NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Considerations With Respect to the Design of Solar Photovoltaic Power Systems for Terrestrial Applications

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Preface

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

Foreword

The phenomenal growth of power consumption has been well documented as has the environmental impact associated with satisfying these growth requirements. Public concern is being expressed in increasingly intense terms with respect not only to the obvious pollution caused by conventional electrical power generation but also to nuclear reactor power generation and its inherent safety, waste disposal, fuel, and thermal pollution problems. The insignificant effort expended to develop totally nonpolluting terrestrial photovoltaic power systems in comparison with that being expended in the development of conventional and nuclear power generation is a matter of public record. One reason for this inequity is the lack of large economic interests promoting photovoltaic systems, and another is the rather narrow, immediate, and simplistic "cost" criterion presently used to determine feasibility.

While the purpose of this report is to outline what must be done to achieve significant improvements of the economics associated with fabrication of terrestrial solar photovoltaic arrays, it would be misleading not to admit to the possibility that such a system, even though cost-optimized in the manner suggested, will not be economically competitive with existing electrical power generation systems, at least for the near-term, when the costs of extracting fuels and of the required pollution controls are not exorbitant. It is not inappropriate, however, even in the near-term, to consider that cost criteria are not presently tolerated as justification for the sale or use of a potentially hazardous product (e.g., pharmaceuticals, electronic devices, transportation equipment, etc.), and therefore, one should not fail to explore fully a totally benign but possibly more expensive source of electrical power.

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Abstract

The various factors involved in the development of solar photovoltaic power systems for terrestrial application are discussed. The discussion covers the trade-offs, compromises, and optimization studies which must be performed in order to develop a viable terrestrial solar array system. It is concluded that the technology now exists for the fabrication of terrestrial solar arrays but that the economics are prohibitive. Various approaches to cost reduction are presented, and the general requirements for materials and processes to be used are delineated.

Considerations With Respect to the Design of Solar Photovoltaic Power Systems for Terrestrial Applications

I. Introduction

Basically, the solar cell is a solid-state device which operates at ambient temperature and converts solar energy directly to electrical energy. It is totally nonpolluting, has no moving parts, does not consume fuel of any kind, and does not require heat (in fact, heat decreases its efficiency). It has operated for many years in the hostile environment of space, degraded only by the radiation belts which surround the earth, and has been the backbone of the NASA Unmanned Space Program.

Solar photovoltaics might well be the most significant sociological contribution of the entire space program, if it can be successfully translated to terrestrial use. This is not at all unreasonable. The solar cells are made of silicon, one of the most abundant elements on earth. The major roadblock is not one of technology, since solar arrays can presently be made to operate on the earth's surface, but rather one of economics. The costs of fabrication of a solar array are prohibitively high for wide-scale terrestrial use at this time. However, one must bear in mind that the primary emphasis has been on low volume, high reliability, and high efficiency, as dictated by the requirements of the space programs for which the solar arrays are designed. A change in philosophy, the removal of the severe constraints associated with space use, can result in significant cost reductions.

If one considers the use of solar arrays as a primary power source, it is necessary to provide means of storing the electrical power for periods of time when there is no solar energy available (such as night time and periods of inclement weather). However, if the solar array is to be used only as a means of *auxiliary* electrical power, storage considerations become unnecessary. That is to say, if one agrees to use the power of the solar array as it is generated, to whatever degree it is generated, and to supplement it with power from conventional sources as required, storage systems are not required. This approach would conserve natural fuel resources and reduce the pollutants resulting from the conversion of fuel or nuclear sources to electrical power. It would not supersede or replace, but would supplement. In any case, this report treats only the photovoltaic aspects of the problem, independently of storage and power regulation and distribution. Such a program could directly involve many facets of our present-day space program, including personnel, equipment, and analytical techniques. It would lead to an improved environment and reduce the demands upon natural resources. These very significant potential advantages appear to warrant a far greater investment philosophically and economically than is being made at the present time.

