2
m 1 x

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1573

Photovoltaic Solar Array Technology Required for Three Wide-Scale Generating Systems for Terrestrial Applications: Rooftop, Solar Farm, and Satellite

Paul A. Berman

(NASA-CR-128381) PHOTOVOLTAIC SOLAR ARRAY TECHNOLOGY REQUIRED FOR THREE WIDE SCALE GENERATING SYSTEMS FOR TERRESTRIAL APPLICATIONS: P.A. Berman (Jet Propulsion Lab.) 15 Oct. 1972 27 p CSCL 10A G3/03

N72-33061

Unclas 44953

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

October 15, 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1573

Photovoltaic Solar Array Technology Required for Three Wide-Scale Generating Systems for Terrestrial Applications: Rooftop, Solar Farm, and Satellite

Paul A. Berman

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

October 15, 1972

Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

Preface

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

Contents

Tables

Abstract

Three major Options for wide-scale generation of photovoltaic energy for terrestrial use are considered: (1) Rooftop Array, (2) Solar Farm, and (3) Satellite Station. The Rooftop Array would use solar cell arrays on the roofs of residential or commercial buildings; the Solar Farm would consist of large ground-based arrays, probably in arid areas with high insolation; and the Satellite Station would consist of an orbiting solar array, many square kilometers in area. The Technology Advancement Requirements necessary for each Option are discussed, including cost reduction of solar cells and arrays, weight reduction, resistance to environmental factors, reliability, and fabrication capability, including the availability of raw materials. The majority of the Technology Advancement Requirements are applicable to all three Options, making possible a flexible basic approach regardless of the Options that may eventually be chosen. No conclusions are drawn as to which Option is most advantageous, since the feasibility of each Option depends on the success achieved in the Technology Advancement Requirements specified.

Photovoltaic Solar Array Technology Required for Three Wide-Scale Generating Systems for Terrestrial Applications: Rooftop, Solar Farm, and Satellite

I. Introduction

In a previous report (Ref. 1) the author discussed general areas for investigation that could significantly reduce the cost of photovoltaic solar arrays to be used for wide-scale terrestrial solar-to-electrical power generation. In the present report, the same considerations have been used with a broader philosophical scope to suggest an approach for solar array development applicable to three major systems for using solar photovoltaics to generate electrical power for terrestrial purposes. These systems include two Earth-based concepts (Rooftop Array and Solar Farm) as well as a Satellite Station.

The principal Technology Advancement Requirements to attain a viable solar array for wide-scale terrestrial use are (1) a reduction in the dollars-per-watt cost of solar arrays, as fabricated and installed, by approximately three orders of magnitude over those presently experienced in the space program and (2) a drastic increase in production capability of such arrays and systems, so that many square miles of arrays can be fabricated and installed in a routine manner. Three Options for achieving the objectives of wide-scale terrestrial power generation by photovoltaic systems are defined in the following section. Each of these Options has major Technology Advancement Requirements other than those associated with the solar arrays. Options 1 (Rooftop Array) and 2 (Solar Farm), for example, require an efficient means of energy storage for a truly self-contained energy generation system (however, this will not be required if photovoltaic energy conversion is to be used as a supplementary power system). Option 3 (Satellite Station) requires a method of transmitting and converting the generated power into a usable Earth-based power distribution center and technology for the insertion, deployment, and maintenance of large area solar arrays in synchronous orbit. The solar array problem, however, is common to all three Options and the success of any or all Options is predicated upon satisfaction of the Technology Advancement Requirements for the solar array. These Technology Advancement Requirements are described in detail in this report.

II. Definition of Three Options

The three Options to be discussed in this report are defined as follows:

Option 1. Rooftop solar generator
Residential and commercial buildings
(Rooftop Array)

Option 2. Large-area photovoltaic solar generator
Large flat land areas
(Solar Farm)

Option 3. Satellite solar power station
Large arrays in synchronous orbit
(Satellite Station)

These Options are described below.

A. Rooftop Array

The Rooftop Array is an Earth-based system using the roofs of buildings, both residential and commercial, as an area upon which solar cell arrays are to be mounted. The arrays then provide electrical power for the building in either a supplementary manner, being augmented as needed by power from more conventional sources, or an independent manner by means of suitable electrical energy storage devices. The latter approach requires (1) a considerable effort to economically produce energy storage devices with the required storage capacity and minimum maintenance requirements, and (2) a probable major effort in improving the utilization of electrical power so as to drastically reduce the overall electrical power demands of the building (because array area and hence generating capacity is limited). The supplementary approach would circumvent these requirements, but would impose a requirement for essentially a dual (redundant) system to supply the differential between the power that is available at the moment and the power that is needed. This dual system requirement is economically less attractive, since the costs associated with the backup system (generators, transmission lines, maintenance, etc.) must be considered as part of the total system costs. Both the supplementary and independent approaches would, however, significantly reduce the demands on natural resources and the pollution by-products (particulate, radioactive, and thermal) associated with the conventional means of electrical power generation.

B. Solar Farm

The Solar Farm, the large-area Earth-based central generating station of Option 2, has many of the characteristics of the Rooftop Array. If the Solar Farm is to operate in an independent mode, a low-cost, low-maintenance storage system is also required. More options might exist, however, for the large storage systems of the Solar Farm (e.g., pumped-water storage dams) than for the small storage system of the Rooftop Array. Also, because of the "sharing" nature of the generated power, the demand loads would be somewhat smoother than the sharper demand peaks and valleys of the individual systems of the Rooftop Array. In the supplementary approach, the smoothing effect of user sharing associated with this Option would also be more advantageous, but the cost disadvantage of maintaining a redundant backup system would still exist.

The Solar Farm, or Farms, interconnected, would require transmission lines to the user for both the independent and supplementary approaches, whereas the independent approach for the Rooftop Array would have no such requirement. In both the Earth-based systems, improvements in the efficiency with which electricity is used (energy conservative systems) would greatly enhance the success probability of the independent approach since it would reduce the requirements imposed on the power generating and storage capacity of the system. For the Rooftop Array, the generating capacity is expected to be a limiting factor, while for the Solar Farm, the storage capacity might be a limiting factor.

C. Satellite Station

The large-scale space satellite generating station of Option 3 has probably received the greatest amount of study of the three Options listed (Refs. 2–7), most likely because the system has some extremely tantalizing advantages, although it represents an almost science-fiction-like undertaking in resource commitments and technology advancements. It is probably only due to NASA's commitment to the Space Shuttle, with its expected drastic decrease in payload costs, that Option 3 can be considered at all since the weight of the proposed system will be 18-45 million kg (40-100 million lb)!

The major advantages of the Satellite Station are:

(1) The system receives full sunlight, unattenuated by atmospheric absorption (including clouds) for all but a 1.2-h interval every 24 h for 25 days

before and after equinox in the 35,600-km (22,300-mi) synchronous orbit proposed. Thus, by using multiple stations, the need for storage systems is eliminated, even for the independent approach.

(2) Since, in the most optimistic case, the Earth-based systems will receive less than an average of 6 usable sun hours per day (and even this is attenuated by atmospheric absorption of usable photons) while the Satellite Station will receive close to 24 h of (unattenuated) sunlight per day, the solar array area of the latter system would be only 10–20% that of an Earth-based array producing equivalent power.

(3) While the Earth-based arrays must take into account such factors as wind, dust, sand, precipitation, etc., the Satellite Station arrays would not be exposed to such conditions, although they would be subject to ionized particle irradiation.

The problems associated with the Satellite Station, aside from those discussed in detail in the following section on Technology Advancement Requirements, are in transportation (e.g., launch and insertion into orbit) of the system, which weighs 18–45 million kilograms (40–100 million pounds), erection and maintenance (e.g., attitude control) of the system, which presently entails 33 km^2 (13 mi^2) of array area plus 133 km^2 (52 mi^2) of solar concentrator area, and the transfer of the generated power to usable Earth-based power (e.g., through direct current–to–microwave conversion, transmission, collection, and reconversion).

The discussion above makes no attempt to suggest adoption of any one of the Options, but is intended to supply some overall perspective. Each of the Options has many advantages and disadvantages, and selection of the most desirable Option must await the results of a concentrated effort to attain the required technology advances and an assessment of the degree of success achieved in accomplishing these advances.

III. Rationale for Concentration on Solar Array Development

Each of the three defined Options, integrated into a viable system, is quite complex, the complexity increasing according to the Option number assigned (i.e., the Rooftop Array is least complex, the Satellite Station, most complex); however, all three Options have one common primary technology requirement, namely, large scale, economical fabrication of reliable solar arrays. If this primary need is not satisfied, *none* of the Options is viable.

Over the past 10 years, the economic viability of solar photovoltaics has been evaluated several times; however, the divergence between the optimistic and pessimistic evaluations is about three orders of magnitude. At the recent Ninth Photovoltaics Specialist Conference of the Institute of Electrical and Electronics Engineers, still another series of economic forecasts was presented. Once again there was a discrepancy of several orders of magnitude between the optimistic and pessimistic forecasters. It therefore appears that the forecasting of the eventual cost for photovoltaic solar power conversion has not come very far in the last decade, no matter how wise in the ways of economics the forecaster may be (applying such factors as amortized capitalization investment, inflationary trends on interest rates, etc.). There is really no appropriate cost data to use, since the fabrication of photovoltaic solar arrays has been, without exception, on an extremely small scale, nonautomated (in an industrial context), high-reliability, custom-made basis. Hence, the first order of business is to provide the required cost information.

