5:30 CRYSTAL GROWTH SILICON ION IMPLANTATION FOR MODULE EXPERIENCE
REPLENISHMENT & REFRACTORY SOLAR CELL PRODUCTION;
MATERIALS DEVELOPMENTS PRESENTATIONS BY SPIRE CORP.
M. Leipold, 3½ hr, Ramo Aud D. Bickler, 4 hr, Gates 22
L. Dumas, 2 hr, Baxter Lec Hall

2:30 - 4:00 Coffee Available at Baxter/Ramo Lobby
5:30 - 6:30 Task 1 Intra-Task Session - R. Lutwack ................................ Baxter Lecture Hall

Thursday, April 13, 1978

7:30 - 9:00 Coffee Available at Baxter/Ramo Lobby
8:00 - 12:15 COMPOSITIONAL ANALYSIS SOLAR CELL METALLIZATION;
OF SILICON PRESENTATIONS BY 4 CONTRACTORS
R. Lutwack, 3 hr, Baxter Lec Hall D. Bickler, 4 hr, Beckman 24

10:15 - 11:30 Coffee Available at Baxter/Ramo Lobby
11:15 - 12:15 SOLAR CELL PERFORMANCE MEASUREMENTS
H. Brandhorst, 1 hr, Gates 22

11:15 - 12:15 Task 1 Intra-Task Session - R. Lutwack .......................... Baxter Lecture Hall
12:15 - 1:30 Lunch Break

1:30 - 3:00 SOLAR CELL PERFORMANCE MEASUREMENTS (Cont.) SAMIS COMPUTER PROGRAMMING Task 1 Intra-Task
H. Brandhorst, 1 hr, Gates 22 SESSION (1½ hr) Session
R. Chamberlain, Kerckhoff 119 R. Lutwack, 1½ hr, Baxter Lec Hall
In addition: Solar cell and module sessions may continue as desired;
Special sub-sessions may be convened

2:15 - 3:30 Coffee Available at Baxter/Ramo Lobby
2:30 - 3:00 Module Requirements Summary; for Task 2 - R. Ross (30 min) ........ Beckman Labs 24
3:30 - 5:00 Summary .......................................................... Ramo Auditorium
Silicon Sheet and Ingot Status (4/11 meeting summary) - K. Koliwad (30 min)
Technology Development - J. Goldsmith (30 min)
Comments - M. Prince/R. Forney

5:00 End of Meeting

Intrastask and intertask meeting agendas are shown on the following pages.


A-1
Crystal Growth Silicon Replenishment and Refractory Material Developments

Wednesday, April 12 1:15-5:00

Chairmen: M. Leipold and Lee Hunt

I. Forms of Silicon from Processes Under Development — Solid (Size, Shape), Liquid, Gas

II. Transport and Injection Experience — Melt or Gas

III. Materials That Are Used in Contact with Molten Silicon

Battelle
Coors-Porcelain
Eagle-Picher
RCA
Tylan Inc.
Comments from others
Discussion
Coffee

IV. User Requirements

V. Molten Silicon Properties

VI. Implications and Future Activities

VII. Summary

R. Lutwack, 20 min

Open discussion, 30 min

80 min

Open discussion, 15 min

Open discussion, 20 min

Open discussion, 30 min

M. Leipold, 10 min
Detail Agendas

Encapsulation Assessment – Meeting 1986 Goals

Wednesday, April 12  10:00-12:15

I. Encapsulation Task  Cliff Coulbert
   a. Objective and Approach
   b. Scope and Status of contract and in-house work on materials, processes, and life prediction.

II. Material U.V. Degradation and Test Methods  Amitava Gupta

III. Approach to Low-Cost 1986 Encapsulant System Design  Ed Cuddihy

IV. Assessment  Cliff Coulbert
   c. Experimental Results and Conclusions.
   d. Plans for Near and Long-Term R&D.
Module Experience

Wednesday, April 12 1:15-3:15

Chairman: L. Dumas

Introduction
Environmental Test Results
Field Test Results
Problem/Failure Analysis
Test and Application Project Experience
Discussion
L. Dumas, 10 min
J. Griffith, 20 min
P. Jaffe, 20 min
S. Sollack, 20 min
S. Forman (MIT/LL), 20 min
30 min

Module Engineering Agenda

Wednesday, April 12 3:30-5:30

Chairman: R. Ross

Design Requirement Studies
Boeing Air Enclosure Study
Bechtel Central Power Study
D. Zimmerman, 20 min
W. Stolte, 20 min
Reliability Studies
Cell Reliability Testing (Clemson Univ)
Series/Parallel Redundancy Study
J. Prince, 20 min
C. Gonzalez, 20 min
Module Testing
U.V. Humidity Testing
Module Testing Potpourri
A. Garcia, 20 min
R. Ross, 20 min
Applications of Ion Implantation to Solar Cell Production

Wednesday, April 12 1:15-5:30

Chairman: D. Bickler
Presentations by Spire Corporation

I. Introduction: Basic Theory and Technical Description
   Allen R. Kirkpatrick, 40 min

II. Rationale for Solar Cell Production Using Implantation
    Allen R. Kirkpatrick, 10 min

III. Ion Implantation Equipment
   a. Existing Machines and Special Requirements for Solar Cells
      Allen R. Kirkpatrick, 15 min
   b. Study of Implanter Design for High Volume Automated Production
      Peter H. Rose, 30 min

