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EVALUATION OF SOLAR CELLS AND ARRAYS FOR POTENTIAL SOLAR POWER SATELLITE APPLICATIONS

Report to

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

March 31, 1978

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Arthur D. Little, Inc.

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NASA Contract # NASA 9-15294

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Dr David W. Almgren, Program Manager
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Dr. Peter E Glaser
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Program Director

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I. SUMMARY

A PURPOSE AND SCOPE

Under contract NAS 9-15294, Arthur D Little, Inc., was authorized by the NASA Lyndon B Johnson Space Center, Houston, Texas, to evaluate proposed solar array designs and manufacturing methods, to identify options which show the greatest promise of leading to the development of a cost-effective SPS solar cell array design and to define the key program elements which will have to be accomplished as part of an SPS solar cell array development program This evaluation extended from October 1, 1977, to March 31, 1978, and focussed on the following issues

- Definition of one or more designs of a candidate SPS solar array module, using results from current system studies;
- Development of the necessary manufacturing requirements for the candidate SPS solar cell arrays and an assessment of the market size, timing, and industry infrastructure needed to produce the arrays for the SPS program,
- Evaluation of current DOE, NASA and DOD photovoltaic programs to determine the impacts of recent advances in solar cell materials, array designs and manufacturing technology on the candidate SPS solar cell arrays, and
- Definition of key program elements for the development of the most promising solar cell arrays for the SPS program

Our evaluation was based on published data and on information obtained from SPS system studies being performed by the Boeing Aerospace Company and Rockwell International and from discussions with photovoltaic specialists at NASA, JPL, DOE, WPAFB, academic institutions and industrial laboratories

B. BASIC ASSUMPTION OF STUDY

To provide a focus for the development of SPS solar cell arrays, we assumed a scenario for the production of these arrays based on the deployment of one SPS in 1995 that would generate 10 GW of electrical power at the utility interface (See Figure 1) This scenario would require the accumulation of an inventory of solar cell arrays so that about 20 GW of solar cell arrays would be available to be deployed in the SPS by that date. There would then be a steady state annual output of solar cell arrays to meet a deployment rate associated with adding 10 GW of generated power at the utility interface per year Any increase in the SPS deployment rate would require a corresponding increase in the solar cell array production volume A four-year period has been assumed to design and construct the initial large-scale manufacturing facility and a three-year period has been assumed for the design and construction of each subsequent major facility, after completing such preliminary studies as site selection and environmental impact statements, and after receiving the necessary approvals The large-scale manufacturing processes will have to be initially demonstrated in pilot production facilities so that the uncertainties and risks involved in bringing the major production facilities on line will have been reduced to a level consistent with the investments required The output from the pilot plant facilities would also be used to support the needs of large-scale orbital testing programs

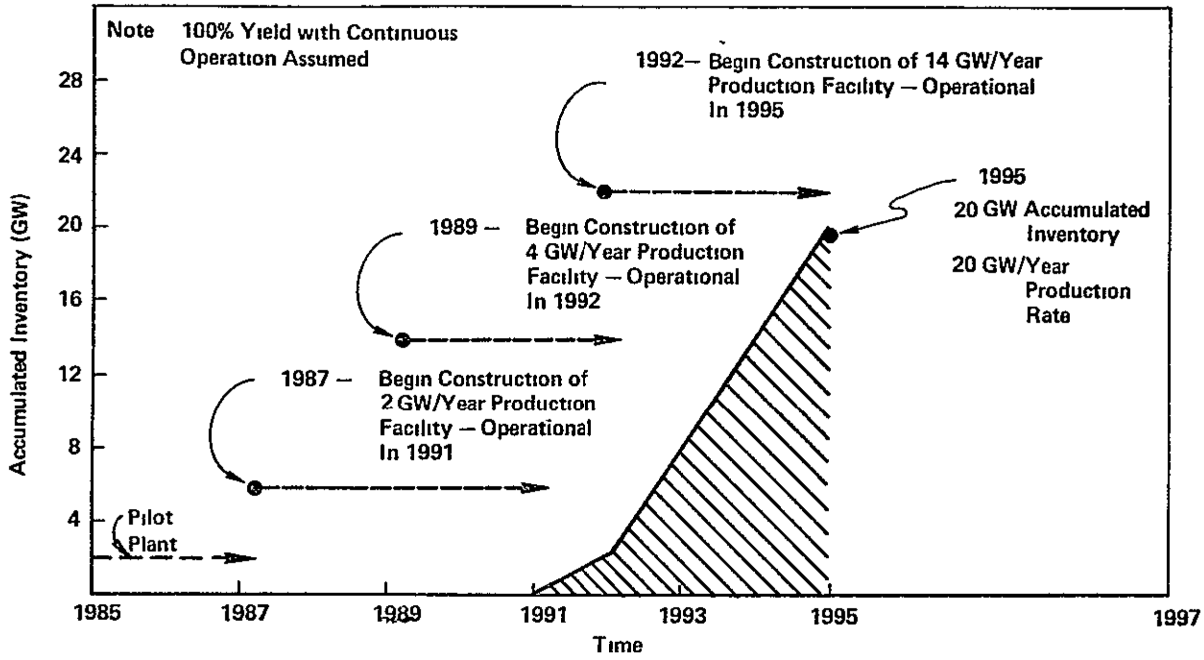

FIGURE 1 SOLAR CELL/ARRAY PRODUCTION SCENARIO FOR 1995 SPS DEPLOYMENT (INVENTORY ACCUMULATION)

C CONCLUSIONS

1. Utilization of Advanced Solar Energy Conversion Technology

An SPS program based on photovoltaic energy conversion should be able to utilize both existing and developing technologies for the design of the solar cells and arrays The several solar cell materials and array configurations being considered for the SPS today differ in the specific choices of photovoltaic material, substrates and coverglasses, structural arrangements, solar concentration factors, and methods to minimize the degrading effects of the space environment Silicon and gallium arsenide are the leading candidate materials and have been incorporated in solar cell array designs being evaluated as part of ongoing SPS system studies (1,2)

It is important that current SPS system level studies consider designs that will facilitate the incorporation of advanced solar cell arrays as the state-of-the-art in photovoltaics materials advances. Of particular significance would be the development of a higher efficiency cell, with a concomitant reduction in total area of an SPS and/or the development of a solar cell that could optimize the design of the SPS at a different level of concentration than available with a current configuration

2. Solar Cell Material for SPS Array Testing in 1980-1985

Based on an initial SPS deployment date of 1995, silicon is the only photovoltaic material that is well enough defined and available in sufficient quantity to meet the needs of the proposed SPS test programs in the time-period of 1980-1985. The initial SPS program activities should proceed using silicon as the candidate photovoltaic material Gallium arsenide is a promising alternative material, however, its availability in sufficient quantity and with reproducible characteristics is uncertain for the SPS solar cell array test period of 1980-1985

3. Solar Cell Array Development Schedule

Assuming that initial SPS flight operations are to start either in 1995 or in 2000, the development milestones for the solar cell arrays are shown in Table 1 For a 1995 operational date, pilot plant production would have to start in 1985

An operational date of 2000 permits the time period from 1980 to 1985 to be used for basic and applied research on advanced solar cell materials and associated array development, and would increase the possibility that photovoltaic materials other than silicon would be ready for pilot production before 1990.

4. Long-Term Solar Cell Array Test Program

Long-term tests of candidate solar cell arrays in geosynchronous orbit will be necessary to provide data on the performance of the arrays in the space environment prior to a commitment to a pilot plant program by 1985.

5. SPS Solar Cell Array Production Schedule

The production scenario for an SPS solar cell array inventory buildup for a 1995 SPS launch date indicates that the decision on the choice of solar cell materials and array designs will have to be made by 1985, for a 1995 operational SPS, and by 1990 for a 2000 operational SPS

TABLE 1

SPS SOLAR CELL/ARRAY DEVELOPMENT SCHEDULE FOR TWO DATES OF INITIAL FLIGHT OPERATIONS

Development Time Period	Initial Flight Operations	
	1995	2000
1978-1980	• Basic/Applied Research and Development in Solar Cells/Arrays	• Basic/Applied Research and Development in Solar Cells/Arrays
1980-1985	• Basic/Applied Research and Development in Solar Cells/Arrays • Initiate Long Duration Exposure Tests at GEO • Orbital Testing of Arrays	• Basic/Applied Research and Development in Solar Cells/Arrays • Initiate Long Duration Exposure Tests at GEO
1985-1990	• Pilot Plant Operation • Initiate Construction of Manufacturing Facilities	• Basic/Applied Research and Development in Solar Cell Arrays • Orbital Testing of Arrays
1990-1995	• Full Scale Production of Arrays	• Pilot Plant Operation • Initiate Construction of Manufacturing Facility
1995-2000	• Flight Operations	• Full Scale Production of Arrays
2000-	• Flight Operations	• Flight Operations

The scale of commitment of capital, materials and labor to construct large-scale manufacturing facilities, and to proceed with solar cell array production, will require that the risks and uncertainties in achieving solar cell performance and cost goals be acceptably low Because of increasing production experience with single crystal silicon, an SPS development program based on silicon solar cell arrays will have a low risk associated with the expansion of the industrial infrastructure required to achieve pilot plant production in 1985 and the subsequent construction of manufacturing facilities to achieve a large-scale output of silicon solar cell arrays for the SPS

Funding commitments at levels approaching those made to the Low-Cost Silicon Solar Array Project would be required for gallium arsenide solar cells to meet performance and cost goals and to obtain the necessary industry commitment to develop the production processes starting with gallium resources and ending with a flight-qualified gallium arsenide solar cell array Without such commitments in the near future it is unlikely that gallium arsenide solar cell array would meet the schedule for even a year 2000 operational SPS

6. R&D on Advanced Photovoltaic Material

The near-term level of funding for R&D on advanced photovoltaic materials, although appropriate to the present stage of development of such materials, is inadequate to provide an alternative to silicon solar cells to meet schedule requirements for the 1980 to 1985 SPS test program. A significant expansion of the present R&D program would be required for other photovoltaic materials to approach the level of development of silicon which has been the focus of the national photovoltaic conversion program.

Because data from the SPS test programs is a prerequisite to an SPS solar cell array production commitment, a five-year delay in the operational readiness of the SPS to 2000 may not result in the successful development of an alternative photovoltaic material. Significant developments would have to occur soon, resulting in a substantial increase in development funds, if alternative materials are to be available in sufficient quantity for tests in 1985-1990

7. Large-Scale Manufacturing Capability

The industrial capability needed to manufacture the SPS solar cell arrays will require the development of large-volume production technology, using the results obtained from the national photovoltaic conversion program The particular industries that will have the largest expansion of their current production capacity are producers of semi-conductor-grade silicon or producers of gallium and high-purity arsenic and the manufacturers of 50 and 75 μm borosilicate glass, or the manufacturers of 20 μm thick sapphire ribbon and of 25 μm Kapton sheet

Cost projections for the 50 and 75 μm borosilicate coverglass and substrate for the silicon solar cell array and for the 20 μm sapphire substrate for the gallium arsenide array are extrapolations based on production capacities that are much less than the capacities required for an SPS program As these are major cost drivers (84% of material costs for silicon array, 78% for gallium arsenide), the cost projections for the solar cell array have large uncertainties

8. Solar Cell Market Considerations

The solar cell market represented by the SPS program (20 GW/year) and the rate of buildup of facilities to meet SPS large-scale production requirements are significantly larger than optimistic projections for solar cell production requirements for all other markets which have been identified for the same time period (4 GW/year)

D. RECOMMENDATIONS

1 Use Silicon Solar Cell Arrays for Initial SPS Development Programs

The design and testing of solar cell arrays as part of the SPS development program should be based on silicon solar cells until results from R&D on other promising photovoltaic materials reduce the uncertainties in the reproducibility of their characteristics and their availability to levels comparable to or lower than those associated with the use of silicon solar cells

2. Include Capability for Large-Scale Manufacturing in R&D Goals

The R&D goals for promising solar cell materials should include the definition of processes for large-scale manufacture which are consistent with low-mass SPS solar cell array designs

3 Include Risk Analysis of Solar Cell Array Parameters in System Level Definition Studies

SPS system definition studies should include a risk analysis of the solar cell array to assess the impact of solar cell array performance uncertainties on SPS designs and operations and to quantify the system-level cost uncertainties associated with uncertainties in performance of the solar cell arrays

4. Involve Potential Industrial Participants from Solar Cell Array Manufacturing Industries in Current System-Level Studies

Potential industrial participants in the SPS solar cell array manufacturing program should be involved during the early stages of solar cell array development and testing so that they can assess and plan for the industrial infrastructure that would be required for a large-scale manufacturing commitment in 1987. An assurance that industrial facilities to support solar cell array manufacturing programs would be available when needed will require an early commitment to clearly identified program elements so that industry can plan for the capital investments in the manufacturing, test and support facilities.

5 Establish a Long-Duration Exposure Program in Geosynchronous Orbit

A long-duration exposure program in geosynchronous orbit should be established so that tests of candidate SPS solar cell arrays could be completed prior to a commitment to pilot production facilities and to large-scale manufacturing facilities Early orbital testing of candidate solar cells should be conducted during next period of peak solar activity (1979-1982).

6 Establish an SPS Solar Cell Array Development Program

An SPS solar cell array development program should be established which has the following key elements

1 Basic and applied research in photovoltaic materials
2. Low mass solar cell array technology development
3. Large-scale solar cell array manufacturing technology
4 Terrestrial/orbital testing program
5 Pilot plant operations for candidate SPS solar cell arrays
6 Manufacturing facilities for SPS solar cell arrays.
7 Supporting studies

7. Define a Formal Interface Between the SPS Development Program and the National Photovoltaic Conversion Program

The interface between the SPS development program and the national photovoltaic conversion program should be defined so that key program elements for the development of SPS cell arrays can be integrated with the ongoing national program

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II. DEFINITION OF CANDIDATE SPS SOLAR CELL/ARRAY DESIGNS

A. CURRENT DESIGNS FOR SPS SOLAR CELL/ARRAY MODULES

Two baseline designs for an SPS utilizing a photovoltaic energy conversion system are displayed in Figures 2 and 3. The design which utilizes single-crystal silicon as the photovoltaic material was developed by the Boeing Aerospace Company and the details of the solar array used in this assessment of solar cell manufacturing requirements were taken from Reference 1 Basically the solar cell/array design utilizes 50 μm thick silicon solar cells which are individually sized at 6 55 x 7 44 cm and are electrostatically bonded, with suitable electrical interconnections, between a layer of 75 and 50 μm 7070 borosilicate glass Table 2 summarizes the mass properties of this design.

The design which utilizes a 5 μm gallium arsenide solar cell was developed by the Space Division of Rockwell International and the details of the solar array were taken from Reference 2 A 5 μm thick layer of GaAs is assumed to be formed by a vapor deposition process which uses a 20 μm thick layer of sapphire as the substrate/coverglass for the cell. The solar cell is covered by a 500 Å thick window of GaAlAs and the array is then encapsulated with 13 μm of Teflon bonding the solar cell to a 25 μm Kapton cover. Table 3 summarizes the mass properties of the design based on gallium arsenide solar cells

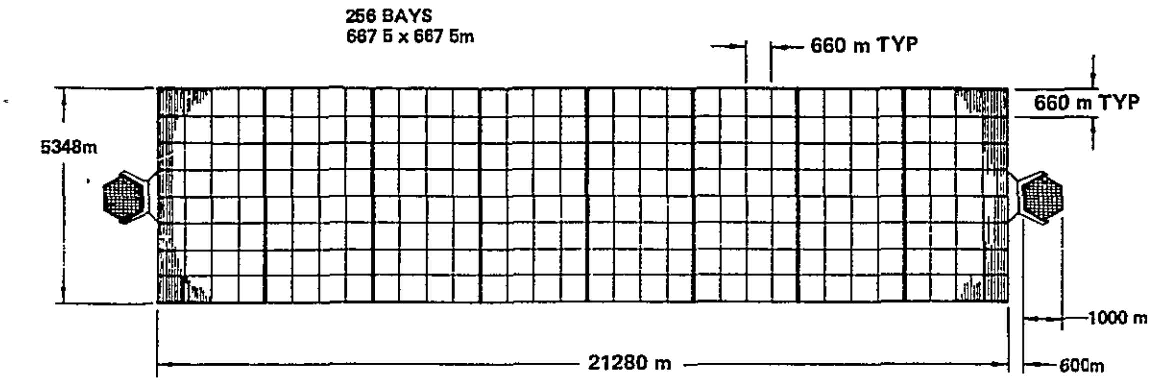
Both the silicon and the gallium arsenide solar cell array mass properties indicate that they represent a significant fraction of the total mass of an SPS Therefore, the development of an optimized solar cell array is crucial to the effective performance and economic competitiveness of the SPS.

B. ADDITIONAL DESIGN CONSIDERATIONS FOR SPS SOLAR CELL/ARRAY MODULES

There are many factors and parameters which are involved in the system level optimization of the design of the solar cell/arrays for the SPS. To date the system level studies have been mainly concerned with such array factors as (1) Beginning of life (BOL) efficiency, (2) rate of degradation of output on-orbit, (3) efficiency recovery techniques, (4) cost, (5) mass of the array, and (6) resource availability In addition to these parameters, the system level design will have to include considerations of: (1) availability of large-scale manufacturing processes, (2) handling and packaging techniques on Earth and during launch and (3) on-orbit assembly and operating procedures Table 4 itemizes eight evaluation criteria that will need to be considered in defining a solar cell/array for an SPS.

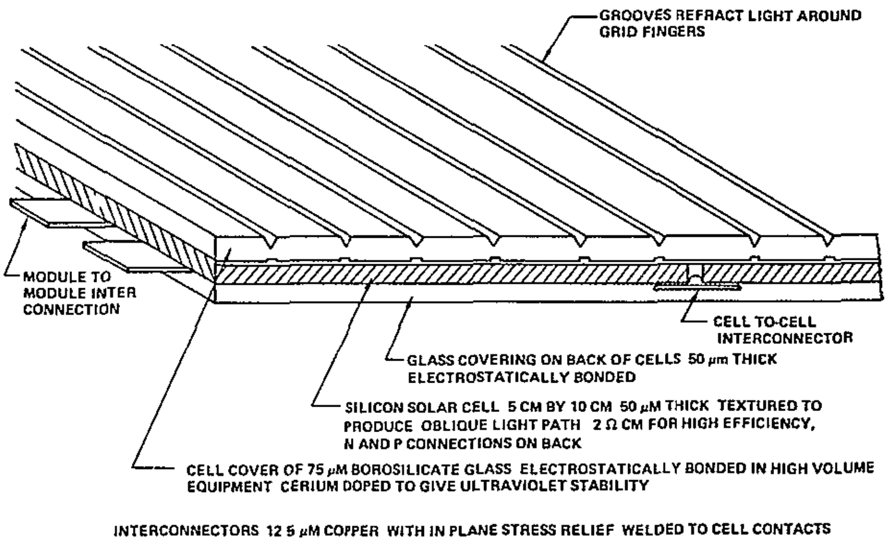
Applying the evaluation criteria as shown in Table 4 to the two given baseline designs identifies several specific areas where additional definition in the solar cell/arrays subsystem is needed as the overall design of the SPS matures The single-crystal silicon approach has defined process steps for fabricating the cell and array in the required quantity but further definition is required in the techniques for handling and packaging the glass and silicon array on Earth and for deploying and assembling it on-orbit There is currently no demonstrated manufacturing process to produce 5 μm thick, high efficiency GaAlAs/GaAs solar cells on a sapphire substrate The production of high efficiency cells by a chemical vapor deposition (CVD) process on any type of substrate will require further development. In the GaAs baseline design there is also a need for further definition in the techniques required for packaging, handling, deploying and assembling the array both on Earth and on-orbit.