Since financial and personnel budgets are always finite, and in fact usually quite limited, it is imperative to direct the available resources into areas that will provide the greatest number of options. Indeed, this was NASA's philosophy in supporting the Space Shuttle, which will provide a tremendous number of future options, at the expense of some interesting but very specific missions. This rationale should also prevail in developing technology needed for electric power from solar energy.

The major technology effort over the near term should therefore be the development of materials, techniques, and processes for large-scale, low-cost production of photovoltaic solar arrays. This emphasis would maintain the greatest program flexibility by concentrating on the solar array aspects until it is established which Technology Advancement Requirements can be satisfied and the relative economics of doing so. This information would then be used to determine which of the three defined Options are feasible. Parallel low-level feasibility studies on the other critical aspects of the three Options could also be begun at this time, or at some time in the future as determined by a milestone event in the solar array program (that is, at such time as certain feasibility criteria are met). Such parallel studies might consist of:

(1) Methods of energy storage (Options 1 and 2).

(2) Conversion to microwave power (Option 3).

(3) Microwave beam forming and collecting (Option 3).

(4) Conversion to commercial electrical energy (all Options).

(5) Launch and assembly in space including teleoperators (Option 3).

(6) Station keeping and attitude control (Option 3).

(7) Maintenance in space (Option 3).

(8) Environmental/ecological effects of systems (all Options).

A document entitled *Solar Energy R & D Policy Assessment,* prepared by E. L. Ralph, Heliotek Division of Textron, for submission to the Committee on Energy R & D Goals established by the Federal Council on Science and Technology presents one set of possible costs and time schedules for various phases of the three Options defined above. These are summarized in Table 1 and indicate a greater expenditure of money than the present author would have estimated. As early as Phase B, expenditures of $60 million for each of the three Options is estimated by Ralph. Phase C requires $300 million for Options 1 and 2 and over $2 billion for Option 3. Phase D requires $1 billion for Options 1 and 2, and $8 billion for Option C. Therefore it is obvious that, at this time, one will have to pick and choose areas of investigation carefully so as to make the greatest impact for the least expenditure of money and manpower. Again, it is the present author's belief that this can be accomplished by directing our resources toward development of the solar array.

One of the major objectives of this report is to show that most of the solar array Technology Advancement Requirements are at least qualitatively important to all three defined Options, although they may vary in priority among the Options. If this is indeed the case, a very logical development program can then be generated to maintain flexibility with respect to all three Options. Such a program would generate a baseline series of solar arrays, in an iterative process, using the most sophisticated applicable technologies available at the time of each iteration. The results obtained through analysis of these baseline arrays will provide information on the cost-vs-performance tradeoffs associated with materials and process modifications, based on the boundary conditions associated with each of the three Options. That is, what performance penalties must one pay in accepting a less sophisticated technology, and what, if any, are the economic gains in doing so? The magnitude and direction (i.e., positive or negative) of the resultant balance might be different for each of the Options. This methodology is the only way in which one can ascertain, for example, whether an inexpensive process for solar cell contact deposition really gives rise to an economically more attractive system than a more controlled and expensive process. The Option 3 (Satellite Station) can be expected to require the most technically sophisticated array because of the significant cost of the other aspects of the system and the more limited amenability to maintenance and replacement.

IV. Technology Advancement Requirements

A. Background

The techniques for fabricating and installing very-high-reliability photovoltaic solar arrays are well known. Photovoltaic solar arrays have been the backbone of electrical power generation for almost all unmanned spacecraft and have successfully operated in near-Earth space and at distances closer to the Sun than Venus and further away from the Sun than Mars, for extended periods of time. In these cases, however, the cost was only a secondary consideration, while reliability and end-of-mission performance were the major criteria. Each mission, or series of missions, used custom-built arrays designed by engineers who felt that their particular design was the only one that would satisfy the mission requirements. This resulted in dollars-per-watt ratios of between $200 and $1000 per watt (depending upon what factors are put into the derivation of the ratio: for example, development costs, type approval models, documentation, orientation mechanisms, etc.). This situation is analogous to spending $200,000 to develop and fabricate an automobile that will win a specific, highly competitive race as opposed to a $2000 compact automobile capable of getting its owner down to the corner grocery store.

Table 1. Projected program costs and schedule for three Options[a]

Phase	Option 1 Rooftop Array		Option 2 Solar Farm		Option 3 Satellite Station	
	Cost, $M[b]	Schedule, years	Cost, $M	Schedule, years	Cost, $M	Schedule, years
Pre-phase A Preliminary design and feasibility assessment. Conceptual design of alternative approaches. Identification of critical system parameters.	None	None	0.1	1.5	3	1.5
Phase A Establish system feasibility and most desirable approaches. Assessment of technical advances needed. Gross cost and schedule projection.	None	None	3	1.5	20	1.5
Phase B Preliminary design of preferred system. Detail assessment of requirements including resource, manufacturing and test requirements. Preliminary system cost and schedule projection. All precommitment objectives completed.	60	3	60	3	60	3
Phase C Final definition: Freezing of concepts, approaches, designs, schedules, and costs of program. Intensive development of operational systems. Initiation of testing.	300	3	300	3	2,100	3
Phase D Final development and operational phase. Operational system components developed. Demonstration hardware fabricated and extensively tested. Prototype built. Commercial readiness achieved and competitive position ascertained.	1,000	5	1,000	5	8,000	8
Total	1,360	11	1,364	14	10,183	17

[a]Extracted from Research Paper No. 135, Heliotek Div. of Textron, Inc., "Solar Energy R & D Policy Assessment" by E. L. Ralph.
[b]$M = millions of dollars.

The overall requirements, then, are those that will enable us to reduce the $1000-per-watt figure down to a more reasonable $1.00 per watt and the cost per square meter of array from $100,000 to $100.00. Furthermore, technology needs to be developed to fabricate not square meters of array but square kilometers, and the generation not of watts but of 10,000s of megawatts. This could result in a major impact on existing industries or the creation of new industries. For example, to cover 2.6 km^2 (1 mi^2) of area with single-crystalline silicon cells 0.25 mm thick, assuming a wastage of 50% of the silicon (which, unfortunately, is optimistic at present), represents six times the yearly production of such silicon in the United States (Ref. 8). (This of course assumes that one wants to use single-crystalline silicon in the fabrication of the arrays, which may not be true.) Thus the required Technology Advances are formidable, but the very fact that the dollars-per-watt numbers *are* so high and that so little has been done to significantly reduce them can only make one optimistic that progress can be made toward this end.

B. General Considerations

In the past, cost reduction has been of only secondary importance in the space program, where the capability of the solar array to successfully satisfy the mission power requirements within the constraints of the mission boundary conditions has been of prime importance. Fabrication capability, that is, the capability of fabricating very large quantities and areas of solar arrays, has also not been a major concern (e.g., there has been no need for concern that there would not be enough single-crystalline silicon produced in the United States to satisfy the needs of the space program). Weight reduction, likewise, has not been of prime importance, although recent development efforts have been extended toward achieving significant weight reduction because of mission requirements such as those proposed for ion propulsion utilization. Oddly enough, the advent of the Space Shuttle, which would significantly reduce the payload cost, might actually inhibit significant further efforts in weight reduction of solar arrays for the normal class of missions. This, of course, would not be the case for the Option 3 satellite power system, which requires 33 km^2 (13 mi^2) of solar array area plus 133 km^2 (52 mi^2) of concentrator area with a proposed system weight of 18–45 million kg (40–100 million pounds). Thus, in this case, transportation costs are expected to be a significant portion of the total system cost.

The fact, then, that major efforts have not been expended to provide improvement of the factors so critical to the viability of the photovoltaic system for wide-scale terrestrial use certainly does not detract from the expectation that required improvements can indeed be achieved. In addition, basic technologies appropriate to fabrication of solar arrays have already been established and the problem areas clearly delineated, so that there is a firm baseline from which to extrapolate toward major improvements. The Technology Advancement Requirements previously discussed are of an engineering nature and do not require fundamental breakthroughs. Therefore, immediate and significant near-term improvements can be expected to occur. A fundamental breakthrough in the area of the photovoltaic conversion, for example by development of a high-efficiency, thin-film gallium arsenide cell or an organic photovoltaic converter, would most certainly increase the probability of success of photovoltaics for terrestrial applications, but success does not at this time appear to hinge upon such developments.

