AUTOMATED ARRAY ASSEMBLY

Quarterly Report No. 2

B. F. Williams

June 1976

Work Performed Under JPL Contract No. 954352

**RCA Laboratories
Princeton, New Jersey**

**ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy \$5.50 (domestic)
\$8.00 (foreign)
Microfiche \$2.25 (domestic)
\$3.75 (foreign)

PRRL-76-CR-31

AUTOMATED ARRAY ASSEMBLY

**B. F. Williams
RCA Laboratories
Princeton, New Jersey 08540**

QUARTERLY REPORT NO. 2

June 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

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

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

**Prepared Under Contract No. 954352 For
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91103**

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

PREFACE

This Quarterly Report, prepared by RCA Laboratories, Princeton, NJ 08540, describes work performed during April through June 1976 in the Communications Research Laboratory, K. H. Powers, Director; Process and Applied Materials Research Laboratory, P. Rappaport, Director; Materials Research Laboratory, J. J. Tietjen, Director; and at the Advanced Technology Laboratory, Government and Commercial Systems, Camden, NJ, P. Wright, Director. The Program Manager is B. F. Williams. Others who participated in the research and writing of this report are: R. D'Aiello, R. Denning, P. Joy, Jr., W. Kern, M. Krouthamel, D. Redfield, D. Richman, G. Schnable, B. Shelpuk, and J. Toner.

The JPL Project Monitor is Walter Hasbach.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

Section	Page
I. SUMMARY	1
II. INTRODUCTION	3
III. TECHNICAL DISCUSSION	4
A. Cost Analysis	4
B. Starting Materials	12
C. Processing Studies	13
1. Deposition of Metallization Patterns by Vacuum Evaporation	13
2. Deposition of Metallization Patterns by Thick-Film Screen-Printing Techniques	24
D. Panel Assembly and Design	36
1. Introduction to Panel Design Considerations	36
2. Baseline Module Assembly	38
3. Solar Cell Panel Computer Model Simulation (Thermal)	41
4. Solar Panel Life-Stress Analysis	48
5. Panel Materials Discussion	60
6. Panel Designs and Cost Breakdown	72
IV. CONCLUSIONS	78
V. RECOMMENDATIONS	80
VI. NEW TECHNOLOGY	81
REFERENCES	82
APPENDIX	83

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

LIST OF ILLUSTRATIONS

Figure	Page
1. Estimated cost per watt using Ti/Ag evaporation metallization . .	5
2. Estimated cost per watt using Al evaporation metallization. (Both Al processes, Figs. 2 and 4, will require a different bond- ing technique from that of the Ag processes. This has not yet been included; the only difference in these figures is the metallization cost itself.)	5
3. Estimated cost per watt using thick-film Ag metallization (screen printing)	6
4. Estimated cost per watt using thick-film Al metallization (screen printing)	6
5. Manufacturing cost estimate using Ti/Ag evaporation metallization	7
6. Baseline solar cell module	8
7. Process parameters for vacuum evaporation metal, Al	15
8. Process parameters for vacuum evaporation metal, Ti/Ag	17
9. Cost summary, step 9:Al metallization-front (includes 50.5% allocation of vacuum evaporation metal, Al)	19
10. Cost summary, step 10:Al metallization-back (includes 49.5% allocation of vacuum evaporation metal, Al)	20
11. Cost summary, step 9:Ti/Ag metallization-front (includes 50.5% allocation of vacuum evaporation metal, Ti/Ag)	21
12. Cost summary, step 10:Ti/Ag metallization-back (includes 49.5% allocation of vacuum evaporation metal, Ti/Ag)	22
13. Process parameters for thick-film Al metallizing, manual	26
14. Process parameters for thick-film Al metallizing, automatic	27
15. Process parameters for thick-film Ag metallizing, manual	28
16. Process parameters for thick-film Ag metallizing, automatic	29
17. Cost summary, step 9:thick-film Al metallizing, manual	31
18. Cost summary, step 9:thick-film Al metallizing, automatic	32
19. Cost summary, step 9:thick-film Ag metallizing, manual	33
20. Cost summary, step 9:thick-film Ag metallizing, automatic	34
21. Relationship between pressure and wind velocity	37
22. Preliminary layout assembly flow	40
23. Solar cell panel simulation model	43
24. Panel daytime heating and power loss vs ambient temperature, no wind	46

LIST OF ILLUSTRATIONS (Continued)

Figure	Page
25. Panel daytime heating and power loss vs wind velocity	47
26. Panel nighttime cooling, no wind	48
27. Interconnect expansion loop	50
28. (a) Finite element model of contact strength test configuration. (b) Stress contours in pull test configuration	51
29. (a) Finite element representation of typical interconnector solder joint area in cross section. (b) Finite element repre- sentation of typical welded joint area. (c) Typical inter- connector loop model for soldered joints, A, and its free body diagram and finite element representation, B	52
30. Model for method of universal slopes	53
31. (a) Schematic representation of weld joint. (b) Finite element model of the weld joint	54
32. Comparison of shear stresses for various interconnector materials materials	55
33. Solar array candidate design #1 cell backside mounting	73
34. Solar array candidate design #2 cell front side mounting	74
35. Solar array candidate design #3 diaphragm mount/thermal collector collector	75

LIST OF TABLES

Table	Page
1. Comparative Cost Summary	35
2. Thin and Thick Case Calculations for a Variety of Materials	57
3. Material Properties - Substrates	61
4. 1974 Metals Prices	62
5. Creep Properties of Plastics	64
6. Prices and 1974 Price Trends for Plastics	65
7. Material Properties - Substrates - Composites, Luminates	67
8. Flexural Load Capacity of Representative Expanded-Core Panels . . .	68
9. Material Properties - Clear Cover Sheets	69
10. Material Properties - Plastic Films - 1-mil Thick	71
11. Adhesive Price Changes and Availability, 1974 and 1975	72

SECTION I

SUMMARY

Our analysis of the existing technologies applicable to solar module fabrication is nearing completion. In this report, we describe as an example one basic module whose manufacturing costs were derived from first principles.

In this case, four basic cost analyses were made using our computerized cost analysis procedure. Excluding raw wafer cost, the estimated module processing cost per watt for the Ti/Ag evaporation metallization base case is about \$2.40. An experimental thick-film Al screen-printing technique could reduce the cost to about \$1.55/W. These estimates use a derived overall process yield of about 65%. The major cost of manufacture, however, is the raw wafer cost. If we assume \$2 to \$3 cost per starting 7.6-cm wafer (0.5 W), the array module total manufacturing cost (base case) is expected to be in the \$8.50 to \$11.50/W range; assuming 65% overall yield. Marketing, administrative, and distribution costs are enormously sensitive to the specific business situation but typically would result in a selling price at least twice the manufacturing cost.

We have reviewed the many elements of the materials matrix. From this review we conclude that wafers cut from pulled ingots of silicon are the only current commercial source of starting material for solar cell application. It is further concluded that the large effort into finding suitable cheaper forms of starting silicon has a reasonable probability for success, and, therefore, any processes developed for automated array assembly must be compatible with ribbon or rectangular starting material as well as circular wafers.

A module material study has been completed which indicates that it will be difficult to reduce the cost of materials used in module assembly to substantially less than \$10.00/m². It is not clear that the lowest cost alternatives can meet program life and environmental requirements. Task 3 results will be incorporated into the study as they become available. In the absence of such information, parallel designs are being pursued which utilize glass, plastic films, and conformal coatings.

Preliminary analytical efforts have been completed which show that 15 to 20% of the available panel output will be lost due to temperature rise of the

panel. Designs which structurally decouple the cells from the protective skins will surely require active cooling of the semiconductor.

Structural analysis has shown that thermal stress at the interconnect/cell interface will not limit panel life to less than 20 years. Further, it has been shown that structural deflections will not appreciably add to interconnector stress. Substrate moisture absorption could create stress and cell life problems and will be investigated further.

SECTION II

INTRODUCTION

As described in our program plan, our general approach to the entire problem of establishing a cost effective manufacturing procedure for the Automated Array Assembly task is two-fold. First, we are conducting an extensive analysis of existing technologies which may be applicable to array module fabrication and, second, we will propose solutions to any cost bottlenecks which appear. Accordingly, the beginning of this program has been devoted to studies into each of the identified technologies to estimate their manufacturing costs. These studies will be completed on schedule at the end of next month. The key to the cost comparisons is the cost accounting procedure adopted. In this report we have included part of the output of our study for four specific module fabrication processes which differ only in the metallization technique. As will be seen, the most important factors are starting wafer cost, process yield, and metallization. An important input to the cost analysis procedure is the calculated efficiency of a given cell-module configuration. We are continuing to evaluate cell design tradeoffs from the point of view of maximizing the performance while minimizing the cost.

In Quarterly Report No. 1 [1], manufacturing costs associated with most of the junction formation techniques were presented. In this report more emphasis is placed on metallization techniques and module fabrication. At the conclusion of this evaluation part of the program, a complete listing of the alternative manufacturing processes will be available.

-
1. B. F. Williams, "Automated Array Assembly," Quarterly Report No. 1, ERDA/JPL-954352-76/1, prepared under Contract No. 954352 for Jet Propulsion Laboratory, March 1976.

SECTION III

TECHNICAL DISCUSSION

A. COST ANALYSIS

Four alternative manufacturing schemes have been defined and cost estimates completed. These processes differ only in the metallization step used. The base case analysis utilizes the Ti/Ag evaporation metallization technique. Alternative schemes use Al evaporation metallization, and thick-film screen-printing of Ag or Al. Figures 1 through 4 show the estimated processing cost per watt of each of these processes, excluding fixed factory overhead and raw wafer cost. Raw wafer cost is quite significant. At an optimistic yield estimate of 65%, 1.5 starting wafers are needed to produce 1 final 0.5-W solar cell assembled into an array module.

Figure 5 shows the estimated cost per watt as a function of starting wafer cost for Ti/Ag evaporation metallization. In Fig. 5 the incoming "sheets" are 3-in. (7.6-cm) diameter wafers. These estimates do not include fixed factory overhead, which will add about \$0.23/W in the case of Ti/Ag.

Fixed factory overhead is currently estimated as 50% of direct labor cost. This includes such items as taxes, insurance, rent, process engineering, and other support functions. Although important from a total manufacturing cost viewpoint, these costs are not very sensitive to manufacturing process alternatives and are very small compared with present starting wafer costs. As the total manufacturing cost approaches \$0.50/W, a closer look at fixed factory overhead will be warranted. For starting wafer costs of \$2 to \$3, a manufacturing cost of \$8.50 to \$11.50/W is anticipated.

Selling price is very difficult to estimate. Manufacturing cost usually represents 35 to 50% of selling price. The markup is due primarily to marketing, administrative, and distribution costs. With a single large volume product line, these costs might be reduced.

The cost analysis procedure that has been developed utilizes a performance analysis to convert from cost per unit area to cost per watt. This procedure has been applied to a hypothetical, conventional array module for validation of the calculations. This module has an area of 0.93 m^2 (10 ft^2) and contains 140 wafer-type cells, each 7.62 cm (3 in.) in diameter, mounted in a hexagonal

PROCESS COST OVERVIEW-\$/WATT				
STEP	PROCESS	TOTALS	PER CENT	YIELD
1	SYSTEM "Z" WAFER CLEANING	0.043	2.00	0.99
2	SPIN-ON SOURCE-1	0.045	2.08	0.99
3	200 DEGREE C. OVEN BAKE-1	0.024	1.09	0.99
4	SPIN-ON SOURCE-2	0.044	2.04	0.99
5	200 DEGREE C. OVEN BAKE-2	0.023	1.07	0.99
6	HIGH TEMPERATURE DRIVE	0.048	2.19	0.99
7	OXIDE SOURCE STRIP	0.084	3.86	0.99
8	SILICON ETCH	0.180	8.31	0.95
9	TI/AG METALLIZATION-FRONT	0.473	21.79	0.98
10	TI/AG METALLIZATION-BACK	0.514	23.67	0.98
11	TEST	0.044	2.03	0.80
12	ARRAY FABRICATION	0.648	29.88	0.96
TOTALS		2.170	100.00	

Figure 1. Estimated cost per watt using Ti/Ag evaporation metallization.

PROCESS COST OVERVIEW-\$/WATT				
STEP	PROCESS	TOTALS	PER CENT	YIELD
1	SYSTEM "Z" WAFER CLEANING	0.043	2.19	0.99
2	SPIN-ON SOURCE-1	0.045	2.27	0.99
3	200 DEGREE C. OVEN BAKE-1	0.024	1.19	0.99
4	SPIN-ON SOURCE-2	0.044	2.23	0.99
5	200 DEGREE C. OVEN BAKE-2	0.023	1.17	0.99
6	HIGH TEMPERATURE DRIVE	0.048	2.39	0.99
7	OXIDE SOURCE STRIP	0.084	4.21	0.99
8	SILICON ETCH	0.180	9.08	0.95
9	AL METALLIZATION-FRONT	0.406	20.41	0.98
10	AL METALLIZATION-BACK	0.397	20.01	0.98
11	TEST	0.044	2.22	0.80
12	ARRAY FABRICATION	0.648	32.64	0.96
TOTALS		1.987	100.00	

Figure 2. Estimated cost per watt using Al evaporation metallization. (Both Al processes, Figs. 2 and 4, will require a different bonding technique from that of the Ag processes. This has not yet been included; the only difference in these figures is the metallization cost itself.)

PROCESS COST OVERVIEW-\$/WATT				
STEP	PROCESS	TOTALS	PER CENT	YIELD
1	SYSTEM "Z" WAFER CLEANING	0.043	2.18	0.99
2	SPIN-ON SOURCE-1	0.045	2.27	0.99
3	200 DEGREE C. OVEN BAKE-1	0.024	1.19	0.99
4	SPIN-ON SOURCE-2	0.044	2.22	0.99
5	200 DEGREE C. OVEN BAKE-2	0.023	1.16	0.99
6	HIGH TEMPERATURE DRIVE	0.048	2.39	0.99
7	OXIDE SOURCE STRIP	0.084	4.20	0.99
8	SILICON ETCH	0.180	9.06	0.95
9	THICK FILM AG METALLIZING:AUTO	0.808	40.58	0.92
10	TEST	0.044	2.21	0.80
11	ARRAY FABRICATION	0.648	32.55	0.96
	TOTALS	1.992	100.00	

Figure 3. Estimated cost per watt using thick-film Ag metallization (screen printing).

PROCESS COST OVERVIEW-\$/WATT				
STEP	PROCESS	TOTALS	PER CENT	YIELD
1	SYSTEM "Z" WAFER CLEANING	0.043	3.07	0.99
2	SPIN-ON SOURCE-1	0.045	3.18	0.99
3	200 DEGREE C. OVEN BAKE-1	0.024	1.67	0.99
4	SPIN-ON SOURCE-2	0.044	3.12	0.99
5	200 DEGREE C. OVEN BAKE-2	0.023	1.63	0.99
6	HIGH TEMPERATURE DRIVE	0.048	3.36	0.99
7	OXIDE SOURCE STRIP	0.084	5.91	0.99
8	SILICON ETCH	0.180	12.72	0.95
9	THICK FILM AL METALLIZING:AUTO	0.234	16.51	0.92
10	TEST	0.044	3.11	0.80
11	ARRAY FABRICATION	0.648	45.73	0.96
	TOTALS	1.418	100.00	

Figure 4. Estimated cost per watt using thick-film Al metallization (screen printing).

COST/WATT AS A FUNCTION OF STARTING SHEET COST *

PROCESS YIELD=65.31%					
SHEET \$	SHEET YIELD LOSS \$	PROCESS \$	TOTAL \$	\$/WATT	
0.0	0.0	1.09	1.09	2.17	
0.05	0.03	1.09	1.16	2.32	
0.10	0.05	1.09	1.24	2.48	
0.15	0.08	1.09	1.31	2.63	
0.20	0.11	1.09	1.39	2.78	
0.25	0.13	1.09	1.47	2.94	
0.30	0.16	1.09	1.54	3.09	
0.35	0.19	1.09	1.62	3.24	
0.40	0.21	1.09	1.70	3.40	
0.45	0.24	1.09	1.77	3.55	
0.50	0.27	1.09	1.85	3.70	
0.55	0.29	1.09	1.93	3.85	
0.60	0.32	1.09	2.00	4.01	
0.65	0.35	1.09	2.08	4.16	
0.70	0.37	1.09	2.16	4.31	
0.75	0.40	1.09	2.23	4.47	
0.80	0.42	1.09	2.31	4.62	
0.85	0.45	1.09	2.39	4.77	
0.90	0.48	1.09	2.46	4.93	
0.95	0.50	1.09	2.54	5.08	
1.00	0.53	1.09	2.62	5.23	
1.25	0.66	1.09	3.00	6.00	
1.50	0.80	1.09	3.38	6.76	
1.75	0.93	1.09	3.76	7.53	
2.00	1.06	1.09	4.15	8.29	
2.25	1.20	1.09	4.53	9.06	
2.50	1.33	1.09	4.91	9.83	
2.75	1.46	1.09	5.30	10.59	
3.00	1.59	1.09	5.68	11.36	
3.25	1.73	1.09	6.06	12.12	
3.50	1.86	1.09	6.44	12.89	
3.75	1.99	1.09	6.83	13.65	
4.00	2.12	1.09	7.21	14.42	
4.25	2.26	1.09	7.59	15.19	
4.50	2.39	1.09	7.98	15.95	
4.75	2.52	1.09	8.36	16.72	
5.00	2.66	1.09	8.74	17.48	
5.25	2.79	1.09	9.12	18.25	
5.50	2.92	1.09	9.51	19.01	
5.75	3.05	1.09	9.89	19.78	
6.00	3.19	1.09	10.27	20.54	

*Manufacturing cost, excluding fixed factory overhead of approximately \$0.23.

Figure 5. Manufacturing cost estimate using Ti/Ag evaporation metallization.

pattern. (See Fig. 6.) A description of this panel and a conceptual manufacturing process which produces it can be found in Subsection III.D. The electrical performance of each cell is calculated from the known effects of

Figure 6. Baseline solar cell module.

the conventional process steps used in *present* cell fabrication. The performance of the array is then computed from the 72% area coverage by the cells.

The baseline module's electrical performance was evaluated from the calculated performance of 140 cells having the following characteristics. The

wafers are 300 μm thick, (100) orientation, p-type with 1- to 5-ohm-cm resistivity. The minority carrier lifetime is initially $\sim 10\ \mu\text{s}$ but it declines to 4 μs as a result of the high temperature processing, thus producing a minority carrier diffusion length of 100 μm in the bulk. An n^+/p junction is diffused in to a depth of 0.3 μm , producing an n^+ layer with a minority carrier diffusion length of 0.3 μm and a sheet resistance of 40 ohms/square. After final processing, the surface recombination velocities are $10^8\ \text{cm/s}$ at the back ohmic contact and $10^3\ \text{cm/s}$ at the front. Light losses into the cell are 10% overall due to the AR coating and an additional 5% due to masking of the cell by the front contact metallization. These parameters have been used in a computation of the short-circuit current density leading to a value of $I_{\text{sc}} = 27\ \text{mA/cm}^2$ for air mass one sunlight.

The values of the other major electrical parameters of a solar cell (V_{oc} and F) are less sensitive to small variations in processing so they are assumed to be equal to those of conventional cells: $V_{\text{oc}} = 0.55\ \text{V}$ and $F = 0.70$. Then the calculated electrical power density is $10.7\ \text{W/cm}^2$ which corresponds to 0.50 W per cell and an 11% conversion efficiency. (This cell does not represent the reference cell mentioned in Quarterly Report No. 1.) The module with 140 cells and 72% area coverage produces 70-W electrical ($75\ \text{W/m}^2$) for an overall power efficiency of 8%. For a starting wafer cost of \$2 to \$3 per wafer, the manufacturing cost of this array module using Ti/Ag metallization is \$8.50 to \$11.50/W.

Because the preceding work has shown the metallization to be a major cost factor in cell processing, it is receiving special attention. The front contact is particularly complicated because it is the potential source of several types of losses in cell performance which must be evaluated for each possible alternative metallization process. There is the obvious loss in cell *current* which is proportional to the area shadowed by the front grid. In addition there are three distinct losses in external cell *voltage*: (1) sheet resistance of the front layer of Si, (2) contact resistance at the metal-Si interface, and (3) resistance in the metal grid itself. All three voltage drops are, of course, proportional to the actual operating current density.

It is possible to show quite generally that for the optimization of output power a "comb" or "finger" type grid pattern is preferable to a square grid. For large cells where a hierarchy of combs may be needed, this result

is still valid. For a comb pattern, it has also been shown that maximum power always requires the narrowest possible grid lines so that parameter should be the minimum set by practical limits of the technology used [2]. Beyond these general rules, optimization of performance requires considerable analysis, the most important parts of which are given here as an extension and update of prior efforts. This analysis is confined to the finest grid in a possible hierarchy because (1) it involves the largest number of intrinsic physical parameters of the cell, (2) the extension to coarser grids should be simpler, and (3) such extensions will require data not now available. Even for the fine grid a complete optimization is not possible, as will be discussed, although there seems to be some fairly good approximations available for initial purposes.