SOLAR ARRAY CONFIGURATION



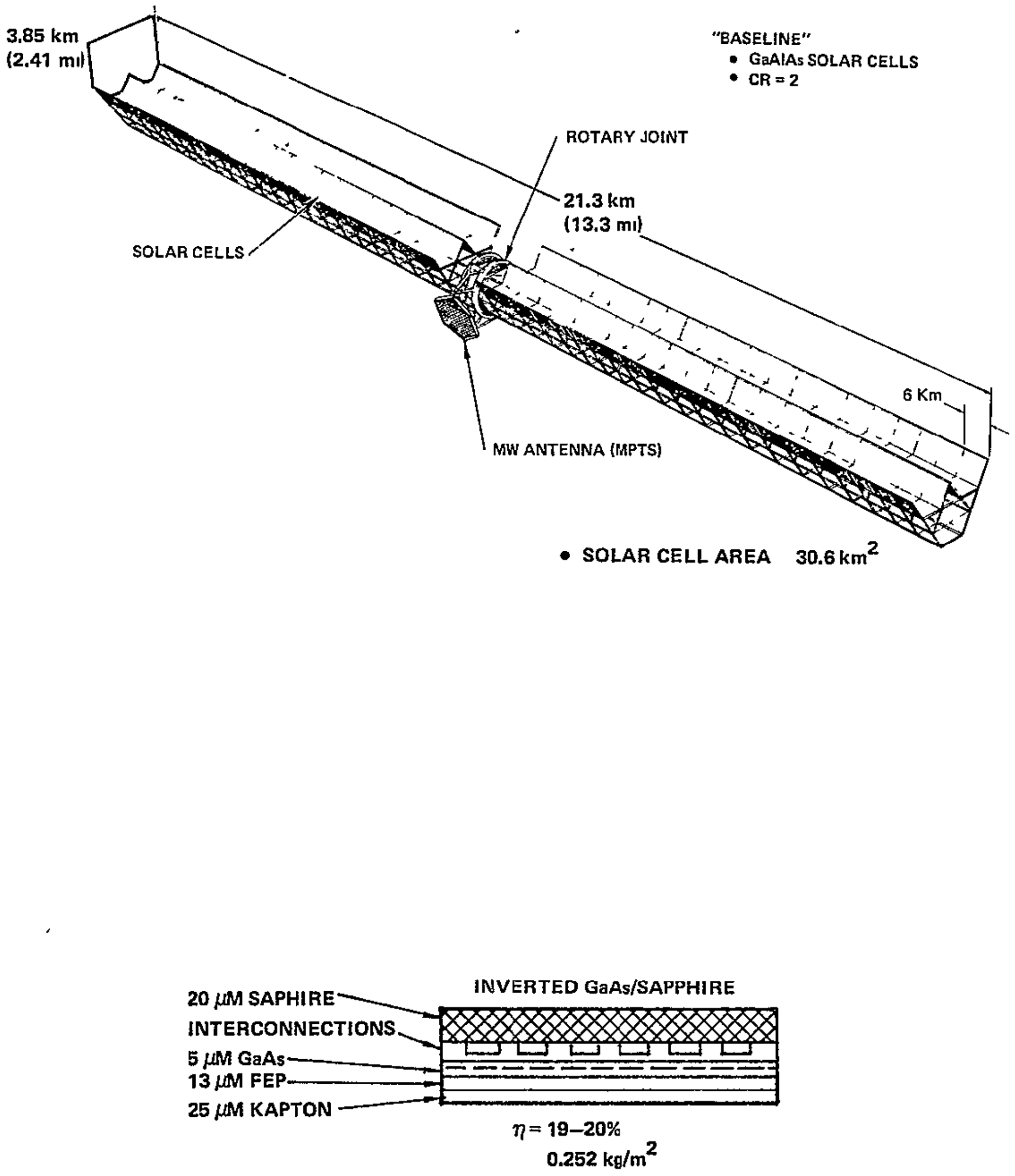
TOTAL SOLAR CELL AREA 101 4 km^2
TOTAL ARRAY AREA: 110 2 km^2
TOTAL SATELLITE AREA 114.5 km^2
OUTPUT: 17 GW MINIMUM TO SLIPRINGS

ANNEALABLE SOLAR CELL BLANKET STRUCTURE



Source: Reference 1

FIGURE 2 SPS CONCEPT USING SILICON SOLAR CELLS (CR = 1) WITH 10 GW OUTPUT AT TWO RECEIVING ANTENNAS



Source: Reference 2

FIGURE 3 SPS CONCEPT USING GALLIUM ARSENIDE SOLAR CELLS (CR = 2) WITH 5 GW OUTPUT AT A SINGLE RECEIVING ANTENNA

TABLE 2

MASS PROPERTIES FOR AN SPS USING SILICON SOLAR CELLS (CR=1) 10 GW AT UTILITY INTERFACE

Component		Mass (MT)
Solar Energy Collection System		**55,602**
Primary Structure	7,155	
Mechanical Systems	67	
Control	178	
Instrumentation/Communications	4	
Solar-Cell Blankets	45,773	
Power Distribution	2,425	
Microwave Power Transmission System		**26,379**
Total Satellite Mass (10 GW Output)		**81,998**
Growth (21%)		**17,590**
Total Predicted Mass		**99,568**

Source: Reference 1

TABLE 3

MASS PROPERTIES FOR AN SPS USING GALLIUM ARSENIDE SOLAR CELLS (CR=2) 5 GW AT THE UTILITY INTERFACE

Component		Mass (MT)
Solar Array		**13,917,000**
Structure and Mechanisms	3,777,000	
Attitude Control System	95,000	
Energy Conversion	8,830,000	
Power Distribution and Control	1,166,000	
Information Management & Control	49,000	
Microwave Power Transmission System		**14,167,000**
Total Satellite Mass (5 GW Output)		**28,084,000**
Margin (30%)		**8,425,000**
Predicted Actual Mass		**36,509,000**

Source: Reference 2

TABLE 4

SPS SOLAR CELL/ARRAY EVALUATION CRITERIA

Solar Cell Performance
Solar Cell Degradation
Recovery of Cell Performance
Solar Array Performance
Material Requirements
Cell/Array Manufacturing Process
Packaging and Transportation
On-Orbit Assembly and Operations

III. MANUFACTURING REQUIREMENTS FOR THE CANDIDATE SOLAR CELL/ARRAY MODULES

To compare the manufacturing requirements for the two baseline designs on a common basis, it was necessary to establish an identical (10GW) level of generated power at the utility interface for both designs. This assumption implies one 10 GW SPS based on single-crystal silicon cells and two 5 GW SPS's based on thin film GaAs cells. The total array areas for both designs and an hourly production rate for the arrays are given in Table 5.

TABLE 5

SPS SOLAR CELL ARRAY HOURLY PRODUCTION REQUIREMENTS FOR 10 GW AT UTILITY INTERFACE

- **One Si SPS (CR=1) with 110.2 km^2 of Array**
- **Two GaAs SPS's (CR=2) with 30.6 km^2 of Array Each**

Material	Concentration Ratio	Total Array Area (km^2)	Necessary Production Rate[1] (m^2/hour)		
			1 SPS/Year	3 SPS/Year	6 SPS/Year
Silicon	1	110.2	12,600	37,800	75,600
Gallium Arsenide	2	61.2	6,990	20,970	41,940

1. Assuming 100% Yield, 24 hours/day, 365 days/year.

A. PROCESS STEPS FOR FABRICATING CANDIDATE SILICON SOLAR CELL ARRAYS

The fabrication of a single-crystal silicon cell requires, initially, a source of silicon and a process for purifying the material to a level that is consistent with a high efficiency solar cell. Silicon can be obtained from quartzite and there is no problem in the availability of this mineral in sufficient quantity. The efficiency of the single-crystal silicon solar cell is affected by impurities such as V, Ti, Fe, Mn and Cr which are present in varying concentrations in the raw quartzite (SiO_2).(3) Typically, quartzite (silica) can be purchased for approximately $10/ton however, as part of the terrestrial photovoltaic conversion program, purer sources of silica have been identified selling for approximately $50-$150/ton.(3) (About 134,000 MT of silica are needed for one 10 GW SPS.) From this silica, 106,800 MT of metallurgical grade (MG) silicon ($1/kg) would be derived to satisfy the requirements for one SPS. The overall process for the purification of silicon by a carbon reduction process in an electric arc furnace is shown in Figure 4. If one started with a purer grade of silicon, the carbon used in the reduction process could be a major source of contamination. Bark free charcoal is a preferred source of high purity carbon, however, coal, which is in ample supply, is another source for the carbon.

The single crystal silicon solar cell is currently made from a semi-conductor grade (SeG) silicon and one SPS would require approximately 23,700 MT of this high purity material. The current process for producing SeG silicon from MG silicon is energy intensive and involves the

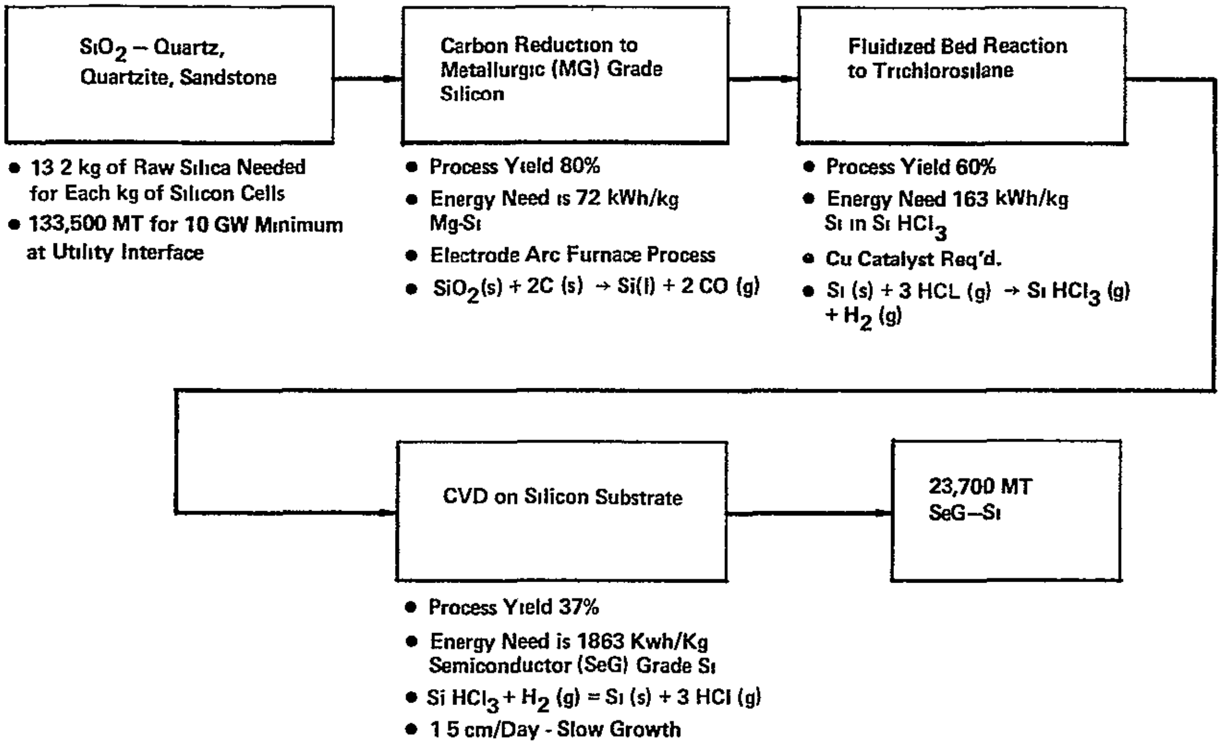


FIGURE 4 PROCESS STEPS FOR PREPARING SEMICONDUCTOR GRADE SILICON FROM QUARTZITE

formation of trichlorosilane gas ($SiHCl_3$) which, in turn, is deposited on a silicon substrate to form purified polycrystalline silicon. The current price for SeG silicon is approximately \$60/kg and the current estimated U S. production capacity of 1100 MT/year(4) is insufficient for the 23,700 MT needed for one 10 GW SPS using 50 μm silicon solar cells

The U S terrestrial solar cell program is developing new processes for the production of SeG silicon and is, in parallel, attempting to identify and characterize a solar-cell grade of silicon (SoG) that is less pure than SeG grade silicon but of sufficient purity to make 12-15% cells (AM1). The goals of the U S photovoltaic conversion program are to develop low cost photovoltaic power for terrestrial applications (\$2/Wp by 1982, \$ 50/Wp by 1986 and \$ 10-\$ 30/Wp by 1990).(5) The trade-offs which define the requirements for developing a lower cost but less efficient silicon cell to meet these terrestrial price goals are not the same trade-offs that apply to the SPS program The SPS solar cell/array requires a low mass per unit area to minimize transportation costs and any loss of efficiency would require transporting additional array area and mass to the assembly site in orbit

If a 10% efficient (AM0) cell could be made using a SoG silicon which could be obtained for \$10/kg, an additional area of 58.3 km^2 of solar cells and 63.4 km^2 of array, with 26,320 MT additional mass, would be needed to provide the same generated power as the baseline 15.75% efficient cell. The total array cost which, using present estimates, appears to be dominated by the cost of fabrication (~ \$34/m^2) would be \$65/m^2 using a 15.75% silicon cell (\$60/kg SeG Si) for a total array cost of \$7.2 B, and would be \$53/m^2 using a 10.0% silicon cell (\$10/kg SoG Si) for a total array cost of \$9.2 B. Therefore the less efficient and less expensive SoG silicon would result in a more costly array plus the addition of 26,320 MT of mass to be transported to the on-orbit assembly site This result is based on assumptions regarding both the costs in fabricating the array and also the efficiency of a less costly cell. A first order analysis, however, shows that, even if the 10% efficient silicon were free, the less efficient array cost would be \$8.9 B (based on the costs defined in Tables 11 and 14) which is still more expensive than the smaller array using the more efficient silicon solar cell material The goal of the terrestrial photovoltaic program is to develop low \$/W_p cells The parts of the terrestrial program which is most applicable to the SPS program are the development of less costly methods for producing a high purity silicon photovoltaic material and for fabricating the encapsulated cells These efforts are part of DOE's Low-Cost Silicon Solar Array Project being managed by the Jet Propulsion Laboratory

To continue with the definition of the process steps for fabricating single crystal silicon solar cells, using the high purity polycrystalline silicon as a starting material, a single-crystal silicon ingot is formed by the Czochralski method. Starting with molten silicon in a crucible at a temperature just above its melting point, a small seed crystal is introduced into the melt and slowly withdrawn, with simultaneous rotation, to produce a crystalline ingot by freezing at the solid-liquid interface A dopant introduced into the melt will transfer into the solid crystal at a reduced concentration level. Table 6 shows the distribution coefficients for impurities in silicon with the coefficient defined as the ratio of the impurity content in the solid to that in the melt under equilibrium conditions The relatively high coefficient for boron is one of the main reasons for its use rather than Al or Ge as the dopant in p-type silicon (7) Table 7 shows the distribution coefficients for impurities in GaAs and, again, because the coefficient of Zn in GaAs is considerably greater than that of other dopants, nearly all the diffused GaAs cells have been of the p/n variety with Zn diffused into n-type substrates (at 600°C-800°C) to form the junction

TABLE 6

DISTRIBUTION COEFFICIENTS FOR IMPURITIES IN SILICON

Impurity	Coefficient	Impurity	Coefficient
B	0.8	Fe	8×10^{-6}
P	0.35	Ti	10^{-5}
As	0.30	Cr	10^{-5}
Sb	0.023	V	10^{-5}
Ga	0.008	Mn	10^{-5}
Al	0.002	Ni	10^{-6}

Source: Reference 11

TABLE 7

DISTRIBUTION COEFFICIENTS OF IMPURITIES IN GaAs

Impurity	Coefficient	Impurity	Coefficient
S	0.3	Zn	0.4
Se	0.3	Si	0.14
Sn	0.08	Mg	0.1
Te	0.059	Ge	0.01

Source: Reference 12

In addition to a consideration of the distribution coefficient for choosing a dopant for a semiconductor material, there is the added concern of obtaining a good atomic match to the host lattice(7) Tables 8 and 9 show the tetrahedral radii of impurities in both silicon and gallium arsenide Most Si solar cells today are based entirely on the two dopants, boron and phosphorus, which have relatively poor atomic matches to silicon. Arsenic is seen to be a better match to the lattice than phosphorus while Al and Ga are better matches than boron. Al has been tried as the base dopant, however problems of uniformity have been encountered in Czochralski grown Si[7] For n-type diffused regions, phosphorus has been used almost exclusively because of its well developed diffusion technology. For space applications boron and phosphorus also have the undesirable effect of contributing to the radiation degradation by adding to the formation of electron-hole recombination centers.(7)

TABLE 8

TETRAHEDRAL RADII OF IMPURITIES IN Si

Atom	Radii (Å)	Atom	Radii (Å)
(Si)	(1.176)	(Si)	(1.176)
P	1.07	B	0.91
As	1.18	Al	1.25
Sb	1.35	Ga	1.25

Source: Reference 11

TABLE 9

TETRAHEDRAL RADII OF IMPURITIES IN GaAs

Atom	Radii (Å)	Atom	Radii (Å)
S	1.02	Zn	1.30
Se	1.16	Si	1.17
Sn	1.40	Mg	1.36
Te	1.45	Ge	1.22

Source: Reference 12

Figure 5 shows the process steps for fabricating a silicon solar cell, starting with purified silicon. Instead of using the Czochralski method for producing single crystal silicon, with an inherent yield of 41% from the boule to the wafer due to boule cutting and wafer sawing losses, we are projecting a process based upon a ribbon technology. The process for producing a ribbon of single crystal silicon is based on "pulling" the material from a container of molten silicon, using a seed crystal to initiate the crystalline structure. There are several techniques currently under development by the Low-Cost Silicon Solar Array Project as shown in Figure 6.(8)

Westinghouse is developing a silicon ribbon growth technique which uses the thin web dendrites of silicon growing in the molten silicon ahead of the crystal sheet to serve as guides for shaping the silicon ribbon which is being withdrawn. This process eliminates the potential contamination source of dies made from materials other than silicon and has produced 27 mm wide ribbons having continuous length of over two meters.(9)

Mobil-Tyco Solar Energy Corporation's edge-defined, film-fed growth (EFG) and IBM's capillary shaping technique (CAST) are both based on the principle of feeding molten silicon through a slotted die with the shape of the ribbon being determined by the shape that the silicon assumes in contact with the wetted outer edge of the die. Current efforts are directed towards extending the capacity of the EFG process to a speed of 7.5 cm/minute for a ribbon width of 7.5 cm. Problems encountered have included buckling of the ribbon due to guidance and alignment problems and the inclusion of detrimental impurities (Fe, Cr, Ni, Co) in the ribbon. Recent results reported by Mobil-Tyco indicate that a proper die design can be used to produce a fluid motion that concentrates the impurities in the edges of the ribbon. Further experimentation is needed to show that the distribution of impurities and SiC particles (from the die) can be reliably manipulated in the ribbon to minimize their harmful effect on the final cell. One-inch by four-inch solar cells have been made from the center portion of the ribbon with a measured efficiency of 10.6% (AM1).(10)

The Inverted Stepanov Technique being developed by RCA attempts to avoid the problem of impurities from the material being included in the molten silicon by using a non-wetted die in the ribbon process. The introduction of the feed from above and the growth of the single crystal in a downward direction compensates, in part, for the hydrodynamic drag in the slot and for the lack of the capillary rise which feeds the material to the die edge in the EFG method. Difficulties such as mechanical vibration of the melt and erratic wetting behaviour were encountered when using a die made of SiO_2 due to the evolution of SiO as a gas. Unacceptable doping of the grown silicon ribbon occurred with dies made of boron nitride. Several silicon ribbon specimens with dimensions of about 2 cm wide, 500 μm in thickness and a few centimeters long have been grown with dies coated with a 25 μm thick layer of Si_3N_4.(13)

Motorola is studying a laser zone crystallization process for converting a ribbon of polycrystalline silicon into a continuous ribbon of single crystal silicon. This ribbon to ribbon (RTR) process is basically a float zone process in which a laser beam is used to melt the silicon material. A few runs with a 1.2 kW laser have demonstrated the capability to grow one inch wide ribbons at a rate of two inches per minute. Solar cells made from silicon material developed by the RTR process have had measured efficiencies of only 9.5% (AM1) and additional material and device analysis is underway to better understand the current limitations of this process.(1)