Table 2. Relative priority of technical requirements and needs (highest priority = 1)

Technology Advancement Requirement	Option 1 Rooftop Array	Option 2 Solar Farm	Option 3 Satellite Station
Cost reduction			
Higher efficiency cells	2	3	1
Lower cost cells	1	1	1
Improved fabrication techniques	2	1	1
Large area cells	1	1	2
Use of concentrators	2/4	2/4	1
Orientation mechanisms/techniques	2/4	2/4	1
Weight reduction			
Higher efficiency cells	2	3	1
Radiation resistance	4	4	1
Lightweight substrate and mechanism	2	3	1
Life extension			
Radiation resistance	4	4	1
Resistance to ultraviolet	2	2	1
Resistance to humidity	1	1	2
Resistance to wind/dust precipitation	1	1	4
Temperature variation			
Large number cycles	1	1	2
Large excursions	2	2	1
Reliability			
Definition of environment	1	1	1
Characterization	3	3	1
Maintenance	2	3	1
Fabrication capability			
Cell fabrication techniques	3	1	1
Array fabrication techniques	3	1	1

C. Specific Technology Advancement Requirements

The specific Technology Advancement Requirements are listed in Table 2 and ranked in order of priority with respect to the three Options previously defined. The priority is defined as increasing with decreasing numerical value; that is, priority 1 is of greatest importance, priority 4 is of little importance. The Technology Advancement Requirements and the priority ranking are discussed below.

*1. **Cost Reduction.*** Low cost is a prime criterion for Options 1 and 2, the two Earth-based systems. Some sacrifices in the other areas of high power density and light weight can be tolerated if costs can be kept very low. For Option 3, cost is important for the solar cell modules and arrays but not as important as achieving high power density and light weight, because of the costs involved in other aspects of the system, such as transportation and insertion into orbit, erection and maintenance of the array, conversion to microwave power, beam forming, microwave collection, reconversion to electrical power, attitude control, etc. Reference 1, which discusses at length the studies and tradeoffs that could significantly reduce the cost of solar arrays, was primarily directed at Earth-based systems (e.g., Options 1 and 2) to be used as supplemental power and therefore not requiring an energy storage system.

At present, as previously mentioned, solar arrays cost about $200 to $1000 per watt, produce about 90 W/m² and about 4 W/kg. If we take the higher figure, this results in about $90,000 per square meter. Of this, the solar cells represent about 10–20% of the cost, or about $100 per watt for the cells alone. With a little imagination, one can easily see the array costs, exclusive of the solar cells, decreasing three orders of magnitude from approximately $90,000 per square meter to about $90 per square meter by using a substrate of Kapton or some even less expensive material with printed circuits for interconnections deposited onto the substrate in an economical manner. Reduction of the solar cell costs by three orders of magnitude requires somewhat more imagination, especially if we constrain ourselves to the use of single-crystalline silicon, which presently costs about $0.30 per gram, and which in ingot form (cylindrical in geometry) results in wastage of 75% or more of the silicon by the time it is cut into rectangular blanks having a thickness of approximately 0.3 mm. Thus, in the future, one can envision the cost of the solar cells as being the principal contributor to the cost of the solar array.

The costs of solar arrays must be reduced by approximately three orders of magnitude from the present level. To this end, careful consideration must be given to the areas discussed below.

a. Higher-efficiency cells. High efficiency, or, as a corollary, high power density, is obviously important for all Options, since it directly affects the array size and weight necessary to achieve a specified power output. It is most important, however, for Option 3 (Satellite Station) since even with an efficiency of 18% (based on normal measurement conditions), the solar array alone is proposed to be 33 km² (13 mi²), with 133 km² (52 mi²) of solar concentrator area (Ref. 7). Present-day solar cells have an efficiency of only about 11.5% and a thickness of about 0.3 mm, as opposed to the 0.05-mm-thickness cells proposed for Option 3. At present, cells of this latter thickness have never been made, but even cells having a thickness of 0.1 mm exhibit significantly decreased efficiency (about 9–10%) so that Option 3 is predicated on an approximate 100% improvement in solar cell efficiency. High-efficiency arrays also have a high priority for the Rooftop Array since the area of this system is limited and therefore the highest power density is desired to meet the user's needs. It is assumed that for Option 2 (Solar Farm), the area would not be critical, since land that is not useful for any other purpose might be used. This might well be the case, because land areas having the greatest insolation are usually arid and not amenable for farming or even desirable for living.

It has been tacitly assumed that the solar cells from which the arrays are fabricated would be made from silicon; however, the band gap of gallium arsenide is such that higher theoretical efficiency could be obtained, although investigations in the early 1960s did not prove this to be true in practice. Gallium arsenide, being a direct-band semiconductor, has a very sharp light absorption edge, and all the usable hole-electron pairs are created in one or two micrometers of material, as opposed to silicon, which absorbs usable light at depths greater than 200 micrometers. The technique for fabricating thin-film gallium arsenide cells, for example by vapor-phase or liquid-phase epitaxy, might result in a very-high-efficiency, ultra-lightweight cell which, because of the small amount of material required per unit area, might also be very economical. This area of investigation could be quite costly and require a good deal of time to pursue but, if successful, could have a favorable effect upon all three Options, especially if high power density is required. Furthermore, with respect to the Satellite Station, since solar concentrators are an integral part of the system, with their attendant increase in cell operating temperature, gallium arsenide with its more desirable high-temperature characteristics presents an additional advantage, as would also be the case if concentrators were to be used in the Earth-based systems.

In all cases, the cost of fabricating higher efficiency cells must be traded off against the overall systems costs. For example, for Option 2 (Solar Farm), it might be advantageous from a systems point of view to accept a lower efficiency and utilize a far less expensive grade of silicon to achieve a lower overall dollar-per-watt figure.

Higher silicon solar cell efficiencies can be achieved by improving the materials and processing involved in the fabrication of the cells, such as (1) fabrication of very shallow, high-quality electrical junctions, (2) decrease of surface recombination velocity through careful blank preparation, diffusion, and surface passivation, (3) utilization of low-resistivity silicon with high minority carrier diffusion length, combined with fabrication processes that do not adversely affect these parameters, and (4) improvement of reflection properties of the portion of the array blanket between the junction and the incoming solar energy. Improvements in efficiency might also be obtained through the use of thin-film gallium arsenide photovoltaic converters, but this would require a major research effort.

b. Lower cost cells. In general, cell costs must be decreased by approximately three orders of magnitude. A significant portion of these cell costs is associated with the use of ultrapure, single-crystalline silicon, which presently costs approximately $0.30 per gram, and which, in cylindrical ingot form, results in wastage of more than 75% of the silicon by the time it is cut into rectangular blanks having a thickness of approximately 0.3 mm. Ingot utilization can be improved by making use of the natural cylindrical geometry of the ingot to fabricate disk-shaped cells, which could be utilized with individual conical concentrators to achieve still greater cost effectiveness.

A second technique for better silicon utilization, now being investigated*, is a process capable of growing silicon ribbons having the proper thickness and aereal dimensions for fabrication of large area solar cells. In this process, there would be no wastage of the silicon material in the slabbing and cutting operations, and no loss of silicon that could not be cut into rectangles. Furthermore, the silicon would not require lapping and etching to remove mechanical damage induced by the cutting and lapping operations but would have a high-quality, damage-free surface. The use of large area blanks can also be expected to reduce the overall costs of the cell on a unit area basis if the cell processing is modified to optimally integrate the large area blanks.

Another possible cost reduction for the Earth-based systems would be to reduce the purity of the silicon used in the solar cells (Ref. 8). The single-crystalline silicon costs about $300 per kilogram. High-purity silicon costs about $10 per kilogram, and low-purity metallurgical silicon costs only about $0.45 per kilogram. As the quality of the silicon is reduced, the efficiency of the resultant cell can also be expected to be reduced, so that the investigation of using lower-quality silicon for fabrication of solar cells would probably not be applicable to the Satellite Station, which requires very high efficiency. However, the reduction of the material costs between one and two orders of magnitude could have a favorable impact on the array costs of the Earth-based systems if, as assumed, the array costs become so low that the cost of the cells determine the cost of the array.

A fourth possibility for decrease in the cost of the cells is the investigation of thin-film solar cells. Two materials, cadmium sulfide and gallium arsenide, come immediately to mind, with a third possibility being cadmium telluride. Significant effort has already been expended on cadmium sulfide, with only limited success (Refs. 9–11); however, one wonders whether this concept should be completely abandoned. The major reasons for disenchantment with cadmium sulfide were cell instabilities. One instability could probably be avoided by proper sealing or encapsulation of the cell during fabrication. The second instability was more fundamental and due to the mobility of the copper in the cell, which is really a Cu_x CdS cell. Whether this instability can be controlled is debatable, but possibly further low-level funding would not be inappropriate. Very little work has been done on gallium arsenide since the early 1960s and very, very little work has been done on thin-film gallium arsenide (Ref. 12). As discussed previously, gallium arsenide has a band gap more theoretically optimal to photogeneration by solar energy and absorbs almost all usable photons within one or two micrometers. Thus, a thin-film gallium arsenide cell could have a very high efficiency, and since little gallium arsenide material would be used per unit area, it could be highly economical. As stated above, however, a considerable research effort would be necessary before feasibility could even be determined, and with only limited resources one might not consider this to be an appropriate allocation of significant resources at this time, especially if very large cost reductions can be achieved in the reasonably near future by improved array fabrication techniques.

In general, the use of highly automated, large-batch or continuous-belt processing techniques is required for the low-cost production of solar cells, and this is a major Technology Advancement Requirement.

---

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

C

c. Improved array fabrication techniques. Fabrication of solar arrays for space use has been, without exception, on a very-small-volume, custom-built basis, and it has therefore been uneconomical to pursue seriously the high-volume, automated manufacturing techniques that are so prevalent throughout industry in general. Furthermore, cost considerations have not played a major role in the design of space-type solar arrays, where highest priority has been given to ensuring the reliable operation of the array within rather diverse mission constraints. Therefore, the major cost reductions can be expected to be achieved by improved fabrication techniques in the near term, with a significant effort in production and manufacturing engineering, especially since the array, exclusive of the cost of the solar cells, now account for 80–90% of the total cost.

