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LOW COST SOLAR CELL ARRAYS

by P. A. Iles and H. M[c]Lennan

(NASA-CR-134815) LOW COST SOLAR CELL ARRAYS (Globe-Union, Inc.) 96 p HC $4.75 CSCL 10A

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Globe - Union Inc
Centralab Semiconductor
4501 N. Arden Drive
El Monte, California, 91734

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract.

This report describes the present limitations in both space and terrestial markets for solar cells. Based on knowledge of the present state-of-the-art, six cell options are discussed; as a result of this discussion, the three most promising options (involving high, medium and low efficiency cells respectively) were selected and analyzed for their probable costs. The results showed that all three cell options gave promise of costs below $10 per watt in the near future. Before further cost reductions can be achieved, more R & D work is required; suggestions for suitable programs are given.

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Summary

This study was intended to identify possible methods by which low cost solar cell arrays could be made. The intended use was to alleviate the national power shortage.

A broad survey was made of possible combinations of solar cell and array technology. Using present evaluation of the state-of-the-art, six combinations of process methods were analyzed; from this analysis, the three approaches with most promise were selected and evaluated.

These three approaches appeared to cover possible high, medium and low cost options, with corresponding differences in the time scale estimated for their implementation. However the analysis showed that the cost estimates for near future use were not widely different. All three approaches sho showed promise of costs below $10 per watt (peak), with future large cost decreases predicted when the production volume reaches that required by the goal of the contract.

The study showed the need for more research and deve;opment work; suggestions were made for suitable R & D programs.

LOW COST SOLAR CELL ARRAYS

1.0 Background

1.1 Introduction

This report describes several different methods for fabricating solar cell arrays which are capable of providing terrestrial power at reasonably low cost.

The approach is as follows:

(a) To describe the market factors operating for the present solar cell markets, both for space power and for terrestrial power.

(b) To list possible options for various parts of the system.

(c) To choose and analyze the six most promising options, subsequently narrowing the field to the three best options.

Later it will be shown that many of the factors required for a quantitative analysis are not available, and therefore some judicious selection must be made. As far as possible, the considerations underlying such selections will be described.

1.2 Space Solar Cell Factors

The space solar cell market is a very special one. It depends entirely on government funding. It is very sophisticated because the serviceable lifetime and reliability requirements are extreme, causing extensive, detailed development and leading to stringent mechanical and electrical requirements for the device. Both of these factors lead to high costs for the cells and thus lead to a tendency to overestimate the cost of cells made for terrestrial arrays. There are additional factors that further raise the cost of solar cells for space applications and these factors are discussed next:

<u>Variable Production Volume</u>

Because of the unpredictable funding for space programs and also the stringent requirements on the manufacturer which preclude stockpiling of cells, the month by month production volume varies extremely. Figure 1 is an example of such variation and shows actual numbers obtained in large scale manufacture.

<u>Effect on Labor Efficiency</u>

This variation in volume causes increased labor costs in terminating and rehiring, adding significantly to the overhead costs associated with employing highly trained personnel during periods of low productivity.

<u>Effect on Production Yield</u>

These variations month by month cause equipment and process material to stand idle. In addition to equipment problems, there is a much lower yield of suitable cells resulting from the need to rehire and retrain personnel in the same period that production buildup is proceeding.

<u>Effect on Material Procurement</u>

It is well understood that material cost savings are gained by buying in volume on a regular basis. The large production volume variations directly increase both the inventory costs and the procurement prices of material.

<u>Effect on Capitalization</u>

Because of the large variations in production volume, the plant capacity must be much larger than the average output. Consequently, the production facility is overcapitalized in equipment for the average loading, making an inefficient use of capital.

<u>Cell Specification</u>

All space cell users have their own particular cell requirements. There has been no success in standardizing cell design on specifications and this lack of standardization (with consequent difficulty of stockpiling) causes significant cost increase. Table 1 lists cell specifications presently required and shows the wide variety of specifications a cell manufacturer must satisfy.

1.3 Terrestrial Solar Cell Array Market Factors

The terrestrial solar cell array markets are open and unexplored in contrast to the space solar cell market. This section will deal with the reasons for this market being unexplored.

1.3.1 Possible Market Areas

The terrestrial market is unlike the space market, being restricted at this time because of the present high cost of suitable terrestrial arrays. In this market four broad areas can be identified:

(a) custom solar arrays for government and other agencies to be used in isolated sites;

(b) emergency or peak power supplement arrays for police stations, hospitals, etc.;

(c) general public, low cost arrays for supplementing home power demands and hobbies such as pleasure boats; and

(d) large solar array "farms" for public utilities.

At present in three out of these four areas the funding agencies have been pressured to cut costs and raise efficiency. Therefore, the entrance of solar cells into these markets will be delayed since the major advantage, namely lower environmental pollution and long life, is offset by the higher cost.

1.3.1.1 Entrance Into The Custom Array Market

In particular, the only market that is presently being penetrated is the custom array market. The cost of producing a solar cell array now is simply too high to penetrate further. Present prices are not realistic because rejected space solar cells are used most frequently in the arrays. However, some cells are also being made specifically for earth uses, and it is possible to use these production costs as an upper limit for future uses, and as a basis for extrapolating costs in a projected, expanding commercial market.

1.3.2 Custom Array Specifications

The custom solar cell array costs suffer for the same reason as space solar cell arrays in that both have a wide variation in customer specifications leading to high engineering costs for small numbers. As mentioned above, these variations preclude stockpiling, an essential prerequisite for low cost production.

1.4 Cost Estimate Approach (Cell and Array)

There is limited market and production data on which to base an extrapolation for cost reduction for an expanded volume usage.

It is possible to use experience gained in the transistor market to give costing guidelines.

Figure 2 shows a graph of production cost vs. production volume for solar cell arrays based on production data for transistors. The cost and volume of solar cells for space are used for the first data point to scale the curve. The first data point also reflects the present ratio of costs between solar cell arrays and cells - $2.50/cm^2 for a cell in an array vs. $1.00/cm^2 for a cell. Assuming the general curve is correct, this estimate may be an upper limit to the cost vs. volume curve for marketing arrays. In this report, however, the main emphasis will be on estimating costs for the <u>near future</u> for comparison. When extrapolation to larger production numbers is required, curves such as those in Figure 2 can be used.

1.4.1 Present Cell Production Cost Limitations

The production of the present space solar cell can be divided roughly into three cost factors, ignoring overhead, G & A, and profits:

1/3 direct materials cost (silicon, titanium-silver contacts, and SiO anti-reflective coating)

1/3 direct labor costs (salaries)

1/3 indirect materials (acids, solvents, tooling, supplies, etc.)

Any major over-all cost reduction must include reductions in all three factors to be successful.

Silicon Costs

Recognizing the cost structure above, drastic changes in silicon cost must be made. Best estimates for the present polycrystalline silicon market are $75/kilogram dropping to $40/kilogram with large volume increases. When the cost of both growing crystals from this material and the high kerf losses are considered, present fabrication methods must be drastically changed to effect a suitable cost reduction.

Labor Costs

Present trends in the labor market indicate a large increase in labor costs which just about balances out any increase in labor efficiency with increased volume. As a consequence, a large decrease in the labor force by mechanization is necessary.

Indirect Material (Supplies) Costs

Present processes use expensive materials very inefficiently. Future fabrication methods must endeavor to reduce material costs, either at the source or by recycling, in addition to a reduction resulting from the introduction of mechanization.

Equipment Capitalization

The present plant facilities are operating between 1/2 and 1/3 of full capacity. Consequently, new equipment and plants will be necessary to make large scale increases in volume. This places a strong emphasis on cutting capitalization costs initially if no external incentives, such as government subsidies, are provided to get started on increased production volumes.

1.4.2 Pollution Precautions

One of the objectives for using solar cells is to reduce pollution. Any cost reductions made must not be negated by the additional costs required to minimize pollution when making the cells.

NOTE: The discussion above was confined to solar cells alone. This present study must also include estimates for array costs. The necessary extension to include arrays will follow from consideration of the options listed below. The discussion above stressed the drastic steps needed to reduce costs for the basic building block, the cell. Long term schemes include some to integrate the cell formation and interconnection and encapsulation all in the same continuous process. It will be evident when the option list is evaluated later that one strong criterion for retaining certain options will be a good possibility of combining array formation with cell fabrication.

1.4.3 Array Maintenance

A significant cost factor to be considered is maintenance of the arrays, especially keeping the array light-absorbing surfaces clean. In a remote location such as in the desert with normal weather conditions, weekly or monthly cleaning of accumulated dust (trapped by dew) would probably be adequate. After a dust storm, immediate cleaning may be necessary. In the rainy season bi-monthly service would probably suffice. On the other hand, on a building rooftop, daily cleaning would be practical. Provision of automatic sprinklers for cleaning in remote locations may be practical if underground water were available.

1.5 Possible Technology Options

The list of options presented is based on the Low Cost Solar Array Matrix (Figure 3).

This matrix shows the link between customer wants: electrical output (1.1), cost to be determined; and serviceability (1.2); and manufacturing processes (4.0), which involve cell (2.1) and array (2.6) design; and cell (3.1) and array (3.7) methods of production. The matrix, also, indicates the flow of these linkages. The steps are numbered to relate to the list of options.

The List of Options (Table 2) details the areas under consideration within each step.

2.0 Selection of Six Combinations

Table 2 listed many of the available technical options which can be combined to provide solar cells and arrays.

Here the steps leading to selection of six promising combinations are outlined.

2.1 Option Rating

In order to make optimum selections of cell and array fabrication options out of the great number listed, each option was carefully evaluated for use in low-cost terrestrial solar arrays. Each was rated on two scales: first, according to potential cost reduction; and second, according to expected development time for the required technology.

Potential cost reduction was rated on a scale from 0 (increased cost) through 1 (no expected change in cost) to 4 (anticipated cost reduced to approximately 1/40 present cost).

Development time for the technology required was rated on a scale from 4 (present state-of-the-art technology) to 0 (expected to require an unacceptably long development time). For each option the two corresponding ratings (the average of evaluations made by three engineers) were multiplied together to obtain a composite overall rating and a figure of merit for the option. Unfortunately, no definitive guidance could be obtained from these ratings. Therefore the more likely options were combined with experience-supplied judgment factors to give six combinations which are summarized in Table 3 and which are described in the following sections. These combinations include promising alternatives as possible improvements in the cell or array technologies.

2.2 Description Of The Six Combinations Selected

2.2.1 Combination 1 - High Efficiency, High Concentration Cell Arrays

(Advanced state-of-the-art, high efficiency, high concentration, single crystal cell arrays for roof-top or limited-area use)

The solar cell for this option is one in which the starting material, processing, parameters and sequences have been optimized to provide a very high efficiency cell (approximately 20% AM1) in order to effectively produce useful power from a very limited array area. A large matrix of material and process parameters exist that remain to be studied carefully, but general trends are presently indicated.

Low resistivity cell blanks, as thin as practical to minimize silicon costs; careful processing to reduce surface and bulk silicon damage which cause current and voltage losses; and appropriate trade-offs in junction depth, cell thickness, number and type of contact multi-grids to reduce the series resistance, consistent with the incident sunlight spectrum; as well as improved, compatible, possibly double-layer AR coatings all combine to make such a cell very practical in the near future. Another demonstrated improvement involves processing to provide a back surface field for bulk enhancement. Each process step must be carefully balanced between gain achieved versus the added cost of yet another process step in the search for low-cost cells, since not all these improvements are simultaneously available.

Additionally, since the array accounts for more than half the total system cost, such time and labor-saving array configurations as, for example, "wraparound" contacts, easily bondable metals, PC interconnects and backings, abrasion-resistant coatings optimized for the total array, and FEP Teflon encapsulation, are particularly attractive. Further, large savings in labor costs can be provided by mechanizing many of the process steps for both cells and arrays.

A high degree of concentration of light by a suitable lens/concentrator (10 to 20 times) would be practical since it is anticipated these arrays would not be used in remote areas, but in environments where cooling of the cell would provide energy for heating and cooling of a building, for example. A mounting that provides for tracking the sun, or occasional tilting of the structure with seasonal changes, will maximize useful power output.