II. General Requirements

The general optimization requirements for low-cost terrestrial photovoltaic power systems are:

- High-volume production
- Automation of processes
- Minimum rejects
- Compatibility with other materials/processing requirements
- Minimum use of specialized equipment
- Maximum process simplicity
- Maximum allowable tolerances
- Maximum rework capability
- Maximum reliability for anticipated environments
- Minimum material/equipment costs
- Maximum material/equipment utilization
- Maximum overall conversion efficiency in anticipated environments

These requirements are obvious ones for the production of any low-cost item. High-volume production makes it feasible to invest more effort and funds in the automation of processes which are at present nonautomated or only semi-automated because of the small quantity requirements of the space program. Maximizing allowable tolerances would result in fewer rejects and less specialized processing than is required for the very tight tolerances used in the space program. The anticipated environments, including insolation as a function of time and geographical location, for earth-surface use of photovoltaic systems have not been completely defined and should be one of the first objectives of any terrestrial solar power program. Some aspects of the environment, such as the rates and limits of temperature excursions, will be much less stringent for terrestrial than for space applications, and the radiation problem is nonexistent. However, wind loading, abrasion by particles such as dust and sand, the effects of inclement weather, etc., present new boundary conditions. An advantage to be found in the terrestrial photovoltaic systems is the fact that rework, maintenance, and replacement become possible, which is not the case with spacecraft-associated photovoltaic systems once they have been launched. Thus, a new balance must be struck among cost, reliability, and overall conversion efficiency for the terrestrial solar array.

III. Areas of Investigation

A summary of the investigations required to determine the applicability of solar photovoltaics for terrestrial power systems is presented in Table 1. The items listed in the table are discussed in more detail below.

A. Solar Cell Development

Table 2 summarizes the various aspects of a program for solar cell development described in the following paragraphs.

1. Starting material. It is the author's opinion that a major emphasis should be placed on the use of silicon as the material from which the solar cells are fabricated. This would make efficient use of the multimillion-dollar effort already expended by the semiconductor industry in general for development of silicon as a semiconductor device material. The use of single crystalline silicon ingots would be considered as a baseline since most cells presently utilize this form of silicon, and hence at this time it appears to offer the greatest economic advantage. Polycrystalline silicon should be considered from the point of view of reduced material costs, keeping in mind, however, that in general, cell efficiencies can be expected to be lower than for the single-crystalline silicon ingots (Ref. 1). An optimization study is required with respect to the higher material costs and cell efficiency associated with single-crystalline silicon, and the lower material cost and cell efficiencies associated with polycrystalline silicon. This, of course, would be dependent upon the ratio of material- and fabrication-associated costs for the photovoltaic array as installed. The investigation of other types of starting material should be undertaken if they have the potential to be more economically advantageous.*

In the case of rectangular cells, the silicon ingots must be cut into blocks and subsequently sliced to size. This results in considerable material waste due to the number of saw cuts required and to the amount of silicon which cannot be made into rectangles (the silicon ingot having basically a cylindrical geometry). The waste would be considerably reduced if the disc-shaped cell were used, since it would be unnecessary to cut the ingot into the

*This does not necessarily mean that the cell itself would have to be less expensive but rather that the resultant system would be more economical. Thus, a photovoltaic material which could be deposited directly on a substrate with suitable interconnections could present economic advantages, even if the material itself were more expensive.

Table 1. Investigations summary

Area of investigation	Specific considerations
Solar cell development	*Starting material*
	Cell configuration
	Contacts
	Grid configuration
	Processing
Solar concentrators	Cost
	Compatibility with array design
	Temperature effects
	Environmental degradation
	Effect of concentrator design on overall system efficiency
Cell interconnection	*Materials*
	Configuration
	Techniques
	Cell matching requirements
Array fabrication	Substrate
	Insulation
	Protection (environmental)
	Configuration
	Laydown techniques and materials
	Wiring
	Cell/module replacement
Sample array fabrication	*Cell fabrication*
	Submodule fabrication
	Substrate fabrication
	Submodule laydown and interconnect
	Transparent protective surface
	Installation of concentrators (if applicable)
Testing and evaluation	Cell tests (optimization of design) (lab)
	Module tests—electrical and mechanical (lab)
	Array tests—electrical and mechanical (lab)
	Array tests—extended-time in natural sunlight—continuous electrical
	Array tests—post-extended-time—electrical and mechanical (lab)