The improvement of array fabrication techniques will require materials and fabrication investigations for substrates, printed circuitry, wiring, module interconnection, and cell laydown, and a considerable effort must be placed on automating the processes involved. Inexpensive techniques for applying the protective layer or coverglass directly onto the cell, or, even better, the completed array, would greatly simplify the process. Automated pulse soldering techniques or parallel gap welding are good candidates for performing interconnections. Techniques for inexpensive cell laydown onto the substrate should be developed, and one should think not only of bonding by means of adhesives and epoxy, but also of possible mechanical attachment, perhaps using the interconnections themselves to hold the cells to the substrate. Work at the NASA Lewis Research Center on encapsulating cell modules in FEP Teflon (Refs. 13 and 14) also appears to be encouraging and should probably be pursued with greater emphasis.

The use of large-area cells (for example, cells fabricated from large-area thick-film silicon ribbons) would significantly reduce the number of required interconnections (and also yield higher packing factors) and would therefore reduce the complexity of array fabrication.

So many options appear to be available for fabricating arrays more economically than is done at present that one would be surprised if effective cost reductions could not be made.

d. Large-area cells and arrays. The use of large-area cells presents an overall cost advantage in array fabrication if the cells on a unit basis are no more expensive than the smaller area cells, because the cell laydown and interconnection for fewer large-area cells should be significantly less expensive than for a greater number of small-area cells. Where large-area cells would, of course, also present significant advantages for the fabrication of the Option 3 (Satellite Station) arrays, in this case it would be expected to be of secondary importance, as against requirements of high power density and light weight that are critical for Option 3. Furthermore, the present techniques for cell blank sizing will result in a tradeoff between minimizing thickness and maximizing area due to breakage factors. Large area *arrays*, on the other hand, have prime importance for Options 2 and 3, where many square kilometers of array area would be required. For Option 1, the area of the array would have to be only large enough to cover the roof. Three methods for fabricating large-area cells are as follows:

(1) Large-area cells can be achieved by cutting the silicon ingot into large disk-shaped blanks, rather than rectangular blanks, as is presently the case, thus making use of the natural cylindrical geometry of the ingot, which can be grown with diameters as large as 7.6 cm. These cells, however, having a poor panel packing factor compared with that of rectangular cells, would probably not be appropriate for Option 3 and possibly not for Option 1.

(2) Large rectangular cells can be obtained by a second method, namely, by slicing the ingot so that the major axis of the rectangle is parallel to the ingot growth axis, thus making use of the length of the ingot rather than the width (which is of smaller dimension).

(3) The third, and most tantalizing, method for achieving large-area cells is growth of large-area, rectangular-shaped silicon ribbons. This latter method has the further advantage of allowing very thin large-area cells to be fabricated; this is not true for method 2, which requires a tradeoff among the breakage, thickness, and area associated with the process. Furthermore, method 2 involves yet another tradeoff: the size of the blank as against ingot utilization, because of the geometric constraints associated with cutting rectangles from cylinders. This, of course, would not be true for method 3.

e. Use of concentrators. One way of avoiding the expense of fabricating solar cells and arrays is to use inexpensive concentrators that would significantly reduce the cost per resultant power output unit. The proponents of Option 3 (Satellite Station) propose using a concentrator system to achieve a 3-to-1 concentration ratio (Ref. 7). This results in the need for developing a cold-mirror concentrator (to minimize array temperature) that can be fabricated, transported, and erected at a cost less than 1/4 that of an installed solar cell array of the same area (since the concentrator system proposed for the Satellite Station is four times the area of the array and results in a net power increase of about 100%).

Because of the temperature rise associated with concentrating the solar energy in this manner for Option 3, and the fact that solar cells decrease in efficiency as temperature is increased, it is estimated that the cell efficiency will drop from the assumed 18% to 11.7%. The decision to use such a system implies that the cost penalties involved in fabricating and erecting a solar concentrator four times the area of the array and the efficiency penalty due to the cell and array heating are more than offset by the 100% increase in power generated by the array.

The desirability of using concentrator systems with solar arrays for the Earth-based systems (Options 1 and 2) is apparently less clear-cut. It was suggested by the author in the early 1960s and later in 1966 (Refs. 15–17) that the use of simple, inexpensive, conical concentrators in conjunction with disk-shaped cells fabricated from a centerless-ground silicon ingot (taking advantage of the natural cylindrical geometry of the ingot) could achieve significant reduction in cost per watt of a solar array system. This certainly appears to be the case for light normally incident upon the cell surface. In actual use, however, the light would not be necessarily normally incident unless a solar tracking system is utilized. Thus, a tradeoff study would be required to determine the cost effectiveness of solar concentrators for optimally oriented stationary systems as against solar-oriented systems that would track the Sun, and both of these against unconcentrated systems. This tradeoff study would probably provide different answers for different geographical locations, and the optimal concentration ratio could also vary with geographic location. To obtain a valid answer, a reasonable estimate of the relative costs of the solar array and the concentrators would be required, and these numbers are simply not available at this time. In the extreme cases, the use of solar concentrators could result in a less cost-effective system than an unconcentrated system or, conversely, the use of solar concentrators could be the only mechanism by which solar photovoltaics could be economically competitive with the more conventional means of electrical power generation. It thus appears that more careful scrutiny is required for the use of solar concentrators (some additional details are given in Ref. 1).

Some effort should certainly be devoted to the use of solar concentrators systems for Options 1 and 2; it is already being considered as an integral part of Option 3. Thus the relative priority is ranked as 1 for Option 3 (Satellite Station) since it is an integral part of the proposed system and ranked either 2 or 4 for the Earth-based systems, depending on whether concentrator systems are required to render the Earth-based systems economically viable.

If concentrator systems are indeed determined to be useful, the arrays must be kept compatible with such systems. For the Satellite station, this means primarily that the additional heating that results from the solar concentration does not adversely affect the array components or the array itself. Again, for the Earth-based systems, the situation is more complex. Not only must the array and components be compatible with the increased temperatures, but the impact of the concentrators on the array performance with respect to sand, sedimentation, dust, and precipitation must also be considered, as must the environmental effects on the concentrating material. The use of large concentrators or smaller individual concentrators is still another tradeoff topic to be studied.

f. Orientation mechanisms/techniques. Here, again, the case is more clear-cut for the Satellite Station than for the Earth-based systems. For the Satellite Station, it would certainly be advisable to provide solar tracking and orientation for the solar arrays, so as to achieve maximum efficiency; this is even more important with solar concentrators. With the Earth-based systems, a tradeoff must be made between the costs of providing the capability for solar tracking, including the implicit requirement that the array be rigidized in some manner, plus the solar tracking and orientation mechanisms required, as against the costs of an unoriented array to achieve the same average daily, monthly, or yearly power output from the array.

At this time, and for some time to come, this question cannot be answered, since the cost associated with all the aspects that need to be considered are completely unknown. The answer might also be expected to vary according to geographic location. One aspect, however, does seem to be intuitively obvious: if it is determined that even an unconcentrated solar array would require provision for solar tracking and orientation of the array, then it is reasonable that the greatest cost effectiveness can be achieved by using inexpensive solar concentrator systems to enhance power output per unit cell. Here, again, the Earth-based systems rank this Technology Requirement either 2 or 4 for reasons similar to those outlined above.

2. ***Weight reduction.*** This is of greatest importance for the Satellite Station, in order to reduce the transportation system costs for putting the array into orbit. At present, these costs are about $700 per kilogram, which of course would be greatly reduced by the use of the Space Shuttle. The costs of transportation and insertion into orbit, however, are still expected to be of major concern since the station weight is estimated to be 18–45 million kilograms (40–100 million pounds). For Option 1 (Rooftop Array), it is simply a matter of logistics, that is, getting the array up on the roof and deploying it, so that light weight would be desirable. For the Solar Farm, weight is not expected to be so critical a parameter, and the low-cost requirement would probably dictate a reasonably low weight in any case.

The proponents of the Satellite Station estimate that a weight reduction by a factor of about 50 is necessary to ensure the feasibility of the economics involved. The Earth-based systems are less stringent as to the technology need for light weight, but even in these cases, weight reduction is desirable for transportation and installation of the arrays. Whereas current Mariner technology utilizes solar arrays capable of approximately 22 W/kg, and roll-out array feasibility of 66 W/kg has been demonstrated, the literature on satellite solar power stations suggests that this figure must grow to 950 W/kg. Technology needed to approach such a requirement includes higher-efficiency cells, lighter-weight substrates and mechanisms, and cells that can better resist the detrimental effects of ionized particle radiation.

a. Higher-efficiency cells. At present a Mariner-class solar cell array weighs 6.5 kg/m^2. The use of similar weight, higher-efficiency cells would proportionately decrease the panel area and therefore the weight required to achieve a given power output. While the absolute value of weight reduction would not be so great for lightweight arrays, the *percentage* weight reduction would be the same, assuming the higher-efficiency cells weighed no more (i.e., if the cell efficiency were doubled, the array area and weight would be halved). Furthermore, as lightweight array development proceeds, the cells could become the dominant weight factor, and it would therefore be important not only to achieve higher cell efficiencies, but also lower cell weight, primarily by reducing the cell thickness and eliminating requirements for solder. Higher cell efficiencies will be achieved by methods previously discussed.

b. Radiation resistance. The radiation resistance requirement is applicable only to the Satellite Station. The rationale for this Technology Requirement is identical to that discussed for high-efficiency cells, since radiation degradation directly affects the power-producing capability of the array and hence the required array area and weight. Of particular concern for the Satellite Station would be the effects of solar flares (Ref. 18), which occur sporadically. It has been observed in the past that one major solar proton event can introduce as many protons into the near-Earth space environment as would be accumulated in a relatively quiet 5-year period. Thus a major solar flare proton event occurring the day after the satellite system is erected in space could result in an immediate decrease of power output capability that would be very significant.

