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ABSTRACT

An evaluation of the main terrestrial photovoltaic development projects (LSA and Concentrator) has been performed. Technologies that may have applicability to space power are identified. Where appropriate, recommendations are made for programs to capitalize on DOE developed technology. It is concluded that while the funding expended by DOE is considerably greater than the space (NASA and DOD) budget for photovoltaics, the terrestrial goals and the means for satisfying them are sufficiently different from space needs that little direct benefit currently exists for space applications.

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SECTION I

INTRODUCTION

Five years ago an ambitious program was initiated to develop solar photovoltaic conversion into a major energy source for commercial use in the United States. The program, as originally constituted, sought to bring about a major reduction (orders of magnitude) in the cost of photovoltaic power systems using a 2-stage approach. The initial phase would emphasize the relatively mature silicon technology in order to demonstrate that photovoltaics could be cost competitive, at a certain production level, with conventional energy sources. In parallel, a broad-based research effort keyed to advanced photovoltaic materials, preferably in thin film form, would be implemented. It was planned that after silicon technology had been used to demonstrate the effectiveness of photovoltaics, further cost reductions would occur with the introduction of new photovoltaic materials expressly tailored for terrestrial use.

The purpose of this report is to evaluate the U.S. terrestrial photovoltaics program and attempt to identify areas of new technology which could be employed to benefit the nation's space power needs. It is extremely important to realize at the onset that the goals and needs of the terrestrial photovoltaics program are not the same as those required for space power applications. The areas of technology that must be brought to readiness by the terrestrial program are more numerous and in some cases, more challenging, thus requiring a significantly higher level of funding as compared to space photovoltaics. We should not be deceived into expecting obvious and immediate major benefits for space power simply because an order of magnitude more funding is being expended in the photovoltaic area. Support of this view will be developed in greater detail in subsequent sections of this report.

There are two major efforts to bring silicon to commercial readiness. The larger of the two, the Low-Cost Solar Array (LSA) Project, managed by the Jet Propulsion Laboratory, seeks to achieve low-cost photovoltaic power by using flat plate solar cell arrays. The other approach, the Photovoltaic Concentrator Technology Development Project, managed by Sandia Laboratories, is attempting to reach the low-cost goals by employing solar cell arrays in conjunction with solar concentrating systems. Although both projects emphasize silicon, each is also active in alternate materials such as CdS and GaAs. The fundamental research in alternate photovoltaic materials is managed by the Solar Energy Research Institute (SERI). The great majority of research is still in an embryonic stage so an accurate evaluation of the SERI work for space applicability cannot be performed at this time.

The LSA and Concentrator Development projects have adopted different approaches to achieve low-cost terrestrial photovoltaics. The LSA Project has developed a complete strategy for meeting the 1986 target of $0.50 per peak watt (1975 dollars) using flat plate photovoltaic arrays. There are no major intermediate cost milestones because the success of the LSA Project depends on the development of a number of major technical objectives which when combined will yield their cost goal. This is not to imply that cost reductions will not occur until 1986. In fact, the cost of flat plate terrestrial silicon solar cell modules has decreased by at least an order of magnitude in the last 4 years.

In contrast, the Concentrator Development Project is following an incremental plan. FY'80 has been identified as the point where an intermediate cost goal of $2 per peak watt will be demonstrated. In FY'81 it is planned to show technical feasibility for obtaining $0.50 per peak watt, with the demonstration of technical readiness occurring in FY'83.

SECTION II

LOW-COST SOLAR ARRAY (LSA) PROJECT

The processes required to produce a silicon solar cell module were carefully examined and, as a result of this analysis, target cost goals were established for each major operation. Four key technical objectives were defined. The cost of polysilicon, from which semiconductor silicon is produced, had to be reduced by a factor of 6. A silicon sheet-forming process had to be developed in order to eliminate the costly and wasteful process of sawing ingots. Techniques for encapsulating modules cheaply in such a way as to yield a 20-year operating lifetime were necessary. Finally, automated processes for producing solar cells and modules were required.

In the following sections, a brief progress summary and evaluation of each technical objective of the LSA Project will be presented. An attempt will be made to identify any technology that has potential for space power applications. If appropriate, recommendations for implementing those technologies deemed useful will be offered. Whenever possible, projections of future progress will be made.

