Feasibility of Large-Scale Orbital Solar/Thermal Power Generation

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This paper explores the feasibility of large-scale orbital solar/thermal power generation. For the large-scale orbital thermal plant the most important system parameters are transportation cost, weight of the solar concentrator and system component efficiencies. The thermal conversion concept discussed in this paper is potentially feasible with today's solar concentrator technology and component efficiencies if the low Earth orbit transportation cost is approximately \$60/lb. The system is also potentially feasible with space shuttle transportation cost of approximately \$160/lb and 1980 component efficiencies if the solar concentrator can be constructed at approximately 0.03 lb/ft^2. Large-scale collection of solar power in space for use on Earth has been discussed by several authors in the past five years. Typical schemes involve direct photovoltaic conversion to electricity, microwave conversion and transmission, and reconversion to electricity on Earth. This paper describes the alternative of heat engines for initial conversion. Significant economic leverage results from collecting the solar energy with a thin reflective film at a few cents per square meter. A Brayton cycle heat engine is utilized to convert thermal energy to electricity. Economic feasibility is dependent on system technical performance, transportation cost, and cost of alternative power sources.

Introduction

THERE are presently only three major sources of energy which may be developed in the remainder of this century to supplement and eventually replace oil and natural gas. These are coal and its derivatives, nuclear, and solar energy.

New national and world energy sources are required in the time frame of the next 20 to 30 yr. The "energy crisis" is the problem of developing a cost-effective nonpolluting energy source for future use.

Large-scale collection of solar power in space for use on Earth has been discussed by several authors in the past five years.[1,2] Typical schemes involve direct photovoltaic conversion to electricity, microwave conversion and transmission, and reconversion to electricity on Earth. This paper describes the alternative of heat engines for initial conversion.

Solar energy is abundant but its density is low. For economical utilization a proposed concept must receive the low density solar flux with a system which has a relative low cost per unit area. The basis of the thermal-energy cycle solar collector is that lightweight low cost structure is utilized. Tremendous economic leverage is obtained by collecting the solar energy with a thin reflective film at a few cents per square meter. The energy collected per unit area by an orbiting system is approximately

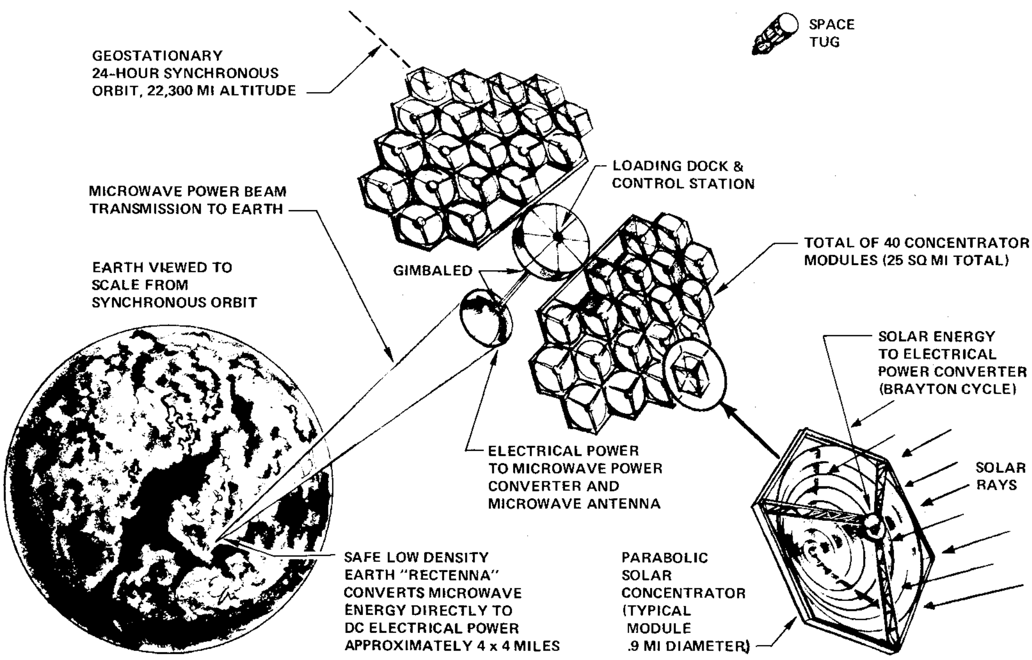

Fig. 1 Large-scale orbital solar/thermal power generation.

