MEASURING RESEARCH PROGRESS IN PHOTOVOLTAICS

JET PROPULSION LABORATORY

B. Jackson and P. McGuire

Role of PA&I

SUPPORTING THE DECISION-MAKING PROCESS
PREPARATION OF PLANS FOR PROJECT DIRECTION
SETTING GOALS FOR PROJECT ACTIVITIES
MEASURING PROGRESS WITHIN THE PROJECT
DEVELOPMENT AND MAINTENANCE OF ANALYTICAL MODELS

Module Cost Versus Time
Original Goals of FSA Project

MODULE PERFORMANCE:
50¢/Wp (1974 DOLLARS)
10% MODULE EFFICIENCY
20 YEAR LIFETIME

26¢/kWh (1985 DOLLARS)

Costs Involved in the Use of State-of-the-Art
Czochralski Silicon Technology

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>1985$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILICON MATERIAL</td>
<td>0.390</td>
</tr>
<tr>
<td>INGOT GROWTH</td>
<td>0.368</td>
</tr>
<tr>
<td>INGOT SAWING</td>
<td>0.304</td>
</tr>
<tr>
<td>CELL FABRICATION</td>
<td>0.208</td>
</tr>
<tr>
<td>MODULE ASSEMBLY</td>
<td>0.179</td>
</tr>
<tr>
<td>TOTAL COST (1985$)</td>
<td>$1.45/Wp</td>
</tr>
<tr>
<td>ENERGY COST (Using Baseline Parameters of the National PV Program)</td>
<td>$0.275/kWh</td>
</tr>
</tbody>
</table>

Assumptions Made in Arriving at Costs Involving Czochralski Silicon

FACTORY SIZE
25 MWp/yr

YEAR OF PRODUCTION
1988

SILICON COST, 1985$/kg
$43/kg

CRYSTALLIZATION RATE
1.5 kg/hr (Cz)

INGOT DIAMETER
5 in.

SAWING SLICE + KERF
19 mil

SAWING BLADE PLUNGE RATE
2.0 in./min

SAWING YIELD
95%

CELL SIZE
9.83 x 9.83 cm MODIFIED SQUARE

AREA PER CELL
94.6 cm²

PACKING FACTOR
91.4%

MODULE SIZE
122 cm x 61 cm (4 ft x 2 ft)

MODULE POWER
101 Wp

ENCAPSULATED CELL EFFICIENCY
14.8%

MODULE EFFICIENCY, STC
13.5%
Costs Involved in the Use of Dendritic Web Technology (Projection)

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>1985$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILICON MATERIAL</td>
<td>0.153</td>
</tr>
<tr>
<td>WEB GROWTH</td>
<td>0.341</td>
</tr>
<tr>
<td>CELL FORMATION</td>
<td>0.119</td>
</tr>
<tr>
<td>METALLIZATION</td>
<td>0.162</td>
</tr>
<tr>
<td>MODULE ASSEMBLY</td>
<td>0.244</td>
</tr>
<tr>
<td><strong>TOTAL COST (1985$)</strong></td>
<td>$1.02/Wp</td>
</tr>
<tr>
<td><strong>ENERGY COST (Using Baseline Parameters of the National PV Program)</strong></td>
<td>$0.220/kWh</td>
</tr>
</tbody>
</table>

Module Cost Versus Dendritic Web Growth Rate
National Research Program Goals

REVISED SINCE BEGINNING OF PROJECT

SLOWER INCREASES IN CONVENTIONAL ENERGY COST
HIGHER BALANCE OF SYSTEM COST

PRESENT PROGRAM GOALS

17.1d/kWh (1985 DOLLARS) FOR LIFECYCLE ENERGY COST

SAMICS Methodology

ESTIMATES MODULE PRODUCTION COSTS
COSTS DEVELOPED FROM INDIVIDUAL PROCESS DESCRIPTIONS
BASED ON COMPANY DESIGNED SPECIFICALLY FOR MODULE PRODUCTION
METHODOLOGY ASSURES COMPARABILITY OF FINDINGS

Annual Cost for Each Process Step in the Production of Solar Cell Modules (in 1975 $/Wp)