A. MATERIALS TASK

Two approaches were selected for obtaining low-cost polysilicon. One was to use alternate, energy efficient technologies such as fluidized bed reactors and pyrolysis coupled with less costly feedstock to develop a new inexpensive process for producing semiconductor grade silicon. The other was to investigate techniques for producing a lower grade of silicon from metallurgical grade polysilicon. Although this "solar" grade of finished silicon would probably not possess the purity of semiconductor grade material, it was hoped that solar cells produced from this material would have a conversion efficiency sufficient to satisfy the overall cost goal of $0.50 per peak watt. However, a more detailed analysis of those factors controlling module cost indicates that cell conversion efficiency has to be much higher than originally estimated (Reference 1). The net effect of this information has been to deemphasize the "solar" grade silicon approach and concentrate most of the activity towards producing semiconductor grade polysilicon.

Today the silicon materials effort is entering the experimental process system development phase with at least two candidate semiconductor grade polysilicon processes (References 2 and 3). It will require from 3 to 5 years for these processes to be proven with respect to production capacity, cost, and silicon purity. Then depending on the polysilicon requirements of the terrestrial solar cell industry, it may be another 3 to 5 years before low-cost polysilicon useful for space power applications would be available.

There is some activity still proceeding in the solar grade silicon area that could have some potential application for space. In the time prior to the realization that high efficiency terrestrial solar cells were necessary, a great deal of effort was expended on characterizing the influence of impurities on the conversion efficiency of silicon solar cells. In addition, more sophisticated diagnostic tools were developed for detecting and measuring the impurities in silicon.

A relatively large number (200-500) of impurity doped silicon solar cells have been made using aerospace fabrication techniques and process controls (Reference 4). An extremely sensitive method (analytical photon catalysis) for detecting impurities in the parts per billion range is being developed (Reference 5). These cells and this technique could constitute the nucleus of a cost-effective program aimed at a better understanding of the factors influencing the behavior of silicon solar cells in the space radiation environment.

It is claimed by some that the space radiation induced degradation observed in silicon solar cells can be explained completely in terms of the major known impurities in silicon (carbon and oxygen) coupled with the dopant (boron) and associated crystalline defects such as vacancies. However, other workers in the field have suggested that trace impurities below the limits of conventional detection techniques are also involved. It is possible that this could be investigated using the newly developed detection techniques. The irradiation and analysis of carefully selected impurity doped silicon solar cells might provide additional information to support either view.

In summary, even if low-cost (factor of 6 cheaper) semiconductor grade polysilicon were available, there would be almost no effect on the cost of silicon space cells. This can be better appreciated by analyzing the cost of the polysilicon used to produce 1 watt of power for space use. In terms of 1975 dollars, 1 kilogram of polysilicon costing $60/kg would yield enough solar cells to produce 30 to 40 watts of power in space. Thus the cost of polysilicon is $1.50-$2 per watt. Space cells cost approximately $60 per watt (1975 dollars). Reducing the cost of polysilicon by a factor of 6 would result in a savings of between $1.25 and $1.65 per watt. This represents less than a 3 percent reduction in the cost of space cells.

B. SILICON SHEET TASK

The second major technical objective of the LSA project is to develop an economical method of producing large area silicon sheets that can yield solar cells with acceptable (13-15 percent AM1) conversion efficiency. As a general rule, the AM1 (terrestrial) efficiency is approximately 10 percent greater than AM0 (space environment), e.g., 13-15 percent AM1 translates to approximately 11.5-13.5 percent AM0. This is due to the difference in the distribution of energy between the two spectrums. The AM1 spectrum has a higher proportion of long wavelength (lower energy) photons which can be more efficiently converted by the silicon solar cell.

The major objective of the sheet task effort is the conservation of silicon. The cost of silicon in both polysilicon and finished form has been shown to be the limiting factor in achieving the goal of $0.50 per peak watt. With current ingot growing and cutting technology, approximately 75 percent of the finished silicon is wasted. By growing sheet directly from the melt, most of the losses that now occur would be eliminated.

Originally two main approaches were taken for silicon sheet formation, namely shaped growth and supported film technology. However, it was soon suggested by DOE that some work in ingot technology also be supported in hopes that an intermediate cost goal of $2 per peak watt could be demonstrated in 1982. The early assessment (Reference 6) that ingot technology could not achieve the ultimate cost objective has been revised. The present estimate is that the ingot approach may be capable of coming very close to the target cost requirements for finished silicon material. Therefore there are now three approaches being pursued, with ingot growth appearing to be the likely candidate for initial implementation. Reconsideration of ingot growth has focused more attention on sawing techniques.

