PHOTOVOLTAIC CONVERSION OF SUNLIGHT TO ELECTRICITY--CONSIDERATIONS FOR DEVELOPING COUNTRIES

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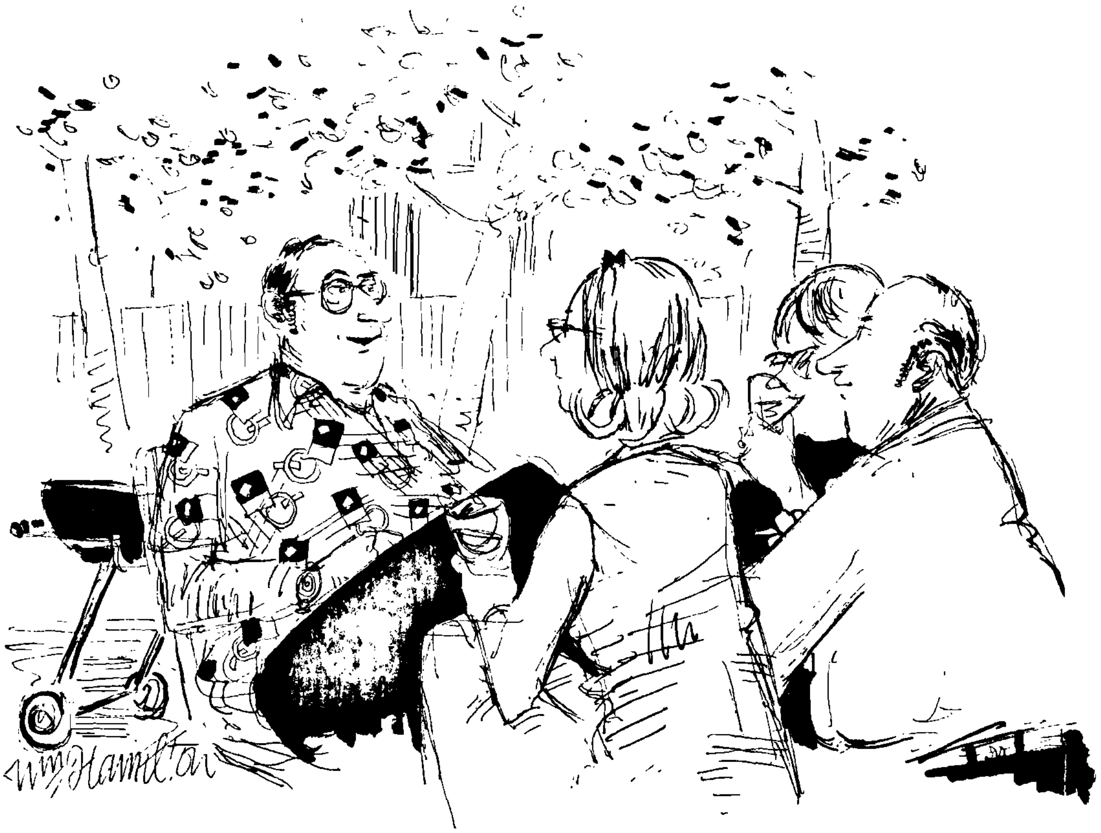

"Basically, all your nations—and this includes Communist China—would rather be Los Angeles."

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PREFACE

This paper is a part of a larger report in preparation by the National Acadely of Sciences Ad Hoc Committee on Alternative Energy Technologies for Developing Countries. The purpose of this paper is to summarize the current and projected state of the art of photovoltaic technologies for direct conversion of sunlight to electricity, with special emphasis on the possible significance of such technologies for developing countries.

Because the problems of introducing and diffusing innovative energy technologies into a society are substantially sociocultural and only partly technical in nature, I have included some personal observations on the problems which need to be overcome if technically proven and economically interesting alternative energy technologies are ever to be widely used in developing countries. I have also been presumptuous enough to indicate what I feel to be the main ingredients of an effective plan of action to develop, introduce and assist in diffusing such technologies widely and rapidly.

Because this report is preliminary, I welcome comments and criticisms, preferably detailed and specific to contribute to later revision and expansion.

Summary

Present Availability

Photovoltaic systems with 10 percent solar conversion efficiency and with peak power capacities from 1 watt to hundreds of kilowatts are available from manufacturers in Japan, the United States, Britain, France and West Germany. Packaged systems for use in remote applications, such as navigational buoys and lighthouses, environmental monitoring stations, microwave relay stations and forest ranger communications are available as commercial products in the range of a few watts to a kilowatt, with larger systems available on a custom basis. Costs of a complete system are dominated by the photovoltaic array; twenty to thirty dollars per peak [redacted]watt, corresponding to $ 100,000 to $ 150,000 per average kilowatt installed capacity, is now being quoted and these costs are expected to decrease by as much as a factor of four within the next few years. These systems all incorporate silicon solar cells produced by modifications of spacecraft solar cell production technology, and include batteries, voltage and current regulation, and other components such as DC/AC inverters as options.

Next Five Years

During the coming five years, over a hundred million dollars will be spent by industry and government in the US, Japan, W. Germany, France and Britain in the development of lower cost terrestrial photovoltaic power systems. During this period the emphasis will on the research and development of new processes for mass production of integrated solar modules, and by 1980 integrated ribbon silicon arrays incorporating wide aperture concentrators without diurnal tracking requirements will probably be on the market. An interesting development is the entry of 3 major U.S. oil companies into this field, (   ) with a combined investment of approximately $ 50 million projected over the coming five years.

The author believes that with a continuation of this intense and diversified R and D effort that solar cell modules with a cost of a few thousand dollars per average kilowatt could be available by 1980, with conversion efficiencies approaching 15 percent.

Next 5-10 years

It is perhaps unwarranted optimism, but this author believes that there is a good chance for the development of commercial photovoltaic conversion arrays at costs of a few hundred dollars per average kilowatt ( ) by 1985 or sooner. The integration of such arrays into a complete system incorporating energy storage, power conditioning and transmission and distribution will be required before these are useful on any substantial scale for power generation greater than a few kilowatts per system. In this regard, availability of economically interesting storage systems will be a crucial factor in determining the extent to which such technology is used. In the industrialized nations the incorporation of photovoltaics into integrated utility systems will be the primary aim of present programs and preliminary studies are currently underway to assess the feasibility of doing this in a number of European countries with an abundance of low cost pumped storage facilities ( ).

In this price range there would be great interest in the potential use of such technology, perhaps in the establishment of local (village and community sized) "minigrids" with the eventual growth and interlinking of these into larger and more diverse electrical networks. However, if this technology is to be transformed into something which can meet the special technical, economic and cultural constraints and needs of various LDC's, a deliberate and specific effort to do this will be required, since the direct "transfer" of photovoltaic systems developed for integration into modern utility grids to the remote village level is unlikely to otherwise occur easily, if at all. Issues of special concern for the LDC's are discussed later in this paper.

Solar Conversion Technologies and the Less Developed Countries

Human Well-Being in the LDC's

The potential role of advanced solar energy technologies for the less developed nations may be far more significant than has generally been thought. Substantial improvements in the nutrition, health, housing and education of the two-thirds of the world's population living in underdeveloped regions can be achieved only by economic development in these regions, coupled with reductions in the high rates of population growth that have recently prevailed there. Worldwide development in the pattern established by the rich nations, however, implies environmental and economic burdens which the developing nations should wish to avoid, and a global environmental burden that may prove unsustainable. The resolution of this dilemma may lie in technologies and lifestyles that bypass the environmental, social and economic pitfalls which have plagued established industrial processes and patterns of economic development. The bypass or "overleap" process, if it is possible at all, will require substantial contributions of money and technological expertise from the wealthy and the industrialized nations.

Role of Energy Technologies

Energy technology goes to the core of the development/environment/economic dilemma. Energy is an indispensable ingredient of prosperity, a major contributor to environmental disruption, and an important determinant of patterns of living. The prosperity gap between rich and poor nations corresponds closely to an energy gap; the developing nations, with about two-thirds of the world's population, account for only 15% of the world's energy consumption. Prospects for narrowing the energy gap are clouded by the uneven geographical distribution of fossil fuels (especially deficient in Latin America and Africa), by the high economic costs of technology to extract, convert and usefully employ energy, and by the environmental, social and economic liabilities of the various energy sources. Hydropower, with enormous potential in Latin America and Africa, may flood fertile land, drown revenue-bearing attractions, increase evaporative losses of water, displace indigeneous populations, impair soil fertility downstream, and facilitate the spread of parasitic diseases such as schistosomiasis. Nuclear power is economically attractive only in plant sizes too large to suit most developing countries, and it bears, among other threats, the already partially realized potential for the proliferation of nuclear weapons capability. Fossil fuels are almost prohibitively expensive for most developing regions already, and do not represent a long term source of energy in any event. It seems likely that in the final half century or so of massive oil use, the industrialized nations will use most of the resources, with little available to non-industrialized nations.

Solar energy technology offers possible solutions to many of these problems. Historically, most advocates of solar energy for the developing nations have confined their attention to low technology, very small scale applications, such as solar cookers, solar stills, and food drying. Convergence of several technical and social trends now make it apparant that sophisticated and innovative uses of solar energy technologies can play an important role in ecologically sensible development.

Recent events as well as trends of the past few decades have led to recent renewed interest in the potential constributions of solar, wind, and other renewable energy sources to solving energy problems in the LDC's. These trends include a) dramatic recent interest and financial support for the development of a broad menu of solar energy conversion alternatives for production of heat, shaft horsepower, electricity and synthetic fuels such as hydrogen, b) growing recognition in industrial nations that energy-efficient design of buildings, industrial processes, transportation systems --- indeed, patterns of living -- can greatly reduce energy requirements per unit of economic good; and c) some recent awareness that the achievement of a decent standard of living in developing regions will require under any circumstances the ambitious and imaginative transfers of capital and technological knowledge from the rich countries to the poor ones.

As a result of a recent trip which I and three other scientists took for the U.S. Information Agency, in 1974, covering parts of Asia and the Middle East, I have the impression that the following are important requisites to effective development in the poor regions of the world:

1) Introduction of both techniques and the materials (energy, fertilizer, storage facilities, transportation, market and distribution techniques) to facilitate the transition of the rural farmer from subsistence farming to cash cropping (with substantial increases in yields in the process) on a very large scale,

2) Provision of a reliable, low cost, non-vulnerable source of energy for operating irrigation systems, farm machinery, crop drying, transportation systems and fertilizer production plants,

3) Substantial increases in the quality of life (health, diversity of opportunity, increased possibilities for education, security and old age support, etc.) at the rural level which permits maintenance of disperssed populations, removing the pressure on the cities and decreasing the costs of absorbing large numbers of people in cities,

4) Dramatic reduction in population growth, achieved in part through accomplishment of 1) - 3) and

5) Development of human settlements which do not rely on fossil fuels for their operation on a large scale. (Everyone cannot become Los Angeles).

Accomplishing these, if it is really possible at all, would be an extraordinary task of almost unthinkable proportions. At the heart of it will be the energy issue. Rapid upgrading of the human environment while retaining dispersed patterns of human settlement and increasing food production dramatically may require energy sources themselves well suited to such patterns of settlement and rural agriculture.

The development of an economically interesting commercial terrestrial version of spacecraft solar arrays could be one of the most important technological elements of such a transition. Suitably coupled with energy storage and power conditioning devices and an array of simple and rugged pumps, motors, tools, etc., low cost, long life panels which convert sunlight into DC electricity with nomoving parts and efficiencies as high as 20% would be an attractive technology indeed for such regions, as well as for the industrialized nations.

Potential Advantages of Photovoltaic Systems

Assuming that such systems become economically interesting in comparison with alternatives, photovoltaic conversion systems appear to offer some specific advantages relative to large (100 to 1,000 Mwe) fossil and nuclear powered generation systems, in LDC's.

These include the following:

In principle, the systems can be highly rugged, requiring a minimum of repair and replacement.

High throughput efficiency (10-15%) of total system possible.

Modular design, permitting simple replacement of elements without downtime for entire power plant (for storage and power conditioning as well as direct conversion elements).

Possible integration with rooftops and other structures, permitting multiple uses of land.

Systems can be deployed locally, without requirements for massive rural electrification infrastructures; very expensive for Asia, Latin America, Africa and parts of the Middle East.

Local deployment, minimizing transmission and distribution infrastructure requirements on large scale. Possibility of autonomous operation, eventually looking up with others and growing with a grid system.

Systems can grow along with load growth, permitting full amortization of capital investment, while conserving capital for other purposes. (As contrasted with the $ 300 million to $ 1 billion investment required for large thermal power plants, fossil or nuclear fueled). System growth with load growth may minimize the forced growth of demand.

The level of technical sophistication and equipment required to operate and maintain such systems is compatible with indigineous capabilities or much closer to those capabilities than nuclear or large fossil fuel generation facilities.

Economies of scale do not acrue as they do in large thermal power plants. Small systems can be as economical as large systems.

Minimal environmental disruption compared with fossil or hydropower systems. Dams decrease fertility of revenue bearing downstream lands, flood scenic areas, and facilitate the spread of schistosomaisis in slow running irrigation ditches.

No fuel requirements; particularly important to the LDC's both in terms of the cost of primary fuels and the cost of transportation into rural, population disperssed areas.

Systems do not bear the nuclear power hazards of:

a) power plant operational safety, a problem in technically sophisticated societies and a very serious issue indeed in technically emerging societies,

b) radwaste disposal - not a solved problem anywhere,

c) diversion of fissionable materials for weapons fabrication, blackmail and terrorist activities using radioactive material (not necessarily in the form of a bomb).

The creation of such a "kit of parts" is going to require a synthesis of technical, economic and socio-cultural capability in international programs of technology development, introduction and diffusion, conducted in an atmosphere of intimate involvement between industrialized and non-industrialized nations and regions. Although the final form, ruggedness, suitability for local use and adaptation of these modular systems may be simple (such as the photovoltaic array), the technology required for their development will not be.

An ultimate goal would be the development of technologies which represents the best synthesis of high technology and local needs, including the ability to replicate and repair such technology locally, and within the local economic capabilities. (I.e., the economic gains associated with introduction and use of solar conversion technologies should not be offset by the high costs of maintenance, repair, replacement and manufacture).

I belive that some of the ingredients of an effective international program to develop and diffuse such technologies are:

1) Establishment of a well funded, mission oriented organization (perhaps similar to the International Rice Research Institute) which would work as an international center (with field stations) for development and introduction of various solar and wind technologies. Such an institute would be characterized by:
    a) outstanding social scientists, engineers, economists and others dedicated to problem solving in the context of energy technology related needs in developing countries,
    b) tenured positions providing high salaries, first rate facilities, and decent living environments,
    c) hardware capabilities, including for example, establishment of an international solar energy technology development center, perhaps in conjunction with the emerging Natural Energy Resources Laboratory planned for the State of Hawaii in conjunction with the University of Hawaii,
    d) an unusual and effective synthesis of socio-cultural and technical/economic understanding, as a crucial ingredient in the process of development and diffusion of technical innovations in a society.
2) Committment of substantial, long term financial support by wealthy nations to such centers.
3) Active involvement and leadership from the "client" regions.

The remainder of the paper is devoted to a brief summary of the status of photovoltaic conversion systems and of various projections for the costs and performance of such systems within the coming decade or less.

Photovoltaic Conversion

Introduction

Solar cells, usually in the form of thin films or wafers, are semiconductor devices which convert from 3% to 30% of incident solar energy into DC electricity, with efficiencies depending on illumination spectrum intensity, solar cell design and materials, and temperature. A solar cell behaves very much like a half volt battery whose charge is continuously replenished at a rate proportional to incident illumination. Integration of such cells into series-parallel configurations permits the design of solar "panels" with voltages as high as several kilovolts. Combined with energy storage and power conditioning equipment, these cells can be used as an integral part of a complete solar electric conversion system. Following their invention as practical devices in 1955, they have been used primarily for the purpose of providing electrical power to spacecraft. Figure is a photograph of silicon solar cells; their operation is described in Fig. . A Mariner IV spacecraft is shown in Fig. incorporating four large panels designed to deliver 400 watts of DC electrical power with an incident solar illumination of 1 000 watts/m^2.

The extraordinary simplicity of a solar-photovoltaic system (Fig. .) would appear to be a highly desirable energy system for terrestrial purposes, both in the highly industrialized nations and in the less developed countries. These advantages include the absence of moving parts, very slow degradation of properly sealed cells, possibility for modular systems at sizes from a few watts to megawatts, and extreme simplicity of use. However, the extremely high costs of development and fabrication of spacecraft solar arrays has discouraged any serious thought of widespread terrestrial use of such a technology, in spite of the potentially attractive characteristics of such systems. A complete spacecraft solar cell array costs anywhere from $500,000/kwe (average) for the Skylab 10 kwe array to several million dollars per average kilowatt for early Mariner spacecraft arrays.

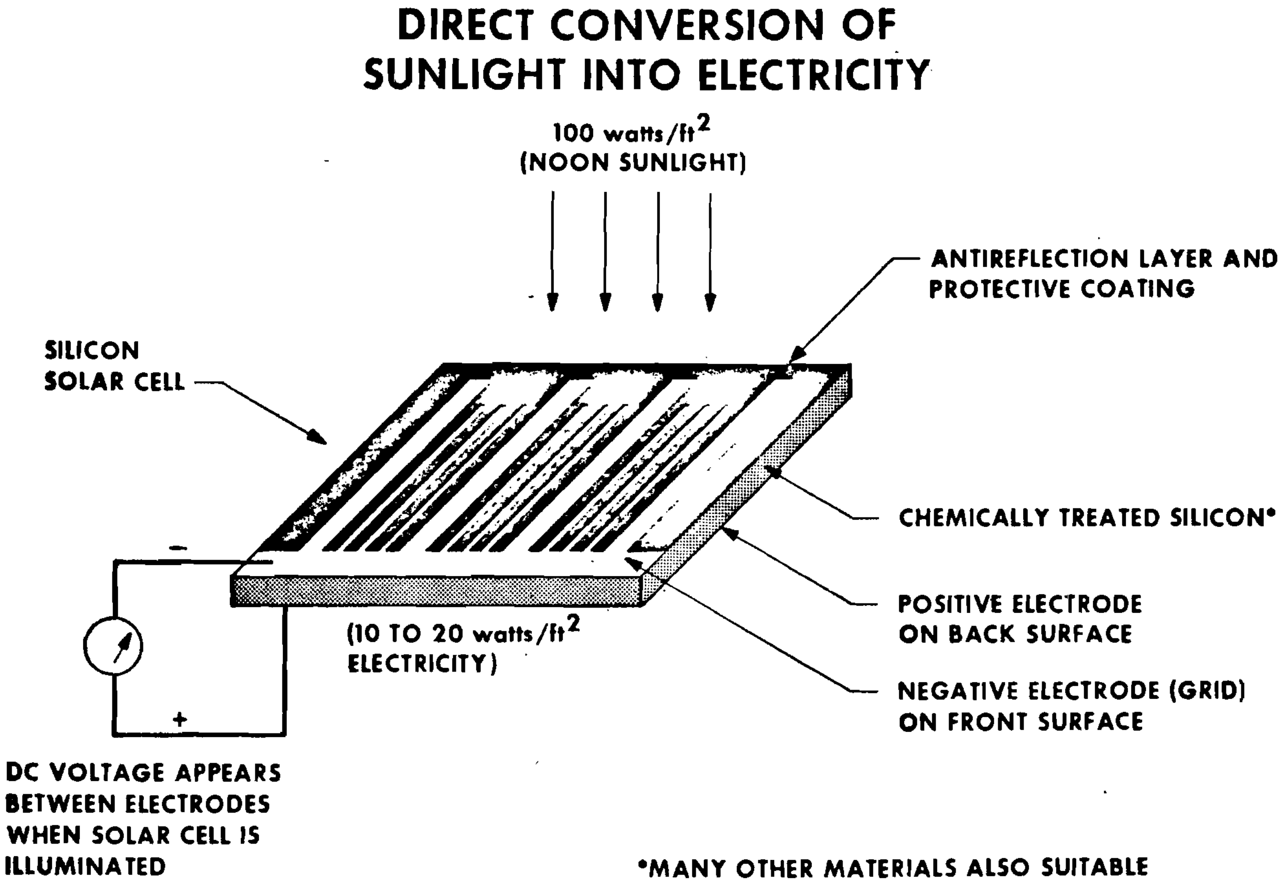
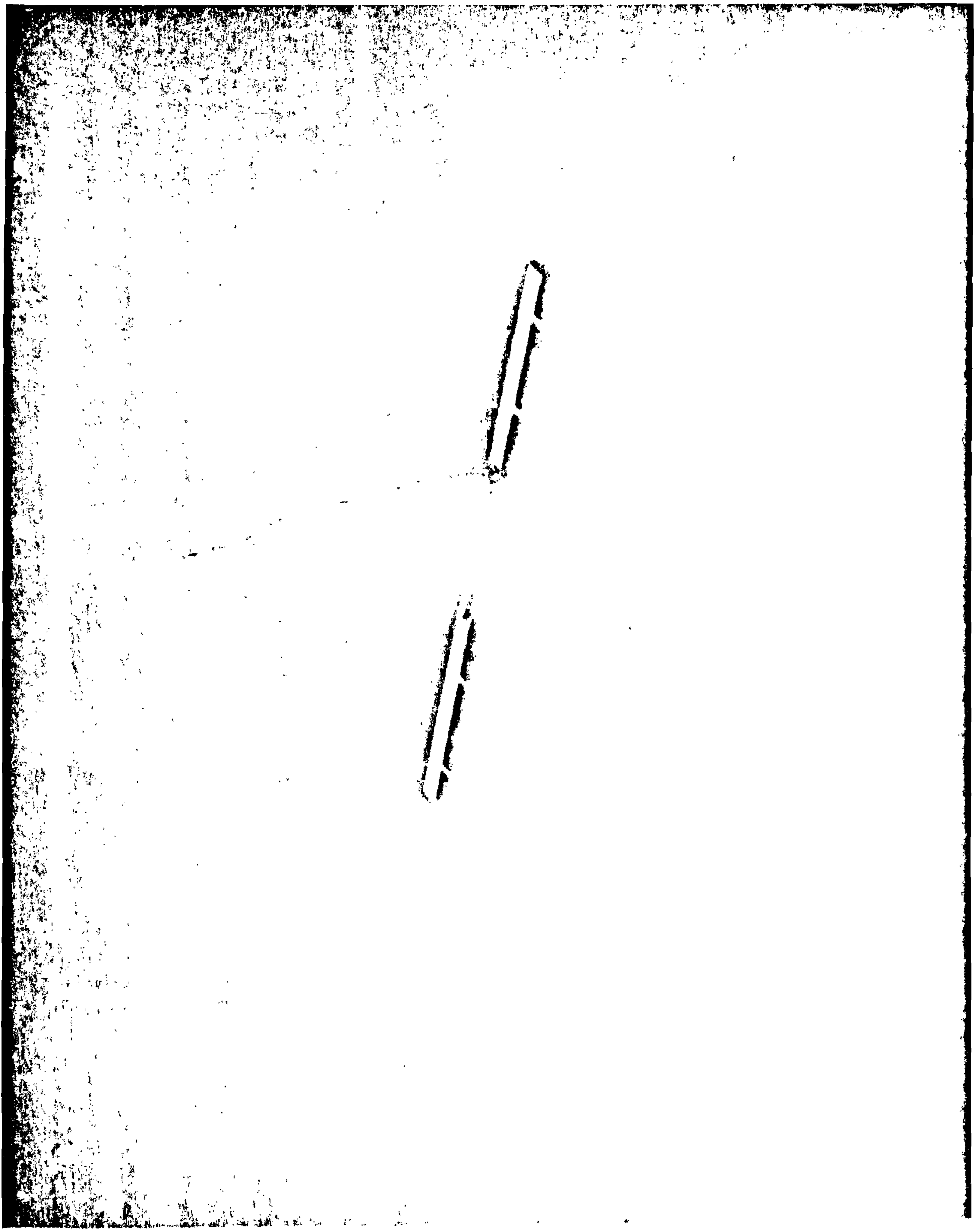


Figure ____ Simplified Representation of Solar Cell Conversion Operation (courtesy J. Weingart)

Figure ____ Silicon solar cell (1cm x 2cm x .04 cm)
Typically Used for Spacecraft Applications
(Courtesy NASA/Jet Propulsion Laboratory)