We use the following symbols: grid metallization lines have thickness t , width $2b$, spacing $2a$, and length L . The various specific resistances are ρ_s in ohms/square for the front layer of the Si, ρ_c in ohm-cm² for the contact resistance, and ρ_m in ohm-cm for the metallization lines. Operating voltage and current density are V_{op} and J , respectively.

The fractional current loss is simply the fractional area shadowed $S=b/(b+a) \approx b/a$. To the lowest order, this reduces the output power P by the same ratio (since the associated change in V_{op} is small). The fractional change in power due to voltage drop in the front layer of the Si is approximately $J \rho_s a^2 / 2 V_{op}$ (to the same order). The fractional power loss due to contact resistance is $J \rho_c / S V_{op}$, and voltage drop in the grid causes a fractional power loss of $(J L^2 \rho_m) / (2 S t V_{op})$. Optimization of cell performance requires the minimization of the sum of these four losses within any constraints imposed by technology or costs.

Not only is the general optimization of these terms with many parameters mathematically intractable, but several of the parameters are poorly known and some constraints may differ significantly for different metallization processes. Specifically, ρ_c is known for a very limited number of metal-Si combinations. For those in normal use, ρ_c is usually low enough (10^{-4} ohm-cm²) as to be

2. *Review and Evaluation of Past Solar Cell Development Efforts*, Final Report prepared by RCA Astro-Electronics Division for NASA under Contract NASW-1427, June 1968.

negligible in unconcentrated sunlight, but for alternatives such as screen-printed metals, ρ_c is not established. For the loss in metal grid lines, there are significant questions to be answered concerning the achievable values of b and t as well as determination of ρ_m for the various alternatives. Here, extra steps such as double silk screening or solder dipping can influence the range of values attainable. Finally, the length L of a reliable line of the fine grid may vary with the process used.

Thus, analyses to date omit the term with ρ_c , and we shall do so until more data are available. Further, in cases when

$$\frac{\rho_m L}{tb} \ll \rho_s \frac{a}{L} \quad (1)$$

then the grid line resistance can be neglected. We shall show that this condition is satisfied even for a silk-screened Ag grid provided its finger length does not exceed $L \sim 1$ cm. Then the optimization can be completed, and it is found that the optimum spacing is [2]

$$a_o = \left(\frac{V_{op}}{J \rho_s} \right)^{1/3} b^{1/3} \quad (2)$$

For the efficient cells required by this program, we can estimate the parameters in this equation at $V_{op} = 0.45$ V, $J = 30$ mA/cm² (peak), and $\rho_s \sim 40$ ohms/square. Then $a_o = 0.72 b^{1/3}$.

If silk-screened Ag is used with present technology, $\rho_m \sim 3.2 \times 10^{-6}$ ohm-cm, thickness of $t \sim 12$ μ m is attainable, and a minimum width might be $2b \sim 125$ μ m (with less-than-perfect connectivity). This width leads to an optimum spacing of $2a_o = 0.27$ cm by Eq. (2).

There is now enough information to test the validity of relation (1) which can be rewritten as $L^2 \ll abt (\rho_s/\rho_m)$. The result $L^2 \ll 12$ is consistent with the earlier condition that $L \sim 1$ cm.

It can further be shown that under these conditions the fractional power loss is given by

$$PL = \frac{3}{2} \left(\frac{J \rho_s}{V_{op}} \right)^{1/3} b^{2/3} \quad (3)$$

For the case just evaluated, using optimized finger spacing, PL = 7.0%. If the finger width had to be doubled to 250 μm for reliable connectivity, this power loss would increase to 11%.

It should be noted that the coarser grid lines or contact strips will add further losses whose evaluation will require knowledge of the total cell size and may be performed more or less independently.

B. STARTING MATERIALS

We are evaluating the starting Si by developing a materials matrix in which we consider three grades of Si: semiconductor, solar cell, and metallurgical. The matrix becomes three-dimensional when we consider the crystallinity of the Si (i.e., single, polycrystalline, or amorphous) and then the form in which it is produced (ingot, ribbon, slab, epitaxial layer, etc).

During this quarter, we have begun to assess the materials matrix in terms of what is now commercially available. For forms not yet available, we shall assess the present state-of-the-art.

Semiconductor-grade and metallurgical-grade Si are both commercially available in polycrystalline form. Only semiconductor-grade Si is commercially available as single-crystal material. Metallurgical-grade Si is not suitable for solar cell fabrication because of the high concentration of heavy metal impurities. Solar-cell-grade Si, which would be of a purity between metallurgical and semiconductor grades, is only now being defined. Therefore, only semiconductor-grade Si exists commercially today as a source of solar cell material.

Polycrystalline semiconductor-grade Si is presently produced in large quantities in the form of rods. This is the starting material for all of the pulled and float-zoned single crystal prepared for the semiconductor industry. Single-crystal semiconductor Si is also commercially prepared as epitaxial layers on Si or sapphire substrates. Of these various forms of single-crystal material, wafers cut from Czochralski pulled ingots are the cheapest and therefore constitute the starting material for present-day solar cell manufacture. The cost of this material, however, has been recognized since the start of this work as a major barrier in reaching the cost goals of this program.

Epitaxy has the advantage of depositing only as much silicon as is needed for the device. As practiced in the semiconductor industry, it is a batch process and too expensive for the goals of this program. However, as stated

in the last report, an epi-process designed specifically for solar cells could be considerably cost reduced. It then becomes a problem of having a sufficiently inexpensive substrate. At the present time, single-crystal Si and sapphire are used, and neither of these is cost-effective.

Among the newer technologies, ribbon pulling from a wetted die appears to be the furthest along. Here, there are still many problems to be solved before a commercial process will be developed, but the potential has been shown. The other ribbon techniques have not been studied as extensively and therefore have not progressed as far. Most of the other techniques are concerned with preparing coarsely polycrystalline silicon. Before these can be considered, ways of neutralizing the electrical effects of the grain boundaries must be developed. It is significant that most of these new techniques will yield material of rectangular or long ribbon geometry. Therefore, in developing automated processing, the ability to handle these geometries must be kept in mind.

C. PROCESSING STUDIES

1. Deposition of Metallization Patterns by Vacuum Evaporation

The most frequently used metallization systems for present-day Si solar cells include vacuum-evaporated Al metal or evaporated bilayer systems, such as Ti/Ag. Al provides a simple single-metal system that makes good ohmic contact to p^+ , p , and n^+ -type silicon, with excellent adhesion and moderately good current-carrying capability. However, it is not readily suitable for solder connection technology unless a solderable area is created in a separate evaporation step to provide a contact point for each cell. Otherwise bonding of interconnect wires would have to be done by a mechanical method, preferably by ultrasonic techniques. The Ti of the Ti/Ag bimetallic system forms good ohmic contacts even in the presence of a thin layer of native oxide on the Si. Adhesion is good with Ti because of its ability to form titanium dioxide by reaction with silicon oxide. Ag represents a metal with high conductivity, good solderability, low susceptibility to electromigration, but high cost. These metallization systems are deposited by vacuum evaporation from a heated tungsten filament-type source or by electron-beam evaporation. Ti/Ag metallization requires the sequential evaporation in a single vacuum system of Ti followed by Ag.

Contact and interconnect patterns of limited but adequate geometric configurations can be created directly by evaporation of the metal through a mask. Patterns of any configuration can be formed, but at considerably greater expense, by screen printing of an organic masking material on the front side of the metal-coated Si wafer to be fabricated into a solar cell, followed by removal of the exposed metal coating by chemical etching. The backside of the wafer must be protected by an organic coating prior to etching. Both mask coatings must be removed after the etching operation. A third patterning technique, delineation by photolithographic techniques as used in semiconductor device fabrication, is too expensive to be viable for the present application, as will be shown.

A heat treatment is required as a subsequent and separate step to sinter the metal into the underlying Si, thereby ensuring a reliable low-resistance ohmic contact. It is essential that the metal sintering step be performed at an optimal temperature at which effective, but not excessive, alloying occurs.

Process parameters for direct (masked) evaporation of metallization patterns for Al are presented in Fig. 7 and for Ti/Ag in Fig. 8. The explanations of the data input and output statements are given in the appendix. In the case of Al, a 4- μm -thick layer is deposited from 99.9% pure metal in wire form. For the Ti/Ag system, a 0.2- μm -thick film of 99% pure Ti followed immediately by a 4- μm -thick 99.99% Ag film is deposited, both from wire. The process is based on the use of an electron-beam evaporator having, for each type metal wire, one electron-beam source with crucible, shutter, water supply, and 14-kW electron-beam power supply with sweep controller. Associated equipment includes processing control equipment and a vacuum pumping system consisting of a 35-cfm mechanical pump and a 10-in. diffusion pump. A planetary substrate fixture accommodates 75 3-in.-diameter wafers. At a throughput efficiency of 90% the effective production capacity for depositing metal films in the thickness range of 1 to 5 μm at a deposition rate of 2.5 $\mu\text{m}/\text{min}$ is 75 sheets (3-in.-diameter wafers) per hour. Seven of these systems would be required for metallizing both sides (each side separately) of 1.25×10^6 sheets per year in three shifts.

Cost summaries for the Al system are presented in Fig. 9 for the cell front side, and in Fig. 10 for the backside. Figures 11 and 12 list the analogous cost for the Ti/Ag system. Specific processing steps and some important considerations are discussed below.

COMMON METALLIZATION STEP=AL

ASSUMPTIONS:

1. 4 MICRON METALLIZATION LAYER THICKNESS
2. CAPACITY OF EQUIPMENT SAME IN 1-5 MICRON RANGE
3. ELECTRICITY COSTS \$.025/KWH
4. LIQ. NITROGEN COSTS \$.20/LITER
5. SINGLE METAL WIRE-FED SYSTEM NEEDED

YIELD:0.98 IN:SHEETS OUT:SHEETS

SALVAGE VALUE: 0.0

3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS	AREA(SQ.FT.)	INPUT UNITS	AREA(SQ.FT.)
0.	60.	0.	60.
0.	60.	0.	60.

INVESTMENTS

NAME:ELECTRON BEAM EVAPORATOR EFF.:0.90 THRUPUT: 75. SH/HR

FRACT. PROC.:1.00 COST: 62555. MAINT. \$/HR: 0.0 TAX CR.:YES

YEARS OF LIFE-USEFUL:10 BOOK: 7 TAX: 7 AREA: 100. SQ. FT.

NAME:HOOD EFF.:0.95 THRUPUT: 650. SH/HR

FRACT. PROC.:1.00 COST: 9000. MAINT. \$/HR: 0.0 TAX CR.:YES

YEARS OF LIFE-USEFUL:10 BOOK: 7 TAX: 7 AREA: 20. SQ. FT.

DIRECT LABOR TYPE INPUT UNITS/HR FRACTION EFFICIENCY

ASSEMBLER/TESTER	101.	1.00	0.85
------------------	------	------	------

INDIRECT LABOR TYPE 1ST SHIFT RATIO 2ND SHIFT RATIO 3RD SHIFT RATIO

	1ST SHIFT RATIO	2ND SHIFT RATIO	3RD SHIFT RATIO
SUPERVISORY	0.100	0.100	0.100
ENGR. SUPPORT	0.0	0.0	0.0
CLERICAL	0.0	0.0	0.0
QUALITY CONTROL	0.0	0.0	0.0
MAINTENANCE	0.130	0.130	0.130

MATERIAL/EXPENSE NAME PRCD. LIMIT FIXED \$ PART VAR. \$ PART BASE FRACT. PRD.

MATERIAL/EXPENSE NAME	PRCD.	LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRD.
ELECTRICITY	0.	0.0	0.0	0.006970	AREA	1.00
LIQUID NITROGEN	0.	0.0	0.0	0.011623	AREA	1.00

NOTE: FOR VAR. \$ PART BASE= "UNIT"=PER INPUT UNIT;"AREA"=PER 100 SQ. CM.

Figure 7. Process parameters for vacuum evaporation metal, Al.

SUBPROCESS USED: VACUUM EVAPORATION METAL.-AL
 BACK SIDE METALLIZATION-AL

ASSUMPTIONS:

1. ARRAY FABRICATION USES ULTRASONIC BONDING.
2. AL AT \$.04/G.
- YIELD: 0.98 IN: SHEETS OUT: SHEETS
- SALVAGE VALUE: 0.0
- 3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
C.	C.	0.	0.
0.	0.	0.	0.

MATERIAL/EXPENSE NAME	PROD. LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRO.
ALUMINUM	0.	0.0	0.033673	AREA	1.00

NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT; "AREA"=PER 100 SQ. CM.

SUBPROCESS USED: VACUUM EVAPORATION METAL.-AL
 FRONT SIDE METALLIZATION-AL

ASSUMPTIONS:

1. ARRAY FABRICATION USES ULTRASONIC BONDING.
2. AL AT \$.04/G.
- YIELD: 0.98 IN: SHEETS OUT: SHEETS
- SALVAGE VALUE: 0.0
- 3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
0.	0.	0.	0.
0.	0.	0.	0.

MATERIAL/EXPENSE NAME	PROD. LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRO.
ALUMINUM	0.	0.0	0.033673	AREA	1.00

NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT; "AREA"=PER 100 SQ. CM.

Figure 7. (Continued).

COMMON METALLIZATION STEP-TI/AG

ASSUMPTIONS:

1. 4 MICRON METALLIZATION LAYER THICKNESS

2. CAPACITY OF EQUIPMENT SAME IN 1-5 MICRON RANGE

3. ELECTRICITY COSTS \$.025/KWH

4. LIQ. NITROGEN COSTS \$.20/LITER

5. TWO METAL WIRE-FED SYSTEM(TI/AG) NEEDED.

YIELD:0.98 IN:SHEETS

OUT:SHEETS

SALVAGE VALUE: 0.0

3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS AREA(SQ.FT.) INPUT UNITS AREA(SQ.FT.)

0. 60. 0. 60.

0. 60. 0. 60.

INVESTMENTS

NAME:ELECTRON BEAM EVAPORATOR EFF.:0.90 THRUPUT: 75. SH/HR

FRACT. PROC.:1.00 COST: 73275. MAINT. \$/HR: 0.0 TAX CR.:YES

YEARS OF LIFE-USEFUL:10 BOOK: 7 TAX: 7 AREA: 100. SQ. FT.

NAME:HOOD EFF.:0.95 THRUPUT: 650. SH/HR

FRACT. PROC.:1.00 COST: 9000. MAINT. \$/HR: 0.0 TAX CR.:YES

YEARS OF LIFE-USEFUL:10 BOOK: 7 TAX: 7 AREA: 20. SQ. FT.

DIRECT LABOR TYPE INPUT UNITS/HR FRACTION EFFICIENCY

ASSEMBLER/TESTER 101. 1.00 0.85

INDIRECT LABOR TYPE 1ST SHIFT RATIO 2ND SHIFT RATIO 3RD SHIFT RATIO

SUPERVISORY 0.100 0.100 0.100

ENGR. SUPPORT 0.0 0.0 0.0

CLERICAL 0.0 0.0 0.0

QUALITY CONTROL 0.0 0.0 0.0

MAINTENANCE 0.130 0.130 0.130

MATERIAL/EXPENSE NAME PROD. LIMIT FIXED \$ PART VAR. \$ PART BASE FRACT. PRO.

ELECTRICITY 0. 0.0 0.006970 AREA 1.00

LIQUID NITROGEN 0. 0.0 0.011623 AREA 1.00

NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT;"AREA"=PER 100 SQ. CM.

Figure 8. Process parameters for vacuum evaporation metal, Ti/Ag.

~~SUBPROCESS USED: VACUUM EVAPORATION METAL.-TI/AG~~
~~FRONT SIDE METALLIZATION-TI/AG~~
~~ASSUMPTIONS:~~
~~1. 0.2 MICRONS OF TI UNDER AG.~~
~~2. ARRAY FABRICATION USES SOLDER.~~
~~3. TI AT \$.07/G; AG AT \$.18/G.~~
~~4. SILVER RECOVERY 40% BACK & 80% FRONT @ \$.12/G.~~
~~YIELD: 0.98 IN: SHEETS OUT: SHEETS~~
~~SALVAGE VALUE: 0.0~~
~~3 SHIFT(S) UTILIZED~~
~~PRODUCTION AREA FLOOR SPACE REQUIREMENTS~~

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
0.	0.	0.	0.
0.	0.	0.	0.

MATERIAL/EXPENSE NAME	PROD. LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRO.
SILVER	0.	0.0	0.070300	AREA	1.00
TITANIUM	0.	0.0	0.001464	AREA	1.00

~~NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT; "AREA"=PER 100 SQ. CM.~~

~~SUBPROCESS USED: VACUUM EVAPORATION METAL.-TI/AG~~
~~BACK SIDE METALLIZATION-TI/AG~~
~~ASSUMPTIONS:~~
~~1. 0.2 MICRONS OF TI UNDER AG.~~
~~2. ARRAY FABRICATION USES SOLDER.~~
~~3. TI AT \$.07/G; AG AT \$.18/G.~~
~~4. SILVER RECOVERY 40% BACK & 80% FRONT @ \$.12/G.~~
~~YIELD: 0.98 IN: SHEETS OUT: SHEETS~~
~~SALVAGE VALUE: 0.0~~
~~3 SHIFT(S) UTILIZED~~
~~PRODUCTION AREA FLOOR SPACE REQUIREMENTS~~

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
0.	0.	0.	0.
0.	0.	0.	0.

MATERIAL/EXPENSE NAME	PROD. LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRO.
SILVER	0.	0.0	0.110000	AREA	1.00
TITANIUM	0.	0.0	0.001464	AREA	1.00

~~NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT; "AREA"=PER 100 SQ. CM.~~

Figure 8. (Continued).

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	
MATERIAL: SHEETS	245625.	0.185	0.491	
MATERIAL ADDED	21692.	0.016	0.043	
TOTAL MATERIAL	267317.	0.201	0.535	
DIRECT LABOR	63169.	0.048	0.126	
DIRECT EXPENSES	12049.	0.009	0.024	
INDIRECT LABOR	19064.	0.014	0.038	
E.S.E. & SHIFT PREMIUM	34264.	0.026	0.069	
TOTAL PROCESS OVERHEAD	53327.	0.040	0.107	
INTEREST EXPENSE	20313.	0.015	0.041	
DEPRECIATION EXPENSE	32243.	0.024	0.064	
TOTAL INTEREST & DEPRECIATION	52556.	0.040	0.105	
TOTAL COST	448419.	0.337	0.897	
1355770. INPUT SHEETS	@ \$	0.181 EACH.		
1328655. OUTPUT SHEETS	@ \$	0.337 EACH.		
27115 SCRAPPED SHEETS	@ \$	0.0 EACH.		
ESTIMATED PROCESS COST PER WATT:\$	0.406			
CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:				
TOTAL \$	225699.	\$/WATT: \$	0.451	
ESTIMATED FLOOR AREA:	394. SQ. FT.			
CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	21692.	0.016	0.043	4.84
DIRECT LABOR	137149.	0.103	0.274	30.59
DIRECT EXPENSES	93232.	0.070	0.186	20.79
PROCESS OVERHEAD	121202.	0.091	0.242	27.03
INTEREST	29043.	0.022	0.058	6.48
DEPRECIATION	46100.	0.035	0.092	10.28
CUMULATIVE TOTAL	448419.	0.337	0.897	100.00

Figure 9. Cost summary, step 9: Al metallization-front
(includes 50.5% allocation of vacuum evaporation metal, Al).

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT
MATERIAL: SHEETS	448419.	0.344	0.897
MATERIAL ADDED	21259.	0.016	0.043
TOTAL MATERIAL	469677.	0.361	0.939
DIRECT LABOR	61906.	0.048	0.124
DIRECT EXPENSES	11806.	0.009	0.024
INDIRECT LABOR	18682.	0.014	0.037
E.S.E. & SHIFT PREMIUM	33578.	0.026	0.067
TOTAL PROCESS OVERHEAD	52261.	0.040	0.105
INTEREST EXPENSE	19907.	0.015	0.040
DEPRECIATION EXPENSE	31598.	0.024	0.063
TOTAL INTEREST & DEPRECIATION	51505.	0.040	0.103
TOTAL COST	647156.	0.497	1.294
1328655. INPUT SHEETS	@ \$ 0.337 EACH.		
1302082. OUTPUT SHEETS	@ \$ 0.497 EACH.		
26573 SCRAPPED SHEETS	@ \$ 0.0 EACH.		

ESTIMATED PROCESS COST PER WATT: \$ 0.397

CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:
TOTAL \$ 221186. \$/WATT: \$ 0.442

ESTIMATED FLOOR AREA: 386. SQ. FT.

ITEM	CUMULATIVE COST COMPONENT BREAKDOWN			
	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	42951.	0.033	0.086	6.64
DIRECT LABOR	199055.	0.153	0.396	30.76
DIRECT EXPENSES	105041.	0.081	0.210	16.23
PROCESS OVERHEAD	173463.	0.133	0.347	26.80
INTEREST	42950.	0.033	0.098	7.56
DEPRECIATION	77648.	0.060	0.155	12.01
CUMULATIVE TOTAL	647157.	0.497	1.294	100.00

Figure 10. Cost summary, step 10: Al metallization-back
(includes 49.5% allocation of vacuum evaporation metal, Al).