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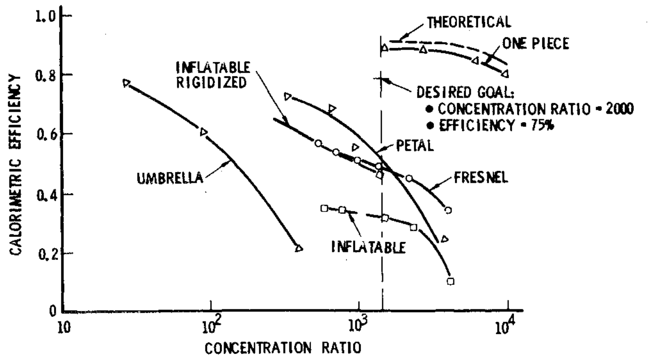


Fig. 2 Solar collector efficiency experience.

15 times that of a terrestrial system.[3] The potential magnitude of the orbital solar power concept, should it become a reality, is enormous compared to any of the other future space applications that have been examined. A total investment in solar power of over $300 billion during the next 30 yr might be economically justified.

An artist's illustration of the concept is shown in Fig. 1. The systems consists of seven major subsystems which are: 1) Solar Collector; 2) Brayton Cycle Power Conversion System including Waste Heat Radiators; 3) Microwave Generator; 4) Microwave Antenna; 5) Control System; 6) Electrical Propulsion System (for transfer to geosynchronous orbit); and 7) Earth Receiving "Rectenna."

The system operates by concentrating solar thermal energy. This heat energy is converted into electrical energy by a Brayton gas turbine cycle. The electrical energy is transported by microwave beam to a ground station. The orbiting plant is essentially stationary relative to the Earth's surface and collects solar energy 24 hr per day.

The following discussion first considers technology requirements and status, then a reference system design concept, and finally sensitivity analyses and comparisons to the photovoltaic alternative for space solar power.

Technology Status

Solar Collector Technology

Various solar collectors have been constructed and include: Fresnel; fixed geometry inflatable; one-piece; petal; umbrella; and inflatable rigidized forms. Each of these collectors fails to give sufficient calorimetric efficiency at the concentration ratios needed for an efficient heat engine or else cannot be economically constructed for large power plants. If a thermal conversion system with peak temperatures over 3000°F is required, only the one-piece mirror is capable of efficient operation at the present time. All of the present expandable collectors are relatively inefficient even at temperatures around 1540°F. The low efficiencies of the present inflatable collectors are attributed to large transmission and reflectance losses from the front expandable face as well as the reflecting face. The umbrella collector shows very low concentrating ability because the reflecting surface gores between the metal ribs take a nonparabolical shape.[4] Typical collector efficiencies are shown in Fig. 2 based on 1963 technology. The literature abounds with small scale solar collector technology and Refs. 4–9 are representative. The basic technology is well defined for the construction of solar furnaces and is directly applicable to this concept. However, an appreciable improvement in large inflatable or expandable solar collectors is required for this concept. It is presumed that inflatable structure concentrator efficiency will improve if geometry control is achieved. Today's control technology can be applied to a variable geometry collector as shown in Figs. 3 and 4. A control system with feedback based on solar flux into the collector aperture is designed to optimize the concentration ratio. The amount of improvement is speculative at this time, however, terrestrial experiments could be carried out and a factor of 2.5 improvement (giving an efficiency of ~0.75) could reasonably be expected today as compared to 1963 efficiencies shown in Fig. 2.

Large terrestrial expandable structures are being constructed at this time. The handling and fabrication of these large structures have been proven. For example, a half-acre air structure has been designed for Princeton University. A one-acre air structure is now in place at Antioch College in Columbia, Md. There is also a one-acre air structure built by Goodyear near Wooster, Ohio. All of the air structures to date are being applied in building field houses, agricultural complexes, production facilities and warehouses. However, future air structures are being designed to enclose square miles rather than square feet. There is a proposal for a 2000-acre Expo City air structure. These large structures give rise to special problems resulting from the uplift from the air pressure and reinforcing cables must be large enough to carry the required tension. Also aerodynamic lift caused from winds has considerable effect on cable design. Although the terrestrial air structures are somewhat different when compared to the orbital solar collector, the similarity arises from the applicability of the