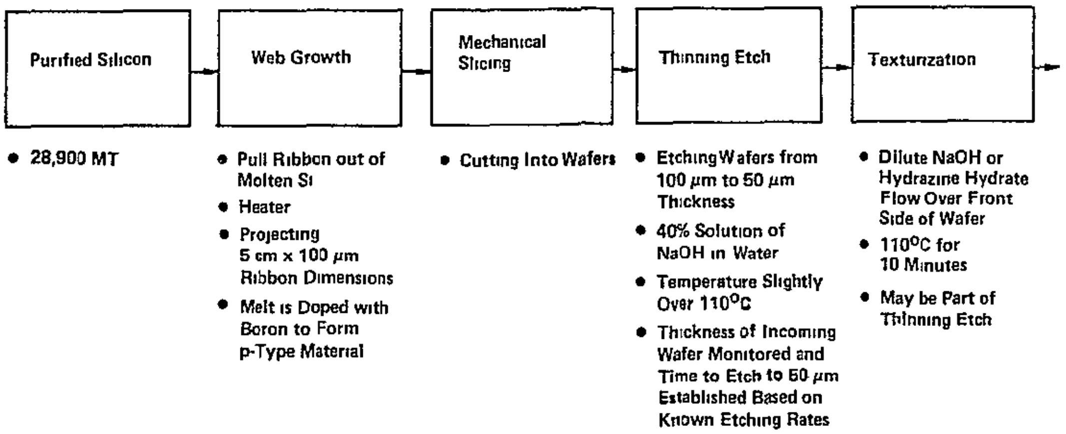


FIGURE 5 PROCESS STEPS FOR CRYSTAL SILICON SOLAR CELL PRODUCTION

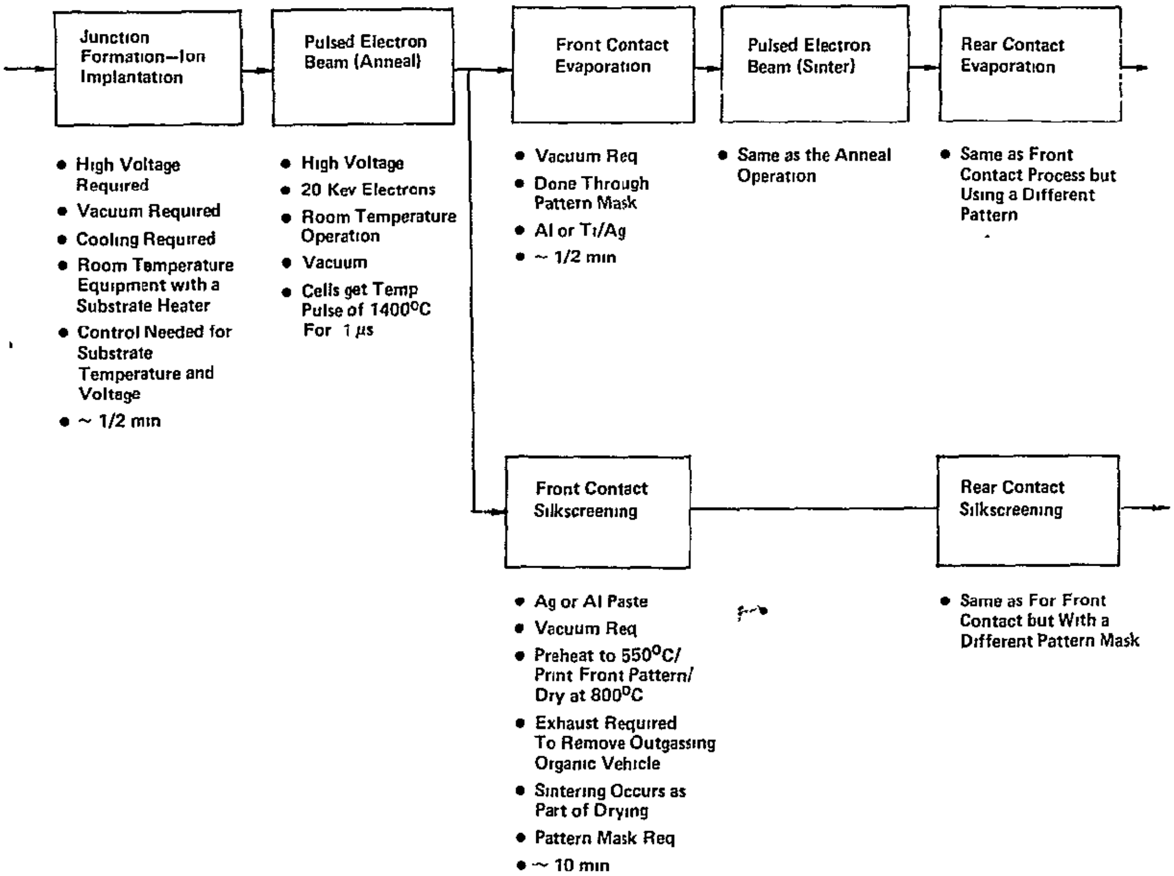


FIGURE 5 (Continued)

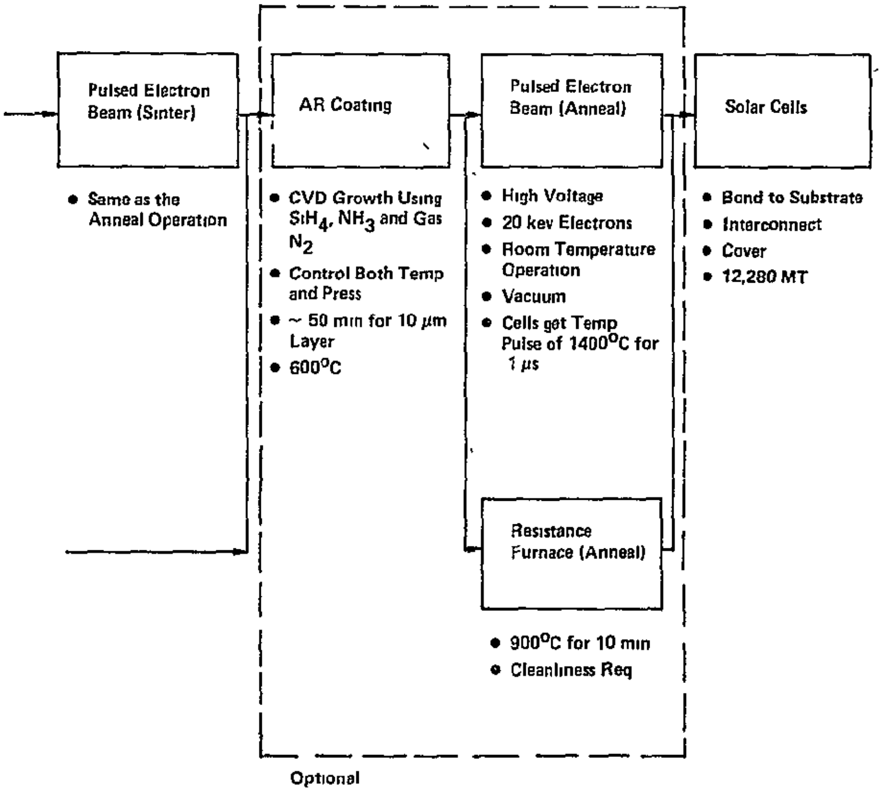


FIGURE 5 (Continued)

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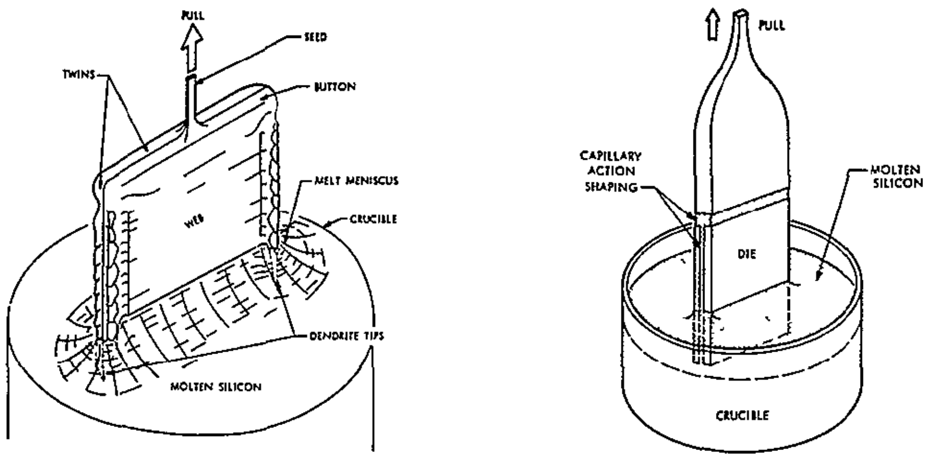
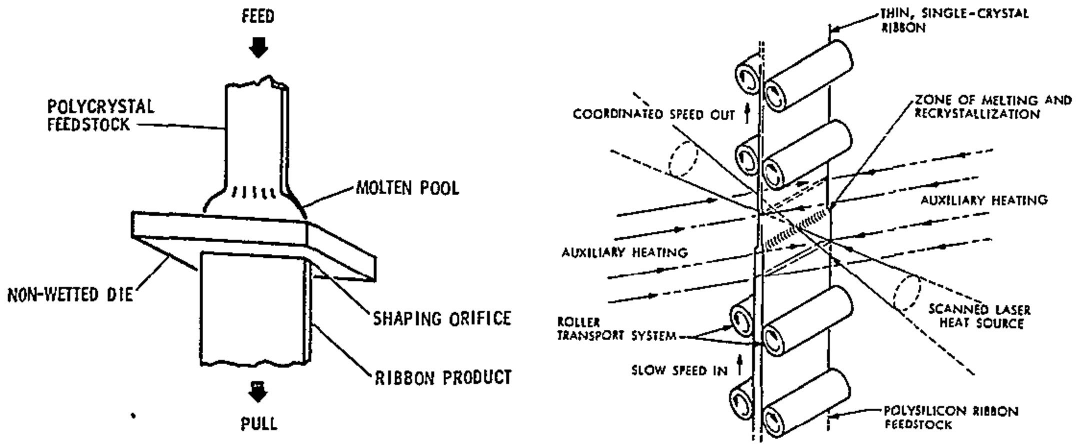


a) Web Dendritic

b) Edge Defined Film Fed Growth (EFG)



c) Inverted Stepanov Technique

d) Laser Zone Crystallization

FIGURE 6 RIBBON GROWTH TECHNIQUES FOR SILICON SOLAR CELLS

In the advanced technology process for producing single crystal silicon solar cells as shown in Figure 5, we have assumed a ribbon growth technique for producing the 100 μm thick, doped silicon ribbons. These ribbons are subsequently cut to the desired rectangular dimension (90% yield) and etched to a thickness of 50 μm. The etching process, which has been demonstrated by Solarex(14) and Spectrolab,(15) utilizes sodium hydroxide

$$Si + NaOH + H_2O = Na_2SiO_3 + H_2$$

Etching 101.4 km^2 of silicon cell material from 100 μm to 50 μm consumes 33,640 MT of sodium hydroxide (NaOH) and generates 51,330 MT of sodium silicate (Na_2SiO_3). The silicon in the sodium silicate is the purified silicon that was prepared from quartzite and because the amount of silicon in the silicate represents 45% of the purified silicon in the original melt, we have assumed a process for recovering 95% of the silicon in the etching solution but have assumed no re-cycling of the sodium hydroxide. Additional work is needed to determine if it is economically justified to recover the silicon from the used etching bath as compared to processing more quartzite to produce the same quantity of purified material. Economics might also make it feasible to sell the "waste" sodium silicate on the commercial market, e.g., to the soap industry. It has a value of approximately \$ 22/kg (\$.10/lb)(16) which would translate into a savings of approximately \$.10/m^2 of the final array.

Texas Instrument's semiconductor manufacturing experience has indicated that with increasing wafer size, thicker wafers are required to minimize wafer warpage and breakage.[17] The breakage is related to mechanical handling and to a degree can be controlled by the proper design of automated handling equipment; however, warpage of the thin cells may be more of an intrinsic problem. The effect on process yield due to warpage and breakage in the automated processing of SPS solar cell arrays could not be quantified at this time. We have assumed no breakage losses in calculating the amount of material needed to fabricate the solar cell arrays for an SPS.

Junction formation is the next step in forming the silicon solar cell and the characteristics of the front side junction are very critical in the fabrication of high efficiency cells. Open tube diffusion using a gaseous source, e.g., $POCl_3$ or PH_3 has been used for many years to produce excellent results, however, because all exposed surfaces are doped with one type of impurity, separate steps, with masking, are needed to produce both n^+ and p^+ regions.

An ideal process for producing the n^+ and p^+ solar cell structure would introduce both dopants at the same time; and ion implantation and polymer dopant technologies are two processes that approach this goal.

Polymer dopant or paint-on techniques have been used in the semiconductor industry for well over 10 years as a low technology process. After the dopant is painted on, a thermal treatment is necessary for the diffusion process. Existing formulations suffer from a shelf life problem with typical shelf lives from one to six months. Texas Instruments has recommended that in a solar cell factory using polymer dopant, the dopant formulation should be produced in the factory to ensure good quality control over the product.(17)

Ion implantation is the junction formation process that was assumed in the manufacturing process for silicon solar cells for an SPS. This dry process can be carried out at room temperature, is easily automated for accurate and reproducible junction formation, permits both sides of a 50

μm cell to be implanted in rapid succession and does not deposit or form any surface residues requiring subsequent removal. Present generation ion implanters, with a 2 milliampere ion beam, can process several square meters of solar cell devices per hour The next generation machine, with beams exceeding 200 milliamperes will be able to process hundreds of square meters of cell area per hour To be able to process 12,600 square meters of cells per hour with a fluence of 10^{15} ions/cm^2 to form the shallow junction, requires a total beam current of approximately 6 amperes which could come from many machines operating in parallel For a 10 keV beam, the ion implant power is 6 x 10^4 watts and for a total implantation process efficiency of 10%, 6 x 10^5 watts would be needed to operate the ion implantation machines (18)

Ion implantation is followed by a pulsed electron beam process to anneal the damage caused by the implanted ions. The method employs a pulsed beam of electrons with a mean electron energy under 20 keV and maximum energy less than 125 keV, the threshold for lattice displacement damage in silicon The duration of the pulse is approximately 10^{-7} second and in response to this pulse, the surface temperature momentarily exceeds 1400°C. After a few microseconds, the entire region cools back to ambient temperature For a pulse energy of 10^4 joules/m^2, approximately 3.5 x 10^4 W is needed for a cell production rate of 12,600 m^2/hour For a total process efficiency of 50%, approximately 7 x 10^4 W of electrical power is required as input to the pulsed electron beam process (18)(19)

After junction formation, front and back electrical contacts are applied to the cell Metallization technologies can be broadly categorized into two groups, vacuum and non-vacuum processes The vacuum processes include evaporation and sputtering technologies, however, the use of a mask stencil is wasteful of materials since only a small portion of the metal ends up in the metallization pattern on the cell. There are also problems of mask cleaning (to keep the openings clean and to recover the excess metal) and fixturing to get proper registration of the metallization pattern on the cell.(17)

For the nonvacuum metallization processes, thick film screen printed metallization and electroless plating of metals are the most promising With both technologies there is considerable industry experience but not in the application to silicon solar cells The screen process prints a paste pattern on the substrate through a mask stencil (screen) The majority of commercial pastes or inks contain precious metals (Au, Pt, Pd, or Ag), however, experimental pastes are becoming available that contain base metals (Cu, Ni, and Al). There is little waste as the paste that is left on the screen can be used on subsequent substrates, however, the high firing temperature used with commercial pastes (> 800°C) is a drawback to having a low cost solar cell fabrication process Experimental work being conducted at Texas Instruments to examine the usefulness of the Cu and Ni inks has shown that these inks are not yet ready for implementation in a manufacturing process. The commercial Cu paste, for example, alloyed into the silicon surface and shorted the shallow junction (17)

Electroless plating of non precious metals, e g , Ni, has been used for many years in the semiconductor industry on deep junction devices Masking techniques must be used unless the metal plate can be patterned as part of the plating operation A patterned electroless plating process called PIMDEP, for Photo Impeded Metal DEPosition has been used on plastic (Kapton) and ceramic substrates and there does not seem to be any inherent reason why it would not work on silicon devices The process uses a sensitizer, $SnCl_2$, that can be desensitized by light, followed by an activator, $PdCl_2$, that activates the nonexposed regions, followed by electroless plating A photomask is required but the mask is not consumed nor does it accumulate deposits. [17]

In our defined process for the fabrication of silicon solar cells, we have shown two alternative approaches to metallization, vacuum metallization and screen printing.

Figures 7 and 8 show the process steps for installing the solar cell module coverglass and for bonding the cells to the module substrate Both processes assume an electrostatic bonding process for joining the borosilicate glass and the silicon solar cell The electrostatic field between glass and silicon surfaces imparts about 350 psi pressure upon the glass as the glass and cell are heated to between 450°C and 500°C. At this temperature, the glass is sufficiently plastic that the electric field causes it to deform around minor irregularities such as cell contacts.(20) The 7070 borosilicate glass is one of many borosilicate glass compositions and is the preferred glass because its coefficience of thermal expansion closely matches that of silicon over the temperature range of the bonding process New glass compositions are being developed to provide an even better match to silicon while having appropriate transmission characteristics.(21)

There is also a potential variation in thickness of the 50 and 75 μm borosilicate glass from one piece to the next that could probably be controlled to less than ± 25 μm (21) A system level study is required to examine the potential impact on the control and operation of an SPS or consequences of non-uniform degradation rates if there were a systematic or random variation in thickness and mass per unit area of the array. The results of the study would be used to determine the need for either a tight control on the thickness of the borosilicate glass as it is being manufactured or a measuring and sorting process for the final pieces of the array after they have been fabricated.

B. PROCESS STEPS FOR FABRICATING CANDIDATE GALLIUM ARSENIDE SOLAR CELL ARRAYS

Gallium and arsenic are the two primary materials used in the gallium arsenide solar cell Because of its high absorption coefficient only a 5 μm thickness of the GaAs material is needed to achieve a high efficiency cell Thick GaAs cells (> 200 μm wafer thickness) can be produced by processes that are very similar to those for producing single crystal silicon cells except that stoichiometry must be maintained to ensure an equal number of Ga and As ions. Also a GaAs wafer is much more fragile than silicon and more care is needed during handling (22) The techniques for producing a 5 μm thick cell layer, involves the epitaxial growth of the cell structure on a substrate that has the proper lattice structure. Liquid phase epitaxy (LPE), vapor phase epitaxy (VPE) and molecular beam epitaxy (MBE) are three processes that could be used. Typically, for laboratory work, gallium arsenide solar cells are grown on gallium arsenide wafers serving as substrates. For an SPS using gallium arsenide solar cells, it has been proposed to use a 20 μm thick layer of sapphire (Al_2O_3) as the substrate on which the cell is grown (2) The sapphire would remain attached to the cell and serve as a coverglass on orbit. Using today's cost numbers, the sapphire substrate is the most costly and most massive part of the SPS gallium arsenide solar cell array.

Because of the proprietary technology used to extract gallium from its source, Figure 9 shows a hypothetical process for preparing high purity gallium from bauxite (23) The process requires 19,500,000 MT of bauxite as input to provide the 780 MT of gallium needed for 2 SPS's (providing a total of 10 GW at the utility interface). The most energy intensive part of the gallium extraction process is the collection of liquid gallium by electrolytic deposition from a gallate rich solution For a gallium production rate of 780 MT/year (80 kg/hr), 6 MW of electrical power is estimated to be required to operate the electrolytic cell(s).