THE PHYSICAL CHARACTERISTICS OF A TYPICAL n/p SOLAR CELL

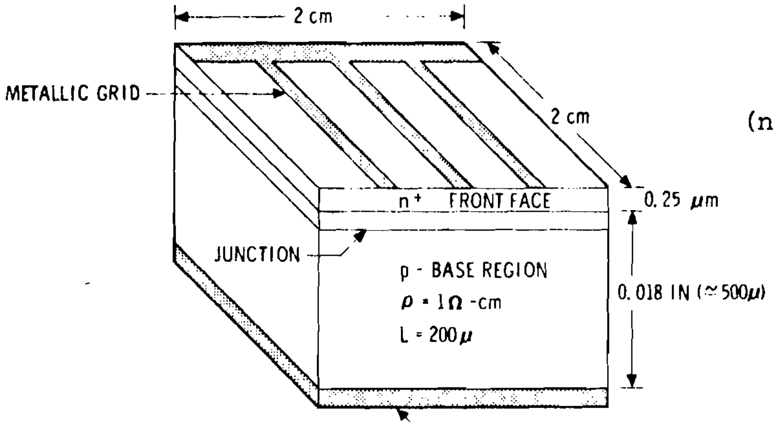


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FIGURE 1

ILLUMINATED SOLAR CELL WITH AN EXTERNAL LOAD

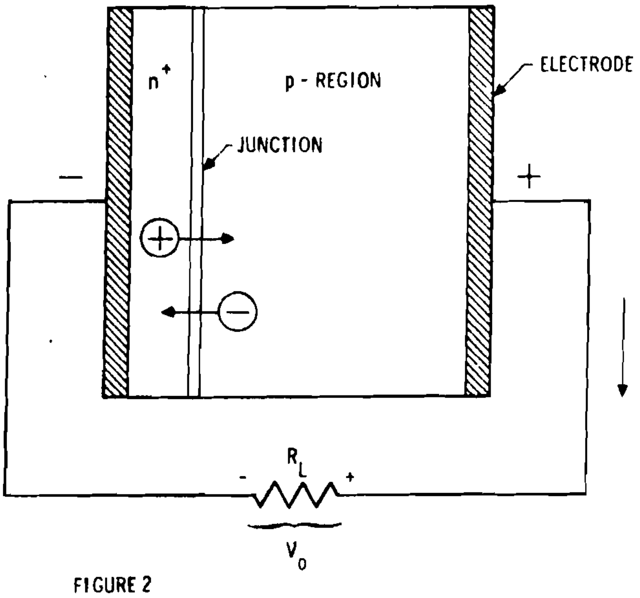


FIGURE 2

TYPICAL SOLAR CELL I - V CHARACTERISTICS

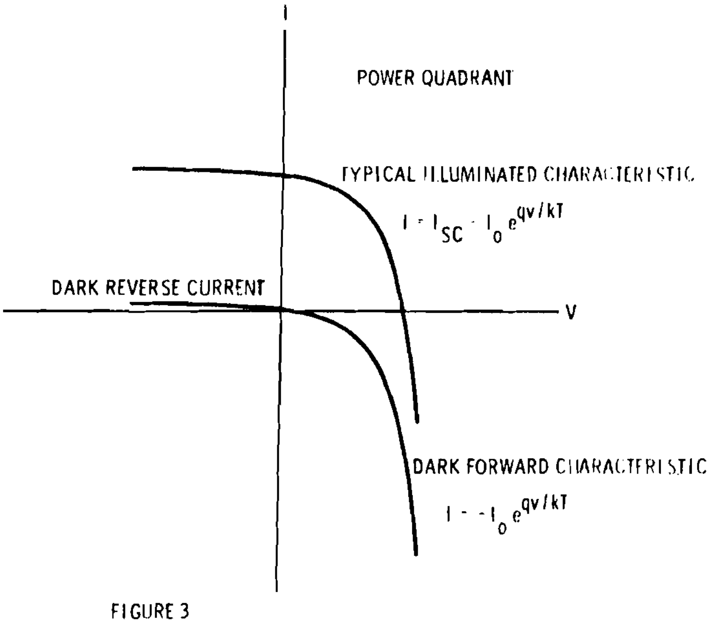
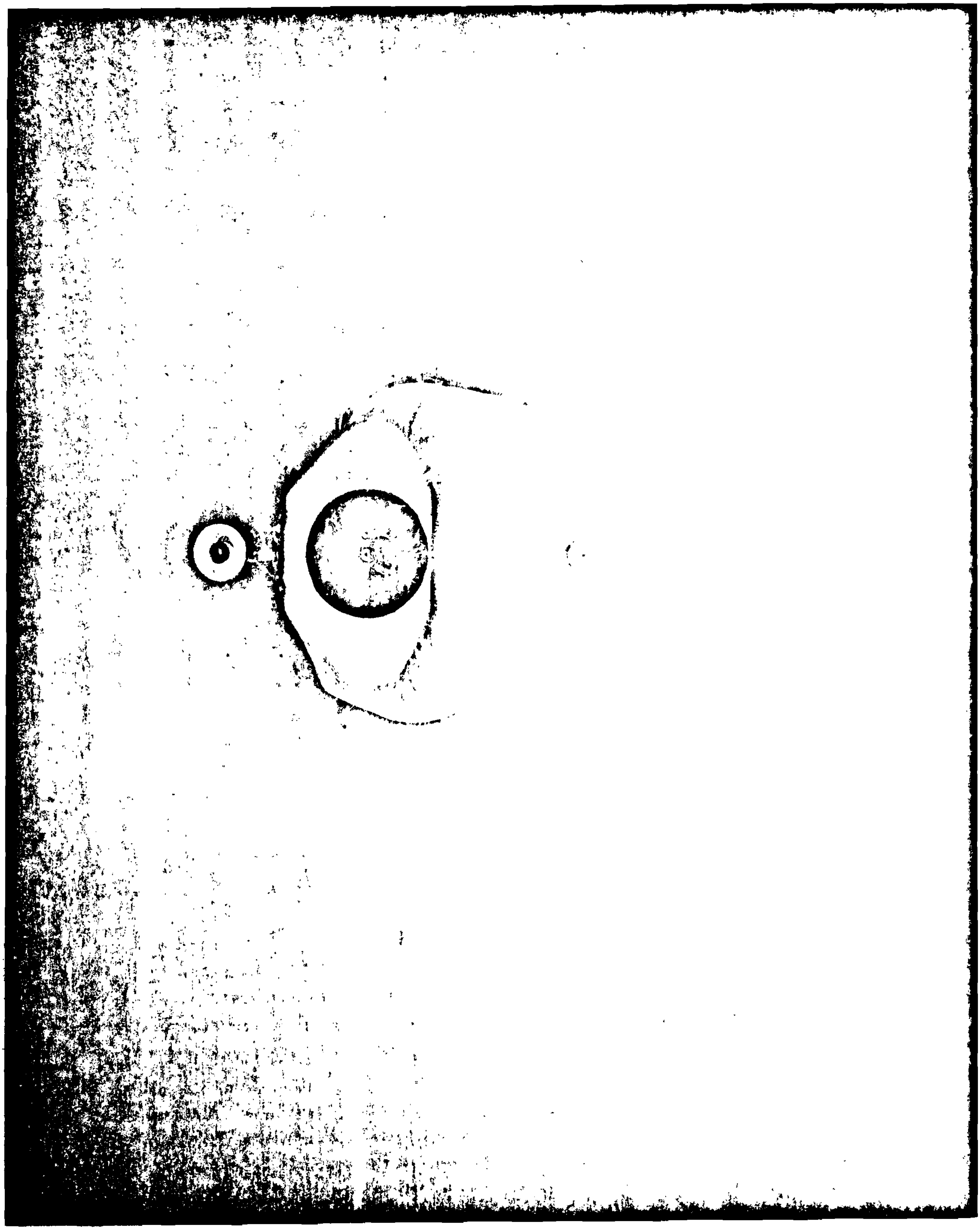
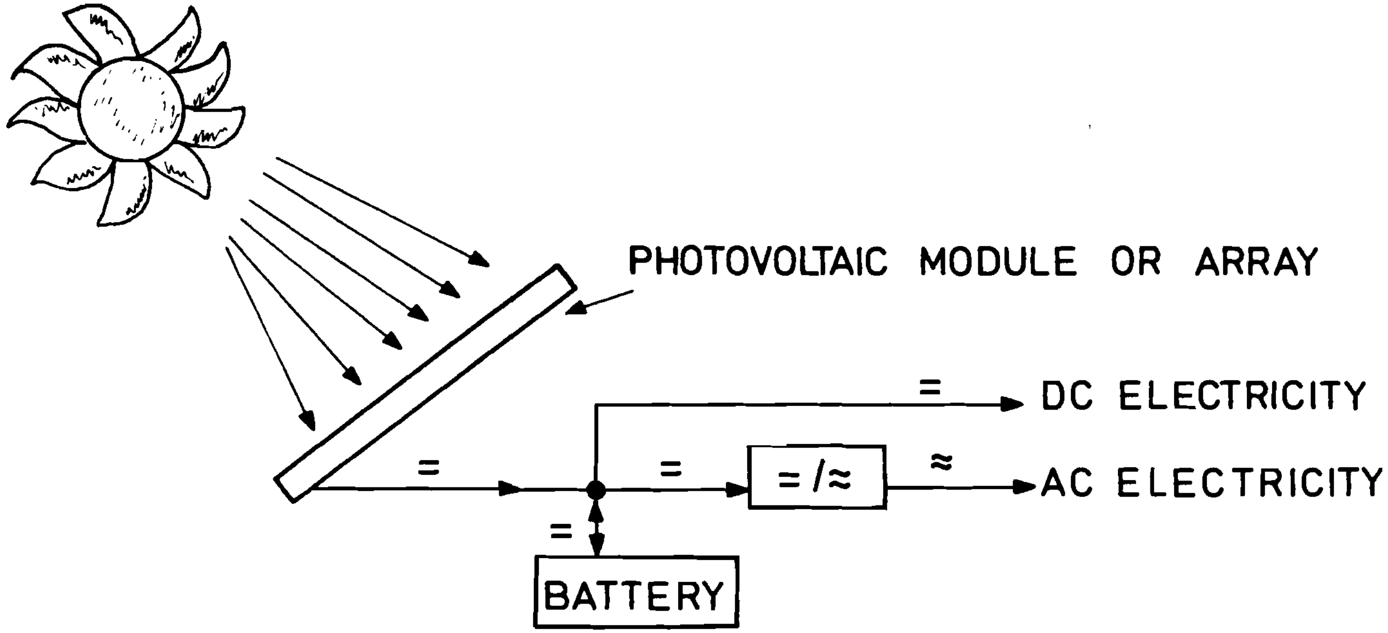


FIGURE 3





SIMPLIFIED PHOTOVOLTAIC SYSTEM

There is now good evidence that with appropriate technological developments and mass production techniques, the cost of such solar arrays can be lowered to the point where a complete system (solar conversion, storage, power conditioning and transmission/distribution) can compete on a life cycle cost basis with other large scale energy system alternatives (perhaps as early as the mid-80's).

Recently initiated and very substantial program for the development of commercially interesting photovoltaic systems in the United States, West Germany, Japan and elsewhere perhaps $10 - 20 million per year) coupled with important developments in the past few years now provide some concrete basis for such a prognosis. Important recent steps include the development of continuous production of ribbon silicon suitable for solar cells, improvements in efficiency and stability of CdS solar cells, and the development of inexpensive wide aperture concentrators (Winston collector).

Thermal Behavior of Silicon Solar Cells

Silicon solar cells exhibit a decrease in conversion efficiency with increasing temperature. Recent work by Patterson and Yasui ( ) has resulted in the characterization of this behavior for 10 ohm-cm and 2 ohm-cm N/P silicon solar cells over the temperature range -140 deg. C to +160 deg. C, over an intensity range of 0 to 850 watts per cm^2 AMO simulated solar illumination. The higher resistivity cells exhibit a decreasing conversion efficiency with increasing illumination at all temperatures within the regime measured (above 60 deg. C for illumination above 250 mW/cm^2). The lower resistivity 2 ohm-cm cells do not exhibit this behavior - their characteristics are essentially linear with temperature and intensity over this regime. Using the graphical data presented in ( ) the author has calculated the thermal coefficients for conversion efficiency.

The behavior of the cells at a given illumination can be reasonably well described by the linear expression:

$$P = P_o \left(1 + C \, \Delta T\right) \quad , \quad \Delta T = T - T_o$$

$$C = \left(\frac{\delta P}{\delta T}\right)_I = f(I,T)$$

where,

P is the power output at a given temperature T,

P_o is the power output at temperature T_o (at a specified illumination), and

$C = C(I,T)$ is the coefficient of thermal degradation (conversion efficiency)

Typical results obtained from ( ) are shown below:

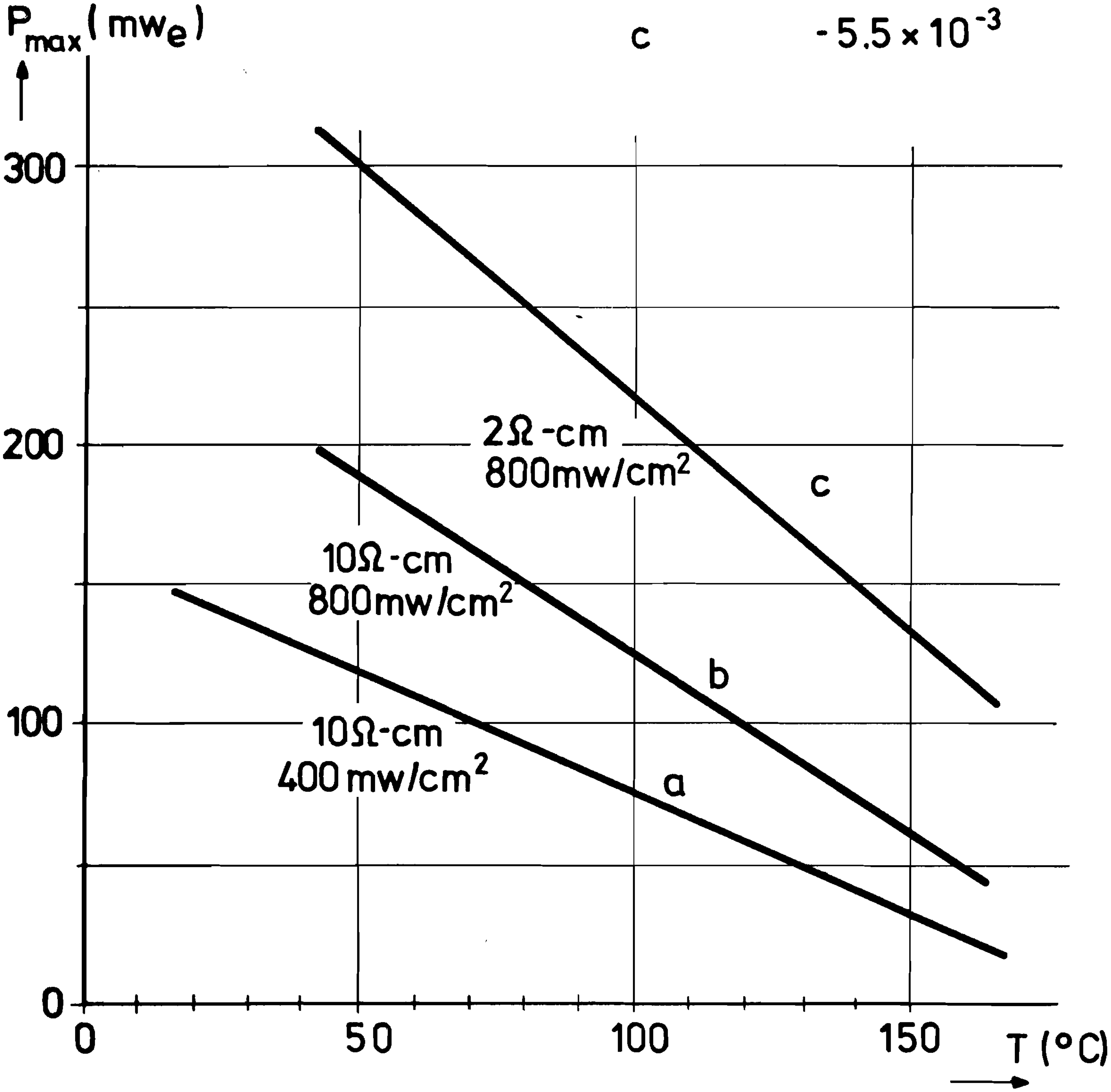
Cell Type	Intensity (AMO)	C (deg C^{-1})
10 ohm-cm	400 mw/cm^2	$-7.3\text{x}10^{-3}$
10 "	800 "	$-6.8\text{x}10^{-3}$
2 "	800 "	$-5.5\text{x}10^{-3}$

The parameter C is constant over the range 100 to 800 mW/cm^2 to within 5 percent. The decrease of efficiency by one half percent per degree C of increasing temperature is a factor which must be considered in the design of economically optimum solar cell modules for terrestrial use.

MAXIMUM POWER P_{max} AS F(T) FOR SILICON SOLAR CELLS (JPL, 1974)

$$P_{max} = P_o \, [\, 1 - C \, \Delta T \,]$$

SAMPLE	C
a	-7.3×10^{-3}
b	-8.3×10^{-3}
c	-5.5×10^{-3}



Candidate Materials and Configurations

Literally dozens of materials, alone or in combination, possess the semiconductor properties required for high efficiency (> .10) conversion of solar radiation to electricity. A number of these have been investigated as possible commercial solar cell materials, and three of these - silicon, cadmium sulphide and gallium arsenide - have all been successfully used in spacecraft applications. Others are in experimental stages of investigation ann still others, though known theoretically to be potentially interesting candidates, have yet to be thoroughly studied for these applications. Table ___ includes a brief summary of some of these and their status.

In addition to the possible materials and combinations, there are many possible combinations of configurations and processes for achieving these possible. Configurations include the use of elemental material in thick and thin films (silicon and selenium), variations in junction design including the possibility for "vertical" junction cells to permit high voltage operation (Fig. ___), multiple layers such as GaAs(Al) for increased efficiency (Fig.___), and the use of graded bandgap materials to also increase the possible efficiency above that possible with one or two materials. The various possibilities are discussed in detail in the current literature (e.g., ______).

Processes for forming the semiconductor junction include diffusion at high temperatures, evaporation to form a Schottky barrier layer on the surface of a semiconductor (such as silicon) (Ref. ____), and chemical epitaxial growth of multiple layers (GaAlAs) (   ), as well as ion implantation (   ). Base materials can be formed by single crystal growth by various methods including dendritic webb growth (   ), Czhocralski growth (   ), and EFG ribbon growth (   ). Thin films can be formed by sputtering, evaporation, vapor deposition and other techniques (   ). Electrodes can be attached through evaporation, silk screening and application of metal "lace" (   ).

These examples are merely illustrative of the enormous combinations of materials, cell designs and fabrication processes possible. Although theoretical investigation indicates that over a dozen possible [illegible] material combinations can yield high conversion efficiencies and that certain fabrication processes (such as EFG and thin film formation) can lead to economically interesting cells in principle, the search for a practical near-optimum

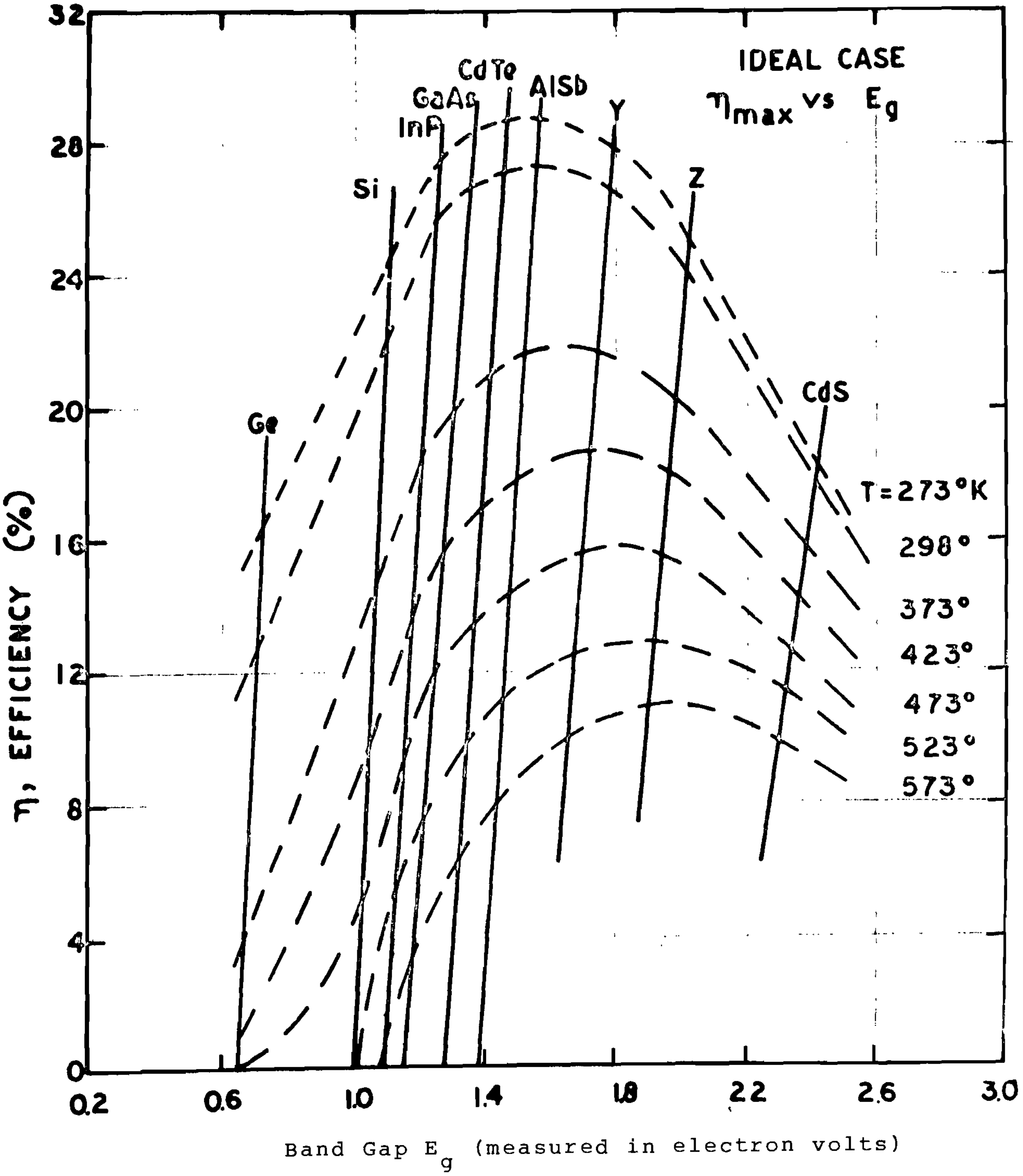


FIGURE THEORETICAL SOLAR CELL CONVERSION EFFICIENCY FOR SELECTED EXAMPLES combination of these will probably take the better part of a decade and perhaps a hundred million dollars or more in funding; as much as a billion dollars may be required. However, given an adequate level of sustained funding and the involvement of outstanding people from industry, universities and other centers, the goal of an economically interesting terrestrial solar cell system seems invevitable.

NASA
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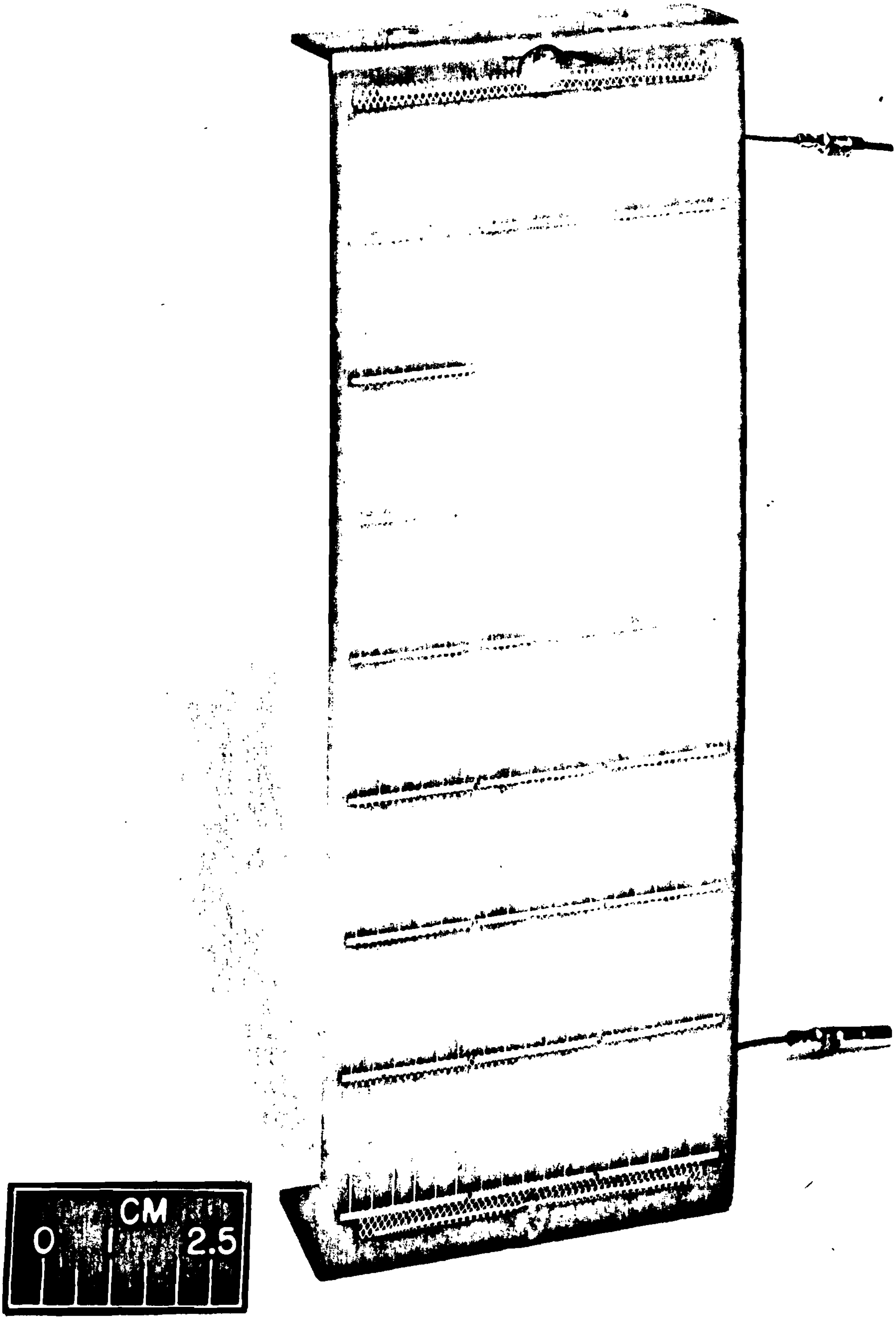

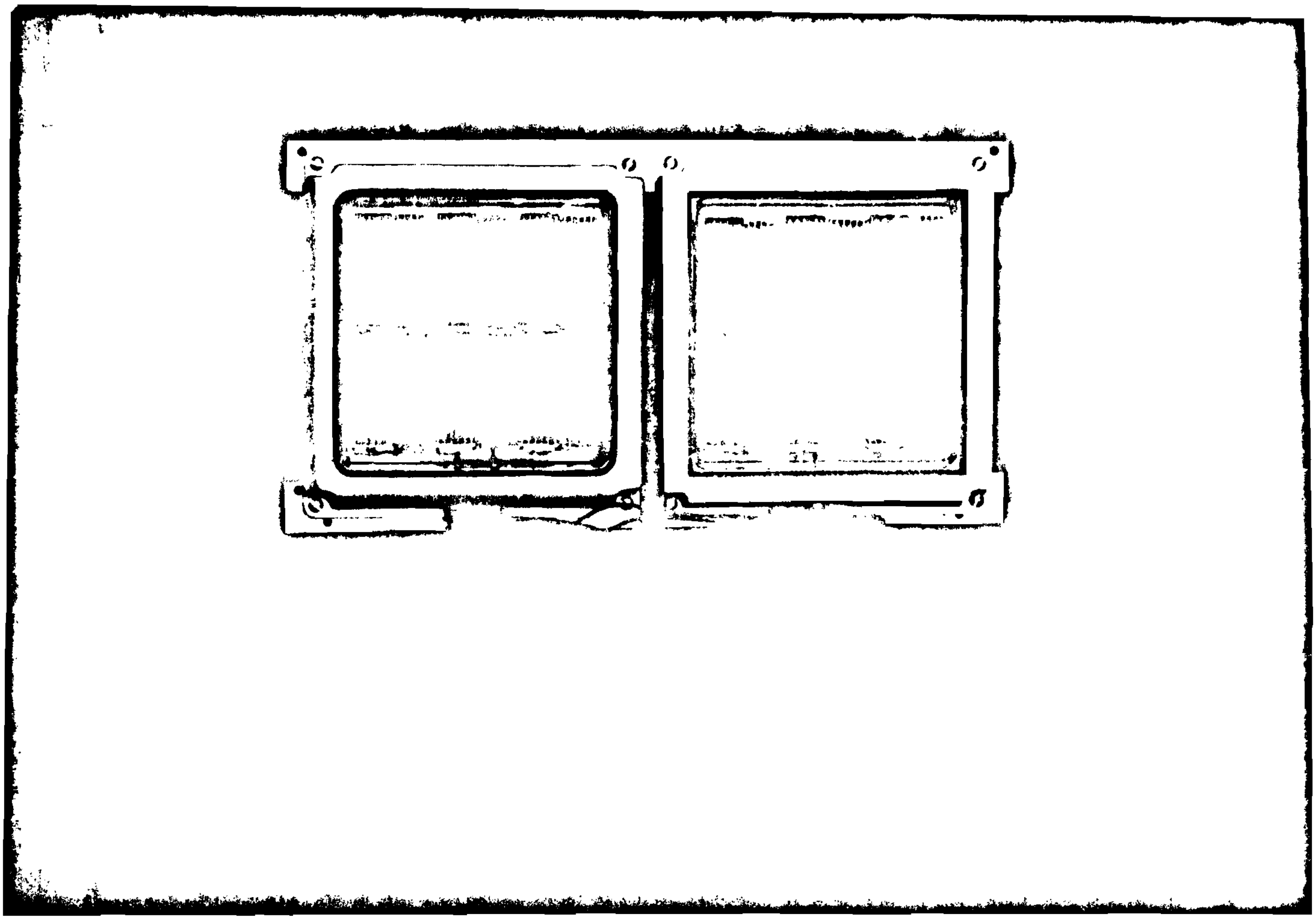

Figure ____ Commercial Terrestrial Solar Conversion Photovoltaic Module (courtesy Centralab)