The supported film approach has shown the least progress of the three. The main problem is cost. Technologies such as chemical vapor deposition and epitaxy have failed to show sufficient promise with respect to achieving $0.50 per peak watt, to warrant continued activity. In the case of epitaxy, the throughput rate using present equipment was not capable of meeting project goals. This particular activity had been previously supported by NASA as a means of providing better solar cell radiation performance in space (Reference 7). The only viable candidate remaining is a method for forming thin layers of silicon on extremely inexpensive ceramic substrates (Reference 8). There are two drawbacks in this technology for most space applications. The cell efficiency goal is only 12 percent AM1 (11 percent AM0) and the mass of the ceramic substrate does not appear to be compatible with the mass constraints placed on most space solar cells. There is no doubt that silicon on ceramic cells would be a strong candidate technology for shuttle launched low earth orbital power sources if they became available at a cost approaching $0.50 per peak watt, since volume rather than mass is the main constraint for this class of NASA missions. In the case of epitaxial or chemical vapor deposited silicon solar cells, the fact that they are no longer considered viable for terrestrial applications should not preclude NASA from independently considering these technologies on their other merits (low mass, potential for improved radiation resistance).

The leading candidate technologies for producing shaped silicon are dendritic web growth and edge-defined film-fed growth (EFG) ribbon. These techniques, like supported films, produce finished silicon in geometries (rectangular rather than round) that allow solar cell modules to have a high cell packing factor. In addition, the silicon thickness can be as thin as is practical (50-150 μm) for the fabrication of cells and modules. Due to the high packing factors that can be attained, the requirements for cell conversion efficiency can be relaxed as compared to silicon ingot technology.

The three criteria, all related to cost, used to judge shaped silicon are growth rate (cm2/min), geometry (length, width and thickness) and conversion efficiency. Since each technique has its own unique limitations, the criteria vary for each method. The efficiency requirement is perhaps the most important for space applications since it largely determines the mass and area of solar cell panels. Therefore, it appears that dendritic web which has demonstrated conversion efficiency equal to that of single crystal Czochralski silicon (Reference 9) shows the greatest potential for space power applications. It should be pointed out that dendritic web technology was originally supported by DOD (Reference 10) and later by NASA (Reference 11). This is only one example of space power technology which has been translated to the terrestrial area.

There are a number of concerns that should be mentioned with regard to the utility of shaped silicon for space. Since these techniques have the potential for efficiently utilizing silicon, a lower cell efficiency can be tolerated because an overall economic advantage is still possible. Target values of $\sim$12 percent AM1 ($\sim$11 percent AMO) are presently considered acceptable. Both approaches (web and EFG) appear capable of meeting this efficiency requirement. It is quite possible that in scaling any of these processes to production quantities, some conversion efficiency may be sacrificed in favor of growth rate or geometry.

There is no apparent reason to expect shaped silicon to possess any better resistance to radiation than present single crystal silicon. In fact, since contaminants are one of the major problems in EFG ribbon silicon, this material may have inferior radiation behavior in space. It would be prudent for NASA to consider evaluating EFG silicon with respect to radiation performance on a continuing basis as the technology evolves. Another major concern is the inherent stress of shaped (EFG or web) silicon. Although stress levels may be reduced to the point that they have no effect on cells performing in the terrestrial environment, this is no guarantee that such material would be acceptable for space use. This would appear to be another area that requires testing and evaluating by NASA.

The ingot portion of this task is primarily oriented towards rapid growth of very large diameter silicon crystals using melt replenishment to reduce the cost of crucibles and other expendable materials. Growth rates of over 2 kg per hour are required, and this in turn demands that the crystal diameter be in excess of 10 cm because of thermodynamic considerations in pulling from the melt. The concept of pulling more than one ingot from a crucible has been demonstrated (References 12 and 13). Another approach is to cast large blocks of silicon using a heat exchanger. The cast silicon because of its geometry can be more efficiently utilized. Since grown ingots yield slices whose circular shape would reduce the packing factor of modules, the terrestrial conversion efficiency requirements are high, in fact they would satisfy the present requirements for most space missions (12.5-13.5 percent AMO). The cast silicon can have a lower efficiency (10.5-12.0 percent AMO) and still be competitive because of its rectangular geometry which yields higher module packing factors. Obviously, the cost penalty for shaping a circular slice of silicon into rectangular form would be minor if the cell were to be used for space power applications ($50-100 per watt). However, if the terrestrial cost target ($0.50 per peak watt) is to be met, it appears that silicon conservation is a critical requirement.

Progress in the melt replenishment method has been extremely rapid and it is possible that crystal growers expressly designed to operate in this mode will be available to the terrestrial solar cell industry within 2 years. The impact will probably be minimal on those companies producing silicon solar cells for space because of the relatively small demand for space cells. In the event that a significantly greater demand for space cells occurred in the next decade, the space solar cell manufacturers might consider replacing their present crystal growing equipment with growers employing melt replenishment. It should be pointed out that the use of melt replenishment is an attempt to reduce the cost of labor and expendable materials such as crucibles. The cost advantage using this approach is only a few cents per watt and can only be gained by full utilization of the production output of the equipment.