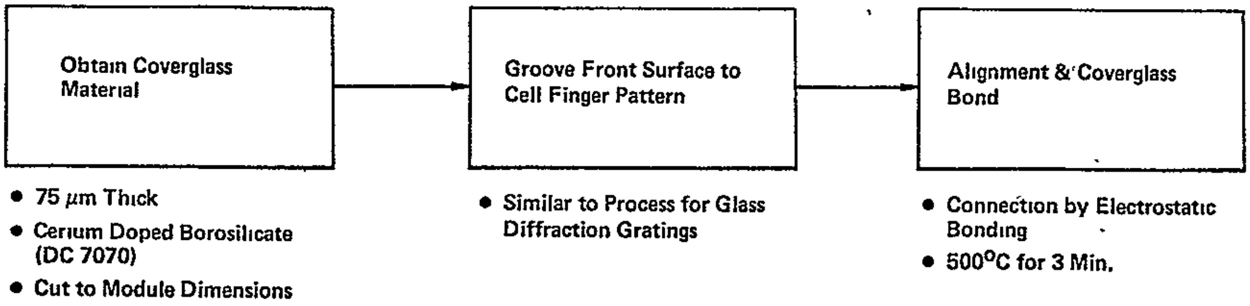


FIGURE 7 PROCESS STEPS FOR INSTALLING SOLAR CELL MODULE COVERGLASS

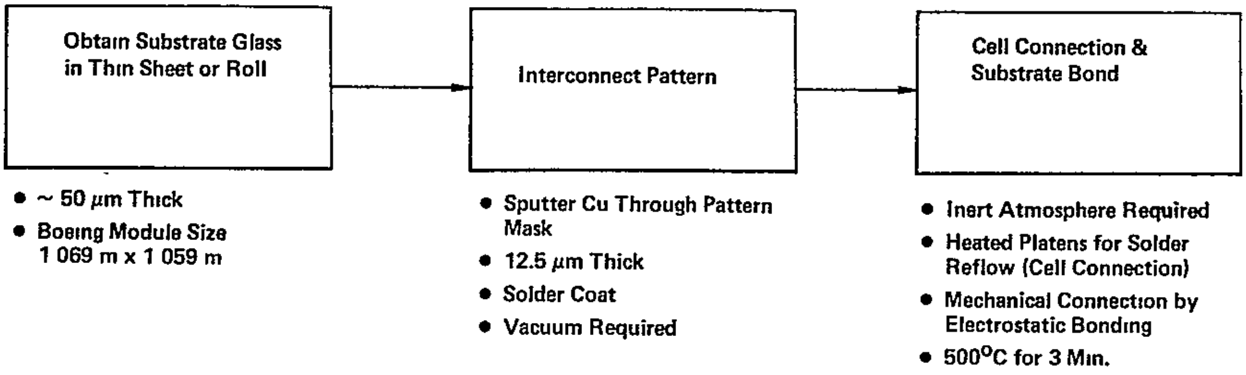
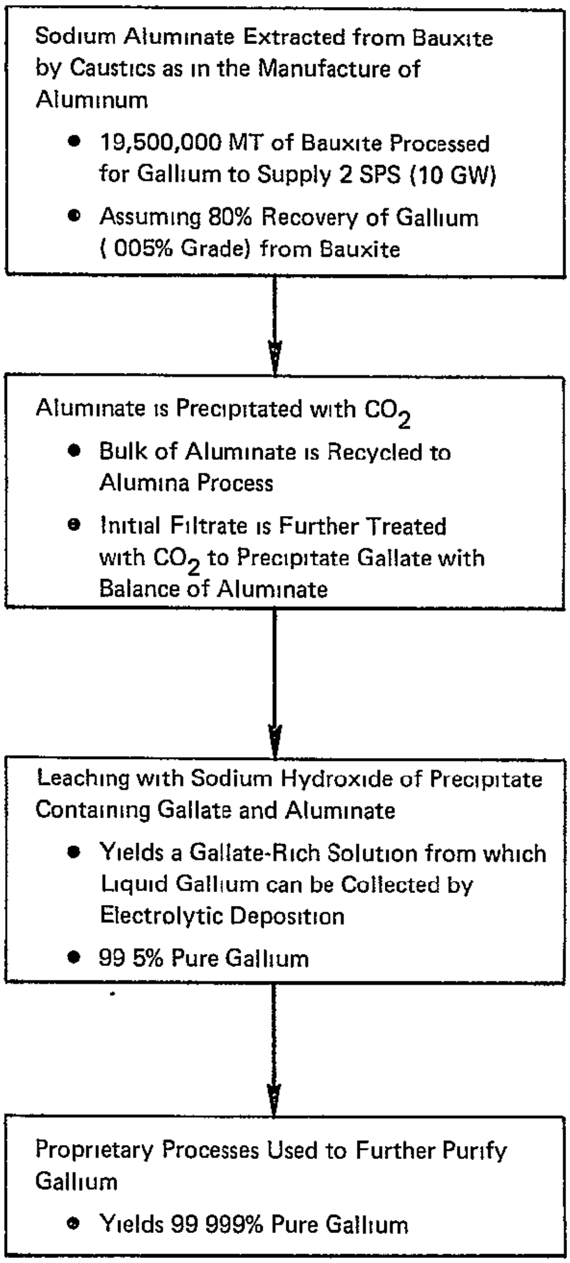


FIGURE 8 PROCESS STEPS FOR BONDING CELLS TO MODULE SUBSTRATE



Sodium Aluminate Extracted from Bauxite by Caustics as in the Manufacture of Aluminum

- 19,500,000 MT of Bauxite Processed for Gallium to Supply 2 SPS (10 GW)
- Assuming 80% Recovery of Gallium (005% Grade) from Bauxite

Aluminate is Precipitated with CO_2

- Bulk of Aluminate is Recycled to Alumina Process
- Initial Filtrate is Further Treated with CO_2 to Precipitate Gallate with Balance of Aluminate

Leaching with Sodium Hydroxide of Precipitate Containing Gallate and Aluminate

- Yields a Gallate-Rich Solution from which Liquid Gallium can be Collected by Electrolytic Deposition
- 99 5% Pure Gallium

Proprietary Processes Used to Further Purify Gallium

- Yields 99 999% Pure Gallium

Source: Reference 23

FIGURE 9 HYPOTHETICAL PROCESS STEPS FOR PREPARING HIGH PURITY GALLIUM FROM BAUXITE [ ]

Figure 10 shows the proposed process steps for large scale production of gallium arsenide solar cell arrays Starting with a suitable (inverted) substrate, e g , 20 μm sapphire, a contact metallization is first applied. It is next projected that a 4-6 μm layer of n-type GaAs (GaAs doped with selenium) will be deposited on the substrate by a chemical-vapor-deposition (CVD) process from gases such as trimethylgallium, AsH_3, and H_2Se. At 750°C the deposition rate would be approximately 0.25 μm/minute for a total process time of 24 minutes (6 μm layer) (21) There is still a great deal of research and development required to determine the feasibility of this CVD growth of a high efficiency GaAs cell Typically a polycrystalline cell structure is achieved (1 μm grain sizes) because crystal growth is initiated at many different nucleation sites on the substrate Subsequent thermal annealing will enhance the grain size and it may be feasible to use laser heating to recrystallize the material to produce larger grains. A contact metallization pattern on the substrate could also make it difficult to achieve a uniform, thin film (5 μm) layer of GaAs.

The junction in the GaAs cell would be formed by vapor deposition of a 1-2 μm thick layer of p-type GaAs (doped with zinc) on top of the existing 4-6 μm layer of n-type GaAs The gases could be trimethylgallium, AsH_3, and diethylzinc with a deposition ratio of 0 25 μm/minute at 750°C (21)

The difficulties of surface recombination and low lifetimes in the diffused region are largely overcome by the addition of a $Ga_{1-x}Al_xAs$ window resulting in a $pGa_{1-x}Al_xAs$-pGaAs-nGaAs solar cell.(7) Assuming a CVD growth process, the gases could consist of trimethylgallium, AsH_3, trimethylaluminum, and diethylzinc, which are brought into contact with the substrate to grow a layer of Zn doped $Ga_{1-x}Al_xAs$ (24)

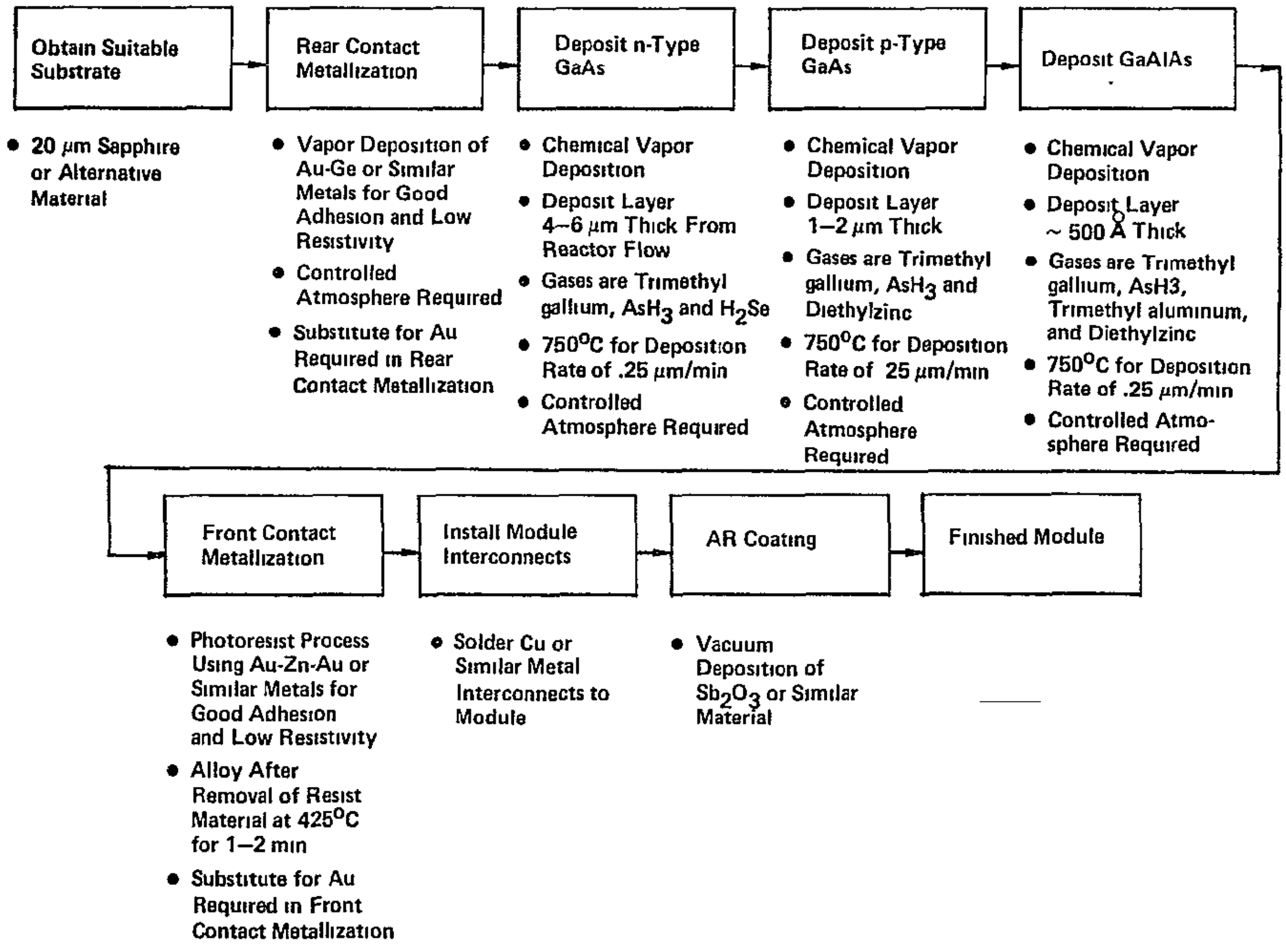
After vapor deposition of the solar cell onto the substrate, additional contacts have to be applied to each cell and individual cells have to be interconnected. Processes similar to those defined for silicon cells could be employed with one significant change from current technology being the elimination of the gold content of the metallization process for economic reasons.

C. SUMMARY OF MATERIAL COST AND ENERGY REQUIREMENTS FOR FABRICATING CANDIDATE SPS SOLAR CELL ARRAYS

Table 10 summarizes both the material requirements for the silicon solar cell arrays of an SPS which delivers 10 GW of power to the utility interface for two different cell/array fabrication techniques, and also the projected U.S annual production of these materials in the year 2000.

The two fabrication techniques represent 1) a current technology, with Czochralski grown ingots sawed to produce 300 μm thick wafers which are etched to a 50 μm thickness, and 2) an advanced technology, which assumes that 100 μm thick ribbons of silicon can be pulled, cut and etched to 50 μm thickness with a 95% recovery of the silicon from the etching bath

Of particular significance, from a limitation of materials point of view, is the demand for 23,700 MT of a purified grade of silicon (with a current U S production rate of 1,000 MT/year of semi-conductor grade silicon) and the need for 29,800 MT of 50 and 75 μm borosilicate glass (with a current production rate of 29,000 MT in sizes approximating 1/8 inch thick sheets) Table 11 summarizes the cost of the needed materials and identifies the borosilicate glass as being a major cost driver based on today's best estimates



- 20 μm Sapphire or Alternative Material

- Vapor Deposition of Au-Ge or Similar Metals for Good Adhesion and Low Resistivity
- Controlled Atmosphere Required
- Substitute for Au Required in Rear Contact Metallization

- Chemical Vapor Deposition
- Deposit Layer 4–6 μm Thick From Reactor Flow
- Gases are Trimethyl gallium, AsH_3 and H_2Se
- 750°C for Deposition Rate of .25 μm/min
- Controlled Atmosphere Required

- Chemical Vapor Deposition
- Deposit Layer 1–2 μm Thick
- Gases are Trimethyl gallium, AsH_3 and Diethylzinc
- 750°C for Deposition Rate of 25 μm/min
- Controlled Atmosphere Required

- Chemical Vapor Deposition
- Deposit Layer $\sim$ 500 Å Thick
- Gases are Trimethyl gallium, AsH3, Trimethyl aluminum, and Diethylzinc
- 750°C for Deposition Rate of .25 μm/min
- Controlled Atmosphere Required

- Photoresist Process Using Au-Zn-Au or Similar Metals for Good Adhesion and Low Resistivity
- Alloy After Removal of Resist Material at 425°C for 1–2 min
- Substitute for Au Required in Front Contact Metallization

- Solder Cu or Similar Metal Interconnects to Module

- Vacuum Deposition of Sb_2O_3 or Similar Material

FIGURE 10 PROCESS STEPS FOR GALLIUM ARSENIDE HETEROJUNCTION SOLAR CELL PRODUCTION

TABLE 10

MATERIAL REQUIREMENTS FOR SINGLE CRYSTAL SILICON SOLAR CELLS/ARRAYS FOR SPS (CR=1)

- **10 GW at Utility Interface from One SPS**
- **Total Array Area of 110.2 km^2**

Material	Amount Required Current Technology[1] (MT)	Amount Required Advanced Technology[2] (MT)	U.S. Production[4] (2000) (MT)
Silica	419,000	133,500	4,732,000
Silicon (MG)	335,200	106,800	200,000
Silicon (SeG)	74,380[1]	23,700[2]	1,000 (1978)
Carbon	168,200	53,600	can be derived from coal
Hydrochloric Acid	1,310,355	417,500	2,496,000 (1975)
Hydrofluoric Acid	200	200	213,000 (1976)
Nitric Acid	140	140	6,852,000 (1974)
Boron	20 kg	20 kg	308,000
Phosphate (Rock)	14 kg	14 kg	(415,000,000)
Sodium Hydroxide	168,860[3]	34,300[3]	9,641,000
Aluminum	530	530	19,000,000
Silver	430	430	7,000
Borosilicate Glass	29,800	29,800	29,000

1. Based on Czochralski grown ingots sawed to produce 300 μm thick circular wafers (41% silicon yield) which are cut to form square cells (64% silicon yield) and etched to 50 μm thickness (16 7% silicon yield). 95% of "lost" silicon in water soluble saw kerf and in unused area of circular wafer is assumed recovered No recovery of silicon from NaOH etching solution is assumed. No additional losses assumed
2. Based on pulling a 100 μm thick ribbon which is cut to form rectangular cells (90% silicon yield) and etched to 50 μm thickness 95% recovery of silicon in unused portion of web is assumed. No recovery of silicon from NaOH etching solution is assumed No additional losses assumed.
3. Assumes a stoichiometric reaction for etching process.
4. Reference 27

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TABLE 11

COST OF MATERIALS (CURRENT PRICES) FOR SINGLE CRYSTAL SILICON SOLAR CELL/ARRAYS FOR SPS (CR=1)

- **10 GW Output at Utility Interface from One SPS**
- **Total Array Area: 110.2 km^2**

Material	Amount Required Advanced Technology[1] (MT)		Unit Cost of Material		Total Cost of Material ($M)
Silica	133,500	materials			
Silicon (MG)	106,800	used to	$1/kg		
Silicon (SeG)	23,700	prepare	$10/kg[2]		237
Carbon	53,600	purified			
Hydrochloric Acid	417,500	silicon	$.14/kg	($125/ton)	
Hydrofluoric Acid	200		$.69/kg	($31.50/100 lb)	14
Nitric Acid	140		$.22/kg	($.10/lb)	.03
Born	20 kg		$95/gm @ 99 9995%[3]		1.9
Phosphorous	14 kg		$38/gm @ 99.999%[3]		5
Sodium Hydroxide	34,300		$.15/kg	($.07/lb)	5 3
Aluminum (Front Contact)	530		$1.17/kg	($.53/lb)	6
Silver (Back Contact)	430		$159 39/kg	($72.30/lb)	68.5
Borosilicate Glass	29,800		$8.07/m^2	(.75/ft^2)[4]	1,780
			Total Cost		$2,094M
			$/m^2		$19/m^2

1 100 μm thick ribbon etched to 50 μm.

2. Based upon DOE projections for a solar-cell-grade silicon. Using a current price of $60/kg for purified silicon would produce a total cost of array materials for 1 SPS of $3430M or $31/m^2.

3 Price varies significantly with purity requirement. Listed prices are for high purity material for use as dopants

4. Using 1985 projected price for 25.4 mm (.100 inch) thick glass with an annual production rate of at least 4.6 x 10^6 m^2 (50 x 10^6 ft^2). Current price for 50-75 μm (2-3 mil) 0211 microsheet is $16-15/m^2 ($1 50/ft^2) in quantities of 740-1100 m^2 (8,000-12,000 ft^2).

The cost of the borosilicate glass is based on a 1985 projected price developed by Corning Glass for a production rate of at least 4.6 x $10^6 m^2$ per year.(21) Because of the significant fraction of the total cost represented by the borosilicate glass, it would be important to obtain cost estimates from the glass industry based on the production rates (110.2 x $10^6 m^2$ per year) needed for an SPS program. An industrial commitment to produce this quantity of borosilicate glass could have a significant impact on lowering the cost per unit area

The total material cost for 110.2 km^2 of a silicon solar cell array is estimated to be $2.12B or $19/$m^2$. Using a current cost of $60/kg for the purified silicon would increase the total cost of the materials to $3.43B or $31/$m^2$

Table 12 summarizes the amount of material required to produce gallium arsenide solar cell arrays that would deliver 10 GW of electrical power to the utility interface. Of particular significance is the demand for gallium (780 MT as compared to a projected U S. production capacity of 32 MT/year in the year 2000), and the demand for 3,200 MT of 25 μm thick Kapton film. Table 13 summarizes the cost for the materials of the gallium arsenide solar cell/array and indicates that the sapphire substrate is a major cost driver.(25)

The costs to fabricate the array have to be added to the material costs to determine the total cost for the final array. Table 14 shows a breakdown for the fabrication costs of a "most" cost-effective terrestrial solar cell as developed by RCA (26) For a 95% total process yield, this results in a $34/$m^2$ fabrication cost. The significant cost drivers are the metallization process for the front surface of the cell ($10.22/$m^2$) and the screen printing of the dopant on two sides ($7.00/$m^2$) prior to diffusing the dopants into the cell. The automation of the large scale cell/array manufacturing process for the SPS program (20 GW per year) and replacement of the screen printing by an ion implantation process should reduce the cost per unit area for the fabrication processes below the values shown in Table 14 (which are based on a production rate of 50 MW per year) For $19/$m^2$ materials cost and $34/$m^2$ fabrication cost, the total array cost per unit area is $53/$m^2$ for a silicon array and $67/$m^2$ for a gallium arsenide solar cell array

Table 15 summarizes the electrical energy required to fabricate single crystal silicon solar cells by the Czochralski method for one SPS generating 10 GW at the utility interface. The conversion of the defined electrical energy requirements to a standard equivalent coal energy assumes a conversion efficiency of 33⅓% so that the energy required to generate the electrical power as shown in Table 15 must be multiplied by a factor of three to determine a standard, total input energy requirement.

The preparation of SeG silicon is the most energy-intensive step in the process and any reduction in the energy requirements of this step will make a significant improvement in the energy payback period The defined 18.1 x 10^9 kWh electrical energy requirement to produce silicon solar cells that will generate 10 GW at the utility interface has a payback period of 0.6 years based on the equivalent coal energy required.