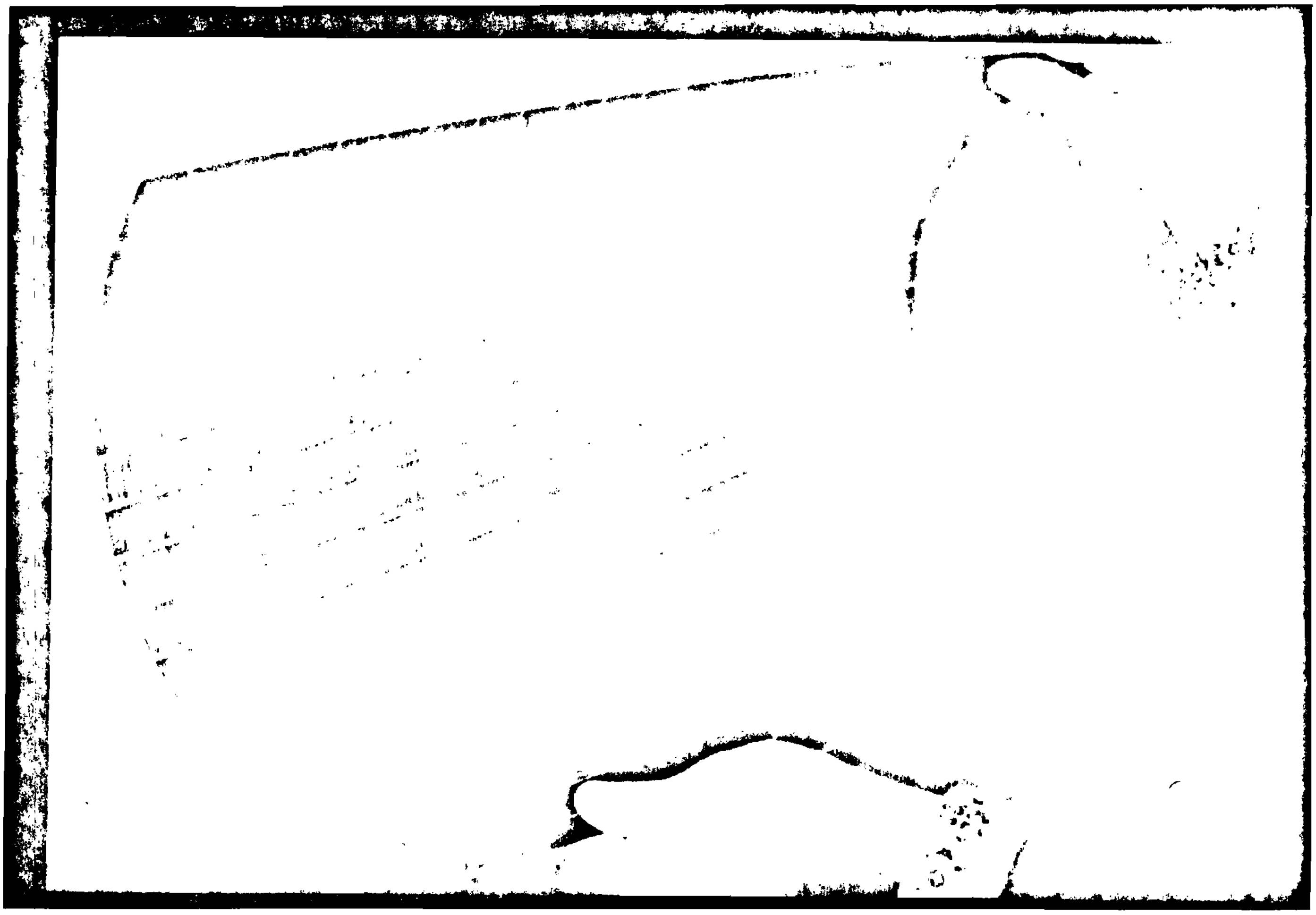

Figure ___ Silicon solar cells in integral terrestrial array with FEP ("Teflon")covering. Courtesy TRW Systems, Inc.

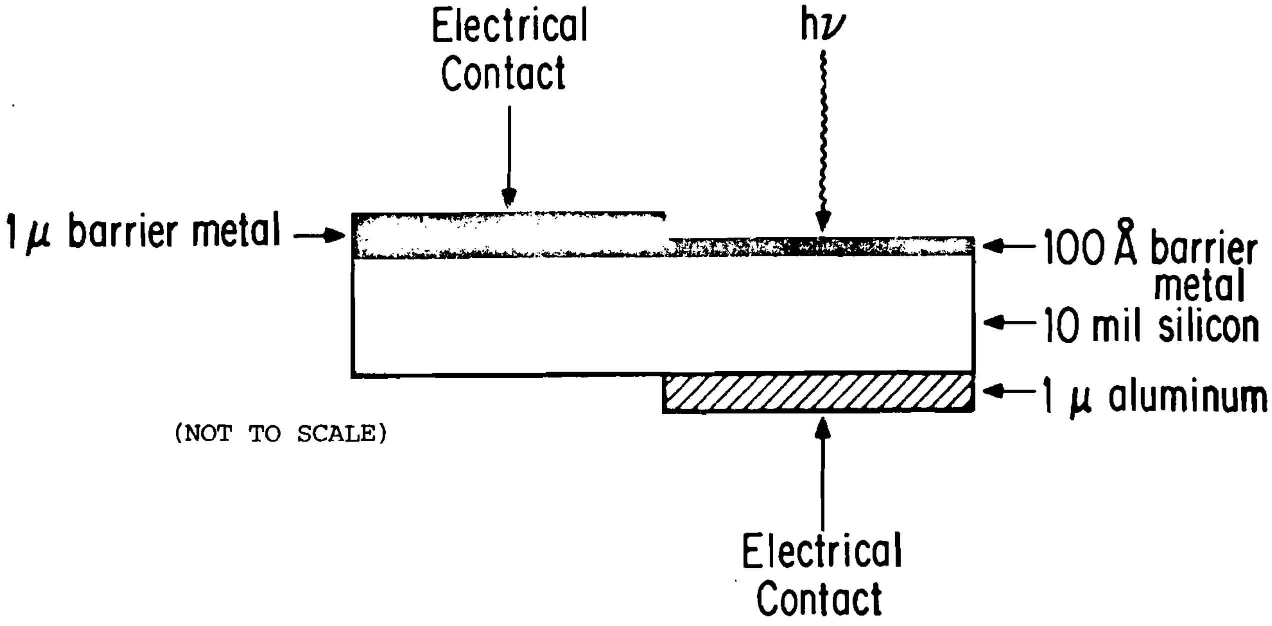

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Figure ___ Structure of a Schottky Barrier Solar Cell - Possible Technique for Low Cost High Speed Formation of Semiconductor p/n junctions for solar cell Fabrication. (Ref. ____)

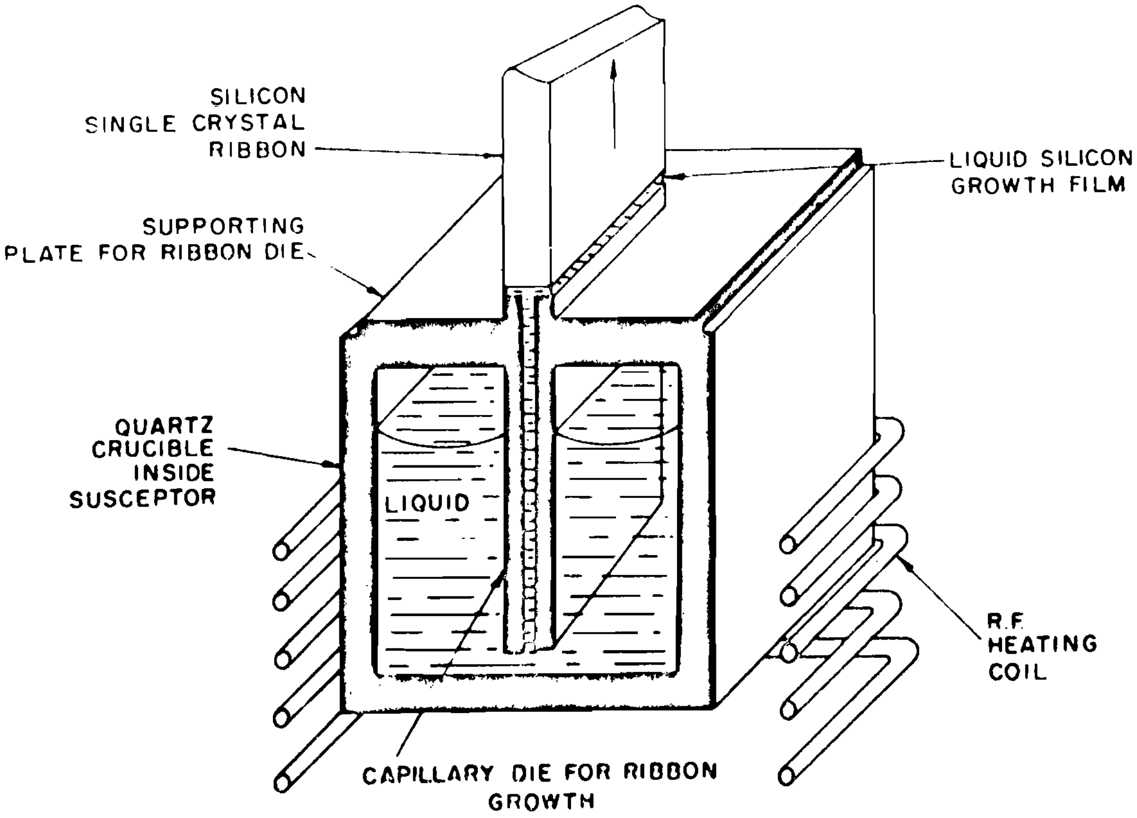


Figure ___ Schematic of Solar Cell Ribbon Silicon Growth (EFG -"Edge Defined Film Growth") (Courtesy Tyco Laboratories)

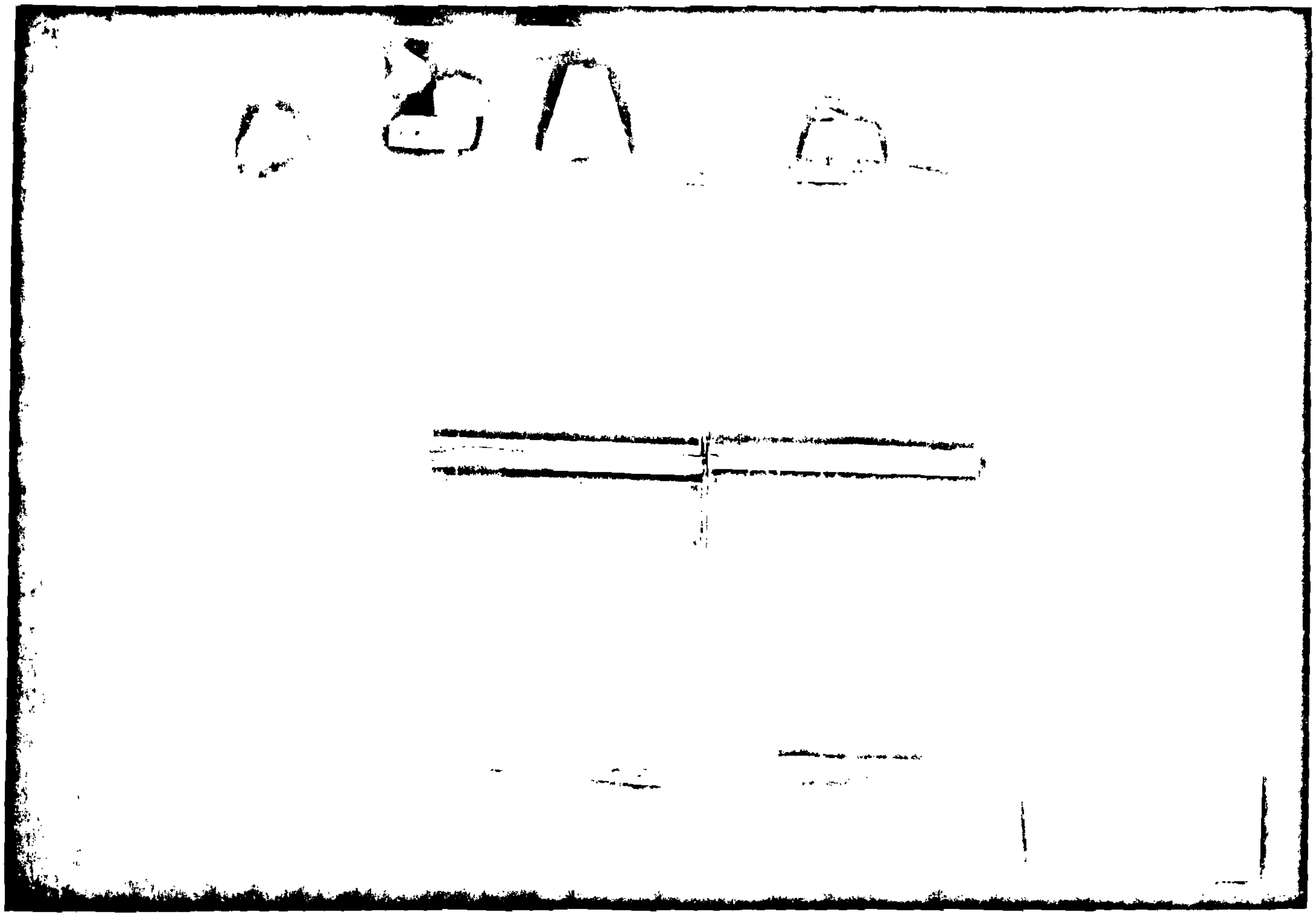
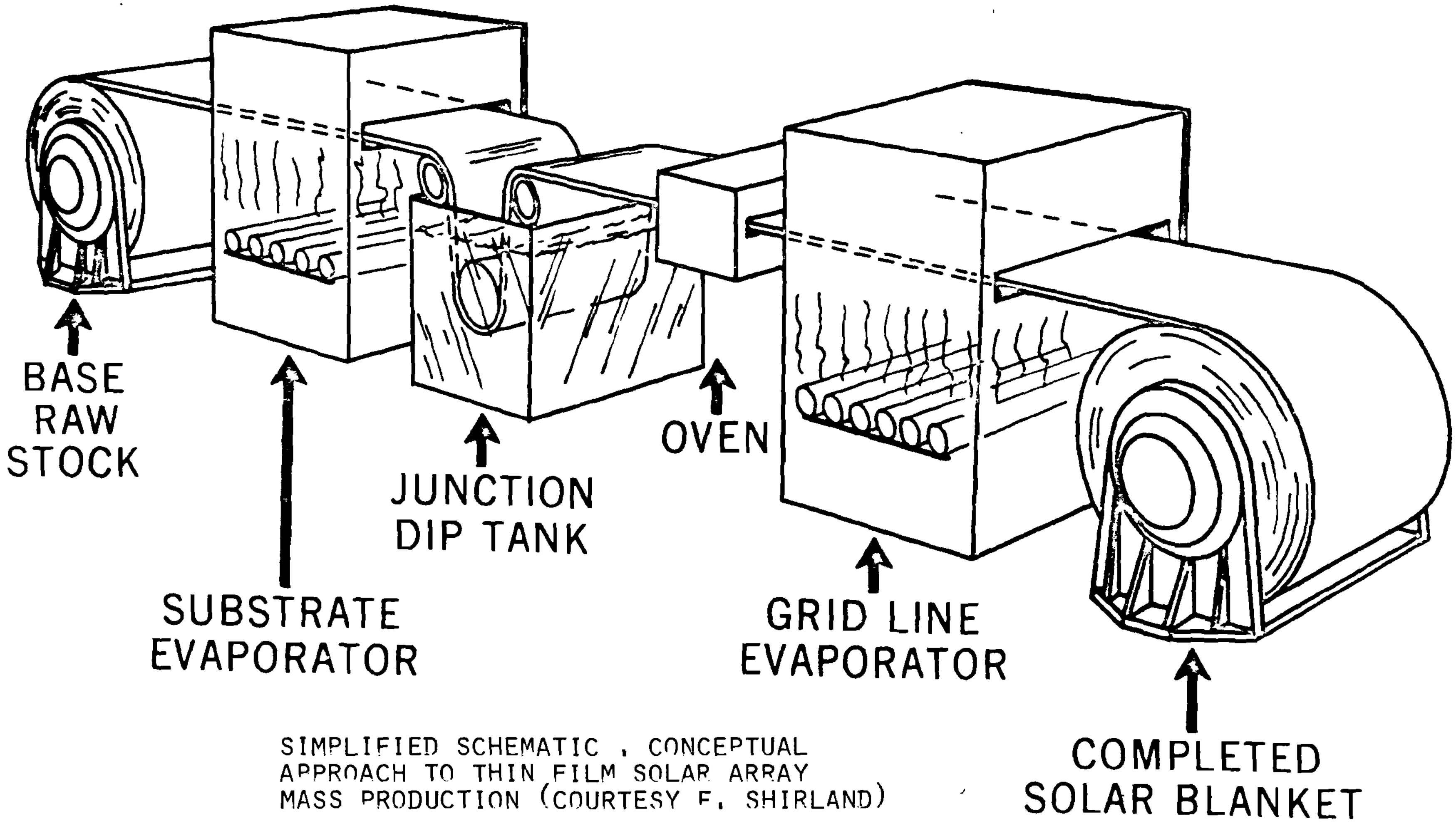


Figure ____ Prototype Cadmium Sulphide Terrestrial Photovoltaic Cell (Courtesy F. Shirland, 1970)

SOLAR ARRAY MANUFACTURING



SIMPLIFIED SCHEMATIC , CONCEPTUAL APPROACH TO THIN FILM SOLAR ARRAY MASS PRODUCTION (COURTESY F. SHIRLAND)

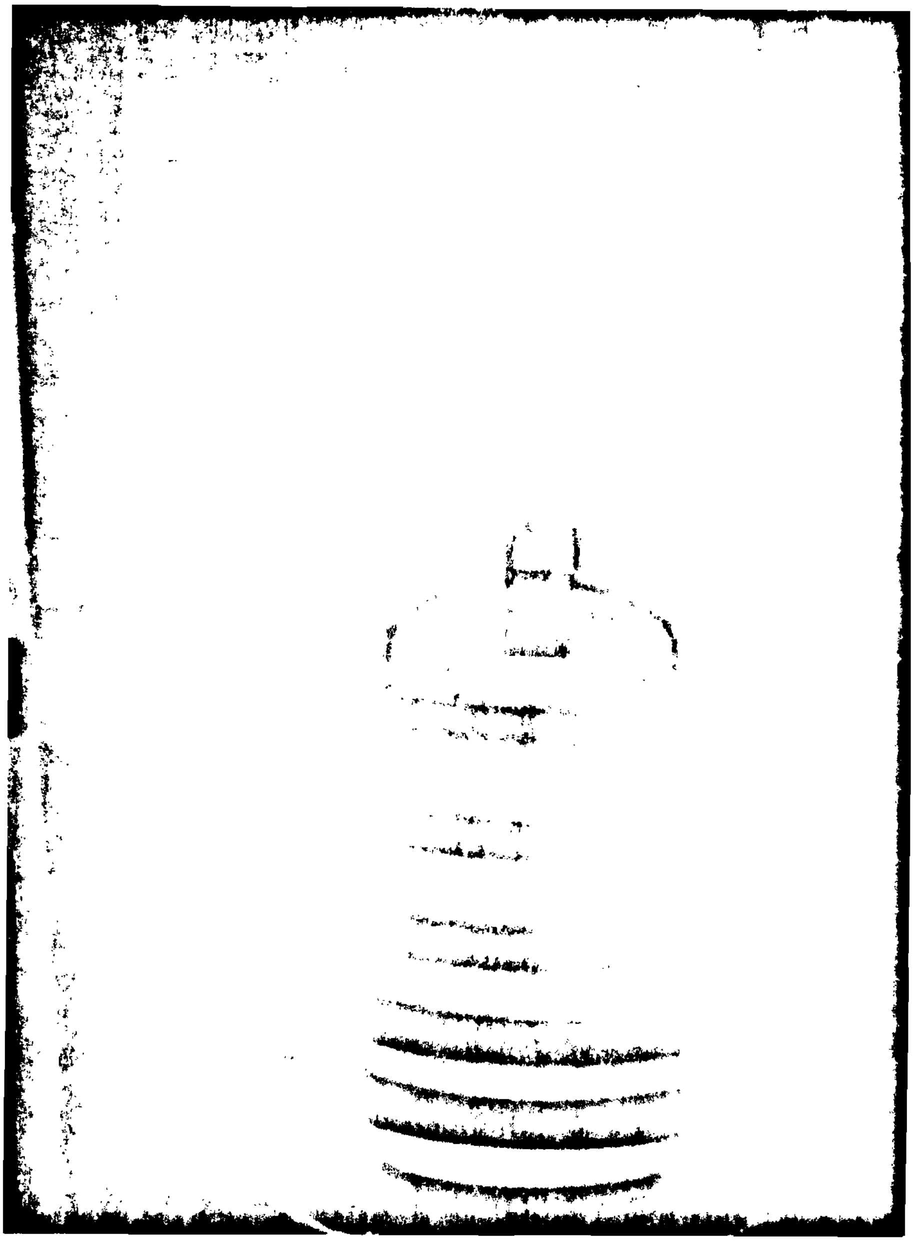


Figure ____ EFG silicon ribbon being pulled from the melt. Courtesy Tyco Laboratories (1974)

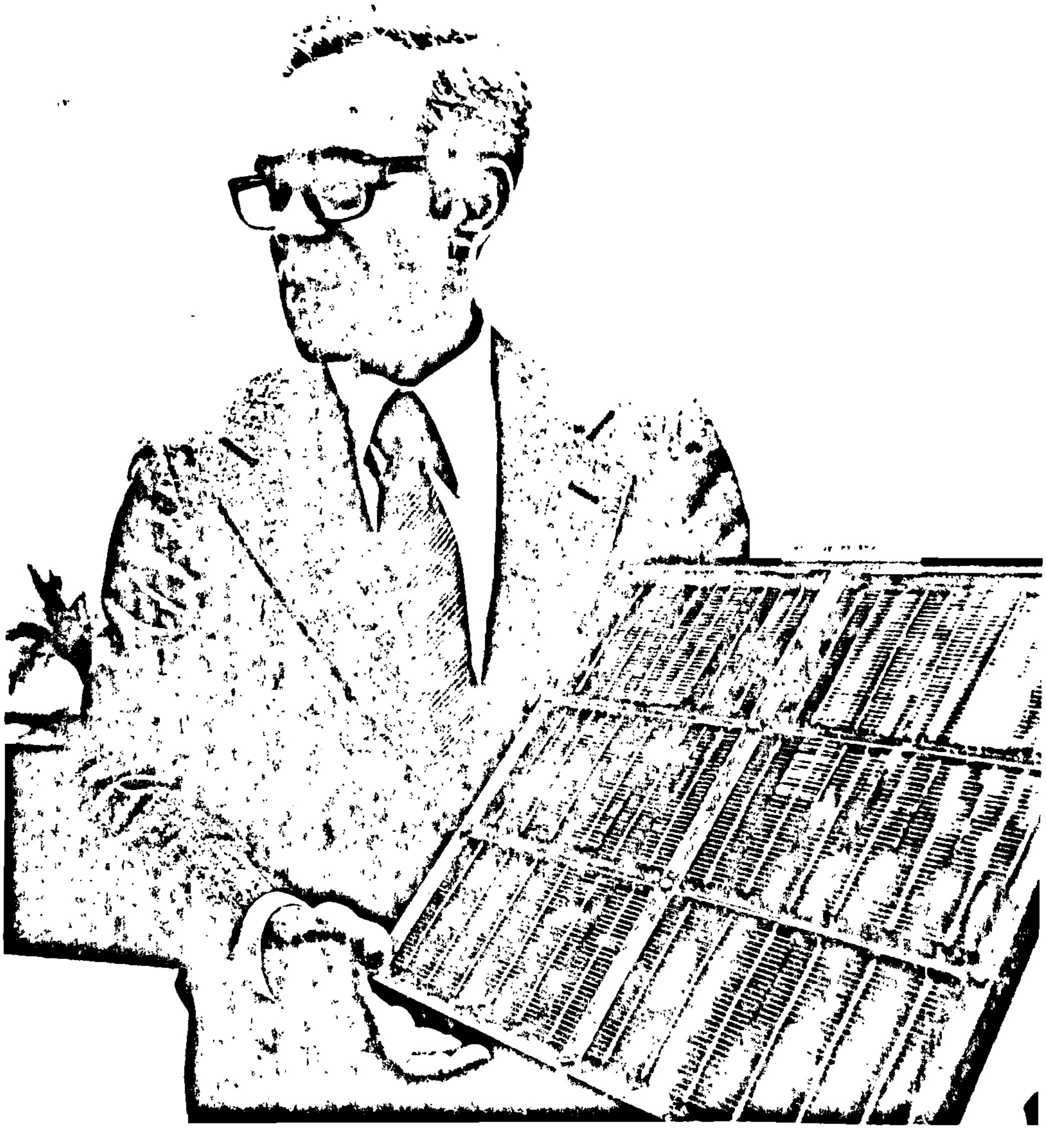


Figure ____ Terrestrial Photovoltaic Array (prototype) Fabricated From EFG Ribbon Silicon (Courtesy Tyco Laboratories)

DRAFT

Economics of Photovoltaic Systems

J. Weingart

Introduction

The economics of the large scale energy systems used in the industrialized nations (and to a considerably lesser extent in the LDC's) vary substantially from the economics of small scale energy systems which might be used in developing countries. In both sets of circumstances, however, the basic capital costs of various system alternatives must be established before any procedure to calculate final costs of energy delivered to the ultimate user can be employed. Because the author is a physicist and not an economist (particularly an economist of energy use in the LDC's) I will only mention briefly the issues which must ultimately be carefully considered before final assessment of the usefullness of photovoltaic conversion systems is made.