2.2.2 Combination 2 - Ribbon-Grown Medium Efficiency Cell Arrays

(Ribbon-grown cells in simple, inexpensive, state-of-the-art arrays)

The solar cell contemplated for this option has a medium efficiency (approximately 10% AM1) and combines ribbons of silicon with mainly present state-of-the-art cell production technology; modified for simplified processing and assuming slightly relaxed electrical, mechanical, and cosmetic specifications, thus giving a higher yield and thereby lower cell costs.

Rectangular cells will be sawn, or laser-cut from single crystal ribbon-grown silicon with little or no kerf loss. After any necessary surface treatment, thermal diffusion will be used to form the junction. The front contact will be composed of a large number of grid lines deposited by evaporation. Conventional evaporated SiO, TiO_2, or Ta_2O_5 anti-reflective (AR) coatings will be applied.

The long, narrow cells will be simply and easily bonded to an inexpensive printed-circuit (PC) board by a flexible epoxy adhesive to reduce cell breakage. The long, narrow ribbon cell is ideally suited to a V-groove or trough concentrator arrangement which will provide up to approximately two or three times concentration, so that no elaborate cell cooling system is required. The total metal surfaces of the V-groove concentrator and PC board will provide a heat sink for cooling. A flexible epoxy or potting compound will be used to provide hermetically-sealed encapsulation. A large array can then be made of V-groove modules placed in a parallel group side-by-side. The array will be fixed in position and located with the long axis perpendicular to the solar rotation axis.

2.2.3 Combination 3 - "Conventional" Medium Efficiency Cell Arrays

(Best state-of-the-art, round, "wraparound" cells in light-weight tracking arrays)

For this option combination a much more simplified process than that used for space-qualified solar cells and arrays will be used in order to reduce cell costs significantly.

Round cells, as-sawn from a single crystal Czochralski ingot, will be cleaned and thermally diffused. "Wraparound" contacts will be used since these will significantly lower the array cost because of simplified mounting and interconnects, and cost only 5-10% more than conventional contacts in high-volume mechanized production.[2] Conventional AR coatings will be used to improve efficiency. Process costs will be further reduced since only electrical and some environmental testing of cells will be specified. The cells will be simply bonded to an inexpensive PC interconnect network.

A stamped metal "egg-crate" concentrator, most suited for round cells, will be epoxied to the front of the array, and FEP Teflon or polyimide coating and encapsulation will be used. For this combination also, a modest concentration of up to two times will be used to avoid the necessity of elaborate cooling systems that are wasteful of power.

The light-weight array will be mounted on a motor-driven structure that tracks the sun to obtain maximum sunlight incident on the "egg-crate" concentrators.

2.2.4 Combination 4 - Edge-On Medium Efficiency Cell Arrays

(Advanced state-of-the-art, medium efficiency, high concentration cell arrays for roof-top or limited-area use)

The edge-on cell array possesses a great advantage in cost reduction by reducing the number of interconnects, as well as providing improved output because of a very low series resistance. However, a difficulty in processing arises because many (500 to 2000 per cm) alternate p-n regions are required to yield a medium to high efficiency cell.

The alternate narrow regions may be grown epitaxially, or, for lower cost arrays, more conveniently on a mechanized basis using ion implantation, which is accurately controllable to the dimensions required. The single-crystal cell must be annealed after ion implantation to restore crystallinity. However, if polycrystalline silicon is useable, the annealing step probably will not be necessary and can be eliminated for a cost saving, since the silicon is polycrystalline, i.e., already disordered.

High concentrations of light on the cell (much greater than 10 times) using appropriate lens/concentrator combinations are appropriate to provide greater output in this combination, i.e., non-remote location, since the cell can conveniently be cooled and thus maintain its efficiency by a heat transfer system such as heat pipes or refrigeration, that utilizes the heat for building heating or cooling purposes. The array, which will be

FEP Teflon encapsulated, can be conveniently tilted for optimum light on the cells with seasonal changes.

2.2.5 Combination 5 - Sputtered Low Efficiency Cell Arrays

(Advanced state-of-the-art, thin, large-area, polycrystalline or amorphous cell arrays for a solar farm, using unified processing)

Unified processing for much of the fabrication of the solar cells will be used for construction of arrays in this option, in which sputtering is described as the example unified process system. In Section 2.2.6, chemical vapor deposition (CVD) is chosen as an attractive, viable alternative.

Sputtering will be used to deposit polycrystalline or amorphous doped silicon to form thin, large-area cells. (Cells with areas larger than 30 x 30 cm and of any appropriate thickness on a suitable substrate material are quite feasible.[3]) The large area will compensate for the low conversion efficiency (5% AM1 or less). The silicon will be deposited on a relatively inexpensive metallic backing to provide the back cell contact.[4]

Continuing with the unified processing approach, the junction will next be formed by sputtering oppositely-doped silicon. Sputtered grids will be applied for current collection. An inexpensive sputtered AR coating will probably next be applied to the large area cells to improve efficiency and thus reduce array area and land area requirements, although an AR coating is not as important for low as for high efficiency cells, if the additional process step is not cost-effective.

If junctions formed by sputtering provide unacceptably low-efficiency cells when the trade-off in costs between solar array area and land costs, for example, is considered, then as a second alternative a standard thermal diffusion step could be used for junction formation.

A third approach for junction formation which fits in well with the unified process fabrication approach, especially if the sputtered junction formation process proves to be unsuitable is to use a Schottky barrier junction. Solar cells produced by this process have demonstrated useful efficiencies.[5] In this technique a thin film of metal, chromium, for example, is sputtered onto the polycrystalline silicon substrate to form the junction. This further simplifies top contact formation, since, with the metal film, a simpler top contact grid structure covering less area, would be sufficient. A suitable AR coating will be applied by sputtering, if deposition temperatures can be held sufficiently low that the metal film is not affected adversely. At present, fabrication and operating temperature, as well as metal-silicon interface problems are limitations in this technology that must be overcome.

A fourth promising technology for junction formation in the polycrystalline substrate is ion implantation of appropriate dopants. Ion implantation, already in production use in microcircuit fabrication, is attractive for several reasons. It can be readily mechanized, is accurately controllable, and the usual annealing process step to remove damage done to the substrate silicon by ion bombardment can be eliminated since the substrate is already polycrystalline, and any additional damage effects will likely not affect performance significantly.

Another attractive, less complicated, alternative to front-grid contacts in the unified process approach, would be to sputter a transparent conductive film such as tin-doped indium oxide,[3] to provide the front contact, followed by a sputtered antiabrasive AR coating if necessary.

The lowest-cost unified process would be one involving a single type of sequential processing of the various layers of materials, such as sputtering. However, it should be pointed out that if, for example, sputtering is unsuitable for a particular step, other deposition techniques, such as CVD or evaporation as alternatives would not be incompatible with the unified process approach, and could readily be incorporated into a unified process system.

Inexpensive interconnects and FEP Teflon or fritted-glass encapsulation will be used to complete the large-cell array unless cell breakage becomes a problem. In this case a more flexible epoxy encapsulant would be desirable.

In the field (e.g., a solar farm), the large cell plates will be soldered or wired together and the connectors encapsulated for weather-proofing. Wood or metal frames will hold the array in place at a fixed angle. Inexpensive reflection-sheet planar concentrators may be placed opposite the array in order to increase the light intensity.

2.2.6 Combination 6 - CVD Low Efficiency Cell Arrays

(Advanced state-of-the-art, thin, polycrystalline cell arrays, using unified processing)

Unified processing of cells for arrays using chemical vapor deposition provides an attractive alternative to sputter processing described in Section 2.2.5. As in that technology, large-area cells are quite feasible (at least 25 cm wide and as long as desirable or practical[6]). However, in this option, small cells will be isolated on the substrate and interconnected to form an array with the desired voltage. An inexpensive V-groove or trough concentrator will be used to enhance the output approximately two times. CVD will also be used for junction formation, grid contact formation, and AR coatings.

In the CVD unified process also, the other alternatives described in the previous Section 2.2.5, such as junction formation by thermal diffusion, Schottky barrier, or ion implantation; both grid and conductive film contacts; and AR coatings may similarly be applied. Additionally, an added process capability with CVD is that it may be used to form the cell and junction by the long-proven, but slower and much more costly method of epitaxial growth of single crystal silicon layers and junctions.

An attractive alternative to the long V-groove concentrator would be to use a simple, inexpensive, plastic cylindrical Fresnel lens to provide a moderate concentration of sunlight on the cell and also to allow less critical positioning of the array structure. As in Combination 2 above, the array would be fixed in a position with the long axis perpendicular to the solar rotation axis.

3.0 Selection of Three Combinations

3.1 Background to Choice

In the previous section, six combinations were selected and described. In order to make more realistic cost estimates, consultations were held with Centalab in-house personnel, including the marketing managers for both space and terrestrial solar cells, the applications engineers concerned with terrestrial cells, solar cell array experts, industrial engineers, solar cell manufacturing managers and R & D personnel. Many of the points raised by this diverse group have been incorporated into the analysis of the three combinations selected for detailed study.

At the same time, experts outside Centralab who were involved in some of the more promising advanced technologies were contacted for their estimates. In some cases where no firm figures could be obtained, experimental work (funded separately from the contract) was undertaken. Although the results of these experiments did not add significantly to the conclusions drawn in this study, the work itself provided good insight into the requirements for such co-operative efforts in the future.

The Centralab in-house information was used to evaluate the chance of significant cost decreases by simplified processing, by some measure of automation, or by use of alternate processes. In addition, in-house studies of advanced concentrator systems were begun.

The external work included tests of transparent conducting films and AR coatings obtained by sputtering, of silicon films formed by sputtering, and of p-n junctions formed by ion implantation.

3.2 Basis of Selection

The rating system described in Section 2.1 did not prove successful. Therefore experience and judgment were exercised to give the six selected combinations described in Section 2.2.

On further evaluation, it was decided that, since there was still a substantial degree of uncertainty in many cost and technology factors involved in these six combinations, five combinations could be compressed into three broad classes as described below.

The combination which was removed from more detailed consideration was that involving multijunction edge-on cells. The reasons for this elimination were as follows: Even if the multijunction structure can be achieved, it does not provide any efficiency advantage over good-quality conventional cells. Also tests to date have shown that the more complicated structure is feasible, but that the cell fabrication costs are high and will probably remain high, even with further development. In addition, the reduced number of interconnects possible may be counter-balanced by the difficulty in extending multijunction structures to large areas. Finally, the advantage of multijunction cells at very high concentration ratios may not be easily exploited for the next generation of systems where concentration ratios between 10 and 20 may be used most. The associated difficulties of heat transfer for very high concentration ratios will complicate system application.

Considering that present technology high-efficiency cells can be made with low series resistance to allow effective operation up to 10-fold concentration with simultaneous large area fabrication, it was decided to include a combination which used high output cells with moderate concentration.

3.3 Description of Three Combinations

Here the three combinations are described and discussed. The next section deals further with cost considerations.

3.3.1 High Efficiency Cell Array

This combination is the high output, limited-area array, Combination 1 of Section 2.2.1.

With the many improvements in cell processing and design parameters briefly described in Section 2.2.1, a very high efficiency cell can be fabricated. Further output increase will also result from the high concentration ratios to be used. (At concentration ratios of 10 to 20 times, approximately 5% of the power generated would be used for cell cooling purposes.)

3.3.2 Medium Efficiency Cell Array

This combination has been formed by selecting the best features of Combinations 2 and 3 discussed in Section 2.2.

Ribbon-grown silicon rectangular cells simply bonded to a low-cost PC board array interconnection, all mounted in a simple coated aluminum V-groove concentrator with FEP Teflon or polyimide encapsulation comprise the module.

NOTE: The manufacturing cost of round cells is roughly 40% less than rectangular cells on a per unit area basis, but this cost saving is effectively reduced by the packing factor penalty loss when the circular cells are placed in an array. Accordingly, recent advances in ribbon-grown cell technology strongly support selection of rectangular cells over round ones, although some estimates of round cells are included below for comparison.

3.3.3 Low Efficiency Cell Array

This combination uses the most desirable features of Combinations 5 and 6 of Section 2.2. It features unified processing and integral array formation, combined into discrete submodules.

Both sputtering and CVD technologies, and especially a combination of these, appear to be very promising.