This defined payback period includes only the energy requirements for fabricating single crystal silicon solar cells by sawing wafers from Czochralski grown ingots and there will be additional energy required to fabricate the 50 μm and 75 μm glass covers. Based on data provided by Corning Glass, 26.0 x 10^6 kWh of electrical energy is required to vitrify, fuse, and remove entrapped bubbles from 29,800 MT of borosilicate glass (28) For 10 GW delivered at the utility interface from one SPS, and a 33⅓% conversion efficiency from coal to electricity, this energy requirement is equivalent to a payback period of 7.8 hours

TABLE 12

MATERIAL REQUIREMENTS FOR GALLIUM ARSENIDE SOLAR CELL/ARRAYS FOR SPS (CR=21)

- **10 GW at Utility Interface from Two SPS's**
- **Total Array Area. 61.2 km^2**

Material		**Amount Required[1]** (MT)	**U.S. Production (2000)** (MT)
Bauxite		19,500,000[2]	1,990,000 (1976)
			12,749,000 (1976) – Imported
Gallium	Cell Materials	780[3]	32
Arsenic		840	23,000 (Commercial Purity)
Selenium		27 kg	1,370
Zinc		9 kg	2,766,900
Aluminum		10	19,000,000
Silver (Front Contact)		310	7,000
Gold	5 μm Back Contact 50/50 Composition	2,960[4]	470
Tin		880	71,000
Al_2O_3 (Sapphire Layer)		4,872	5,200,000[5]
Copper (Interconnects)		860	3,820,000
Teflon (Adhesive)		1,650	8,300 (1974 – PTFE)
Kapton (Substrate)		2,200	272 (1976)

1 Assuming a chemical vapor deposition process for cell fabrication with > 99% recovery of any "lost" gallium.

2. Based on an 80% recovery of gallium from bauxite with a grade (% gallium in bauxite) of .005%.

3 Gallium requirement based on a continuous 5 μm thick layer of GaAs with a density of 5.32 g/cm^3, .432 of total GaAs mass due to gallium content and > 99% recovery of all gallium "lost" in production processes.

4 Gold is used in making the metallization contacts on current GaAs solar cells. For large scale production, gold will need to be replaced by another material for economic reasons.

5. Projected production of 20 μm thick sapphire sheets in year 2000 was not identified. Production figure shown is for bulk material

TABLE 13

COST OF MATERIALS (CURRENT PRICES) FOR GALLIUM ARSENIDE SOLAR CELL/ARRAYS FOR SPS (CR=2)

- 10 GW at Utility Interface From Two SPS's
- Total Array Area: 61.2km^2

Material	Amount Required[1] (MT)	Unit Cost of Material		Total Cost of Material ($M)
Bauxite	19,500,000	$.25/kg	($25 18/long ton — Jamaica)	
Gallium	780	$200/kg[2]		156
Arsenic	840	$100.09/kg	($45.40/lb) (99 999%)	84.1
Selenium	27 kg	$192/kg (99.999%)		
Zinc	9 kg	$1170/kg (99.999%)		
Aluminum	10	$138/kg (99 999%)		1 4
Silver	310	$159.39/kg	($72.30/lb)	49.4
Gold	2,960	$5.47/g	($170/troy oz)	(16,180)[3]
Tin	880	$12.21/kg	($5.54/lb)	10 8
Al_2O_3 (sapphire)	4,872	$325/kg		1,583
Copper	860	$1.17/kg	($ 53/lb)	1.0
Teflon	1,650	$ 08/kg	($.0344/lb)	1
Kapton	2,200	$66 14/kg	($30/lb) (25 μm film)	146
			Total Cost	$2,030M
			$/m^2	$33/m^2

1. Assuming a chemical vapor deposition process for cell fabrication with >99% recovery of any "lost" gallium

2. Based on a projected price for gallium in large quantities Using a current price of $800/kg would produce a total cost of array materials for 2 SPS of $2,500M or $41/m^2

3 Use of gold would not be economically feasible therefore a cost of $ 3M has been included in total cost to account for a front contact made of aluminum as per silicon cell.

TABLE 14

COST ANALYSIS OF MOST COST-EFFECTIVE TERRESTRIAL SILICON SOLAR CELL MANUFACTURING PROCESS UTILIZING SCREEN PRINTING

- **Derived by RCA for 47.78 cm^2 Wafers Producing .717 Watts**
- **Material Costs Have Been Excluded**
- **Based on an Annual Production Rate of 50 MW**
- **81.4% Total Process Yield**

Step	Process	Cost ($/watt)	Cost ($/$m^2$)
1	Wafer Cleaning	.003	.88
2	Screen Print Source. 2 Sides	.024	7.00
3	Diffusion	009	2.63
4	Glass Removal	003	.88
5	Post Diffusion Inspection	.001	.29
6	Thick Ag Metal-Back	.017	4.96
7	Thick Ag Metal-Front	.035	10 22
8	AR Coating· Spray On	.009	2 63
9	Test	.012	3.50
10	Interconnect	.014	4 09
11	Double Glass Panel Assembly	.008	2.34
12	Array Module Packaging	.002	.58
	Totals	.137	$40/$m^2$

Source: Reference 26

NOTES.

For 95% Total Process Yield Total Processing Cost = $34/$m^2$

Si Array Total Cost = Materials (Table 11) + Processing Costs = $19/$m^2$ + $34/$m^2$ = $53/$m^2$

GaAs Array Total Cost = Materials (Table 13) + Processing Costs = $33/$m^2$ + $34/$m^2$ = $67/$m^2$

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TABLE 15

ENERGY REQUIREMENTS (kWh) FOR FABRICATING SINGLE CRYSTAL SILICON SOLAR CELLS FOR SPS (CR=1) BASED ON CZOCHRALSKI INGOT TECHNOLOGY[1]

- **10 GW Output at Utility Interface from One SPS**
- **Total Array Area: 110.2 km^2**
- **Total Cell Area: 101.4 km^2**
- **Total Silicon Mass: 11,808 MT**

Process Step	Energy Required (10^9 kWh)
Silica to SeG-Si	14.7
Crystal Growth and Wafer Slicing	1.8
Junction Formation (Ion Implantation)	(0.005)
Firing Contacts	0.6
A/R Coating	1.0
	18.1 x 10^9 kWh

[1] Reference 30

Table 16 shows an estimate of the electrical energy required to fabricate the gallium arsenide solar cells for two SPS's that will deliver 10 GW to the utility interface. The energy data was derived from a study of the energy required to fabricate 125 μm thick single crystal GaAs cells for terrestrial applications.(23) The thin film GaAs cell proposed for the SPS will use a different manufacturing process for growing and preparing the basic cell material than the sawn ingot process assumed for the 125 μm terrestrial cell, however, it is significant that the energy required to purify the gallium (99.999%) is projected to be significantly less than the energy required to prepare the semi-conductor grade of silicon. The energy required to purify the gallium is based upon the hypothetical purification process defined in Reference 23 and shown in Figure 9. For 10 GW delivered at the utility interface from two SPS's and a 33⅓% conversion efficiency from coal to electricity, the estimated energy required to produce the GaAs solar cells is equivalent to a payback period of 18.6 days

The processes used to extract and purify arsenic for use in GaAs solar cell and semi-conductor devices were considered proprietary by the U.S. and Canadian arsenic producing companies and detailed energy requirements were not available. Assuming that the energy required to purify the arsenic is equivalent to the energy required to purify gallium would increase the total payback period by no more than 6.5 days.

An estimate of the energy required to prepare the sapphire ribbon was made based upon the energy required to heat 4,872 MT of Al_2O_3 from 21°C to its melting temperature of 2045°C and to supply the heat of fusion. The electrical energy required was 5.0 x 10^6 kWh which is equal to 15.0 x 10^6 kWh of coal energy and the calculated SPS payback period was 1.5 hours for 10 GW delivered to the utility interface

TABLE 16

ENERGY REQUIREMENTS (kWh) FOR FABRICATING SINGLE CRYSTAL GALLIUM ARSENIDE SOLAR CELLS FOR SPS (CR=2) DERIVED FROM ESTIMATES FOR A 100 MWp TERRESTRIAL PROGRAM[1]

- **Terrestrial Program:** 125μm Thick, 18% Efficient Cell with 1274 MT of Polycrystalline GaAs Required to Produce 370 MT of GaAs Cells (29% Process Yield). Total Array Area is 0.556 km^2
- **SPS Program:** 1620 MT of GaAs Cells Required to Produce 10 GW at Utility Interface from Two SPS's. A 90% Process Yield is Assumed so that 1800 MT of Polycrystalline GaAs is Required. Total Array Area is 61.2 km^2

Process Step	Energy Required (10^9 kWh)
Gallium Extraction from Bauxite (Electrodeposition)	0.21
Gallium Refining, GaAs Formulation and Single Crystal Growing	0.31
Cell Production	0.97[2]
	1.49×10^9 kWh

[1] Reference 23

[2] Based on Silicon Cell Fabrication Energy Requirement per Unit Area

Based upon an equivalent rail transportation energy of 0 12 kWh/Mt-km (600 Btu/ton-mile)(29) the energy payback period for the 46,404 MT of silicon solar cell arrays for one SPS is increased approximately 2 seconds for every kilometer that the finished arrays have to be transported from the manufacturing facilities to the launch site For the 15,450 MT of GaAs solar cell arrays, the energy payback period would increase approximately 2/3 seconds for every kilometer that the finished arrays were transported.

D. INDUSTRIAL INVOLVEMENT IN THE MANUFACTURING OF SOLAR CELLS/ARRAYS FOR THE SPS PROGRAM

Table 17 identifies the U S industrial sectors that would be most involved in a buildup of production capacity to manufacture solar cells/arrays for the SPS program. The level of involvement has been identified for both a silicon and a gallium arsenide solar cell/array manufacturing program. This section highlights the industrial sectors that could be potentially impacted

1. Industrial Division B — Mining

This division includes all establishments primarily engaged in the extraction of naturally occurring minerals whether they be solids, liquids or gases

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TABLE 17

INDUSTRIAL SECTORS AFFECTED BY AN SPS SOLAR CELL MANUFACTURING PROGRAM

- Classifications Derived From Standard Industrial Classification Manual[1]

Industrial Classification	Level of Impact	
	Silicon	Gallium Arsenide
Division A — Agriculture, Forestry and Fishing	L	L
Division B — Mining	L	H
Division C — Construction	L	L
Division D — Manufacturing	H	H
Division E — Transportation, Communications, Electric, Gas and Sanitary Services	M	M
Division F — Wholesale Trade	L	L
Division G — Retail Trade	L	L
Division H — Finance, Insurance and Real Estate	H	H
Division I — Services	M	M
Division J — Public Services	H	H
Division K — Non-Classifiable Establishments	L	L

L — Low or no significant impact
M — Moderate impact in specific areas
H — High impact in specific areas

[1] Reference 31

For the SPS silicon solar cell/array manufacturing program, the largest requirement for a naturally occurring mineral is for the silica used as the starting material in the process to purify silicon The 133,500 MT of silica required to produce 23,700 MT of purified silicon are less than 3% of the 4,732,000 MT total U S annual production (year 2000) of silica If, however, selected deposits of silica were mined, e g., to take advantage of a higher mineral purity, then the level of impact could increase based on the availability of the purer mineral and the required buildup of mining operation at selected sites

Bauxite, a naturally occurring mineral, could serve as a source of gallium to manufacture the gallium arsenide solar cell/array. At a grade (% gallium) of .005% and an assumed 80% recovery factor, 19,500,000 MT of bauxite would have to be mined to provide a source for the 780 MT of gallium needed to generate 10 GW at the utility interface. The 1976 U S annual rate of mining of bauxite is 1,990,000 MT/year with another 13,749,000 MT/year being imported, primarily for the aluminum industry.(27) The need for 780 MT of gallium would require processing more bauxite than the total U. S. domestic plus imported production of bauxite for the year 1976 The

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1976 world production of bauxite was 83 x 10^6 MT which could yield 3300 MT of gallium, however, the required industrial involvement would be international in scope We project a high level of impact for the mining sectors of U S. industry for producing gallium arsenide solar cell arrays for the SPS. There are other possible sources of gallium, e.g., coal, however, commercial processes have yet to be developed to demonstrate the feasibility of using these alternative sources.

2. Industrial Division D — Manufacturing

The manufacturing division includes establishments engaged in the mechanical or chemical transformation of materials into new products. The new product may be ready for utilization or consumption "as is" or it may be used as a raw material by another manufacturer

For a silicon solar cell/array manufacturing program, the two largest impacts are (1) the production of 23,700 MT/year of a solar cell (SoG) or semi-conductor grade (SeG) of silicon and (2) the production of 29,800 MT/year of 50 and 75 μm borosilicate glass.

The current U. S production capability for SeG silicon is estimated at 1,000 MT/year [4] Table 18 shows a breakdown of the current producers of purified silicon Of the five potential suppliers, only Dow Corning has regularly sold SeG silicon on the open market The other suppliers typically make the material to satisfy their own requirements.

TABLE 18

U.S. SUPPLIERS OF SEMI CONDUCTOR GRADE SILICON [1]

Source	**Annual Production Capability (Est.) (MT/year)**	
Monsanto	200	
Dow Corning	400	(+ 200 which could come on stream)
Texas Instruments	100	
Motorola	100	
Great Western	(100)	potential supplier
Total Current U S. Production	800 MT/year	
Total Potential U.S. Production	1100 MT/year	

[1] Reference 27

There will be a significant impact in achieving an annual production capacity of 23,700 MT/year of SeG silicon to meet the projected SPS requirements, when the current production capacity is only 1,000 MT/year At present, the purification of silicon is an energy intensive step so that current development efforts both to find an alternative, less energy intensive process and also to examine the feasibility of using the less pure, SoG silicon to fabricate solar cells could have a significant impact on the manufacturing sector.

The requirement for 29,800 MT of 50 μm and 75 μm borosilicate glass would have a significant impact on the glass industries.

The technology exists for making this glass in the required thickness (± a tolerance to be determined), however, there is currently no market for the thin glass sheets. There are many compositions of borosilicate glass made today, typically for high temperature application in home appliances or for industrial applications and an expansion of production capacity would normally occur in increments of 200-400 MT/year(21). There would, therefore, be a significant impact on the glass industry to install the capacity for producing 29,800 MT/year of 7070 borosilicate glass, or its equivalent, to meet the projected SPS requirements

The largest impacts of the manufacture of gallium arsenide solar cell/arrays are (1) the production of 780 MT/year of gallium, (2) the production of 840 MT/year of purified arsenic and,(3) the manufacture of 6,050 MT/year of a 20 μm thick sapphire substrate.

There are two domestic sources of gallium The Aluminum Company of America (Alcoa), using proprietary gallium production processes, produces the metal at its Bauxite, Arkansas, plant as a by-product from residues of its aluminum production process In 1976, Alcoa announced that it began gallium recovery from its alumina operation at Mobile, Alabama, to meet increasing worldwide gallium demand The second domestic source, Eagle Picher Industries, Inc , produces gallium, oxide and trichloride from zinc production residues at its Quapaw, Oklahoma, facility Almost the entire U S gallium output is used to manufacture light emitting diodes with the remainder used for research and development and for the preparation of dental alloys

Domestic production of gallium is supplemented by imports coming from West Germany, Switzerland, Canada, and Italy. In the first nine months of 1977, 1.8 MT of gallium were imported With a projected U S gallium production in the year 2000 of 32 MT/year and a need for 780 MT of gallium, for 10 GW of generated power at the utility interface, there would be a high level of impact on the manufacturers extracting the gallium from its mineral sources

There is currently only one facility in the U S. that produces high purity arsenic and the highest available purity of the product is 99.999% The facility, located in Denver, Colorado, is operated by ASARCO, Inc , and produces the high purity arsenic in 1 5 kg ampules. An SPS production requirement of 840 MT/year (560,000 ampules/year) would have a significant impact on the U. S manufacturers of purified arsenic. The current U S. production capacity for high purity arsenic is estimated to be 4800 kg/year.(32)

The 20 μm sapphire substrate proposed for the gallium arsenide solar cell/array would have a significant impact on the industries which could produce this material.

This substrate material is currently available from Tyco's Saphikon division in Waltham, Massachusetts, however, current production is for 12 7 mm (½ inch) wide ribbon with a thickness of 500-625 μm (20-25 mils) (25) This material is being produced for use as a hermetically sealed window for Erasable Programmable Read Only Memories (EPROM) for microprocessors

The sapphire window provides a high transmission for the UV light which is used to erase the memory unit Saphikon projects that it would be possible to form thin sapphire ribbon (20 μm) in suitable widths based on their experience growing both 50 μm thick ribbons (in 12.7 mm widths) and also 75 mm (3 inch) wide ribbons. The purified Al_2O_3 used as input to the ribbon

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growing process is imported from Europe where, in the past, it was used for jewel bearings in watches. The advent of electronic watches has caused a "surplus" of production capability for the purified Al_2O_3

The Saphikon process is material and energy intensive and the current cost per unit area of \$1,240/m^2 (\$.80/$inch^2$) for 500 μm (20 mil) thick ribbon could be significantly reduced when 25 μm (1 mil) thick ribbon is produced. The current raw material cost is \$30-\$35/kg and the final product sells for approximately \$1,500/kg. A projected cost of \$325/kg for the sapphire ribbon in large quantity was considered reasonable by the manufacturer.(25)

3. Industrial Division H — Finance, Insurance and Real Estate

This division includes establishments operating primarily in the fields of finance, insurance and real estate. Finance includes banks and trust companies, brokers, and dealers in security and commodity contracts and security and commodity exchanges. Insurance covers carriers of all types of insurance

The scenario proposed for the first SPS (see Figure 1) is to gain array manufacturing experience over a time span of several years at a reduced production level while accumulating the necessary inventory of solar cell/arrays for the first SPS. This stepwise buildup of annual production capacity permits the accumulation of experience with the manufacturing process prior to making a commitment for a large production capacity. This proposed approach, however, results in the warehousing of a significant inventory of solar cell/arrays with an associated cost for the invested capital. Table 19 summarizes the cost of one day's production of SPS solar cell/arrays using silicon or gallium arsenide solar cells, and the total cost for the full array area required to produce 10 GW at the utility interface. The total array cost of \$5.8B for silicon and \$4.1B for gallium arsenide solar cell/arrays represents a significant investment of capital that would be tied up during storage of the arrays. The optimum approach would be to minimize the inventory of SPS solar cell/arrays held in storage by matching the availability of the largest production rate from the array manufacturing facilities with the launch schedule. The warehouse would then serve as a buffer between the manufacturing and launch facilities.

TABLE 19

COST OF DAILY PRODUCTION OUTPUT AND OF STORED ARRAYS FOR 10 GW OF SPS SOLAR CELL BLANKETS

Material	Array's Unit Cost (\$/m^2)	Cost of One Day's Production	Cost of SPS Array for 10 GW at Utility Interface[1]
Silicon	53	\$16.0M	\$5.8 B
Gallium Arsenide	67	\$11.3M	\$4.1 B

1 Does not include transportation costs to warehouse.

The buildup and operation of the production facilities for the SPS solar cell/arrays will require a significant investment of capital from either government or private sources. For an ongoing SPS program to be financed by the industrial and utility participants will require a significant involvement of large financial institutions. The capital requirements to build and operate the array production facilities, and to support the costs of warehousing of a significant inventory of SPS arrays, would make a significant impact on the industrial sector that would provide private sources of capital. DOE's Low-Cost Silicon Array Project has projected a $40M cost for a manufacturing facility that could produce 20 MWp/year of terrestrial solar cell/arrays. Additional studies would be necessary, however, to determine the capital cost of a manufacturing complex that could produce 20 GW of SPS space-qualified arrays per year once the manufacturing process was determined.

E. BUILDUP OF INDUSTRIAL CAPACITY TO MEET REQUIREMENTS OF MANUFACTURING PROGRAM

The development of the solar cell/array production capacity to support a photovoltaic SPS program will have an impact on selected industrial sectors. These impacted sectors can be classified into two general categories. (1) the companies that will provide a defined quantity of products in response to a firm order, e g , the necessary buildings and production equipment for the manufacturing facilities; and (2) the companies that will provide materials to the manufacturing facilities on a continuing basis, e g , purified silicon, borosilicate glass, process chemicals, and energy.