This section will review the current and projected costs of solar conversion elements (solar cells), solar conversion modules (fully integrated terrestrial array) and solar conversion systems including conversion, storage, power conditioning and transmission and distribution. In addition, various estimates of the rate of market growth for photovoltaic systems as a function of time and system costs are reviewed and their credibility discussed. Finally, this section will conclude with an examination of the relative first and life-cycle costs of various solar photovoltaic and non-solar energy options for electricity production, in the context of the LDC's. I begin, however, with a brief discussion of the systems considerations involved in evaluating the total costs to the final user of a photovoltaic system.

Systems Considerations

The costs of energy from a solar energy conversion system in an LDC include many factors beyond the capital cost of the solar conversion module. Capital or initial costs include, of course, the costs of the array modules, including support and orientation structures, plumbing (if forced cooling is used) and other elements, including batteries, inverters and other power conditioning equipment, and hardware for local distribution of electricity. Additional capital investment costs include provisions for replacement parts, tools, chemicals for cleaning surfaces and inhibiting corrosion, and possible backup systems, such as inexpensive internal combustion engines plus generators, and occasional use of fuel. Other costs will of course include the costs of packaging and transporting the system elements to site, fees and tarrifs for importation, and labor costs for assembly and operation of the system. Still additional costs include the development of a local infrastructure to handle replacements, training for people to use the equipment, development and printing of manuals for instruction in system operation and possible additional costs associated with local institutional factors, such as the need to monitor how much each member of a settlement is drawing (electricity) from the system. Other social costs might include payment to people who make their living delivering kerosine or other fuels which are totally or partially displaced by the solar systems. There are precendents for such considerations **. A partial list of such costs is shown in table ____ .

Finally, the cost of capital will be an important factor in determining the cost of energy. In a photovoltaic system where the costs of the system operation depend primarily on the total capital investment in the delivered system, the interest rates applied to the loans will be extremely important, since the amortized costs of electricity will be almost linearly proportional to the interest rate.

** Maria Telkes tells of an incident on a Greek Island where a large solar still was installed under her direction. The glass plates were mysteriously broken night after night soon after the still went into operation. Investigation showed that boys who had been earning their money bringing fresh water to the villages from the hills were resonsible and the damage did not stop until they were suitably paid.

Cost Components for a Photovoltaic System

Capital Costs

Equipment

Solar conversion modules including mechanical supports, heat transfer (active or passive), orientation mechanisms, concentrators, etc.

Batteries

Power Conditioning (Inverters, voltage regulation, current stabilization, transformers, etc.)

Local transmission and distribution components, including cables, plugs and connections, switches and relays, etc.

Transportation

Packaging for shipment

Transport from sources to LDC's (for those components not produced locally)

Internal transport

Fees

Import duties
Taxes
Hidden costs

Support Locally

Spare parts
Tools
Manuals
Training

Array Deployment

Cost of land
Labor and materials for deployment
On-site structures for housing storage batteries, power conditioning equipment, etc.

Continuing Costs

Equipment

Replacement components for damaged system elements

Replacement of batteries (3 to 5 years) and other elements due to corrosion and other forms of degradation , engines after 3 years

Tools, manuals, etc. which are needed continuously and which break or wear out (or are stolen, sold or otherwise made unavailable)

Maintanence and Operation

Labor for maintaining equipment, possible costs for night time protection.

Labor for operating system, including handling billings or other techniques for dividing up local support of the system

Capital Costs

Interest on capital borrowed to purchase systems

Local taxes and other fees

Possibility of taxes or fees of various kinds imposed locally.

Fuel

Fuel costs for backup system(s) which may be required to minimize risk of solar system outages to acceptable levels

Solar conversion elements - current costs

Of the various types of photovoltaic devices, only silicon solar cells have really become an established product, although CdS cells have been used in space applications (USA and France) and GaAs cells were used by the USSR in near-sun deep space probes. Although various types of cells will be discussed under "future costs", this section will be limited to a discussion of the present costs of silicon solar cells.

The cost of a cell can be unambiguously expressed in terms of the cost per unit area of the finished device. The actual cost of energy produced in a working environment will depend on such factors as the efficiency of the cell as a function of tempearture, intensity and wavelength; insolation patterns and other environmental factors. Since the realistic applications of such cells will be in integrated modules, the final costs must be determined in terms of the performance of these modules and not of the cells alone. However, in order to understand the costs of the modules, it is important to understand the characteristics of individual solar cells or conversion elements first.

As discussed earlier, the process of fabricating silicon solar cells consists of a number of steps leading from sand to a completed cell, followed by integration into an array unit. Each step of processing and fabrication entails added costs. Sand is available for about a half cent per Kg. Metalurgical silicon, with a purity of approximately 95 percent, typically used in steel making, costs about sixty cents per Kg. Chlorosilane ($SiHCl_3$) costs about six dollars per Kg (Si content) and is available at purities exceeding 99.999 percent. The usual use of such material is for production of silicones and pure polycrystalline silicon. This polycrystalline silicon is 99.9999 percent pure and is usually used for semiconductor devices. The 1973 costs were approximately $ 65 per Kg. Single crystals of silicon grown by the Czochralshi method cost $ 250. per Kg and Silicon solar cell blanks cost approximately $ 1500. per Kg. This final calculation is for silicon solar cells 0.01 cm thick with a 10 percent conversion efficiency (AM1) The equivalent cost of the solar cell blanks produced by this process (of cutting and slicing the cylindrical single crystals of Si) is $ 3500 per Kwe (peak) and roughly $ 14,000 to $ 20,000 per average Kwe. The current price for individual silicon solar cells is approximately $ 10,000 per peak kwe ($ 40,000 to $ 60,000 per average Kwe) and the cost of a completed array (with or without batteries and power conditioning, since these are relatively cheap) is $ 30,000 to $ 70,000 per peak Kwe ($ 120,000 up for average power).

CURRENT MATERIALS COSTS IN SILICON SOLAR CELL FABRICATION

COMPONENT	\$/Kg	\$/Kwe(peak) [a]	$\$/m^{2}$ [a]	REFERENCE
SAND	.005	.01		Ralph (1)
METALLURGICAL	.60	1.40		Ralph (1)
GRADE SILICON	.66	2.50	.30	Lesk (2)
	.51		.12	Wolf (3)
TRICHLOROSILANE	6.00	14.00		Ralph (1)
($SiHCl_3$)	6.00	23.00	2.75	Lesk (2)
	6.58		1.54	Wolf (3)
SEMICONDUCTOR	60.00	140.00		Ralph (1)
GRADE SILICON		350.00		Goldsmith (4)
	65.00	250.00	30.00	Lesk (2)
	59.80		14.00	Wolf (3)
	60.00			Iles (5)
	60.00			Crossman (6)
SINGLE CRYSTAL	250.00	600.00		Ralph (1)
SILICON	300.00			Iles (7)
SINGLE CRYSTAL	1300.00	3000.00		Ralph (1)
SILICON SOLAR		3200.00		Goldsmith (4)
CELL BLANK		3800.00	460.00	Lesk (2)
COMPLETE SOLAR		5000.00 (extension of 1973 tech.)		Ralph (8)
CELL		60,000.00 (spacecraft cell)		Goldsmith(4)
COMPLETE SILICON CELL ARRAY		30,000		Greeley (9)
TERRESTRIAL		30,000		Lindmeyer(9)
SYSTEM(Battery, Power cond.)		40,000 - 70,000		Centralab(9)
SPACECRAFT ARRAY				

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a) These costs are computed on the basis of a ten percent conversion efficiency at Air Mass One (AM1) incident solar radiation. Variation in computed costs reflects differing assumptions about the cell thickness.

References

Current Materials Costs in Silicon Solar Cells

1. E.L. Ralph, "Material Factors in Manufacturing Solar Cells" Ref. I
2. I.A. Lesk, "Large Scale Use of Single Crystal Silicon for Solar Energy Conversion" Ref. I
3. M. Wolf, "Methods for Low Cost Manufacture of Integrated Silicon Solar Arrays", Ref. I
4. P. Goldsmith, "Evaluation of Solar Cell Cost Predictions", Ref. II
5. P. Iles, "Polycrystalline Silicon Solar Cells - The Centralab-Dow Corning Program" Ref. II
6. L. D. Crossman and L.P. Hunt, "Proposal for Low Cost Silicon Processes" Ref. II
7. P. Iles, private communication (1973)
8. E. Ralph, "Silicon Photovoltaic Device Development Plan", Ref. II
9. A. Rosenblatt, "Energy Crisis Spurs Development of Photovoltaic Power Sources", Electronics (G.B.), 4 April, 1974

NOTE: The various references quoted ranged from 1972 to 1974; some variation in prices over this time have taken place in terrestrial arrays. The prices shown are, with the exception of the projected costs of terrestrial solar cells, reflective of the current market environment for silicon materials and photovoltaic devices and arrays.

Reference I: Procedings of the Symposium on the Material Science Aspects of Thin Film Systems for Solar Energy Conversion, May, 1974. Published by the National Science Foundation/RANN under Grant No. GI-43795 Available from NTIS

Reference II: Workshop Procedings: Photovoltaic Conversion of Solar Energy for Terrestrial Applications, Vol. I and II. October, 1973. Published by the National Science Foundation/RANN under Grant No. AG-485. Document No. NSF-RA-N-74-013

The process for producing solar cells (current technology) from silicon can be automated to reduce the costs of terrestrial arrays to perhaps $ 25,000 per kwe (average) However, as Wolf (___) puts it:

> "While the application of existing silicon solar cell technology to terrestrial solar energy utilization would be technically feasible today, the process methods by which these cells are fabricated, even if fully automated, do not have the capability of reaching the mentioned (approx. $ 1000 per average kwe) cost goals. It is therefore necessary to develop an entirely new fabrication process for silicon solar arrays"
>
> (emphasis added)

Potential for Reduction of Silicon Solar Cell Array Costs

It is clear from Table ___ that two important areas for development of new techniques to reduce costs is the production of silicon solar cell "blanks" of suitable quality (as measured in defect and impurity concentrations) and in the conversion of the blank to a finished cell. Production of solar arrays or modules at interesting prices (under $ 1000 per average kwe) will require a mass production technique for combining the cell, mechanical supports, protective diodes, electrical contacts and connections, transparent covers and other components in an efficient manner. One particularly important component in the completed module is a concentrator, to increase the effective area of the solar cell or conversion element without a significant increase in cost. Since the costs of metal or metalized glass or plastic concentrators will be ten to a hundred times less expensive per unit area than the cells themselves, the integration of concentrators into a finished module may be the important final "stage" of cost reduction processes to achieve an economically interesting terrestrial photovoltaic system.

Reduction in the Cost of Suitable Quality Silicon

Estimates by Ralph (__) and others indicate that an increase in present solar cell production by 5 orders of magnitude will result in a reduction of the cost of semiconductor grade silicon by a factor of only two. (Figure ___ , Table ___). The reason is that the projected demand for polycrystalline semiconductor quality silicon for all uses will not be sufficient, in the view of a representative of a major supplier of silicon ( ) to reduce the price substantially. Such a view is open to challenge. The projected demand for semiconductor silicon is shown in Figure ___ .

Solar Conversion Modules - Current Costs

Solar conversion modules, like the Centralab module shown in Figure ___ , are currently available at a price of $ 30,000 per kwe(peak) The author has not seen a detailed breakdown of the costs of components and assembly of these modules so a detailed discussion of the economics is not possible at this time. (Information has been requested from a number of the module manufacturers.) The current costs of $ 120,000 to $ 150,000 per kwe(average) can be reduced.

Production is estimated by Union Carbide (__) to be approximately one million Kg in 1975, growing at 20 percent per year to 150 million Kg in the year 2000. Such increases in production might result in substantial price reductions. If, however, price reductions (in present dollars) follow the industrial experience of the past for many industries*, the cost reduction will be approximately by a factor of 5.3. It seems therefore that reduction in the cost of semiconductor quality silicon will not alone make the difference required.

Increased Conversion Efficiency, Decreased Thickness of Cells

A number of experts believe that solar cells can be made with a conversion efficiency approaching 20 percent (AM1, 20 deg. C) with the usual thickness (.025 cm) and with a conversion efficiency of 10 percent with a thickness of 0.01 cm. Increased efficiencies at a given thickness (or an increase in the ration of efficiency to thickness) will reduce the costs further, although only another factor of two or so is to be expected.

New Fabrication Approaches

A large number of techniques for reducing the cost of the cell blank and of subsequent processing of the blank to produce a finished cell have been discussed extensively in the open literature. Production of lower cost blanks for cells, using processes to convert relatively low cost metallurgical grade silicon or trichlorosilane into finished blanks, include fabrication of polycrystalline and single crystal ribbons and sheets, ion deposition of thick silicon "films" and a number of other techniques.

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* Past experience has shown that the price of many materials and products decreases in proportion to the cube root of the production level. This means an increase in production by a factor of 150 would result in a cost reduction of a factor of 5. (   )

Of these various techniques, discussed elsewhere in this report, only one is sufficiently advanced, in the author's opinion, to estimate the potential cost reduction in cell blanks and finished cells. This is the technique developed by Tyco Laboratories (Waltham, Massachusetts) for the production of continuous silicon ribbon of sufficient quality to produce solar cells with conversion efficiencies in excess of ten percent under standard conditions. The process is known as the EFG or Edge-Defined Film-Growth technique ( ). In this technique a "seed" crystal of silicon is dipped in a bath of molton silicon and a film is pulled through a capillary die (figures ___ and ____) to produce a ribbon. Ribbons of one inch width with thicknesses down to .oo8 " (.02 cm) have been continuously pulled at rates of one to one and a half inches per minute. A detailed economic analysis of this process has been carried out on the assumptions that multiple ribbon growth from a single machine could decrease costs. The parameters are shown in figure ___ . Mlavsky (___) estimates that with silicon at $ 22 per Kg, finished solar cells could be produced for the cost of $ 165/kw(peak, AM1, lo percent efficiency , .004 " or .01 cm thick) or between $ 500 and $ 825 per kilowatt average.

His estimates are that a cell blank could be produced for costs equivalent to $ 120 per Kwe(peak), a reduction of 25 over the cost of cell blanks prepared for convetional cells, and a factor of ten better than projections of improved technology (lower sawing losses, ten percent efficiency at .01 cm) using otherwise current techniques.

	Current Technology	Tyco Proposal	Relative Advantage
Cell effic.	0.10	0.10	x 1
Silicon loss in cell mfg.	.60	.30	2
Thickness	.03 cm	.01 cm	3
Silicon cost	$ 60/Kg	$ 22/Kg	3
			x 18

ESTIMATES OF PHOTOVOLTAIC (SILICON) CONVERSION
ELEMENT COSTS (Mlavsky (__)

ECONOMICS OF EFG SILICON RIBBON

ASSUMPTIONS:
- MULTIPLE RIBBON GROWTH: 20 AT ONCE.
- DIMENSIONS: 2 INCH x 0.004 INCH
- YIELD FROM RAW MATERIAL: 70%
- MINIMUM UNIT MANUFACTURING OPERATION: 12 MACHINES WITH ANNUAL OUTPUT OF 300,000,000 SQUARE INCHES (100,000 POUNDS) -20 MW-

MANUFACTURING COST*: ~ $15/LB PLUS RAW SILICON COST

RIBBON TO CELL COST: (ESTIMATE) $10/LB

RAW SILICON TO CELL COST: $25/LB

FOR $10/LB RAW SILICON, AND 10% EFFICIENT CELLS,
CELL COST* = $165/KW (PEAK)

*DIRECT LABOR, MATERIALS, AND MANUFACTURING O/H, INCLUDING UTILITIES AND EQUIPMENT DEPRECIATION.

TYCO LABORATORIES, INC.

The difference of roughly a factor of 20 is shown above. The basis for the cost estimates for the silicon ribbon in mass production comes from extensive industrial experience with an analogous process for the production of large quantities (_____ m tons/year) of single crystal, gem quality synthetic sapphire for use in high intensity lamps for highways and other applications. The process of fully commercializing the EFG ribbon and tubular sapphire process has resulted in good cost estimates for an virtually identical industrial process using silicon. The figure of $ 165/kwe(peak) is based, according to Mlavsky (___), on a detailed calculation of the components of direct labor, materials, and manufacturing overhead, including utilities and equipment depreciation.

Use of Concentrators

Mlavsky estimates that the incorporation of a collector (in particular the Winston collector discussed below) into a terrestrial photovoltaic module incorporating the EFG silicon ribbon solar cells could result in costs of approximately $ 200 per kwe (average) and a price of perhaps $ 400/kwe(average). Assuming that these estimates are low by a factor of 3, the availability of a module at $ 1200 per kwe average could result in electricity in LDC's at competitive prices providing the initial capital were made available for purchase. A detailed discussion of the effect of concentrators on silicon solar cell performance is presented in Attachment A.

Use of Concentrators with Solar Cells

Introduction

Even if the more is realized optomistic economic scenarios for the EFG ribbon silicon solar cells actually happens, the cost of the cells alone will still be on the order of \$ 165/Kwe(peak) = \$ 825/Kwe(average) or \$ $16/m^2$.

One appealing approach, at least in theory, to reducing the costs of photovoltaic arrays, is through the use of concentrators to increase the effective areas of the photovoltaic conversion elements. If the cost per unit area of the solar cells is significantly higher than the per unit area cost of a concentrator, the total cost per installed kilowatt can be reduced through integration of solar cells and concentrators. The costs of mass produced concentrators from aluminum, aluminized plastic and other materials are estimated at one to two orders of magnitude less than the cells themselves.

A number of things occur simultaneously when the optical flux incident on a solar module is increased. First, the equilibrium temperature of the module, determined by the equilibrium between incident radiation and the energy transported from the module by radiation, convection and conduction, will increase. (Fig. ___) In addition, the efficiency of the conversion element or solar cell is a decreasing function both of increasing temperature and increasing intensity of incident radiation. (Fig. __ and __) As the concentration ratio increases, the optimum cell design will change, the cooling system will become more complex (and presumably more expensive) and the tracking requirements more stringent. Work is underway (___) to determine the economically optimum mix of cell design, concentration ratio and concentrator design, cooling system and module configuration.

Disadvantages and Advantages of Using Concentrators

The advantages of using a concentrating optical system with a photovoltaic element include the potential for significant (factor of 5 or greater) in the installed cost per Kwe of the module, possibility of reduction dual mode operation to provide heat (through cooling water) as well as electricity for local purposes, and, in the event of scarce materials (relative to demand for photovoltaic device use of them), the opportunity to significantly "stretch" the available supply.

There are also, however, a number of disadvantages in such schemes. As the concentration ratio increases, so will the complexity and cost of the module. Concentration factors above 4x will require tracking mechanisms and possibly simple finned heat exchangers for air cooling. Concentration of a factor of 10x and above will probably require water cooling with silicon and CdS solar cells to minimize the decrease in conversion efficiency (0.5 percent per degree C increase) with increasing temperature. Solar cell efficiency will fall off somewhat with increased illumination above 10x and the high temperatures plus larger differentials in high and low temperatures of the module could result in shorter lives for the active components. (This may be offset by the availability of spares). In addition, a system with a forced cooling system will experience failures which would result in probable destruction of the active elements. Finally, systems with concentration ratios above 4x will, in general, be able to make use only of direct solar radiation and many of the LDC's are in tropical and semitropical regions with a very high percentage of diffuse radiation. Only combine concentration without tracking requirements and with acceptance of some diffuse radiation as well as direct radiation.

Some of these disadvantages are not as important as others. A high system may be sufficiently less expensive in first costs but concentration higher in operation costs, due to periodic replacement of deteriorated elements, than a lower concentration system. The system with lowest first costs will probably have an economic advantage in a society where initial capital is hard to come by but where maintanence and operation costs can be borne. The availability of concentration systems will make it possible to make some tradeoff in first costs against operating costs in a way which may be to the advantage of an LDC.

Examples of Concentration Schemes

A number of approaches to integration of solar cells and optical concentrators have been explored over the past several decades. Both single axis and double axis concentrators can be used. A single axis concentrator is essentially a reflective "trough" with the solar cells located at the bottom, as shown in Fig. . Simple modular channel concentrators described by Ralph ( ), Zarem ( ) and others can concentrate both direct and diffuse radiation with an effective concentration factor 2.5 to 3. Tabor later showed ( ) that a maximum concentration of approximately 4 was possible using such planar concentrators. An "egg crate" concentrator system was proposed over a decade ago by Ralph ( ) using aluminized plastic (Fig.).

Parabolic or focusing troughs can achieve concentrations of a factor of twenty or more, but can make use only of the direct solar radiation and must continuously track with the motion of the sun.

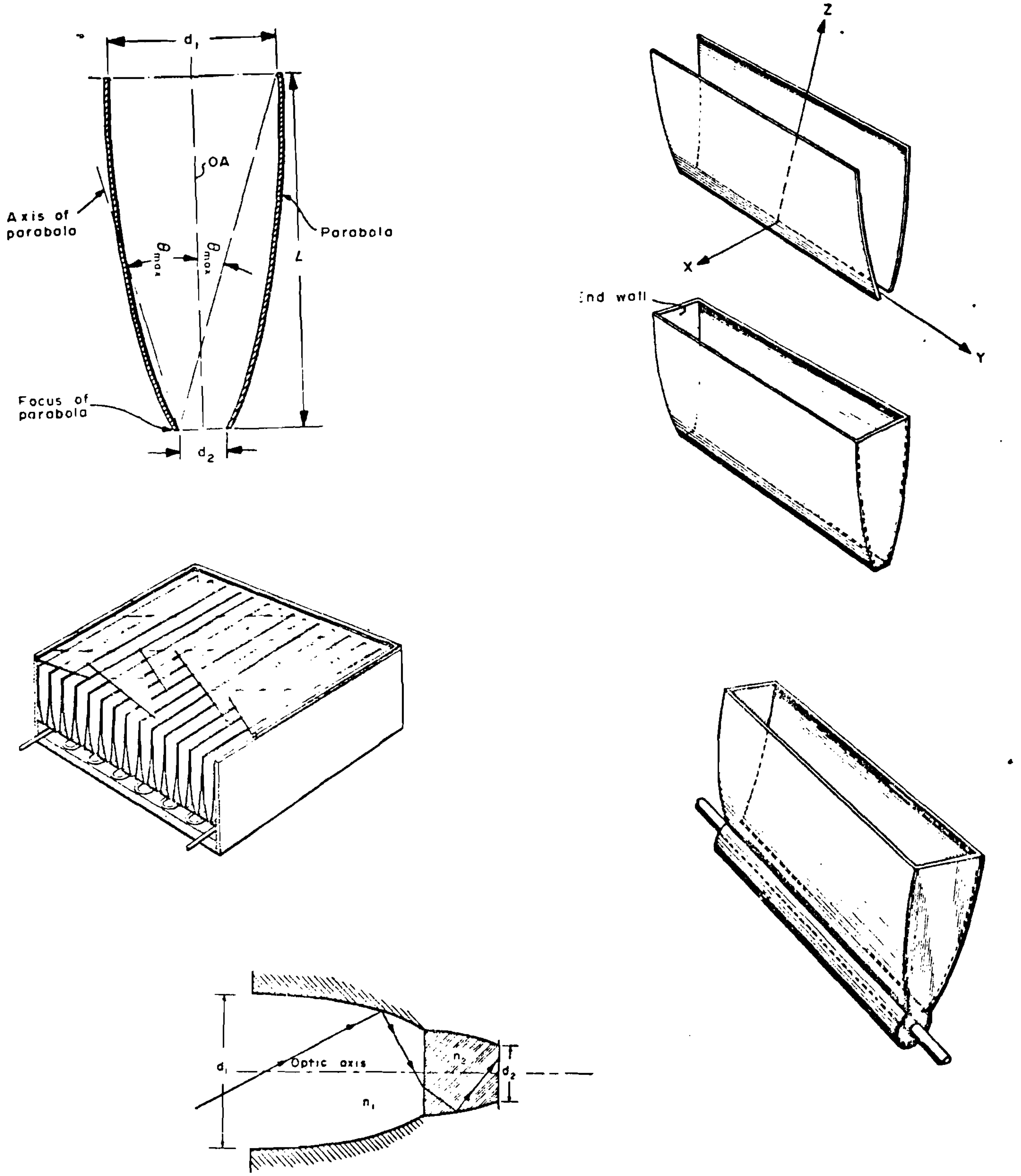
Two axis parabolas of revolution can increase the concentration to a factor of 100 or more (as in the case of other axially symetric concentrators, such as the Cassegrainian system shown in figure) and, like the single axis concentrators, track the motion of the sun and can collect only direct solar radiation.