<table>
<thead>
<tr>
<th></th>
<th>Value Added</th>
<th>Capital Costs</th>
<th>Direct Labor</th>
<th>Materials &amp; Supplies</th>
<th>Utilities</th>
<th>Indirect Expenses</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILICON PREP*</td>
<td>0.043</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet Fab</td>
<td>0.145</td>
<td>0.063</td>
<td>0.0312</td>
<td>0.0140</td>
<td>0.0049</td>
<td>0.0320</td>
<td>0.800</td>
</tr>
<tr>
<td>P + Back</td>
<td>0.002</td>
<td>0.0010</td>
<td>0.0004</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0005</td>
<td>0.998</td>
</tr>
<tr>
<td>Etch</td>
<td>0.010</td>
<td>0.0036</td>
<td>0.0018</td>
<td>0.0033</td>
<td>0.0000</td>
<td>0.0018</td>
<td>0.994</td>
</tr>
<tr>
<td>Ion Implant</td>
<td>0.012</td>
<td>0.0067</td>
<td>0.0018</td>
<td>0.0000</td>
<td>0.0003</td>
<td>0.0032</td>
<td>0.998</td>
</tr>
<tr>
<td>Pulse Anneal</td>
<td>0.066</td>
<td>0.0038</td>
<td>0.0004</td>
<td>0.0000</td>
<td>0.0003</td>
<td>0.0011</td>
<td>0.992</td>
</tr>
<tr>
<td>Back Metal</td>
<td>0.036</td>
<td>0.0108</td>
<td>0.0013</td>
<td>0.0206</td>
<td>0.0005</td>
<td>0.0030</td>
<td>0.980</td>
</tr>
<tr>
<td>Front Metal</td>
<td>0.036</td>
<td>0.0111</td>
<td>0.0013</td>
<td>0.0202</td>
<td>0.0005</td>
<td>0.0030</td>
<td>0.980</td>
</tr>
<tr>
<td>AR Cost</td>
<td>0.009</td>
<td>0.0038</td>
<td>0.0018</td>
<td>0.0014</td>
<td>0.0002</td>
<td>0.0016</td>
<td>0.990</td>
</tr>
<tr>
<td>INTERCON</td>
<td>0.033</td>
<td>0.0104</td>
<td>0.0040</td>
<td>0.0135</td>
<td>0.0000</td>
<td>0.0054</td>
<td>0.995</td>
</tr>
<tr>
<td>Encapsulate &amp; Assemble</td>
<td>0.130</td>
<td>0.0368</td>
<td>0.0062</td>
<td>0.0750</td>
<td>0.0001</td>
<td>0.0120</td>
<td>0.999</td>
</tr>
<tr>
<td>Test</td>
<td>0.001</td>
<td>0.0003</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.980</td>
</tr>
<tr>
<td>Package</td>
<td>0.001</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.9999</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.464</strong></td>
<td><strong>0.1515</strong></td>
<td><strong>0.0505</strong></td>
<td><strong>0.1918</strong></td>
<td><strong>0.0068</strong></td>
<td><strong>0.0639</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Based on 10 $/kg silicon
SIMRAN Methodology

EVALUATION OF COMPLEX R&D DECISIONS
SIMULTANEOUS CONSIDERATION OF SEVERAL PATHS OF ACTION
ELEMENTS OF EACH PATH CAN BE DESCRIBED AS UNCERTAIN

Task Network for Solar-Cell Module Production (SIMRAND)
Cumulative Probability Versus Solar Cell Cost

Comparison of Cumulative Probability Versus Cost for Various Ways to Produce Silicon
LCP Methodology

SIMULATES LIFETIME PERFORMANCE OF PV SYSTEM

ESTIMATES SYSTEM OUTPUT, REVENUES AND COSTS

MODELS LOCATION SPECIFIC ENVIRONMENT

APPLICABLE TO UTILITY, RESIDENTIAL OR COMMERCIAL INSTALLATIONS

LCP Simulation
SMUD Net Load Versus Time of Day
(0 and 5% Penetration on a July Peak Day)

FIXED, TILT = LAT, AZIMUTH = 30 DEG.

PVARRAY Methodology

USED TO OPTIMIZE ARRAY DESIGN
SELECT DIODE PLACEMENT
COMPARE ALTERNATE MODULE REPLACEMENT STRATEGIES
Fraction of Array Power Versus Time
(Cell Failure Rate = $1 \times 10^{-4}$/year)

Economic Evaluation Methodology for PV Array Design

CELL SPECS ----> P V ARRAY
CIRCUIT DESIGN ---> PEAK POWER vs TIME ---> HOURLY ENERGY
MAX POWER ----> SYSTEM DESCRIPTION ---> vs. TIME
CELL FAILURE RATE ---> WEATHER DATA ----> PRE-TAX REVENUE
REPLACEMENT RATE ---> ABOS & PBOS COSTS ---> FROM PV
---+O&M COSTS
---+SOILING PROFILE
---+RATE STRUCTURE
---+GEN. ECON. DATA
---+MODULE COSTS

PROCESSES DESC. ----> PROCESS VALUE ADDED
CO. FINANCIAL ----> SAMICS
CO. DESCRIPTION ----> LOGICAL COLLECTION OF
IND. DESCRIPTION ----> (LOAD SERVICED BY PV)
ANNUAL PRODUCTION ----> (FLEC. PURCHASES)

SAMICS: SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS
LCP: LIFETIME COST AND PERFORMANCE MODEL
This session consisted of eight presentations on reliability physics.

R. Liang, of JPL, reported that there have been observations of cracks forming in Tedlar back cover films on PV modules mounted outdoors in the natural environment. The cracks appear to approximate reasonable straight lines and, in general, are parallel to each other. It is implied that the directionality of these cracks may be in some way related to film orientation. Preliminary results from JPL studies investigating the causes of these cracks indicate that Tedlar does not become brittle on aging. It was speculated that perhaps compounding ingredients employed in EVA may migrate into the Tedlar film, thus causing a potential for chemical effects. This will be investigated.