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT
MATERIAL: SHEETS	245625.	0.185	0.491
MATERIAL ADDED	46507.	0.035	0.093
TOTAL MATERIAL	292132.	0.220	0.584
DIRECT LABOR	63169.	0.048	0.126
DIRECT EXPENSES	12049.	0.009	0.024
INDIRECT LABOR	19064.	0.014	0.038
E.S.F. & SHIFT PREMIUM	34264.	0.026	0.069
TOTAL PROCESS OVERHEAD	53327.	0.040	0.107
INTEREST EXPENSE	23724.	0.018	0.047
DEPRECIATION EXPENSE	37657.	0.028	0.075
TOTAL INTEREST & DEPRECIATION	61381.	0.046	0.123
TOTAL COST	482058.	0.363	0.964
1355770. INPUT SHEETS	@ \$	0.181 EACH.	
1328655. OUTPUT SHEETS	@ \$	0.363 EACH.	
27115 SCRAPPED SHEETS	@ \$	0.0 EACH.	
ESTIMATED PROCESS COST PER WATT: \$	0.473		
CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:			
TOTAL \$ 263598. \$/WATT: \$	0.527		
ESTIMATED FLOOR AREA: 394. SQ. FT.			

CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	46507.	0.035	0.093	9.65
DIRECT LABOR	137149.	0.103	0.274	28.45
DIRECT EXPENSES	93232.	0.070	0.186	19.34
PROCESS OVERHEAD	121202.	0.091	0.242	25.14
INTEREST	32454.	0.024	0.065	6.73
DEPRECIATION	51514.	0.039	0.103	10.69
CUMULATIVE TOTAL	482059.	0.363	0.964	100.00

Figure 11. Cost summary, step 9: Ti/Ag metallization-front (includes 50.5% allocation of vacuum evaporation metal, Ti/Ag).

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	
MATERIAL: SHEETS	482058.	0.370	0.964	
MATERIAL ADDED	70790.	0.054	0.142	
TOTAL MATERIAL	552849.	0.425	1.106	
DIRECT LABOR	61906.	0.048	0.124	
DIRECT EXPENSES	11808.	0.009	0.024	
INDIRECT LABOR	18682.	0.014	0.037	
E.S.E. & SHIFT PREMIUM	33578.	0.026	0.067	
TOTAL PROCESS OVERHEAD	52261.	0.040	0.105	
INTEREST EXPENSE	23249.	0.018	0.046	
DEPRECIATION EXPENSE	36904.	0.028	0.074	
TOTAL INTEREST & DEPRECIATION	60153.	0.046	0.120	
TOTAL COST	738977.	0.568	1.478	
1328655. INPUT SHEETS	@ \$	0.363 EACH.		
1302082. OUTPUT SHEETS	@ \$	0.568 EACH.		
26573 SCRAPPED SHEETS	@ \$	0.0 EACH.		
ESTIMATED PROCESS COST PER WATT: \$ 0.514				
CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:				
TOTAL \$ 258327. \$/WATT: \$ 0.517				
ESTIMATED FLOOR AREA: 386. SQ. FT.				
CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	117298.	0.090	0.235	15.87
DIRECT LABOR	199055.	0.153	0.398	26.94
DIRECT EXPENSES	105041.	0.081	0.210	14.21
PROCESS OVERHEAD	173463.	0.133	0.347	23.47
INTEREST	55703.	0.043	0.111	7.54
DEPRECIATION	83418.	0.066	0.177	11.96
CUMULATIVE TOTAL	738977.	0.568	1.478	100.00

Figure 12. Cost summary, step 10: Ti/Ag metallization-back (includes 49.5% allocation of vacuum evaporation metal, Ti/Ag).

For either metallization system, a contact grid mask is positioned on the front side of the wafers to shield all nonmetallization areas (95%) from evaporating metal vapor. The loaded system is evacuated and the metal film evaporated. The coated assembly is removed, the wafers turned over to expose the back without use of masks, and the evaporation repeated. Metallization coverage on the cell front is assumed to be 5% of the area, and 100% on the back. The metal coating on the masks must be stripped by chemical etching after at least every second or third run. Other fixtures inside the evaporator may be used for 10 to 20 runs before stripping becomes necessary. The etchant containing the Ti and Ag is chemically treated in an exhaust hood to recover the Ag at an estimated efficiency of 80%. Since about 50% deposits on the walls of the evaporation chamber and on the substrate holder between the circular wafers, the net recovery for front side coating at 5% coverage is 76%; for the backside coating at 100% coverage it is 40% in terms of the Ag evaporated. The value of the recovered Ag is estimated at \$0.12/g, as compared with the market spot price of \$0.15/g for 99.99% Ag in ingot form, and of \$0.18/g in wire form. The prices of bulk Al and Ti are far too low to make recovery profitable. The operator's time during pumpdown is fully utilized for load and unload of the evaporators operating in cycles, for metal etch of the fixtures, and for metal recovery, if required.

The estimates of processing cost* presented in Figs. 9 through 12 show that the cost/sheet (excluding the initial cost for the Si) prior to metallization is \$0.24. Vacuum deposition of metallization patterns adds \$0.31 per good wafer in the case of Al, or \$0.38 in the case of Ti/Ag. It is interesting to note that use of Al instead of the much more expensive Ag decreases the total cost of metallization by only 19% because the materials cost in the process accounts for 33% of the total processing cost in the case of Ag, and for 16% in the case of Al.

The alternate technique of creating front side metallization patterns by masking and chemical etching (prior to metallizing the wafer back side) has not been included in the detailed cost analysis. Estimates indicate the

*Note that costs include only the following overhead expenses: fringe benefits shift differentials, and interest and depreciation on production equipment. The processing costs stated include yield losses, but not the value of recovered materials from reject product or the cost of silicon starting material.

following additional approximate cost. For screen printing and etching (similar to the techniques described in Subsection C.2 below) the added cost is about \$0.15/sheet. Photolithographic masking and etching techniques would be based largely on mechanized and semi-automated processing techniques. These steps include loading, photoresist application by spinning or spraying, baking, noncontact exposure without optical alignment, resist developing, metal etching, resist removal, and individual wafer inspection. A processing yield of 95 to 98% can be expected, despite the many steps. The processing cost per sheet within specification is approximately \$0.50/sheet.

An additional unaccounted process step associated with metallizing is alloying by heating the wafers in an accurately controlled furnace. The cost of this simple step is estimated at \$0.03/sheet.

2. Deposition of Metallization Patterns by Thick-Film Screen-Printing Techniques

The applicability and cost of this technique for producing metallization contact and grid line patterns on solar cells has been examined in some detail. Linewidth of 250 μm can be attained on 100-mm wafers; short runs of 125- μm linewidth can be attained on smaller substrates. It is desirable to use a metallization pattern in which occasional opens in collection grid lines do not significantly reduce cell efficiency. Design of optimal patterns (such as herring bone structures between two lines) can overcome these problems. The results of cost analysis show that screen printing is a viable process for fabricating solar cells. The process can be divided in three separate major areas: (1) printing materials, (2) printing equipment and techniques, and (3) firing of the patterns.

Two types of conductor materials have been considered: ink (paste) formulations based on Ag and on Al. They may consist of organic and inorganic materials which control the deposition and electrical performance characteristics, respectively. The organic portion serves as a vehicle for inorganic constituents, and it can be further divided into binder, solvent, flow control, and wetting agent constituents. The principal function of the binder, solvent, and flow control agent is to adjust the ink viscosity and to permit control of the inorganic solids content. Wetting agents are added to ensure adequate dispersion of the inorganic particles, i.e., the metal powder and

glass-forming frit of complex composition. Constituent morphology and particle size have an important influence upon ink viscosity and rheological properties, as well as upon metallization adhesion. Inks capable of printing the required fine lines are thixotropic in nature. This property permits rather high shear rates to be utilized during screening, with freedom from slumping or run-out of the ink. The metal-to-glass ratio is critical and is an important consideration in establishing a conductor with low sheet resistance and high adhesion to the substrate. The frit content necessary for adequate adhesion is generally in the range of 2 to 10 wt % after firing. Lower frit content leads to poor adhesion, while excessively high frit levels result in low conductivity.

For high production rates the inks are applied to the substrate by screen-printing techniques which have been refined to a high degree. Equipment is available to control the important printing variables such as screen-to-substrate snap-off distance (in off-contact printing), squeegee angle and compression against the screen, and the squeegee horizontal and vertical speeds. Modern "silk" screens are now constructed of stainless steel prepared with light-sensitive emulsions; mesh sizes of 165 to 325 are generally available; the finest lines being given by the 325-mesh variety.

Important parts of the printing equipment are the substrate-holding fixture, which must be capable of accurately locating, registering, fixing and holding the substrate in position, and the screen mounting device which must hold the screen rigidly in place. Transfer mechanisms are available to move the substrate from load to print position and could be adapted for automatic transfer through drying and firing furnaces.

Firing of the printed and dried ink is accomplished in a continuous belt furnace with multi-zone temperature controllers. The firing cycle consists of a preheat during which the carbonaceous (organic) vehicle is pyrolyzed and oxidized and the gaseous products are exhausted. The substrate then moves into the highest temperature zone to increase the fluidity of the glass frit constituents rapidly, providing wetting of the substrate. Simultaneously, the metal particles begin to coalesce or sinter into a continuous network. As the substrate passes into successively cooler zones, the metal continues to sinter until the glass constituents increase in viscosity so that no more aggregation can occur. The glass frit composition and its fluidity and surface tension

at the peak firing temperature, the duration of exposure to elevated temperatures, the glass and metal particle size and distribution, and the fired thickness all interact to affect the conductivity, adhesion, and cohesive strength of the conductor pattern.

Process parameters for manual and for automated screen printing on 3-in.-diameter Si wafers are presented for Al in Figs. 13 and 14 and in Figs. 15 and 16 for Ag compositions. The capital production equipment consists of a screen-printing machine, a substrate loader, a dryer-furnace, a reloader, and a supply of magazines or trays. Metallized area coverage on the front side was estimated

SCREEN PRINTING AND SINTERING CONDUCTIVE NETWORK-BOTH SIDES

ASSUMPTIONS:

1. SILICON WAFER, 3" DIA.
2. ALUMINUM METALLIZATION 0.5 MIL THICK (12.5 MICRONS).
3. ALUMINUM AREA COVERAGE: 100% BACK; 5% FACE.
4. ELECTRICITY @ \$.025/KWH
5. MANUAL EQUIPMENT (\$44K): PRINTER @ \$7K; DRYER-FURNACE @ \$35K;
MAGAZINES/TRAYS @ \$2K.

YIELD: 0.96 IN: SHEETS OUT: SHEETS

SALVAGE VALUE: 0.0

3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
0.	0.	0.	0.
0.	0.	0.	0.

INVESTMENTS

NAME: MANUAL SYSTEM EFF.: 0.85 THRUPT: 600. SH/HR
 FRACT. PROC.: 2.40 COST: 44000. MAINT. \$/HR: 0.0 TAX CR.: YES
 YEARS OF LIFE-USEFUL: 15 BOOK: 7 TAX: 7 AREA: 1600 SQ. FT.

DIRECT LABOR TYPE	INPUT UNITS/HR	FRACTION	EFFICIENCY
ASSEMBLER/TESTER	600.	2.40	0.85

INDIRECT LABOR TYPE	1ST SHIFT RATIO	2ND SHIFT RATIO	3RD SHIFT RATIO
SUPERVISORY	0.125	0.125	0.125
ENGR. SUPPORT	0.075	0.075	0.075
CLERICAL	0.072	0.072	0.072
QUALITY CONTROL	0.100	0.100	0.100
MAINTENANCE	0.210	0.210	0.210

MATERIAL/EXPENSE NAME	PROD.	LIMIT	FIXED	\$ PART. VAR.	\$ PART. BASE	FRACT.	PRC.
ELECTRICITY	C.	C.	C.	0.003670	AREA		2.00
INK AL	C.	C.	C.	0.053000	UNIT		1.00
SCREENS	C.	C.	C.	0.002880	UNIT		1.00
SQUEEGEES	C.	C.	C.	0.000303	UNIT		1.00
SOLVENT	C.	C.	C.	0.000076	UNIT		1.00
SUPPORT ETC	C.	C.	C.	0.000006	UNIT		1.00

NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT; "AREA"=PER 100 SQ. CM.

Figure 13. Process parameters for thick-film Al metallizing, manual.

SCREEN PRINTING AND SINTERING CONDUCTIVE NETWORK-BOTH SIDES				
ASSUMPTIONS:				
1. SILICON WAFER, 3" DIA.				
2. SILVER METALLIZATION 0.5 MIL THICK(12.5 MICRONS).				
3. SILVER AREA COVERAGE: 100% BACK; 5% FACE.				
4. ELECTRICITY @ \$.025/KWH				
5. AUTOMATED EQUIPMENT(\$98.8K):PRINTER @ \$24.4K,LOADER @ \$10.7K;				
DRYER-FURNACE @ \$45K;RELOADER @ \$14.7K;MAGAZINES/TRAYS @ \$4K				
YIELD:0.96 IN:SHEETS OUT:SHEETS				
SALVAGE VALUE: 0.075				
3 SHIFT(S) UTILIZED				
PRODUCTION AREA FLOOR SPACE REQUIREMENTS				
INPUT UNITS	AREA(SQ.FT.)	INPUT UNITS	AREA(SQ.FT.)	
0.	0.	0.	0.	
0.	0.	0.	0.	
INVESTMENTS				
NAME:AUTOMATED SYSTEM EFF.:0.85 THRUPUT: 1800. SH/HR				
FRACT. PROC.:2.40 COST: 98800. MAINT. \$/HR: 0.0 TAX CR.:YES				
YEARS OF LIFE-USEFUL:15 BOOK: 7 TAX: 7 AREA: 1600. SQ. FT.				
DIRECT LABOR TYPE INPUT UNITS/HR FRACTION EFFICIENCY				
ASSEMBLER/TESTER	9000.	2.40	0.85	
INDIRECT LABOR TYPE 1ST SHIFT RATIO 2ND SHIFT RATIO 3RD SHIFT RATIO				
SUPERVISORY	0.125	0.125	0.125	
ENGR. SUPPORT	0.025	0.013	0.013	
CLERICAL	1.100	1.100	1.100	
QUALITY CONTROL	1.500	1.500	1.500	
MAINTENANCE	0.350	0.350	0.350	
MATERIAL/EXPENSE NAME PRGD. LIMIT FIXED \$ PART VAR. \$ PART BASE FRACT. PRO.				
ELECTRICITY	0.	0.0	0.004030 AREA	2.00
INK AG	0.	0.0	0.260000 AREA	2.00
SCREENS	0.	0.0	0.002880 UNIT	1.00
SQUEEGEES	0.	0.0	0.000303 UNIT	1.00
SOLVENT	0.	0.0	0.000076 UNIT	1.00
SUPPORT & TC	0.	0.0	0.000606 UNIT	1.00
NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT;"AREA"=PER 100 SQ. CM.				

Figure 14. Process parameters for thick-film Al metallizing, automatic.

SCREEN PRINTING AND SINTERING CONDUCTIVE NETWORK-BOTH SIDES

ASSUMPTIONS:

1. SILICON WAFER, 3" DIA.
2. SILVER METALLIZATION 0.5 MIL THICK (12.5 MICRONS).
3. SILVER AREA COVERAGE: 100% BACK; 5% FACE.
4. ELECTRICITY @ \$.025/KWH
5. MANUAL EQUIPMENT (\$44K): PRINTER @ \$7K; DRYER-FURNACE @ \$35K;
MAGAZINES/TRAYS @ \$2K.

YIELD: 0.96 IN: SHEETS OUT: SHEETS

SALVAGE VALUE: 0.075

3 SHIFT(S) UTILIZED

PRODUCTION AREA FLOOR SPACE REQUIREMENTS

INPUT UNITS	AREA (SQ. FT.)	INPUT UNITS	AREA (SQ. FT.)
0.	0.	0.	0.
0.	0.	0.	0.

INVESTMENTS

NAME: MANUAL SYSTEM EFF.: 0.85 THRUPUT: 600. SH/HR
 FRACT. PROC.: 2.40 COST: 44000. MAINT. \$/HR: 0.0 TAX CR.: YES
 YEARS OF LIFE-USEFUL: 15 BOOK: 7 TAX: 7 AREA: 1600. SQ. FT.

DIRECT LABOR TYPE INPUT UNITS/HR FRACTION EFFICIENCY

ASSEMBLER/TESTER	600.	2.40	0.85
------------------	------	------	------

INDIRECT LABOR TYPE 1ST SHIFT RATIO 2ND SHIFT RATIO 3RD SHIFT RATIO

SUPERVISORY	0.125	0.125	0.125
ENGR. SUPPORT	0.075	0.025	0.025
CLERICAL	0.072	0.072	0.072
QUALITY CONTROL	0.100	0.100	0.100
MAINTENANCE	0.210	0.210	0.210

MATERIAL/EXPENSE NAME	PROD. LIMIT	FIXED \$	PART VAR. \$	PART BASE	FRACT. PRO.
ELECTRICITY	0.	0.0	0.003670	AREA	2.00
INK AG	0.	0.0	0.280000	AREA	2.00
SCREENS	0.	0.0	0.002880	UNIT	1.00
SQUEEGEES	0.	0.0	0.000303	UNIT	1.00
SOLVENT	0.	0.0	0.000076	UNIT	1.00
SUPPORT & TC	0.	0.0	0.000606	UNIT	1.00

NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT;"AREA"=PER 100 SQ. CM.

Figure 15. Process parameters for thick-film Ag metallizing, manual.

SCREEN PRINTING AND SINTERING CONDUCTIVE NETWORK-BOTH SIDES				
ASSUMPTIONS:				
1. SILICON WAFER, 3" DIA.				
2. ALUMINUM METALLIZATION 0.5 MIL THICK(12.5 MICRONS).				
3. ALUMINUM AREA COVERAGE: 100% BACK; 5% FACE.				
4. ELECTRICITY @ \$.025/KWH				
5. AUTOMATED EQUIPMENT(\$98.8K):PRINTER @ \$24.4K,LOADER @ \$10.7K;				
DRYER-FURNACE @ \$45K;RELOADER @ \$14.7K;MAGAZINES/TRAYS @ \$4K				
YIELD:0.96 IN:SHEETS		OUT:SHEETS		
SALVAGE VALUE: 0.0				
3 SHIFT(S) UTILIZED				
PRODUCTION AREA FLOOR SPACE REQUIREMENTS				
INPUT UNITS	AREA(SQ.FT.)	INPUT UNITS	AREA(SQ.FT.)	
0.	0.	0.	0.	
0.	0.	0.	0.	
INVESTMENTS				
NAME:AUTOMATED SYSTEM EFF.:0.85 THRUPUT: 1800. SH/HR				
FRACT. PROC.:2.40 COST: 98800. MAINT. \$/HR: 0.0 TAX CR.:YES				
YEARS OF LIFE-USEFUL:15 BOOK: 7 TAX: 7 AREA: 1600. SQ. FT.				
DIRECT LABOR TYPE INPUT UNITS/HR FRACTION EFFICIENCY				
ASSEMBLER/TESTER	9000.	2.40	0.85	
INDIRECT LABOR TYPE 1ST SHIFT RATIO 2ND SHIFT RATIO 3RD SHIFT RATIO				
SUPERVISORY	0.125	0.125	0.125	
ENGR. SUPPORT	0.025	0.013	0.013	
CLERICAL	1.100	1.100	1.100	
QUALITY CONTROL	1.500	1.500	1.500	
MAINTENANCE	0.350	0.350	0.350	
MATERIAL/EXPENSE NAME PROD. LIMIT FIXED \$ PART VAR. \$ PART BASE FRACT. PRO.				
ELECTRICITY	0.	0.0	0.004030 AREA	2.00
INK AL	0.	0.0	0.053000 UNIT	1.00
SCREENS	0.	0.0	0.002880 UNIT	1.00
SQUEEGEES	0.	0.0	0.000303 UNIT	1.00
SOLVENT	0.	0.0	0.000076 UNIT	1.00
SUPPORT & TC	0.	0.0	0.000606 UNIT	1.00
NOTE: FOR VAR. \$ PART BASE- "UNIT"=PER INPUT UNIT;"AREA"=PER 100 SQ. CM.				

Figure 16. Process parameters for thick-film
Ag metallizing, automatic.

to be 5% of Si surface, if lines and spaces are kept at 254 μm (10 mils) or greater. Mean thickness of the lines after firing is 12.5 μm (0.5 mil). Backside (ground plane) coverage has been assumed to be 100%, although partial coverage would be acceptable if the backside diffusion treatment is conducted to yield favorable type and concentration of dopant (such as p^+ for cells with n-type front side) to minimize the contact (series) resistance between the metal and the semiconductor. The overall product yield is expected to be 96% for both a hand-fed machine and an automatic (magazine-fed) machine. Presently available automatic silk screening equipment has been designed for use with less fragile ceramic substrates rather than for silicon wafers. While automatic handling of large silicon wafers without breakage is considered feasible, development work would be necessary to improve commercially-available magazine-fed screen printers to eliminate breakage losses. The annual production capacity for the equipment, if continuously operated on three shifts, is 3.67×10^6 sheets (metallized on both sides).