The first category of industrial involvement will be in response to a well defined, short-term market, where the cost and price of products would be predictable based on the specified quantity and quality of product purchased. To avoid future scheduling problems for long lead time items, that may be repurchased when an expansion of industrial capacity total production is increased to fulfill an initial order may be required, e g., ion implantation machines This would result in lower costs for subsequent purchases of the same (or nearly the same) products. The competitive pricing of the product in response to the initial purchase requests would involve a risk assessment of the future market opportunities

The second category of industrial involvement would entail a significant expansion of production capability in anticipation of a significantly larger future market Industry would not embark on significant expansion programs until there would be firm commitments for products over a suitable period of time or a guaranteed equivalent compensation if the planned purchases were not made. The financial risks associated with significant expansion of production capability in response to projected future needs of the SPS program are great enough to prevent the expansion from occurring unless guaranteed buys are negotiated prior to initiating the expansion program. A good example is the glass industry which today manufactures ⅛-inch thick sheets of borosilicate glass (Pyrex) for use in high temperature home appliance, e g , for ovens and industrial applications Expansion of production capability in such a specialty glass would typically occur in 200-400 MT/year increments, while an on-going SPS program would require a production rate of approximately 30,000 MT/year of borosilicate glass sheets in 50 and 75 μm thicknesses. The technology exists for making this glass in the required thickness, however, the incentives to create the production capability in anticipation of a future need of the SPS program would have to include an agreed upon rate of return on the investment, i e., a guaranteed buy or equivalent compensation based on defined markets.

There are two scenarios which could lessen the impact of the required industrial expansion The first involves a large and expanding terrestrial solar cell market resulting from the national photovoltaic conversion program, which could support a fraction of the increasing production capability, e.g., purified, SoG silicon. Expansion of production capacity to meet the future market needs of two or more comparable programs would tend to lessen the risk of building capacity that would become unnecessary due to program changes. If the solar cell/array requirements of the on-going terrestrial photovoltaic program (1985-1990) were much smaller than those of the SPS Program, then the situation remains that of a single, large program with requirements independent of other on-going programs and represents a high risk to potential manufacturers.

The second scenario involves a gradual expansion of industrial capacity to meet the full production requirements of an on-going SPS program. There are obvious technical and economic advantages to this approach which builds an accumulation of the necessary solar cell/array inventory over a number of years for the first SPS flight operation. The gradual expansion of industrial capacity to meet the needs of the SPS program would reduce the risk asssociated with adding the largest fraction of industrial capacity by delaying the decision for the final 70% expansion effort until a time, e.g., 1992, when the first expansion (10%) of industrial capacity was in place and had been operating for a year and the second expansion (an additional 20%) would be just beginning initial operations Table 20 summarizes the schedule for this build-up in industrial capacity in the two materials potentially most affected by the requirement for expansion of industrial capacity for a 10 GW SPS using silicon solar cells.

TABLE 20

SCHEDULE FOR BRINGING ADDITIONAL INDUSTRIAL CAPACITY (MT/YEAR) ON LINE FOR MATERIALS REQUIRED TO PRODUCE SILICON SOLAR CELL/ARRAYS

	Additional Industrial Capacity (MT/Year)		
	Time		
Material	**1991**	**1992**	**1995**
Solar Cell Grade Silicon	2,370	4,740	16,590
Borosilicate Glass	2,980	5,960	20,860

Management and technical representatives from the potential production industries, such as the producers of the materials listed in Table 20 should be kept informed of the on-going activities in the SPS program and be invited to attend and participate in SPS presentations being made by NASA/DOE contractors. This early involvement will provide both a useful exchange of information concerning projected program requirements and industry's reactions, as well as an extended period of time for the nonaerospace industrial sector to familiarize itself with the SPS conceptprior to being faced with decisions concerning expansion to meet SPS program needs

IV. CURRENT U.S. PHOTOVOLTAIC CONVERSION PROGRAMS

There are currently three separate U S. photovoltaic research and development programs (1) The National Photovoltaic Conversion Program being managed by DOE, (2) DOD's activities being managed by Wright-Patterson Air Force Base (WPAFB), and (3) NASA's activities which are being managed by various NASA centers Table 21 shows the breakdown of the current total budget of $62.1M among the three agencies and clearly indicates the leading role that DOE has in directing photovoltaic research in the United States ($57.2M out of $62.1M) This section discusses the three photovoltaic programs and the applicability of their current goals to the SPS program.

TABLE 21

CURRENT ANNUAL U.S. FUNDING LEVELS FOR SOLAR CELL R&D ACTIVITIES

Department of Energy		$ 57.2 M[1]
Advanced Materials	$ 7.7 M	
GaAs	$ 1.7 M	
NASA		$ 3.4 M[2]
DOD		$ 1.5 M[3]
Total		$ 62.1 M

[1] Reference 33
[2] Reference 34
[3] Reference 35

A. DOE'S TERRESTRIAL PHOTOVOLTAIC CONVERSION PROGRAM

DOE's current emphasis is on meeting a $2/Wp cost goal by 1982 at an annual production rate of 20 MWp/year using single crystal silicon solar cells, produced from Czochralski ingots, with or without concentrators. DOE's midterm goal is to achieve photovoltaic array prices of $0 50/Wp in 1986 with a production capability of 500 MWp/year. The solar cell technology being projected to meet this goal includes the ribbon technique for producing the silicon wafer. As a far term goal, DOE wants to achieve an array price goal of $0.10 to $0 30/Wp in 1990 with an annual production rate of 50 GWp/year by the year 2000 [6]

The near term goals of DOE's photovoltaic program that will be most applicable to the SPS program include: (1) the development of solar cell manufacturing technologies that would be suitable for an automated array manufacturing facility, (2) the development of industrial sources for low-cost, single crystal silicon wafers for use in fabricating 50 μm thick solar cells for the SPS 1980-1985 array test programs, and (3) the increase in understanding and characterization of advanced and emerging photovoltaic materials.

The mid term goals of the DOE photovoltaic conversion program most applicable to the SPS solar cell/array program include. (1) the development of the ribbon technology for producing a thin, single crystal silicon material, and (2) results from the research and development activities of advanced photovoltaic materials (gallium arsenide, polycrystalline and amorphous silicon and cadmium sulfide). Thin film gallium arsenide is a possible alternative photovoltaic material for use in the solar cell/array of the SPS and the funding from DOE is a significant source of support for its development The additional requirements associated with using gallium arsenide for the SPS program that are currently not being pursued by DOE are· (1) the capability for large scale production rates on a low cost substrate and (2) characterization of resistance to degradation by the on-orbit radiation environment

The DOE far term goals to reduce the cost of terrestrial photovoltaic systems to $0 10-$0.30/Wp will include the development of thin film technologies for solar cell arrays as well as continuing support for research in such emerging photovoltaic materials as CdTe, Zn_3P_2, $ZnSiAs_2$, and Cu_2O Assuming that the SPS will be designed to accommodate a change in solar cell materials as the state-of-the-art in photovoltaic devices advances, research and development activity in alternative photovoltaic materials is directly applicable to the SPS Program As is the case with all photovoltaic materials being considered by DOE, the SPS Program will also require an assessment of the capability for large scale manufacture as well as characterization of the radiation resistance

Table 22 shows the range of photovoltaic materials being investigated under the National Photovoltaic Conversion Program, the cell size that has been fabricated and the efficiency that has been achieved.(36) Table 23 summarizes the currently defined areas for further research in three of DOE's advanced solar cell materials (thin film silicon, amorphous silicon and gallium arsenide)

In addition to the technical results of DOE's photovoltaic conversion program, there is a potential benefit to the SPS program resulting from the development of terrestrial markets for solar cells.

If the solar cell being developed for the SPS program would be similar to the cell being developed to meet terrestrial requirements, then the initial output from the SPS manufacturing facilities could be utilized to satisfy all or part of the needs of the terrestrial market, thereby eliminating the need to accumulate a costly inventory of SPS arrays ($5 8B) in anticipation of the date of initial flight operations. It is not presently known whether the solar cells that would be developed for the terrestrial program could also satisfy the additional high efficiency and radiation resistance requirements of the SPS cell It is more likely, however, that the solar cells that would be developed to satisfy the requirement of the SPS program could, with some modifications, also satisfy most of the needs of the terrestrial program A typical modification would be to use an encapsulating system that would survive the terrestrial environment in place of the low mass per unit area system that would be used in SPS arrays

Table 24 summarizes the projected U S. terrestrial market for an SPS/terrestrial type solar cell array based on current applications and shows that, for an annual SPS production rate of 20 GW/year (1995), the projected world-wide terrestrial market of 140,000 kWp (1986) would be less than 1% of the total production capacity.(37) Based on these 1986 projections, the potential terrestrial markets (based on present application), would not be significant for SPS cells unless these markets were to grow significantly between 1986 and 1995

TABLE 22

MEASURED EFFICIENCIES (AM1) AND SOLAR CELL SIZES FOR A RANGE OF PHOTOVOLTAIC MATERIALS CURRENTLY UNDER INVESTIGATION

Cell Material	Cell Size (CM^2)	Efficiency (%)
CdS/Cu_2S	1.3	8.6
$Cd_{0.93}Zn_{0.7}S/Cu_2S$	1.4	6.3
CdS/CuInSe	1.0	6.7
$ITO/CuInSe_2$	0.2	11.3
AMOS (Au-SbO_3) on Single Crystal GaAs	1.0	16.2
AMOS (Au-SbO_3) on Polycrystalline GaAs (100-500 μm Grain Size)	0.2	14.0
$AsCl_3$-CVD $n^+/pGaAs$	0.5	20.0
MO-CVD pGaAlAs/nGaAs (single crystal)	0.3	12.5
Pt Schottky Barrier Cell on CVD GaAs on Tungsten Coated Graphite	8.0	5.6
Pt Schottky Barrier on Hydrogenated Amorphous Silicon	2.0 mm^2	6.0

Source: Reference 36

TABLE 23

AREAS FOR FURTHER RESEARCH IN ADVANCED SOLAR CELLS

Cell Type	Research Areas
Thin Film Silicon	• Develop techniques for growing large grain polycrystalline silicon on low-cost substrates • Investigate laser and E-Beam techniques for grain enhancement • Develop techniques for passivating grain boundaries and forming p-n junctions in polycrystalline silicon
Amorphous Silicon	• Improve methods for neutralizing dangling bonds in amorphous silicon • Investigate diffusion lengths of holes in amorphous silicon and the recombination process • Develop technique for increasing efficiency and area
Gallium Arsenide	• Identify suitable low cost substrate • Develop grain size in polycrystalline GaAs to greater than 10μm diameter • Develop techniques for formation of p-n junctions in polycrystalline GaAs • Characterize grain boundaries

Source: Reference 36

TABLE 24

PROJECTED TERRESTRIAL MARKETS FOR SPS/TERRESTRIAL TYPE SOLAR CELL ARRAYS BASED ON PRESENT APPLICATIONS

Present Terrestrial Applications	Projected U.S.[1]	1986 Sales (kWp) Worldwide[2]
Marking and Warning Devices	2,700	2,700
Corrosion Protection	21,000	26,000
Monitoring and Sensing Devices	33	33
Communications	5,200	11,600
Consumer Products	1,100	1,100
General Power Sources	22,000	99,000
Total	52,000	140,000

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1. Factor of 2 estimate of uncertainty in results.
2. Factor of 3 estimate of uncertainty in results.

Source: Reference 37

Table 25 shows the projected terrestrial market for SPS/terrestrial type solar cell arrays based on potential terrestrial applications By including such applications as highway lighting and irrigation, the projected annual markets for terrestrial solar cells increase to 4 GW/year which is a significant fraction of the proposed 20 GW/year SPS production capacity.(37)

TABLE 25

PROJECTED U.S. MARKETS FOR SPS/TERRESTRIAL TYPE SOLAR CELL ARRAY BASED ON POTENTIAL TERRESTRIAL APPLICATIONS

Potential Terrestrial Applications	Maximum Annual Market Potential (MWp)
Highway Lighting	2,100
Residential Attic Fan	400
LDC Village Pumping/Lighting	510
Irrigation (Nebraska, Texas, Arizona)	1,000
School (Load Center)	430
Total	4,000

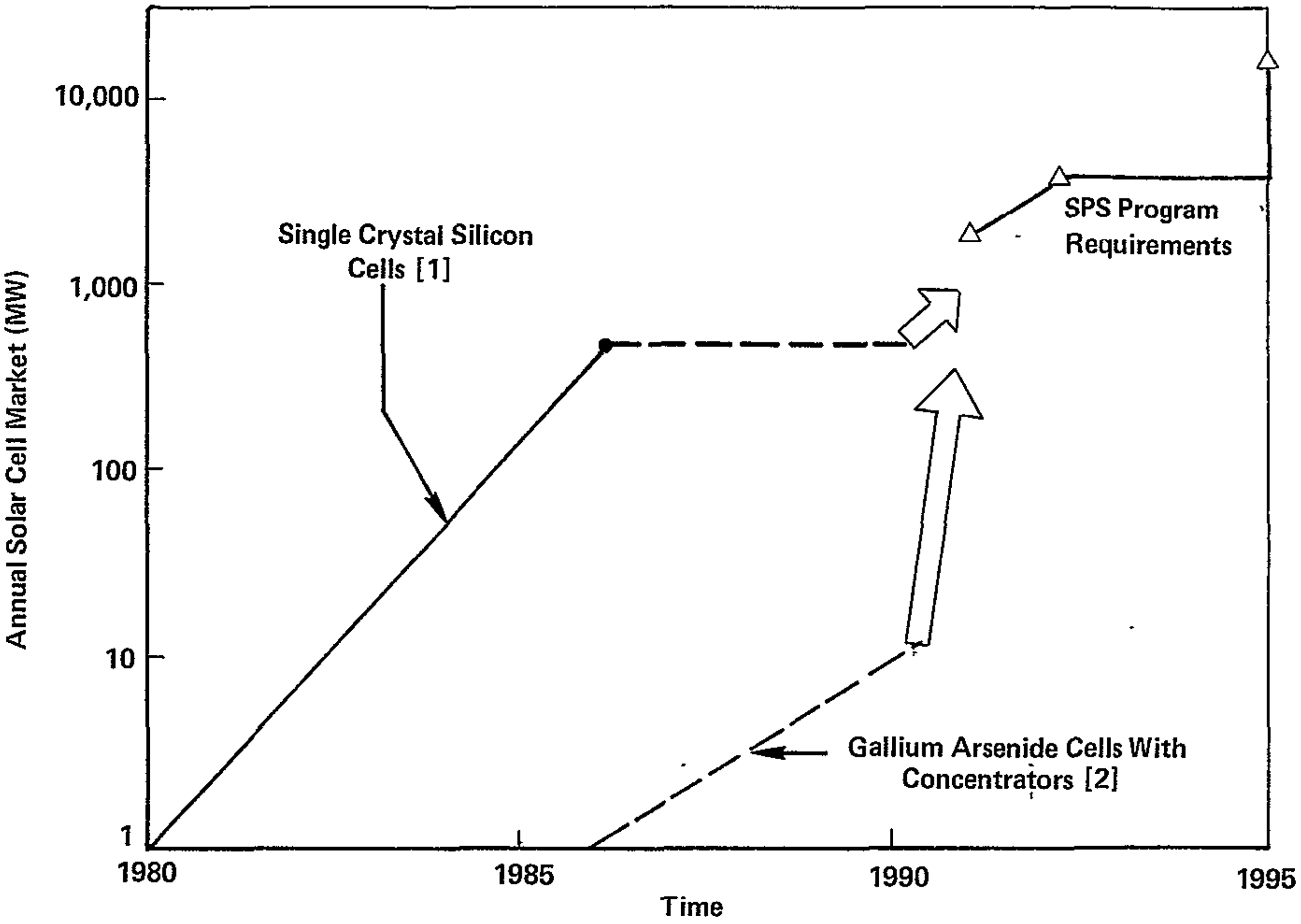
Source: Reference 37

The potential size of the terrestrial market for solar cells in the time period of 1985-1995 is not well known at this time and the markets will be significantly affected by results of the national photovoltaic conversion program between now and 1985 Of particular significance, however, is that the main thrust of the photovoltaic conversion program is toward the utilization of silicon solar cells. There will be only limited experience gained with gallium arsenide solar cells prior to the 1985-1990 time frame Figure 11 shows projected terrestrial solar cell market growth projections for silicon and gallium arsenide solar cells for the time period from 1980 to 1990 The markets for the single crystal silicon cells are based on the DOE projections for a 50 MWp/year production capacity in 1986 The 1986 projection for the gallium arsenide solar cell arrays assumes a scenario similar to the initial growth scenario for the silicon cells (1980) but with a smaller increase per year due to the projected use of concentrators with the more costly gallium arsenide material

Figure 11 shows that the production capacity and experience for silicon solar cells in 1985 will be significantly greater than the experience that will have been accumulated with gallium arsenide solar cells by that date This greater large scale manufacturing experience with silicon solar cells between now and 1985 is a major reason for recommending silicon as the baseline photovoltaic material for the initial SPS flight operations

B. DOD'S PHOTOVOLTAIC CONVERSION PROGRAM

The current emphasis of the DOD photovoltaic conversion program is to develop high efficiency, radiation resistant solar cells that would increase the available power in future operational spacecraft. The current development efforts in this direction include gallium arsenide solar cells as well as two and three junction, discrete band gap cells. The gallium arsenide cells are single crystal cells and the goals of low cost and large scale manufacturing capability for the SPS program are not important factors in DOD's photovoltaic conversion program. The annual



1 **Source:** Reference 5
2. **Source:** Arthur D. Little, Inc., estimates

FIGURE 11 SOLAR CELL TERRESTRIAL MARKET GROWTH SCENARIOS

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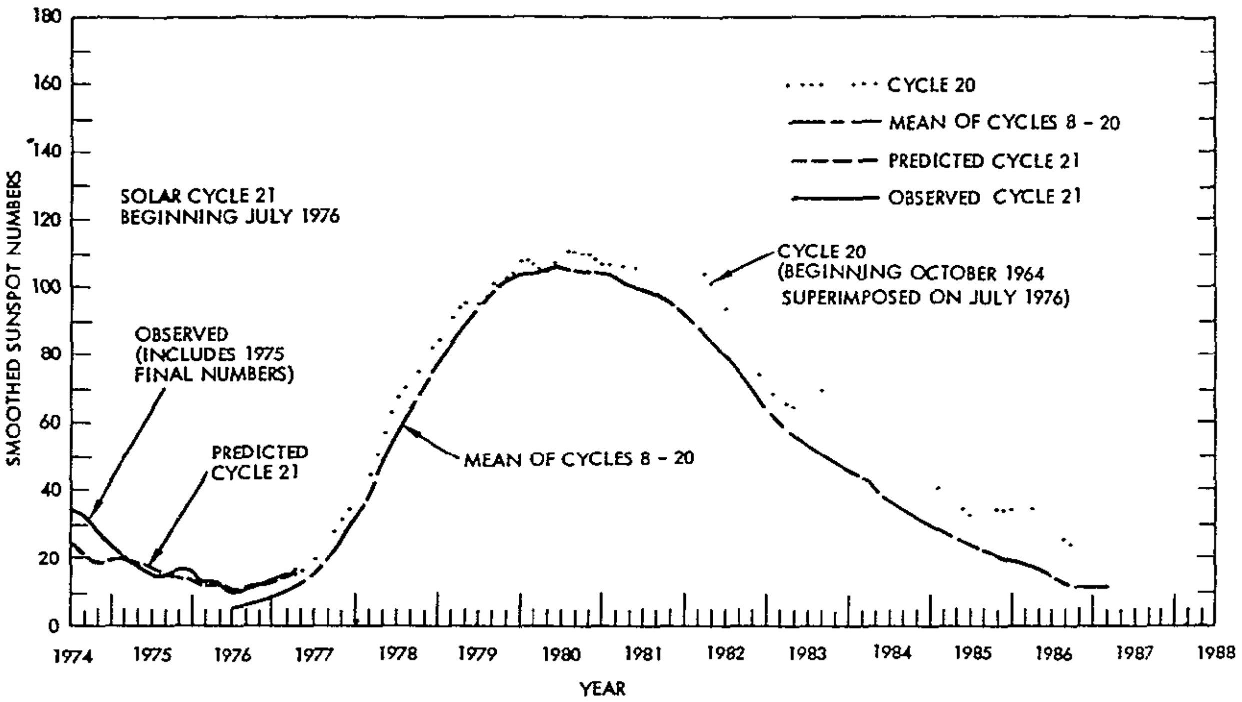
research and development budget of \$1.5M for DOD's photovoltaic conversion program is insufficient to have a significant impact on the development of low cost cells to meet the requirement of the SPS program.