Before using the output of the new machines for space solar cell applications, it will be necessary to demonstrate that the inherent quality of the silicon produced is equivalent to present single crystal material. Melt replenishment has the potential for changing the impurity distribution within the various ingots pulled from the single crucible, and this could have a deleterious effect on the conversion efficiency and radiation resistance of cells made from this material. This concern argues for some effort on the part of NASA to evaluate the utility of melt replenishment silicon for use in the fabrication of space solar cells.

The ultimate success of the ingot or cast silicon approach for terrestrial applications will be determined to a great degree by the progress made in silicon sawing techniques. The critical sawing variables are wafer thickness, kerf loss, cutting speed, amount of damage introduced and the cost of the expendable materials.

Improvements in ID sawing, and multiple blade sawing, both of which are employed by the space solar cell industry, are being developed by the LSA Project. In multiple blade sawing, efforts are being made to use thinner and more closely spaced blades, replace blades with wire and either reduce the amount of abrasive slurry used, or replace the present abrasives with less costly alternates. Novel techniques for decreasing the kerf loss and reducing the thickness of the wafer slices using ID sawing are also being investigated.

It would be premature at this stage to attempt to assess the benefits of this work for space applications. The technology being developed will, if successful, result in commercially available machines. Since the main advantage of these machines will be the ability to rapidly cut silicon, their usefulness for space solar cells will likely be determined by the market for silicon space cells. Without a significant increase in demand for space cells, the suppliers could probably not justify the necessary capital expenditures to procure these machines.

The evaluation of silicon sheet technology merely reinforces the observations made for silicon material. The terrestrial efforts are basically oriented to demonstrating high volume, low-cost technology which is willing to trade off module efficiency against cost to a certain degree. There will be little direct benefits for the space program as it is presently structured, i.e., small numbers of sophisticated solar panels.

The equipment that is being developed to produce low-cost silicon sheet will probably not be adopted by the space solar cell industry because the capital investment cannot be justified by the current or anticipated market for space cells, excluding a venture such as a Space Solar Power System. Even if all the objectives of the sheet silicon phase of the LSA project are demonstrated to be directly applicable to the space effort, the benefits would be minor. Assuming that \$10/kg silicon were used, and no losses in preparation occurred (slicing, polish etching, etc.), the cost savings would only be ~\$1.45 to \$1.90 per watt (see page 5). Based on a 1975 dollar cost of \$60/watt for space cells, the total reduction in cost would only be ~3 percent.

C. ENCAPSULATION TASK

The goal of this effort is to develop a low-cost method of protecting modules from the effects of the terrestrial environment over a 20-year operating lifetime. Since terrestrial encapsulation is somewhat analogous to space panel fabrication, a comparison of the requirements for both is very instructive. For space applications the module must have low mass, possess low vacuum outgassing characteristics, protect against ultraviolet and particulate radiation, withstand very large thermal excursions, and be extremely reliable since maintenance is not possible. Due to the specialized requirements of each space mission, the module is usually customed fabricated in a variety of unique configurations and sizes.

In contrast, weight for terrestrial use is not a concern except as related to cost. For example, glass-reinforced concrete is being evaluated as a substrate candidate. There is no concern about particulate radiation or vacuum. Thermal excursions are much less severe, and on-site repair can be considered. The major problems for terrestrial application are humidity, precipitation (including frost), dust, abrasion, impact resistance, wind loading characteristics, reactions with atmospheric pollutants, and ultraviolet stability. Except for the last mentioned problem, there are almost no common challenges.

It is unlikely that terrestrial substrate development will have any applicability to space. However, the work in superstrates does hold some promise. All space panels employ individually covered cells, a costly process involving a great deal of labor. If space solar cells could be interconnected and then bonded to a protective front sheet (superstrate) in one operation, significant cost savings could be realized in the fabrication of space panels. Although the principal efforts in superstrate development are addressed to thick glass, some attention is now being given to thinner plastics, which are relatively lightweight. In general, plastics are susceptible to ultraviolet induced transmission losses and "weathering." However, the concept of incorporating additives to improve u.v. stability and increase abrasion resistance is being examined as a potential solution (References 14 and 15). Preliminary work along these lines has already been initiated by NASA (Reference 16) and further developments in this area should be closely monitored by NASA because the potential benefits for space could be quite substantial.

Efforts are being undertaken to provide improved adhesive-encapsulant systems. Some of this work, especially in the areas of u.v. stability, low cost, extended shelf life, simple cure cycles and controlled cure flexibility could assist the space power program. It is not possible to identify leading candidate technologies since the test programs being used to evaluate them have little resemblance to the normal space qualification tests. More exotic methods of encapsulation such as ion plating (Reference 17) and electrostatic bonding (Reference 18) are also being investigated. Of interest, the latter technique was originally developed for potential space applications (Reference 19) and has yet to satisfy the particular demands of the space environment.