Table 2. Solar cell development

Area of investigation	Specific considerations
Starting material	Single-crystalline Si ingots
	Polycrystalline Si ingots
	Single-crystalline Si ribbon
	Thin film (e.g., CdS, CdTe, GaAs)
Cell configuration	Large-area rectangle
	Large-area disc
	Thickness
Contacts	Low electrical resistance
	Mechanical compatibility
	With respect to cell interface
	With respect to interconnection requirements
	With respect to environment
Grid configuration	Contact location and design
	Number and dimensions of grid lines
	With concentrators
	Without concentrators
Processing	Blank sizing
	Rectangular
	Disk shape
	Thickness
Junction diffusion	Blank preparation
	Diffusion
	Source
	Time
	Temperature
	Carrier gas
	Loading–unloading
	Batch size/continuous belt
	Post-diffusion treatment
Contact techniques	(See Contacts above.)
Antireflective coating	Stability
	Batch size
	Efficiency
Junction cleanup	Etching
	Abrading
Measurement	Minimum requirements for necessary cell characterization
	Light source
	Associated electrical equipment/display

blocks and a greater portion of the silicon would actually be utilized. Even with the disc-shaped cell, however, the ingot would still have to be sliced to the proper thickness and possibly ground to provide uniform circumference. An advantage could be obtained if silicon could be grown in a ribbon shape inherently having the proper thickness for cell fabrication, and a development program is presently being funded by NASA/JPL to determine the feasibility of such a silicon growth technique.** It is also recommended that effort be continued to develop a usable thin-film solar cell, since this type of cell has the potential of being a very low-cost device amenable to continuous-belt process techniques. Past efforts on thin-film CdS, CdTe, and GaAs solar cell development, however, have met with only limited success (Refs. 2–9).

**"Development of Thick Film Silicon Growth Techniques," JPL contract No. 953365 with Tyco Laboratories, Inc., Waltham, Mass. Contract initiated on Feb. 17, 1972.

2. ***Cell configuration.*** The cell configuration should be such that the largest cell area commensurate with

economic feasibility is used to minimize the number of interconnections between cells required. Large-area rectangles have a very good packing factor, while large-area discs make better use of the natural cylindrical configuration of the silicon ingot and are amenable to utilization in conjunction with simple conical solar concentrators (Ref. 10). The thickness of the cell will be a compromise between breakage loss associated with handling and fabrication of thin cells and the larger amount of silicon required for a thicker cell. Of secondary consideration are the lighter weight of a thin cell versus the somewhat lower conversion efficiency.

3. Contacts. The cell contacts must present low electrical resistance. This means that the contact material should be highly electrically conductive and should present a low-resistance ohmic contact to the silicon material. Moreover, the contact material must be mechanically compatible with respect to the cell surface so that the temperature excursions and other environmental aspects encountered do not degrade the contact, either mechanically or electrically. A cell contact-interconnection system must also be developed which is simple and economical and, again, which will not degrade as a result of exposure to the expected environments. Thus, the contact must be compatible with a low-cost, reliable interconnection system. A compromise will be made between the cost of the contact-interconnection materials and system and their efficiency and reliability. As with other aspects involved in a terrestrial power system, the accessibility of the system for repair and rework during operation will render the reliability requirements less stringent than would be the case with space systems, which cannot tolerate failures during operation since there is no replacement capability.

4. Grid configuration. The location and design of the electrical contacts should be optimized for simplicity of interconnection from one cell to the other, reliability, and cell efficiency. The number and dimensions of the grid lines used on the cell active surface to reduce series resistance should be optimized for the range of solar intensities anticipated. Since the effects of internal series resistance become more detrimental as solar intensities are increased, particular attention must be paid to the design (number, size, electrical conductivity, and configuration) of grid lines for cells to be used in conjunction with solar concentrators. There is a compromise to be considered between the number and dimensions of the grid lines needed to decrease the cell series resistance and the fact that these grid lines decrease the cell active area, and hence the light-generated current (Ref. 10). Decreased series resistance can also be obtained through an increase in cell junction depth, but here, too, a compromise must be made between the decrease in series resistance and the decrease in the spectral response of the cell, which again reduces the light-generated current. (Ref. 10).

5. Processing. Techniques of inexpensive automated cell-blank sizing must be developed. Significant progress has already been made by solar cell vendors, who have replaced the diamond wheel previously used for blank sizing with automated grit cutters. This has allowed the fabrication of very large-area solar cell blanks with minimal operator dependency. The consideration of the shape and thickness of the blanks has already been discussed above.