Two primary approaches to minimizing the adverse effects of radiation degradation are:

(1) Design of solar cells and arrays that are inherently radiation-insensitive.

(2) Design of solar arrays that are capable of annealing out damage caused by radiation. For state-of-the-art silicon solar cells, this approach requires a temperature of about 400°C. Because of the high emissivity of the faces of the solar panel, very large power inputs would be required to heat the arrays or array segments to the required temperature. Furthermore, even if the required 400°C temperature could be achieved, significant attention must be paid to matching the thermal expansion properties of the array stack materials (i.e., substrate, adhesives, cells, contacts, interconnections, and coverglasses) to avoid failure-inducing stresses due to the very drastic thermal excursions. An alternative to the use of state-of-the-art silicon cells would be the

use of lithium-doped silicon cells that exhibit significant annealing at temperatures around 60°C (Refs. 19–24).

For Approach 1, the fabrication of cells in which the base region width is considerably smaller than the minority carrier diffusion length would achieve the desired result. In addition, a shift in the spectral response of the cell toward shorter wavelengths, by significantly reducing the depth of the *p–n* junction, would achieve greater radiation resistance.

Radiation resistance could also be theoretically achieved with gallium arsenide solar cells, since most of the usable photons are absorbed very close to the *p–n* junction, and hence long minority carrier diffusion lengths are not required to collect these photons. This is to be contrasted with the absorption of photons in silicon, which can generate and collect solar-generated minority carriers as far away as 250 μm from the junction. Since the effect of penetrating radiation is predominantly the significant reduction of base-region minority carrier diffusion length, the absorption of usable photons at the junction should, at least in theory, render GaAs cells relatively operationally immune to the effects of penetrating radiation until very high fluences are accumulated. Again, there is no major program that would develop such cells to technology readiness.

On the optimistic side, silicon cells having a thickness of only 0.05 mm should also be relatively operationally immune to the minority carrier diffusion length degradation until high fluences are accumulated, since the initial (unirradiated) diffusion length would be a factor of 2 or 3 greater than the thickness of the cell itself.

c. Lightweight substrate and mechanism. Significant improvements in solar cell array weight have been made as a result of the NASA and Air Force Roll-Out Array Programs and the NASA Large Area Solar Array Program (Refs. 25–28) and could be used as baselines for extrapolation toward even lighter weights. Whereas Mariner-class arrays produce 22 W/kg, roll-out arrays have demonstrated specific power of 66 W/kg. These programs utilize lightweight substrates such as Kapton or stretched tape attached to a lightweight beryllium frame upon which the cells are mounted and interconnected. For the Earth-based systems, the use of exotic materials such as beryllium would not be advisable because of the increased costs, and in this case some less expensive metal or plastic could be used to achieve a semirigid or rigid array. Investigations are required into the various means of fabricating the array and appropriate substrates so as to minimize both weight and cost.

The protective layer for the Earth-based systems would be installed either at the array fabrication facility or on-site, whichever is more economically feasible. This would appear advantageous from the point of view of cost and weight, as well as storage and transportation. For the Solar Farm, the array could be rolled out and tied down in some manner at the site of operation to achieve rigidity and resistance to winds. This could be accomplished by attachment to some sort of inexpensive type of structure, such as plastic rods, or the array could be rigidized by chemical or pneumatic means.

For the Rooftop Array, the array could be flexible or attached to an inexpensive frame, as in the Solar Farm; chemically rigidized on the site; or attached directly to the roof. Another approach for the Earth-based systems would be to modify the array system used on the JPL Large Area Solar Array Program, which utilized a frame with stretched tape to provide the substrate upon which the cells were mounted. Such an array structure would not be as convenient for storage and transportation as a flexible roll-up array system, but might greatly facilitate installation.

Enough options exist for the Earth-based systems that, with a reasonable effort, a very economical and convenient system to satisfy this Technology Requirement could be evolved. The same is true for the Satellite station; however, the latter problem is greater and requires much more effort to achieve success. Basically, the proponents of the Satellite Station anticipate using a Kapton substrate and an FEP Teflon protective layer over the cells (Ref. 7).

The array erection and deployment techniques will be most critical for the Satellite Station since this must be performed in space, preferably in an automated manner (but the involvement of manual assistance by astronauts should not be ruled out). Whether the operation is automatic, manual, or a combination of the two, it could be an important engineering problem. Again, the results of the NASA and Air Force Roll-Out Array programs and the NASA Large Area Solar Array Program could be used as a baseline; however, significant modification would be required since the Satellite Station system involves erection and deployment of 33 km^2 (13 mi^2) of array plus 133 km^2 (52 mi^2) of concentrator.

The erection/deployment techniques appropriate to the Earth-based systems, which are, of course, critical to the program, should be far less difficult to achieve in practice than for the Satellite Station system, as discussed above.

3. ***Life extension.*** The usable lifetime of a solar array system will have a direct bearing on the overall cost per kilowatt-hour of the system. Thus provisions for replacement, rework, or refurbishing the solar arrays could favorably affect the economics involved in solar-electric power generation if the usable lifetime of the system is significantly extended by so doing. As a preliminary design goal, a lifetime of approximately 30 years would not seem inappropriate. The life of solar arrays is generally governed by effects that cause deterioration of the conversion efficiency of the arrays through obscuration of the solar cells, through changes in the physics of the solar cell, or through deterioration of the cell-to-cell contacts. Technology needed to meet the requirement of long life involves the resistance of arrays to ionized particle radiation, ultraviolet radiation, humidity, wind, dust, precipitation, and temperature cycling.

For the Earth-based systems, it is to be expected that routine maintenance, replacement, and refurbishing will be economically feasible and will be used to increase the overall lifetime of the array system. The Satellite Station should be designed for minimum maintenance on a routine basis but should be amenable to repair in case of catastrophic events such as meteorite showers or major equipment malfunctions. Since the solar array has no moving parts (exclusive of orientation and deployment mechanisms) and operates at relatively low temperatures, the array should be inherently long-lived if properly designed for the applicable environmental conditions.

a. *Radiation resistance.* The Technology Advancement Requirements for radiation resistance apply only to the Satellite Station. So far as radiation degradation of the array output is concerned, the concept of the satellite power system is considerably different, and more favorable, than the concept normally used for space missions. In normal space missions, once the array power falls below a certain specified design value there is no longer enough power to operate the associated electronics required for the mission; the mission must then be ended. With the satellite solar power system, however, there is no such sharp termination of the mission, and even a severely degraded solar array could continue to supply power to the receiving station. The 30-year life-span requirement, then, becomes somewhat arbitrary, since at the end of 30 years, the array would not simply turn off, but would continue to produce power, possibly at a lower rate. An additional advantage is that, for penetrating radiation, the power degrades as the logarithm of the fluence; that is, for a constant-radiation environment it would take 100 years to degrade the array by the same percentage as was lost during the first 10 years (assuming no capability for annealing out radiation damage). The Technology Advancement Requirements for improving radiation resistance have been discussed above under "Weight Reduction."

b. *Resistance to ultraviolet exposure.* Degradation of solar arrays because of exposure to the ultraviolet component of the solar spectrum is usually reduced or eliminated by the use of ultraviolet reflecting filters deposited onto the solar cell coverglass. Space-type solar arrays are presently designed so that there is little or no adverse effect from ultraviolet exposure; however, since different materials and techniques are expected to be used in the improved arrays, especially for the Earth-based system arrays, where inexpensive plastics might be used, particular attention must be given to the effects of ultraviolet radiation on these new materials and components. Materials interposed between the cell surface and the solar radiation must be resistant to loss of transparency, and materials used to bond one component to another must be resistant to embrittlement resulting from such exposure.

Many materials are extremely sensitive to exposure to ultraviolet (short-wave-length) light. Some materials become embrittled by such exposure; others lose their optical transparency; still others suffer both types of damage. If the protective coatings, coverglasses, or adhesives interposed between the cell surface and the incoming solar radiation lose transparency, this loss would adversely affect the solar cell light-generated current, and consequently the cell or array efficiency. If materials such as epoxies or adhesives became embrittled by ultraviolet exposure, this degradation could cause loss of mechanical integrity of the array and possibly result in decoupling or delamination of protective layers, coverglasses, or cells from the substrate. Such an effect would, of course, be minimized if predominantly mechanical means were used to attach all, or major portions, of the array blanket.