It is interesting that this part of the LSA project has the greatest potential for providing measurable benefits for space. It is possible that certain encapsulation technology that may be inappropriate for terrestrial use because of the particular constraints of the earth environment, e.g., interactions between u.v. and pollutants or moisture, could find use in the space environment. Conversely, approaches which successfully surmount the synergism of u.v., pollutants and moisture may fail when exposed to vacuum, electron and proton radiation, extreme thermal cycling and the higher levels of u.v. in space. However, this knowledge can only be obtained if NASA implements a program to test and evaluate some of the encapsulants, plastics or u.v. screens for space application. The successful employment of the superstrate concept which dramatically reduces module assembly cost should act as a stimulus for further investigation and development of a superstrate concept that could be used for space modules.

D. PRODUCTION PROCESSES AND EQUIPMENT TASK

This task is responsible for developing the processes for cell and module fabrication. It also will integrate all the technology developed by the LSA Project in order to produce the complete manufacturing process for low-cost solar cell modules. The basic philosophy for cell processing is to choose methods which are intrinsically low cost, energy efficient, use little or no consumable materials, and are capable of being automated. In this area the trade-offs are made between conversion efficiency, quality, reliability, potential for low cost, high yield and throughput. The general trend in this evaluation has been to sacrifice some conversion efficiency for reductions in cost (Reference 20).

A wide variety of individual cell fabrication processes have been evaluated, and based on the criteria just described, an inventory of processes capable of being automated with high yield has been assembled. The rationale for this approach is that at this time the type of silicon material to be used is not known, a number of fabrication steps, such as contacting, have options which are nearly equivalent with respect to cost, and the most cost-effective sequence for fabricating solar cells has not been determined. An important requirement for success is believed to be the ability to design and build machinery which can produce solar cell modules with high yield and throughput.

Of interest, nearly all of the cell fabrication processes now in this inventory were either developed by the space cell industry in the past (plating), used presently by them (back surface fields and texturing), or funded previously by NASA or DOD (ion implantation, screen printed contacts, spin-on diffusants or AR coatings). There are some new technologies such as laser scribing (Reference 21) and plasma etching (Reference 22), plus variations in space-derived technology such as palladium-nickel plating (Reference 21). In general, however, it does not appear that any novel cell fabrication technology has been developed which will produce space cells with equivalent or superior performance with respect to conversion efficiency or reliability.

The equipment design and development phase of the task is beginning, and by the end of FY'80 pilot facility construction is scheduled to start. Automation can consist of automating individual process steps or automating the entire process in a single step. Both approaches are under examination with the bulk of effort expended on individual process automation. By considering individual process steps, a maximum manufacturing versatility can be obtained and alternate or additional process steps can be more readily incorporated if necessary.

The concept of individually automated process steps with cassette or modular maintenance of wafers between steps is the most promising approach. Even though automated equipment compatible with LSA goals does not yet exist in a fully demonstrated form, some significant predecessors are available. At this time all steps in cell fabrication, i.e., surface preparation, diffusion, back surface field, contacts, AR coating and scribing, are considered automatable.

To illustrate the capacity of some existing equipment, screen printers are presently being used that can contact 1800 9-cm diameter wafers per hour. If diced into 2 x 4 cm solar cells, a standard space cell size, over 13 million cells could be processed annually on a single shift basis. This is approximately 10 to 15 times greater than the present annual throughput of space solar cells. Some of the equipment being considered will be discussed in order to point out potential advantages for space cells. Trade-offs and investigations that would be necessary for implementation for space applications will be described.

All the processes now developed by the LSA Project can accept round or rectangular silicon. Based on our evaluation of sheet silicon technology, it appears that ingot, dendritic web or heat exchanger grown silicon will be initially employed. For the first two candidate materials, it would be necessary to have a cutting or dicing step in any cell process sequence in order to achieve a rectangular part in the case of ingot, or to remove the dendrite "rails" in the case of web. Fortunately, the recent development of laser scribing provides a rapid and cost-effective method for dicing these materials into smaller rectangular parts. As an additional advantage, many steps can be carried through on the ingot or web material, thus eliminating opportunities for chipping the final rectangular cells. Further advantages are obtained because while one slice or web is "handled" it represents many smaller rectangular wafers, significantly reducing the processing effort per individual cell. These obvious advantages have not been ignored by the space solar cell industry.