6. Junction diffusion. A low-cost automated process for pre-diffusion blank preparation is required. While pre-diffusion etching of the blanks to remove surface damage is a relatively simple task, in the interest of economy it would be desirable if the blank sizing operation were such that an etching operation would not be required at all, that is, a sizing technique in which surface damage is minimized. The junction diffusion operation itself should be optimized to obtain the greatest utilization of the diffusion furnaces and minimize operator requirements. Basically, this means diffusion of very large batches of cells and automated loading and unloading or continuous-belt diffusion techniques. Post-diffusion treatments should also be minimized and make use of large-batch or continuous-belt techniques. Other means of forming the P/N junction (e.g. epitaxial growth) should be investigated as to the cost relative to the diffusion process, including the requirements for minimized operator dependency, large-batch/continuous-belt capability, etc.

7. Contact techniques. The requirements for the solar cell contacts are given in Section 3 above. As a baseline, it is recommended that the state-of-the-art evaporation techniques presently used be continued and improved, with major reductions in tolerances and cosmetic requirements. While evaporation techniques are amenable to very large-scale operations and present good economy when properly optimized for large quantities, it is recommended that other low-cost contact deposition techniques, such as silk screening or plating, be investigated.

8. Antireflective coating. In order to achieve maximum efficiency, space-type solar cells make use of evaporated silicon monoxide antireflective coatings. (Polished silicon reflects about 30% of the usable photons.) At the present time, this represents a considerable expense in equipment and man-hours (cleaning, loading, evaporating, unloading, etc.). The junction diffusion processes commonly used, however, result in a natural phosphorus glass deposition on the cell which is removed by etching in hydrofluoric acid prior to silicon monoxide coating. While the phosphorus glass diffusion-induced layer is not optimized for minimum reflection of usable photons, it does provide a reasonably good antireflective coating. Therefore, a study is required to determine the costs associated with large-scale evaporation of silicon monoxide onto the cell surface and those associated with the loss of power due to the use of the diffusion-induced phosphorus glass as the antireflective coating. If the latter appears to result in lower cost per watt, the silicon monoxide evaporation should be eliminated.

9. Junction cleanup. At the present time, the diffused layer is removed from the backside of the cell to expose the base layer, and the junction edges are etched to reduce leakage paths across the cell edges. This technique has been semiautomated by the solar cell manufacturers and could be completely automated with a reasonable effort. It is recommended that, as a baseline, the etching technique be continued for terrestrial cells; however, techniques such as sandblasting or abrading should be investigated to perhaps obtain even lower-cost processing.

10. Measurement. Measurement and characterization of space-type solar cells, modules, and arrays represent a significant portion of the system cost. These requirements can be greatly reduced in the case of terrestrial cells, and the minimum requirements necessary for cell, module, and array characterization for low-cost terrestrial solar power systems should be determined. Most measurements are now made under expensive solar simulator light towers. Lower-cost tungsten lighthouses (using, for example, automobile headlamps), although not spectrally matching natural sunlight, could probably be employed quite effectively. Furthermore, additional use should be made of automated electronic classification systems. Automated loading-unloading-sorting equipment would present further cost advantages.

B. Solar Concentrators

The general considerations to be investigated with respect to the use of solar concentrators are outlined in Table 3 and discussed below.

1. Cost. The use of inexpensive solar concentrators may present a considerable cost advantage for a terrestrial solar array (Refs. 1, 10, 11, and 12). It is therefore recommended that the applicability of such concentrators to terrestrial solar arrays be thoroughly investigated. The compromise involved is basically the relationship between the cost of the solar concentrators, operational requirements (e.g., requirements for orientation, etc.), installation, and the cost of the unconcentrated cells required to obtain equivalent power. In order to be competitive, the materials and forming methods used in the fabrication of the solar concentrators must be minimized. It appears likely that aluminum sheet, which is relatively inexpensive and can be formed readily, might be used successfully. Other considerations are the stability of the concentrator and its overall collection efficiency, which involves the configuration, reflectivity, orientation requirements, and interaction with the solar array.