C. NASA'S PHOTOVOLTAIC CONVERSION PROGRAM

The current emphasis of NASA's \$3.4M photovoltaic program includes (1) research on thin silicon solar cells (50 μm) and development of lightweight arrays by JPL, (2) research on single crystal, gallium arsenide cells by NASA Langley, (3) research on silicon cells, encapsulation and radiation resistance by NASA Lewis and (4) SEPS array technology development by NASA MSFC. A 1976 study by NASA to determine the applicability to the SPS program of their current research and development programs in solar cells identified the need for work on thin film gallium arsenide cells (34)

The LDEF program, being managed by NASA Langley, is providing an opportunity for on-orbit testing of promising new solar cells starting in 1980 As shown in Figure 12 the initial LDEF flight will occur in a period of peak solar activity and will provide useful degradation information on candidate solar cells The list of solar cell experiments being flown on the first LDEF mission is shown in Table 26.(38)

The orbit of the initial LDEF payload will be at 225 nautical miles at an inclination of approximately 24.8° so that the radiation environment in this near Earth orbit will be different from the environment to be encountered at GEO The proposed extended LDEF mission (10 years starting in 1982) would be a useful test vehicle for candidate SPS solar cells, particularly if the vehicle were to be placed in a geosynchronous orbit.(39)



Source: ' Reference 40

FIGURE 12 PREDICTED AND OBSERVED SUNSPOT NUMBERS

TABLE 26

U.S. PHOTOVOLTAIC EXPERIMENTS UNDER DEVELOPMENT FOR FIRST LDEF MISSION (1980)

Title	Source	Objectives
Advanced Photovoltaic Experiment	A F. Forestieri and H W Brandhorst, Jr. NASA Lewis Research Center (216) 433-5257	Investigate the effect of space exposure on new solar cell and array materials, evaluate their performances and calibrate solar cells for space use
Solar Array Materials and Assembly Techniques Evaluation	E.N. Costogue Jet Propulsion Laboratory (213) 354-4166	Determine the performance characteristics of space solar array candidate materials and assembly techniques when exposed to space environment that would be used for space power station applications, etc.
Advanced Solar Array Technology	E.M. Gaddy, J.A Bass and S.H. Rosenthal NASA Goddard Space Flight Center (301) 982-5762	Test and qualify advanced solar array components for space-flight for example, filterless coverglasses and high efficiency solar cells
Space Evaluation of Advanced Solar Arrays	A.F Whitaker, C.F. Smith and L.E. Young NASA George C. Marshall Space Flight Center (205) 452-1504	Determine the effects of space on mechanical, electrical and optical properties of candidate lightweight solar array materials such as those needed for a satellite power station, a space station and solar electric propulsion solar arrays

Source: Reference 38

V. KEY PROGRAM ELEMENTS FOR THE DEVELOPMENT OF SPS SOLAR CELL ARRAYS

A. PARAMETERS AFFECTING CHOICE OF SPS ARRAY DESIGN

The parameters which will influence the system level evaluation and the definition of an optimized solar cell array for the SPS include the following

1. Solar energy conversion efficiency
2. Mass and cost per unit area.
3. Rate of degradation when exposed to the space environment
4. Restoration of near beginning of life performance after prolonged exposure to the space environment
5. Adaptability to mass production processes
6. Material resource availability.
7. Energy payback period
8. Packaging and deployment for orbital assembly

Several of these parameters are common to both the SPS solar cell array development program and the terrestrial photovoltaic conversion program. The requirements for the SPS solar cell arrays which differ from the requirements for terrestrial applications of solar cell arrays pertain primarily to mass per unit area, effects of the space environment, and orbital deployment and assembly. The challenge at this stage in the SPS development program is to define system level optimized solar cell/array designs which could be available in sufficient quantity to achieve operational readiness, before the year 2000, so that decisions regarding major commitments to energy conversion technology options could be made during this time period. The most critical need now is to obtain detailed information on various aspects of SPS solar cell array technology, in order that decisions regarding the next steps in the development program can be based on the best available data from system studies, technology advancement efforts, and terrestrial and orbital testing programs

Figure 1 indicates the required buildup of SPS solar cell array production capabilities, starting in 1987, assuming that pilot plant production has been successfully demonstrated prior to that date. This buildup would be carried out in stages so that experience with a complete production line of significant output (about 2 GW) would be obtained prior to construction of the major production capacity and an array inventory would be accumulated over four years to provide the necessary quantity of arrays for the 1995 SPS. To construct the first large-scale solar cell array manufacturing facilities by 1987 will require that the key program elements, defined in the next section, be carried out

B. PROGRAM ELEMENTS FOR THE DEVELOPMENT OF SPS SOLAR CELL ARRAYS

The following key program elements have been identified

1. Basic and applied research in photovoltaic materials
2. Low mass array technology development

3 Interfaces with national photovoltaic conversion program

4 Large-scale array manufacturing technology

5. Terrestrial and orbital testing program

6. Pilot plant operation to produce candidate SPS solar cell arrays.

7 Manufacturing facilities for SPS solar cell arrays.

8. Supporting activities.

The schedule for carrying out the individual elements is shown in Figure 13. This schedule is designed to meet the requirement to construct the first large-scale manufacturing facility by 1987 It will be desirable to continue most of the key program elements beyond the indicated dates as part of an SPS technology advancement program so that new materials and processes can be introduced at various stages of the SPS development program The organizational elements of the SPS solar cell array program are shown in Figure 14 which indicates the close relationship between the national photovoltaic conversion program and the SPS solar cell array development program. Should the decision be taken to proceed with the construction of pilot plant and large-scale manufacturing facilities along the lines indicated, the SPS solar cell array development program could be structured to also meet the terrestrial solar cell requirements up to the process step where a common technology exists, as determined by the choice of the photovoltaic material and the array performance goals. These goals will be different for the terrestrial and the SPS solar cell array The degree of commonality between solar cells developed for both the terrestrial and SPS applications will have to be further evaluated so that design approaches and processes could best meet both of these requirements If common process steps could be developed, this would have beneficial results for the future of photovoltaic applications on Earth and in space The eight program elements are discussed in greater detail in the following sections.

1. Basic and Applied Research in Photovoltaic Materials — Program Element No. 1

The objectives of this program element are to increase the understanding of photovoltaic materials so as to provide a wider choice of solar cell materials for the SPS, and to reduce uncertainties which are now associated with specific candidate materials. Program Element No 1 has six subelements.

a Cell Characterization of Candidate Photovoltaic Materials

Table 27 lists available, advanced and emerging photovoltaic materials which may be applicable to the SPS solar cell arrays Among these materials, only single crystal silicon has been sufficiently characterized so that solar cells of predictable performance characteristics can be produced, e.g , from Czochralski grown single crystals Ribbon or web-grown, single crystal silicon is still in an early development stage, and further work is required to control the process parameters to achieve acceptable efficiencies for a 50 μm silicon solar cell Polycrystalline silicon, although promising, requires further characterization to assess its applicability to SPS solar cells.

Among the advanced photovoltaic materials, gallium arsenide is the most promising for applications in the SPS. However, further work is required to characterize the thin film gallium arsenide solar cells which are being considered for the SPS solar cell arrays. At this time, the

Element No.	Element Title	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
1.0	Basic/Applied Research In Photovoltaic Materials	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●	●	●	●	●
2.0	Lightweight Array Technology Development	▲	▲	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●	●	●
3.0	Interface With National Photovoltaic Conversion Program	▲	▲	▲	▲	▲	▲	▲	▲	▲										
4.0	Large Scale Array Manufacturing Technology					▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●	●	●
5.0	Terrestrial/Orbital Testing Program			▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●	●	●
6.0	Pilot Plant Operation For Candidate SPS Solar Cell/Array								▲	▲	▲	▲	▲	●	●	●	●	●	●	●
7.0	Manufacturing Facilities For SPS Solar Cell/Arrays										▲	▲	▲	▲	▲	▲	▲	▲	▲	
8.0	Supporting Studies	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●

▲ 1995 SPS

● SPS Technology Adv. Program

FIGURE 13 KEY PROGRAM ELEMENTS FOR DEVELOPMENT OF 1995 SPS SOLAR ARRAYS

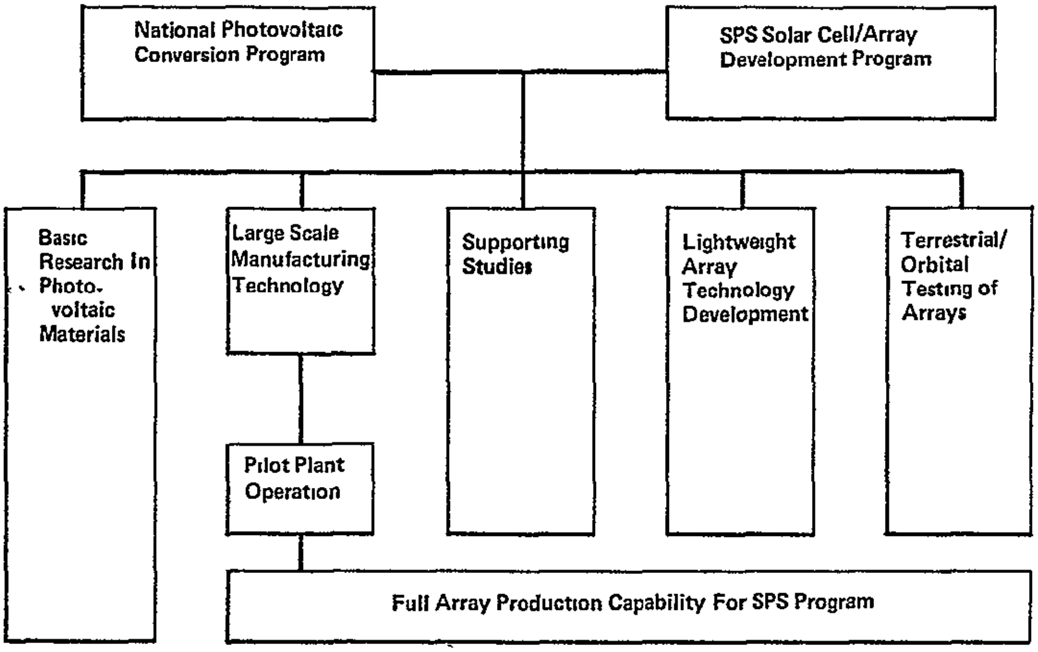


FIGURE 14 ORGANIZATION OF PROGRAM FOR DEVELOPMENT OF SPS ARRAYS

TABLE 27

MEASURED EFFICIENCIES
CANDIDATE PHOTOVOLTAIC MATERIALS

Development Status	Material	Measured Efficiencies	Conditions
Available.	Single Crystal Silicon	15	AM0
Advanced:	GaAlAs/GaAs	17.2	AM0
	Polycrystalline Silicon	15	AM1
	Amorphous Silicon	6	AM1
	CdS	8.6	AM1
Emerging:	Cu_2O	1	AM1
	CdTe	2	AM1
	Multiple Band Gap Cells	(32)	Projected

development of thin film gallium arsenide solar cells has not progressed to the point that cells in sufficient quantities, having desired efficiencies and demonstrated performance characteristics are, likely to be available for orbital testing of SPS arrays in 1980-1985

b Degradation of Solar Cells by the Space Radiation Environment

There has been encouraging progress in the understanding of radiation degradation of solar cells. Results with 50 μm silicon solar cells have indicated that such cells are less susceptible to a reduction in output due to radiation damage than are the thicker silicon cells (15) To optimize the electrical output from the solar cell arrays during prolonged exposure in geosynchronous orbit requires a tradeoff between the thickness of the cover glass, the substrate, and the solar cell material. In addition, the solar cell itself will have to be designed for prolonged exposure to the space environment and all performance and degradation rates will have to be verified by orbital tests dates

c. On-Orbit Solar Cell Efficiency Recovery Technology

Preliminary experiments have indicated that annealing of radiation degraded silicon solar cells by localized, pulsed laser heating has led to a recovery of cell performance Gallium arsenide solar cells carried on a recent NTS-2 satellite which operated at a temperature just over 100°C, indicated limited performance recovery after an initial drop.(41) The development of solar cell efficiency recovery technology by heating methods will have a significant effect on solar cell array performance and the long-term effectiveness of the SPS.

d. Solar Cell Substrate Development

The efforts to develop low mass per unit area arrays utilizing 50 μm, single crystal, silicon solar cells and 5 μm, gallium arsenide solar cells have led to requirements for thin substrates and coverglass materials that can withstand the temperature extremes associated with both thermal annealing of the cells and also orbital temperature transients For example, a 50 μm silicon solar cell could be electrostatically bonded between a 50 μm substrate and a 75 μm coverglass made from borosilicate glass, resulting in an array having a mass per unit area of 406 g/m^2

Sapphire is being proposed as an inverted substrate for thin-film gallium arsenide solar cells, however the 20 μm thick layer may be difficult to mass produce at the desired rate, thickness and cost The interactions between the gallium arsenide solar cell and its substrate also need further study. The mass per unit area for the proposed gallium arsenide array is 252 g/m^2

e. *Large-Scale Manufacturing Compatibility*

Although considerable progress is being made in the development of manufacturing processes for silicon solar cells as part of the national photovoltaic conversion program, several of these processes are not optimum for the production of 50 μm silicon solar cells. The processes now being evaluated to produce thin silicon wafers — for example, multiple band sawing of single crystal silicon boules and subsequent etching — lead to high losses of the semi-conductor grade silicon

There is presently no process developed for mass producing thin-film gallium arsenide solar cells, although promising approaches based on CVD deposition of gallium arsenide have been demonstrated on a laboratory scale. Increasing the rate of production and lowering the costs of the processes required to produce gallium arsenide solar cells with the desired efficiency will require substantial development to reach the state of the art of silicon solar cells.

f. *Integration of Solar Cell Array Design with Deployment Procedures*

Current space solar cell array design approaches and deployment mechanisms, e g., for the SEPS applications, although useful as bench marks, are not directly applicable to the development of the large, lightweight SPS solar cell arrays Development of appropriate solar cell array designs and materials which can meet the low mass, low cost criteria, e.g., 1 kW/kg at a cost of \$50/m^2, will require that the array designs consider packaging and deployment procedures to ensure that the solar cell arrays are not damaged during assembly handling and deployment Specific design approaches will have to be verified in terrestrial and orbital tests to select the most appropriate solar cell array designs and materials

The output of Program Element No. 1 will be a definition of the most suitable photovoltaic material which can meet solar cell array design, production and schedule criteria

2. Solar Cell Array Development — Program Element No 2

The objective of this program element is to analyze, design and test candidate solar cell array configurations applicable to the SPS development program and to verify that the performance and mass per unit area will meet the packaging, handling, deployment, and operational requirements. Program Element No 2 has five subelements

a. *Definitions of Requirements for Orbital Operations*

Candidate solar cell array designs will have to be developed to meet orbital performance requirements, withstand the thermal transients of eclipse periods, and the potential repeated thermal cycling during annealing as well as the effects of plasma charging and micrometeoroid impacts The definition of the operating requirements for the solar cell array is an important first step in the solar cell array development program.

b. *Definitions of Requirements for Packaging, Handling, and Deployment*

The detailed steps and the conditions which will be encountered by the solar cell arrays from the time that they are manufactured to the time of their operational use will have to be defined so that the requirements for packaging, handling, and deployment can be incorporated into the solar cell array designs. For example, it will be necessary to define both the mechanical loads experienced during transportation from the manufacturing facility to the launch site, during launch assembly and during deployment and also the electrical loads experienced during on-orbit integration with adjacent arrays and the power distribution network. Potential harmful effects from prolonged warehousing on Earth will also have to be considered

c. *Verification of Solar Cell Array Performance Parameters*

The performance of solar cell arrays which have been designed to meet the requirements for orbital operations, packaging, handling, and deployment will have to be verified through analyses and experiments performed as part of the terrestrial and orbital testing programs (Program Element No. 5)

d. *Compatibility with Large-Scale Manufacturing Requirements*

The selected solar cell array designs will have to be compatible with a defined large-scale solar cell array manufacturing process to meet array output volume requirements The specific requirements will be established in Program Element No 4, and will be integrated with preferred solar cell array designs.

e. *Definition of Environmental Impacts*

The environmental impacts due to candidate solar cell/array materials and production processes will have to be established. For example, the effect on the environment due to disposal of effluents from the cell manufacturing process, and orbital re-entry of solar cell arrays which may be accidentally released during LEO construction will have to be evaluated

The output of Program Element No 2 will be a definition of the solar cell/array design for the 1995 SPS, so that decision regarding pilot plant construction by 1985 could be made

3. Interfaces With the National Photovoltaic Conversion Program — Program Element No. 3

The objective of this program element is to utilize to the fullest extent the developments of the national photovoltaic conversion program and to integrate the SPS solar cell array development requirements with future program plans Program Element No 3 has five subelements

a. *Supply of Solar Cells for 1980-1985 SPS Solar Cell Array Verification Test Program*

Silicon solar cells which are being developed for terrestrial application will also be available for the 1980-1985 SPS solar cell array test program. Silicon solar cells which are being mass produced to meet terrestrial requirements would have to be modified so that they can be integrated with the SPS solar cell array test articles These modifications will provide information on the applicability of using solar cells developed for terrestrial applications in the SPS solar cell development program

b. *Integration of SPS Solar Cell Array Requirements with National Photovoltaic Conversion Program R&D Efforts*

The results from the SPS solar cell array definition studies, the terrestrial and orbital test results, and the SPS system level economic studies will define designs and requirements for the

SPS solar cell array. These requirements, to the extent that they are already included in the national photovoltaic program, should be integrated with the SPS development program, so that the most effective use of ongoing solar cell development programs could be made. For example, processes up to silicon wafer production could be common to both terrestrial and SPS solar cells The areas where there is no commonality between the manufacturing technology required for terrestrial silicon solar cells and SPS solar cells will indicate where additional R&D efforts will have to be placed, for example, producing 50 μm thick silicon wafers, choice of substrate and coverglass material and array module size.

c. *Identification of Markets for SPS Solar Cell Arrays*

DOE's projections of terrestrial markets for solar cell arrays indicate that, by 1986, about 500 MW of solar cells are to be produced annually These markets, in subsequent years, could be served by SPS solar cells suitably modified to meet the terrestrial application requirements An assessment of developing terrestrial markets for solar cell applications will be required to establish the performance and cost criteria of SPS solar cells for these applications. The results of this assessment will indicate whether SPS solar cells will be competitive in projected terrestrial markets

d *R&D on Advanced and Emerging Photovoltaic Materials*

Increased support for R&D efforts on the most promising thin film solar cell materials such as gallium arsenide will be required if the advanced photovoltaic materials and concomitant production processes are to reach technology readiness by 1985, so that they could be considered for the large-scale production of solar cell/arrays to meet an SPS operational date between 1995 and 2000. Successful development of gallium arsenide solar cells also implies a market growth scenario which at first would supplement and subsequently compete with the markets for single crystal silicon solar cells.

e. *Applicability of DOE/NASA/DOD Photovoltaic R&D Programs — to SPS Solar Cell Array Development*

Continued assessment of the progress being achieved in ongoing photovoltaic development programs will assure that significant developments will be incorporated in the various program elements applicable to the SPS solar cell array development Continuous interchange of data on a programmatic and working level between the SPS solar cell array development program and other photovoltaic programs will have to be accomplished through appropriate formal and informal communications

The output of this program element will be information and data on solar cell materials, manufacturing processes, test programs and markets which will be used for SPS solar cell array development

4. Large Scale Solar Cell Array Manufacturing Technology — Program Element No. 4.

The objectives of this program element are to establish both the technical and economic performance as well as the uncertainties and risks in the large-scale manufacture of the preferred SPS solar cell array design Program Element No 4 has five subelements

a *Definition of Commonality Between Manufacturing Processes for SPS and Terrestrial Solar Cell Arrays*

The manufacturing processes for candidate solar cell array designs will be selected to meet performance and economic requirements and to minimize uncertainties and risks associated with large-scale manufacture of the solar cell arrays. To the fullest extent possible, the manufacturing processes should utilize processes already developed for the national photovoltaic conversion program, so as to maximize the commonality between the terrestrial and the SPS development programs

b *Definition of Resource and Energy Requirements for Selected Processes*

The resource and energy requirements will be established in order to establish constraints which may be imposed upon the selected process, and if necessary, alternate processes will be selected.

c *Definition of Costs and Schedules to Implement Manufacturing Processes*

The costs of the selected manufacturing processes will have to be defined to establish capital investment requirements and to identify sources of capital Schedules for implementing the manufacturing processes will have to meet both technology and economic requirements consistent with the SPS operations goals of 1995 and 2000

d. *Preparation of Environmental Impact Statements*

The environmental impacts of the selected manufacturing processes need to be assessed both for the pilot plant, as well as for all the facilities required to meet SPS solar cell array production requirements.

e. *Determination of Optimum Solar Cell Array Manufacturing Processes*

The results of the tasks carried out in this program element will need to be integrated with SPS system level analyses so that the optimum solar cell array design and manufacturing processes can be defined and a timely commitment made to the construction of the 1985 pilot plant

The output of this task will be a definition of the SPS solar cell array manufacturing processes, production costs, capital investment requirements, environmental impacts, assessments and implementation schedule

5. Terrestrial and Orbital Solar Cell Array Testing Program — Program Element No. 5

The objective of this program element is to evaluate the performance of candidate solar cell materials and solar cell array designs. Program Element No 5 has two subelements.

a *Definition of Requirements for Terrestrial Testing of Solar Cell Arrays*

The definition of the SPS solar cells terrestrial testing program, including the initial screening of proposed cell designs, will be an extension of the requirements placed on solar cells being developed as part of the national photovoltaic conversion program.