The Winston Collector

A potentially important contribution to the reduction of photovoltaic array costs has been made by Winston working with several colleagues, he has invented the ideal cylindrical light collector. The collector, shown schematically in Fig. , consists of a reflective trough whose walls are shaped in such a way to concentrate the maximum light possible consistent with physical principles. As Winston describes it ( )

> "The ideal cylindrical light collector is capable of accepting solar radiation over an average 8 hour day and concentrating it by a factor

Figure ______ The Winston Collector in Various Configurations (Ref. ____)



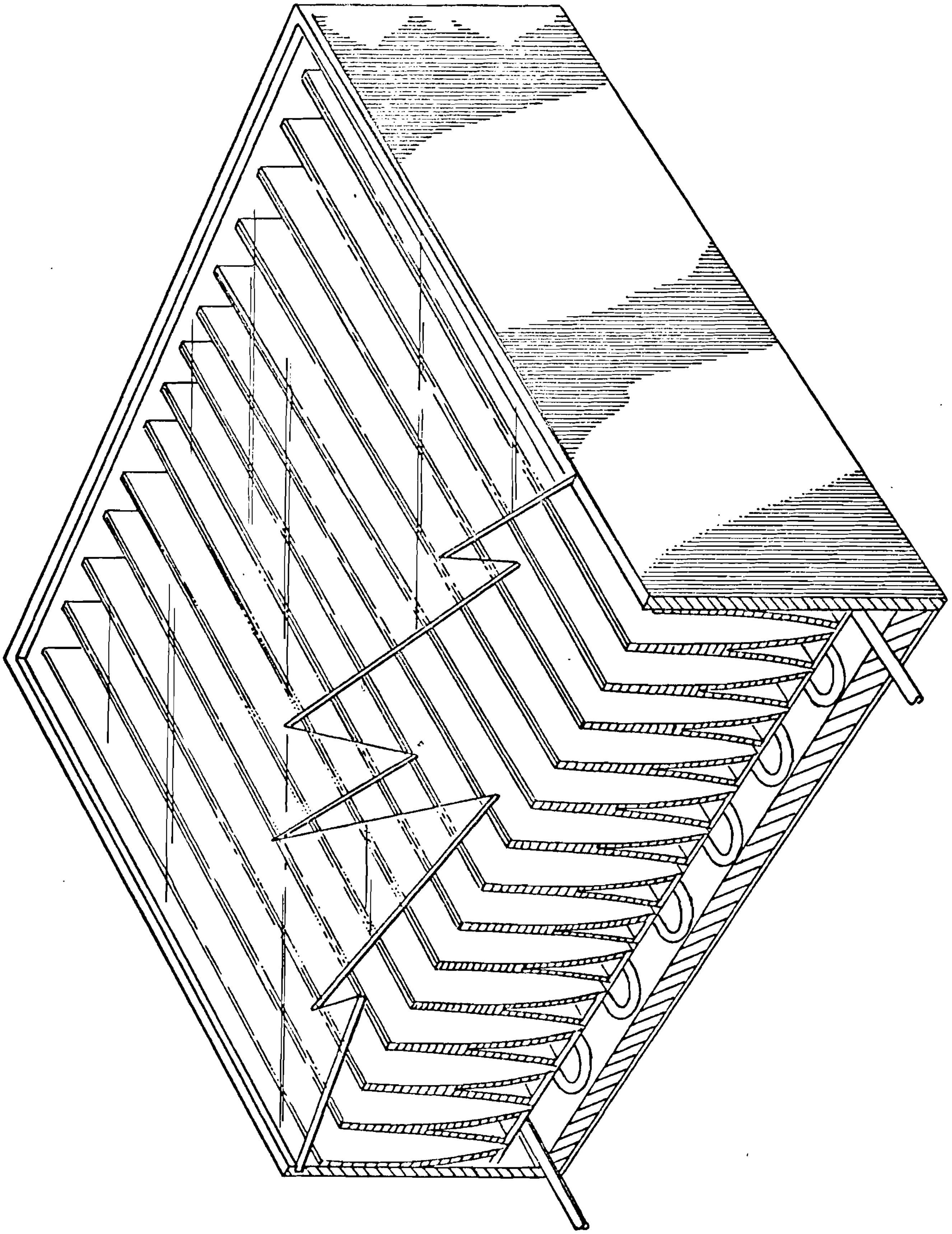


Figure 4 - Winston Collector

of 10 without diurnal tracking of the sun. This is not possible by conventional imaging techniques. The ideal collector is non-imaging and possesses an effective relative aperture of 0.5... The efficiency for collecting and concentrating isotropic radiation, in comparison with a flat plate collector, is just the reciprocal of the concentration factor."

(emphasis added)

The ability to collect and concentrate a portion of the indirect or diffuse radiation is by itself not a particularly significant feature of this collector. In an environment consisting of 70% direct and 30% diffuse radiation, with a concentration factor of 3, one-third of the diffuse radiation of the total insolation is collected along with the direct radiation. This increases the total radiation collected by only 13% - useful but not really significant. In an insolation environment in which virtually all of the radiation was scattered (high clouds for example), the use of concentrators would redirect no more diffuse light to the solar cells than if they had been laid out with the same spaces between them without any concentrators.

The much more important aspect of the Winston collector, in terms of photovoltaics, is the ability to achieve a concentration of direct radiation by a factor of 10 without the need for diurnal tracking. This feature would be extremely important in situations in which the collectors were at a fixed orientation (roof tops) and where interesting economics could be achieved only through concentration or in which the cost of a tracking mechanism would be prohibitive.

Note: These collectors also take on special significance in conjunction with flat plate thermal collectors, since they permit much higher conversion efficiency of sunlight to heat at temperatures required for absorption refrigeration or driving organic fluid rankine cycle turbines than possible without concentration.

The concept evolved from the development of an ideal optical collector used for the collecting of Cherenkov radiation (Fig.). This particular collector is a hollow, axially symetric conical shape. The extension for the purposes of solar energy collection has been to a trough shaped collector whose cross section is identical to that of the conically shaped concentrator.

The effective aperture of such a concentrator can be increased through the use of a second concentrator incorporating a fluid of refractive index greater than 1. In Fig. Winston has indicated how an increase in concentration by the ration n_2/n_1 (or n_2 if the first medium is air) is obtained through a two stage concentrator. In such a concentrator, the fluid with refractive index n_2 might also act as a thermal transfer medium, to maintain the solar cell at some established temperature and possibly use the heat for other purposes as well.

In the view of the author, (JMW), the coupling of the Winston collector and the EFG Tyco silicon ribbon solar cells appears the most promising near term otpion for a major breakthrough in reduction of photovoltaic conversion module costs. (See section on economic aspects of silicon convertors).

Concentrator Type	Concentration Factor	Tracking Requirements	References
Flat plate	1	non	
Flat plate with truncated pyramid	3	seasonal	
Low concentration Winston	~ 3-4	none	
High concentration Winston	~ 10	seasonal	
Parabolic trough	20	diurne	
Parabola of revolution Cassegrainian	> 50	diurne	

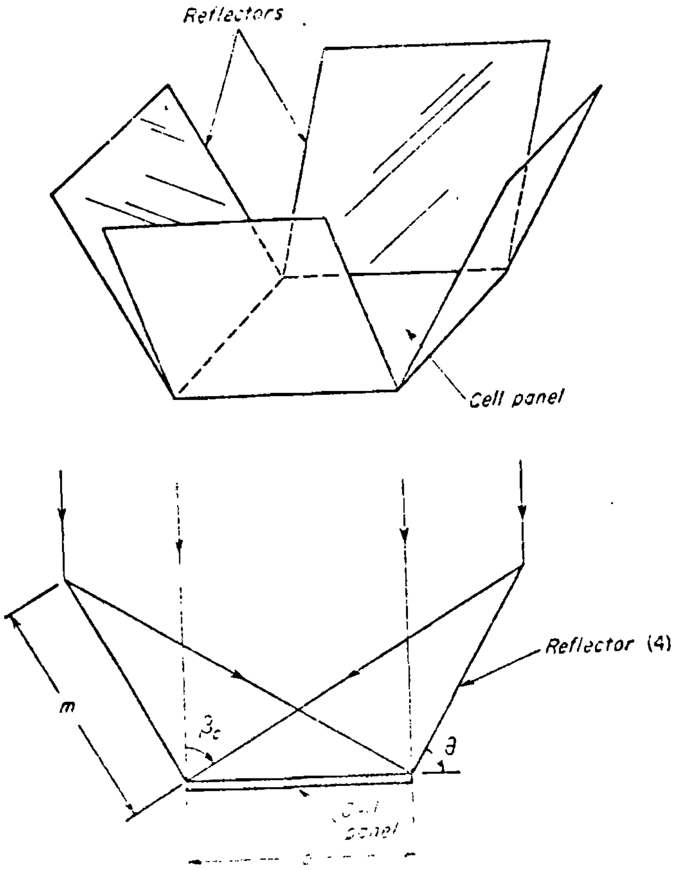
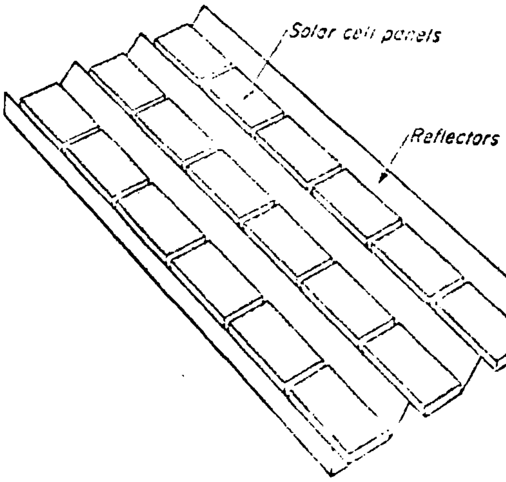
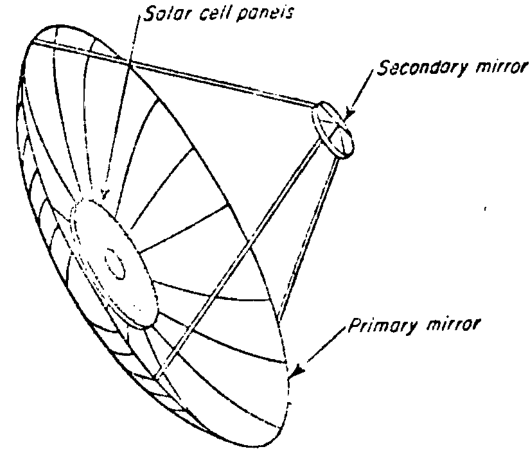


Figure ____ FLAT MIRROR CONCENTRATOR (Zarem, Ref. ___)

Fig. ____ Truncated Channel Concentrator Design (Zarem, Ref.)





Cassegranian Collector Design (Zarem, Ref.   )

Figure ______

Production and Cost Scenarios For Photovoltaic Systems - A Credibility Assessment

The production scenarios shown in Figure ___ represent a highly optimistic view of the future of photovoltaic systems production rates. The rough estimates by Weingart and Weyss (__) shown in Figure ___ suggest that production rates of 10 to 100 Mwe(peak) per year will occur when the cost of the delivered systems is below $ 1,000 per Kwe (rated). Although these estimates are only an attempt to scale the discussion, it seems likely that the future experience will roughly resemble the indicated guess. The "gap" in Figure ___ indicates the assumption by Weingart and Weyss that the costs of photovoltaic arrays produced by new techniques, such as EFG production of ribbon silicon, will take a quantum jump downward. The "high cost" range for the photovoltaic systems represents the region attainable through various levels of production sophistication based on existing technology. The best it appears possible to do with extensions of current silicon technology is $ 20,000 per kwe(rated) for a terrestrial array. The "low cost" regions represents the product of new technology in the case of silicon arrays, a highly sophisticated version of the CdS technology or a new production technique, and new techniques for thin film device fabrication. Only the Tyco EFG ribbon growth technique for silicon appears well enough advanced to permit some responsible estimates of the cost of a terrestrial solar array in this low cost regime. If we assume that the $ 30 million invested by Mobil in the new Mobil-Tyco Solar Energy Corporation is to generate a return on investment of 20% per year before taxes, and the finished arrays cost $ 1,000 per kwe(rated) or $ 200 per kwe (peak), the annual production rate would have to be roughly 7 Mwe. This falls within the low range of the Weingart/Weyss "quesstimate" and suggests that, if successful, the Mobil/Tyco venture could return a much higher rate of return on investment since some 20 Mwe(peak) can be produced annually at a lower total investment than $ 30 million (according to their estimates) (__).

Although this author feels strongly that with sufficient effort, mass production techniques can be developed to produce various types of photovoltaic arrays which can be installed for costs below $ 1,000 per kwe(rated), this "feeling" is based on rough estimates (__) of what such a mass production technology would look like if fundamental materials problems could be solved.

A much more "bullish" set of projections appear in the FEA Project Independence Blueprint (   ). Two scenarios, one labeled "Business as Usual" and one labeled "Accelerated" are shown in Table ___ and plotted in Fig. ___ . The projections are considered extremely "bullish" or optomistic in that they imply that the competition for large scale production of electrical energy will have very high costs indeed, in excess of several thousand dollars per kWe (rated). For example, with a system cost of $ 2000 per kwe (rated), it is estimated that the annual market might be as high as 50 Gwe,
for new generating capacity in the United States prior to the events of Fall, 1973.

Production of Silicon - A Survey of Estimates

Country	Date **	Grade of Silicon	Production (m tons/yr)**	Mwe(R)/yr *
Global	1971	Semiconductor	10^3 (1)	
Wacker (G.)	1971	Semiconductor	300 (1)	
USA	1977	Semiconductor	1500 (2)	
USA	1980	Semiconductor	2038 (2)	
USA	1985	Semiconductor	3300 (2)	
USA	1990	Semiconductor	5560 (2)	
USA	1995	Semiconductor	8625 (2)	
USA	2000	Semiconductor	15,800 (2)	
USA	1973	Single Crystal	750 (3)	
USA	1974	Single Crystal	1250 (3)	
USA	1973	Metallurgical	125,000 (4)	

References

(1) Private Communication with Prof. Martin Wolf, 10 October, 1971

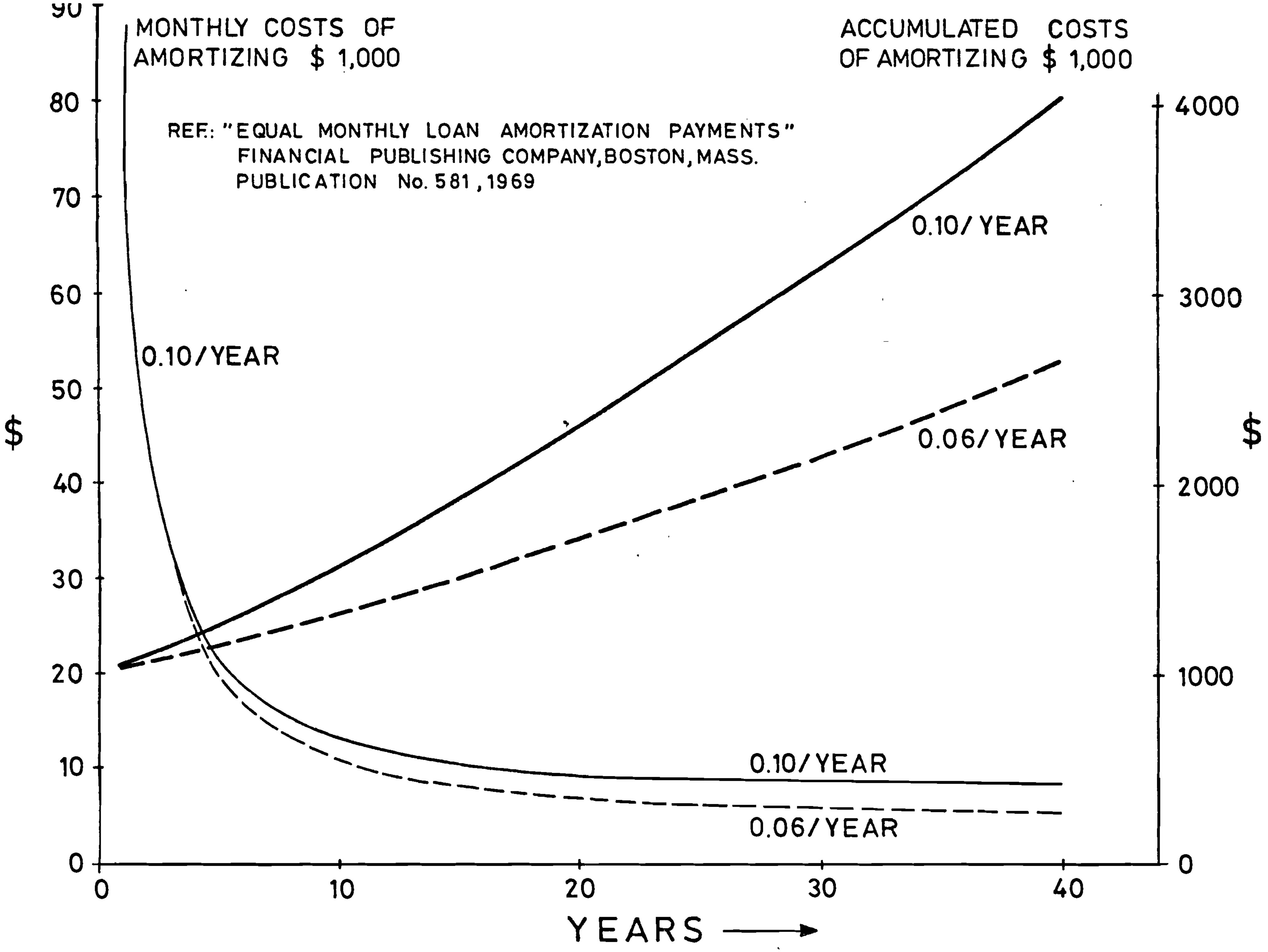
(2) Project Independence - Solar Energy Task Force Report, p. VII-A-3

(3) Ibid., p. VII-25

(4) I.A. Lesk, "Large Scale Use of Single Crystal Silicon for Solar Energy Conversion", p. 419, *Procedings of the Symposium on the Material Science Aspects of Thin Film Systems for Solar Energy Conversion, NSF/RANN, May,* 1974

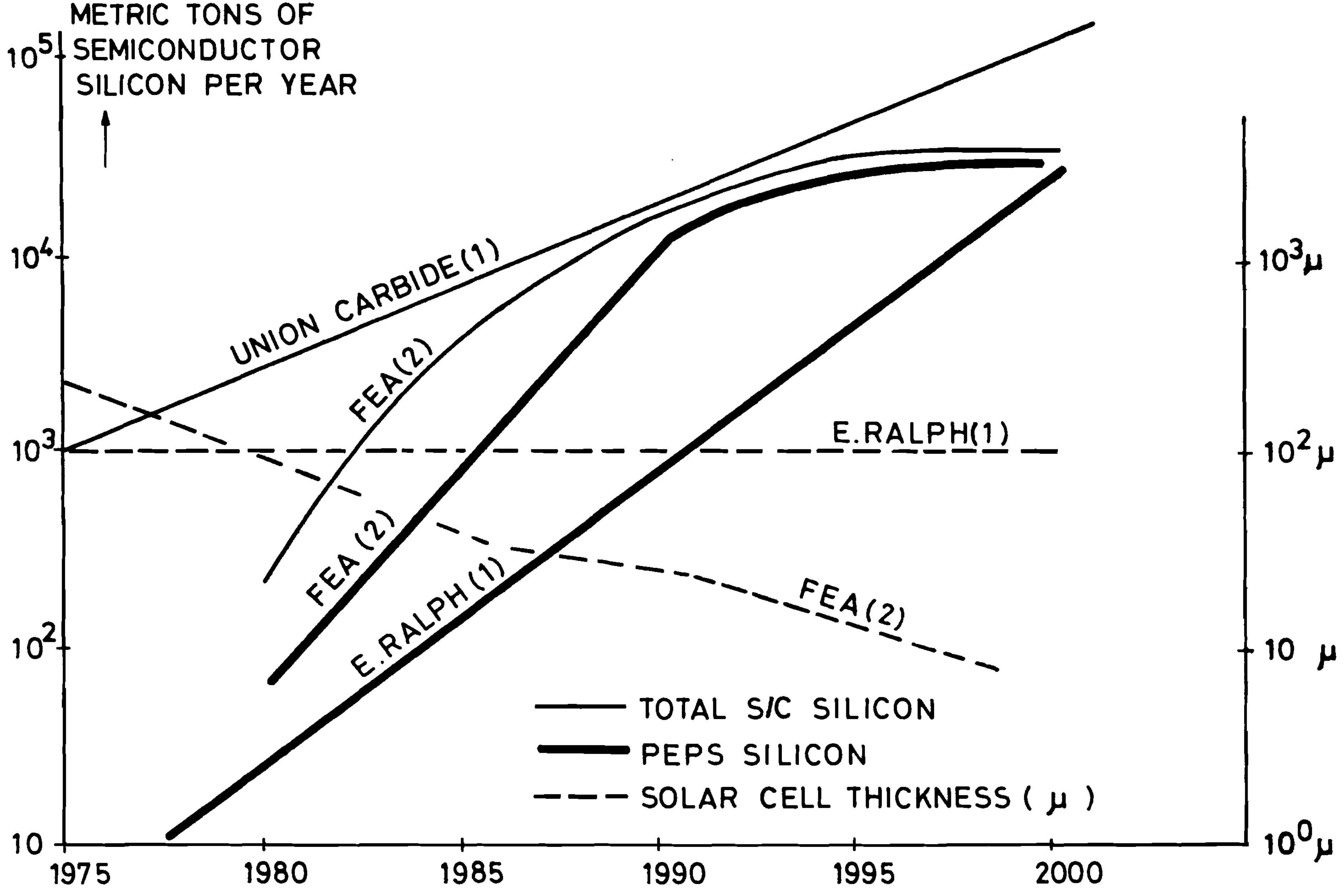
** Actual production or (estimated) production

* Under the following assumptions: 0.25 cm thick cells with conversion efficiency of 0.10 under AM1 illumination at 50 deg. C equilibrium cell temperature. Rated power (R) at 0.20 of peak power output under AM1 conditions.