Table 3. Solar concentrators

Area of investigation	Specific considerations
Cost	Stationary Oriented Materials Forming methods Stability Collection efficiency
Compatibility with array design	Installation Removal/replacement Maintenance Wind loading Effects on array components/materials
Temperature effects	Cell heating (effects on efficiency) Heating of array components (stability)
Environmental degradation	Surfaces Reflectivity Dust/dirt/sand Cleaning requirements Effects on other components/materials Mechanisms (if applicable)
Effect of concentrator design on overall system efficiency	Average power output with concentrators Stationary Oriented Average power output without concentrators Stationary Oriented

2. Compatibility with array design. The installation of solar concentrators must be simple, rapid, and relatively operator-independent. Moreover, removal, replacement, and maintenance of the concentrator should be simple enough so that it can be accomplished on-site. Other maintenance required as a result of concentrator installation should be minimal. Adverse effects of the environment such as wind loading, sand and dust abrasion, etc., should be minimized, as should the adverse effects of the solar concentrators on the other array components and materials.

3. *Temperature effects.* Silicon solar cells exhibit a decrease in power output as the cells are heated (approx. 0.3%/°C) (Ref. 13). This must be considered when using solar concentrators since, while the concentrators increase the number of photons available for generating electrical power, they also increase the cell heating. A compromise must be made in the design of the solar concentrator between the increase in light-generated current and the loss in power resulting from increased heating. The configuration of the concentrator and the reflectivity of the material from which it is fabricated will determine the concentration ratio, the solar cell electrical characteristics, and the cell heating for a given solar input. One might allow a spacing between the concentrator and the cells to provide convection cooling. Other means of heat rejection should also be evaluated. The effects of heating of the other array components such as substrates, adhesives, etc., must also be determined and minimized.

4. *Environmental degradation.* The stability of the concentrators should be high with respect to the anticipated environments (temperature excursions, rain, snow, wind, etc.). The concentrator should be designed so that it does not act as a trap for dust, dirt or sand, and maintenance requirements in general must be minimized.

5. *Concentrator design/system efficiency.* Comparisons should be made between arrays using solar concentrators and nonconcentrated arrays with regard to overall power/cost effectiveness. This would include consideration of orientable arrays and concentrator systems, and stationary systems. Daily, monthly, and yearly (or, for example, 30-day moving) averages of available power should be determined for typical geographic locations for the various systems.

C. Cell Interconnections

Development of cell interconnections can be considered as a separate study or as part of cell or array development. The general requirements are outlined in Table 4. It appears to be advantageous to make the cell interconnections at the same time, in the same operation used for cell contacting, since fabrication of large contacted and interconnected cell matrices in one operation should be highly economical. This assumption, of course, is predicated on a low-cost operation for the cell contact/interconnection process in comparison to a process involving separate application of contacts and interconnections. This may not, in fact, be the case. For example, some preliminary investigations funded by NASA/JPL have been made with respect to the use of aluminum electroforming techniques for developing simultaneous solar cell contact/interconnection operations (Refs. 14 and 15). At the present time, the electroforming process, with its attendant masking requirements and control problems, proved to be uneconomical and would not be competitive with an inexpensive method of contact formation, such as an optimized evaporation technique or a very low-cost silk-screening contact application technique, coupled with another independent economical means of making the interconnections. With additional work, however, this situation might be altered.

Table 4. Cell interconnections

Area of investigation	Specific considerations
Materials	Low electrical resistance Good mechanical strength (reliability) Stability
Configuration	Minimum stress Maximum strength
Techniques	Minimum stress Maximum strength Rework/replacement capabilities
Cell matching	Maximum tolerance Minimum power losses Simple, high volume matching techniques

The processes presently used for interconnections vary from highly operator-dependent hand operations to quasi-automated techniques, such as the use of continuous-belt tunnel ovens and pulse soldering. Again, it is likely that if the stringent requirements of the space program were relaxed, the existing interconnection techniques could be made more economical than they are at present.

1. *Materials.* The general material requirements for electrical contacts are low electrical resistance, a high degree of mechanical strength, and stability of the mechanical and electrical characteristics in the anticipated environments. The most stringent aspects of the terrestrial environment appear to be the large number of temperature cycles in going from full sunlight (especially if concentrators are used) through the coldness of night, possible corrosive reactions due to precipitation and chemical interaction with the surroundings, and abrasion due to sand, dust, etc.

2. *Configuration.* The configuration of the interconnect must be such that the amount of induced stress is minimized, especially with respect to the anticipated tem-

perature cycling and the thermal coefficient mismatches between the contact material and the silicon cell. The strength of the interconnection and its bond with the cell electrical contacts must be maximized.