Since the Earth's atmosphere absorbs a considerable amount of ultraviolet light (short-wavelength photons) contained in the solar spectrum, the Earth-based systems might be expected to be somewhat less sensitive to this parameter than the Satellite Station, which receives the total solar spectrum, unattenuated by the Earth's atmosphere. This, assumption, however, may be too simplistic, since the total environments of interest consist of many components that are not necessarily simply superimposed upon one another as independent variables, but that might indeed be dependent variables. Thus, the cumulative effects of two environmental conditions could well be of greater magnitude than the sum of the two separately taken. For example, a combination of high humidity plus ultraviolet light exposure might result in a degradation greater than the sum of exposure to ultraviolet alone plus humidity exposure alone.

For the Earth-based systems, it might be more economical to use a protective layer of a low-cost material, such as an inexpensive plastic, which experiences some amount of degradation from ultraviolet light, and to replace this layer periodically, rather than to use a more ultraviolet-radiation-resistant but expensive material, assuming provisions are made for simple replacement (e.g., by mechanical attachment). This tradeoff would probably not be applicable to the Satellite Station, since it is anticipated that periodic protective layer replacement would be technologically and economically expensive to perform in space.

c. Resistance to humidity. A considerable effort has been expended by JPL to determine the effects of humidity (as well as other environmental conditions) on solar cell behavior, using both electrical and mechanical criteria (Refs. 29–32). The urgency of such investigations was clearly delineated by internal communications within NASA organizations indicating that severe degradation occurred in titanium–silver solar cell contacts, which proved to be a result of exposure to humidity. It should be emphasized that these degradations were the result of exposure to the then-normal storage conditions (where humidity was not controlled) and not a result of specific testing to induce such failures. The problem of solar cell contact degradation in humid environments has been extensively studied, and it appears that the degradation mechanism is a result of a corrosive reaction between the titanium and the silver in the presence of moisture which permeates through the rather thin silver layer to the titanium–silver interface. The JPL investigations indicated that this condition could be greatly alleviated through the application of a solder coating over the contact metals, which acts as a physical barrier to moisture permeation. The JPL studies also indicated, however, that the solder-coating could have adverse effects in other environments, particularly for deep thermal shocks to temperatures about $-196°C$, due to the thermal coefficient of expansion mismatch between the solder and the silicon (Refs. 29, 30, and 32), and to storage at temperatures of approximately 150°C, probably because of the interaction between the tin component of the solder and the silver at this temperature (Refs. 29 and 30).

A second approach to increasing resistance of titanium–silver solar cell contacts to the detrimental effects of humidity was reported several years ago by AEG Telefunken (Ref. 33): palladium was used in the titanium–silver contact system to minimize or eliminate the corrosive reaction. Under JPL funding, two solar cell manufacturers (Heliotek, a Division of Textron, Sylmar, Calif., and Centralab, a Division of Globe-Union, Inc., Milwaukee, Wis.) fabricated and supplied cells utilizing the palladium-containing contact system for JPL evaluation. This evaluation (Ref. 31) indicated little or no advantage to these particular cells in a high-humidity, 80°C environment. Further extensive analysis of these cells by JPL indicated extremely poor process control used by the manufacturers to produce these cells, both in the deposition of the contact materials and in the very high variation in the amount of palladium actually incorporated into the system. (In some cases, analysis showed no measurable quantity of palladium.) Hence, the results of the JPL evaluation are probably not indicative of those that could be achieved with an optimized process.

The problem of contact degradation as a result of humidity exposure is extremely important with respect to the Earth-based systems, where considerable humidity and precipitation exposure for long periods of time can be expected to occur, and such exposure, especially when compounded with exposure to high temperatures, could be disastrous. The problem is somewhat less serious for the Satellite Station, since the only humidity exposure would occur during storage, and this, of course, can be circumvented by careful control of the storage environment. The humidity problem could also be circumvented for all Options by encapsulation of the cells/modules/arrays in a manner similar to that presently being investigated by NASA-Lewis Research Center utilizing FEP Teflon (Refs. 13 and 14). In any case, enough options exist to lead one to believe that with a reasonable effort this Technology Advancement could be acomplished.

d. Resistance to wind/dust/precipitation. The arrays must be protected from the adverse affects of wind, dust, and precipitation for the Earth-based systems. This can probably most conveniently be accomplished by a means of encapsulating the array, somewhat similar to the method being investigated by NASA-Lewis Research Center using FEP Teflon (Refs. 13 and 14); however, perhaps some less expensive alternative material could be used. The replacement or refurbishing of a protective layer to guard against the adverse affects of these environmental factors should also be considered. Such a layer must be highly transmissive with respect to the usable photons of the Earth-surface solar spectrum and must be compatible with the other technology requirements. This Technology Advancement Requirement is not applicable to the Satellite Station, since the storage conditions can be carefully controlled.

e. Capability of withstanding temperature variations. Many spacecraft have been successfully designed to withstand both large numbers of temperature cycles and deep temperature cycles (thermal shocks). Since radical departures in array design and materials are anticipated in the future, care must be exercised to ensure that this capability is not compromised. Degradation resulting from large numbers of temperature cycles is usually associated with fatique mechanisms, while deep temperature cycle degradation usually results from thermal expansion coefficient mismatches between the composite materials of the solar array stack, which can cause very significant stresses.

Resistance to large numbers of temperature cycles. For the Earth-based systems, very large numbers of temperature cycles can be expected due to seasonal variations, diurnal variations, and climatic fluctuations throughout the day. In these cases, the thermal variations could be combined with variations in humidity (the problems of which were previously discussed). The components of the array should not interact adversely with one another (for example, by severe thermal coefficient expansion differences) in a way detrimental to the array performance, and the materials used should not become fatigued by such repeated temperature cycles.

For the Satellite Station, the number of temperature cycles is considerably reduced. The satellite would be exposed to full sunlight most of the time, except for a 1.2-h interval every 24 h for 25 days before and after equinox in the 35,600-km (22,300-mi) synchronous orbit proposed by the proponents of this system. Thus the number of cycles is not nearly so severe as for the Earth-based systems, but the temperature excursions in going from full sunlight with a 3-to-1 concentration ratio to a 1.2-h orbital night would be very large and rapid with respect to time-rate of temperature change, because of the low thermal mass of the array.

Resistance to large temperature excursions. As discussed above, the Satellite Station would undergo very severe and rapid thermal excursions during the 1.2-h orbital night, experienced every 24 h for 25 days before and after equinox. It has been the experience of panel designers that the failure mechanisms resulting from a large number of rather shallow temperature cycles can be quite different from those resulting from a smaller number of very deep temperature cycles. In the former, the failure is generally a fatigue mechanism, and in the latter, the failure mechanism is due to thermal expansion coefficient mismatches of the component materials of the array. Deep temperature cycles would be much less likely for the Earth-based systems than for the Satellite Station.

Technology Requirements to solve temperature variation problems include careful selection of the materials, with respect to fatigue characteristics and thermal expansion coefficient matches, and proper integration of the materials to form the solar array blanket (e.g., mechanical design of interconnectors to ensure compliancy and adequate stress-relief). Enough materials and design alternatives appear to be available to satisfy these requirements with a reasonable amount of effort. Furthermore, the considerable progress being made in stress analysis and modeling appropriate to solar array design (Refs. 34 and 35) provides a good baseline from which advancements can be made.

4. Reliability. As discussed above under "Life Extension," reliability in the three Options being considered has a somewhat different connotation than reliability in normal solar arrays for space application. In normal space-type arrays, certain finite boundary conditions, primarily in array power output, are imposed, and once the array no longer satisfies these boundary conditions, which are very specific, the array can be considered as having "failed." Thus, for example, under the normal concept of reliability we would demand that the array produce an amount of power equal to or greater than a specified value for the 30-year design goal lifetime. Furthermore, reliability considerations presently used tacitly assume that there is no capability for repair, rework, or replacement of defective components, but that the deployed array, as originally designed and fabricated, must survive and satisfy the boundary conditions.

Clearly, the highest reliability (as presently defined in our space program) is desired in the environments to which the arrays in these Options will be exposed; however, there will very likely be a major tradeoff between reliability and the costs of array fabrication. That is, there will generally be some adverse cost implications as a result of increasing reliability. It might therefore be economically advantageous, on a long-term systems basis, to accept a somewhat lower reliability and a requirement that the degraded elements be repaired, replaced, or refurbished, rather than to demand that the array operate for the 30-year design goal without such maintenance requirements.

The Earth-based systems, being easier to maintain, could be expected to benefit especially from such a maintenance concept, whereas, for the Satellite Station, replacement, refurbishment, and rework would be considerably more difficult. Therefore, the reliability and stability requirements have the greatest priority for the Satellite Station, with a somewhat lower priority for the Earth-based systems. For the Solar Farm, some periodic and routine maintenance is expected, so that defective parts could be replaced or refurbished and the array could be cleaned periodically. For the Rooftop Array, the homeowner or the service contractor would be required to get up to the roof, locate the defective part, and replace or rework it; therefore, reliability and stability are somewhat more important for this Option than for the Solar Farm.