Due to automation needs, thermal processes are tending towards belt furnace systems rather than the normal closed tube methods. This in turn constrains the types of ambient gases that can be tolerated for health and safety reasons so that the diffusion and baking processes become restricted. Whether this limitation will compromise the cell performance is still being examined although indications are that spin-on diffusion sources may be comparable to the closed tube gaseous types. Of concern to the space cell manufacturer is the problem that belt type thermal systems do not always make economic sense until around-the-clock usage is established, thus closed tube gaseous systems can be more cost-effective when limited noncontinuous use is anticipated.

Equipment for contacting cells using either screen printing or plating is being evaluated by the LSA Project. The advantages over vacuum deposition are overwhelming with respect to throughput, material utilization and energy required to perform the operation. Whether these processes can compete with the traditional method of depositing space cell contacts (vacuum evaporation) with respect to gridline width and space quality requirements such as pull strength, humidity resistance, and weldability has yet to be completely resolved. These would appear to be fruitful areas for NASA evaluation and possible improvements.

The needs of automation require the use of spin-on or spray-on, heat curable, antireflection coatings to replace the conventional vacuum deposited types. The present nonvacuum AR coatings do not have the transmission characteristics or control of optical thickness required for space type AR coatings, resulting in a loss of power output. Even though improved coatings are being developed, it is not known if they could satisfy the typical requirements for space application.

Although plasma etching equipment does not have the capability of matching the throughput of many of the processes described, it offers great potential for space cell processing. Plasma etching can be used to clean and etch wafers. Not only does the plasma etching eliminate the need for costly processing chemicals, but it also leaves a clean surface, one which does not require extensive washes and rinses for residue removal. Further, wet chemical reaction rates are sensitive to the number of parts treated, solution concentration and purity, and tend to be difficult to control unless careful precautions are taken.

Plasma etching offers a unique approach to solving the handling problems germane to the recently developed NASA/OAST ultrathin silicon solar cell (Reference 23). Much of the process-induced breakage of ultrathin silicon solar cells, especially for larger sizes, occurs during "wet processing" steps where differential surface tension effects during passage from air to the wet medium can cause extreme flexure and cracking of the cell. The application of plasma etching for the production of ultrathin silicon solar cells is well worth the attention of NASA, and is perhaps the most immediate application of terrestrial derived technology for space.

In summary it is possible that many of the terrestrial processes now available could be used in the fabrication of space cells. Present space cell processes that employ vacuum deposition are not effective when handling silicon wafers which do not allow a high packing factor in the evaporator. By eliminating vacuum deposition operations, significant savings in silicon cutting, handling, and materials utilization could be achieved in addition to the inherent cost savings that would occur from nonvacuum processes. The development of such a process sequence was funded by NASA (Reference 24) a few years ago with encouraging results.

A major obstacle to incorporating the terrestrial approach of nonvacuum processing is the concern over reliability, quality, and cell conversion efficiency. There are probably certain NASA missions (low earth orbital) that could benefit from less than optimized cells provided that the cost benefits were significant and the conservative behavior of program managers could be modified.

The applicability of automation to the space cell industry is intimately connected to the current and projected market for silicon space cells. Since automation normally demands a large initial capital investment, it is necessary that the costs be recovered either through a high volume production capability or high selling price. Although it appears that automated equipment for processing solar cells is or will soon be available, it is not clear that the demand for space cells will make automation attractive. There may be other reasons for automating, such as the desire to reduce quality control costs or the inability to attract and retain skilled production personnel. However, as long as space cell applications are sensitive to mass, conversion efficiency, quality, reliability and "custom" manufacturing of arrays, there will be little incentive to automate at any level using the type of equipment now being considered for terrestrial photovoltaics.

It is obvious that the present market for space cells (30-50 kW/year) will not allow for large scale automation. A Space Solar Power System type effort would be required to fully justify such a venture. Even then there is no assurance that an automated terrestrial production line could supply cells that would satisfy the quality, reliability and efficiency requirements necessary for space applications.

E. ENGINEERING AND OPERATIONS TASK

Although this task, by strict definition, is not considered to be technology development, it is an extremely important part of the LSA Project. By examining the objectives of this task, a deeper appreciation of the differences between space and terrestrial photovoltaics can be obtained. During the period 1976-79, over 350 kW of solar panels from seven manufacturers were purchased by the LSA Project for testing, evaluation, and demonstration. Over the same time the space solar cell industry, represented by two manufacturers, produced 120 kW!

This task has been addressing the following problems: developing methods to rapidly test the output of solar modules, choosing appropriate field test sites, devising methods for accelerating life tests, defining the proper environmental tests to be performed, studying failure mechanisms, examining the interfaces between modules and the type of service that will be provided, and developing techniques for analyzing data.