A cost summary for manual and automated screen printing of the Al-based metallization system is presented in Figs. 17 and 18, and for the Ag-based system in Figs. 19 and 20. Manual processing with Al adds \$0.13/sheet* to the process cost, of which 44% is for the materials. Automatic processing with Al adds \$0.090/sheet; 61% is for materials. In the case of Ag, the process cost is \$0.35/sheet for manual and \$0.31/sheet for automated processing. The materials cost is 80 and 90%, respectively, of the process cost.

It is obvious that automatic processing using Al conductor inks is the most economical technique. However, questions concerning ink composition, ohmic contacts, adhesion, series resistance, and solderability must first be resolved experimentally. By adjusting diffusion parameters appropriately, higher temperatures of fusion could be used to increase the conductivity of the metallization patterns, which would allow reduction in thickness with corresponding cost savings in material. Further savings can be realized by partial metal coverage of the backside (by doping of the Si and the use of a metallization grid pattern).

*Sheet of in-specification material, as above.

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	
MATERIAL:SHEETS	245718.	0.189	0.491	
MATERIAL ADDED	71886.	0.055	0.144	
TOTAL MATERIAL	317604.	0.244	0.635	
DIRECT LABOR	25531.	0.020	0.051	
DIRECT EXPENSES	10001.	0.008	0.020	
INDIRECT LABOR	18690.	0.014	0.037	
E.S.E. & SHIFT PREMIUM	18364.	0.014	0.037	
TOTAL PROCESS OVERHEAD	37054.	0.028	0.074	
INTEREST EXPENSE	7920.	0.006	0.016	
DEPRECIATION EXPENSE	12571.	0.010	0.025	
TOTAL INTEREST & DEPRECIATION	20491.	0.016	0.041	
TOTAL COST	410681.	0.315	0.821	
1356335. INPUT SHEETS	@ \$	0.181 EACH.		
1302082. OUTPUT SHEETS	@ \$	0.315 EACH.		
54253 SCRAPPED SHEETS	@ \$	0.0 EACH.		
ESTIMATED PROCESS COST PER WATT:\$ 0.330				
CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:				
TOTAL \$	88000.	\$/WATT: \$	0.176	
ESTIMATED FLOOR AREA: 3200. SQ. FT.				
CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	71886.	0.055	0.144	17.50
DIRECT LABOR	99542.	0.076	0.199	24.24
DIRECT EXPENSES	91218.	0.070	0.182	22.21
PROCESS OVERHEAD	104958.	0.081	0.210	25.56
INTEREST	16650.	0.013	0.033	4.05
DEPRECIATION	26429.	0.020	0.053	6.44
CUMULATIVE TOTAL	410681.	0.315	0.821	100.00

Figure 17. Cost summary, step 9: thick-film Al metallizing, manual.

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT
MATERIAL: SHEETS	245712.	0.189	0.491
MATERIAL ADDED	71886.	0.055	0.144
TOTAL MATERIAL	317604.	0.244	0.635
DIRECT LABOR	1702.	0.001	0.003
DIRECT EXPENSES	10468.	0.008	0.021
INDIRECT LABOR	6575.	0.005	0.013
E.S.E. & SHIFT PREMIUM	3448.	0.003	0.007
TOTAL PROCESS OVERHEAD	10022.	0.008	0.020
INTEREST EXPENSE	8892.	0.007	0.018
DEPRECIATION EXPENSE	14114.	0.011	0.028
TOTAL INTEREST & DEPRECIATION	22006.	0.018	0.046
TOTAL COST	362802.	0.279	0.726
1356335. INPUT SHEETS	at \$	0.181 EACH.	
1302082. OUTPUT SHEETS	at \$	0.279 EACH.	
54253 SCRAPPED SHEETS	at \$	0.0 EACH.	

ESTIMATED PROCESS COST PER WATT: \$ 0.234

CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:

TOTAL \$ 98800. \$/WATT: \$ 0.198

ESTIMATED FLOOR AREA: 1600. SQ. FT.

CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	71886.	0.055	0.144	19.81
DIRECT LABOR	75713.	0.058	0.151	20.87
DIRECT EXPENSES	91685.	0.070	0.183	25.27
PROCESS OVERHEAD	77926.	0.060	0.156	21.48
INTEREST	17622.	0.014	0.035	4.86
DEPRECIATION	27971.	0.021	0.056	7.71
CUMULATIVE TOTAL	362802.	0.279	0.726	100.00

Figure 18. Cost summary, step 9: thick-film Al metallizing, automatic.

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	
MATERIAL: SHEETS	245718.	0.189	0.491	
MATERIAL ADDED	363064.	0.279	0.726	
TOTAL MATERIAL	608781.	0.468	1.218	
DIRECT LABOR	25531.	0.020	0.051	
DIRECT EXPENSES	10001.	0.008	0.020	
INDIRECT LABOR	18690.	0.014	0.037	
E.S.E. & SHIFT PREMIUM	18364.	0.014	0.037	
TOTAL PROCESS OVERHEAD	37054.	0.028	0.074	
INTEREST EXPENSE	7920.	0.006	0.016	
DEPRECIATION EXPENSE	12571.	0.010	0.025	
TOTAL INTEREST & DEPRECIATION	20491.	0.016	0.041	
TOTAL COST	701859.	0.539	1.404	
LESS SALVAGE	-4047.	-0.003	-0.008	
NET COST	697811.	0.536	1.396	
1356335. INPUT SHEETS	@ \$	0.181 EACH.		
1302022. OUTPUT SHEETS	@ \$	0.536 EACH.		
54253 SCRAPPED SHEETS	@ \$	0.075 EACH.		
ESTIMATED PROCESS COST PER WATT:\$	0.904			
CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:				
TOTAL \$ 28000. \$/WATT: \$	0.176			
ESTIMATED FLOOR AREA:	3200. SQ. FT.			
CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	363064.	0.279	0.726	51.73
DIRECT LABOR	99542.	0.076	0.199	14.18
DIRECT EXPENSES	91218.	0.070	0.182	13.00
PROCESS OVERHEAD	104958.	0.081	0.210	14.95
INTEREST	16650.	0.013	0.033	2.37
DEPRECIATION	26429.	0.020	0.053	3.77
CUMULATIVE TOTAL	701859.	0.539	1.404	100.00
LESS: SALVAGE	-4047.	-0.003	-0.008	
NET COST	697812.	0.536	1.396	

Figure 19. Cost summary, step 9: thick-film Ag metallizing, manual.

ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT
MATERIAL: SHEETS	245718.	0.189	0.491
MATERIAL ADDED	363064.	0.279	0.726
TOTAL MATERIAL	608781.	0.468	1.218
DIRECT LABOR	1702.	0.001	0.003
DIRECT EXPENSES	10468.	0.008	0.021
INDIRECT LABOR	6575.	0.005	0.013
E.S.E. & SHIFT PREMIUM	3448.	0.003	0.007
TOTAL PROCESS OVERHEAD	10022.	0.008	0.020
INTEREST EXPENSE	8892.	0.007	0.018
DEPRECIATION EXPENSE	14114.	0.011	0.028
TOTAL INTEREST & DEPRECIATION	23006.	0.018	0.046
TOTAL COST	653980.	0.502	1.308
LESS SALVAGE	-4047.	-0.003	-0.008
NET COST	649932.	0.499	1.300

1356335. INPUT SHEETS @ \$ 0.181 EACH.
1302082. OUTPUT SHEETS @ \$ 0.499 EACH.
54253 SCRAPPED SHEETS @ \$ 0.075 EACH.

ESTIMATED PROCESS COST PER WATT: \$ 0.808

CURRENT YEAR ADDITIONAL INVESTMENT REQUIRED:

TOTAL \$ 98800. \$/WATT: \$ 0.198

ESTIMATED FLOOR AREA: 1600. SQ. FT.

CUMULATIVE COST COMPONENT BREAKDOWN				
ITEM	TOTAL \$	\$/OUTPUT UNIT	\$/WATT	%
MATERIAL	363064.	0.279	0.726	55.52
DIRECT LABOR	75713.	0.058	0.151	11.58
DIRECT EXPENSES	91685.	0.070	0.183	14.02
PROCESS OVERHEAD	77926.	0.060	0.156	11.92
INTEREST	17622.	0.014	0.035	2.69
DEPRECIATION	27971.	0.021	0.056	4.28
CUMULATIVE TOTAL	653980.	0.502	1.308	100.00
LESS: SALVAGE	-4047.	-0.003	-0.008	
NET COST	649932.	0.499	1.300	

Figure 20. Cost summary, step 9: thick-film Ag metallizing, automatic.

A condensed comparative cost summary is presented in Table 1. The cost of the initial Si wafer is not included in these figures.

TABLE 1. COMPARATIVE COST SUMMARY

<u>Process</u>	<u>Process Cost</u>	
	<u>\$/Watt</u>	<u>% of Total*</u>
Al printing, automated	0.234	16.5
Al printing, manual	0.330	21.8
Al evaporation	0.803	40.4
Ag printing, automated	0.808	40.6
Ag printing, manual	0.904	43.3
Ag evaporation	0.987	45.5

*Total cost is for all processes such as diffusion, cleaning, metallization, and array fabrication.

Ag metallization by either process constitutes the greatest cost fraction (41-45%) for any of the 11 single process steps (total cost 100%) starting with prepared Si wafers. In the case of the evaporation process, 67% of the cost is non-material expense (equipment, labor, etc.), whereas in the screen-printing process the main expense (80% manual, 90% automated) is in the material. The main advantages of using Ag as the conductive element are its excellent conductive properties, its solderability, and the fact that the system is well-established. The automated screen-printing process is about 11% cheaper than the manual operation and is 18% cheaper than the masked evaporation process but offers distinct possibilities of further cost reduction by the techniques indicated. The use of secondary patterning techniques in the case of unmasked evaporated films could reduce the metallization area but would further increase the cost of this process.

The use of Al instead of Ag would decrease the cost only 19% in the masked evaporation process, but would substantially lower it in the screen-printing process (71% automatic, 63% manual), reducing the cost to 17 to 22% of the total (non-Si) process cost. However, further studies are needed, as indicated, to optimize this process.

D. PANEL ASSEMBLY AND DESIGN

1. Introduction to Panel Design Considerations

Materials used in terrestrial solar panels must perform in an environment very similar to that for commercial roofing materials. The design considerations presented in this section are based on the following sources:

- (1) environmental conditions which occur in continental United States,
- (2) preliminary analysis of mechanical and thermal loading on flat plates, and
- (3) design requirements for solar panels to be purchased under the 130-kW procurement phase of the Large Scale Production Task.

a. Mechanical Requirements

A terrestrial solar panel must be designed to withstand the static and dynamic mechanical loads imposed by the panel's weight, by wind effects, by snow and ice loads, and by impact loading due to hailstones. Of all the distributed loadings which a panel must withstand, the highest loads are those imposed by the wind. Figure 21 depicts the relationship between pressure and wind velocity for flat plates at various angles of attack. From Fig. 21 it can be seen that the highest pressure loading occurs at an angle of attack of 20° and is a pressure in the negative or outward direction. In the case of a pitched roof, at a 20° angle with the wind, the pressure related force is acting to pull the roof away from its mounting points. Considering a plot of 50-year mean recurrence steady-state winds in the U.S., a wind velocity of 100 mph is the highest mean velocity which may occur. From Fig. 21, this velocity results in a dynamic pressure of 32 psf, and using a pressure coefficient of 1.2 for square shapes results in a maximum pressure loading due to wind effects of 38 psf. Snow loading for most areas of the U.S. except the Rockies and the far Northeast U.S. is 20 psf. Live roof loads for residential structures are taken in the range of 12 to 20 psf. Hailstones would appear to induce the highest naturally caused impact loads on exposed panels and for hailstones on the order of 3-in. diameter falling at terminal velocities, the impact stress would be on the order of 3000 to 5000 psi. It is difficult to project a scenario in which all of these loads act simultaneously. Therefore, the worst-case static loading on a terrestrial solar panel can be taken as ± 38 psf due to wind

Figure 21. Relationship between pressure and wind velocity.

pressure. Dynamic loads on roof structures due to wind loading is not generally a design consideration due to the nonperiodic nature of wind gusts which would serve as the forcing function. Self-induced vibration due to vortex shedding is another mechanical load which is not generally a problem in structural design of roof structures due to the manner of edge supports which limit the panel deflection.

In summary, the primary mechanical design requirements for solar panels consist of a distributed static load of ± 38 psf and concentrated impact load of approximately 5000 psi.

b. Thermal Requirements

The worst-case hot thermal environment for terrestrial solar panels occurs for panel designs which are insulated on one side, receive normal insolation at 1 kW/m^2 and cooling by radiation and natural convection only. This environment results in panel surface temperatures that approach 200°F (93°C) for

125°F (52°C) ambient temperatures. The worst-case cold panel temperatures are based on the coldest nighttime temperatures in U.S. which are approximately -40°F and the condition of a clear, still night which results in panel temperature levels of 5°F (3°C) below the -40°C ambient due to the clear sky radiation to an effective sky temperature of -60°F (51°C). Thus all materials used in terrestrial solar panels must perform in actual thermal environment ranging from -45°F to 200°F (-43°C to 93°C). A more detailed thermal and mechanical analysis has been performed for terrestrial panels and the results appear below.

c. Electrical Isolation

For a 4 ft x 4 ft (1.2M x 1.2M) basic panel size with cell packing density of 91% and cell diameters of 3-in. (7.6 cm), about 295 cells can be arranged within a panel; in a series connection with 0.6-V open-circuit voltage, the highest voltage point in the panel will be about 180 V. Using data from JPL document number 5-342-1, related to purchasing commercial solar panels, panel voltages as high as 250 V dc and panel resistance from cell to ground of 10 Mohms at 100 V dc should be accommodated in panel design.

d. Other Environmental Factors

In addition to the mechanical and thermal environment previously described, terrestrial solar panels must also withstand the effects of ultraviolet radiation. Materials which may be particularly sensitive to UV include the cell cover material and any clear adhesive. Other environmental factors include salt spray, blowing dust, freezing/thawing, rain and snow, chemical effects of air pollution and impact loads from thrown objects.

2. Baseline Module Assembly

a. Module Design

The baseline solar cell module which has been specified for use in the initial cost studies is shown in Fig. 6. The construction calls for the structural optical and functions in a 1/4-in. acrylic sheet with the cells bonded to it using RTV silicone adhesive and back moisture protection provided by a conformal coating (Conap #2525). The module will be provided with an extruded aluminum frame for structural mounting and a hermetic connector for electrical interconnection.

Cells are mounted in the module in a close hexagonal arrangement so that each array contains seven parallel strings of 20 cells with an area packing factor of 81.4% (71.9% including mounting area).

b. Module Assembly

Module assembly is completed on a semiautomated basis using the line shown schematically in Fig. 22. Input into the assembly area is from the cell sorting equipment which exists at the end of the semiconductor processing line. The throughput of the line is 750 wafers per hour which is converted into 34 solar cell modules per day. The output of the line goes to panel inventory for ultimate disposition.

There are four major assembly areas shown in Fig. 22.

(1) Interconnect Equipment

Interconnection is completed in a reflow furnace. This is a standard 8-in. belt furnace with a controlled atmosphere and operating at 15 in./min. The furnace is supported by automatic fixture loading and interconnect forming equipment. The basic material handling principle being used is pick and place, using robot arms for handling both wafers and interconnects. This area is serviced by one operator whose primary function is to handle soldering fixtures on completion of reflow and to monitor the equipment operation. Preparation of this position for a day's operation can be completed in 2 hours (0.25 man days) of maintenance at the end of each working day.

(2) Module Assembly

Module assembly involves automatic dispensing of adhesive onto the module substrate and placement of 20 element series strings onto it using a multi-position pick and place robot arm. We are projecting 84% yield in the interconnection process of which 12% can be recovered in a repair station which is part of the panel assembly area. This station will require one assembler; another assembler will be responsible for substrate preparation and assembled panel handling.

(3) Testing

Intermediate in the assembly operation is a test position which consists of Xenon flash lamp and associated electronics and logging equipment for

Figure 22. Preliminary layout assembly flow.

generating I-V plots for illuminated solar cell strings. This test position could be a modification of the large area pulsed solar simulators produced commercially. It would generate an accept/reject signal for the string handling equipment and generate a hard copy record of the accepted string performance. The only labor associated with this test position is clerical to properly file the record of string performance.

(4) Final Assembly

Assembly of mounting frame and module connector plus spraying of conformal coating is assumed to be a hand operation supported by appropriate spray booth and assembly tooling equipment. One operator can provide these operations. Maintenance is provided for preparation of spray and adhesive stations.

(5) Cost Summary

It is estimated that module assembly to produce 1 mW per year can be accomplished by 3-1/2 operators supported by a combination of 1.4 supervisor, maintenance, and clerical personnel. The capital equipment required in the proposed line is estimated as:

Interconnect equipment	\$103,000
Panel Assembly	\$ 52,000
Final Assembly	\$ 15,000
Test Equipment	\$ 75,000

Consumed materials total \$29.45 per module or \$0.42/W.

Total assembly cost is \$0.65/W.

3. Solar Cell Panel Computer Model Simulation (Thermal)

a. Introduction

A general purpose computer model of a solar panel was developed to evaluate the power loss due to panel self-heating at the peak power point. This power loss and its economic impact on the \$0.50/peak W goal of this program must be considered. However, the model is completely general and could (with modest modification) assess the hourly performance of a panel over a whole season using weather bureau data of hourly insolation, 3-hour wind velocity, and dry bulb temperature.

This model is functionally described in Fig. 23. It takes into account all known significant effects that modulate the performance of a solar panel to produce an hour by hour accounting of power output per square foot of active panel surface. This simulation model uses several techniques and subroutines very similar to a solar thermal collector model that RCA developed previously for ERDA. This provided two distinct advantages:

- (1) A rather complex solar cell panel simulator was developed in a short time.
- (2) The dual function of thermal collector covered with solar cells, thereby delivering electrical and thermal energy, can be assessed at some point in the future.

b. Solar Cell Panel Simulator Characteristics

The functional character of major elements of the model are discussed below.

- (i) Total incident radiation on panel front surface. The weather bureau measures integrated hourly values of measured total radiation (direct plus diffuse) incident on a horizontal surface. At that hour, day, day, and month the precise extra-terrestrial direct normal insolation is calculable. Through the work of Liu and Jordan [3] the measured value can be broken into direct and diffuse components by specific empirical relationships. Then, for the panel tilt and latitude, the direct and diffuse components incident on panel surface can be found. This is augmented by reflection from the ground (at some defined reflectivity) of the direct and diffuse components. Thus, the total insolation on the panel surface is the sum of these two factors.
- (ii) Total radiation absorbed by cells. If a cover sheet of some kind is used, the total incident radiation is reduced by reflection at one or more interfaces and by bulk absorption as well. Given the transmission and reflection characteristics of any material as a function of incident angle, this loss is calculated.

3. Y. Liu and R. Jordan, "Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Radiation," Solar Energy, July 1960.

Figure 23. Solar cell panel simulation model.

- (iii) Cell temperature rise within panel. The net radiant energy absorbed by the cells is reduced by the present efficiency (based on cell temperature of the previous hour). The remaining heat must be conducted to the front and back panel surfaces for transfer to the environment. The weather bureau provides instantaneous 3-hour dry bulb temperatures and integrated mean wind velocity. These values are linearly interpolated for hourly values. The ground is assumed to be at the dry bulb temperature for the current hour. The overall heat transfer coefficient (UOVERAL) of the front and back is found for the present conditions and the cell temperature rise is found by $\Delta T = \text{net insolation absorbed} / \text{UOVERAL}$.

The UOVERAL is the sum of the parallel front and back conductances. Each conductance is the sum of the material thermal resistances of the panel (cover sheets, glues, substrates, etc.) plus the surface thermal resistance. The surface thermal conductance is the parallel sum of a convective and radiative conductance. The radiative conductance during the day is assumed to be black body radiation at the dry bulb temperature. The back is assumed to be in free convection, with the wind never acting on the back. Appropriate relationships are used for laminar or turbulent-free convection for an average tilted panel of some defined characteristic dimension. The front surface convection assumes the wind moves parallel to the surface. That is, if the wind is at an angle the panel should deflect it to parallel flow. From zero to a logically determined wind velocity the front surface remains in free convection while above this point forced convection correlations are used. An accurate UOVERAL total value is found by iterating through this loop several times for each hourly calculation.

- (iv) Solar cell power output. At this time, the model assumes that power conditioning circuits will load the panels at their maximum power point as temperatures change. For the first results, it is assumed that over the terrestrial temperature range of interest the power delivered at maximum power varies linearly with cell temperature. It also assumes that cell power varies linearly with incident radiant flux. The power output is also corrected for active panel cell packing density.

- (v) Nighttime cooling. For panel thermal stress temperature range definition it is important to know the temperature depression of the panel below the ambient air on a clear night. Obviously, the maximum depression occurs on a windless, clear night. A subroutine was written for nighttime cooling based on the following logic. The front and back surfaces are assumed coupled to a defined black-body sky (usually -51°C) through a view factor defined by the tilt angle. The balance of the front-end back-view factors couple the panel to the ground at the ambient temperature. This net radiative coupling results in a heat loss which must be compensated by convective warming by the ambient air. Through an iterative process this temperature depression can be found for any panel design.

c. Simulation Results

Three real panel designs used in the baseline cost analysis were analyzed as designs 1, 2, and 3, and two limiting designs were also analyzed.