Ion implantation for junction formation is particularly attractive since it allows elimination of several costly process steps, such as cell back etching and edge etching, and facilitates fabrication of "wraparound" cells with suitable fixturing, because of the accurately-controllable implantation geometries. Further, the technique lends itself particularly well to solar cell manufacture. The typically-shallow junctions and closely-controllable dopant concentrations can provide better blue response and increased lifetimes in the implanted region (after annealing). (Dopant levels can range from very low to above the solid solubility limit.) Additionally, the implanted dopant distribution can be tailored to provide an accelerating field for the carriers toward the junction to further improve cell efficiency. Even if the ion implantation advantages are not realized in practice, advanced thermal diffusion methods may still be useable.

3.4 Pertinent Cost Considerations

3.4.1 High Efficiency Cell Array

A clearer picture of the concept for the high efficiency, high concentration array option has been developed. The solar cells with their parameters optimized for high efficiency would be more costly than those described in the other options. However, the overall combination is very promising since it uses high-quality silicon already available and it uses processes already adequately developed. Some cost reduction may be expected from larger scale production rates. Due to the probably limited area usage, rectangular cells would be used to achieve maximum fill factor. Cell costs may be reduced by lowering the efficiency somewhat (say from 20% to 15% AM1), by decreasing cell fabrication cost through modification of some of the standard process steps along the lines indicated in Section 3.4.2.1 below. However, because of the high concentration ratios to be used, process steps must be used to insure that series resistance is kept very low. The 10 to 20 concentration ratio would be achieved by such means as a parabolic or hemi-cylindrical concentrator array, and, of course, would result in a great cost reduction in cell area required.[7]

To provide an appropriate indication of costs of producing the high efficiency cells, it is instructive to estimate briefly changes in costs in various areas of cell fabrication compared to the present costs of producing space-qualified solar cells, but retaining or improving present conversion efficiencies.

Within a year, direct labor costs can be halved without mechanization of processes, and can be reduced by a much greater factor if automatic process equipment is made available. The reduction by a factor of two applies to the four areas of cell manufacture: crystal growing, mechanical, diffusion, and fabrication. This reduction in labor costs is very significant because usually high overhead costs are decreased significantly as well. Material (silicon, contact grid metals, AR coatings) costs will not decrease as much, probably to 75% of present costs, with a slight reduction in the crystal growing area and a similar slight decrease in contact and AR coating areas. The cost of supplies (indirect material), which includes quartz crucibles and helium in crystal growing; cell surface preparation materials in mechanical; chemicals such as etchants, solvents and furnace-ware in diffusion; and chemicals, solvents, evaporation masks, gloves, tape, etc. in fabrication, is expected to drop almost to half its present value.

Alternative processes such as chemical etching and polishing should be studied carefully and compared with mechanical lapping and polishing with regard to cost reduction since both these techniques do not seem to change cell efficiency. Another promising cost-reducing technology is the use of aluminum rather than the more expensive (at least four times, depending on aluminum purity required) silver-titanium grid contacts. On the other hand, alternate efficiency-improving processes described in Section 2.2.1 above may offset these cost reductions. This is an area requiring much more R & D analysis and experimentation, and various trade-offs should be examined as discussed in Section 5.0 below.

3.4.2 Medium Efficiency Cell Array

At present ribbon-grown silicon is of sufficiently high quality, and projected costs sufficiently low, that it is a very strong contender for use in low-cost solar cell arrays. Recent samples 30 cm by 2 cm by 1/2 mm thick have demonstrated carrier diffusion lengths up to 10 micrometers,[8] indicating that this material can now be produced to make adequate medium-efficiency solar cells, and it is believed that with improvements in purity and crystal structure, diffusion lengths for ribbon silicon comparable to those now obtained in Czochralski-grown single-crystal ingots (approximately 150 micrometers) will be available within six months.[9]

The 30 cm by 2 cm samples mentioned above are not completely single crystal, but have small sections containing deposits of polycrystalline silicon. However, this presents only a relatively minor problem since sections with these defects can be cut out. Thus both the advantages of nearly 100% packing factor resulting from use of rectangular ribbon silicon in an array, as well as practically zero kerf loss are retained.

Very simple processing would be used in the fabrication of the cells from the ribbon in order to achieve lowest cost: no elaborate surface finish, deep diffusions, simple wraparound contacts (for example, inexpensive nickel plating following initial deposition of a very thin film of a more expensive contact grid metal). If a transparent conductive front coating, such as was mentioned in previous sections proves suitably inexpensive, a very simple contact would be adequate, rather than the complex grid contact patterns presently used.

A simple V-groove reflector concentrator submodule for the ribbon silicon cells still appears to be the simplest and least expensive means for increasing the power output for a given cell area. A recent thorough study[10] indicates that a yearly averaged concentration factor of two for this type of concentrator is to be expected, with only four seasonal adjustments in orientation required. (This is in contrast to the system using egg-crate concentrators and round cells, since, while round cells are less expensive, their packing factor is poor, and the egg-crate has a low concentration ratio, requires more complicated interconnections, and also requires accurate tracking of the sun.)

Bonding of the cells to the concentrator/array would be done by flow soldering to the bottom of the V-groove which contains a previously-tinned substrate PC board interconnection configuration.

An estimation of costs over and above the solar cell itself, i.e., of suitable V-groove concentrator-array structures has been made. These costs must be added to the cell area cost mentioned above.

The proposed array module consists of a polished aluminum V-groove concentrator, suitably coated for bonding to the cell substrate, aluminum back plate, stiffener, and frame, coverglass, and assorted hardware, electrical connections and encapsulant.

3.4.2.1 Alternative Medium Efficiency Cell Array

An attractive possible alternative to the ribbon-silicon cell for the V-groove array configuration using presently available well-established technology involves replacing the silicon ribbon with cells fabricated from large silicon single crystals (e.g., 7.5 cm diameter, 45 cm long). The slabs are cut on two sides only, sliced to minimum economical cell thickness, then mounted end-to-end in the V-groove (see Figure 4). The two cuts, instead of four, reduce the waste of silicon, but any cutting loss still is sufficiently large that this costly process step requires substantial attention.

Again the goal is to obtain a rugged cell using simple processing, such as is based on the following assumptions:

1. Cell blanks, as-sawn (no further polishing), with liberal cell chipping allowance in the specifications.
2. Minimal etching and cleaning steps.
3. Diffused cells; stains acceptable.
4. Single contact evaporation, front and back, possibly aluminum instead of titanium-silver.
5. Simple AR coating, probably SiO, and sintering.
6. Mechanical inspection for gross breakage and electrical test for minimum output.

For this configuration, a wraparound construction would probably not be effective; rather the cells would be bonded down and jumper bars used to connect end contacts instead (eliminating complex grids). Thus each V-groove has parallel-connected cells, and a module with the required voltage would be obtained by interconnecting the ends of several V-groove cell submodules (Figure 4).

3.4.3 Low Efficiency Cell Array

This array option includes the most speculative features, since it combines several process steps which have not yet been demonstrated beyond "primitive" feasibility.

For sputtered, evaporative, or CVD processing, polycrystalline silicon (at best) is expected (using appropriate substrate temperatures), and one must consider the real chance that even low efficiency cells cannot be made satisfactorily without large changes in cell structure. Consequently, cost estimates are very difficult to make.

The most desirable approach would be to try to combine cell formation with array module formation since the goal is low overall cost, and if the cell structure must be changed a great deal, then one might as well form the array as well. It was decided to combine sputtering, CVD, and evaporative processing in the "unified processing" option, since all have roughly the same degree of uncertainty regarding reduction to practice and successful combination for processing.

Similarly, CVD technology has recently been used to demonstrate feasibility of continuous low-cost deposition of silicon dioxide,[11] particularly suitable for process mechanization. A very similar system could readily be used to produce polycrystalline silicon and subsequent layers of a solar panel at low cost.[12]

The system would be based on the same principles as the continuous SiO_2 deposition system as far as general configuration is concerned, but would use larger solar cell substrates in the Inconel trays used to carry wafers in the system described in Reference 11. Also, it may be possible to process the substrates on the belt without using the trays. In order to produce high quality polycrystalline silicon for efficient solar cells, the substrate temperature would have to be much higher than 400° C (say 1000° C), so some modification of the equipment would be necessary, but no significant breakthrough would be needed.

Subsequent process steps, i.e., junction formation, front contact and AR coating could be performed further along the continuous process system.

As stated in Reference 11, the continuous CVD system offers several economic and technical advantages over high capacity horizontal reactor batch systems. There are substantial savings in labor costs, and further savings in improved efficiency in utilization of reactant gases. The system described would offer to the production of polycrystalline silicon the same advantages that have been shown for forming layers of SiO_2.[12] These are high throughput (and therefore lower cost), highly uniform films (and therefore higher yield), and are especially suited to being more easily adaptable to mechanization of complete solar cell processing. These factors indicate more promising cost reductions.

3.5 Cost Analysis of Three Combinations

After outlining the background factors which must be taken into account we will now present analyses of the predicted costs for the three main combinations selected above.

NOTE: The analyses will present costs which are considered realistic for the near future. As mentioned in Section 1.4 above, extrapolation from near future cost estimates to the lower costs expected for large production numbers can later be carried out for all combinations. The expected lower cost limit of the three combinations will probably be decreasing in the combination order: high to medium to low efficiency cell arrays.

3.5.1 High Efficiency Array

Using as a base line for this analysis the present approximate costs and conversion efficiencies of space-quality cells, rejected for reasons other than electrical output, one can make cell and array cost estimates that can be expected with process changes and improvements in the near future.

Assuming present terrestrial systems provide power at roughly \$40 per peak watt* (i.e., 1000 W/m^2 input) or \$160 per watt for the average incident sunlight specified for this project (250 W/m^2), then it is estimated that at present the cell contributes \$50 per watt to the total cost, since roughly 2/3 of the complete cell and array system cost is array material, array assembly labor, overhead costs, G & A, and profit. Thus for a 15% (AM1) efficient cell, which is a reasonable assumption for present 1 ohm-cm cells, the basic cell cost is \$1900 per square meter.

The initial goal in this cell and array system is to produce a cell with exceptionally low series resistance, while retaining at least 15% (AM1) efficiency, under concentration ratios of 10 to 20 times. In order to do this, as mentioned in Section 2.2.1, an optimum combination of junction depth, cell thickness, and grid contact pattern must be used in fabrication. Present estimates indicate that the additional

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*All costs mentioned in this section are estimated to have an uncertainty of ± 20% at best; but they are projections based on actual costs of proven cell process and array fabrication technologies.

refined processing steps will add approximately 30% to the cell cost. Then the "improved" cell will cost approximately $2500 per square meter. Further, array fabrication cost (which includes encapsulation, interconnections, concentrators; as well as allowing 5% of generated power for cell cooling) is estimated to equal the cell fabrication cost. That is, the completed system (cells in the array structure) will cost twice as much as a finished cell of the same area (i.e., $\$5000/m^2$) compared to three times as much now.

As outlined in Section 3.4.1, it is estimated that in approximately a year, assuming the same production quantities as at present, the cost of producing cells will be roughly 60% of the present cost as a result of reducing direct labor costs, material costs, and supplies (indirect materials) costs, while still producing a cell possessing the same (or better) characteristics as present space-quality cells. Taking these factors into consideration (the 30% cost increase for refined processing and the 60% decrease due to more efficient use of labor, materials, and supplies), it is estimated that in about a year the complete system of cells in their array structure will cost roughly $3000 per square meter.

For low series resistance cells with 15% (AM1) efficiency, 250 W/m^2 incident sunlight, and a concentration ratio of 10, generated power at the present time, costs \$5 per watt for the cell alone and \$16 per watt for the system which includes both the cells and array structure. This corresponds to a system cost of \$6000 per square meter. The "improved" system, as discussed above, costs \$3000 per square meter, so that for the same conditions as above, photovoltaic power will be produced for \$8 per watt by the complete system (\$4 per watt for the cells alone). The costs of cells and completed systems at the present time and estimated costs in one or two years are summarized in the following table (Table i) for concentration ratios of both 10 and 20 times:

Table (i)

AM1 Effic.	Conc. Ratio	Cost at Present				Cost in 1-2 years			
		Cell		System**		Cell		System**	
		\$/W	\$/m^2	\$/W	\$/m^2	\$/W	\$/m^2	\$/W	\$/m^2
15%	10x	5	1900	16	6000	4	1500	8	3000
15%	20x	2.5	1900	8	6000	2	1500	4	3000

** System cost includes both cell and array structure costs.

3.5.2 Medium Efficiency Cell Arrays

Ribbon-grown single crystal silicon shows considerable promise, initially to fabricate medium efficiency cells, and, as the process is improved and perfected, eventually to make high efficiency cells. Recent encouraging results were described above in Section 3.4.2.