The requirements for terrestrial testing of solar cell arrays will include the following.

1. Performance evaluation of candidate solar cell arrays
2. Tests of handling, packaging, shipping and storage survivability/losses.
3. Evaluation of the effects of thermal cycling on solar cell array integrity.
4. Effects of exposure to simulated space environment to verify predicted performance including simulation of radiation and plasma charging effects.
5 Simulation of solar cell array deployment procedures to verify scenarios for man/machine interface.
6. Simulation of worst case accidents involving solar cell arrays at various stages in the production, transportation, deployment and assembly to establish potential environmental impacts and safety hazards

b Definition of Requirements for Orbital Testing of Solar Cell Arrays

The requirements for orbital testing of solar cell arrays will include the following·

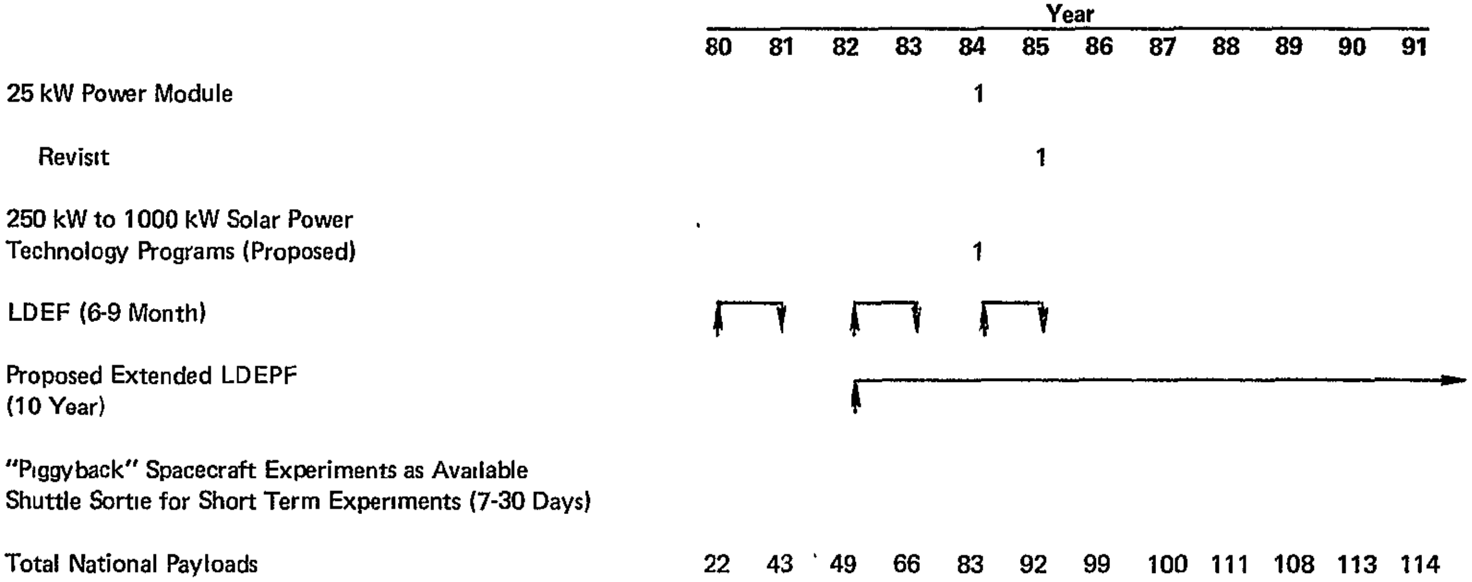
1. Performance evaluation of candidate solar cell arrays.
2. Evaluation of degradation effects caused by prolonged exposure to the space environment to establish confidence in performance predictions as a function of time
3 Evaluation of handling, deployment and assembly procedures and manned operations to avoid unsafe conditions
4 Evaluation of unexpected effects caused by space environment phenomena which cannot be predicted or duplicated in a terrestrial test program.

Figure 15 summarizes the currently defined opportunities for orbital testing of the solar cell arrays Although the 25 kW power module will not use technology applicable to the SPS solar cell arrays, experimental data of value to the SPS solar cell array development program could be obtained A 250 kW power module would be able to utilize SPS solar cell array designs and provide significant new information.

Starting in 1980, the Long Duration Exposure Facility (LDEF) will provide a number of opportunities for experiments with a 6 to 9 months duration on orbit Planned LDEF missions already include the following photovoltaic experiments

- Advanced photovoltaic experiments (APEX) being conducted by NASA Lewis Research Center in which about 140 solar cells obtained from many sources are to be tested
- Evaluation of advanced solar cell arrays being developed by NASA MSFC during passive tests of the materials in orbit.
- Evaluation of solar cells and second surface mirrors with and without conductive coatings by MBB (Germany).

Further experiments for 1982 and 1984 LDEF missions are currently being defined. The LDEF Program Office at NASA Langley Research Center will determine the interest of potential



Source: Reference 42

FIGURE 15 OPPORTUNITIES FOR ORBITAL TESTING OF SPS SOLAR CELL ARRAYS investigators in an extended LDEF mission (10 years), to test materials and components which are being proposed for missions extending from 20 to 30 years At present, a 1982 launch of such an extended LDEF mission is being considered.

Shuttle sortie flights for short term experiments of up to 30 days in duration will be possible in the period from 1980-1985. In addition, piggy-back spacecraft experiments may be available to meet specific orbital test objectives. An extended LDEF mission in GEO will be useful to evaluate solar cell arrays being exposed in this orbit for long periods

The output of these tasks will provide the data on which selection of the preferred solar cell array design can be based so that by 1985, a commitment to pilot plant production could be made.

6. Evaluation of Pilot Plant Operation — Program Element No 6

The objective of this program element is to evaluate the technology and the economics of large scale solar cell array manufacturing processes in a pilot plant operation before making a major financial commitment to a full scale manufacturing facility. Program Element No 6 has three subelements

a Definition of Requirements for Pilot Plant

The output from Program Element No 4 — Large Scale Manufacturing Technology, will be used to establish the requirements for the pilot plant operation.

b Design and Construction of Pilot Plant

The design and construction of the pilot plant to produce the preferred solar cell arrays will be based on the information developed in preceding program elements

c Operation of Pilot Plant

The operation of the Pilot Plant will be evaluated and documented so that all performance and cost data can be analyzed in detail Modifications, if required, will be made to the pilot plant operation to insure that the decision regarding a commitment to a full scale manufacturing facility can be based on demonstrated performance and costs of all required manufacturing processes, starting with input materials and ending with the shipment of the packaged solar cell arrays produced in the pilot plant.

The output of this program element will be technical and economic data on which the design of the first large scale solar cell array manufacturing facility will be based

7. Manufacturing Facilities for SPS Solar Cell Arrays — Program Element No. 7

The objective of this program element is to construct the manufacturing facilities to produce solar cell arrays to meet the requirements of the SPS launch and deployment schedule. Program Element No. 7 has three subelements.

a -Construction of Manufacturing Facilities

Based on the output of the preceding program elements and the experience obtained with the operation of pilot plant facilities, the location, design and construction of one or more optimum sized manufacturing facilities will be accomplished The location of the facilities will be influenced by the logistics of materials resources and finished solar cell arrays, availability of land, electric power, demographic considerations, and environmental effects.

b Construction of Solar Cell Array Warehouse

The location, design, and construction of warehouses to store the completed solar cell arrays will have to meet a requirement for inventory storage which is consistent with the deployment and assembly schedule of the first and subsequent SPS. Warehouse locations will most likely be in proximity to the launch sites and the environmental conditions inside the warehouses during storage will depend on the requirements of the solar cell array materials inside their storage containers.

c Establishment of Required Industrial Infrastructure

The location, design, and construction of the manufacturing facilities will have to be coordinated with the network of industrial suppliers and the necessary industrial infrastructure created so as to meet the manufacturing schedules. This will require setting up a network of reliable suppliers which will form an integral part of the production sequence and which have to be in place at the same time that the manufacturing facilities begin to produce the solar cell arrays (1991).

d. Detailed Documentation and Performance Monitoring

At every stage during the construction of the manufacturing facilities, detailed documentation will be required to assure the financial investors that the solar cell array production schedule and cost goals are being met. This documentation will also serve as a reference for the construction of the major production facilities starting in 1992.

The output of this program element will be the manufacturing facilities to supply the solar cell arrays to meet the SPS program schedule

8. Supporting Studies — Program Element No. 8

The objective of this program element is to assess all significant factors which may impact the manufacture of the SPS solar cell arrays Program Element No. 8 has two subelements.

a Environmental Impact Studies

The magnitude of the SPS solar cell array development and production program will require that environmental studies be performed so that the required environmental impact statements for the facilities will be available on schedule. These studies will be concerned with an assessment of the potential for environmental modifications, the use of natural resources, potential effects on human health and safety, land use, energy requirements, social factors, effects on the local and national economy, and any intangible effects such as aesthetics and the use of alternate approaches.

b Commercialization Studies

The impact of the large scale manufacture of SPS solar cell arrays on several industry sectors will be significant. An assessment of the diversion of materials and capital resources from other industrial activities will have to be made to assure that the buildup of the industrial infrastructure can be accomplished with a maximum positive effect on labor and industry. An input-output model and similar analytical techniques will be needed to establish the impacts on industry and the requirements for labor, financial investments, and any constraints which may be imposed by regulatory and market factors. An assessment of potential markets for SPS solar cell arrays for other space missions and terrestrial applications will indicate other benefits of a commitment to the large scale manufacture of SPS solar cell arrays

The output of this task will identify the actions required to permit a commitment to the large scale manufacture of SPS solar cell arrays to be made by 1987.

C. PROPOSED ALLOCATION OF 1980-1985 DEVELOPMENT FUNDS FOR SPS SOLAR CELLS/ARRAYS

Table 28 shows a recommended percentage allocation of 1980-1985 development funds for the SPS solar cells/arrays between four key program elements, as well as a brief summary of the main objectives to be accomplished by each of the elements. The majority of the funding has been allocated to the terrestrial and orbital testing activities which are necessary to verify the design performance of the arrays prior to making a commitment to a pilot plant by 1985 and to the first large scale production facilities by 1987. No funding has been allocated to basic research and development in photovoltaic materials as this effort is being supported by the National Photovoltaic Conversion Program Table 29 shows a detailed percentage breakdown of the total funding for the development of the SPS solar cell arrays into an annual budget for each of the program elements over the 1980-1985 time period

TABLE 28

RECOMMENDED (1980-1985) FUNDING ALLOCATIONS FOR SPS PHOTOVOLTAIC DEVELOPMENT PROGRAM

Program Element No.	Task Definition	Percentage of Total Development Funding	Comments
2.0	Design Definition of Low Mass Array(s) for SPS	20%	*Factors in Design Definition to Include* • Low Mass/Unit Area • Low Cost • Compatibility with Large Scale Manufacturing Processes • On Orbit Development and Assembly Procedures • Terrestrial Handling and Packaging • Thermal Cycling
3.0	Evaluation of Applicability of Silicon Terrestrial Solar Cells for Space Use in 1980-1985 Testing Program	10%	*Determine if Cells Produced to Satisfy Low $/W Terrestrial Goals can be Used or Economically Modified to Satisfy Goals of SPS Program* • Low Mass/Unit Area • High Efficiency (> 15%) • Low Cost (~$30-$50/m² for assembled arrays) • High Process Yields with Thin Cells, e.g., Metallization Interconnections and Encapsulation in Low Mass Arrays • Sensitivity to Radiation Damage • Sensitivity to Annealing

TABLE 28 (Continued)

Program Element No.	Task Definition	Percentage of Total Development Funding	Comments
4.0	Definition of Large Scale Manufacturing Processes	20%	*Definition and Verification of Manufacturing Process for Candidate SPS Array* • Define Processes for Large ($\geqslant$ 2 GW/Year) Manufacturing Rates • Evaluate Technical and Economic Feasibility of Recovering Lost Materials, e.g., Silicon in Etching Bath, Cleaning Fluids • Determine Process Yields, Energy and Material Requirements • Define Required Industry Infrastructure, e g., borosilicate glass source and price for required quantities • Evaluate Economics of Process to Determine Price of Final Array
5.0	Terrestrial and Orbital Testing	50%	*Terrestrial Screening of Candidate Array Designs* • η Measurements • 1 MeV Degradation Rates • Recovery of Degraded Performance by Annealing • Thermal Cycling • Testing of Handling Procedures • Evaluate Failure Rates *In-Situ Testing of Most Promising Array Designs* • η Measurements • Radiation Degradation Rates • Recovery of Degraded Performance by Annealing • Testing of Deployment and Assembly Procedures • Thermal Cycling • Safety Procedures • Evaluate Failure Rates

TABLE 29

SCHEDULE FOR ALLOCATION OF 1980-1985 NASA FUNDING FOR SPS PHOTOVOLTAIC DEVELOPMENT PROGRAM[1]

Program Element No.	Task Definition	% Allocation of Total Budget Total	1980	1981	1982	1983	1984	1985
2.0	Array Definition	20	5	10	2	1	1	1
3 0	Evaluation of Terrestrial silicon cells	10	3	5	2	0	0	0
4.0	Manufacturing Processes[2]	20	1	2	4	8	5	0
5.0	Testing	50	5	10	20	5	5	5
	Totals	100	14	27	28	14	11	6

1. Basic research in photovoltaic materials to be conducted by DOE
2. Does not include funding for a pilot plant in 1985

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REFERENCES

1 Boeing Aerospace Company, "Solar Power Satellite System Definition Study — Part III" D180-24071-1, prepared for NASA JSC under Contract NAS9-15196. March 1978.

2 NASA Marshall Space Flight Center, "Preliminary Baseline SPS Concept Recommendations to DOE/NASA" presentation at NASA Headquarters, Washington, D C , January 24, 1978

3 L.P. Hunt, V D Dosaj and J R. McCormick, J.R , "Solar Silicon via, Improved and Expanded Metallurgical Silicon Technology," — Quarterly Report No 1 prepared by Dow Corning Corporation under JPL Contract No 954559, ERDA/JPL-954559-761, October 1976

4 Private communication with L P. Hunt, Dow Corning Corporation

5 U.S Department of Energy, "Photovoltaics Program — Program Summary January 1978," DOT/ET-0019/1.

6 L.P Hunt, "Total Energy Use in the Production of Silicon Solar Cells from Raw Material to Finished Product," The Conference Record of the Twelfth IEEE Photovoltaic Specialists Conference — 1976, p 347-352

7 H J Hovel, "Semiconductors and Semimetals Volume 11 — Solar Cells," Academic Press, N Y 1975.

8. DOE/JPL,'s Low-Cost Silicon Solar Array Project, "First Annual Report for the Period January 1975 — March 1976," ERDA/JPL-1012-76/5, August 1976

9. DOE/JPL, Low-Cost Silicon Solar Array Project, "Eighth Project Integration Meeting Handout" 5101-47, December 7-8, 1977, p. 56

10 Ibid, p 47

11. R.G Rhodes, "Imperfections and Active Centers in Semiconductors," Macmillan, New York, 1964

12 R. K Willardson and W P. Allred, "Symposium on GaAs (Proceedings) Reading, p. 35 Institute of Physics and Physical Society, London, 1966.

13 DOE/JPL, Low Cost Silicon Solar Array Project, "Eighth Project Integration Meeting Handout," 5101-47, December 7-8, 1977, p. 50

14. J Lindmayer and C. Y Wrigley, "Development of a High Efficiency Thin Silicon Solar Cell" Final Report prepared by Solarex Corporation for JPL under Contract No. 954290, Report No. SX/105/F, September, 1977

15. C. F Gay, "Development of High Efficiency, Radiation Tolerant Thin Silicon Solar Cells" Final Report prepared by Spectrolab Inc., for JPL under Contract No. 954600, October 1977

16 Chemical Economics Handbook, Manual of Current Indicators, Stanford Research Institute, Menlo Park, California, Supplemental Data, December 1977, p. 246.

17 B G. Carbajal, "Automated Array Assembly Task — Phase I," Final Report prepared by Texas Instruments Incorporated for JPL under Contract No. 954405, Texas Instruments Report No. 03-77-44, October 1977.

18 Private communications with A. R Kirkpatrick, Spire Corporation

19. A R Kirkpatrick, J A Minnucci, T.S Shaughnessy, "Silicon Solar Cells by Ion Implementation and Pulsed Energy Processing," The Conference Record of the Twelfth IEEE Photovoltaic Specialists Conference — 1976, p 299-302

20. P.R Younger, W S. Kreisman, A R Kirkpatrick, "Integral Glass Encapsulation for Solar Arrays," Interim Report No. 1 prepared by Spire Corporation for JPL under Contract No 954521 DOE/JPL-954521-77/3, November 1977.

21. Private communications with M Slifkin, Corning Glass

22 M G Gandel and P.A Dillard, "Assessment of Large-Scale Photovoltaic Materials Production," Task Report No 15 prepared by Lockheed Missiles and Space Company, Inc for Industrial Environmental Research Laboratory, EPA, under Contract No EPA 68-02-1331, July 1976, p 56.

23. Ibid., p. 52

24 R D Dupuis, P.D. Dapkus, R.D. Yingling, L A Moudy, "High-Efficiency GaAlAs/GaAs Heterostructure Solar Cells Crown by Metalorganic Chemical Vapor Deposition," Applied Physics Letters, Vol 31, No 3, August 1977, p 201-203.

25. Private communication with H. LaBelle, Tyco's Saphikon Division

26 DOE/JPL Low-Cost Silicon Solar Array Project, "Project Quarterly Report-5 for the period April 1977-June 1977 "

27. Mineral Facts and Problems, 1975 Edition, Staff Bureau of Mines, United States Department of the Interior, p. 28-29.

28. Private communication with T. Howitt, Corning Glass Works.

29 Battelle Columbus Laboratories, "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing," Bureau of Mines Report OFR 96-75 (NTIS Report PB-246 357) September 1975.

30. L P Hunt, "Total Energy Use in the Production of Silicon Solar Cells from Raw Material to Finished Product," The Conference Record of the Twelfth IEEE Photovoltaic Specialists Conference — 1976, p 347-352

31 Office of Management and Budget-Statistical Policy Division, "Standard Industrial Classification Manual — 1972," U.S. Government Printing Office, Catalog No. PREX 2 6/2 IN, 27/972

32 Private communications with personnel in arsenic producing company.

33 U S Department of Energy, "Photovoltaic Program — Program Summary, January 1978," DOT/ET-0019/1

34 Private communications with J Mullin, NASA Headquarters

35 Private communications with J. Wise, WPAFB

36 U S. Department of Energy, "Proceedings of the Photovoltaic Program Semi-Annual Review, Advanced Materials R&D Branch, October 4-6, 1977, Golden, Colorado " CONF — 771051

37 "Photovoltaic Power Systems Market Identification and Analysis," Report prepared by BDM Corporation for DOE under Contract No. EG-77-C-01-2533.

38 Data provided by W Kinard at NASA Langley Research Center, LDEF Program Manager

39 Private communication with W Kinard, NASA Langley Research Center, LDEF Program Manager.

40 H Y Tada, and J.R. Carter, Jr , "Solar Cell Radiation Handbook," Prepared by TRW Systems Group for JPL under Contract No NAS 7-100, JPL Publication 77-56, November 1977, p. 5-12

41 Private communication with R Statler of the Naval Research Laboratory, Washington, D C

42 "NASA STS MISSION MODEL," JSC-13829, October 1977

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