The requirement for reliability and stability for all Options implies that the worst-case and nominal-case environmental conditions be accurately known, and this in itself would require a significant effort.

a. Definition of the environment. One of the first orders of business must be the definition of the anticipated environments. Oddly enough, the space environment appropriate to the Satellite Station is probably most easily defined, with the exception of the sporadic solar flare protons, about which there is very little information, and the possibilities of meteorite showers, which are also sporadic and hence unpredictable. The need does exist, however, to define this environment as best we can, using the considerable body of existing information on the space environment and perhaps performing additional selected experiments to fill in any remaining gaps.

The definition of the Earth-based systems' environments will vary with geographical location. While a good deal of information on certain aspects of the environment is available through the United States Weather Service, very little is known of how wind, dust, wind-borne particles, sedimentation rates etc., may affect solar arrays. Thus, the existing information and its applicability to solar array operations must be evaluated, and the type of additional information that is required must be determined. Since the real combined effect of all the environments can be discovered only by actually operating and measuring the arrays installed in representative geographical locations, a program for accomplishing this must be initiated. Such a program would define nominal and worst-case levels for the environmental components and develop testing procedures (preferably accelerated tests) to be applied to candidate array systems.

This Technology Requirement is of major importance; a significant effort involving literature searches, compilation of data, statistical analysis, computer modeling, laboratory testing, and on-site testing and evaluation will be required.

b. Characterization of cell, module, and array. The cell, module, and array electrical and mechanical characteristics must be determined, principally as a function of the environment (including insolation) in which the system is to be operated. Design information may initially require a significant amount of characterization, possibly even down to microscopic evaluations of the crystalline perfection of the solar cell. Such a study could utilize analytical techniques presently used by JPL and other organizations to evaluate and modify the cell, module, and array design. The development effort will require comprehensive characterization; for actual production of solar arrays, however, the minimum characterization measurements to achieve a desirable system must be determined and used because the degree of characterization is reflected in the total system cost. Since the Earth-based systems are amenable to rework and replacement, the characterization required for these arrays should be less than those required for the Satellite Station, where such operations would have to be accomplished in space. Typical techniques and processes for characterization are described in detail in Refs. 18–24 and 29–35.

c. Maintenance. Because there will likely be some tradeoff between reliability and array fabrication costs, as discussed above, considerable attention must be given to possible cost reductions and increase of overall system lifetime associated with maintenance techniques to replace, refurbish, or rework degraded portions of the array. This appears to be particularly appropriate for the Earth-based systems and should not even be ruled out for the Satellite Station.

In the ideal case, for any Option, no maintenance whatsoever would be required; however, it is to be expected, especially for the Earth-based systems, that some maintenance *will* be required, such as periodic cleaning of the surfaces and/or replacement of elements that have been damaged by such factors as sand or pebble abrasion, excessive wind loading, etc. Perhaps the space environment, other than the radiation problem previously discussed, would be more benign in this respect, meteorites being the only other element one could envision as causing physical damage to the array. In this case, enough redundancy and diode protection devices might be designed into the system so that maintenance would not be required, except for very highly improbable events, such as large meteorite showers impinging directly on the spacecraft and/or arrays.

Because a homeowner or building manager might be reluctant to do his own rooftop maintenance, a minimum-maintenance requirement might be more important for the Rooftop Array than for the Solar Farm, where routine maintenance would be expected to be performed by semiskilled technicians. However, material and fabrication costs for both Earth-based systems must be traded off against maintenance costs to achieve greatest overall cost effectiveness; if the degraded elements of the array could be located and replaced very cheaply, it might be most economical to accept some measure of maintenance requirement for both systems.

Technology for simple replacement of defective array segments is especially needed in the Satellite Station, since this will have to be accomplished in space; the replacement-simplicity requirement would probably be least stringent with respect to the Solar Farm and somewhat more important for the Rooftop Array, so that the person responsible for the building could replace defective segments himself, should he so desire, or hire a semiskilled operator to do it. For all three Options, the replacement of solar cells must be relatively simple for the systems to be viable.

A simple, accurate means of locating defective or degraded elements would be required for the Satellite Station and would also be very important for the Solar Farm, since, in this array, areas of the order of square miles would be involved. For the Rooftop Array, some system of monitoring array segment performance within the dwelling could perhaps be utilized, especially since the array area involved is not nearly so large as the others, and location of defective segments might therefore in practice be simpler.

5. Fabrication capability. The requirement for total combined power output of solar arrays for terrestrial applications is in the thousands of megawatts rather than the kilowatt range. In addition to the obvious problem of fabricating arrays for the Solar Farm and the Satellite Station, even if done piecemeal, there are production problems in terms of the large demand for silicon solar cells for all three Options. Cell production in the United States would have to increase by at least five orders of magnitude. Moreover, the energy consumed in producing silicon cells and solar arrays must be considered in relation to the energy that can be extracted from the system. The development of simplified automated cell and array production techniques and the development and use of low-cost, readily available materials are significant Technology Advancement Requirements if photovoltaic solar arrays are ever to become feasible producers of commercially available electrical energy.

a. Cell fabrication techniques. Improvements in cell fabrication techniques are discussed in detail in Ref. 1. The first consideration must be the choice of solar cell material on the basis of (1) economy, (2) amenability to fabrication of high-efficiency, stable solar cells, and (3) availability. Silicon was recommended as the baseline cell material since it satisfies requirement (2) and is the most well-understood semiconductor material. Silicon is the second most abundant element on Earth, but the availability of silicon in the ultrapure, single-crystalline form presently used for solar cell fabrication is very limited. For example, to cover one square mile of area with single-crystalline silicon cells 0.25 mm thick, assuming a wastage of 50% of the silicon (which unfortunately is optimistic with respect to present-day fabrication techniques), represents six times the yearly production of such silicon in the United States (Ref. 8). Ultrapurity single-crystalline silicon costs about $0.30 per gram. As discussed previously, the use of high-purity or metallurgical grade silicon (as opposed to ultrapurity single-crystalline silicon) would help solve the problems of economy and availability but might result in lower efficiency cells. The increased demand for ultrapurity single-crystalline silicon should also make more silicon available at lower cost because of the savings and automation improvements of high-volume production. More efficient use of the silicon—for example, by growing it in the form of large-area silicon films—would offer further improvement. The availability of other solar cell materials that may be used must also be considered. For example, some proponents of cadmium sulfide advocate reclaiming the cadmium, which is in limited supply, from cells that are no longer usable (Ref. 36). Reclamation of materials used in the Earth-based systems should be considered, while this would probably not be appropriate for the Satellite Station.

The use of large-area cell blanks should present significant advantages for cell processing, since fewer pieces must be handled to achieve a required total cell area. To optimally integrate large-area cell blanks into the cell processing, severe modifications and improvements in production techniques are required, but such modifications and improvements are required in any case to significantly improve the quantity and economics associated with cell fabrication. All processing steps must be greatly improved and automated, including blank sizing, junction formation (diffusion, epitaxial growth, ion implantation, etc.), electrical contact (or contact–interconnect) formation (evaporation, electroforming, plating, silk screening, etc.), antireflective coating, measurement, and all associated pre- and post-operation cleaning/etching treatments. "Endless-belt" processing steps are to be preferred.

b. Array fabrication techniques. The key to improved fabrication techniques lies in total automation of the processes, a drastic departure from the traditional concept of solar arrays as a highly specialized custom-built product to the consideration of solar arrays as a mass-market, *very*-high-volume product. This requires the involvement of a new body of talent with expertise in the area of such mass-market, high-volume fabrication. It requires the merging of the experience of the aerospace community in the design, testing, and evaluation of the array, with the experience of the high-volume production-oriented industrial community, hitherto untapped in the fabrication of solar arrays. The design engineer must ensure minimum material costs and compatibility of all materials and processes with one another, as well as maximum reliability, allowable tolerances, and efficiency in anticipated environments. The manufacturing engineer must ensure high-volume production capability, minimum equipment costs, automation of processes, minimum reject rate, minimum use of highly specialized equipment and controls, maximum process simplicity, maximum rework capability, and maximum materials and equipment utilization. In actuality this start with cell fabrication, integrated into module fabrication, substrate fabrication (material, techniques, size, weight, printed circuitry), cell/module laydown and interconnection techniques and materials (e.g., welding, mechanical bonding, chemical bonding, mechanical attachment), protective layer attachment (coverglass, integral coverglass, plastics, Teflon, spray-on, roll-on, mechanical, etc.), characterization (mechanical/electrical), and rework as required.

It is imperative that automation of all processes be developed and coupled with low-cost, readily available materials.

V. Discussion and Conclusions

The Technology Advancement Requirements represent a 3-order-of-magnitude reduction in costs and a 5-order-of-magnitude increase in production capability. While these approximate order-of-magnitude numbers appear formidable, such cost reductions and capacity increases have been achieved with reasonable regularity in other areas. Furthermore, the fundamental technologies of fabricating solar arrays and their components are rather well understood, so that we have a firm baseline from which to work. The Technology Advancements do not require major breakthroughs (although, of course, major breakthroughs would increase the probability of success) or the use of exotic materials, but rather are predicated on significant extensions of existing technology. The approach toward achieving the Technology Advancements will center around engineering and manufacturing improvements and not around major commitments to fundamental research (as was the case at the inception of the nuclear reactor electrical generator development and will be the case with the development of a fusion-process generator) and, therefore, the success probability should be reasonably high.