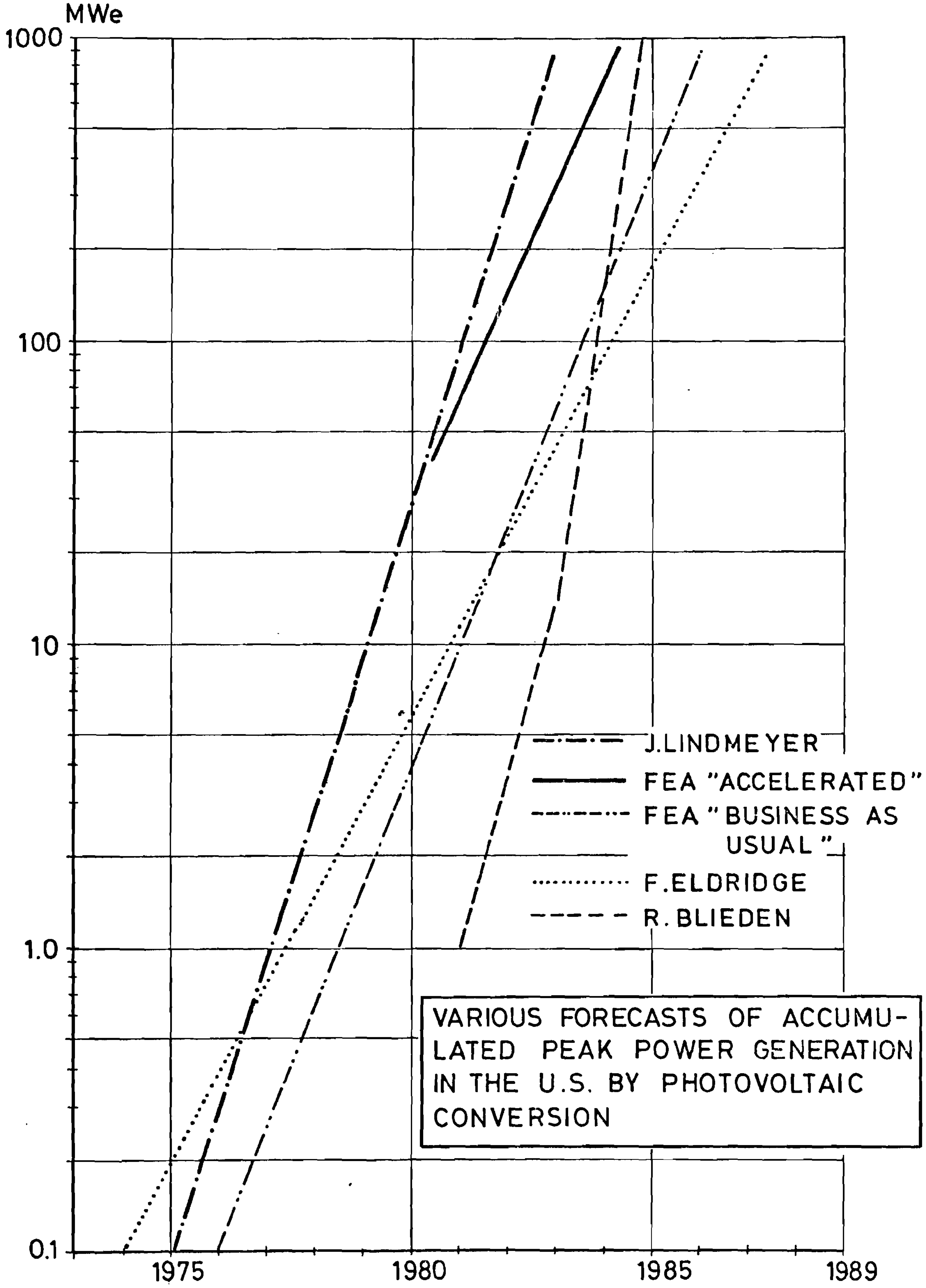


REF.: "EQUAL MONTHLY LOAN AMORTIZATION PAYMENTS"
FINANCIAL PUBLISHING COMPANY, BOSTON, MASS.
PUBLICATION No. 581, 1969

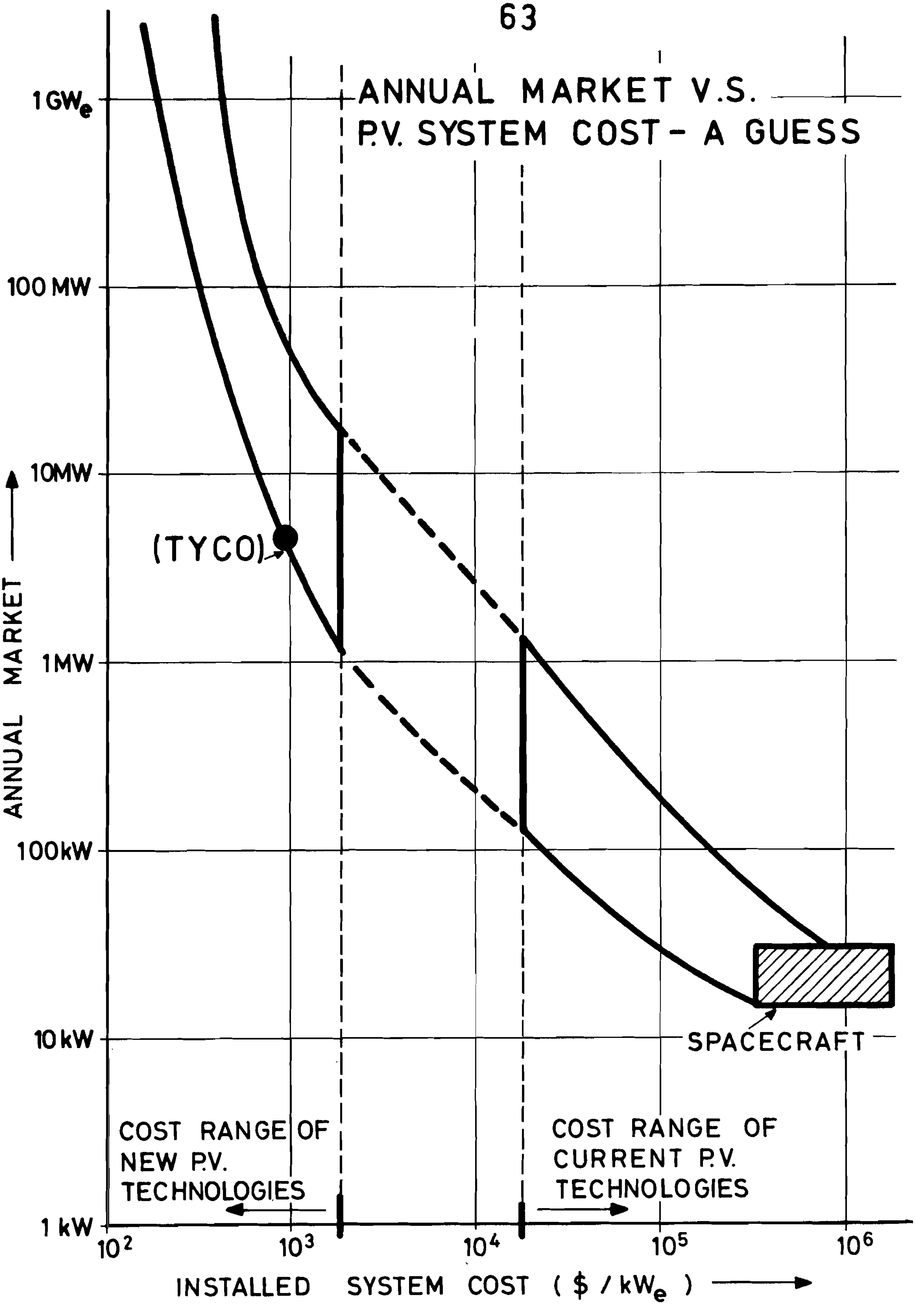
TWO PROJECTIONS - U.S. SILICON AND PHOTOVOLTAIC SILICON PRODUCTION, 1975 - 2000



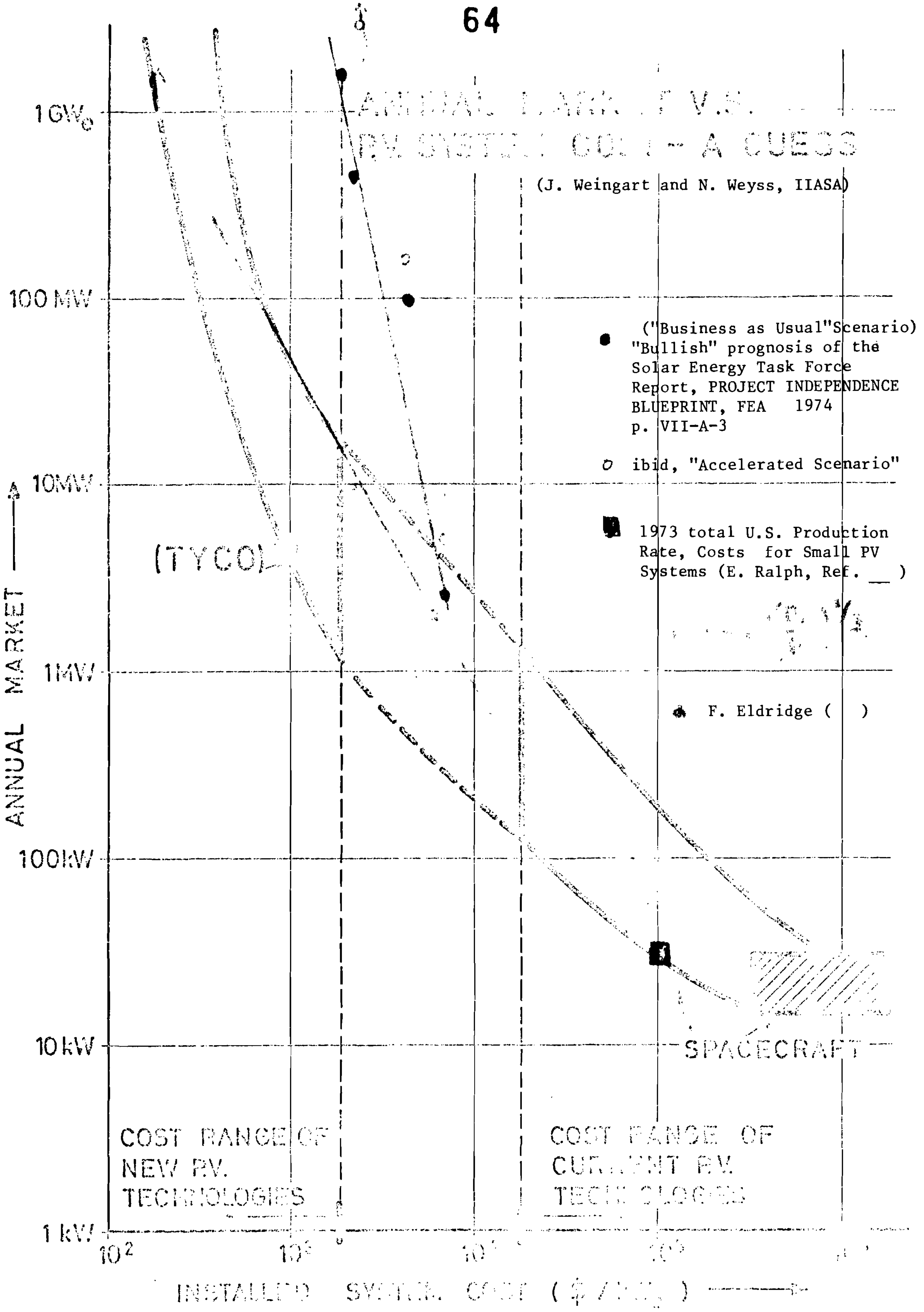
ACCUMULATED PEAK POWER [MWe]



VARIOUS FORECASTS OF ACCUMULATED PEAK POWER GENERATION IN THE U.S. BY PHOTOVOLTAIC CONVERSION



ANNUAL MARKET V.S. P.V. SYSTEM COST - A GUESS


ANNUAL MARKET OF U.S. PV SYSTEM COST - A GUESS
(J. Weingart and N. Weyss, IIASA)
("Business as Usual"Scenario) "Bullish" prognosis of the Solar Energy Task Force Report, PROJECT INDEPENDENCE BLUEPRINT, FEA 1974 p. VII-A-3
ibid, "Accelerated Scenario"
1973 total U.S. Production Rate, Costs for Small PV Systems (E. Ralph, Ref. __)
F. Eldridge ( )
(TYCO)
SPACECRAFT
COST RANGE OF NEW PV. TECHNOLOGIES
COST RANGE OF CURRENT PV. TECHNOLOGIES
1 GWe
100 MW
10MW
1MW
100kW
10 kW
1 kW
ANNUAL MARKET
10^2
10^3
10^4
10^5
INSTALLED SYSTEM COST ($/kWe)

Annual Market Vs. Systems Costs (Photovoltaic) *

Total Average Power Capacity of PEPS per Year (MWe)			Costs of PEPS SYSTEMS (1974 $ per kWe average)
Scenario 1	Scenario 2	Scenario 3, Weingart/Weyss	
3	6	.3 - 5	$ 7500
100	200	.5 - 7	$ 4500
500	4,000	1 - 12	$ 2500
2500 to 10,000	25,000 to 50,000	1 - 15	$ 2000

Scenario 1 is the FEA "Business As Usual" Scenario. *
Scenario 2 is the FEA "Accelerated Schedule" Scenario*
Scenario 3 is the Weingart/Weyss (   ) questimate of market vs. costs for photovoltaic solar energy conversion systems.

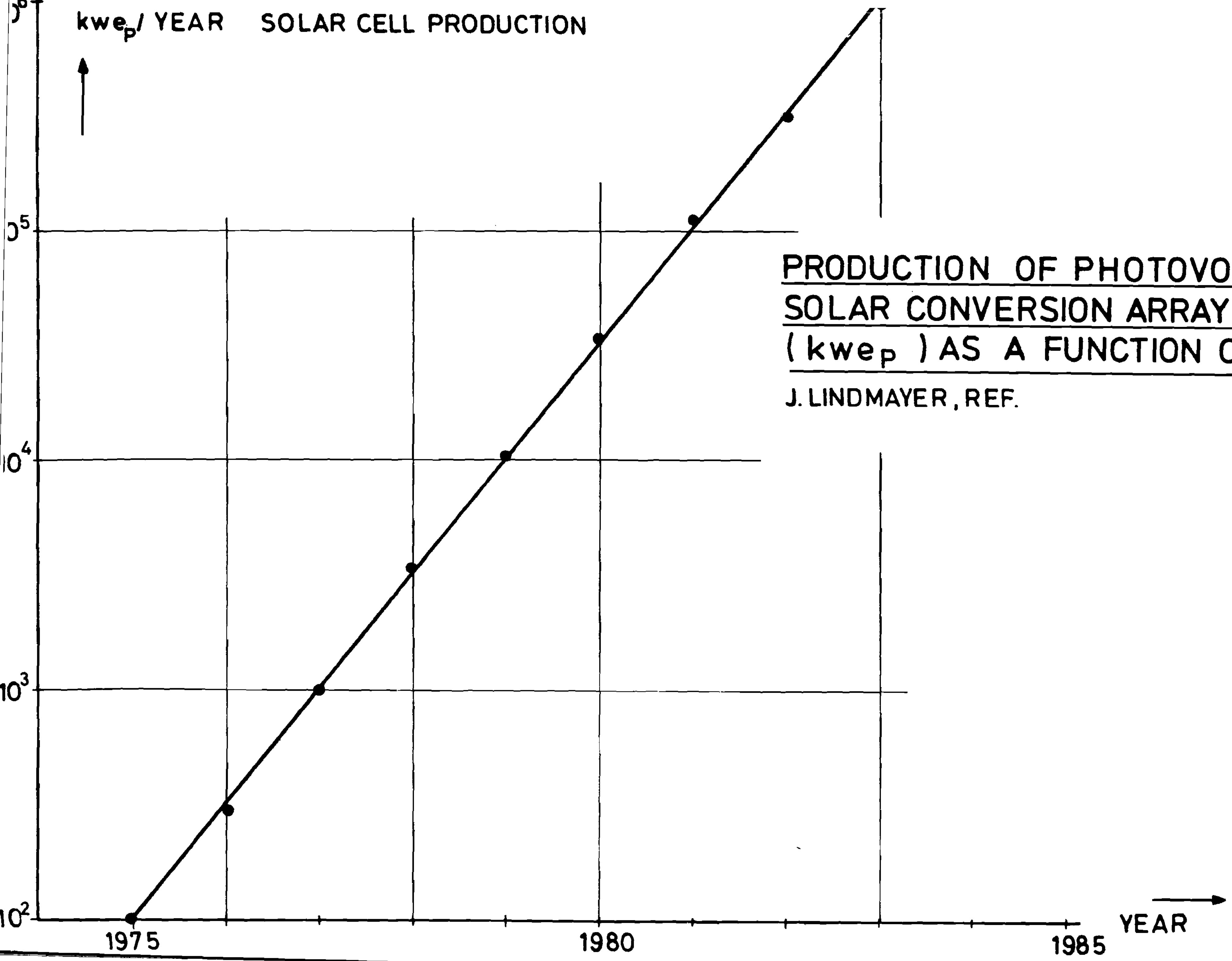
* Federal Energy Administration, PROJECT INDEPENDENCE BLUEPRINT, Solar Energy Final Task Force Report, November, 1974   Page VII-A-3,4

INVESTMENT-PRODUCTION TABLE FOR PRODUCTION
OF PHOTOVOLTAIC CONVERSION ARRAYS (,Lindmayer)

YEAR	AMOUNT INVESTED	PRODUCTION	Kwe_p/year *
1975	0.5 to 1.0 x 10^6	P	100
1976	1.0 million	3.2P	300
1977	1.0 "	"	1,000
1978	2.0 "	"	3,400
1979	4.0 "	"	10,500
1980	6.0 "	"	34,000
1981	11.0 "	"	107,000
1982	19.0 "	"	320,000
1983	42.0 "	"	1,000,000
1984		"	3,500,000
	Total $ 88 million	Cumulative	4,976,300

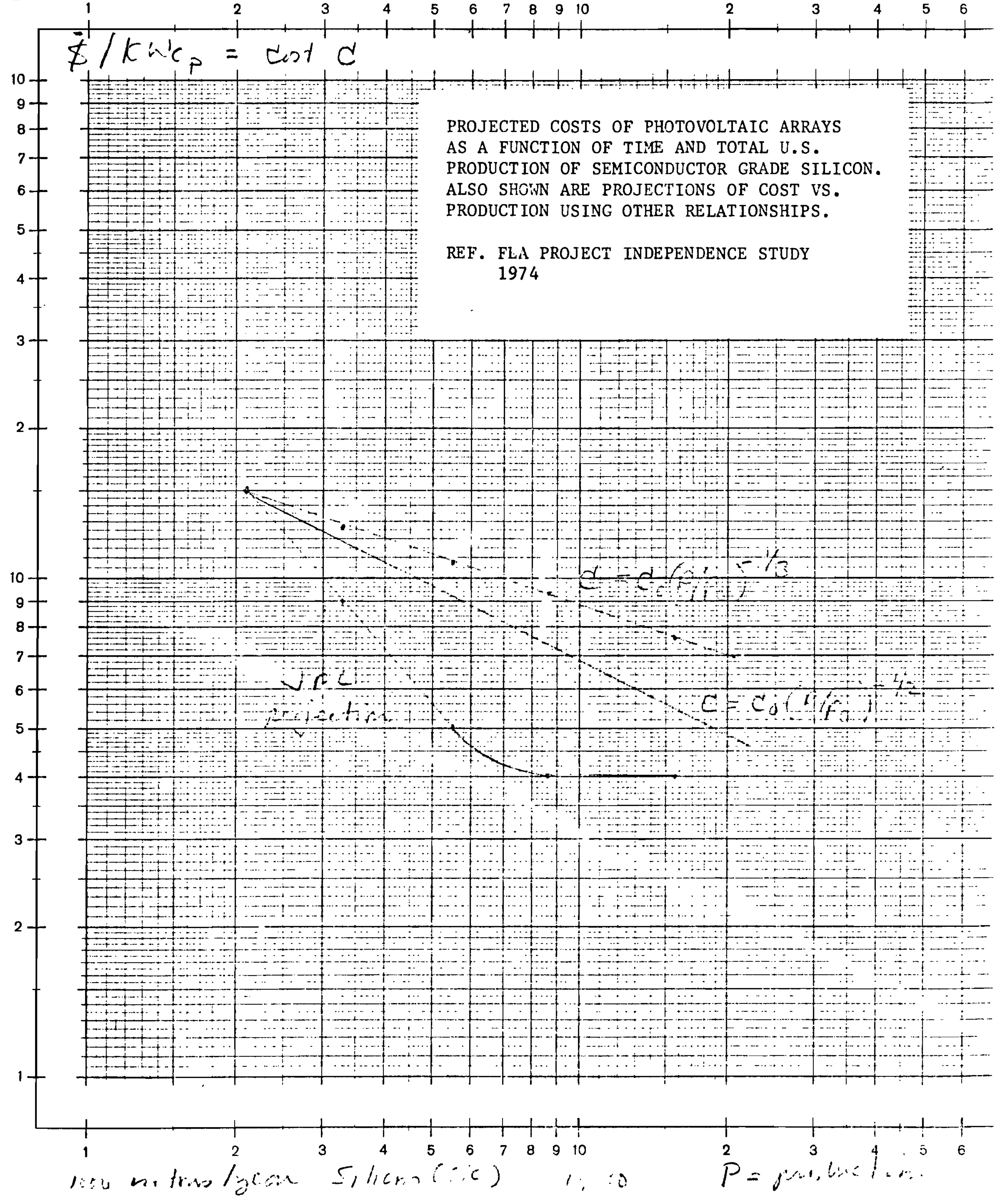
Table ____

* Peak kilowatt electric production under conditions of AM1 Insolation



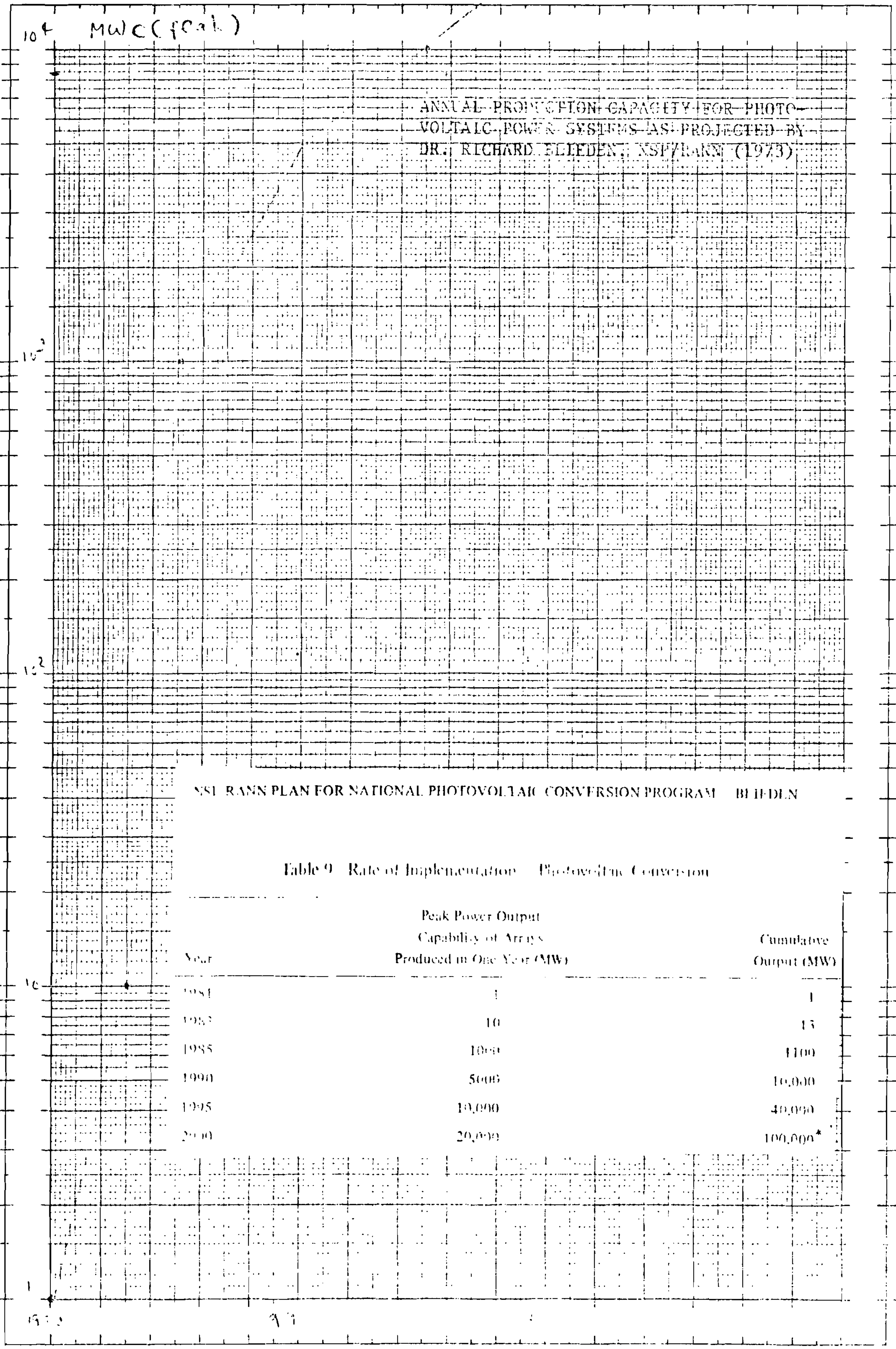
PRODUCTION OF PHOTOVOLTAIC SOLAR CONVERSION ARRAYS (kwe$_p$) AS A FUNCTION OF TIME

J. LINDMAYER, REF.



PROJECTED COSTS OF PHOTOVOLTAIC ARRAYS AS A FUNCTION OF TIME AND TOTAL U.S. PRODUCTION OF SEMICONDUCTOR GRADE SILICON. ALSO SHOWN ARE PROJECTIONS OF COST VS. PRODUCTION USING OTHER RELATIONSHIPS.

REF. FEA PROJECT INDEPENDENCE STUDY
1974



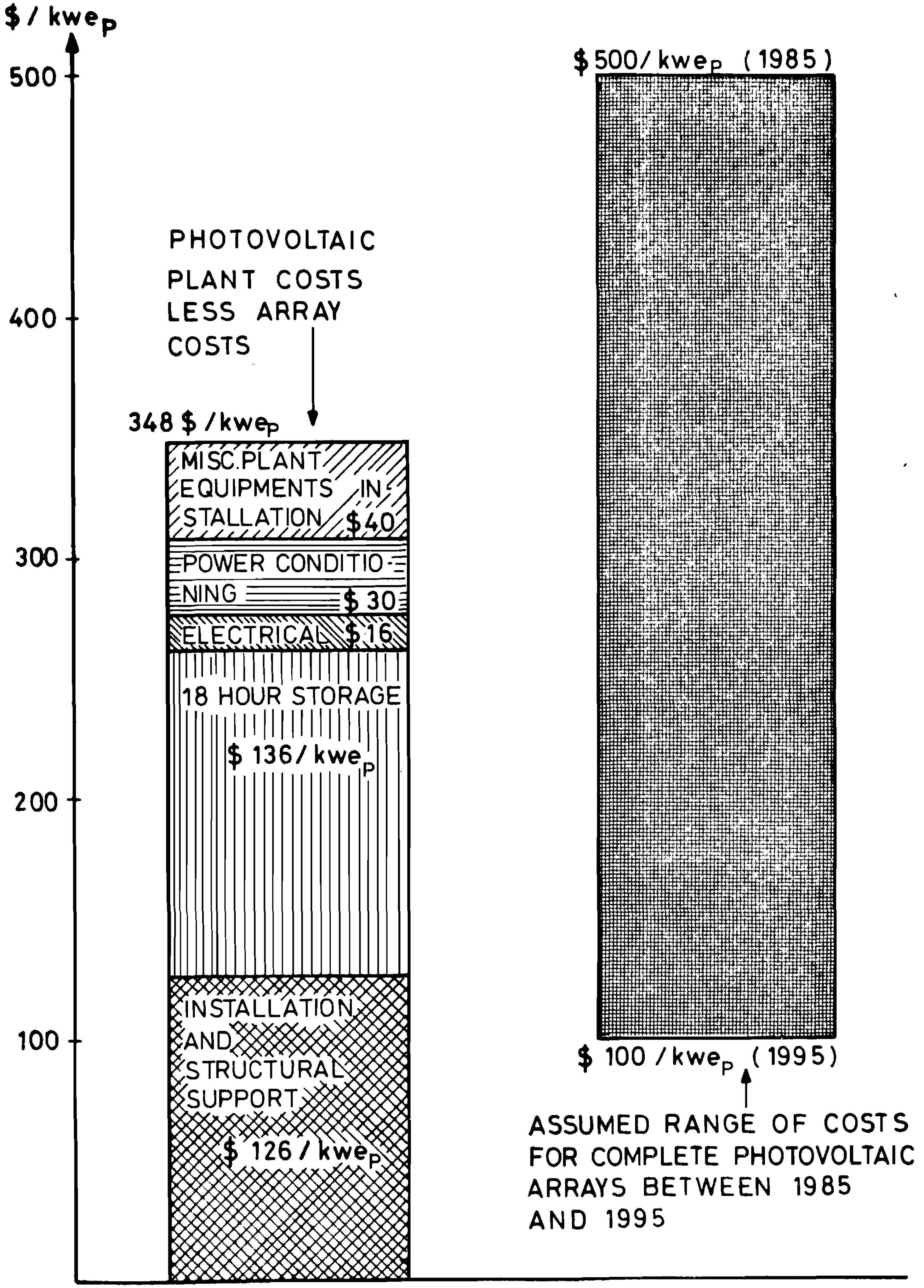
ANNUAL PRODUCTION CAPACITY FOR PHOTO-VOLTAIC POWER SYSTEMS AS PROJECTED BY DR. RICHARD BLIEDEN, NSF/RANN (1973)

NSF RANN PLAN FOR NATIONAL PHOTOVOLTAIC CONVERSION PROGRAM — BLIEDEN

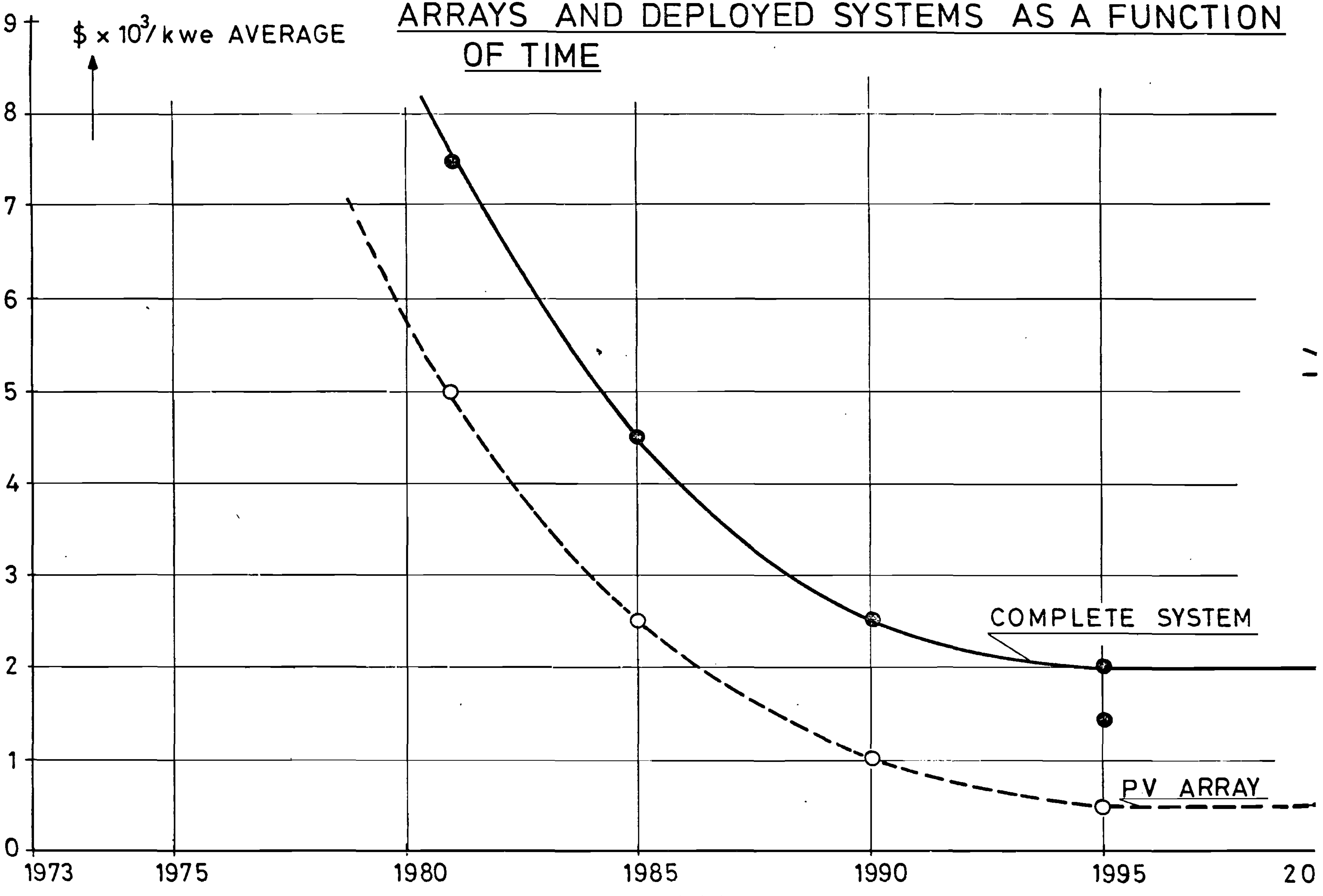
Table 9 Rate of Implementation — Photovoltaic Conversion

Year	Peak Power Output Capability of Arrays Produced in One Year (MW)	Cumulative Output (MW)
1981	1	1
1983	10	13
1985	1000	1100
1990	5000	10,000
1995	10,000	40,000
2000	20,000	100,000*

ESTIMATED $/kwe$_p$ PHOTOVOLTAIC POWER SYSTEM COSTS FOR U.S. RESIDENTIAL APPLICATION



VARIOUS ESTIMATES FOR THE COST OF PHOTOVOLTAIC ARRAYS AND DEPLOYED SYSTEMS AS A FUNCTION OF TIME



Land and Materials Considerations

By the year 2000 the LDC's will have a population of roughly six billion people ( ). Suppose that the ultimate goal is to provide energy in the form of synthetic fuels (perhaps hydrogen) and electricity. Suppose further that human settlements which function well and which provide more than the basic human necessities of decent nutrition, health and shelter can operate on a total of 3 kw (1.5 kw fuel + 1.5 kw electricity).