Anticipated costs of producing power using ribbon-grown silicon cells will be approximately $7 per watt* or $350 per square meter of cell area (i.e., not including array costs) in approximately two years, based on the following assumptions:[13] polycrystalline silicon $60 per kg, pulling ten 1 cm ribbons simultaneously at 2.5 cm per min., 24 hours per day, with a 50% yield, a 10% (AM1) conversion efficiency, 250 W/m^2 incident sunlight (as specified for this project) and a concentration ratio of two. (With moderate improvements in the technology, the cost of generated power is expected to halve within 10 years to $3.50 per watt.[13])

For the aluminum V-groove concentrator structure and other parts of the array discussed in Section 3.4.2 above, we have as a guideline the costs of similar

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* The uncertainty of cost estimates in this section is estimated to be at least ± 50% for the first "ribbon" cell array; and ± 20% for the alternative "semi-round" cell array.

presently-manufactured (i.e., no development time required) terrestrial array modules. For single units the concentrator/array cost is approximately \$100 per square meter.[14] In large quantities, this cost will be reduced by a factor of 3 to 4, yielding a cost of approximately \$30 per square meter[14] for the V-groove array module. Then the complete system (cells and array) module will cost roughly \$380 per square meter, or \$7.50 per watt based on the assumptions listed above.

3.5.2.1 <u>Alternative Medium Efficiency Cell Array</u>

For the process combination which uses the "semi-round" single crystal silicon slices with only two cuts, placed in a V-groove concentrator (Figure 4), we can use projected costs obtained from an analysis based on the six assumptions of the simplified processing described in Section 3.4.2.1 above, and using present-day costs for material (5 cm diameter silicon slices, silver-titanium grid contact metal), labor (<u>including</u> overhead costs), and supplies (e.g., etchants, solvents, gloves). This analysis indicates the solar cell cost is approximately \$1500 per square meter now for 5 cm discs.[14] However, by using 7.5 cm diameter slices which have roughly twice the area, it is estimated the cell cost will be 25 to 30% less, or $1100 per square meter. The cost of the concentrator and support structure is estimated to be the same as described in the previous sections, $30 per square meter. Through more efficient use of labor, materials, and supplies, it is expected the cell fabrication cost could be halved within the next year, i.e., to $550 per square meter,[15] or $580 per square meter for the completed system. Then, based on a cell conversion efficiency of 15% (AM1), 250 W/m^2 incident sunlight, and a concentration ratio of two, it is expected that in a year, power from this type of array module will cost approximately $8 per watt.

3.5.2.2 Longer Range Ribbon Cell Estimates

Currin et al[23] have made predictions for the costs for cells made from silicon ribbon, using estimates of volume cost reductions in polycrystalline silicon ($35/kg), in silicon ribbons ($25/$m^2$), and reduced cell costs ($40/$m^2$). 25 MW output was available for $38 x 10^6 cost. These estimates are tentative, but indicate a lower limit within the range of present predictions (with no allowance for production yields). Table (ii) summarizes the estimates for the three medium-efficiency cell approaches.

Table (ii)

System Cell	AM1 Effic.	Conc. Ratio	Cost in 1-2 years			
			Cell		System	
			\$/W	\$/m^2	\$/W	\$/m^2
Ribbon	10%	2x	7	350	7.5	380
Semi-round*	15%	2x	7.5	550	8	580
Ribbon**	10%	1x	1.5^+	40^+	3^+	80^+

3.5.3 Low Efficiency Cell Arrays

Here we attempt to estimate the costs of fabricating cells using two examples of unified, or continuous, processing: sputtering and chemical vapor deposition (with evaporation as a probable alternative for certain process steps).++

Several examples of large-scale processing using these three technologies are already in operation, others have been planned, and serve as guide-lines for expected costs if they prove feasible for terrestrial solar cell and array production.

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* Estimates for 7.5 cm diameter cells.

** Estimates from Currin et al,[23] where drastic cost extrapolations have been made. The numbers here are corrected for the same insolation conditions as the other two cases.

\+ For this option, the numbers quoted refer to 5-10 years' estimates.

++ Cost estimates in this section have an uncertainty up to a factor of 2 since the successful reduction to practice of several process steps cannot be reliably predicted without further work.

A very large-scale operation used to evaporate thin coatings (100Å) of chromium on large sheets of building glass[16] is estimated to cost \$5 to \$10 per square meter when all costs are taken into account.

Another example of a process operation which would appear to be more closely associated with one envisioned for the production of large-area solar cells involves evaporation of a complex alloy on turbine blades heated to approximately 1000°C.[17] This coating is estimated to add approximately \$30 per square meter to the turbine blade cost.[18]

Also, an estimate has been made of the cost of producing CdS solar cells in large scale production for approximately \$10 per square meter.[19]

<u>Cells Made By Sputtering</u>

For solar cell fabrication, assuming sputtering to be a viable process (especially regarding p-n junction formation), an estimate of cell costs for large-scale production can be made.[20] We assume present sputtering technology is used (i.e., no great technical breakthrough is required), a large 1.3 meter diameter chamber 15 to 20 meters long with sections for four sequential sputtering processes (e.g., p-Si, n-Si, front contact or transparent conductive coating, and AR coating) and appropriate substrate temperature provision for each section. Cells approximately 10 micrometers thick and 30 x 30 cm sputtered onto an appropriate supporting substrate material can be sputtered in 10 to 60 minutes (most conservative estimate), yielding an hourly output of approximately 100 sections 30 x 30 cm square, or roughly 100,000 square meters per year. In the case of large numbers of such sputtering units, each apparatus is estimated to cost $2.5 million and would be depreciated over 10 years. Taking manufacturing materials, supplies, labor, and substrate costs into account, the polycrystalline cell cost is approximately $5 per square meter. Assuming no concentrators are used, 1% (AM1) conversion efficiency and 250 W/m^2 incident sunlight, the power produced would cost approximately $2 per watt. Array costs would add roughly $3 per square meter for a total of approximately $8 per square meter of complete system producing electrical power for roughly $3 per watt. Thus if an adequate p-n junction can be fabricated, and neglecting system factors such as land costs, this technology also appears to provide low-cost power.

Cells Made By Chemical Vapor Deposition

The second example of unified processing is cell fabrication using chemical vapor deposition (CVD). Based on the same principles as the continuous SiO_2 CVD system[11] described in Section 3.4.3 as far as general configuration is concerned but using large solar cell substrates and, of course, with a much higher substrate deposition temperature (say 1000°C), it is estimated polycrystalline silicon of suitable quality for cells can be deposited for $10 per square meter.[12] Subsequent process steps (junction formation, front contact, and AR coating) could be carried out using CVD, but evaporation or sputtering is recommended for the metallization, since either process produces a better and much less expensive metal contact than can be achieved by CVD.[12] Then, it is estimated that junction formation (again assuming it is feasible using CVD), front contact deposition, and AR coating deposition would add approximately $10 per square meter to the cell cost. Costs for a simple array structure would add $3 per square meter (use the same apparatus as in the sputter process described above). According to these estimates the complete array cost would be roughly \$23 per square meter. Using the same assumptions for performance as in the sputter process, i.e., no concentrators, 250 W/m^2 incident sunlight, and 1% (AM1) conversion efficiency, photovoltaic power from this system would cost roughly \$9 per watt.

Table (iii)

System Cell	AM1 Effic.	Conc. Ratio	Cost in 1-2 years*			
			Cell		System	
			\$/W	$\$/m^2$	\$/W	$\$/m^2$
Sputtered	1%	1x	2	5	3	8
CVD	1%	1x	8	20	9	23

The costs for all three combinations are summarized in Table 4.

3.5.4 Cost Estimates For Promising Alternative Process Technologies

Several alternative cell fabrication techniques have been described in the discussion of the three combinations selected as best candidates for producing low-cost photovoltaic power. Some are well-proven techniques; others require considerable work to establish feasibility at lower cost than present technologies. It is the purpose of this section to estimate costs of these "unproven"

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* Assuming the technologies are feasible for fabricating suitable p-n junctions.

techniques, to compare them with present technology costs, and to suggest which combination(s) would benefit from application of the various techniques.

3.5.4.1 Mechanization of Cell Fabrication

The cost of labor and supplies for all three combinations can be greatly reduced by mechanization or automation of as many process steps as possible to reduce the time-consuming tasks of loading and unloading blanks or cells. Another benefit from mechanization is the higher cell throughput volume which greatly reduces fixed overhead costs in addition to those overhead costs directly connected to labor costs.

A specific example of mechanization of several of the wet chemical process steps in batch-fabricating solar cells of the space-quality type described above, is use of Allied Chemical Corporation's automatic materials handling system MESA APR-1000.[21] Its use would be especially advantageous for the high volume cell throughput anticipated for economical production of electricity by photovoltaic means. Specific information on the use of the apparatus is given for photoresist removal, but with only slight modifications this apparatus can be used in the following process steps in solar cell fabrication.

Mechanizable wet chemical process steps:

1. Degrease and clean sawn blanks;
2. Chemical etch cell blanks;
3. Back-etch diffused cell blanks;
4. Tape residue removal; diffusion glass removal; pre-metallization cleaning.

This example of mechanization of the four process steps above involves efficient batch processing of cells and can be compared with regard to advantages and disadvantages with the continuous processing of low efficiency cells described above in Section 3.5.3.

Some advantages in using this system include reduction of chemical consumption by an estimated 75%, for example by recycling solvents; reduction of costs associated with cell breakage due to handling (costs which are approximately equivalent to the apparatus lease costs); a greatly increased cell throughput (say four times) while the apparatus occupies roughly half the floor space that is used in present hand processing. Another important advantage is the reproducible nature of the processing: the automated cell boat transfer mechanism and steady-state condition of etches or cleaning solutions assure that every cell is processed identically.

The cost of processing cells using mechanized processing for the steps indicated can be estimated based on the following assumptions: process the same area of solar cells as wafers per hour; continuous operation except for an average 1/2 hour shutdown every 24 hours; leasing each apparatus for $3000 per month. Such calculations yield a cost for these four steps in cell fabrication of approximately $1 per square meter for leasing each apparatus, with utilities and chemicals adding about $1.50 to this cost. Accordingly, the four wet chemical batch processing steps add approximately $10 per square meter to the cost of cells.

These costs can be compared to present costs of the same four steps with hand processing now used for space-quality 2 x 4 cm cells. Actual present direct labor costs are used, with approximately 30% added for supplies (indirect material), but with no overhead costs, since, in large volume production, the present overhead rate would be much reduced.

Hand wet chemical process step costs:

1. Degrease and clean sawn blanks: $8 per square meter
2. Chemical etch cell blanks: $21 per square meter

3. Back-etch diffused cell blanks: $30 per square meter

4. Tape residue removal; diffusion glass removal; pre-metallization cleaning: $10 per square meter.

Thus, for these four wet chemical process steps, approximately $70 per square meter is added to cell costs when hand processed compared to roughly $10 per square meter when mechanized processing is used.

The most time-consuming and therefore costly steps are loading and unloading the blanks or cells at many stages in cell fabrication. A very large saving could be made if the cell blanks were processed through many steps in the same holder or fixture, if batch processing is used. The continuous processing method suggested for the lower efficiency cell option discussed above (Section 3.5.3) is a goal to strive for as much as possible regardless of the type of cell or process eventually chosen as the lowest cost technique.

Additional process mechanization could be achieved by the use of belt diffusion furnaces and annealing furnaces. Another alternative that can more immediately reduce process costs is the use of programable diffusion boat push and pull apparatus presently available for standard diffusion furnaces.

At present, the most time-consuming process step and bottleneck is loading and unloading cells into and out of the metallization mask fixtures. If continuous transparent conductive front coatings can be used, the front contact step could also be mechanized. It is not difficult to envision a mechanized form of the present front contact application, e.g., use of a hinged shadow mask which is flipped over the slices after pre-metallization cleaning. The indexing could be easily arranged by shaking the slices into "wells", spaced to match the shadow mask pattern.