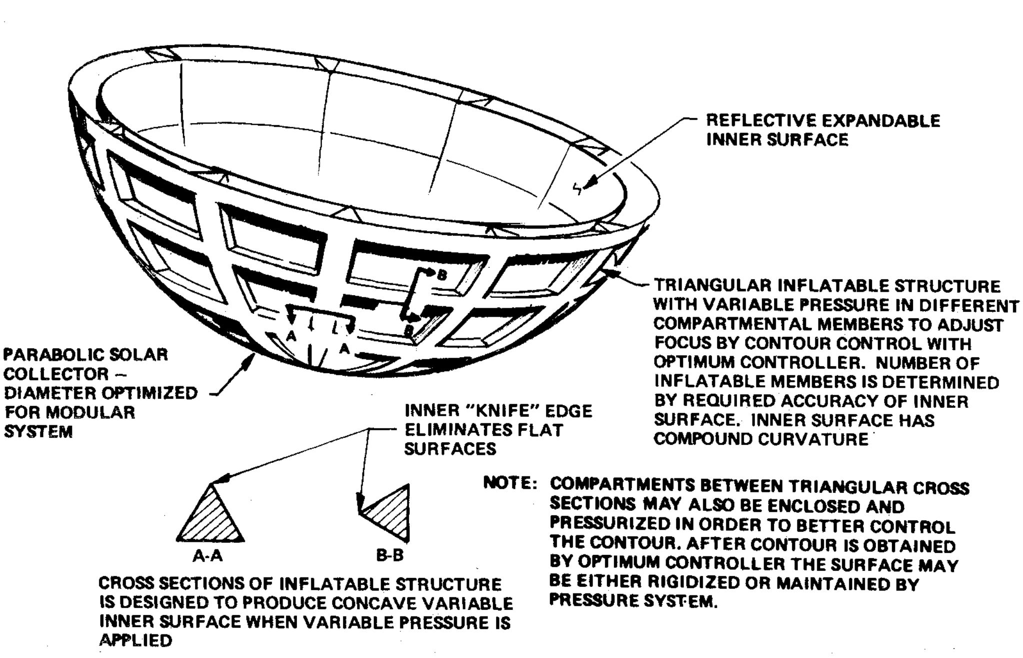


Fig. 3 Variable geometry solar energy concentrator.