In panel design No. 1, cells are mounted on the backside of 1/4-in. plexiglass, bonded with 3 mils of Conap and coated on the back surface with 10 mils of Conap. Panel design No. 2 is the same as No. 1 except clear glass is substituted for the plexiglass. In panel design No. 3, cells are mounted on the top of 1/4-in. plywood, bonded with 3 mils of Conap, and the tops of the cells covered with 2 mils of FEP. Panel design No. 4 is conceptual; bare cells would hang in space. Panel design No. 5 is also conceptual, with bare cells mounted on a near-perfect thermally insulating substrate (36-in. urethane foam).

In order to assess primarily peak power heating effects, these panels were assumed to be (1) installed at Albuquerque, NM latitude 35° ; (2) operated at summer solstice, 6/21; and (3) panel tilt angle 11.5° , i.e., normal insolation at meridian passage.

The program increments through a 24-hour day; therefore, a switch was installed in the program with two options:

- (1) Run over a full day which can be actual weather bureau data, i.e., no insolation before 5 a.m. and after 10:00 p.m. (on 6/21) or dummy data: different arbitrary insolation and temperature ranges.

- (2) Hold insolation constant at 12:00 noon values and have a dry bulb temperature incremented over a desired range.

In Figs. 24 and 25, the temperature rise and power loss of design Nos. 1 through 3 are compared with conceptual designs Nos. 4 and 5. The power loss

Figure 24. Panel daytime heating and power loss vs ambient temperature, no wind.

of design No. 4 is most strongly affected by wind and drops by more than 3 to 1. Notice that real designs Nos. 1, 2, and 3 all run cooler than the intuitively "optimum" base cell design No. 4 at 0 wind velocity. This is caused by the fact that real panel cover sheets have an emissivity of about 0.9 whereas the Si has value of 0.275. The real design with the greatest front conductive resistance is design No. 1 with 1/4-in. plexiglass and, accordingly, benefits least from the wind. Since all the real designs are bunched, the general effect (at peak power, normal incidence) is a 16% power loss at zero wind versus an 8% power loss for a typical average wind of 7 mph.

Figure 25. Panel daytime heating and power loss vs wind velocity.

Figure 26 shows the windless nighttime cooling effect for the various panel designs. Note as the ambient temperature increases, the depression increases due to the improved radiant coupling. However, these two effects are largely self-cancelling. At -20°F (-29°C) ambient, the real panel design can get to -30°F (-34°C) which should not aggravate the panel thermal stress design problem significantly.

In conclusion, real panel designs will experience a power loss of 16% at no wind to 8% at 7 mph mean wind at a typical 80°F (27°C) ambient. The implications of this on cell design to maintain 10% module efficiency are significant. The maximum temperature conditions expected are -45°F to 200°F (-43°C to 93°C).

No attempts to lower panel temperature by extended surface or active cooling appear to be warranted at this time. The most effective low-cost tool to lower cell temperature appears to be a high-emissivity front panel surface.

Figure 26. Panel nighttime cooling, no wind.

4. Solar Panel Life-Stress Analysis

The objective of this analysis is to assess the 20-year panel life goal with respect to mechanical-stress-caused failures. These stress failures can be due to one of two causes:

- (1) Mechanical stress of any part of the electrical circuit beyond the ultimate strength causing fatigue.
- (2) Fatigue cracking due to cyclic stresses in the electrical circuit.

These two stress failures could drop the panel out of service, but the more likely result is a gradual degradation in panel efficiency. For example, a fatigue-cracked interconnect region may exhibit a higher resistance thus reducing power output. The goal for a panel design is that no foreseeable stress mechanism can be projected to lead to a failure over the 20-year life.

There is a hierarchy of levels throughout the panel that are largely independent of each other and can thus be analyzed independently. These are:

- (1) Interconnector/Si bond region level - differential expansion between interconnector and Si and interconnector spring forces can cause failure in the Si bond region.
- (2) Interconnector level - stresses in the interconnector can cause the metal to fracture.
- (3) Si/substrate and Si/cover sheet level - hard mounting the wafers can cause problems such as metallization delamination or wafer cracking.
- (4) Panel level - (a) Substrate and cover sheet stresses due to environmental loads, human intervention, thermal, and humidity effects;
(b) Panel edge mounting stress concentrations.

An ideal solution or tool to assess all panel stress questions would seem to be the finite element model (FEM). A FEM computer model can, in principle, be constructed to represent any mechanical structure by replacing finite regions of the structure with equivalent cross-coupled springs connected at the defining nodes of the elements. There presently exist about a dozen different commercially available FEM software packages. However, the vast scale range of 5000/1 of significant dimensions (0.010 to 48 in.) from level 1 to level 4 makes an overall FEM model completely impracticable. In fact, this large scale range decouples the low-level design from the higher level designs. For example, the panel (level 4) strength is not materially affected by the design for levels 1, 2, and 3. However, higher level design considerations will generally affect the lower level designs. For example, panel deflection will cause a change in the interconnector/Si bond stress level. Thus, the stress analysis at all levels can be decoupled and pursued independently if the downward propagating effects are checked at the end.

The analysis conducted to date has assessed level 1 completely and made tentative assessments at all other levels. The literature on solar panel life considerations is quite extensive and has been reviewed and will be summarized below. Spacecraft panels always have separate cover sheets on each wafer and typically utilize a soft RTV mount under each wafer to a honeycomb panel. Therefore, virtually all the spacecraft literature deals with level 1 life considerations.

a. Summary of Existing Art

Ralph and Roger [4] developed a two-dimensional analysis of interconnects stressed beyond the ultimate strength as well as interconnect fatigue failure. The loop is shown in Fig. 27 and accounts for the cyclic stress produced in the

Figure 27. Interconnect expansion loop [4].

circular bonding due to the change in cell spacing ΔY_1 due to differential thermal expansion. Ralph goes on to show that the required loop height h to keep the loop stress just below the endurance limit is given by:

$$h = \frac{L_c \Delta\alpha \Delta T}{2} \left(1 - \frac{E D}{S_F R} \right) \quad (4)$$

where L_c is the wafer length; $\Delta\alpha$ is the differential expansion coefficient between Si and substrate; ΔT is the temperature change; E is the modulus of elasticity of interconnect material; S_F is the endurance limit (5×10^9 cycles) for interconnect material; and R is the loop radius.

Salama, Rowe, and Yasui [5] developed a more detailed two-dimensional analytical technique (Fig. 28) for soldered cells using a finite element digital

4. E. L. Ralph and J. Roger, "Silicon Solar Cell Interconnectors for Low Temperature Applications," Proceedings of the International Colloquium of Solar Cells, Gordon and Breach, Toulouse, France, pp. 503-518, 1970.
5. A. M. Salama, W. M. Rowe, and R. K. Yasui, "Stress-Analysis and Design of Silicon Solar Cell Arrays and Related Material Properties," Proceedings of the Ninth IEEE Photovoltaic Specialists Conference, pp. 146-157, 1972.

Figure 28. (a) Finite element model of contact strength test configuration. (b) Stress contours in pull test configuration [5].

computer analysis. Salama et al. concluded from their work that the main advantage of the finite element technique used in their work is its versatility in handling various designs with different geometries and material properties. They demonstrated correlation between the calculated and measured pull test to produce fracture at the solder fillet. Their work showed the need for accurate data on thermophysical properties of the materials.

Rauschenbach and Gaylord [6] performed finite element analyses of (1) soldered kovar interconnect, (2) welded kovar interconnect, and (3) an interconnect spring loop, all shown in Fig. 29. Note that the interconnect spring loop provides the boundary force values for models 1 and 2. These FEM models when loaded with a temperature equivalent to the maximum and minimum of the temperature range can predict the maximum and minimum cyclic stress and strain range experienced by all the parts of the interconnect region.

Figure 29. (a) Finite element representation of typical interconnector solder joint area in cross section. (b) Finite element representation of typical welded joint area. (c) Typical interconnector loop model for soldered joints, A, and its free body diagram and finite element representation, B [6].

6. H. S. Rauschenbach and P. S. Gaylord, "Prediction of Fatigue Failures in Solar Arrays," Proceedings of the Seventh Intersociety Energy Conversion Engineering Conference, (IECEC), San Diego, California, Sept. 1972.

Rauschenbach uses the methods of Manson [7,8] to relate cyclic strain range $\Delta\epsilon$ to the number of cycles to failure N_f as follows:

$$\Delta\epsilon = D^{0.6} N_f^{-0.6} + 3.5 \frac{F_{tu}}{E} N_f^{-0.12} \quad (5)$$

where $\Delta\epsilon$ is the total strain range (double amplitude); N_f is the number of cycles to failure; D is the ductility or true fracture strain; F_{tu} is the ultimate strength; and E is Young's modulus.

When strain range $\Delta\epsilon$ is plotted versus fatigue life N_f on a log-log scale, Eq. (5) describes a curve which is asymptotic to a straight line of slope -0.12 in the elastic strain range and to a straight line of slope -0.6 in the plastic strain range (Fig. 30).

Figure 30. Model for method of universal slopes [6].

Kaplan [9] analyzes the stresses in a round parallel gap weld joint made between various Ag-plated materials and Ag-metallized Si (Fig. 31) using FEM techniques. He shows that when two materials with different coefficients of expansion are bonded, a line shear force at the bond edges is generated when the temperature is changed. Since this is an infinite shear stress, then plastic deformation must begin at the edge and propagate inward to spread the shear force over a finite region. If subsequent temperature cycles are less severe, then further plastic deformation may not occur. These effects are

7. S. S. Manson, "Fatigue: A Complex Subject--Some Simple Approximations," Experimental Mechanics, 1965.
8. S. S. Manson, Thermal Stress and Low Cycle Fatigue, (McGraw-Hill, New York), 1966.
9. A. Kaplan, "Fatigue Analysis of Solar Cell Welds," Photovoltaic Specialists Conference, Palo Alto, CA, Nov. 1973.

Figure 31. (a) Schematic representation of weld joint.
(b) Finite element model of the weld joint [9].

shown in Fig. 32 as function of radius for various materials cycled from $+100^{\circ}\text{C}$ to -196°C . Kaplan shows by using Manson's methods that the Invar material should service 2000 cycles across the 296°C range.

Curtin and Billerbeck [10] reviewed the work of Kaplan and also present some difficult-to-find thermophysical properties of candidate interconnect materials.

10. D. J. Curtin and W. J. Billerbeck, "Advanced Interconnect Systems for Lightweight Solar Arrays," Photovoltaic Power and Its Applications in Space and on Earth, International Congress on the Sun in the Service of Man, Paris, France, July 2-6, 1973.

Figure 32. Comparison of shear stresses for various interconnector materials [9].

From the existing literature we find that:

- (1) The relative merits of various candidate interconnector materials are well defined, and
- (2) Successful interconnect schemes have been demonstrated analytically and experimentally that survive much wider temperature cycles than will be experienced terrestrially for a cycle life commensurate with a 20-year life.

b. Analysis of Low-Cost Panel

In this subsection, we perform a closed-form analysis of various aspects of the panel design to provide design guidelines.

(1) Differential Expansion Stresses in a Laminated Stack

If a series of sheets are bonded together at a given temperature, then two criteria must be met.

First, there must be dimensional compatibility, i.e., the unrestrained expansion plus the real strain in all sheets must be equal:

$$\alpha_1 \Delta T + (1 - \mu_1) \frac{\sigma_1}{E_1} = R \quad (6)$$

$$\alpha_2 \Delta T + (1 - \mu_2) \frac{\sigma_2}{E_2} = R \quad (7)$$

•

•

•

(8)

$$\alpha_n \Delta T + (1 - \mu_n) \frac{\sigma_n}{E_n} = R \quad (9)$$

where α_i is the thermal expansion coefficient; ΔT is the temperature change from assembly temperature; μ_i is Poisson's ratio; E_i is the modulus of elasticity; and, R is the change in length of laminate.

Second, the sum of all the internal forces must equal zero.

$$\sum_{i=1}^n \sigma_i T_i = 0 \quad (10)$$

where σ_i is the stress in the x or y direction and T_i is the thickness.

Thus, the effective expansion coefficient α_e of the laminate can be shown to be

$$\alpha_e = \frac{\sum_{i=1}^n \alpha_i \frac{E_i T_i}{(1 - \mu_i)}}{\sum_{i=1}^n \frac{E_i T_i}{1 - \mu_i}} \quad (11)$$

And the effective modulus of elasticity E_e of the laminate is

$$E_e = \frac{\sum_{i=1}^n E_i T_i}{\sum_{i=1}^n T_i} \quad (12)$$

Now without an external load, the stress in an individual laminate is

$$\sigma = (\alpha_e - \alpha_i) \Delta T \frac{E_i}{1 - \mu_i} \quad (13)$$

The case of Ag metallization on Si or on various candidate interconnector materials can be considered as a two-part laminate. For this case, the stress $\sigma/^\circ\text{C } \Delta T$ can be found by combining Eqs. (11) and (13) as

$$\frac{\sigma_1}{\Delta T} = \frac{E_1}{1-\mu_1} \frac{\Delta\alpha}{1 + \left(\frac{1-\mu_2}{1-\mu_1} \right) \frac{E_1 T_1}{E_2 T_2}} \quad (14)$$

where $\Delta\alpha$ is the average differential expansion coefficient between Si and material 1.

For very thin materials, the second term in the denominator can be neglected, whereas for thick interconnectors it cannot be. Using Eq. (14) for the stress per $^\circ\text{C}$, a thin and a thick case were calculated and are shown in Table 2 for a variety of materials. Also included is the ΔT required to exceed the elastic limit for annealed and hardened materials. Notice that Al undergoes plastic deformation after only 11°C temperature change. Even hardened Al undergoes plastic deformation after 47°C change. On the other hand, Invar must be changed by 11331°C to plastically deform. Note that the results for the thick case allow slightly larger temperature swings because of the compliance of the Si.

TABLE 2. THIN AND THICK CASE CALCULATIONS
FOR A VARIETY OF MATERIALS

Material	Thin Case		Thick case†			
	Interconnector Material on Si		1.4-mil Interconnector Material		7-mil Si	
	$\sigma/\Delta T$ psi/ $^\circ\text{C}$	ΔT for Yield*	$\sigma/\Delta T$ psi/ $^\circ\text{C}$	ΔT for Yield*	$\sigma/\Delta T$ psi/ $^\circ\text{C}$	ΔT for Failure**
Aluminum	469	11/47	377	13/58	-75	192
Copper	316	33/143	254	41/177	-47	308
Silver	264	30/167	228	35/193	-46	317
Kovar	113	524	89	669	-18	815
Invar	12	11331	9	15043	-1.8	7914
Molybdenum	145	565	136	602	-27.2	532

*Annealed/hardened

**Si stressed at ultimate strength

† $\Delta T < 0$ (cools down from assembly temperature)

†Thick case is for 1.4-mil interconnector on 7-mil Si.

Note that the following points are implicit in Table 2.

- Line force coupling between materials means shear stress at edges is higher.
- Stress shown is, therefore, the biaxial stress in the internal region of bond.
- Stress in this model is independent of bond size.

(2) Interconnector

The objective of this section is to draw some engineering conclusions about practical interconnect tab designs. Effectively, the tab must take up center-to-center differential expansions plus the change in length due to overall panel deflection from environmental loads.

The expansion required is composed of the components as follows:

$$X_o = De + Mo$$

where De is the deflection required of interconnector due to differential expansion and Mo is the movement due to panel deflection.

If the wafer is hard-mounted to the substrate, the wafer will expand essentially as the substrate, whereas if it is self-mounted, as in spacecraft designs, the differential coefficients applied to wafer center-to-center spacing will control.

$$\text{Soft mount} \quad De = Lc \Delta\alpha_1 \Delta T$$

$$\text{Hard mount} \quad De = Gc \Delta\alpha_2 \Delta T$$

where Lc is the center-to-center distance of wafers; Gc is the gap between wafers assumed to be small compared with Lc ; $\Delta\alpha_1$ is the differential expansion coefficient between substrate and Si; and $\Delta\alpha_2$ is the differential expansion coefficient between interconnect and substrate.

The movement Mo required due to panel deflection from wind loading can be found by geometry in terms of the distance of the wafer from the panel neutral axis.

$$Mo = \left(\frac{\frac{2H}{2}}{\frac{c}{4D} + D} \right) Gc \quad (15)$$

where H is the distance of wafer from neutral axis; C is the span length between supports; and D is the allowable deflection.

Thus, for typical values of

$\Delta T = 250^\circ\text{F}$, total maximum estimated temperature

$L_c = 3.25$ in. wafer-to-wafer

$G_c = 0.10$ -in. gap between wafers

$H = 0.25$ -in. distance to neutral axis

$C = 48$ -in. span length

$D = 1$ -in. allowable deflection

The result values are:

$D_e = 8.7 \times 10^{-3}$ in., soft

$D_e = 2.6 \times 10^{-4}$ in., hard

$M_o = 8.66 \times 10^{-5}$ in., panel deflection

Thus, it appears that in any reasonable panel design the deflection demands on the interconnector due to panel deflection can be neglected. Also a hard-mount wafer technique will reduce the interconnect spring forces very significantly.

From our analysis, we have reached the following conclusions.

An interconnector design for a 20-year life is achievable for the following reasons:

- (a) Spacecraft power systems have successfully endured cycle lives equivalent to 20 years with thermal cycles nearly twice as large as terrestrial cycles.
- (b) The inability to have interconnections with loops above the Si can be accommodated by careful design.
- (c) When a total panel design is complete, the methods described in the literature using the Manson low-cycle fatigue analysis can be used to prove 20-year interconnector life.

The merits of hard vs soft wafer mounting must be considered because hard-mounting structurally ties the cover sheet to the substrate and reduces interconnect flexure.

Humidity expansion must be further studied.

5. Panel Materials Discussion

a. Substrate Materials

(1) Substrate Materials Function and Requirements

A substrate material functions as the primary structural mounting surface for the solar cell array. Its requirements, therefore, are to provide a low-cost, high-strength, low-weight surface which is smooth, bondable, and chemically compatible with other typical materials of solar array panels. The substrate may be transparent, if mounted on the incident energy side of the cell. For spacecraft applications, the rigid substrate of Al honeycomb with a dielectric cover has been universally applied. Flexible roll-up solar arrays for spacecraft have also been developed using laminations of plastic films. For terrestrial applications, the Al honeycomb can meet most of the substrate requirements, with the most notable exception being cost. The flexible, laminated approach requires additional structure for mechanical strength and some added protection from long-term exposure to humidity.

(2) Materials Listing and Discussion

Mechanical, thermal, electrical, and economic data for candidate substrate materials which are representative of metals and plastics are given in Tables 3 and 4. In cases where there are property variations due to alloy, temper, or grade, the indicated properties are in middle of the range. Also shown in Table 3 is a listing for Si for comparative purposes.