A second example of mechanization is applicable to the "unified" process, low efficiency cell array. It is a new automated sputtering apparatus,[22] suited to meet the requirements of high volume, high yield batch production. In order to eliminate any possibility of error and to ensure process repeatability, "one button" automation was required. The automated apparatus has the capability to handle wide variations of sputtering processes, such as etch, deposit, heat, and bias modes of operation occurring in different orders. Such a complex process requires that the mechanization provide the flexibility to program the sequence of events, as well as set the power levels and operating times. Especially with rf sputtering, the apparatus programer must operate reliably in a high electrical noise environment. A specific example, which involves some 60 automated process steps, is described, for sputtering platinum on silicon for Schottky devices. With modification such an apparatus could be used to process large volumes of solar cells with a very large reduction in labor costs and higher yield because of the reproducibility of the processing. A similar programable device could be used to mechanize the continuous-process CVD cell manufacture.

Substantial cell fabrication cost reductions can be expected as was the case in mechanizing wet chemical processing described above.

3.5.4.2 Other Alternative Techniques for Various Process Steps

Alternative technologies exist for almost all the steps presently used or contemplated in solar cell fabrication. Feasibility as lower-cost alternatives for some has been demonstrated, while others are not well-established, or are not cost-effective compared to process technologies presently used. Reference has been made to many of these processes in earlier sections of this report.

The use of silane (SiH_4) as the starting material instead of trichlorosilane ($SiHCl_4$) has some advantages, particularly for the CVD polycrystalline cells, since it readily decomposes at relatively low temperatures with a higher proportional yield of silicon than from trichlorosilane, and hydrogen is the other useful reaction product. The molten salt method for producing silane[1] yields silicon metal with greater than 500 ohm-cm resistivity directly, probably pure enough for low-cost cells without further purification processing. Substantial energy savings will be realized because of the much lower decomposition temperature of silane compared to trichlorosilane. A large manufacturer of silane estimated that with higher production rates of silane (ten times present volume) and with a different (unspecified) process, the cost of silane (which yields about 90% silicon upon decomposition) can be reduced well below $100 per kg, making it nearly competitive with polycrystalline silicon, which is now roughly $75 per kg.

Cell blanks as-sawn, cleaned and etched briefly, with no costly elaborate mechanical or chemical polishing of the front surface, demonstrate conversion efficiencies comparable to highly polished cells. Accordingly, savings of the order of 20% can be made for rectangular cells, and 35% for "semi-round" cells by eliminating the polishing step.

Ion implantation is a promising alternative to diffusion for p-n junction formation, offering several advantages, such as larger volume throughput, controlled dopant profile, accurate geometric implantation (no edge-etch required) and no back-etch process step required. However, at the present time, ion implantation of the dopants to the concentrations required for solar cells, and at somewhat increased cell volume throughput, costs approximately $15 per square meter, compared to $3 per square meter for junction formation by standard diffusion. For large volumes and mechanization, ion implantation will be more nearly competitive. The usual anneal process after ion implantation can probably be eliminated for the already-disordered polycrystalline silicon cell combinations.

Another substantial saving can be realized in large volume production by the use of aluminum grid contacts rather than silver-titanium. Depending on the aluminum purity required, a cost reduction of at least 5% can be expected. (The 5% reduction was calculated assuming the purest aluminum is necessary; investigation of the use of lower purity aluminum should be carried out.) As mentioned above, a hinged shadow mask would greatly reduce the labor costs in the metallization step.

A further simplification and reduction in cell costs can be made if transparent conductive front coatings with good transmission characteristics over the AM1 spectrum can be substituted for the costly metal grid contacts. Results from spectral response experiments with tin-doped (18%) indium oxide coatings show the lower wavelength cut-off is approximately 0.45 micrometers, causing a substantial loss of the incident energy in the blue region of the AM1 spectrum. Techniques to improve short wavelength transmission are being investigated. The uniform conductive coating, when it is made practical for production, will cut contact costs substantially, especially if the transparent conductive coating is an efficient AR coating as well.

The cost of the silver-titanium metallization process step for 2 x 4 cm cells, assuming 30% additional cost for supplies (indirect materials) and no overhead costs is now $65 per square meter. It is estimated the conductive coating can be deposited by sputtering for between $5 and $10 per square meter for large production volumes, a reduction in the cost of the cell for this process step of a factor of roughly 5 to 10 times.

The SiO AR coating process step for 2 x 4 cm cells, with the same assumptions as those given for metallization, presently adds $36 per square meter to the cell cost. A sputtered AR coating (SiO, or coatings with better transmission characteristics, such as TiO_2 or Ta_2O_5) will add approximately $5 to $8 per square meter to the cell cost, a reduction of a factor of about 5 for this step. A similar reduction of costs would follow from scaled-up production in the present SiO process.

It is evident that, even with the small amount of work that has been done on these alternative technologies, very substantial cost reductions can be made. Accordingly, for low-cost terrestrial solar cells and arrays, those techniques which greatly reduce costs as production volume is substantially increased should be investigated thoroughly, the objective being much improved cell characteristics at much lower cost.

4.0 Discussion on Cost Analysis

4.1 Comparison of the Three System Combinations

The final three combinations described above were chosen in an attempt to combine and balance the conflicting requirements of ultimate low cost/watt, and of the time of realization of the technology. Thus the three combinations selected can be described as:

(a) High Cost--short term realization

(b) Medium Cost--medium term realization

(c) Low Cost--long term realization.

In addition, the ultimate cost/watt should decrease from (a) to (b) to (c), but the numbers given in Table 4 do not always suggest that this sequence will be found.

Within any combination, the cost/watt can be expected to decrease steadily with time, approaching a lower limit for (a) and (b). Combination (c) involves more unknown factors. Should some of the remedial steps necessary to obtain reasonable conversion efficiency in a cell (e.g., to offset grain boundary effects in polycrystalline cells) prove successful, the cost/watt will decrease with early improvements. However, if the remedial steps become increasingly complex the cost/watt may begin to increase again.

There is another complicating factor which was described in Section 1.3 above. There are several potential large-scale markets for terrestrial solar cells. However, not all the combinations chosen here will be available for all these markets.

For example, the low efficiency approach does not appear promising for the limited area uses (houses, markets, etc.) unless considerably increased efficiency (up to 10 fold) can be achieved. This factor may delay the development of the low cost approach because only arrays such as those in (a) and (b) above can fill the immediate need and will, therefore, attract most development effort.

4.2 Independent Evaluation of Photovoltaic Options

It is of interest to quote the results of a recent questionnaire given to participants in a photovoltaic specialists workshop (NSF Workshop, Cherry Hill, New Jersey, October, 1973). The questionnaire was prepared and assessed by the staff of Arthur D. Little, Inc. The results of the more detailed follow-on questionnaire (January, 1974) show both the consensus opinions of the participants and also the divergence within this consensus of opinion. The highlights of this questionnaire were as follows:

1. <u>Most Promising Photovoltaic Materials</u>

   Silicon - with equal weighting for single crystal and polycrystalline forms.

2. <u>Most Promising Processing Methods for Scaled-Up Operations</u>

   Chemical Vapor Deposition or Evaporation. (The results indicated edge-defined film growth ribbon silicon showed some promise.)

3. Making the assumption that the Government has decided to promote photovoltaic uses by supplying between 10 and 100 million dollars per year:

   (a) <u>Estimated Cost per Peak Watt</u>

   After 5 years - $5

   After 10 years - $1

   After 25 years - $0.5

   (b) <u>Percentage of Total Energy Supply</u>

   After 5 years - 0.1%

   After 10 years - 1 %

   After 25 years - 13 %

In (b) it is estimated that the three usage areas will be satisfied as indicated in the following table:

Time Frame: after	5 years	10 years	25 years
Specialized (Remote areas, etc.)	10 %	25 %	50 %
Residential or Industrial	0.3%	1 %	12.5%
Central Power Stations ("solar farms")	0	0.1%	5 %

There was quite a wide range in the estimates made in the various categories. Also the background factors were examined, and it was found that often similar predictions were made, but based on differing sets of assumptions.

However, for this report, the interesting feature of this questionnaire is that the predictions concerning cost/watt in 3(a) above agree very closely with estimates made earlier in this project; these estimates have been re-examined and are still considered to represent the best that can be made based on present data.

5.0 Research and Development Technology Required

5.1 Difficulties in Predicting Technology

There are several reasons which make prediction of the appropriate technology very uncertain:

(a) It is difficult to extrapolate from present solar cell and array methods, because these methods have been developed for very specialized applications involving cell numbers many orders of magnitude lower than those in the goals of the present study.

(b) It is difficult to predict the complete range of technology required, because the fabrication sequence for cells and arrays often involves interactions between the various steps. Also special rapid advances ("breakthroughs") cannot be predicted, but often have a dominant effect on the technical options which will prevail.

(c) The history of similar predictions shows low success, e.g. the utilities made predictions six years ago to guide their future energy development plans. All the promising methods considered at that time are not at present serious competitors. Similarly, in microelectronics, the rapid proliferation of low cost pocket-sized electronic calculators was not foreseen several years ago.

Despite all these pessimistic factors, it is useful to attempt to make the best predictions possible on future work needed on photovoltaics, using present knowlege; the hope is that the accumulated technology will lead to an atmosphere more able to take advantage of (and hopefully create) further advances in the future.

5.2 General Comments on the Three Combinations Selected

The cost figures in Section 3 above showed that for all three options, costs below $10 per watt can be predicted. However, the differences between the three options were not as pronounced as expected from previous work (the numbers quoted for the lower efficiencies did not show potential for drastic cost reduction). The reason was probably that less information was available for predicting cost reduction in manufacturing, for options which depart most from present methods. Because much more work is required to obtain reliable technological and manufacturing information, more R & D work is proposed for the low cost option. The incentive for this increased funding is the greater chance of reduced costs per KW for such options.

5.3 Research and Development Programs Suggested

For all three options, the programs suggested are broken down into:

(a) the technological advances needed in the various process steps;

(b) the manufacturing scale-up effort required to fabricate cells in arrays.

The programs (duration and costs) are given in Tables 5 through 7. Before studying these, the comments below should be read.

5.3.1 Comments

(i) Because of the interaction between various steps, some additional money has been budgeted for systems analysis of the best combination of the steps.

(ii) Many of the steps suggested are common to all three approaches,* particularly in the scaling-up effort; the amount of effort predicted may vary somewhat. Therefore, some funding common to all options can be started, to provide a broad background for all three approaches.

---

* These steps are indicated by an asterisk in the figures.

(iii) Considering that the high efficiency cells combined with concentrators will reduce overall system costs, the projected array expenditure for this option appears reasonable.

(iv) The projected costs assume that the separate advances in technology will all be available in a restricted number of locations. This implies either a broad based cooperative effort involving several sources (Government, university, and industrial) or at least a very tight-knit program based on detailed monitoring of projects with allowable interchange of information.

(v) In general, the amounts predicted are considered conservative, but are adequate to lead to the next phase of evaluation.

(vi) It is planned that the overall approach in this area will be gradual and evolutionary, i.e. that as each reasonably large cost reduction is achieved, an additional market segment will open up and will be available for commercial implementation. This will provide feedback on the technology state-of-the-art, and will also allow consolidation of the necessary hardware.

It will also help in providing funding for further advances. Thus the funding proposed is not entirely charitable in nature, but is more seed-funding. The overall goals sought are large and important enough to justify Government support to accelerate the industrial advances.

(vii) If past estimates are typical, continual revision of this scheme must be done annually, taking into account the recent advances made.

5.3.2 Additional Notes on a Specimen Case: Silicon Ribbon Development

The developments in this restricted area of research can be used to suggest some trends to be expected for other work.

Technologically, the silicon ribbon was based on a sound technology (EFG formation, sapphire ribbons) which had been developed into a competitive manufacturing method.

Application of the EFG process to form silicon ribbons was accelerated both by an optimistic case study (Currin et al[23]) which used admittedly bold extrapolations to suggest the achieving of low cost goals, and also by the fact that ribbon silicon had promise to fall between the extremes of very good and very poor quality silicon, and to remove all slicing and polishing operations.