On another topic, an experimental technique called "Flash Electron Spin Resonance (ESR)" was described which offers the promise of a quick method for identifying upper temperature limits for accelerated testing of module encapsulation materials.

The presentation by C. Gonzalez, of JPL, described a new, combined environmental aging chamber that was developed at JPL. The chamber has an ultraviolet (UV) light source that can be varied between 1 to 2 suns, temperature control from -40 to +175°C, and adjustable relative humidity. Results from two initial aging experiments (Tedlar and amorphous silicon solar cells) were presented.

J. Guillet reported that the University of Toronto is developing a computer program to simulate the photothermal degradation of materials exposed to terrestrial weathering environments. Input parameters would include the solar spectrum, the daily levels and variations of temperature and relative humidity, and materials such as EVA. A brief description of the program, its operating principles, and how it works was initially described. After that, the presentation focused on the recent work of simulating aging in a normal, terrestrial day-night cycle. This is significant, as almost all accelerated aging schemes maintain a constant light illumination without a dark cycle, and this may be a critical factor not included in acceleration aging schemes. For outdoor aging, the computer model is indicating that the night dark cycle has a dramatic influence on the chemistry of photothermal degradation, and hints that a dark cycle may be needed in accelerated aging schemes.

E. Plueddemann reported that Dow Corning is developing the primers employed in bonding together the various material interfaces in a PV module (such as EVA to glass, for example). The Dow Corning approach develops interfacial adhesion by generating actual chemical bonds between the various materials being bonded together. Dr. Plueddemann described the current status of this program, and the progress toward developing two general purpose primers for EVA, one for glass and metals, and another for plastic films.

J. Boerio reported that the University of Cincinnati is studying the aging behavior of chemically bonded interfaces between metals and pottants, such as EVA, using the Dow Corning primer systems. As part of this study, it
has been observed that the primers seem to function as anticorrosion agents on metal surfaces. Dr. Boerio has been able to demonstrate that EVA, and the A-11861 EVA/glass primer will stop corrosion of the aluminum used on the back surfaces of crystalline silicon solar cells. However, this same treatment does not seem to work for the aluminum on the back surfaces of amorphous silicon solar cells. This is being investigated.

G. Mon reported that leakage currents are being experimentally measured by JPL in PV modules undergoing natural aging outdoors, and in PV modules undergoing accelerated aging in laboratory environmental chambers. The intent is to identify the significant contributors to module leakage currents, with a long-term goal to develop corrective technologies to reduce or stop module leakage currents. For outdoor aging in general, module leakage current is relatively insensitive to temperature fluctuations, but is very sensitive to moisture effects such as dew, precipitation, and fluctuations in relative humidity. Comparing EVA and polyvinyl butyral (PVB), module leakage currents are much higher in PVB as compared to EVA for all environmental conditions investigated. Leakage currents proceed in series along two paths, bulk conduction followed by interfacial (surfaces) conduction. It is being experimentally observed that leakage current is limited by bulk conduction in EVA modules, but that bulk conduction and interfacial conduction is about the same in PVB modules.

A theoretical modeling of leakage current in EVA and PVB modules is being developed and was described by A. Wen, of JPL. The modeling effort and the experimental effort, described by G. Mon, are two parts of a comprehensive study. The modeling effort derives mathematical relationships for the bulk and surface conductivities of EVA and PVB, the surface conductivities of glass and polymer films, and the interfacial conductivity between glass, polymer films, and the EVA and PVB pottants, all as functions of environmental parameters (temperature, RH, etc.). Some results from the modeling indicate that for glass/EVA, the glass surface controls the interfacial conductivity, although EVA bulk conductivity controls total leakage current. For PVB/glass, the interface conductivity controls leakage currents for RH less than 40 to 50%, but PVB bulk conductivity controls leakage current above 50% RH. This modeling work is continuing.

J. Orehotsky, of Wilkes College, reported that the interface between plastic film back covers and EVA or PVB in PV modules can influence water permeation, and electrical properties of the composite such as leakage current and dielectric constant. The interface can either be of two dissimilar materials in physical contact with no intermixing, or the interface can constitute a thin zone which is an interphase of the two materials having a gradient composition from one material to the other. The former condition is described as a "discrete interface," and Professor Orehotsky was able to develop a discrete interface model to predict water permeation, dielectric strength, and leakage currents for EVA, EMA, and PVB coupled to Tedlar and Mylar films. At this PIM, he compared experimental data with predicted data, and speculated that, in general, EVA and EMA form discrete interfaces, whereas PVB tends to form an interface with an interphase. This developing theory is intended to explain the deviations from expectations for some combinations of materials, on the basis that the properties of the gradient composition interphase controls the interface. His work continues to develop an interphase model for property prediction.
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