If photovoltaics were to provide half of this electical energy demand, the area required would be quite large. Suppose, in an extreme case, that on the average 20 percent of the incoming solar radiation in the LDC's could be converted and delivered in the form of electrical energy, and that the annualized average daily insolation is 5 kwh/m^2-day.

On the average, the area dedicated per capita would be 24 m^2 and the entire aggregate area would be:

$$6 \times 10^9 \text{ people} \times 24 \text{ m/person} = 144{,}000 \text{ km}^2.$$

Perhpas as much as one third of this could be provided through rooftops in low-rise settlements. The remaining 96,000 km^2 (slightly larger in area than Austria) could in principle be provided through ground based and floating arrays.

The total power could be, on the average:

$$P = 9 \text{ TWe}.$$

or 20 times the entire installed peak generating capacity of the United States in 1975.

If the growth of electrical power generation systems were to increase over the next four decades at the previous rate (over the past three decades) of 7 to 8 percent per year (doubling time of one decade), it would take four decades to achieve this. To achieve something of comparable scale in the developing countries would take, in an optomistic view, at least a century.

If the installed cost of such systems turned out to be only $ 500/kwe (1975 dollars) the total cost of 9 TWe would be:

$ 4.5 trillion dollars.

Hence, if something on the order of one percent of the global GNP were invested in such systems (assuming the extreme case of low cost and high conversion efficiency) each year, the job could be done in a century and presumably could be done in three to four decades if the rate of expenditure were 3 percent per year. In the more likely case of a net conversion efficiency of ten percent and a system cost (installed) of $ 1000 per kwe, it would require 12 percent of world GNP per year for 30 to 40 years or 3 percent per year for a century.

In the event that such systems could be built with an average density of support materials (steel and concrete) of perhaps 10 kg per square meter, the total materials requirements, excluding silicon, would be:

1.44 billion metric tons (steel and concrete).

If everything were steel, this would amount to approximately 5 percent of projected USA steel production over the coming hundred years and perhaps a percent or two of total world production. Silicon requirements would be at 5 kg per square meter:

.18 billion metric tons(silicon) (.010" thick silicon).

This would require, on the average, an annual production rate of 7.2 million metric tonns of silicon solar convertors. Since total world production of semiconductor grade silicon is roughly a few thousand metric tons per year today, a ten-fold expansion in production would be required and would have to operate over a century to meet these goals.

Country	Land Area (km^2)	Population (1974)	Population (2000)	Total Area Required for PV Conversion	Fraction of total land area

Cell	Element	U.S. Production$^{(1)}$	World Production$^{(1)}$	U.S. Reserves$^{(1)}$	World Reserves$^{(1)}$	Cost $/Kgm	% Purity	MT/MW
Single Crystal Si	Si	750. (1973)$^{(3)}$ 1250 (1974)$^{(3)}$		(2)	(2)	60.	.2PPB	11.5$^{(11)}$
Cds/Cu$_2$S	Cd	3.0 x 10^3 (4)	17.1 x $10^{3(4)}$	205. x $10^{3(4)}$	850. x $10^{3(4)}$	7.$^{([illegible])}$ 20.$^{(13)}$	99.7 *	5.0$^{(12)}$
	Cu	1.83 x $10^{6(6)}$	8.05 x $10^{6(6)}$	91. x $10^{6(6)}$	407. x $10^{6(6)}$	1.50$^{(6)}$	(7)	
Thin Film Si	S Si	ibid						0.14$^{(14)}$
GaAs	Ga	0.3$^{(5(}$	1.0$^{(5)}$	2.7 x $10^{3(8)}$	110. x $10^{3(8)}$	600.$^{(8)}$	10PPB	2.3$^{(12)}$
	As	19. x $10^{3(9)}$	52. x $10^{3(9)}$	1.43 x $10^{6(5)}$	19.4 x $10^{6(5)}$	0.14$^{(9)}$		1 4$^{(12)}$
CdTe	Cd	ibid						2.8$^{(12)}$
	Te	1. x $10^{2(10)}$	1.92 x $10^{2(10)}$	7.5 x $10^{3(10)}$	34. x $10^{3(10)}$	15.40$^{(10)}$		2.4$^{(15)}$
CuIn Se$_2$	Cu	ibid						0.7$^{(15)}$
	In			5.3 x $10^{2(9)}$	31.8 x $10^{2(9)}$	225.$^{(9)}$		
	Se	3.4 x $10^{2(10)}$	1.02 x $10^{3(10)}$	24.5 x $10^{3(10)}$	10.9 x $10^{4(10)}$	30.$^{(13)}$		

(1) All weights are metric tons (1,000 kgm).
(2) Essentially unlimited.
(3) Chemistry and Engineering News, July 23, 1973
(4) Private communication from Mr. D. Hague, Bureau of Mines, Division of Non-Ferrous Metals, U.S. Department of the Interior.
(5) U. S. Mineral Resources, Geological Survey Professional Paper 820, 1973, Department of Interior
(6) Private Communication from Mr. Schroeder, ibid
(7) By electrolysis.
(8) Private communication from Mr. E. Chin ibid.
(9) Private communication from Ms. G Greenspoon ibid.
(10) Private communication for Mr. L. Moore, ibid.
(11) 200. x 10^{-4} cm thick and 20% efficiency.
(12) 20 x 10^{-4} cm thick and 7% efficiency.
(13) Wald et al, NSF Conference, Cherry Hill, New Jersey
(14) 10^{-4} cm thick.
(15) 10 x 10^{-4} cm thick.

* Semiconductor Grade

TABLE 4 - MATERIAL CANDIDATES AVAILABILITY

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A PRELIMINARY SURVEY OF EXPERIMENTAL AND COMMERCIAL TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION

INTRODUCTION

Since the invention of the silicon solar cell in 1955, there have been perhaps a hundred individual terrestrial applications of photovoltaic solar energy conversion systems, ranging from scientific experiments to commercial use by industry and government. Installations from a few watts to over a kilowatt peak power have been made in Africa, South America, Mexico, the United States, Canada, Europe, Japan and Southeast Asia, and the Middle East. These have provided power for lighthouse navigational and warning lights, radio, microwave and television relay stations, aids to navigation on off-shore oil platforms, weather monitoring stations, remote educational television sets, highway emergency call boxes, aircraft warning lights at airports, and remote communications stations for forest management. The present annual commercial market for photovoltaic arrays is perhaps 10 kwe(peak), divided roughly equally among Japanese, American and European (French, British and W. German) manufacturers.

A limited literature survey was made to develop a preliminary sketch of the pattern of previous and current terrestrial applications of photovoltaic conversion systems. Using the results of this survey, a follow-up survey employing telex, mail and telephone communications has been initiated to obtain detailed written and graphic information about various installations and available products.

In addition to reporting on applications in operation or being planned, a recent report ( ) by Spectrolab, Inc. to the NASA/Lewis Research Center, examining near-term potential markets, was also reviewed Some of the systems proposed in this report may be of special interest in LDC's. A specific example is a proposed photovoltaic-powered system for irrigation and provision of potable water (through the incorporation of a solar powered ultraviolet water purification device) for a small community.

The results of this survey are presented in Appendix A1 in a set of tables and in a set of more detailed single page descriptions of various example systems. The latter have been useful in defining further information needed to provide a fairly comprehensive description of a specific system. Finally, several specific systems, including the solar powered remote educational television system under development in Nigeria and the Spectrolab proposed solar-powered water irrigation, storage and potable water supply-system, are discussed in some detail.

This section of the report will be updated, expanded and refined as information from various sources (users, manufacturers and others) is received.

TERRESTRIAL APLICATIONS OF PHOTOVOLTAIC SYSTEMS

The categories of application of photovoltaic systems for terrestrial use include scientific tests and demonstrations, quasicommercial or prototype commercial applications, fully commercial applications, and (for the future), potential photovoltaic system market areas.

Experimental or demonstration uses of solar cells began in 1955 when Bell Laboratories and the Bell Telephone Company installed a solar-powered rural telephone carrier system ( ) in Americus, Georgia. The system was operated for about six months, as a technical demonstration and publicity effort. In 1973, combined photovoltaic (CdS) and thermal collectors were integrated into a laboratory/house at the University of Delware ( ) to explore the nature of residential solar electric/thermal systems connected to a local electric utility grid. At the California Institute of Technology, scientists ( ) from the Geology Department are using surplus spacecraft solar panels (from Ranger and Mariner spacecraft), suitably modified for protection against weather, to power remote scientific geological stations in California and Mexico, and the Mitre Corporation (Mclean, Virginia) is developing a one kilowatt solar electric/hydrogen system ( ) to demonstrate the combined use of solar generated electricity and electrolytic hydrogen as the secondary energy carrier. All of these applications have been largely scientific in nature, without attempting to explore near term markets for photovoltaic applications although the work at the University of Delaware will eventually lead to an evaluation of combined photovoltaic/thermal solar collectors for building applications

Other experimental systems have been installed in the Chilean Desert as a joint University of Chile/RTC (France) project, in Iran (at Pahlavi University in Shiraz), France, Africa, the Soviet Union, India, Japan, Britain and Germany.

Quasicommercial or commercial prototype systems are those in which the initial installation was made in order to determine the operating economics of the solar system and to make a comparison with other available energy systems. Such applications have generally been made in situations where there has been a need for remote power in the one to one hundred watt range and where replacement of batteries, transportation of fuel or remote power lines were very expensive. Such applications include remote radio beacons, radio, television and microwave booster and repeater stations, warning and navigational lighting on offshore oil platforms, and so forth. A number of installations made on a prototype basis have led to continued commercial installations based on successful operation of the prototype.

Examples include the first remote solar cell application in Japan, to provide power for a 150 MHz VHF repeater station on Mt. Shinobu ( ) and installations by the California Dept. of Forestry of Motorola solar cell powered telecommunications equipment in the late 1960's. In both cases, there have been later commercial installations resulting from economic and technical success of the initial installations.

Commercial (marketplace) Installations

In 1961, Kobayashi ( ) reported that is was more economic, on a life-cycle cost basis, to provide remote power at levels up to fifty watts by a solar cell/storage battery combination costing $ 130/peak watt than to run a power line 1 km. (Figure). Today Spectrolab, Inc. has sold over a hundred systems ( ) for remote power for navigational and warning lights on off-shore oil rigs in the United States; several states in the USA including California, Nevada and Oregon are purchasing photovoltaic power systems for remote radio repeater stations and other similar applications; sailboat owners are purchasing solar arrays to keep batteries charged during long voyages and the French are providing solar television sets in Nigeria ( ) for educational television for the populace. Small solar-powered radio were marketed by Motorola in the early 60's and, at the extreme end of the luxury market, a German company has recently introduced a solar powered (trickle charged battery) electronic cigarette lighter for several hundred dollars! As mentioned earlier, the total world market for diverse commercial and spacecraft applications is roughly 50 kwe(peak) per year and, at present prices for photovoltaic arrays, expected to grow to perhaps three times that within three years ( ).

Commercial systems are considered by us as those which are produced as a regular product line by a company, and commercial applications, in our terms, are those in which such products have been purchased by some organization because the solar option was the most economical on an annualized cost basis. The current commercial market for terrestrial photovoltaic systems could be characterized as one in which some combination of high reliability, low or no maintanence, zero fuel requirements, and noiseless operation, at power levels below one kwe (peak), justify, on an economic basis, the use of photovoltaic systems.

These "advantages" of photovoltaic systems can certainly be compensated by transportation (horseback, foot, jeep, helicopter, etc.)for fueling and maintanence purposes to remote locations and batteries can be purchased and installed each year. Power lines can be laid and noise insulation installed. Each of these has some specific cost for a given application and a geographic location. Hence, the characteristics of PV systems translate directly into economic advantages. (An economist would say that in these cases the market is operating normally).

Commercial systems (discussed in section , are available from four manufacturers in the USA, two in Japan, and one each in Germany, France and England. Manufacturers will provide either individual silicon solar cell modules, appropriately encapsulated in rugged supports, or complete systems including batteries and power conditioning equipment. All of the present commercial applications use arrays fabricated by one of these 9 manufacturers.

Commercial Applications - Examples

The National Aeronautics and Space Administration (NASA) Lewis Research Center and the National Oceanic and Atmospheric Administration (NOAA) are cooperating on a project ( ) to design, fabricate and install a number of solar power systems for remote atmospheric monitoring stations. Two installations, one in Virginia (Sterling) and one in California (Mammoth Mountain) were made in 1973 and further installations are expected. As a precommercial application, solar arrays have been fabricated by NASA/Lewis using solar cells purchased from a domestic supplier( ). The solar arrays are made up of modules each containing 48 (six by eight) circular silicon solar cells. (3 watts AM1). The total array at each installation contains 20 modules, for a peak power of 60 watts. The arrays are encapsulated in FEP sheets.

In 1973 the Tidelands Signal Corporation of Houston, Texas fabricated a complete aid-to-navigation warning light system, including silicon solar arrays fabricated by Solar Power Corporation (Massachusetts) and installed the system on an offshore oil platform in the Texas Gulf Coast.

The lighting system on the referenced oil platform consists of one 2-mile fog signal and four 5-mile lamps. Energy consumption is about 25 am-hour/day x 12 volts = 300 whe/day. Previously this lighting system was powered by 40 1.2 volt. 3300 amp-hr primary batteries. The total weight was 2,000 lbs and these were replaced annually. The solar generator system incorporates 80 photovoltaic modules (1.5 watts peak under AM1 illumination, 25 deg.C) into an array with overall dimensions 4 x 5 feet (1.22 x 1.52 m). The reference implies a retail cost of roughly $ 20/peak watt and indicates that at such prices for a terrestrial array (sealed, ready to install), such arrays begin to compete with primary and secondary batteries in markets traditionnally served by this hardware. The ref. claims that "solar cell/secondary battery systems clearly compete on an economic basis with heavy duty primary batteries" (presumably on a life-cycle cost basis, although the specific numerical details are not discussed).

Solar Powered Educational Television Sets in Nigeria

Because this particular example is one of the very few documented applications to have actually been made in an LDC environment, I have translated a portion of the paper by ( ) into English. The synopsis follows:

- The Educational Television System of Nigeria (TVSN - Télévision Scolaire du Niger) was created in 1966 in order to upgrade the inadequate level of primary education in the country. Since 1966, some 800 students in 22 classes have received instruction via television broadcast from the production center in Naimey (through use of solar powered television). As a result of the encouraging results of this experiment, the Nigerian government has decided to put in place, progressively, a network of (solar powered) television sets which, within ten years, would reach eighty percent of the population with educational programs.

The programs of the Nigerian educational television system are primarily intended for schools located in regions without electricity. Reception is assured through the design of television sets especially constructed to operate in very cold and very hot climates. These sets are transitorized, designed for a wavelength of 61 cm, and are designed to operate on a continuous source of electricity at 34 volts plus or minus fifteen percent. Their consumption is 35 watts. Currently these sets are powered by batteries with a life of about 2,000 hours.

This solution, the most widely used in actual practise, is quite costly. An hour of television costs roughly 1.38 francs. In order to develop a more economical source of energy, the technical services of TVSN and the Office of Solar Energy (NIAMEY) installed, in 1968, an experimental solar panel to power the television of a school near Niamey.

This experiment demonstrated that it is practical to provide solar powered television in NIAMEY during the entire school year (October to June).

An applications study has been carried out by the Engineering Service of the ORTF and six new installations have been made in 1972.

Considerations for Deployment of Photovoltaic Systems in LDC's

The attractiveness of a photovoltaic system application in an LDC will depend on the economic significance of that application to those who have to pay for and maintain it. In some cases this may be some agency of the government, or an international agency (AID, UNEP, World Bank, etc.); in others it will be the local inhabitants themselves. It is the author's conviction that a fairly sophisticated analysis of the value of various energy-related or energy-derived (specifically electrical energy) services in various cultural and geographic environments is required before a useful assessment of the potential market for solar power systems can be made, (unless the cost of these systems drops to the point it is the cheapest alternative available for large scale power generation). The nature and size of various LDC markets will depend, of course, on the delivered cost of the PV systems as well as on the value of electrically-derived services. Part of the required analysis would be an eeconomic assessment of the value associated with the following features of PV systems:

1) High reliability,
2) Low maintenance requirements,
3) Zero fuel requirements,
4) Intermittant output without storage, continuous with storage,
5) Modularity (when one piece of the system goes out, the rest can continue to function; not true with generators)

Reliability

Photovoltaic arrays have no moving parts and the basic physical mechanism which accounts for the photovoltaic property has a lifetime measured in thousands of years for silicon. (I.e., it is basically related to the rate at which impurity atoms, which form the pn junction, diffuse through the lattice, degrading the junction). Techniques have been developed to encapsulate silicon solar cells in a clear silicone material which provides excellent shock isolation and protection from environmental effects.

Such reliability may be of crucial importance if such systems, when they appear economically attractive, are to be diffused rapidly and widely. People are slow to put total reliance on innovations until a long period of test and experience has gone by. (   )

Low maintenance requirements

This is not the same as high reliability, although the two are sometimes confused. An automobile engine is a highly reliable device, providing a specific level of maintenance is sustained. The relationship between maintenance schedules (and costs) and the reliability of various types of machinary is generally well known in industrialized countries. In the case of suitably designed solar cell arrays, the level of maintenance required to provide very high reliability (on the order of one failure per ten years of operation) is probably low and inexpensive. It primarily involves protection of the transparent surfaces from extreme abrason and periodic cleaning of both the surface and perhaps the electrical connections. The author expects that modules could be developed for which maintenance would consist only of occasional cleaning at most. A number of photovoltaic systems have operated for close to a decade with NO cleaning and with NO OBSERVABLE DEGRADATION in relatively dirty industrial atmospheres (the Cleveland airport, for example).

Low maintenance requirements means little labor required for upkeep (although labor is generally cheap in the LDC's). The fact that unsophisticated maintenance procedures, requiring minimal equipment (perhaps soap, water and a rag) can be used means no supportive infrastructure for maintenance and repair, no specialized training of maintenance personnel, no special tools, etc. (Compare this with the minimum tools, training and access to spare parts required for the simplest internal combustion engine/generator combination).

Zero Fuel Requirements

This may have special significance in some LDC's. This aspect of PV systems means that the users are insulated from variations in the price and availability of fuels. The local delivered price of fuel could include local costs not normally included in such calculations, such as graft and corruption by those controlling the distribution infrastructure. (More about these cultural issues later). With sufficient electrical storage, the PV systems could then be more reliable than many other alternatives, in which transportation of fuel may be uncertain.

Modularity

The modular nature of PV systems permits the users to gain experience with a relatively small investment. This is a crucial aspect of rapid diffusion of an innovation (Rogers). When large investments in innovations are required, they may never be adapted due to the lack of opportunity to "test them out" at an acceptable level of financial risk. Systems can grow as the affluence of the local community grows, and system elements could be designed to permit the development of local "grids" as neighboring systems grow and eventually become contiguous. Loads can grow with supply, meaning essentially full amortivation of the investment. Finally, a modular power system means that one or a few PV elements can fail and the system can continue to operate. Replacements can be obtained at the most convenient and least expensive time (such as when a government team makes its annual visit or some such occasion).

REFERENCES - Terrestrial Applications of Photovoltaic Solar Energy Conversion Systems

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A7 G. Pearson, "Applications of Photovoltaic Cells in Communications", Proceedings of the Conference NEW SOURCES OF ENERGY, Vol. IV, P. 236. August, 1961, United Nations.

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A9 J. Ravin, "Study Terrestrial Applications of Solar Cell Powered Systems", Report prepared for the NASA Lewis Research Center under Contract NAS 3-16828. NASA Report number NAS-CR-134512. September, 1973.

A10 R. Yasui, Jet Propulsion Laboratory, Caltech (Private communication)

A11

A12 E. Costoque & H. Vivian, "Solar Energy Rechargeable Power System", internal document, Caltech Jet Propulsion Laboratory, June 15, 1969. JPL Document No. 650-81.

Attachment A1

SUMMARY OF TERRESTRIAL APPLICATION OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION

SUMMARY DESCRIPTION OF SOME SELECTED EXAMPLES OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS (1955 to 1975)

DATE INSTALLED (REMOVED)	LOCATION	APPLICATION	ARRAY DESCRIPTION	OTHER SYSTEM COMPONENTS	COSTS	REFERENCE
1955 (1956)	Americus, Ga. (USA)	Power for rural telephone carrier system	22 VDC, 10 W, Silicon (Bell Labs)	22 VDC, 15 AH Ni-Cd battery	(N/A)	A7
1961	Chilean desert	Experimental small remote power system	3.3 VDC, 27 A, 89 W, Si (RTC France)			A4
1959-1960	JAPAN (Eight locations)	10 W or 25W Westinghouse lighthouse warning lights	12 VDC, 12 W Silicon, sealed in acrylic res.	Ni-Cd batteries	$ 130/watt for complete system	A6
1958-1960	JAPAN (six locations)	VHF radio repeater stations (remote)	12V, 60V, or 130 V, 3 to 70 Watts, Silicon		$ 130/watt for complete system	A6
1968 (1971)	St. Girons, Bordeaux (FRANCE)	Remote radio beacon (aerial navigation)	50 W, 24 V Si (RTC)			A4
1971	FRANCE (Paris?)	12 W radio relay station at the French Nat'l Center for the Study of Telecommunications	Si, RTC type BPX-70 modules			A4
1972	Lake Erie, Ohio (USA)	Cleveland Coast Guard Station (tele communications)	Si with FEP covers. 1.0 W modules (NASA/ Lewis Research Center)		$ 15/watt (cells) $ 40/watt (system)	A1
1973	Newark, Delaware (USA)	Experimental solar powered/heated lab ("Solar One")	CdS experiment. cells	(complex, see data sheet)		A11

SUMMARY DESCRIPTION OF SELECTED EXAMPLES: PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS FOR TERRESTRIAL APPLICATIONS

DATE INSTALLED (REMOVED)	location	APPLICATION	ARRAY DESCRIPTION	OTHER SYSTEM COMPONENTS	COSTS	REFERENCE(S)
1973	SAUDI ARABIA	Power for seven aircraft warning lights at airport (Médine airport)	Silicon(BPX 47) solar arrays (RTC France)			A4
1973	FRANCE?	Maritime navigational aid light	" "			A4 A2
1970's	SOUTH AMERICA	Television signal booster stations	eight 12 W modules			A4 A2
1970's	USA Elsewhere?	Lighting for warning and navigation on approx. 100 oil rigs in Gulf of Mexico	Spectrolab 12W 12V, 6 W Si array, sealed in clear silicone			88 A2
???	INDIA	Remote power for villages	Centralab Si sealed arrays	??	??	A8 A2
1973 ?	TEXAS GULF COAST(USA)	Aids to Navigation Equipment(lights?) on Offshore Oil Platform	Solar Power Corp. Si cell modules , 120W peak power	Batteries,lights power condit.	$ 20/watt(P)	A5
1972	NIGERIA	Remote television for education, 6 systems operational	RTC France, BPX-47 Si modules (8 watts)	Battery,TV, diode, antenna	$ 100/watt(P) for array	A4

NOTE: Reference A4 is primarily a journalistic account and mentions some examples, such as the Indian village power systems, essentially as hearsay. This example is being included until the source of the quote mentioning it provides more details or disavows it. (Letter sent to source of quote).

SUMMARY DESCRIPTION OF SELECTED EXAMPLES: PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS FOR TERRESTRIAL APPLICATIONS

DATE INSTALLED (REMOVED)	LOCATION	APPLICATION	ARRAY DESCRIPTION	OTHER SYSTEM COMPONENTS	COSTS	REFERENCES
1970's ? Current	California, USA	40 station, radio repeater network	silicon, 10 W	battery, power conditioning	$ 1200 for 40 W complete system from Solarex	A4
1966	JAPAN	Lighthouse, lights for navigation and warning	silicon, 1156 watts			A12
[illegible] 1966 (?)	Fairbanks, Alaska (USA)	Remote telecommunications (environmental data station)	silicon, 7 W	13.6 V battery, 18 watt transmitter		A12
1968	California (USA) mountains	Remote communications equipment	silicon, 4 W	Ni-Cd battery		A12

Attachment A2

DETAILED DATA SHEETS FOR INDIVIDUAL PHOTOVOLTAIC SOLAR ENERGY CONVERSION APPLICATIONS

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Solar Water Pump System (Conceptual); Proposed for use in LDC's	
SYSTEM DESCRIPTION	Array Type: Size:229 x 183 cm 12,90 Volts DC(peak)* 90 & 12 3,2.1 Current " 216 Power (watts), 71 Kg Supplier: Cost ($/Kwe$_{peak}$) $ 4600.	<u>Other Components</u> Controller Water level sensor Motor/water pump Water holding tank Water purifier(ultraviolet) 10 gallons/minute from aver. depth of 6 meters average expected flow rate.
LOCATION, DATE OF DEPLOYMENT	Conceptual, proposed for LDC's for irrigation and human water consumption/bathing	
PARTICIPATING ORGANIZATIONS		
COMMENTS	The "storage" is accomplished by storage of water so all available solar energy can be used.	

<u>SYSTEM DESCRIPTION/PERFORMANCE</u> (Taken from Reference indicated below)

"The system consists of an electric motor operating on direct current in conjunction with a solar power supply to drive a pump for irrigation in remote areas and underdeveloped countries. The pumping system is designed to operate where the water table is relatively high. At 10 gallons per minute agerage pumping for 10 hours per day, the system will deliver approximately 0.44 inches (1.11 cm) of water over one-half acre every day. These are the specifications to which the solar water pump system was designed.