The author's personal bête noire is estimating the eventual costs of a solar array system to provide large-scale electrical power generation for terrestrial applications, mainly because there are no hard data from which to draw sound conclusions. Qualitatively, however, there appears to be good reason for considerable optimism. Silicon, which is proposed as the baseline material for fabrication of the solar cells, is the second most abundant element on Earth, and therefore there is certainly no lack of material: it is simply a question of processing this material inexpensively into a form usable for photovoltaic energy conversion.

Despite all the problems outlined in the Technology Advancement Requirements, it seems almost inconceivable that such a simple thing as a solar array substrate with printed circuit interconnections and wiring upon which cells are mounted in some simple, economical manner, and over which some inexpensive protective layer is positioned, having no moving parts and using no exotic materials, cannot be made for a few dollars a square meter rather than the thousands of dollars per square meter experienced in the space program. History gives us many examples of items which were once prohibitively expensive but which have now become so inexpensive that they have become disposable. (Aluminum was once so expensive to produce that regal crowns were fabricated from this exotic and precious material—we now use it for wrapping our leftovers.) It is almost more difficult for the author to believe that economically viable solar arrays *cannot* be built rather than that they *can* be built.

The same philosophy can be applied to the other problems mentioned in Section III (i.e., electrical energy storage devices, satellite-to-Earth power transmission, attitude control, etc.). Since no major fundamental breakthroughs are required, but rather drastic modification and improvement of existing technologies, it might appear that successful attainment of the goal of widespread, pollution-free generation of electrical power could fail to be achieved only because of a lack of inventiveness, resourcefulness, or commitment of resources to achieve that goal.

References

1. Berman, P. A., *Considerations With Respect to the Design of Solar Photovoltaic Power Systems for Terrestrial Applications,* Technical Report 32-1556. Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1972.

2. Glaser, P. E., "Power From the Sun," *Mech. Eng.,* Vol. 91, No. 3, Mar. 1969.

3. Gaucher, L. P., "Energy Sources of the Future for the United States," *J. Solar Energy Soc.,* Vol. 9, 1965.

4. Goubau, G., "Microwave Power Transmission From an Orbiting Solar Power Station," *J. Microwave Power,* Vol. 5, No. 4, Dec. 1970.

5. Robinson, W. J., Jr., *The Feasibility of Wireless Power Transmission for an Orbiting Astronomical Station,* NASA Technical Memorandum TM-X-53806. National Aeronautics and Space Administration, Washington, D.C., May 1969.

6. Brown, W. C., "The Receiving Antenna and Microwave Power Rectification," *J. Microwave Power,* Vol. 5, No. 4, Dec. 1970.

7. Ralph, E. L., and Benning, F., "The Role of Solar Cell Technology in the Satellite Solar Power Station," *Conference Record of the 9th IEEE Photovoltaic Specialists Conference,* held at Silver Spring, Md., May 1972, Institute of Electrical and Electronics Engineers.

8. Ralph, E. L., "Large Scale Solar Electric Power Generation," presented at the Solar Energy Society Conference, NASA Goddard Space Flight Center, Greenbelt, Md., May 1971.

9. *Cadmium Sulfide Thin-Film Solar Cell Review,* NASA Technical Memorandum TM-X-52920. NASA Lewis Research Center, Cleveland, Ohio, Apr. 1970.

10. Palz, W., et al., "Analysis of the Performance and Stability of CdS Solar Cells," *Conference Record of the 8th IEEE Photovoltaic Specialists Conference,* held at Seattle, Wash., Aug. 1970, Institute of Electrical and Electronics Engineers.

11. Bernatowicz, D. T., and Brandhorst, H. W., "The Degradation of Cu_2S–CdS Thin Film Solar Cells Under Simulated Orbital Conditions," *Conference Record of the 8th IEEE Photovoltaic Specialists Conference,* held at Seattle, Wash., Aug. 1970, Institute of Electrical and Electronics Engineers.

12. *Thin Film GaAs Photovoltaic Solar Energy Cells,* RCA Final Report, Contract NAS-8510, Aug. 1967.

13. Broder, J. D., et al., Recent Results of FEP Solar Cell Cover Development," *Conference of the 9th IEEE Photovoltaic Specialists Conference,* held at Silver Spring, Md., May 1972, Institute of Electrical and Electronics Engineers.

14. *Investigation of FEP Teflon as a Cover for Silicon Solar Cells,* NASA CR-72970, Contract NAS 3-14398. Lockheed Palo Alto Research Laboratory, Palo Alto, Calif., Aug. 1971.

References (contd)

15. Berman, P. A., *High Efficiency Silicon Solar Cells, Report No. VIII, Final Report,* U.S. Army Electronics Laboratories contract DA 36-039-SC-907, covering the period from June 1962 to July 1964. Heliotek, a Division of Textron, 1964.

16. Berman, P. A., "Design of Solar Cells for Terrestrial Use," presented at the Solar Energy Conference, Boston, Mass., Mar. 1966; published in *Solar Energy,* Vol. 11, Nos. 3 and 4, 1967.

17. Berman, P. A., and Ralph, E. L., "Improved Solar Cells for Use in Concentrated Sunlight," *Proceedings of the 18th Annual Power Sources Conference,* U.S. Army Signal Corps, Ft. Monmouth, N.J., May 1964.

18. Berman, P. A., *Effects of Solar Proton Flares on the Power Output of Solar Cells Having Various Configurations,* Technical Report 32-1251. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1968.

19. Berman, P. A., "Summary of Results of JPL Lithium-Doped Solar Cell Development Program," *Conference Record of the 9th IEEE Photovoltaics Specialists Conference,* Silver Spring, Md., May 1972, Institute of Electrical and Electronics Engineers.

20. *Proceedings of the Fourth Annual Conference on Effects of Lithium Doping on Silicon Solar Cells,* Technical Memorandum 33-491, edited by P. A. Berman. Jet Propulsion Laboratory, Pasadena, Calif., Sept. 15, 1971.

21. Berman, P. A., *Effects of Lithium Doping on the Behavior of Silicon and Silicon Solar Cells,* Technical Report 32-1514. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 1, 1971.

22. *Proceedings of the Third Annual Conference on Effects of Lithium Doping on Silicon Solar Cells,* Technical Memorandum 33-467, edited by P. A. Berman and J. Weingart. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 1, 1971.

23. Berman, P. A., "Status of Lithium Solar Cell Investigations at the Jet Propulsion Laboratory," *Conference Record of the 8th IEEE Photovoltaic Specialists Conference,* held at Seattle, Wash., Aug. 1970, Institute of Electrical and Electronics Engineers.

24. *Proceedings of the Conference on Effects of Lithium Doping on Silicon Solar Cells,* Technical Memorandum 33-435, edited by P. A. Berman. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1969.

25. Wolff, G., "The Flexible Roll-up Solar Array Flight Experiment," *Conference Record of the 9th IEEE Photovoltaic Specialists Conference,* held at Silver Spring, Md., May 1972, Institute of Electrical and Electronics Engineers.

26. *Flexible Rolled Up Solar Array,* Hughes Aircraft Final Report, Contract AF 33(615)68-C-676. Hughes Aircraft Company, Nov. 1970.

27. *Rollup Sub-Solar Array,* General Electric Final Report, Contract No. JPL 952314. General Electric Company, Oct. 1970.

28. *Lightweight Solar Panel Development,* Boeing Final Report, Contract No. JPL 952571. The Boeing Company, July 1970.

References (contd)

29. Berman, P. A., and Yasui, R. K., *Effects of Storage Temperatures on Silicon Solar Cell Contacts,* Technical Report 32-1501. Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1971.

30. Berman, P. A., and Yasui, R. K., *Supporting Data Package for TR 32-1541, Effects of Storage Temperatures on Silicon Solar Cell Contacts,* Technical Memorandum 33-497. Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1971.

31. Yasui, R. K., and Berman, P. A., *Effects of High-Temperature, High-Humidity Environment on Silicon Solar Cell Contacts,* Technical Report 32-1520. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1971.

32. Moss, R., and Berman, P. A., *Effects of Environmental Exposures on Silicon Solar Cells,* Technical Report 32-1362. Jet Propulsion Laboratory, Pasadena, Calif., Jan. 15, 1969.

33. Fisher, H., and Gereth, R., "New Aspects for the Choice of Contact Materials for Silicon Solar Cells," *Conference Record of the 7th IEEE Photovoltaic Specialists Conference,* held at Pasadena, Calif., Nov. 1968, Institute of Electrical and Electronics Engineers.

34. Salama, A. M., Rowe, W. M., and Yasui, R. K., *Stress Analysis and Design of Silicon Solar Cell Arrays and Related Material Properties,* Technical Report 32-1552. Jet Propulsion Laboratory, Pasadena, Calif., Mar. 1972.

35. Butterworth, L. W., and Yasui, R. K., *Structural Analysis of Silicon Solar Arrays,* Technical Report 32-1528. Jet Propulsion Laboratory, Pasadena, Calif., May 1971.

36. Boër, K. W., "Large Scale Use of Photovoltaic Cells for Terrestrial Solar Energy Harvesting," *Conference Record of the 9th IEEE Photovoltaic Specialists Conference,* held at Silver Spring, Md., May 1972, Institute of Electrical and Electronics Engineers.

NASA — JPL — Coml., L.A., Calif.