3. Techniques. Techniques for interconnecting the cells should be such that minimum stress is induced (both immediate and residual) and maximum strength is obtained. They should maximize rework and/or replacement capabilities, during both fabrication and on-site operation. Techniques such as pulse soldering, tunnel oven soldering, and parallel-gap welding should be investigated and optimized, and methods of simultaneous contact formation/interconnection should be explored.

4. Cell matching. A compromise must be made between allowing maximum tolerance in selecting cells for use in the terrestrial array and minimizing power losses due to differences in cell output characteristics. Maximizing the acceptable cell tolerances allows the use of a larger proportion of fabricated cells and simplifies solar cell categorization. This is absolutely necessary to the fabrication of low-cost solar arrays due to the simple economic fact that the user ultimately pays for *all* solar cells fabricated, and therefore ideally should be able to use every cell made in order to achieve maximum economy. Moreover, complicated systems for cell characterization also result in higher cost, and therefore the minimum number of required measurements and sorting operations will provide maximum economy. Automation of sampling, sorting, and matching would be highly advantageous.

D. Array Fabrication

Characteristics to be considered in array fabrication are outlined in Table 5, and a simplified flow chart is shown in Fig. 1.

1. Substrate. The substrate material should be selected on the basis of cost, stability, ease of fabrication, and compatibility with the cells, adhesives, etc. Intuitively, there would appear to be an advantage in the utilization of a self-insulating substrate material combined with printed circuit wiring, so that, although the substrate fabrication might be somewhat more costly and/or complicated, the overall array costs and reliability would be improved. The optimum size and weight of the substrate must be determined, including consideration of the use of rigid versus flexible substrates. Flexible substrates are easier to store and transport than rigid substrates, but appropriate tiedown techniques must be developed for on-site installation. A possible compromise between a rigid and a flexible substrate could be achieved by rigidizing the substrate (for example, by chemical means) on site.

Table 5. Array fabrication

Area of investigation	Specific considerations
Substrate	Material Fabrication technique Design (size, weight)
Electrical insulation	Self-insulating (nonconducting substrate) Material/application (conducting substrate) Strength Stability
Protection	Transparent layer Plastic Spray Epoxy FEP Teflon Temperature Humidity Wind Dust U-V degradation Storage conditions Servicing Cleaning Replacement Refurbishing
Configuration	Size (width, length, thickness) Weight Module layout Provision for use of concentrators
Laydown techniques and materials	Mechanical Bonding (chemical: e.g., epoxy, adhesive, etc.)
Wiring	Low electrical resistance High mechanical integrity Redundancy (Printed circuitry) Stability Repair-rework capability
Cell/module replacement	Determination of defective cells/modules On-site capability for locating and replacing defective cells/modules Minimum effect on remaining cells/modules Operator-independent

2. Electrical insulation. The use of an electrically self-insulating, nonconducting substrate appears to be highly advantageous. If, for economic or technological reasons, self-insulating substrates are found undesirable, techniques for the application of an efficient insulating layer which is economical and compatible with other array components must be developed. Techniques for rework and

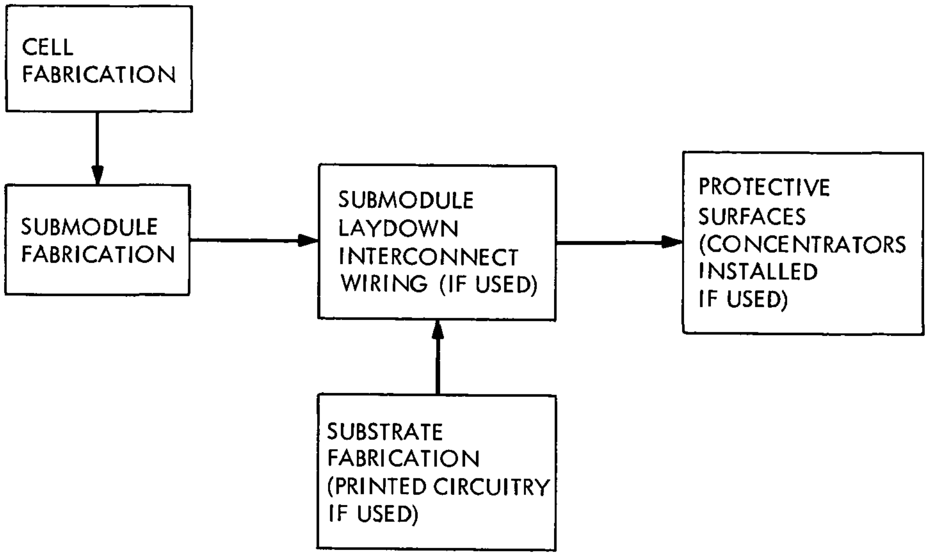

Fig. 1. Sample array fabrication flow chart

replacement must also be developed, and the stability of the layer must be maximized with respect to the anticipated environments.