Because of this promise, dual Government funding (NSF and NASA-JPL) was provided to Tyco Labs-Harvard University, and in two years the feasibility was shown for forming medium efficiency cells (9-10% AM1). At this stage a decision was required, to choose between further work aimed at providing good yield of silicon of medium quality with reduced costs (multi-ribbons, etc.) or work aimed at improved quality silicon. The former would appear to be the most desirable direction for the goals of low cost photovoltaic power generation.

At this time, the developments in the silicon ribbon technology had attracted commercial financing (Mobil Oil). Although the Mobil-Tyco group continues to receive Government contract support, the level of private funding is considerably greater than the Government level. As a result, should any significant advances be made towards a commercial exploitation of the ribbon technology, they will probably be diverted to commercial gain.

Thus at this stage, the Government role in this area will be reduced; however the Government can still use its licensing arrangements to widen the availability of the technology.

The pattern seen here can be expected to repeat for different areas of research. Therefore, any realistic Government program should anticipate such commercial evolution and should regard its own efforts as "seed-funding", to accelerate development of promising technologies. Also where necessary, the Government funding can shift towards investigation of alternative technologies (e.g. of dendritic web as a possible back-up for silicon ribbon) in case the early promise shown by the EFG process is not fulfilled.

6.0 Summary and Conclusions

Many summarizing comments were made in the text above.

The study analyzed three possible approaches, described as high, medium, and low cell efficiency options. Early indications suggested that these options would reach different low cost levels, with the cost per watt decreasing from the high through the low efficiency. The time scales required for these low cost levels would increase similarly from high to low efficiency options.

However, the cost analysis based on present information did not show the expected large differences in short term costs, although all three options give promise of costs below $10 per watt in the near future. For all options, there are further large cost decreases possible, when the production volume is increased to very high levels as demanded by the goals of the project.

The cost analysis showed that for all three options, much more research and development work is needed, to define process steps and manufacturing methods suited to large scale operation. Suggestions for such R & D work were made in Section 5. The overall conclusion is that the photovoltaic approach still shows promise for helping alleviate overall energy needs, but that intensive work is required to yield suitable large scale methods. The most likely course for reaching the large scale operations will be by gradual scaling up in the cell production numbers, with associated cost reduction, and increasing short term markets.

A Government program should encourage advances in the separate cell and array fabrication steps, with the hope that when made these advances are available for use in a wide range of possible lines of work. It is most important that any Government program should be well coordinated to encourage and to provide close cooperation between different groups, to enable real advances to be achieved over a broad enough front that there is good chance of practical realization of the low cost goals.

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TABLE 1

SOLAR CELL SPECIFICATIONS

	PROGRAM:	A	B	C	D	E
1	RESISTIVITY, ohm-cm	7-14	6-14	1-3	7-14	7-14
2	SIZE, cm	1 x 2	2 x 2	2 x 2	2 x 2	2 x 2
	Length, in.	.788 ± .005	.787 ± .003	.788 ± .005	.788 ± .005	.788 ± .005
	Width, in.	.394 ± .005	.787 ± .003	.788 ± .005	.788 ± .005	.788 ± .005
	Thickness, in.	.012 ± .002	.010 ± .002	.014 ± .002	.014 ± .002	.013 ± .002
3	WIDTH OF N-CONTACT	.045 ± .010	.043 min.	.035 ± .010	.035 ± .010	.045 min.
4	SOLDER THICKNESS					
	N-Contact, mils	1-5	1.5 ave.	3 nom.	3 nom.	3 max.
	P-Contact, mils	1-3	1.5 ave.	2-5	2-5	3 max.
5	EDGE CHIP					
	Depth, in.	.050	.025	.025	.015	.025
	Length, in.	no limit	.150	.100	.150	.150
6	CORNER CHIP, in.	.150	.075	.060	.060	.060
7	GRIDLINE BREAKS					
	Per grid	-	-	No break within .100 of N-contact	no req't	-
	Per cell	.100	.150		.100	.240
8	POWER OUTPUT, mW ave	27.1	55.5	60.2	56.7	55.6

TABLE 1 (contd.)

SOLAR CELL SPECIFICATIONS

PROGRAM:	F	G	H	I
1 RESISTIVITY, ohm-cm	1-3	1-3	1-3	1-3
2 SIZE, cm	2 x 2	2 x 2	2 x 2	2 x 3
Length, in.	.788 ± .005	.797 ± .005	.786 ± .005	.788 ± .005
Width, in.	.788 ± .005	.797 ± .005	.786 ± .005	1.182 ± .005
Thickness, in.	.014 ± .002	.014 ± .002	.012 ± .002	.014 ± .002
3 WIDTH OF N-CONTACT	.040 ± .010	.035 ± .010	.035 min.	-
4 SOLDER THICKNESS				
N-Contact, mils	solderless	solderless	2 max.	1-3
P-Contact, mils			5 max.	1-3
5 EDGE CHIP				
Depth, in.	.030	.030	.020	.025
Length, in.	.150	.150	.150	.200 total
6 CORNER CHIP, in.	.060	.060	.060	.060
7 GRIDLINE BREAKS				
Per grid	-	-	no req't	-
Per cell	.240	-	-	.200
8 POWER OUTPUT, mW ave.	59.8	62.6	60	87.5

TABLE 1 (contd.)

SOLAR CELL SPECIFICATIONS

	PROGRAM:	J	K	L	M
1	RESISTIVITY, ohm-cm	1-3	1-3	1-3	1-3
2	SIZE, cm	2 x 4	2 x 4	2 x 4	2 x 6
	Length, in.	.790 ± .003	.788 ± .005	.788 ± .005	.788 ± .005
	Width, in.	1.593 ± .003	1.591 ± .005	1.591 ± .005	2.364 ± .005
	Thickness, in.	.014 ± .002	.012 ± .002	.014 ± .002	.014 ± .002
3	WIDTH OF N-CONTACT	.043 min.	.040 ± .010	.040 ± .010	-
4	SOLDER THICKNESS				
	N-Contact, mils	2 max.	solderless	2 ave.	1-3
	P-Contact, mils	2 max.		2 ave.	1-3
5	EDGE CHIP				
	Depth, in.	.025	.030	.025	.025
	Length, in.	.250	.150	.150	.300 total
6	CORNER CHIP, in.	.075	.060	.075	.060
7	GRIDLINE BREAKS				
	Per grid	-	-	.150	-
	Per cell	.150	.480	.480	.300
8	POWER OUTPUT, mW ave.	118.8	119.6	118.0	175.0

TABLE 2

LIST OF OPTIONS for LOW-COST SOLAR CELL ARRAY PRODUCTION

1.0 **Solar Cell and Array Performance**

1.1 **Solar Cell Performance (watts/m^2)**

High Efficiency Cell
Medium Efficiency Cell
Low Efficiency Cell
High Light Intensity Cell

1.2 **Array Performance (watts/m^2/year)**

Long Life Arrays
Annually Serviceable Arrays
Daily Serviceable Arrays

2.0 **Solar Cell and Array Design**

2.1 **Solar Cell Design**

Cell Geometry
Conventional-Rectangular
Round
Large Area
Thin
Planar
Staggered
Edge on
Random

2.2 **Crystalline Structure**

Single crystal
Polycrystalline
Web or ribbon structure
Noncontinuous structure
Amorphous

2.3 **Junction Formation (N on P or P on N)**

Thermal diffusion
Metal on silicon
Abrupt junction
Multilayered junction

2.4 **Contact Configuration**

Conventional
High grid number
Planar
Wraparound
Optically transmitting contact
Inverted

2.5 **Cell Coatings**

Conventional
Abrasion resistant
Integrative

TABLE 2 (contd.)

LIST OF OPTIONS for LOW-COST SOLAR CELL ARRAY PRODUCTION

2.6 **Array Design**

Array form
Conventional
Modular (high voltage)
Large area (high current)

2.7 **Interconnect Configuration**

Conventional soldered
Printed circuit board welded
Pre-deposited modular

2.8 **Encapsulation**

Conventional glass or epoxy covers
  on site
Liquid

2.9 **Use of concentrators**

Egg carton
Planar or curved reflector
Spherical lens
Cylindrical lens
Liquid lens

2.10 **Array environmental conditioning**

Heat sink backing
Heat sink front
Gas or liquid refrigerant
Heat pipes
Convective cooling
Shock proofing
Self cleaning lens
Dust removing lens
Abrasion resistant

2.11 **Array Orientation**

Fixed
Tiltable
Rotating

3.0 **Chemical and Physical Methods to Process Materials and Cells and Arrays**

3.1 **Chemical and Physical Methods to Process Materials**

Conventional
High rate vapor deposition
Liquid separation
Ion plating

3.2 **Crystal Growth Process**

Vapor deposition
Gaseous epitaxy

TABLE 2 (contd.)

LIST OF OPTIONS for LOW-COST SOLAR CELL ARRAY PRODUCTION

Liquid epitaxy
Ribbon growth
Web growth
Czochralski single crystal
Plasma arc process
Organo-metallic segregation
Ion plating
Sputtering
Vacuum hot pressing
Evaporation

3.3 Cell Shaping

Sawing
Cleaving
Grinding
Etching
Reverse sputtering
Laser cutting
Spark erosion
Electron beam cutting
Electro-etching
Organo-metallic segregation

3.4 Junction Formation

Diffusion
Ion implantation
Liquid epitaxy
Vapor epitaxy
Alloying
Sputtering
Ion plating
Metal barrier (Schottky)
Nuclear radiation

3.5 Electrical Connects

Conventional-evaporated
Electro-plated
Silk screened
Epoxied
Electroless plated
Sputtered
Precipitated
Liquid

3.6 Coatings

Evaporated
Sputtered
Precipitated
High rate vapor deposition
Laminated
Fritted
Rolled organics
Sprayed organics
Vapor-deposited
Liquid-deposited

TABLE 2 (contd.)

LIST OF OPTIONS for LOW-COST SOLAR CELL ARRAY PRODUCTION

3.7 Chemical and Physical Methods to Process Arrays Encapsulation Techniques

Film backing
Printed circuit backing
Sheet fronts
Organic moldings
Non-organic moldings
Ceramic or glass substrates
Organic laminates
Metallic backings
Sprayed organics

3.8 Electrical Interconnects

Soldered
Welded
Conductive organics
Silk screened
Evaporated
High rate vapor deposited
Sputtered
Electro plated
Electro-less plated
Precipitated
Liquid

3.9 Concentrators and Lenses

Stamped metals
Plated metals on organic molding
Evaporated metals on organic molding
Sputtered metals on organic molding
Organic moldings
Fritted glass moldings
Liquids
Air or liquid supported films

3.10 Mounting Techniques

Factory mounted metal frame
Factory mounted molded frame
Field mounted frame
Vandalism shielding
Motor driven mountings
Wind compensation mounting
Heat sinking-convective fins
Heat sinking-liquid refrigerants
Heat sinking-heat pipes

4.0 Automation of Processes and Manufacturing Facilities

4.1 Continuous silicon purification, crystal growth, and junction formation equipment

4.2 Continuous crystal growth and junction formation equipment

TABLE 2 (contd.)

LIST OF OPTIONS for LOW-COST SOLAR CELL ARRAY PRODUCTION

4.3	Continuous contact formation equipment
4.4	Automated cell interconnection and encapsulation techniques
4.5	Automated encapsulation and concentrator array integration equipment
4.6	Automated cell-concentrator array integration equipment
4.7	Continuous coating and encapsulating equipment
4.8	Acid, solvent, and gas recycling equipment

TABLE 3

SELECTED COMBINATIONS OF SOLAR CELL AND ARRAY OPTIONS

OPTION	CELL AND ARRAY DESIGN	CELL AND ARRAY PROCESSING METHODS	PROCESS AUTOMATION
1 Ribbon-grown Medium Efficiency Cell, Fixed Arrays	Long, narrow rectangular cell high grid number conventional contacts and AR coating PC interconnects epoxy encapsulation V-groove concentrator convection cooling fixed orientation	Conventional Si purification* ribbon-grown single crystal laser cutting* diffused junction evaporated multigrid contacts and AR coating PC metal backing and interconnects epoxy bonding stamped metal concentrator factory mounted metal frame	Ribbon grown and cut Si contact formation interconnects and encapsulation process chemical recycling
2 "Conventional" Medium Efficiency Cell, Tracking Arrays	Single crystal round cell "wraparound" contacts conventional AR coating PC interconnects and backing FEP Teflon or polyimide encapsulation egg-crate concentrators convection cooling tracking mounting structure	Conventional Si purification* Czochralski grown crystal sawn blanks diffused junction "wraparound" contacts evaporated AR coating FEP Teflon encapsulation PC interconnects stamped metal egg-crate concentrators factory mounted metal frame motor-driven tracking mounting	Crystal growth and slicing contact formation cell PC interconnects encapsulation process chemical recycling

* See text for alternatives

TABLE 3 (contd.)