To contrast this activity against what is required for space is extremely informative. Rapid test methods for obtaining module output are not necessary because only a limited number of space modules are produced. The environment of space is constant: hard vacuum, electron, proton and u.v. radiation, and in most cases a limited range of operating temperatures. The environment of space is well-known for almost any mission now being considered. Strangely enough the terrestrial environment is not as well-characterized. In one region atmospheric pollution may be a problem, in another, dust or hailstones. In addition the basic environment changes with time (temperature extremes, amount of rainfall, amount of sunlight available) in a manner that does not allow a precise definition of overall operating conditions. This is a good example of the unique challenges faced by terrestrial photovoltaics.

The terrestrial photovoltaic technology is developing rapidly. Module designs and materials are in a continuous state of change as more knowledge is obtained, and suppliers strive to reduce costs. In contrast, the space area is relatively stable; standard qualification tests have been established, a large data base has been generated, the space environment is well-defined and there is 20 years of "field test" information.

In the past, space photovoltaics has benefited from nonspace activities in the area of quality control and testing. It would be very surprising if this were not to occur once terrestrial photovoltaics has stabilized. However, it would appear at this point that it will be many years before such a situation will exist.

SECTION III

PHOTOVOLTAIC CONCENTRATOR TECHNOLOGY DEVELOPMENT PROJECT

Like the LSA Project, the goal of the Concentrator Technology effort is to achieve $0.50 or less per peak watt by 1986. In addition, this project has a major interim milestone of demonstrating commercial readiness of the technology at $2 per peak watt by 1982. The approach taken is to employ solar concentration in conjunction with photovoltaic cells. The rationale is that the cost of concentrators and sun tracking will be less than the cost of the cells that would otherwise be needed. The same philosophy has stimulated NASA interest in concentrator enhanced photovoltaic arrays for space.

Five requirements must be satisfied in order to successfully demonstrate the 1982 interim goal of the Concentrator project. The three most significant are: the production rates for systems (1-10 MW per year), the system efficiency (10-12% AM1), and the cost of the silicon cells (25 cents or less per cm^2). The Concentrator project is modestly funded in comparison to the LSA Project, approximately 8 million dollars in FY'79. A great deal of effort is being expended to develop concentrator materials and designs, heat rejection methods, structures and tracking techniques. The amount of support for solar cell development is relatively small, and it is further diluted because materials other than silicon are being investigated.

Except for certain activities in solar cell development, there does not appear to be any other technology capable of being translated to the NASA space program. The concentrator structures, tracking equipment and the environment in which they must operate are so different that it is unlikely that any of this work could find application for space. Mass is not a concern for terrestrial applications; on the other hand, wind loading factors are. The main thrust in terrestrial concentrator development is extremely high concentration (50-500 suns) which implies active heat rejection schemes. It is doubtful that space power applications could possibly be modified to benefit from such a conceptual approach.

Three categories of photovoltaic materials are being supported: silicon (References 25 and 26), compound semiconductors such as GaAs (Reference 27), and multiple junction concepts such as stacked (Reference 28) or spectrally separated cells (Reference 29). It is not easy to translate the conversion efficiency objectives of concentrator solar cells into terms of 1 sun AM0 conditions. For example, the interim "strawman" ($2 per peak watt) defines the conversion efficiency goal for silicon as 16 percent at 50°C under 30 to 40 times AM1 intensity (Reference 30). Silicon cells exceeding this goal have been reported (Reference 25). The technology employed is very similar to that used to produce high efficiency space cells (texturing, fine grids, back surface fields, etc.).

Regardless of what materials are being used, solar cell development for concentrator applications is now emphasizing technology feasibility. The effort is to demonstrate the maximum conversion efficiency that can be achieved using optimized processing techniques. Results that have been claimed are impressive, ranging from 18 percent for silicon (Reference 25) to nearly 30 percent for spectrally separated devices (Reference 29). Some caution is advised in attempting to convert these values to AMO conditions. The method for calculating efficiency does not generally include the entire cell area. Cells of materials other than silicon given much higher AM1 efficiencies because their spectral response is more nearly matched to the terrestrial solar spectrum. Finally, the effect of extremely high intensity levels can cause injection effects which yield higher efficiency than normally obtained under AMO conditions.

A common obstacle to the development of high efficiency concentrator cells is the effect of series resistance. A dense pattern of very fine (~25 μm wide) gridlines are required to reduce this effect. Since high efficiency space cells also require fine gridlines in order to optimize performance, it is possible that the development of low-cost processes for providing fine gridlines can be translated directly to the space cell industry. Other high technology operations such as back surface fields and antireflection coatings must ultimately be performed using low-cost processes in order to meet the cost objectives for concentrator cells. At this time there is not a significant amount of effort being applied to low-cost cell processing, thus it is not possible to accurately forecast when any technology in this area will be available for space application evaluation.