Of the metallic substrate materials listed in Table 3, plain carbon steel is the most inexpensive per ft², has an expansion coefficient closer to Si than other candidate metals, and has adequate mechanical properties. The primary drawback is its corrosiveness when exposed to moisture, salt air, or acids. Aluminum has excellent resistance to corrosion in many environments due to the formation of a protective oxide film in the presence of air. From a cost standpoint, Al ranks below carbon steel, but is less expensive on an equal volume basis than stainless steel or copper. Of the metals listed in Table 3, Al has the highest thermal expansion coefficient but has also been used extensively in spacecraft solar panel design. A more complete listing of late 1974 metals prices is given in Table 4 which also shows price variations as a function of alloy for aluminum and steel. The high cost of copper and stainless precludes their use in thick sheet form for panel substrates, but

TABLE 3. MATERIAL PROPERTIES - SUBSTRATES

Property	Doped Silicon	6061-76 Aluminum	Carbon Steel	304 Stainless Steel	OFHC Copper	ABS Plastic	Thermo Plastic Resins
<u>Mechanical</u>							
Density (lb/in ³)	0.09	0.1	0.28	0.29	0.32	0.036	0.036
E (psi) x 10 ⁻⁶	16	10	30	28	17		
Yield, Strength (psi)		40,000	48,000	75,000	40,000		
Tensile Strength (psi)		45,000	82,000	110,000	50,000	6,000	17,000
Shear Strength (psi)	7,000 (Modulus)	30,000			28,000	10,000 (Flexure)	18,500
<u>Thermal</u>							
Coeff. of Expansion, 1/°F x 10 ⁶ (1/°F)	2-4	13	8.3	9.6	9.8	33	30
Conductivity (Btu/hr- ft-°F)	67	100	27	9.4	226	0.10	0.13
<u>Optical</u>							
Refractive Index							
<u>Electrical</u>							
Dielectric Strength, V/mil	Semi- Conductor	Conductor	Conductor	Conductor	Conductor	375	500
Cost \$/ft ² (thickness, in.)		1.25 (0.125)	0.63 (0.125)	3.90 (0.125)	8.75 (0.125)	0.93 (0.250)	1.00 (0.250)
\$/lb		0.50	0.12	0.75	1.50	0.70	0.80
<u>Comments</u>							
		Price varies with temper and form				Use below 175°F	Use below 200°F used in injection moldings

TABLE 4. 1974 METALS PRICES [11]

1 Primary nonferrous metals prices, \$/lb, % change

Aluminum, ingot (99.5%)	0.39	+56
Copper, electrolytic wirebar	0.756-0.77	+11.4
Copper, cathode full plate	0.75	+10.3
Lead, common	0.245	+48
Magnesium, ingot	0.75	+92
Magnesium, pig (99.8%)	0.75	+97
Nickel, Canadian	1.85	+21
Tin	3.61	+43
Titanium, sponge	1.90	+33
Zinc, Prime Western	0.38-0.40	+50
Chromium, 99.8% metallic base	2.25	+44
Cobalt, 99.5-99.9%	3.75	+17
Gold (troy oz)	173.25	+74
Indium, 99.9%, commercial (troy oz)	2.00-2.50	+5.8
Iridium (troy oz)	505.00	+127
Molybdenum	255.00	+33
Palladium (troy oz)	150-155	+100.6
Platinum (troy oz)	190-200	+28
Rhodium (troy oz)	350-260	+60
Silver ingot (troy oz)	5.00	+73
Vanadium	2.12-2.25	0
Zirconium, sponge	5.50-7.00	0

2 Aluminum mill product, \$/lb

Sheet, mill finish, in.	0.030	0.047	0.076	0.190
Coiled				
Alloy 1100, 3003	0.587	0.571	0.567	—
5052	0.616	0.60	0.593	—
6061-T6	0.783	0.684	0.634	—
Flat				
Alloy 1100, 3003	0.643	0.624	0.620	0.643
5052	0.672	0.653	0.646	0.685
6061-T6	0.834	0.714	0.678	0.683
Extrusions				
Alloy 6063-T5	0.610			
Screw machine stock				
Alloy 2011-T3, 1 in.	0.910			

Steel prices late 1974 vs year ago^a

Steel type ^b	Price, \$/lb (\$/kg)	Increase from Jan. 1, 1974
Carbon steel		
HR sheet	0.110 (0.242)	26
HR strip	0.115 (0.255)	36
CR sheet, C1 1	0.130 (0.286)	26
CR sheet, C1 2	0.126 (0.277)	29
CR interstitial-free	0.158 (0.348)	31
HR plate	0.114 (0.251)	25
HR bar	0.123 (0.271)	22
Structural shapes	0.120 (0.264)	33
Coated carbon steel		
Galvanized sheet	0.145 (0.319)	32
Aluminized sheet	0.158 (0.348)	30
Long terme	0.155 (0.341)	27
Long terme interstitial-free	0.176 (0.387)	26
High strength low alloy sheet ^c		
45 ksi (310 MPa) yld str		
HR	0.142 (0.312)	43
CR	0.185 (0.407)	55
50 ksi (345 MPa) yld str		
HR	0.144 (0.317)	42
CR	0.187 (0.411)	54
60 ksi (414 MPa) yld str		
HR	0.151 (0.332)	39
CR	0.196 (0.431)	50
Stainless steels		
304 sheet	0.53 (1.17)	e
304 bar	0.63 (1.39)	e
316 sheet	0.87 (1.91)	e
316 bar	0.88 (1.94)	e
410 sheet	0.45 (0.99)	e
410 bar	0.41 (0.90)	e
430 sheet	0.44 (0.97)	e
430 bar	0.49 (1.08)	e
17-4 PH sheet	1.18 (2.60)	e
17-4 PH bar	0.64 (1.41)	e
17-7 PH sheet	0.01 (2.22)	e
17-7 PH bar	0.94 (2.07)	e
Electrical steels ^d		
A-6	0.303 (0.667)	40
M-15	0.303 (0.667)	40
M-17	0.298 (0.656)	41
M-19	0.297 (0.653)	41
M-22	0.284 (0.625)	44
M-27	0.272 (0.598)	47
M-36	0.262 (0.576)	50
M-43	0.250 (0.550)	53

^a Base prices unless otherwise indicated. ^b HR = hot rolled, CR = cold rolled. ^c Net prices, including size and grade extras. ^d Non-oriented, fully processed. ^e In general, stainless steel price rose about 35%; some "PH" grades dropped in price.

11. "The Economics of Materials," Special Report, Materials Engineering, January 1975.

if any of the common metals are applied to panel substrates in the form of thin (0.010 in.) sheets stretched on a rigid frame, the substrate cost is greatly reduced, ranging from about \$0.05/ft² for carbon steel to \$0.70/ft² for copper. All metallic substrates might require the application of an electrically insulating layer to isolate the solar cell voltages, depending on panel design.

In general, plastic materials exhibit strength-to-weight ratios comparable to many metals, have high dielectric strengths, and can be molded into a variety of shapes. Their limitations for solar panel applications include high thermal expansion coefficients, long-term creep under load, and degradation of mechanical properties with increasing temperatures. The glass transition temperature, above which a given load will produce much greater elongation, is below room temperature for polyethylenes and polypropylenes, and is 118°F for nylon and 300°F for polycarbonates. The effect of time, temperature, loading, and glass reinforcement on the apparent modulus (E_a) for various plastics can be seen from the data of Table 5. Apparent modulus is commonly used to describe long-term behavior of plastics and is the stress on a simply supported beam at a known load divided by total strain measured after a given period. The time period is usually 1000 hours for plastics, since most creep occurs within that time period. The blank spaces in Table 5 indicate that such data do not exist. The last two columns of Table 3 show property data for two representative plastics, ABS and thermoplastic resins. The cost per pound of most plastics for substrate applications is in the range of \$0.50 to \$1.00, with the exceptions being those materials which retain good mechanical properties above 200°F such as polyimides (sold in thin films and powders) and polycarbonates. Table 6 is a breakdown of 1974 prices for plastics and shows the change in prices from 1973. Note the high cost of polyimides, fluoropolymers, and glass-reinforced plastics. It is clear that for terrestrial solar panel applications, the thermal and mechanical requirements dictate that if plastics are used as thick sheet substrate materials, they must be glass-reinforced or used in composite or laminate form.

Composite materials are characterized by high mechanical strength and low weight. These features are usually achieved by a mechanical design in which compressive loads are resisted by a core of composite or honeycomb design, and bending and shear loads are resisted due to concentration of materials at the extreme fiber such as the facing sheets in a honeycomb design. The cross

TABLE 5. CREEP PROPERTIES OF PLASTICS [12]

Creep properties

Materials (A)	Apparent modulus after 1000 hr, $E_a \times 10^{-3}$									
	At 500 psi		1000 psi		2000 psi		3000 psi		5000 psi	
	At RT	140 F	RT	140 F	RT	140 F	RT	140 F	RT	140 F
ABS										
High impact ^a (2)	—	—	210	—	250	—	—	—	—	—
Heat resistant ^b (2)	—	—	245	—	210	—	—	—	—	—
Acetals										
Homopolymer ^c (4)	250	120	250	120	210	100	—	—	—	—
GR homopolymer ^d (4)	650	300	550	275	500	190	—	—	775	—
Copolymer ^e (2)	270	70 ^o	270	45 ^{**}	—	—	220 ⁼	—	—	—
GR copolymer ^f (2)	—	—	—	—	—	—	1150 ⁼	—	750	—
Acrylics										
General purpose ^g (4)	—	175 ⁼	245	—	—	—	—	—	—	—
High impact	—	—	—	—	—	—	—	—	—	—
Noryl phenylene oxides										
General purpose ^h (4)	—	—	245 ⁱ	90 ⁱⁱ	230	89 ⁱⁱ	230	—	—	—
GR self-exting ⁱⁱⁱ (4)	—	—	—	—	1050	970 ⁱⁱ	980	860 ⁱⁱ	—	—
Nylons										
Type 6/6 ^{iv} (4)	90	60	85	55	65	25	—	—	—	—
Type 6/6 GR ^v (4)	—	—	—	—	—	—	585 ^v	480 ⁼	625	410 ^o
Type 6/6 MR ^{vi}	—	—	—	—	210	—	—	—	—	—
Type 6/12 ^{vii} (4)	—	—	—	—	75	45	—	—	—	—
Type 6/12 GR ^{viii} (4)	—	—	—	—	—	—	—	—	510	—
Polycarbonates										
General purpose ^j (4)	—	190 ^{**}	—	178 ^{**}	—	225 ^{**}	310	—	—	—
High performance ^k (4)	—	—	—	—	—	—	430	—	—	—
GR ^l (4)	—	—	—	—	—	—	760	950	1050	830 ^o
Polyesters										
General purpose	—	—	—	—	—	—	—	—	—	—
GR	—	—	—	—	—	—	—	—	—	—
Polyethylenes										
High density ^m	55 ^{***}	—	40 ^{***}	—	—	—	—	—	—	—
GR ⁿ (4)	—	—	420 ⁱ	—	—	—	—	—	—	—
Polypropylenes										
General purpose ^{oo}	65 ^{***}	30 ^{***}	60 ^{***}	—	825	—	—	—	—	—
GR ^{pp}	—	—	—	—	—	—	—	—	—	—
Polysulfones										
General purpose ^{qq} (4)	—	—	—	—	—	—	325	310	—	—
GR ^{rr} (4)	—	—	—	—	—	—	—	—	1075	795 ^o
Polyphenylene sulfides										
General purpose ^{ss} (4)	—	—	—	—	—	—	550 ⁼	—	—	—
GR ^{tt} (4)	—	—	—	—	—	—	2100 ⁼	—	1475	795 ^o
Styrenes										
General purpose	—	—	—	—	—	—	—	—	—	—
GR ^{uu} (4)	—	—	—	—	—	—	—	—	1000	490
Acrylonitrile ^{vv}	—	—	—	—	—	—	340	—	—	—
GR ^{ww} (4)	—	—	—	—	—	—	920 ⁼	—	1280	750
Vinyls										
Type I ^{xxx} (2)	320	45 ^o	325	25 ^o	—	—	—	—	—	—
Type II ^{yyy} (2)	160	—	250	—	215	—	—	—	—	—

Data based on the following materials: ^a Cyclocac GSM (Borg-Warner Chemicals); ^b Cyclocac OH (Borg-Warner Chemicals); ^c Delrin 500 (Du Pont); ^d Delrin 570X (Du Pont); ^e Celcon M-90 (Celanese); ^f Celcon GC25 (Celanese); ^g Lucite 140 (Du Pont); ^h Noryl SE100 (General Electric); ⁱ Noryl GFN-3 (General Electric); ^j Zytel 101 (Du Pont); ^k Thermocomp RF-1006 (LNP); ^l Vydene R100 (Monsanto); ^m Zytel 158 (Du Pont); ⁿ Thermocomp IF-1006 (LNP); ^o Lexan 101 (General Electric); ^p Lexan 500 (General Electric); ^q Thermocomp DF-1006 (LNP); ^r DMD-7014 (Union Carbide); ^s Thermocomp FF-1006 (LNP);

^{oo} Pro-Fax 6253 (Hercules); ^{pp} Pro-Fax PC072 30 (Hercules); ^{qq} Udel P-1700 (Union Carbide); ^{rr} Thermocomp GF-1006 (LNP); ^{ss} Ryton R-3 (Phillips Petroleum); ^{tt} Ryton R-4 (Phillips Petroleum); ^{uu} Thermocomp CF-1006 (LNP); ^{vv} Tyrol 880 (Dow); ^{ww} Thermocomp BF-1006 (LNP); ^{xxx} Geon 8700 (B. F. Goodrich); ^{yyy} Geon 8700 (B. F. Goodrich); ^{zz} 180 F; ^{aa} 240 F; ^{bb} 5000 psi; ^{cc} 122 F; ^{dd} 1500 psi; ^{ee} 150 F; ^{ff} 4000 psi; ^{gg} 160 F; ^{hh} 130 F; ⁱⁱ Based on tensile loading; ^{jj} Numbers in () indicate beam span (in.) for which center-loaded sample was stressed. NOTE: All tensile strength values were determined at room temperature after heat aging.

12. "Plastics vs Time," Materials Engineering, October 1973.

TABLE 6. PRICES AND 1974 PRICE TRENDS FOR PLASTICS^a [11]

Prices and 1974 price trends for plastics ^a						Prices and 1974 price trends for plastics ^a					
Materials/grades	Specific gravity	Price (molding grades) \$/lb	¢/cu in	¢/cu cm	1973 price change, ¢/lb	Materials/grades	Specific gravity	Price (molding grades) \$/lb	¢/cu in	¢/cu cm	1973 price change, ¢/lb
Thermoplastics						Polyesters					
ABS						PBT					
General purpose	1.02-1.04	0.495	1.82-1.86	0.112	+12.5	PTMT	1.31	0.85-0.87	4.02	0.245	+21
Medium impact	1.04-1.05	0.455	1.70-1.72	0.104	+12.5	Copolymers	1.20	0.87	3.77	0.230	+15
High heat	1.04-1.06	0.545	2.05-2.09	0.126	+10.5	Glass reinforced PBT (30%)	1.52	0.86	4.72	0.288	+16
Clear	1.07	0.58	2.24	0.136	+9	Polyethylenes					
Acetals						Low density					
General purpose	1.41-1.42	0.70	3.60	0.219	+10	High density	0.94-0.97	0.26-0.28	0.88-0.98	0.056	+11-12
Glass reinforced (25%)	1.61	0.75	4.36	0.266	+10	EEA copolymers	0.92-0.93	0.30-0.40	1.16	0.071	+10
Acrylics						EVA copolymers					
General purpose	1.18-1.19	0.49	2.11	0.129	+3.5	High molecular weight	0.94-0.95	0.315-0.445	1.49-1.51	0.091	+11
Modified	1.11-1.18	0.55-0.60	2.21-2.56	0.146	+3.5	Glass reinforced HDPE (30%)	1.17	0.485-0.51	2.05-2.16	0.129	+8
Cellulosics						Polyimides					
Acetate	1.27	0.80	3.67	0.224	+30	Phenylene oxide based materials	1.7-1.9	4.00-4.50	24-31	1.647	—
Butyrate	1.19	0.82	3.53	0.215	+20	General purpose	1.06-1.10	1.05	4.13	0.252	+30
Ethyl	1.10	1.38-1.50	5.49-5.96	0.335-0.364	+68-70	Glass reinforced (30%)	1.27	1.15	5.27	0.322	+30
Propionate	1.21	0.82	3.58	0.218	+20	Polyphenylene sulfide	1.34	3.50	16.95	1.034	—
Fluoropolymers						Polypropylenes					
PTFE	2.1-2.2	2.95	22.39	1.365	+45	General purpose	0.91	0.24	0.79	0.048	+6
PFA	2.1-2.2	9.00	34.20	2.086	—	Copolymer (ethylene propylene)	0.91	0.28-0.34	0.92-1.12	0.056-0.068	+9
FEP	2.1-2.2	5.20	39.46	2.407	+55	Prop. vinyl chloride copolymer	1.29-1.31	0.39-0.50	1.82-2.33	0.111-0.142	+8-10
PCTFE	2.1-2.2	7.45-11.60	56.5-88.02	3.449-5.371	+255-670	Glass reinforced (30%)	1.13	0.67-0.98	2.73-4.00	0.206	+20-30
ETFE	1.68-1.70	6.00	36.84	2.247	—	Polystyrenes					
ECTFE	1.68-1.70	6.50	39.46	2.407	—	Impact	1.03-1.05	0.315	1.17-1.20	0.072	+15
Ionomer	0.94	0.65	2.20-2.26	0.136	+20	General purpose	1.06	0.305-0.33	1.17-1.26	0.074	+17
Nylons						SAN					
Type 6	1.14	0.90	3.70	0.226	+14	Glass reinforced (30%)	1.07-1.08	0.41	1.58	0.096	+19
Type 66	1.14	0.88	3.63	0.221	+15	Polyurethanes					
Type 612	1.07	1.70	6.56	0.400	+65	General purpose	1.24	2.00	8.96	0.546	+100
Type 11	1.03	2.22	8.26	0.504	+68	Glass reinforced (30%)	1.45	2.20	11.53	0.703	+78
Type 12	1.01	2.02	7.37	0.450	+52	Polyethylenes					
Copolymers	1.08-1.14	0.92	3.59	0.219	+2-17	General purpose	1.11-1.35	1.30-1.65	5.21-8.05	0.396	+15-30
Glass reinforced 66 (30%)	1.37	1.00	4.95	0.302	+15	Vinyls					
Glass reinforced 612 (30%)	1.34-1.36	1.75	8.47-8.60	0.521	+45	Rigid	1.3-1.5	0.30-0.33	1.41-1.79	0.097	+17-19
Mineral reinforced	1.47-1.50	0.70-0.75	3.72-4.07	0.237	+15-20	Chlorinated (compounds)	1.49-1.58	0.64-0.67	2.75-3.83	0.198	+9-12
Poly (amide-imide)	1.41	4.00-6.25	25.47	1.554	—	Alloys					
Polycarbonates						ABS/polycarbonate					
General purpose	1.20	0.96-1.00	4.116-4.34	0.253	+21	ABS/PVC (rigid)	1.12	0.82	3.32	0.202	+28
High performance	1.25	1.08	4.88	0.297	+33	Acrylic/PVC	1.21	0.53	2.32	0.141	+14
Glass reinforced (30%)	1.43	1.42-1.46	7.34-7.48	0.450	+27-29	Alloys					

^a Prices are for molding grades, truck load or equivalent quantities, as of 12-15-74.

section of foamed plastics or honeycomb designs closely resembles an I-beam, which is a very material-efficient design. High strength may also be achieved in composite materials by laminating thin sheets together at right angles such as in plywood laminates, where the mechanical properties vary with direction. Table 7 lists the properties of common composite materials which are applicable to solar panel design. Aluminum-honeycomb core material cost in large quantity is $\$0.22/\text{ft}^2$ based on 3/4-in. honeycomb cell size and 0.003-in.-thick foil which has a compressive strength of 100 psi. Decreasing the honeycomb cell size to 1/4 in. increases the compressive strength to 600 psi and increases the cost of the core to $\$0.44/\text{ft}^2$. We estimate the cost of finished honeycomb panels to be a factor of six to ten higher than the core cost to account for application of facing sheets, adhesives and edge film. This places finished 0.25-in. honeycomb substrates in the range of $\$1.30$ to $\$2.20/\text{ft}^2$ for 3/4-in. cells. Considering a cost goal of $\$1/\text{ft}^2$ or less for all starting materials in a low-cost solar panel, the honeycomb design appears too expensive and has little potential for factory cost reduction due to quantity or development effort.

At the absolute low end of the price spectrum is the 0.25-in. exterior grade plywood which currently sells for $\$0.16/\text{ft}^2$. An additional $\$0.10/\text{ft}^2$ for wood preservative pressure treatment still leaves the cost at $\$0.26/\text{ft}^2$. Wood, like plastic, is permeable to moisture; for long solar cell lifetimes, some type of vapor barrier would be required. In addition, the electrical insulating properties of wood drop sharply with increasing moisture content. With proper treatment, exterior grade plywood can withstand a terrestrial environment for 30 years and is being used in housing foundations. The thermal coefficient of expansion of plywood is a close match to silicon, but the hygroscopic expansion can be 100 times higher than the thermal for a 10% change in humidity.

Fiberglass, foamed plastic composites, and insulating board fall between the plywood-honeycomb cost spread, both in price and mechanical properties. Combinations of composites, such as thin fiberglass sheets laminated to plywood, have potential application to solar array panels and are readily available.

The flexural load-bearing capability of various plastic composite panels is shown in Table 8 as a function of materials and panel thickness. The highest load-bearing panel shown in Table 8 is a polypropylene/aluminum panel which has a combined cost of about $\$1/\text{ft}^2$.

TABLE 7. MATERIAL PROPERTIES - SUBSTRATES - COMPOSITES, LUMINATES.