3. ***Protection.*** It will be necessary to protect the delicate cell surfaces from the adverse effects of the environment (precipitation, abrasion, sedimentation, etc.). The protective layer must be transparent to allow the maximum number of usable photons to reach the solar cells. Application of the protective layer could be by mechanical or chemical attachment of sheets, spraying, or rolling the layer onto the array surface. Materials such as plastics, epoxies, or Teflon (Ref. 16) should be considered. The layer must be resistant to the effects of wind (wind-borne particles causing abrasion), dust, ultraviolet exposure, temperature, humidity, and other storage or environmental conditions. Service requirements for the protective layer should be minimized, and cleaning, replacement, and refurbishing, of the layer must be simple and economical.

4. ***Configuration.*** The size of the array (width, length, and thickness) should be optimized with respect to fabrication, storage, transportation, and on-site setup. The use of flexible substrates would provide greater latitude with respect to these conditions, and would be especially advantageous if the array could be rolled onto a drum in a convenient manner. While weight would be only a secondary consideration, it is obvious that its minimization consistent with the other requirements would be desirable. Module layout should take into consideration ease of fabrication, reliability, and ease of rework and repair both during fabrication and during on-site operation. The module layout must be compatible with requirements of storage, transportation, and operation in the terrestrial environment. The solar cell packing factor will probably be a secondary consideration for the low-cost terrestrial system; however, it should be maximized within the constraints of the other boundary conditions. For systems utilizing solar concentrators, the array must be compatible with the use of such concentrators, particularly with respect to rapid installation and removal of the concentrators and facilitation of such maintenance as would be required.

5. ***Laydown techniques and materials.*** Techniques for rapid, economical, reliable laydown of cell modules and matrices must be developed. Both mechanical and chemical techniques should be investigated, with emphasis on rapid and simple replacement of degraded modules.

6. ***Wiring.*** The requirements for array wiring are similar to those for cell contacts and interconnections, namely, low electrical resistance, high mechanical integrity, good stability, and simple repair and rework capability. Redundant systems commensurate with low cost are preferable. The requirements for wiring accomplished by printed circuits are similar, except that some sacrifice in repair and rework simplicity is to be expected.

7. ***Cell/module replacement.*** A simple, rapid means of locating and replacing defective cells and modules is required both at the fabrication facility and on site. The replacement techniques must be such that adverse effects on the remaining cells and modules in the array are eliminated or at least minimized. Replacement techniques

should be relatively operator-independent so that they can be effected by a semi-skilled operator.

E. Sample Array Fabrication

A simplified flow diagram outlining the fabrication of samples of candidate arrays is shown in Fig. 1. The cells are fabricated and connected into modules or module matrices. Subsequently, the modules (module matrices) are attached to the substrate and wired together in the desired configuration. Finally, protective surfaces are attached or deposited. Concentrators, if they are used, are attached either at the fabrication facility or at the site of operation, as dictated by the economics involved.

F. Testing and Evaluation

An overview of the testing and evaluation flow chart is shown in Fig. 2. This simplified chart indicates a logical progression from cell tests through array tests. In reality, a large number of tests, evaluations, comparisons, and analyses would be performed with respect to each of the items discussed in the preceding sections. Many of the tests would allow an independent evaluation of the merits of the particular process or material under consideration; however, most of the test results would have to be considered in relation to other interacting materials and processes. For example, a cell contact system which corrodes after exposure to anticipated temperature–humidity environments must either be modified or discarded, and thus the negative result can be considered an independent and sufficient test; however, a positive result (no instability of mechanical and electrical characteristics in this environment) is not in itself a sufficient test, since the contact must also be compatible with the other array components (e.g., interconnects, epoxies or adhesives, protective layers, etc.).