SELECTED COMBINATIONS OF SOLAR CELL AND ARRAY OPTIONS

OPTION	CELL AND ARRAY DESIGN	CELL AND ARRAY PROCESSING METHODS	PROCESS AUTOMATION
3 Sputtered Low Efficiency Cell, Fixed Arrays using Unified Processing	Poly or amorphous Si large area, thin cells conventional contacts conventional AR coating Large area array soldered interconnects FEP Teflon or frit glass encapsulation planar concentrator fixed orientation	Conventional Si purification* sputtered poly or amorphous Si* sputtered junction* sputtered contacts & AR coating* Frit glass or FEP Teflon coating metal backing soldered interconnects planar reflection sheet concentrators	Crystal growth junction, contacts formation, and AR coating encapsulation process chemical recycling
4 CVD Low Efficiency Cell, Fixed Arrays using Unified Processing	Poly Si thin, small, rectangular cell multi-grid contacts* conventional contacts and AR coating Small cell array in V-groove soldered interconnects FEP Teflon or frit glass encapsulation V-groove concentrators* fixed orientation	Conventional Si purification* CVD poly Si* CVD junction* CVD contacts and AR coating Metal backing soldered interconnects metal-extruded V-groove concentrators*	Crystal growth junction, formation contacts & AR coating process chemical recycling

* See text for alternatives.

TABLE 3 (contd.)

SELECTED COMBINATIONS OF SOLAR CELL AND ARRAY OPTIONS

OPTION	CELL AND ARRAY DESIGN	CELL AND ARRAY PROCESSING	PROCESS AUTOMATION
5 High Concentration Edge-On Medium Efficiency Cell, Tiltable Arrays	Single crystal Si* edge-on cell conventional contacts and AR coating Limited-area arrays greatly reduced number of interconnects FEP Teflon encapsulation high intensity lens con- centrator combination cooling system provision tiltable mounting	Conventional Si purification* epitaxial junction formation* evaporated contacts and AR coating* Heat conducting substrate heat pipe or refrigerant cooling system plastic lens concentrator	Crystal growth junction formation, contacts, and coating process chemical recycling
6 High Efficiency High Concentration Cell, Tracking Arrays	Single crystal Si thin cells low series resistance multi-grid contacts array-compatible anti- abrasive AR coating Limited-area arrays PC interconnects and backing FEP Teflon encapsulation lens concentrator cooling system provision tracking or tiltable mounting	Conventional Si purification* low resistivity, high quality single crystal diffused junction diffused back surface field multi-grid contact high-quality AR coating(s) Heat conducting substrate PC interconnects FEP Teflon encapsulation plastic lens concentrator heat pipe or refrigerant cooling system	Crystal growth junction formation, back surface field contacts and coating interconnects and encapsulation process chemical recycling

* See text for alternatives.

TABLE 4

COST SUMMARY FOR LOW-COST SOLAR CELL ARRAY SYSTEMS

Combination	AM1 Effic.	Conc. Ratio	System Cost at Present		System Cost in 1-2 years	
	%		\$/W	\$/m^2	\$/W	\$/m^2
<u>High Efficiency</u>						
Single crystal, low r_s cells	15	10x	16	6000	8	3000
	15	20x	8	6000	4	3000
<u>Medium Efficiency</u>						
Ribbon cells (Tyco)	10	2x	-	-	7.5	380
Semi-round cells	15	2x	-	-	8	580
Ribbon cells (Currin)	10	1x	-	-	3^+	80^+
<u>Low Efficiency</u>						
Sputtered, polycrystalline cells*	1	1x	-	-	3	8
	2	1x	-	-	1.5	8
CVD, polycrystalline cells*	1	1x	-	-	9	23
	2	1x	-	-	4.5	23

+ Numbers refer to 5-10 years

\- These figures are unknown, or unavailable.

* Assuming an adequate p-n junction can be formed in polycrystalline silicon.

Assumptions: 250 W/m^2 incident sunlight.

TABLE 5

HIGH EFFICIENCY CELL OPTION

	Eng. Yrs. Req'd	Duration (yrs.)	Total $[+] Required ($K)
(a) Process Step Technology			
1. Produce low resistivity silicon with good quality, or produce BSF cells using high resistivity silicon	3	1	150
2. Form large ingots	2	1	100
3. Inexpensive shaping	6	2	600
4. Surface preparation	2	1	100
5. Large scale diffusion	3	1	150
6. Inexpensive contacts*	3	2	300
7. Multigrid application*	6	1	300
8. Wraparound contacts*	4	1	200
9. Antireflective coating*	3	2	300
10. Bonding scheme for PC board application	4	2	400
11. Encapsulation (e.g. Teflon)*	6	2	600
12. Concentrator design	6	1	300
13. Attaching concentrator, tracking, cooling	2	1	100
	Total		3,600
(b) Manufacturing Scale-up			
1. Continuous silicon growth	4	1	200
2. Continuous shaping	6	2	600
3. Mechanized slice handling*	4	1	200
4. Continuous surface preparation	6	1	300
5. Continuous diffusion*	4	2	400
6. Large scale contact application*	4	2	400
7. Large scale AR coating application*	2	1	100
8. Automatic bonding	4	2	400
	Total		2,600
(c) Systems Analysis for (a) and (b)	8	2	800
	Overall Total		7,000 (7 million)

+ Assume 1 engineer year = $50K

* Steps common to all options

TABLE 6

MEDIUM EFFICIENCY CELL OPTION

	Eng. Years Req'd	Duration (Yrs.)	Total \$ Required+ (\$K)
(a) Process Step Technology			
1. Ribbon silicon (10 ribbons per lot, Ld ~ 75 μm, good resistivity)	10	2	1,000
2. Diffuse ribbons	3	1	150
3. Contact metals*	3	2	300
4. Contact application*	4	1	200
5. Wraparound contacts*	4	1	200
6. Antireflective coating*	3	2	300
7. PC board interconnect	4	2	400
8. Encapsulation (Teflon)*	8	2	800
9. Fabricate V-groove concentrator	4	1	200
10. Assemble cells on V-groove	4	1	200
	Total		3,750
(b) Manufacturing Scale-up			
1. Mechanized ribbon growth	8	2	800
2. Mechanized slicing	4	1	200
3. Continuous diffusion*	5	2	500
4. Mechanized slice handling*	5	1	250
5. Continuous contact application*	4	2	400
6. Continuous AR coating*	4	1	200
7. Automatic bonding to V-groove	4	2	400
	Total		2,750
(c) Systems Analysis for (a) and (b)	8	2	800
	Overall Total		7,300 (7.3 million)