<u>Property</u>	<u>G-2 Fiberglass</u>	<u>Foamed Plastic Composites</u>	<u>Honeycomb Core Aluminum</u>	<u>Exterior Grade Plywood</u>	<u>Asbestos/ Cement Insulating Board</u>
<u>Mechanical</u>					
Density (lb/in ³)	0.054	0.03	0.001	0.025	0.06
E (psi) x 10 ⁻⁶	1.8			1.6	1.5
Yield, Strength (psi)			5000 (flex rigid)		
Tensile Strength (psi)			100 (compression)	1500	1400
Shear Strength (psi)		1500 (working)	100	120	3500
<u>Thermal</u>					
Coeff. of Expansion, 1/°F x 10 ⁶ (1/°F)	9	30	13	3.4	5.0
Conductivity (Btu/hr- ft-°F)	0.17		100	0.08	0.04
<u>Optical</u>					
Refractive Index					
<u>Electrical</u>					
Dielectric Strength, V/mil	425	216	Conductor	Varies With Moisture	
<u>Cost</u> \$/ft ² (thickness, in.)	0.90 (0.125)		0.22 (0.25)	0.16 (0.25)	0.48 (0.25)
\$/lb	0.60	0.80		0.18	0.23
<u>Comments</u>		Use below 200°F	3/4" cell .25 thick .01 facings *finished panel is 8-10 x this	Use below 230°F swells with moisture	

TABLE 8. FLEXURAL LOAD CAPACITY OF REPRESENTATIVE EXPANDED-CORE PANELS [13]

Core Wt (lb/ft²)	Core	Thickness (in.)		Total	Load* (lb)	EI (10⁵ lb-in.²)
		Top Face	Bot Face			
Core and faces: Impact styrene						
1.05	0.5	0.125	0.125	1.0	150	1.46
1.05	1.0	0.125	0.125	1.25	350	3.40
1.05	1.5	0.125	0.125	1.75	580	5.64
Core and faces: Polycarbonate						
0.78	1.0	0.125	0.125	1.25	350	3.40
0.78	1.0	0.125	None	1.13	140	1.36
0.78	1.56	0.125	0.125	1.81	410	3.98
0.78	1.56	0.125	None	1.68	190	1.85
Core: Polycarbonate, Face: Cast acrylic						
0.78	1.0	0.063	0.063	1.13	260	2.53
0.78	1.56	0.125	0.125	1.81	450	4.38
Core and faces: Polypropylene						
0.89	1.94	0.125	0.125	2.14	295	2.86
Core: Polycarbonate; Face: High-pressure laminate						
0.78	1.56	0.063	0.063	1.68	515	5.00
Core: Polypropylene; Face: Aluminum						
0.89	1.88	0.032	0.032	1.94	900	8.75

*Load to produce a 1/8-in. deflection at the center of a 12-in. wide x 24 in. panel, supported on bars 18-in. apart. Load applied at center of panel, on a 12-in. long bar. Data, Norfield Corp., Danbury, Conn.

b. Rigid Cover Sheets

The primary function of a cover sheet for solar panels is to protect the solar cells from damage due to environmental conditions such as rain, hail, and flying objects, while transmitting a maximum of insolation for long lifetimes. A rigid cover sheet can serve several functions on the solar panels. First, it can serve as the primary structural member in which case it would have to meet the previously described substrate requirements; secondly, it can function solely as a protective cover with no load-bearing capability; or, thirdly, it can share the panel load-bearing function with the substrate.

Rigid, transparent materials which have potential application to solar panels are listed in Table 9, which shows relevant properties and current prices. Plain or tempered window glass has several advantages over the clear plastic sheets in that, for equal thickness, it is the cheapest material per square foot, it retains high transmissivity for long lifetimes, and has a

13. "Structural Plastic Panel," Machine Design, June 1976.

TABLE 9. MATERIAL PROPERTIES - CLEAR COVER SHEETS

<u>Property</u>	DS <u>Window Glass</u>	<u>Tempered Glass</u>	<u>Acrylic Sheet</u>	<u>Poly- carbinat</u> e	<u>Glass/ Polyester</u>
<u>Mechanical</u>					
Density (lb/in ³)	0.09	0.09	0.042	0.043	0.05
E (psi) x 10 ⁻⁶	10	10	0.45	0.34	
Yield, Strength (psi)					
Tensile Strength (psi)	1,600	6,400	10,500 (ult)	9,500 (ult)	11,000
Shear Strength (psi)			9,000		12,000
<u>Thermal</u>					
Coeff. of Expansion, 1/°F x 10 ⁶ (1/°F)	4.7	4.7	38	38	14
Conductivity (Btu/hr-ft-°F)	1.0	1.0	0.12	0.12	0.07
<u>Optical</u>					
Refractive Index	1.52	1.52	1.50	1.59	1.52
<u>Electrical</u>					
Dielectric Strength, V/mil	25	250	430	450	
<u>Cost</u> \$/ft ² (thickness, in.)	0.65 (.25)	1.10 (.25)	1.80 (.25)	3.85 (.25)	0.42 (.04)
<u>Comments</u>			Use below 200°F	Use below 250°F	Use below 200°F .06" max. thickness

thermal coefficient of expansion in the same range as Si. The plastic panels have the advantage of high impact resistance but their cost, their tendency to become less transparent with time and temperature, and their degradation in mechanical strength with temperature are limiting factors. Polycarbonate has seen application to solar-thermal collectors, but at \$3.85/ft² for a 0.25-in.-thick panel, its price is well out of range of the solar panel material cost goals, and the price is not likely to be reduced. Glass/polyester sheets could be applied to solar panels as a protective cover sheet, but their availability is limited to thicknesses of 0.06 in. and less. This material is also currently being sold for solar-thermal collector applications.

c. Thin-Film Cover Sheets

A thin-film cover sheet for terrestrial solar panels must serve the same functions as those described for rigid cover sheets, namely, environmental protection and possibly structural support. Desirable properties of thin-film cover sheets include low cost, high solar transmissivity, high electrical insulation, high bonding strength using adhesives or heat sealing techniques, and long-term stability. A list of thin-film cover sheet materials which have potential application to terrestrial solar panels is given in Table 10. The PVF and FEP films can be heat-sealed to themselves, to Si, to polyimide film, or to treated polyester film. FEP and PVF films can serve the dual function of cover sheet and adhesive. NASA-Lewis has developed light weight, flexible solar panels consisting of a heat-sealed lamination of 5-mil FEP cover, solar cell, 2-mil FEP adhesive layer and 1-mil polyimide film for structural support. Fluorocarbon materials can also be sprayed on solar panels and have high adhesion, high dielectric strength, and high chemical stability. PFA is one such fluorocarbon powder which can be sprayed using electrostatic powder spray equipment. Current prices for the PFA powder, however, are quite high at $\$0.30/\text{ft}^2/\text{mil}$ of thickness. A thickness of 5 mils is reasonable for coating solar panels, and this would cost $\$1.50/\text{ft}^2$ which is, again, well above the solar panel material cost goals.

All plastic material and thin plastic films in particular have one characteristic which may limit the lifetimes of solar panels: their permeability to water vapor.

Corrosion of the interconnect material and the cell/interconnect joint is an area which requires further investigation. In a design using nonmetallic materials, the vapor transmission rate through the materials must be determined along with corrosion rate for particular interconnect designs. Another area which warrants further study is the problem of impact loading on solar cells covered with thin plastic films. Thin plastic covers do not afford much protection from impacts such as hailstones and any loading of this type would be transmitted directly to the silicon cell.

The plastic films could function as panel substrates if they were to be stretched on a frame as in a diaphragm arrangement. Both polyester and polyimide films have high tensile strengths at room temperature, and the polyimide film retains its mechanical strength at temperatures well above 200°F , which is close to the maximum solar panel temperature for the continental U. S.

TABLE 10. MATERIAL PROPERTIES - PLASTIC FILMS - 1-MIL THICK

<u>Property</u>	<u>Polyester Film</u>	<u>Polyimide Film</u>	<u>PVF Film</u>	<u>FEP Film</u>
<u>Mechanical</u>				
Density (lb/in ³)	0.05	0.05	0.05	0.05
E (psi) x 10 ⁻⁶				
Yield, Strength (psi)				
Tensile Strength (psi)	45,000 (ult)	25,000 (ult)	16,000 (ult)	3,000 (ult)
Shear Strength (psi)				
Stress @ 5% Elongation	23,000	13,000		
<u>Thermal</u>				
Coeff. of Expansion, 1/°F x 10 ⁶ (1/°F)	17	20	28	60
Conductivity (Btu/hr-ft-°F)	0.08	0.08		0.08
<u>Optical</u>				
Refractive Index	1.64	1.78	1.46	
<u>Electrical</u>				
Dielectric Strength, V/mil	14,000	7,000	3,400	7,000
<u>Cost</u> \$/ft ² (thickness, in.)	0.015 (0.001)	0.19 (0.001)	0.04 (0.001)	0.17 (0.001)
<u>Comments</u>	Use below 200°F	Stable above 200°F	Use below 225°F heat sealable	Use below 225°F heat sealable

d. Adhesives and Potting Compounds

Price information for various adhesives and comments on availability are given in Table 11. In general, silicone rubber adhesives have seen widespread application to spacecraft solar panels because of their bonding ability, chemical resistance, resilience, and good physical and electrical properties. One or two component silicone rubber adhesives costs \$0.03 to \$0.06/ft²/mil, and, in some cases, such as bonding a cell on the insulation side, the clear silicone adhesive may require surface priming at a cost of \$0.10/ft² per surface.

TABLE 11. ADHESIVE PRICE CHANGES AND AVAILABILITY, 1974 AND 1975 [11]

Adhesive price changes and availability, 1974 and 1975

Adhesive	Price	Increase 1974	1975	Availability 1974	1975
Anaerobic	\$22.7/lb	20%	No significant change	2-5 days	No change
Cyanoacrylate	\$60/lb	20%	No significant change	2 weeks, although there are some shortages	Should improve
Elastomeric-solvent based	\$1-2/dry lb	15-100%	Increase	Tight, but easing	Tight again latter part of 1975
Epoxy	—	20-100%	Increase	30-60 days	Tight
Machinery	—	None	No increase expected	Off the shelf	No change
Polyester Pressure-sensitive for tape, 60% solids	\$3.20/lb	30-50% 37%	Up 5% at most Depends on inflation	Adequate Excellent	Should improve No significant change
Rubber	—	20%	5-10%	1 week	Good
Silicone adhesive/sealant	\$2.35-1/12 gal in 500 gal lots	30%	Depends on inflation	Generally good; some spot shortages	No significant change
Thermoplastic rubber	—	45-70%	Stable	On allocation	Should become readily available

Sealing or potting compounds are available for a wide variety of applications and, in general, are much less expensive than the adhesives. Popular sealing compounds used in the electronics industry cost about $\$0.01/\text{ft}^2/\text{mil}$ of thickness. Clear potting compounds could be used in solar panels to function as transparent, nonstructural cover sheets.

6. Panel Designs and Cost Breakdown

In order to assess total terrestrial solar panel costs for raw materials, several candidate panel designs were formulated. The material combinations in the candidate designs, for the most part, have not been experimentally evaluated, and much effort remains to be done in this area. However, the panel designs which were formulated use materials with known properties and prices and appear, on paper, to satisfy most of the solar panel design requirements. Figures 33, 34, and 35 show material and cost breakdowns for three general types of panel designs. Shown in Fig. 33 are cost and material breakdown for five candidate panel designs, all of which use a rigid, clear cover sheet as the

I	II		III		IV		V		VI	
Array Component	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²
Substrate Material	1/4-in. Acrylic	1.80	1/4-in. Tempered Glass	1.10	0.040-in. Glass/Poly-ester	0.50	1/4 Temp. Glass	1.10	1/4 DS Glass	0.65
Cell-Substrate Adhesive	GE RTV 615 0.005-in. thick	0.21	Same as Column II		Same as Column II		2-mil FEP Type A	0.29	RTV 615 005 Thick	0.21
Adhesive Primer	1/2-mil 2 surf	0.20	Same as Column II		Same as Column II				Primer	0.20
Cell Interconnects	0.125 x 0.002 x 0.75 Clad Copper	0.01	Same as Column II		Same as Column II		Welded Cu Ribbon	0.01	Interconnect	0.01
Sealing Compound	Conap 0.-10-in. #2525	0.08	Same as Column II		Same as Column II		5-mil FEP Type A	0.69	Conap 0.010-in. Al Foil 0.003	0.08 0.03
Panel Connector Connector Bus	1 power conn. flat cable 1 x 0.01-in.	0.09	Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Al. Edge Channel	0.06 thick 1-in. leg x 16 ft long	0.10	Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Total		2.49		1.79		1.19		2.28		1.37

Figure 33. Solar array candidate design #1 cell backside mounting.

I	II		III		IV		V		VI		VII	
Array Component	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²	Material	\$/ft ²
Substrate Material	1/4 in. Al Honeycomb	3.00	1/4 in. Transite Asbestos/cement	0.48	1/4 in. Exterior Plywood Treated	0.26	1/4 in. G-2 Fiber-glass	1.50	1/4 in. Molded Plastic	1.25	1/4 in. Steel Plate	1.20
Substrate Insulator	3-mil Tedlar	0.12	Same as Column II		Same as Column II						Same as Column II	
Cell-Substrate Adhesive	RTV 560 0.005 in.	0.20	Same as Column II		Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Cell Interconnects	0.125 x 0.002 in. Cu Ribbon	0.01	Same as Column II		Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Window Material & Sealing Compound	0.005 in. FEP Type A	0.69	DC-13-523 0.005 in. Clear Potting	0.18	Same as Column III		Same as Column III		Same as Column III		Same as Column III	
Panel Connector, Bus		0.09	Same as Column II		Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Al Edge Channel		0.01	Same as Column II		Same as Column II		Same as Column II		Same as Column II		Same as Column II	
Total		4.21		1.18		0.96		2.08		1.83		1.90

Figure 34. Solar array candidate design #2 cell front side mounting.

I Array Component	II Material	\$/ft ²	III Material	\$/ft ²	IV Material	\$/ft ²
Substrate Material	3-mil Polyimide	0.57	3-mil Al sheet	0.03	Same as Column III	
Cell-Substrate Adhesive	2-mil FEP	0.34	Same as Column II		5-mil RTV 560	0.20
Cell Interconnects	Welded Cu ribbon 2-mil	0.01	Same as Column II			
Window Material	5-mil FEP	0.85	Same as Column II		DC13-523 5-mil potting	0.18
Panel Connector, Bus		0.09				
Assembly Hardware		0.08	Same as Column II			
Panel Framing		0.15	Same as Column II			
3 in. Insulation		0.10	Same as Column II			
Subtotal		2.19		1.65		0.84
Credit for Thermal Collector Materials		1.10		1.10		0.43
Total		1.09		0.55		0.41

Figure 35. Solar array candidate design #3 diaphragm mount/thermal collector.

primary structural member. All substrate material thicknesses are 0.25 in. and are currently being analyzed for stress and deflection under various panel loadings. The 0.040 glass/polyester panel would require additional mechanical support, possibly by laminating another 0.04-in. sheet to it which would result in substrate costs of $\$1/\text{ft}^2$. In Fig. 33, it is seen that the substrate or load-bearing member is the major cost item and ranges from 40% to 80% of the total panel material cost. It should be noted that all cost information in Figs. 33, 34, and 35 are for material only and do not include labor or capital costs involved in producing a finished solar panel. From Fig. 33, the most inexpensive 1/4-in. substrate design includes double-strength glass, clear silicone adhesives, and 0.01-in.-thick potting compound with 3-mil aluminum foil for a vapor barrier for a total material cost breakdown of $\$1.37/\text{ft}^2$. Study is continuing into substituting cheaper adhesives or directly bonding silicon cells to the glass substrate.

In Fig. 34 candidate designs are presented in which the cell is mounted on the front side of the substrate and covered with a clear cover sheet. Both the asbestos/cement and plywood material permit a cost of close to the $\$1/\text{ft}^2$ level, but further study and experimentation must be done in the area of moisture effects and insulator bonding quality.

Figure 35 shows three panel designs in which the substrate material is stretched on a rigid frame, like a diaphragm, which gives the substrate mechanical strength in the direction perpendicular to the solar cells. The diaphragm substrates are shown to be integrated with a thermal collector, in which forced air would move in the duct formed by the diaphragm substrate and the backside insulation. All designs in which the solar cells are mounted to a thin-film substrate would require active cooling to maintain reasonable cell operating temperatures; it is a logical step, therefore, to integrate the diaphragm approach with a thermal collector and charge part of the total material cost to the thermal collector subsystem. As Fig. 35 shows, this approach results in panel costs in the range of $\$0.41$ to $\$1.09/\text{ft}^2$.

In summary, much work remains to be done in experimentally evaluating these and other panel designs. A detailed analytical effort is continuing. The designs presented in Figs. 33, 34, and 35 are a first-cut based on preliminary thermal and structural analysis. The $\$1/\text{ft}^2$ cost goal for panel materials, however, appears to be attainable at today's material prices.

Further module pricing studies will be completed on the basis of panel costs in the \$0.50 to 1.00/ft² range. Task 3 results will be closely monitored in order to seek confirmation for any of the proposed alternatives or to identify new approaches to the encapsulation function.

SECTION IV

CONCLUSIONS

Our analysis of the existing technologies applicable to solar module fabrication is nearing completion. In this report, as an example, we describe one basic module whose manufacturing costs were derived from first principles.

In this case, four basic cost analyses were made using our computerized cost analysis procedure. Excluding raw wafer cost, the estimated module processing cost per watt for the Ti/Ag evaporation metallization base case is about \$2.40. An experimental thick-film Al screen-printing technique could reduce the cost to about \$1.55/W. These estimates use a derived overall process yield of about 65%. The major cost of manufacture, however, is the raw wafer cost. If we assume \$2 to \$3 cost per starting 7.6-cm wafer (0.5 W), the array module total manufacturing cost (base case) is expected to be in the \$8.50 to \$11.50/W range, assuming 65% overall yield. Marketing, administrative, and distribution costs are enormously sensitive to the specific business situation but typically would result in a selling price at least twice the manufacturing cost. We conclude that our first principal approach to cost analysis provides a reasonably accurate technique for cost estimation which will retain its usefulness when the cost of undeveloped manufacturing techniques are estimated.

The only viable commercial source of Si starting material available today is wafer Si cut from Czochralski ingots. Progress in being made in the area of ribbon growth and the ability to handle rectangular or ribbon geometry starting material should be a consideration when developing automated processes.

Procedures are on hand for analysis of the cell performance losses associated with variations in front contact metallization. Minimization of those losses will be possible for any process once its technological constraints are determined. It will also be possible to compare the performance impacts of different processes, each at its optimum. Preliminary calculations for screen-printed Ag show that design considerations will not be a serious deterrent to its use.

A module material study has been completed which indicates that it will be possible to reduce the cost of materials used in module assembly to \$10/m². Attaining substantially lower costs may be difficult. It is not clear that

the lowest cost alternatives can meet program life and environmental requirements. Task 3 results will be incorporated into the study as they become available. In the absence of such information parallel, designs are being pursued which utilize glass, plastic films, and conformal coatings.

Preliminary analyses have been completed which show that 15 to 20% of the available panel output will be lost due to temperature rise of the panel. Designs which structurally decouple the cells from the protective skins will surely require active cooling of the semiconductor.

Structural analysis has shown that thermal stress at the interconnect/cell interface will not limit panel life to less than 20 years. Further, it has been shown that structural deflections will not appreciably add to interconnector stress. Substrate moisture absorption could create stress and cell life problems and will be investigated further.

SECTION V

RECOMMENDATIONS

While the costs of labor, materials, and capital can be estimated in a straightforward manner, the yield factors for each process can be the subject of considerable debate. As the program moves into area where processes have yet to be developed, this problem will become severe. We encourage the reader of any such study to show interest in the magnitudes of the assumed yields as well as in the final dollars/watt figures.

SECTION VI
NEW TECHNOLOGY

There are no new technology reports for this quarter.

REFERENCES

1. B. F. Williams, "Automated Array Assembly," Quarterly Report No. 1, ERDA/JPL-954352-76/2, prepared under Contract No. 954352 for Jet Propulsion Laboratory, March 1976.
2. *Review and Evaluation of Past Solar Cell Development Efforts*, Final Report prepared by RCA Astro-Electronics Division for NASA under Contract NASW-1427, June 1968.
3. Y. Liu and R. Jordan, "Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Radiation," *Solar Energy*, July 1960.
4. E. L. Ralph and J. Roger, "Silicon Solar Cell Interconnectors for Low Temperature Application," *Proceedings of the International Colloquium of Solar Cells*, Gordon and Breach, Toulouse, France, pp. 503-518, 1970.
5. A. M. Salama, W. M. Rowe, and R. K. Yasui, "Stress-Analysis and Design of Silicon Solar Cell Arrays and Related Material Properties," *Proceedings of the Ninth IEEE Photovoltaic Specialists Conference*, pp. 146-157, 1972.
6. H. S. Rauschenbach and P. S. Gaylord, "Prediction of Fatigue Failures in Solar Arrays," *Proceedings of the Seventh Intersociety Energy Conversion Engineering Conference*, (IECEO), San Diego, California, Sept. 1972.
7. S. S. Manson, "Fatigue: A Complex Subject--Some Simple Approximation," Experimental Mechanics, 1965.
8. S. S. Manson, Thermal Stress and Low Cycle Fatigue, (McGraw-Hill, New York, 1966.)
9. A. Kaplan, "Fatigue Analysis of Solar Cell Welds," *Photovoltaic Specialists Conference*, Palo Alto, CA, Nov. 1973.
10. D. J. Curtin and W. J. Billerbeck, "Advanced Interconnect Systems for Lightweight Solar Arrays," *Photovoltaic Power and Its Applications in Space and On Earth*, International Congress on the Sun in the Service of Man, Paris, France, July 2-6, 1973.

APPENDIX
GLOSSARY OF TERMS

I. Process Parameters

A "process" is a group of operations associated with a specific technology step. If a step is repeated in a manufacturing operation, the common operations are given one process name (a "subprocess") and are referred to by other processes. (This implies that equipment and personnel are shared rather than having separate facilities.) For example, "Ti/Ag Metallization-Front" and "Ti/Ag Metallization-Back" both use common facilities called "Vacuum Evaporation Metallization-Ti/Ag", whose investments and expenses will be allocated between the first two processes in proportion to throughput.