Cell development employing alternate photovoltaic materials appears to be one area where NASA should derive direct benefits. The main efforts are in the GaAs type cells which offer better performance at high temperatures and have already demonstrated superior AMO conversion efficiency when compared to silicon (Reference 31). The development of stacked junction or cascaded cells in order to achieve greater than 25 percent efficiency parallels the goals of the NASA space photovoltaic program. The quantity of cells needed for terrestrial needs is many orders of magnitude greater than what is anticipated for space. Thus, there is a possibility that the Concentrator project will develop the technology and low-cost production processes that would be needed for the next generation of space solar cells.

Once again it should be mentioned that there is not concern on the part of the Concentrator project for radiation resistance. Therefore it will be necessary for NASA to begin an effort to evaluate the radiation resistance of alternate material solar cells produced by the Concentrator project. If these cells show promise, more ambitious testing for space applicability could then be considered.

SECTION IV

SUMMARY AND CONCLUSIONS

To this point, terrestrial photovoltaics has followed a pattern that is not unexpected when compared to the development of the relatively mature space solar cell industry. Twenty years ago photovoltaics for space benefited from the existing technology produced by the transistor industry. Today space photovoltaics in conjunction with microelectronics is providing the technology base for terrestrial photovoltaics. Many elements of transistor technology were not considered appropriate for the specialized needs of space photovoltaics. A similar evaluation is being performed by DOE, with the result that such sophisticated processes as vacuum deposition and epitaxy have been judged to be inappropriate on the basis of cost or throughput.

Because of the strategy adopted for terrestrial module assembly, namely use of the lowest cost, existing mass produced materials, there is little chance that technology suitable for the assembly of space arrays will result. However, certain concepts such as superstrates and automated assembly could offer some benefit for space.

Since the overall goals of the DOE programs have to do with reduction in cost and increases in production capacity, both by many orders of magnitude, it is not surprising that the potential near and intermediate term return for space use is extremely limited. In fact, it is very likely that additional NASA developed technology will be adopted by DOE within the near term. For example, it is becoming apparent that the cost of solder may necessitate a change to welded interconnections.

The cost reductions of the DOE programs have been accomplished, in many cases, at the expense of conversion efficiency and reliability, and in all cases through economy of scale. However, more detailed analyses of total systems cost and an increasing amount of field test experience has shown that the initial terrestrial technology must be improved with respect to conversion efficiency and reliability. The need to conserve silicon, a fact appreciated by DOE from the beginning of their programs, will ultimately require terrestrial solar cells to be extremely thin (50-150 μm). Thus the long range trends of DOE technology are in the direction that could benefit the nation's space power needs.

Future NASA missions such as low-thrust propulsion, space processing, power modules and space platforms could utilize economy of scale under certain conditions (standardized components, common purchases of materials). The high levels of power required by these programs make power cost a prime consideration. However, the particular requirements placed on the power source -- radiation resistance, thermal cycling, array area, array mass, and reliability in the space environment -- are not of interest for terrestrial needs.

Although there are common objectives for space and terrestrial applications (long life, high conversion efficiency, low cost, reliability), the criteria used to judge success are different and in many instances incompatible.

Based on this evaluation of DOE activities in photovoltaics, the following conclusions have been reached:

(1) Terrestrial photovoltaic technology that has either been developed to date, or is currently under development will not have any significant effect on the performance or cost of solar cells and panels used for space over the near term (1980-1990).

(2) Certain technologies from the DOE programs have limited applicability in a few specialized areas of space solar cell and array development (see Table 1).

(3) Some portions of the DOE technology could be employed for low earth orbital missions such as PEP and PEM, which require significantly greater amounts of space power (≥25 kW), provided there was some relaxation or modification in the specifications defining space qualified components or subsystems.

(4) There is a high probability that the low-cost, high volume terrestrial solar module industry planned for the future would not be capable of providing photovoltaics for a Space Solar Power System mission without relatively major and costly modifications to the technology.

Table 1. Pertinent DOE Technology

Major Area	Task	Potential Benefit to Space
Solar Cells	Low-Cost Silicon Processes	Small
	Understanding/Measuring Impurities	Small
	Thin Silicon	Moderate
	GaAs/Multibandgap[a]	Significant
	Plasma Etching[a]	Significant
Superstrates	Low Cost, Low Mass/Environmentally Tolerant	Moderate
Encapsulants	Low Cost/Large Area	Moderate

[a] Recommend space investment.

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