<u>REFERENCE</u>

J. Ravin, "Study Terrestrial Applications of Solar Cell Powered Systems"

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	U.S. Forest Service - Remote mountaintop radio Transmitters (in current use)
SYSTEM DESCRIPTION	Array Type: Si Size: 40 watts (Solarex)

Other Components

Lead acid batteries
Charge regulators

______ Volts DC(peak)*
______ Current "
40 Power (watts)
Supplier: Solarex

Cost ($/Kwe$_{peak}$) $ 1200/40 watt(P) system = 30 K/Kwe(P)

LOCATION, DATE OF DEPLOYMENT	current use
PARTICIPATING ORGANIZATIONS	US Forest Service (Dept. of the Interior)
COMMENTS	Details being requested from U.S. Forest Service

SYSTEM DESCRIPTION/PERFORMANCE

Basic system by Solarex includes 40 watt silicon solar cell array, lead acid batteries and charge regulators and sells for $ 1200.

REFERENCE A. Rosenblatt, "Energy Crisis Spurs Development of Photovoltaic Power Sources", Electronics (G.B.), April 4, 1974, p. 99ff

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Demonstration solar cell powered weather station, Operational (1972)
SYSTEM DESCRIPTION	Array Type: Silicon Size: Other Components

_____ Volts DC(peak)*

_____ Current " Each module

1.0 Power (watts)

Supplier: ?

Cost ($/Kwe$_{peak}$) $ 15,000 (cells alone), 40,000/module

LOCATION, DATE OF DEPLOYMENT	Cleveland Coast Guard Station, Lake Erie (Ohio,USA) 1972
PARTICIPATING ORGANIZATIONS	NASA/Lewis Research Center, Cleveland Coast Guard
COMMENTS	Module costs reflect internal labor costs at NASA/ Lewis and therefore do not represent ultimate costs under mass production conditions

SYSTEM DESCRIPTION/PERFORMANCE

Not available in reference, details requested from author of ref.

1 watt modules of silicon solar cells were used. These were protected with .005" FEP (flourinated ethylene propylene) films. Modules were mounted at 45 deg.

Under a variety of conditions, FEP showed no degradation under bright sunlight (7 years in Florida) and little or no effect of dirt accumulation, in two years on top of a building at NASA/Lewis (in a dirty industrial atmosphere environment). The FEP (Teflon) is quite slippery and this, combined with 45 deg. tilt of the arrays, results, according to the ref., in virtually no observable degradation in transmitted light.

REFERENCE A. Forestieri, "Photovoltaic Terrestrial Applications", Procedings of the PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY FOR TERRESTRIAL APPLICATIONS Worksho. October, 1973. National Science Foundation/RANN Report NSF-RA-N-74-013

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	VHF (60 MHz and 150 MHz) repeater stations, remotely operated in Japan. Five systems reported operational in 1961 (Ref. below)
SYSTEM DESCRIPTION	Array Type: Si, in acrylic resin Size:

Other Components

12 - 130 Volts DC(peak)*

______ Current "

2 - 30 Power (watts)

Supplier: Nippon Electric Co.

Cost ($/Kwe$_{peak}$) $ 130/watt(p) for complete system. Solar panel, NiCd batteries, etc.

LOCATION, DATE OF DEPLOYMENT	Mt. Shinobu, 1958/Mt. Mitsuji, 1960/Mt. Noki, 1960/ Matsuamo, Gero and Nakatsugawa, 1960
PARTICIPATING ORGANIZATIONS	Nippon Electric Co., Ltd. /NHK Broadcasting Co., Electric Power Devel. Co. Tohoku Elec. Power Co
COMMENTS	See summary in Fig ___

SYSTEM DESCRIPTION/PERFORMANCE

System information given in the preceding application summary sheet also applies here.

REFERENCE [illegible]. Kobayashi, "Utilization of Silicon Solar Batteries" Proceedings of the Conference NEW SOURCES OF ENERGY [illegible], Volume 4 (Solar Energy: I), August, 1961, United Nations

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Solar powered educational television in Nigeria. First systems operational in 1968 (prototype), regular use in 1972 (six schools)
SYSTEM DESCRIPTION	Array Type: Silicon Size: BPX 47 modules 12 or 24 Volts DC(peak)* ______ Current " 8 Power (watts) Supplier: PTC Cost ($/Kwe$_{peak}$) $ 100,000 Other Components 27 ampere-hour battery (16 battery elements, CIPEL type VL 203) 2 type CI 17 (EMO) transistor television sets TV antenna and cable charge limiter
LOCATION, DATE OF DEPLOYMENT	Kirkissoye school near Niamey,, Jan. 1972
PARTICIPATING ORGANIZATIONS	National Educational Television System of Nigeria, Office of Solar Energy (Niamey), PTC (France)
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

The cost of the delivered and installed photovoltaic array in Niger was 16,500 Fr. This is roughly $ 100 per peak watt. On the basis of a ten year life for the panel (very conservative), the cost of an hour of television is .98 Fr compared with 1.4 for a battery system. The cost does not reflect any amortization charges.
The system includes a solar panel constructed from six BPX modules No. 47, to provide a total peak power of 48 watts; a 27 ampere-hour battery composed of 16 elements, CIPEL Type VL 203(??); a charge limiter, a television antenna and cable, a power cable and two transistorized B&W television sets (type CI 17 by EMO).

REFERENCE

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Solar Powered Buoys (Experiments with prototypes)	
SYSTEM DESCRIPTION	Array Type: Size:	Other Components

______ Volts DC(peak)*
______ Current "   NO INFORMATION GIVEN
______ Power (watts)
Supplier:
Cost ($/Kwe$_{peak}$) $

LOCATION, DATE OF DEPLOYMENT	N/A
PARTICIPATING ORGANIZATIONS	U.S. Coast Guard + ??
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

REFERENCE

Ravin, 'Study Terrestrial Applications of Solar Cell Powered Systems", Heliotek Div. of Textron 1973 (For NASA/Lewis Research Center)

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Various experimental applications of RTC solar cells (Details on following sheets)
SYSTEM DESCRIPTION	Array Type: Other Components Size:

______ Volts DC(peak)*

______ Current "

______ Power (watts)

Supplier:la RTC Radiotechnique-Compléc, 130 Avenue Ledru Rollin
75 Paris 11ème, France

Cost ($/Kwe$_{peak}$) $

LOCATION, DATE OF DEPLOYMENT	
PARTICIPATING ORGANIZATIONS	
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

1960	Powering of an experimental station in Chile
1968	Powering of a radio-beacon (50 w) for the Service Technique de la Navigation Aérienne (St. Girons near Bordeaux)
1971	Powering of a radio repeater station (12 w) as a permanent installation for the National Center for the Study of Telecommunications (France)
1973	Powering of seven warning lights (?) for the airport of Médine in Saudi Arabia
1973	An experimental (réémetteur), 25 w, installed in South America
1973	A maritime navigational warning light, 36 w (France?)
1973	Solar powered television sets in Niger

The basic RTC module is fabricated from silicon solar cells made from circular slices of single crystal silicon. The Module Type BPX 47 contains 64 silicon solar cells, each 4 cm in diameter, mounted in a clear epoxy for protection. The net conversion efficiency under AM1 conditions is ten percent. These modules have a net power output under AM1 conditions of 8 watts at 12 or 24 volts.

REFERENCE B. Dalibot, "Generateurs Solaires Pour Applications Terrestres", Proceedings of the 1973 International Solar Energy Society meeting (Paris), p. 565

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	(First terrestrial application) Primary power source for a Bell type P rural carrier system (telephone). Operated October, 1955 until March, 1956.
SYSTEM DESCRIPTION	Array Type: Size:

Other Components

Ni-Cd battery array, 22 v, 15 amp-hours

22 Volts DC(peak)*

____ Current "

10 Power (watts)

Supplier: Bell Laboratories

Cost ($/Kwe$_{peak}$) $ (not provided)

LOCATION, DATE OF DEPLOYMENT	Americus, Georgia October, 1955
PARTICIPATING ORGANIZATIONS	Bell Laboratories, Bell Telephone Co.
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

(reproduce quote from article)

REFERENCE G. Pearson, "Applications of Photovoltaic Cells in Communications", Proceedings of the UN Conference NEW SOURCES OF ENERGY, P. 239, Vol IV 1961 (United Nations)

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Experimental photovoltaic generator at the Univ. of Chile in cooperation with RTC. 1961 Status unknown
SYSTEM DESCRIPTION	Array Type: Silicon Size:

<u>Other Components</u>

3.3 Volts DC(peak)*

26.5 Current "

87.45 Power (watts)

Supplier: RTC

Cost ($/Kwe$_{peak}$) $ N/A

LOCATION, DATE OF DEPLOYMENT	Chilean desert , 1961
PARTICIPATING ORGANIZATIONS	University of Chile, RTC
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

The system included a photovoltaic array made up of 144 modules, each containing 36 solar cells 1.9 cm in diameter.

REFERENCE B. Dalibot, "Generateurs Solaires Pour Applications Terrestres", Procedings of the International Solar Energy Conference, Paris, 1973 p. 565

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Lighthouse - Power for Remote Warning Lights Eight systems operational in Japan by 1961. Present status no known by author.
SYSTEM DESCRIPTION	Array Type: Si, sealed Size: in acrylic resin (See Fig. ___) Other Components Ni-Cd batteries Protective diodes

12-180 Volts DC(peak)*

______ Current "

12-30 Power (watts)

Supplier:Nippon Electric Co.

Cost ($/Kwe$_{peak}$) $130/watt (peak)including battery, containers, diodes, controls,

LOCATION, DATE OF DEPLOYMENT	Eight systems deployed between Nov. 1958 and Dec., 1960 in Japan (See Table ___)
PARTICIPATING ORGANIZATIONS	Japan Maritime Safety Board, Nippon Electric Co,Ltd. (Japan)
COMMENTS	Battery maintanence required twice per year, no operational problems seen between deployment and August 1961 report (ref. below)

SYSTEM DESCRIPTION/PERFORMANCE

In 1961, the experience of the Japanese in the use of small, remote photovoltaic systems for VHF repearter stations and for lighthouse (unattended) operation was reported. At that time, at total of eight remote lighthouse installations had been made and were operating. The systems included a twelve volt silicon solar cell array sealed in an acrylic resin and mounted in a rugged frame. (Fig. ___). The power (peak, AM1 is assumed in absence of specific statement in ref. ranged from 10 watts to 29.5 watts. The number of individual cells, produced from circular slices of single crystal silicon, ranged from 648 to 1404, with individual submodules containing nine cells each. Actual converson efficiency for the deployed modules was not given. However, the reference indicates that " Lately,.., the efficiency has been raised from 8 percent to 12 percent on the average. The maximum efficiency of 18 percent was obtained in our company". Orientation of the panels was due South, oriented at an angle equal to the latitude. The cost of power lines in remote mountainous regions of Japan in the early 60's is reported to be between five and seven thousand dollars per kilometer. For solar powered systems of 50 watts or less such systems, at 130 dollars/watt installed these systems are less expensive than a one kilometer power line.(Fig.)

REFERENCE M Kobayashi, "Utiliyation of Silicon Solar Batteries", Procedings of the Conference NEW SOURCES OF ENERGY, p. S-11, Volume 4(Solar Energy:I). August, 1961, United Nations

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Solar Cell Powering of Remote Atmospheric Monitoring Observation Stations (RAMOS) for use by NOAA. One system operational October, 73. Others to follow.
SYSTEM DESCRIPTION	Array Type: Silicon with FEP integral covers Size: Other Components
	______ Volts DC(peak)* ______ Current " 60 Power (watts) Supplier: NASA fabricated Cost ($\$/\mathrm{Kwe}_{\mathrm{peak}}$) $
LOCATION, DATE OF DEPLOYMENT	Sterling, Virginia (1973), Mammoth Mountain, Califor. 1973, somewhere in Alaska
PARTICIPATING ORGANIZATIONS	NASA, NOAA
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

A NASA/Lewis project reported on in 1973 is the design, fabrication and construction of a number of solar powered remote stations for atmospheric monitoring. Details have been requested from the author of the ref. below.

Mammoth Mountain facility: Solar array is made up of modules, each containing 48 (6 by 8) circular solar cells. Total array contains 20 modules (3 watts peak AM1 each). Cells are encapsulated in FEP dheets.

A. Rosenblatt, "Energy Crisis Spurs Development of Photo voltaic Power Sources", Electronics (G.B.) April 4, 1974

REFERENCE A. Forestieri, "Photovoltaic Terrestrial Applications", Procedings of the PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY FOR TERRESTRIAL APPLICATIONS Workshop, October, 1973. National Science Foundation/RANN Report NSF-RA-N-74-013

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	VHF Repeater stations (JAPAN) Lighthouses Lightbuoys Wireless telephones
SYSTEM DESCRIPTION	Array Type: Silicon Size: Other Components

_______ Volts DC(peak)*

_______ Current "

_______ Power (watts)

Supplier:

Cost ($/Kwe$_{peak}$) $

LOCATION, DATE OF DEPLOYMENT	
PARTICIPATING ORGANIZATIONS	
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

The largest solar power system in Japan was developed for the Maritime Safety Board. It provided a peak power of 1156 watts and was installed in a lighthouse in 1966. Japan has installed a total of 4638 watts of solar energy power systems during the period from 1958 to 1966. The major use of this equipment is for VHF repeater stations.

(paraphrased from Ref. below)

REFERENCE F. Costogue and R. Vivian, "Solar Energy Rechargeable Power System", internal document of the Caltech Jet Propulsion Laboratory, June 15, 1969. JPL document No. 650-81

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Remote data station in Fairbanks, Alaska, operational in the late 60's, present status unknown
SYSTEM DESCRIPTION	Array Type: Si Size: .7 ft^2 ______ Volts DC(peak)* ______ Current " 7 Power (watts) Supplier: Hoffman/Motorola $\text{Cost } (\$/\text{Kwe}_{\text{peak}})\ \$$ Other Components 13.6 V battery 18 watt transmitter
LOCATION, DATE OF DEPLOYMENT	Fairbanks, Alaska 1960's
PARTICIPATING ORGANIZATIONS	??
COMMENTS	

SYSTEM DESCRIPTION/PERFORMANCE

Details not provided

REFERENCE E. Costogue & H. Vivian, "Solar Energy Rechargeable Power System", internal document of the Caltech Jet Propulsion Laboratory, June 15, 1969. JPL Document No. 650-81

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC's)

APPLICATION, STATUS	Remote communications equipment, California Department of Parks
SYSTEM DESCRIPTION	Array Type: Silicon Size: 4 watts Other Components

______ Volts DC(peak)*

______ Current "

__4__ Power (watts)

Supplier: [illegible] Motorola

Cost ($/Kwe$_{peak}$) $

LOCATION, DATE OF DEPLOYMENT	? Deployed in 1968
PARTICIPATING ORGANIZATIONS	State of California, Motorola Electronics (Scottsdale, Ariyona)
COMMENTS	Insufficient information in reference

SYSTEM DESCRIPTION/PERFORMANCE

Motorola communications equipment, operated from a Ni-Cd battery charged by a 4 watt (peak) silicon solar array. Use of Eveready air cells, disposable after one year operation, requires annual transportation plus cost of batteries.

Batteries	$ 150.
Transport	$ 100.

Transporation would be by horseback or helicopter. Clearly the systems available in 1975 would easily be cost effective, since a complete system could be obtained for less than forty dollars per peak watt, including batteries and charge limiter.

REFERENCE E. Costague and H. Vivian, "Solar Energy Rechargeable Power System", internal document, Caltech Jet Propulsion Laboratory, June 15, 1969. JPL document No. 650-81

PRELIMINARY SURVEY OF TERRESTRIAL APPLICATIONS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS. (By J. Weingart for the National Academy of Sciences Ad Hoc Committee on Energy Technologies for LDC

APPLICATION, STATUS	Aids to Navigation Equipment for off-shore oil platforms (currently installed on one platform)
SYSTEM DESCRIPTION	Array Type: Size: 122 cm x 152 cm ______ Volts DC(peak)* ______ Current " 120 Power (watts) Supplier: Solar Power Corp. Cost ($/$\text{Kwe}_{\text{peak}}$) $(approx. $ 20,000) **Other Components** One 2-mile fog signal Four 5-mile lamps 28 100 amp-hour deep discharge batteries one electronic voltage monitor Housing & supports
LOCATION, DATE OF DEPLOYMENT	Approx. 1973 (Texas Gulf Coast?)
PARTICIPATING ORGANIZATIONS	Complete system was fabricated and sold by Tideland Signal Corporation, Houston, Texas using Solar Power Corp. Modules
COMMENTS	A total of 80 modules (Solar Power Corp.), 1.5 watt peak/module

SYSTEM DESCRIPTION/PERFORMANCE

The lighting system on the referenced oil platform consists of one 2-mile fog signal and four 5-mile lamps. Energy consumption is about 25 am-hour/day x 12 volts = 300 whe/day. Previously this lighting system was powered by 40 1.2 volt, 3300 amp-hr primary batteries. The total weight was 2,000 lbs and these were replaced annually. The solar generator system incorporates 80 photovoltaic modules (1.5 watts peak under AM1 illumination, 25 deg.C) into an array with overall dimensions 4 x 5 feet (1.22 x 1.52 m). The reference implies a retail cost of roughly $ 20/peak watt and indicates that at such prices for a terrestrial array (sealed, ready to install), such arrays begin to compete with primary and secondary batteries in markets traditionnally served by this hardware. The ref. claims that "solar cell/secondary battery systems clearly compete on an economic basis with heavy duty primary batteries" (presumably on a life-cycle cost basis, although the specific numerical details are not discussed).

REFERENCE B. Kelly et al, "Investigation of Photovoltaic Applications", presented at the International Congress, The Sun in the Service of Mankind, Paris, 1973.

No.	Letter	Reference
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	B	C.G. Currin and W. A. Smith, "Economics of Silicon For Future Large Solar Cell Arrays"
	C	R.J. Mytton, "The Present Potential of CdS Solar Cells as a Future Contendor for Photovoltaic Space and Terrestrial Power Applications" Solar Energy, Vol.16, pp. 33 - 44, August 1974
	D	E.N. Costague and H.C. Vivian, "Solar Energy Rechargeable Power System" JPL Document 650-81, June 15, 1969. Jet Propulsion Laboratory, Pasadena, California, 91103
	E	Product Data Sheet "Solarex Solar Energizer", Bulletin No. SE-3, Solarex Corporation, 1335 Piccard Avenue, Rockville, Maryland 20850
	F	C.G. Currin et al, "Feasibility of Low Cost Silicon Solar Cells", Proceedings of the Ninth IEEE Photovoltaics Specialists Conference, May 4, 1972
	G	A.E. Spakowski, "An Estimate of the Cost of Large-Scale Power Generation Using Solar Cells", Proceedings of the Ninth IEEE Photovoltaics Specialists Conference, May4, 1972
	H	A.I. Mlavsky, "The Silicon Ribbon Solar Cell - A Way to Harness Solar Energy", Tyco Laboratories, Waltham, Massachusetts, 02154, June 1974
	I	B. Kelley et al, "Investigation of Photovoltaic Applications", International Congress, The Sun in the Service of Mankind, July 5, 1973, Paris
	J	R.J. Stirn, "Feasibility of Economical Silicon Solar Cell Production", JPL Interoffice Memo No. 343-7-71-433, July 27, 1971
	K	R.J. Stirn, "Gallium Arsenide Solar Cells", JPL Interoffice Memo No. 342-70-A-514, Jet Propulsion Laboratory, Pasadena, Calif., December 16, 1970

No.	Letter	Reference
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	M	N. Nakayama, et al., "Ceramic CdS Solar Cell ´SUNCERAM`", National Technical Report, Vol. 15, No. 2, April 1969 (Japanese)
	N	M. Wolf, "A New Look at Silicon Solar Cell Performance", Energy Conversion Vol. 11, p. 63-73, 1971
	O	A. I. Mlavsky, Seminar at International Institute for Applied System Analysis, Laxenburg, Austria. December 1974
	P	*Comparison of Low Power Electrical Generating Systems for Remote Application*, Prepared for the National Bureao of Standards by Thermo Electron Corporation, 85 First Avenue, Waltham Massachusetts, 02154, Report No. TE5317-52-73, 1973
	Q	J. Davis et al., *Proceedings of the Symposium on the Material Science Aspects of Thin Film for Solar Energy Conversion*, May 1974 (National Science Foundation/RANN, Washington, D.C.)
	R	A.I. Rosenblatt, "Energy Crisis Spurs Development of Photovoltaic Power Sources", Electronics (G.B.), April 4, 1974, p. 99ff
	S	*Solar Energy*, Task Force Report prepared by the Interagency Task Force on Solar Energy, under the Direction of the National Science Foundation, Nov. 1974. USGPO Stock No. 4118-00012
	T	J. Weingart, "Solar Energy", McGraw-Hill Encyclopedia of Environmental Science and Technology, p. 569, 1974
	U	P. Ehrlich, A. Ehrlich and J.P. Holdren, *Human Ecology*, W.H., Freeman Company, San Francisco, 1973
	V	*An Overview of Alternative Energy Sources for LDC´s*, Report to the U.S. Agency for International Development, Technical Assistance Bureau Office of Science and Technology, Prepared by Arthur D. Little, Inc., Report No. C-77105, August 7, 1974

No.	Letter	Reference
	A1	Robert Josephs, "The Mariner 9 Power Subsystem Design and Flight Performance", Technical Memorandum 33-616, Jet Propulsion Laboratory, Calif. Institute of Technology, Pasadena, California, May 15, 1973
	B1	E. Sequeira and R. Patterson, "Solar Array Study for Solar Electric Propulsion Spacecraft for the Encke Rendez-vous Mission", Technical Memorandum 33-668, Jet Propulsion Laboratory, Calif. Institute of Technology, Pasadena, California 91103, February 1, 1974
	C1	R. Patterson and R. Yasui, "Parametric Performance Characteristics and Treatment of Temperature Coefficients of Silicon Solar Cells for Space Application", Technical Report 32-1582, Jet Propulsion Laboratory, Calif. Institute of Technology, Pasadena, California 91103, May 15, 1973
	D1	A.F. Forestieri and A.F. Ratajczak, "Terrestrial Applications of FEP-Encapsulated Solar Cell Modules" NASA Technical Memorandum TM X-71608, NASA/Lewis Research Center, Cleveland, Ohio, September, 1974.
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1 C. Pfeiffer

2

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Comments on the Thermo Electron Co. Report*

The assumptions behind the report strike me as somewhat strange. If a village or local community has access to any useful amounts of electrical energy at all, then an additional 100 watts for a few hours each day is clearly well within the local capabilities. Probably a few is of local use. If there is no electricity available, and the purpose of the study is the determination of the best method to provide enough energy for an hour or two day power for local TV set, it is clear that a few reasonably strong people riding an inexpensive bicycle generator could charge a battery sufficiently for such a requirement. Having ridden such a machine myself at the Lawrence Hall of Science at the University of California at Berkeley, I can testify to the fact that generating 100 watts for an hour is possible but takes considerable strength. Perhaps a dozen or more member of the community could take turns at various times of the day to operate the generator. If the generator eventually were no longer used, it would at least indicate the value which local people placed on having television links with the rest of the world.

I would maintain that the needs of the LDC's are not TV communications with the outside world, although this may be helpful PROVIDING THE NECESSARY ECONOMIC AND PHYSICAL AND SOCIOCULTURAL RESOURCES FOR CHANGE ARE ALREADY AVAILABLE.

The report is, in my opinion, completely divorced from the realities of needs in many, if not all, of those LDC's which do not have any major source of wealth. It appears technically competant but not nearly as useful as it could have been, had the technical study been tied to an awareness of real needs. In fact, my own somewhat cynical view of the problems of development prompts me to remark that the last study that was done to examine remote communications for LDC regions was a study of silent, reliable systems to provide military communications and village alarm systems in Southeast Asia. As it turned out, that was not what the people needed either.

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The report is technically deficient in the sense that is examines only the cost of owning and operating very small generating systems (100we). We need to have costs of owning and operating various systems as a function of the size of the output, both for electrical energy and for shaft horsepower which could be used for irrigation, small local industry, etc.

Finally, although this is no fault of the authors, the cost of fossil fuels has gone up since they wrote it. In addition, I doubt if they (and I include myself among the ignorant) have any real idea of the costs of delivering fuels to remote locations in LDC's (most of the LDC's, by our standards of remoteness). The actual costs, when all of the middlemen are paid in addition to the initial high costs, may be between one and five dollars per gallon ($ 40 to $ 200 per barrel). Why should we expect kerosine to be cheaper in the middle of South-central Asia or Africa than it is in Vienna (about $ 1 per gallon)?

The report does emphasize something very important, however. The internal combustion engine, coupled with the very high specific energy density of kerosine and gasoline, is a marvelous device at its best. It is highly reliable, easily maintained and repaired, cheap to buy (a few dollars per kilowatt in sizes of ten horsepower and up) and quite portable.

However, the authors are too pessimistic about the eventual cost of solar arrays. One of the authors (Arvin Smith) was for many years the central figure at NASA in space power systems development; his many years of experience with very high cost arrays, coupled with a lack of real direction in the U.S. in cost reduction for photovoltaic arrays at the time the report was prepared, have probably resulted in the high cost estimates. Assuming that arrays can be delivered to LDC's for $ 5 per peak watt, and the amortization for the array can be over ten years rather than five, the annual costs of owning and operating a PV system would be within ten percent or so of the costs for an ICE system using kerosine at a dollar per gallon (delivered).

The difference between a fuel-dependent system and a fuel-independent system cannot be measured simply in differences in amortized costs and in first costs. There may be a significant value to people using fuel-independent systems in not having to rely on fuels, in not being at the mercy of fluctuations in the cost of the refined product, in not being at the mercy of the delivery system, and so forth. However, this is balanced to some extent by the limited investment capital available in the LDC's.

This also leads to the possibility of dual or hybrid systems, including both photovoltaic and kerosine/gasoline powered convertors. After all, if a solar conversion system can be paid for, the additional samll increment for an engine/generator/regulator system can be assumed possible. The engine, coupled with a small amount of standby fuel, could provide necessary backup for urgent purposes in the event of insufficient sun for long periods of time. The marginal return, in terms of a sense of security or reliability in the delivery of electricity to a community, might be very high.
From a pragmatic short range perspective, which is the only one most people are interested in, it is better to have a low initial cost and higher operating costs than the reverse given equivalent life cycle costs. It clearly is a question of relative values in small human ecosystems whether or not solar or fuel-dependent systems or some combination of the two are to be preferred. With appropriately designed programs of action, the questions can be answered.

SYSTEM	FIRST COST	ANNUAL COST
3M Model 515 TEG (Thermoelectric) Convertor + battery 25 watts	$ 1462.	$ 496. (fuel delivered at $ 16.80 per bbl)
Solar array, limiter, battery; 30 watts cont. 5 year life, 7% deprec.	$ 4500	$ 1215.
Tyco/Winston array at $ 5/peak watt, limiter and battery	$ 800	$ 190. (7%) 5 y $ 204. (10%) 5 y $ 127. (10%) 10 y
TEG with fuel at a delivered cost of $ 40 per bbl		$ 635.
Spark ignition ICE	$ 96	$ $ 60 with kerosine at $ 0.40 per gallon $ 96 with kerosine at $ 1.00 per gallon
Stirling Cycle Engine		$ 126.00
Ormat turbine	$ 400	$ 160.

IT's HARD TO BEAT THE ICE.