+ Assume 1 engineer year \$50K

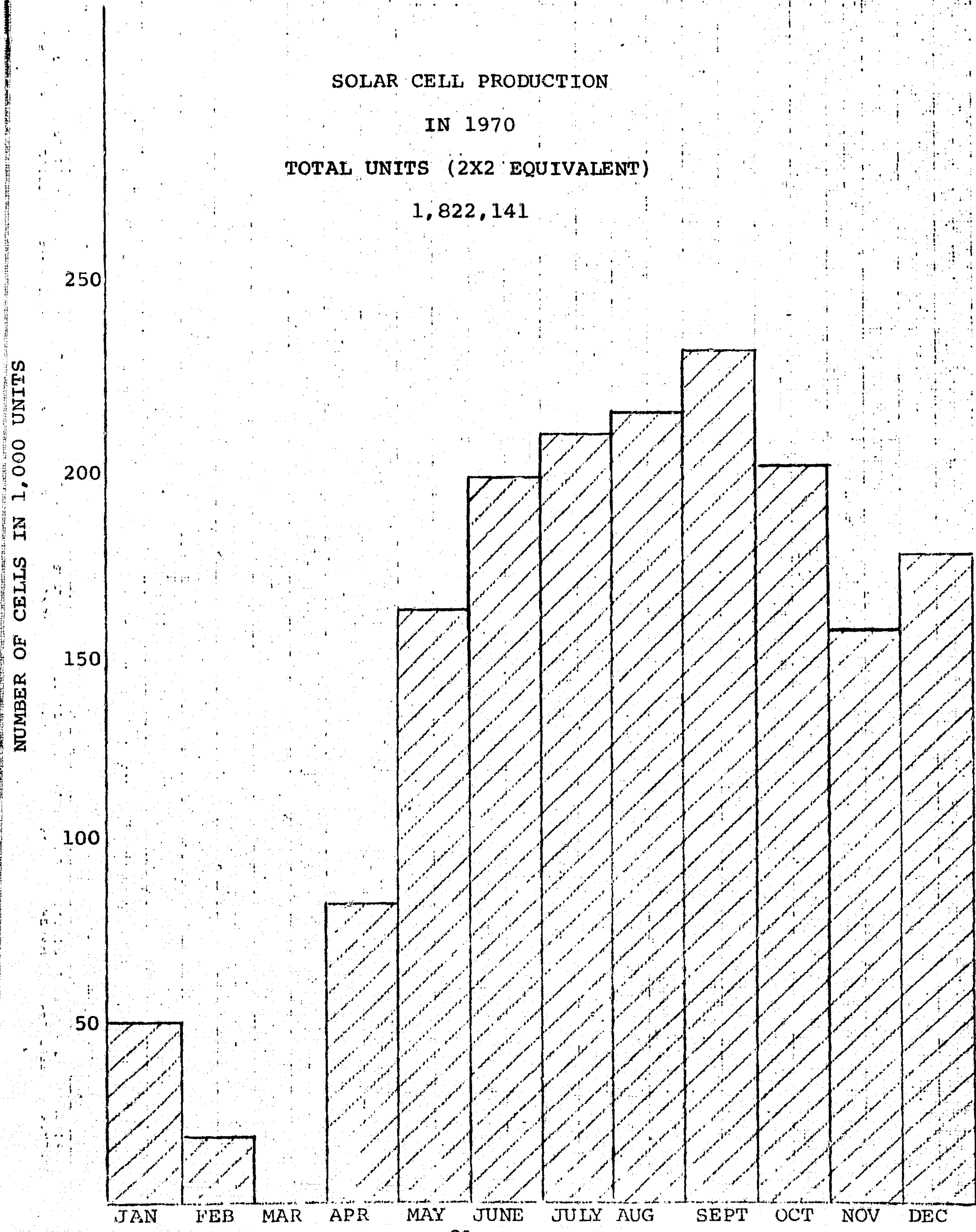
* Steps common to all options

TABLE 7

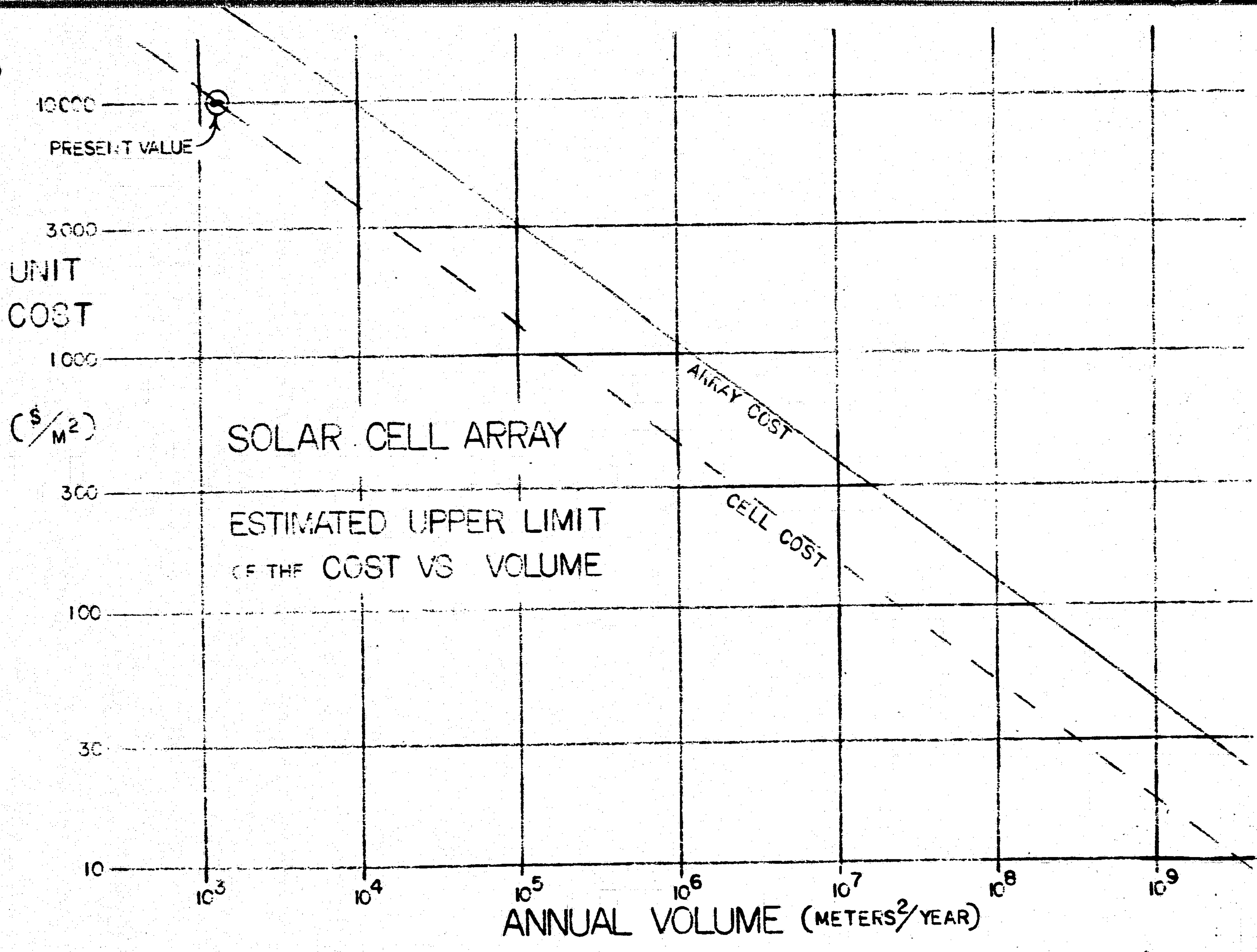
LOW EFFICIENCY CELL OPTION

	Eng. Years Req'd	Duration (Yrs.)	Total $ Required+ ($K)
(a) Process Step Technology			
1. Form polycrystalline silicon (CVD, evaporation, sputtering)	12	2	1,200
2. Remedial measures I (→ 2% efficiency)	8	2	800
3. Remedial measures II (→ 5% efficiency)	15	4	3,000
4. Substrate choice and preparation	10	3	1,500
5. Barrier formation (ion implantation, diffusion)	10	2	1,000
6. Contact metals*	6	4	1,200
7. Contact applications:			
multigrids*	6	1	300
transparent conducting	8	2	800
integrated arrays	10	3	1,500
8. Antireflective coating*	4	2	400
9. Encapsulation*	6	2	600
10. Mount on support	6	2	600
	Total		12,900
(b) Manufacturing Scale-up			
1. Deposition of polycrystalline silicon	12	3	1,800
2. Substrate preparation	8	2	800
3. Mechanized substrate handling*	6	2	600
4. Remedial I scale-up	12	2	1,200
5. Remedial II scale-up	25	4	5,000
6. Continuous barrier formation*	10	2	1,000
7. Contact application on large scale:			
multigrids*	10	1	500
transparent conducting	12	2	1,200
integrated arrays	15	3	2,250
8. Continuous AR coating*	12	2	1,200
9. Large scale encapsulation and mounting	12	3	1,800
	Total		17,350
(c) Systems Analysis for (a) and (b)	10	3	1,500
	Overall Total		31,750 (31.75 million)

FIGURE 1


SOLAR CELL PRODUCTION
IN 1970
TOTAL UNITS (2X2 EQUIVALENT)
1,822,141
NUMBER OF CELLS IN 1,000 UNITS
250
200
150
100
50
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC

C-2


SOLAR CELL ARRAY
ESTIMATED UPPER LIMIT
OF THE COST VS VOLUME
UNIT COST ($/M²)
10000
3000
1000
300
100
30
10
PRESENT VALUE
ARRAY COST
CELL COST
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
ANNUAL VOLUME (METERS²/YEAR)

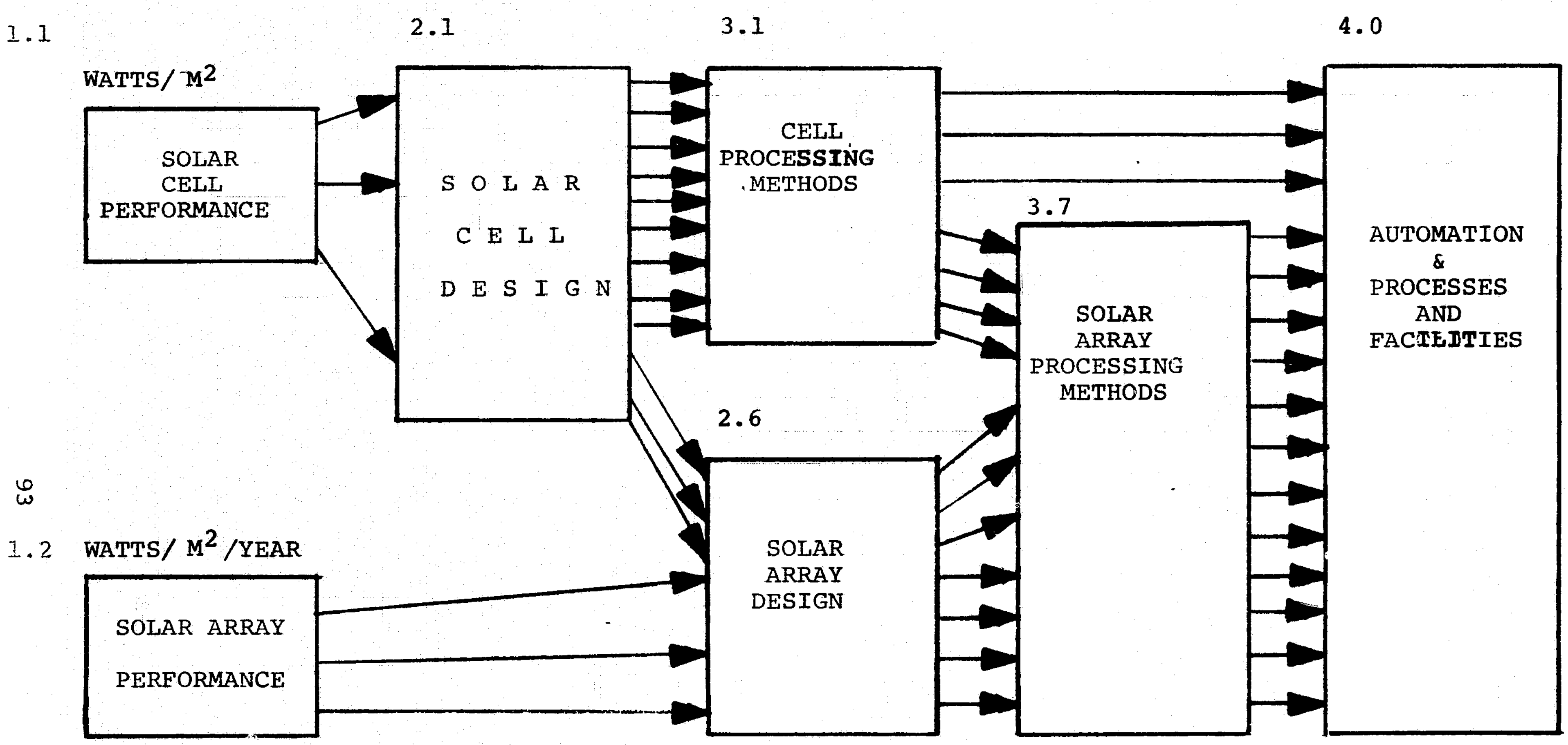


FIGURE 3

LOW COST SOLAR ARRAY MATRIX

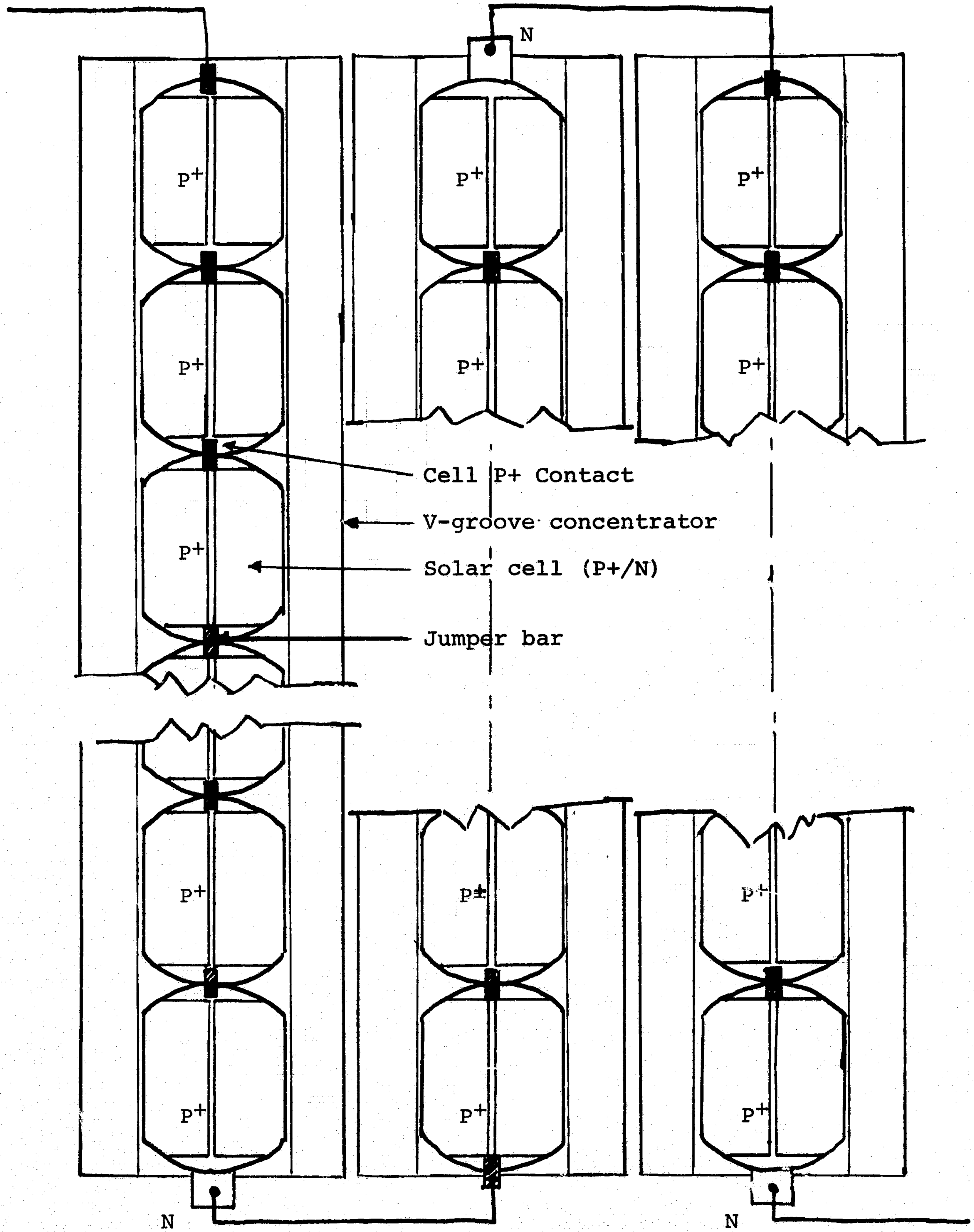


Figure 4. Alternative Medium Efficiency Cell V-Groove Array