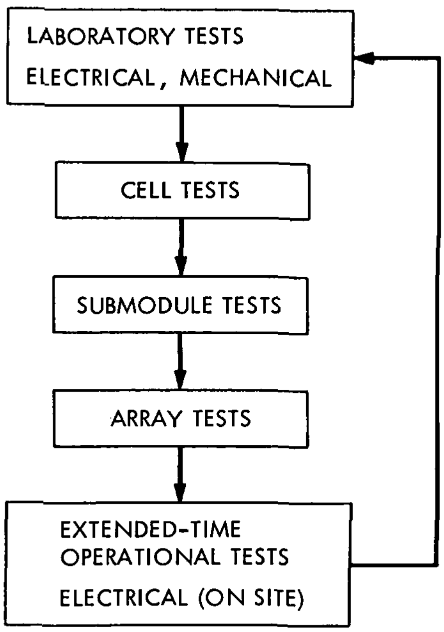

Fig. 2. Testing and evaluation

One of the first studies to be undertaken in the development of terrestrial solar arrays must be the establishment of the required tests and test levels. This involves the determination of typical environmental conditions, including insolation as a function of time of year and geographical location. From this determination, a body of average and worst-case conditions can be extracted and applied. If valid accelerated tests can be established for various components, this should be done.

The testing of the cells, modules, and arrays to be considered falls into two major categories: (1) electrical characterization and (2) mechanical characterization. With respect to electrical characterization, the light-generated current–voltage characteristics must be determined as a function of illumination (intensity and spectrum) and temperature over the anticipated temperature–illumination ranges and combinations, including those applicable to candidate concentrator systems. The electrical characterization must be performed as a function of exposure to the anticipated environments. For analytical purposes and design improvement, it may also be necessary to perform additional electrical measurements, such as dark (unilluminated) forward and reverse current–voltage characteristics. It is to be expected that the initially rigorous electrical characterizations will be simplified as a better understanding of first- and second-order effects is obtained. For example, it may be found that a current measurement at one or more voltages would be sufficient to eliminate or screen out unusable cells/modules. A considerable body of information already exists on state-of-the-art solar cells and arrays with respect to space-type environments and should be incorporated into a terrestrial program, wherever applicable, to eliminate consideration of unworthy designs.

Mechanical characterization would consist of determination of the stability of the various systems as a function of exposure to the anticipated worst-case and nominal environmental conditions. It should include observation of pull-strengths of contacts, interconnectors, and wiring; and of delaminations, discolorations, corrosion reactions, or other defects in such components as epoxies, adhesives, plastics, glasses, and metals used in candidate systems. Wherever possible, degradation mechanisms should be determined to aid in improving the design. (Spectrographic, X-ray, electron diffraction, and infrared analyses might be some appropriate techniques.)

Finally, candidate arrays (including, as a baseline, representative space-type arrays) must be tested in actual operation in terrestrial environments. Arrays could be set up at various geographical locations in the United States, in the desert, on rooftops, on "solar farms," etc. Provisions should be made for continuous, automatic recording of solar power output. At specified intervals, the arrays should be examined and mechanically and electrically tested in the laboratory. Development of nondestructive mechanical tests would be particularly advantageous in this respect.

IV. Conclusions

This report, unlike much of the literature on the problem of terrestrial solar photovoltaic power systems, deals in specifics rather than overall program plans and organization charts. It attacks many (but not all) of the specific criteria and problem areas which must be considered in the development of terrestrial photovoltaic solar arrays. While a number of program plans can easily be generated, selection of an optimum plan must await inputs from the scientific and engineering community at large. It is necessary to know (1) what significant problems were not given adequate attention in this report, (2) what contributions to the solution of various aspects of the problem can be expected, and (3) what expenditures in time, effort, and resources are required and can be expected with respect to the problem aspects discussed.

It is difficult for the author, at this time, to assign priorities to the various aspects examined, since it appears that solutions are required to all of the problems. For example, the best laboratory-developed solar array in the world would be useless if it could not be economically mass-produced. And what is "economically?" How much is one really willing to pay? The technical feasibility of a terrestrial photovoltaic solar array is already assured, but the economic feasibility is not at all clear.

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16. Abstract

The various factors involved in the development of solar photovoltaic power systems for terrestrial application are discussed. The discussion covers the tradeoffs, compromises, and optimization studies which must be performed in order to develop a viable terrestrial solar array system. It is concluded that the technology now exists for the fabrication of terrestrial solar arrays but that the economics are prohibitive. Various approaches to cost reduction are presented, and the general requirements for materials and processes to be used are delineated.

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