Coffee Break
   20 min

IV. Ion Implanted Solar Cell: Performance Status and Process Descriptions
    John A. Minnucci, 45 min

V. Advanced Technology: Combined Ion Implantation – Directed Energy Methods
   John A. Minnucci, 20 min

VI. Production Line Considerations: Development Requirements, Schedule, Economics
    Allen R. Kirkpatrick, 15 min

VII. Workshop Discussion
     45 min
COMPOSITIONAL ANALYSIS OF SILICON

Thursday, April 13

8:00 - 11:15

CHAIRMAN: R. Lutwack

NATIONAL BUREAU OF STANDARDS

R. Lindstrom
P. Paulson
H. Rook

LIVERMORE LABORATORIES

R. Heft

DOW CORNING/WESTINGHOUSE

J. McCormick/R. Hopkins

WESTINGHOUSE - IMPURITY EFFECTS

R. Hopkins/R. Davis

COMMENTS by Task II

DISCUSSION:
TASK I: INTRA-TASK AGENDAS

PROGRESS REPORTS OF SILICON REFINEMENT PROCESS DEVELOPMENTS

Chairman: R. Lutwack

WEDNESDAY, APRIL 12, 1978 5:15 p.m. - 6:15 p.m.

AeroChem ..................... H. Calcote
Dow Corning .................... L. Hunt
Motorola ......................... R. Rosler
J. Schumacher .................... L. Woerner

THURSDAY, APRIL 13, 1978 11:15 a.m. - 12:15 p.m.

SRI International ................. L. Nanis/R. Bartlett
AeroChem ......................... W. Miller

THURSDAY, APRIL 13, 1978 1:30 p.m. - 3:00 p.m.

Battelle ......................... P. Browning
Union Carbide .................... H. Morihiro
Westinghouse ...................... M. Fey
JPL and contractor Encapsulation Task personnel will be prepared to answer in detail questions from the floor:

Round table discussion of:

A. Materials and Processes:
   . Critique of test results
   . Assessment of technology readiness
   . Technology voids perceived
   . R&D approaches to 1986 goal achievement

B. Life Prediction and Material Aging
   . Life-limiting failure modes
   . Industry approach to achievement of long life
   . Industry/Government efforts required for predicting module life & failure rates
### Solar Cell Metallization

**Thursday, April 13  8:00-12:15**

**Chairman: D. Bickler**

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<tr>
<td>Introductory Remarks</td>
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<tr>
<td>RCA Presentation on Thick Film Metallization</td>
<td>40 min</td>
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<tr>
<td>Discussion</td>
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<tr>
<td>Solarex Presentation on Negative Silk Screen and Plating Metallization</td>
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<tr>
<td>Motorola Presentation on Nickel-Palladium Plating Metallization</td>
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<tr>
<td>SpectroLab Presentation on Thick Film Metallization</td>
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**Don Bickler, 10 min**
AGENDA FOR TASK II
CRITICAL REVIEW OF TECHNOLOGY FOR
LARGE AREA SILICON SHEET DEVELOPMENT

J.P.L. Bldg. 167 (Cafeteria) - Entrance left of Cafeteria

Tuesday, April 11, 1978

Ribbon Technologies

8:00 A.M. Mobil Tyco Solar Energy Corporation
9:00 A.M. Westinghouse Corporation
10:00 A.M. Motorola Inc.
11:00 A.M. Honeywell Corporation

Ingot Cast Technology

1:00 P.M. Crystal Systems
2:00 P.M. Varian
2:30 P.M. Hamco
3:00 P.M. Siltec
3:30 P.M. Coffee
3:45 P.M. Texas Instruments

Wafering Technology

4:15 P.M. Varian
5:15 P.M. Crystal Systems
5:45 P.M. J.P.L. (Geos Saw)
The SAMIS III computer program is now available for determination of standardized price estimates. This tutorial on its capabilities and its use complements the workshop on input data preparation and the interim manual calculation procedure which was held at the 8th PIM (December 1977).

I. How to Use the SAMIS III Computer Program

II. SAMIS III Reports

III. What Goes on Inside the Program

IV. Validation, with Emphasis on the User's Role

V. Discussion
LOW COST SILICON SOLAR ARRAYS
ENCAPSULATION TASK
INTRA-TASK MEETING

April 11, 1978 9:00 A.M. - 5:00 P.M.
JPL Bldg 169- Room 531

Chairman: Cliff Coulbert, Task Manager

9:00 Introduction - Cliff Coulbert (20 min)
9:15 SPIRE (15 min)
9:45 ENDUREX (30 min)
10:05 SPRINGBORN (20 min)
10:40 COFFEE BREAK
10:50 Dow Corning (15 min)
11:15 Battelle (20 min)
12:00 LUNCH
1:00 Rockwell Int. (25 min)
1:30 Rockwell Science Center (20 min)
2:00 Case Western (20 min)
2:25 Caltech (10 min)
2:45 JPL-Ami Gupta (20 min)
3:15 JPL-Ed Cuddihy (20 min)
3:45 JPL-Cliff Moran (8 min)
4:00 JPL-Bob Holtze (20 min)
4:30 JPL-Motorola Hugh Maxwell (10 min)
4:45 Closing Remarks Cliff Coulbert (20 min)
5:00 Adjourn

Note: This is a tight schedule. A discussion period of five to ten minutes has been provided between each speaker. We will have to start each speaker at the time indicated and limit the preceding speakers accordingly.
APPENDIX B

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