The following parameters are associated with a process:

General Parameters

1. Process yield ("YIELD") - ratio of output units to input units. This is a measure of physical flow, not process quality.
2. Input unit form ("IN") and output unit form ("OUT") -
 - (a) sheets - 7.8-cm (3 -in.) wafer
 - (b) solar cell - cell before assembly into an array module. (A cell is a sheet after testing.)
 - (c) array module - an array of 140 solar cells
3. Input unit salvage value ("SALVAGE VALUE") - estimated recovery value of a scrapped input unit. At this moment, all values are zero.
4. Production area floor space requirements - estimate of floor area needed, excluding area occupied by investments. If "floor space" is a function of production volume, up to 4 levels may be specified. Floor space is calculated using the "AREA (SQ. FT.)" value associated with the largest "INPUT UNITS" volume less than or equal to current production volume. The area associated with investments is added to this base area amount to determine the "estimated floor area" of the process.

NOTE: The data presented in this Quarterly Report do not include a floor space analysis.

Investment Parameters

5. Investment name ("NAME") - name of investment.
6. Efficiency ("EFF") - average fraction of time investment is available for use.
7. Thruput ("THRUPUT") - thruput of investment (if applicable) at 100% efficiency. Units must be one of the following: "sheets/hr", "solar cells/hr", "kg/hr", or "array modules/hr". (If both sides of an input wafer are to be processed separately, either adjust the thruput rate or adjust the "fraction of input units processed" parameter.)
8. Fraction of input units processed ("FRACT. PROC.") - used to adjust input volume for rework and for processing both sides of a wafer separately. It may also be used for "rework only" investments to specify fraction of input units requiring rework.
9. First cost ("COST") - \$ cost of investment, including delivery and installation.
10. Maintenance \$/hr used ("MAINT. \$/HR.") - materials and outside service contracts. Do not include in-house labor, which is specified under "Labor Requirements".
11. Investment tax credit ("TAX CR.") - "yes" if investment qualifies for the U.S. investment tax credit.
12. Economic life ("USEFUL") - estimated useful life of investment in years.
13. Depreciation book life, tax life - accounting life estimate for book and tax purposes.
14. Area (ft.²) - area (in ft²) required by investment and associated operator.

Labor Parameters

15. Type - name of labor type. Name may be repeated.
16. # input units processed/hr. - number of input units which an operator can process per hour.

$$\# \text{ operators needed} = \frac{\# \text{ input units/year} \times \text{fraction input units processed}}{\# \text{ input units/hr} \times \# \text{ hr/year} \times \text{efficiency}}$$

(where $\# \text{ hrs/year} = \# \text{ days/year} \times 8 \times \# \text{ shifts}$).

17. Fraction input units processed ("FRACTION") - fraction of input units for which this type of direct labor is required. If an input unit is processed more than once (both sides and/or rework), this factor may be greater than 1.0. If only reworked units or units passing some internal test are processed, this factor may be less than 1.0.
18. Efficiency - ratio of time worked to time paid (allows for rest periods; about 0.85 normal).
19. Ratio - the ratio of indirect labor personnel of specified type to total direct labor personnel on specified shift. It is used to estimate indirect labor requirements. (Include only factory personnel, not outside contractors.)

Material/Expenses

20. Item name - name of a material or other expense.
21. Production range ("PROD. LIMIT") - will be used in future to permit volume - dependent fixed cost and variable cost parameters for a particular item.
22. Fixed \$ part - part of expense which is independent of volume.
23. Variable part &/input unit or per 100 cm² - volume-dependent part of expense. If expense is independent of area or assumes a particular input format, it should be specified on an input unit basis. Items which are area dependent should be specified on a "per 100 cm²" basis.
24. Fraction input units processed ("FRACT. PRO.") - see "Investment Parameters".

Item cost per input unit will be computed as follows:

Let a = fixed \$ part

b = variable part \$/unit or variable part \$/100 cm² x (area in cm² of 1 side of sheet)

c = "fraction of input units processed"

u = # input units

Then

Cost/input unit = a + bcu

II. Cost Summary

The cost summary provides an overall cost summary by process step. If a process step utilizes a subprocess, subprocess cost allocation is performed among process steps on a proportional basis (process volume/total subprocess volume).

"Total \$" is the total cost of the item. "\$/output unit" is the "Total \$" divided by "output sheets". "\$/watt" is "Total \$" divided by annual production in watts.

"Material sheets" is the transfer price of incoming units. It has material, labor, and overhead components, but is reported as material since it is a transfer price. (The "Cumulative Cost Component Summary", described below, provides a breakdown of the various cost components). "Total cost" is the sum of "Material:sheets" plus the cost of all other expenses and overhead associated with the process ("value added").

Supplies and expenses are reported in one of the following summary categories: "Material added" (material used in process); "Direct expense" (direct expense items); or "other process overhead" (sum of "variable overhead" and fixed overhead" expense items).

The quantities and transfer process of input, output, and scrapped sheets area also provided. "Estimated process cost per watt" is computed as "Total cost" less "Material:sheets" less scrap value of sheets, divided by annual production in watts. It is important to note the assumed value of "starting wafer cost" (\$0.00 in this analysis). Wafer yield loss may be a significant part of the expense.

The true cost of a process is difficult to measure. It is estimated on a "\$/watt" basis as "value added" less salvage value of scrapped wafers. This total is impacted by the yields of subsequent processes, since some of the sheets processed will eventually be scrapped due to subsequent yield losses. Also, the quality of output is not considered, only material physical flow. Hence, the cost of the test step will be overstated and the cost of process

steps preceding test understated. That is, if the quality of the output of a process is improved, the test yield will be increased. This impact will, in effect, be apportioned among all steps preceding the test step, not entirely allocated to the improved step alone.

Current year additional investment requirements and estimated process floor area are also provided.

The "Cumulative Cost Component Breakdown" shows the distribution of costs of the output sheet divided into its material, direct expense, and various overhead categories. The total cost will be considered a material cost to subsequent process steps. When interpreting this cost analysis, be sure to determine what starting wafer cost was assumed.

III. Process Cost Overview - \$/watt

This summary shows the "estimated process cost - \$/watt" for each process step and its percentage of total processing cost. The assumed starting wafer cost is very important. (\$0.00 for the current analysis.)

IV. Cost/watt As A Function of Starting Sheet Cost

This analysis shows the cost of an input sheet, the resulting material loss due to process yield, the process \$ cost and the sum of these three components. This "Total \$" figure represents raw material cost and processing cost. The only overhead items included are labor shift differential, labor fringe benefits, and interest and depreciation on equipment. Labor costs above the level of foreman are part of factory overhead and are not included. Also, packaging, shipping, selling, general and administrative costs, and a "profit" markup are not included.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ERDA/JPL-954352-76/2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AUTOMATED ARRAY ASSEMBLY		5. TYPE OF REPORT & PERIOD COVERED Quarterly Report No. 2 (4/1/76 to 6/30/76)
		6. PERFORMING ORG. REPORT NUMBER PRRL-76-CR-31
7. AUTHOR(s) Brown F. Williams		8. CONTRACT OR GRANT NUMBER(s) 954352
9. PERFORMING ORGANIZATION NAME AND ADDRESS RCA Laboratories Princeton, New Jersey 08540		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Jet Propulsion Laboratory California Institute of Technology Pasadena, California 91103		12. REPORT DATE June 1976
		13. NUMBER OF PAGES 101
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A
16. DISTRIBUTION STATEMENT (of this Report) Distribution category UC-63		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy. The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Automated solar array assembly Screen-printing Vacuum evaporation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Our analysis of the existing technologies applicable to solar module fabrication is nearing completion. In this report, we describe as an example one basic module whose manufacturing costs were derived from first principles. Four basic cost analyses were made using our computerized cost analysis procedure and are discussed.		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20.

We have reviewed the many elements of the materials matrix. From this review we conclude that wafers cut from pulled ingots of silicon are the only current commercial source of starting material for solar cell application. It is further concluded that the large effort into finding suitable cheaper forms of starting silicon has a reasonable probability for success, and, therefore, any processes developed for automated array assembly must be compatible with ribbon or rectangular starting material as well as circular wafers.

A module material study has been completed which indicates that it will be difficult to reduce the cost of materials used in module assembly to substantially less than \$10.00/m². It is not clear that the lowest cost alternatives can meet program life and environmental requirements. Task 3 results will be incorporated into the study as they become available. In the absence of such information, parallel designs are being pursued which utilize glass, plastic films, and conformal coatings.

Preliminary analytical efforts have been completed which show that 15 to 20% of the available panel output will be lost due to temperature rise of the panel. Designs which structurally decouple the cells from the protective skins will surely require cooling of the semiconductor.

Structural analysis has shown that thermal stress at the interconnect/cell interface will not limit panel life to less than 20 years. Further, it has been shown that structural deflections will not appreciably add to interconnector stress. Substrate moisture absorption could create stress and cell life problems and will be investigated further.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Low-cost Silicon Solar Array Project
Contractor
QUARTERLY AND FINAL REPORT DISTRIBUTION LIST

	<u>Qtrly/Final</u>			<u>Qtrly/Final</u>	
<u>ERDA</u>			<u>NASA</u>		
ENERGY RESEARCH & DEVEL. ADMIN. Office of Solar Elec. Applic. 20 Massachusetts Ave., N.W. Washington, D. C. 20545 Attn: H. R. Blieden Acting Asst. Director	1	1	NATIONAL AERONAUTICS & SPACE ADM. Office of Energy Programs Washington, D. C. 20546 Attn: R. D. Ginter, Code NE Acting Asst. Admin.	3	3
ENERGY RESEARCH & DEVEL. ADMIN Division of Solar Energy 20 Massachusetts Ave., N.W. Washington, D. C. 20545 Attn: L. Herwig Deputy Manager	1	1	NATIONAL AERONAUTICS & SPACE ADM. Energy Systems Division Washington, D. C. 20546 Attn: H. K. Strass, Code NE Program Manager	3	3
ENERGY RESEARCH & DEVEL. ADMIN. Photovoltaics Branch 20 Massachusetts Ave., N.W. Washington, D. C. 20545 Attn: L. M. Magid	2	2	NATIONAL AERONAUTICS & SPACE ADM. Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135 Attn: J. N. Deyo, M/S 302-1 Photovoltaic Project Office	5	5
ENERGY RESEARCH & DEVEL. ADMIN. Photovoltaics Branch 20 Massachusetts Ave., N.W. Washington, D. C. 20545 Attn: M. B. Prince Chief	2	2	<u>JPL</u>		
Argonne National Laboratory ENERGY RESEARCH & DEVEL. ADMIN 9700 South Cass Avenue Argonne, IL 60439 Attn: A. Rabl S. Zwerdling	2	2	JET PROPULSION LABORATORY Repro +2 4800 Oak Grove Drive Pasadena, CA 91103 Attn: G. A. Mitchell, 111-100 Technical Information Div.		5
			JET PROPULSION LABORATORY 4800 Oak Grove Drive Pasadena, CA 91103 Attn: Technology Utilization M/S 200-119	1	1
ENERGY RESEARCH & DEVEL. ADMIN. P. O. Box 62 Oak Ridge, TN 37830 Attn: Technical Information Center T. B. Abernathy	Repro + 5		JET PROPULSION LABORATORY 4800 Oak Grove Drive Pasadena, CA 91103 Attn: (Contract Negotiator) M/S 291-208	3	3
Sandia Laboratories ENERGY RESEARCH & DEVEL. ADMIN. Albuquerque, NM 87115 Attn: R. P. Stromberg R. Berg	2	2	JET PROPULSION LABORATORY 4800 Oak Grove Drive Pasadena, CA 91103 Attn: LSSA Data Center M/S 169-434	50	50

	<u>Qtrly/Final</u>		<u>Qtrly/Final</u>
<u>OTHER GOVERNMENT ORGANIZATIONS</u>		<u>UNIVERSITIES (Cont.)</u>	
FEDERAL ENERGY ADMINISTRATION 12th & Pennsylvania Ave., N.W. Washington, D. C. 20461 Attn: Solar Energy Division	2 2	UNIVERSITY OF DELAWARE Institute of Energy Conversion Newark, DL 19711 Attn: J. D. Meakin K. Böer	2 2
FEDERAL POWER COMMISSION 825 North Capital St., N.W. Washington, D. C. 20426 Attn: Library	2 2	LAMAR UNIVERSITY P. O. Box 10053 Beaumont, TX 77710 Attn: C. Yaws	1 1
NATIONAL SCIENCE FOUNDATION Div. of Adv. Engg. Rsch & Tech. 1800 G Street, N.W. Washington, D. C. 20545 Attn: T. Mukherjee	2 2	UNIVERSITY OF NEW MEXICO Bureau of Engineering Research Faris Eng. Center, Rm. 124 Albuquerque, NM 87131 Attn: W. W. Grannemann	1 1
Commander USAMERDC Ft. Belvoir, VA 22060 Attn: D. Dinger, AMXFB-ZN	2 2	NORTHEASTERN UNIVERSITY Mechanical Eng. Branch/Campus 360 Huntington Avenue Boston, MA 02115 Attn: W. B. Nowak	1 1
<u>UNIVERSITIES</u>			
ARIZONA STATE UNIVERSITY College of Engineering Science Tempe, AZ 85281 Attn: C. E. Backus	1 1	UNIVERSITY OF PENNSYLVANIA 260 Towne Bldg. - D3 Philadelphia, PA 19174 Attn: M. Wolf	1 1
BROWN UNIVERSITY Division of Engineering Providence, RI 02912 Attn: J. J. Loferski	1 1	STANFORD UNIVERSITY Stanford Electronics Labs. Stanford, CA 94305 Attn: G. L. Pearson J. F. Gibbons	2 2
CARNEGIE-MELLON UNIVERSITY Dept. of Electrical Engineering Schenley Park Pittsburgh, PA 15213 Attn: A. G. Milnes D. L. Feucht	2 2	UNIVERSITY OF SOUTH CAROLINA College of Engineering Columbia, SC 29208 Attn: R. B. Hilborn, Jr.	1 1
CASE WESTERN RESERVE UNIVERSITY Div. of Electrical Engineering & Applied Physics Cleveland, OH 44106 Attn: A. B. Kuper C. E. Rogers	2 2	UNIVERSITY OF UTAH Materials Science & Engineering Salt Lake City, UT 84112 Attn: A. Sosin	1 1
		UNIVERSITY OF NEW MEXICO Dept. of Mechanical Engineering Albuquerque, NM 87131 Attn: M. W. Wildin	1 1

	<u>Qtrly/Final</u>			<u>Qtrly/Final</u>	
<u>PRIVATE ORGANIZATIONS</u>			<u>PRIVATE ORGANIZATIONS (Cont.)</u>		
AEROSPACE CORPORATION	3	3	IBM CORPORATION	1	1
P. O. Box 92957			East Fishkill, Route 52		
Los Angeles, CA 90009			Hopewell Junction, NY 12533		
Attn: S. L. Leonard			Attn: G. H. Schwuttke		
L. Gibson					
H. J. Killan			INTELCOM RAD TECH	1	1
BATTELLE COLUMBUS LABORATORIES	2	2	7650 Convoy Court		
505 King Avenue			Box 80817		
Columbus, OH 43201			San Diego, CA 92138		
Attn: D. Carmichael			Attn: J. A. Naber		
M. F. Browning			KAYEX CORPORATION	1	1
CRYSTAL SYSTEMS INC.	1	1	Hamco Division		
Shetland Industrial Park			1000 Millstead Way		
Salem, MA 01970			Rochester, NY 14624		
Attn: F. Schmid			Attn: R. L. Lane		
DOW CORNING CORPORATION	2	2	M7 INTERNATIONAL, INC.	1	1
12334 Geddes Road			210 Campus Drive		
Hemlock, MI 48626			Arlington Heights, IL 60004		
Attn: L. Crossman			Attn: R. Ignatius		
C. G. Currin			MITRE CORPORATION	1	1
ELECTRIC POWER RESEARCH INSTITUTE	1	1	Westgate Research Park		
3412 Hillview Avenue			McLean, VA 22101		
P. O. Box 10412			Attn: G. M. Haas		
Palo Alto, CA 94304			MOBIL-TYCO SOLAR ENERGY CORP.	2	2
Attn: P. Bos			16 Hickory Drive		
EXOTIC MATERIALS, INC.	1	1	Waltham, MA 02154		
2968 Randolph Avenue			Attn: K. V. Ravi		
Costa Mesa, CA 92626			A. I. Mlavsky		
Attn: W. L. Louck			MOTOROLA INC.	1	1
President			New Venture Lab		
GENERAL ELECTRIC COMPANY	3	3	4039 East Raymond Street		
Valley Forge Space Center			Phoenix, AZ 85040		
P. O. Box 8555			Attn: I. A. Lesk		
Philadelphia, PA 19101			MOTOROLA INC.	2	2
Attn: R. T. Frost			Semiconductor Products Div.		
K. Hanson			5005 East McDowell Road		
G. J. Rayl			Phoenix, AZ 85008		
GENERAL ELECTRIC COMPANY	1	1	Attn: M. Ingle		
Corporate Research & Development			E. Philofsky		
Schenectady, NY 12301			MONSANTO RESEARCH CORPORATION	1	1
Attn: M. Garfinkel			P. O. Box 8		
HONEYWELL CORP. RESEARCH CENTER	1	1	St. Peters, MO 63376		
10701 Lyndale Avenue South			Attn: H. Gutsche		
Bloomington, MN 55420					
Attn: J. D. Heaps					

	<u>Qtrly/Final</u>			<u>Qtrly/Final</u>	
<u>PRIVATE ORGANIZATIONS (Cont.)</u>			<u>PRIVATE ORGANIZATIONS (Cont.)</u>		
POWER INFORMATION CENTER University City Science Center 3401 Market St., Rm. 2210 Philadelphia, PA 19014	1	1	TECHNION INCORPORATED 17751 Sky Park East, Suite F Irvine, CA 92707 Attn: G. L. Cann	1	1
RCA LABORATORIES David Sarnoff Research Center Princeton, NJ 08540 Attn: G. W. Cullen B. Williams	2	2	TEXAS INSTRUMENTS INCORPORATED Semiconductor Group P. O. Box 5012 Dallas, TX 75222 Attn: G. Wakefield S. Rea	2	2
ROCKWELL INTERNATIONAL Autonetics Division 3370 Miraloma Avenue Anaheim, CA 92803 Attn: R. P. Ruth D/540, HA 32	1	1	TRW SYSTEMS One Space Park Redondo Beach, CA 90278 Attn: P. Goldsmith W. Rowe R. Yasui	3	3
SENSOR TECHNOLOGY, INC. 21012 Lassen Street Chatsworth, CA 91311 Attn: I. Rubin	1	1	UNION CARBIDE CORPORATION Chemical and Plastics P. O. Box 180 Sistersville, WV 26175 Attn: D. Bailey	1	1
SILTEC CORPORATION 3717 Haven Avenue Menlo Park, CA 94025 Attn: R. E. Lorenzini	1	1	UNITED DETECTOR TECHNOLOGY, INC. 2644 - 30th Street Santa Monica, CA 90405 Attn: P. Wendland	1	1
SIMULATION PHYSICS, INC. 41 "B" Street Burlington, MA 01803 Attn: A. R. Kirkpatrick	1	1	VARIAN ASSOCIATES Vacuum Division 121 Hartwell Avenue Lexington, MA 02173 Attn: M. Hablmanian	1	1
SOLAR POWER CORPORATION 23 North Avenue Wakefield, MA 01880 Attn: P. J. Caruso	1	1	WESTECH SYSTEMS, INC. 4229 South 37th Street Phoenix, AZ 85040 Attn: G. L. Gill, Jr.	1	1
SOLAREX CORPORATION 1335 Piccard Drive Rockville, MD 20850 Attn: J. Lindmayer	1	1	WESTINGHOUSE ELECTRIC CORPORATION Research Laboratories 1310 Beulah Road Pittsburgh, PA 15235 Attn: R. Riel R. Mazelsky J. R. Davis	3	3
SPECTROLAB, INC. 12500 Gladstone Avenue Sylmar, CA 91342 Attn: E. L. Ralph J. A. Beck	2	2			

2/12/76

ADDENDUM

Low-cost Silicon Solar Array Project
CONTRACTOR
QUARTERLY AND FINAL REPORT DISTRIBUTION LIST

Qtrly/Final

PRIVATE ORGANIZATIONS

Advanced Technology Energy Systems 1 1
Boeing Engineering and Construction
A DIVISION OF THE BOEING COMPANY
P. O. Box 3707
Seattle, WA 98124
Attn: J. Lowe

MCDONNELL DOUGLAS ASTRONAUTICS CO - EAST
Materials and Processes (Task 2 1 1
St. Louis, MO 63166 only)
Attn: L. G. Harmon
Bldg. 106/4/E7

ADOLPH MELLER CO. (Task 2 only) 1 1
P. O. Box 6001
Providence, RI 02940
Attn: R. R. Monchamp

OPTICAL COATING LABORATORY, INC. 1 1
15251 East Don Julian Road
City of Industry, CA 91746
Attn: D. Sharman

OWENS ILLINOIS, INC. 1 1
P. O. Box 1035
Toledo, OH 43666
Attn: G. L. Glen
Chief, Materials Research