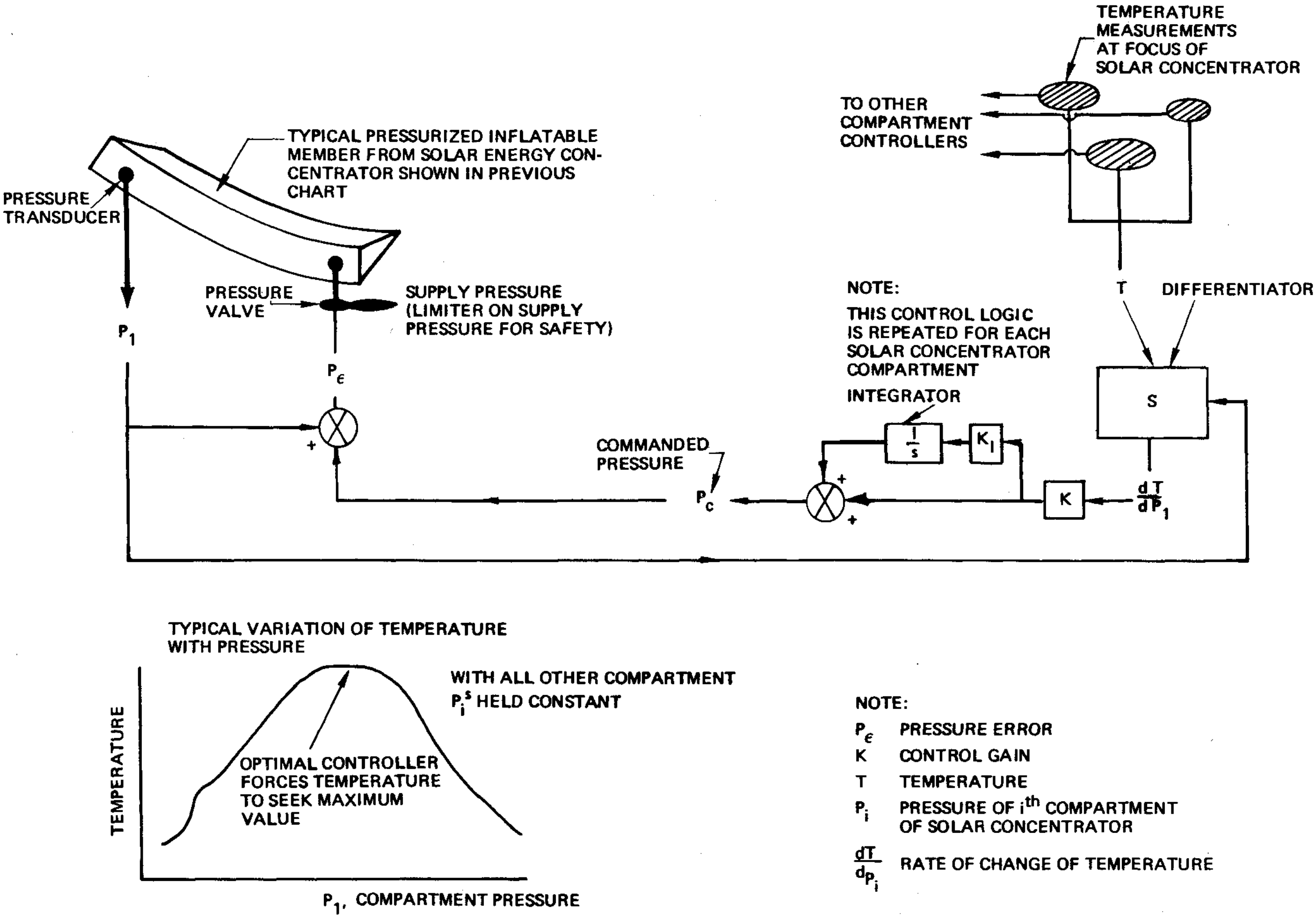


Fig. 4 Schematic of optimal control system to obtain large solar energy concentration ratios.

technology of handling and fabrication of large inflatable structures. The expandable structure for the inflatable solar collector is unique in that the gravity loads are very small when compared to terrestrial inflatable structure. Also the external pressures required to maintain shape in orbit are relatively small and therefore will not require the tension cables utilized in Earth structures.

Brayton Cycle Technology

The efficiency of a Brayton cycle, like all heat engines, is limited by the Carnot efficiency. The efficiency of a simple Brayton cycle falls far short of Carnot efficiency because heat is added and rejected over a range of temperatures. As discussed later, a recuperator heat exchanger improves this situation markedly.

Experimental Brayton cycle machinery for space use in the 2–15 kW range has been built and tested.[11] This equipment is typically designed to operate from a nuclear reactor or isotope heat source. The working fluid is a mixture of inert gases (e.g., helium/xenon) selected to optimize heat transfer and mean molecular weight. These systems have generally been limited in cycle temperature by allowable fuel element temperature. No severe technology problems have been encountered. Nonetheless, a dynamic system, using nuclear or solar heat, has never been selected for development for an operational space system. For low power levels (up to 10 kW or so) a static system, either solar photovoltaic or thermoelectric, has always been preferred. At high power levels, dynamic systems are believed to be more competitive.

The large solar heated system discussed here will optimize at high temperatures, assuming that solar reflector technology can be so developed. In the vacuum and inert gas environment to be used, refractory metals and alloys will prove attractive. Peak temperatures on the solar heat exchanger of over 3500°F will be desirable. At these temperatures, only a few metals such as tungsten and tantalum have usable properties. Stresses in the solar heater can be kept very low. Further research is needed to select and characterize alloys and establish operating limits. Turbine inlet temperatures on the order of 3000°F are desired. Experimental aircraft turbines have operated at this temperature using refractory alloys and/or blade cooling. It is expected that within a few years operational aircraft engines will reach this level.[12]

Microwave Technology

Microwave power transmission technology has been extensively discussed. Demonstration of highly efficient generation, transmission, and reception has been achieved, although not on the multimegawatt level. A detailed report which supports the microwave efficiency used in this paper was presented in briefings before the Congressional Task Force on Energy, Honorable Mike McCormack, Task Force Chairman.[13] Principal technology challenges appear to be 1) the extreme precision, to be achieved by mechanical precision or electronic calibration or both, required for beam-forming by the very large phased array antenna; and 2) elimination or circumvention of communications interference due to scattering of the power beam.

Transportation and Space Operations Technology

Space transportation and operations are major issues in the feasibility of space solar power, whatever the conversion system. The 10,000 mW plant used as a design reference in this paper

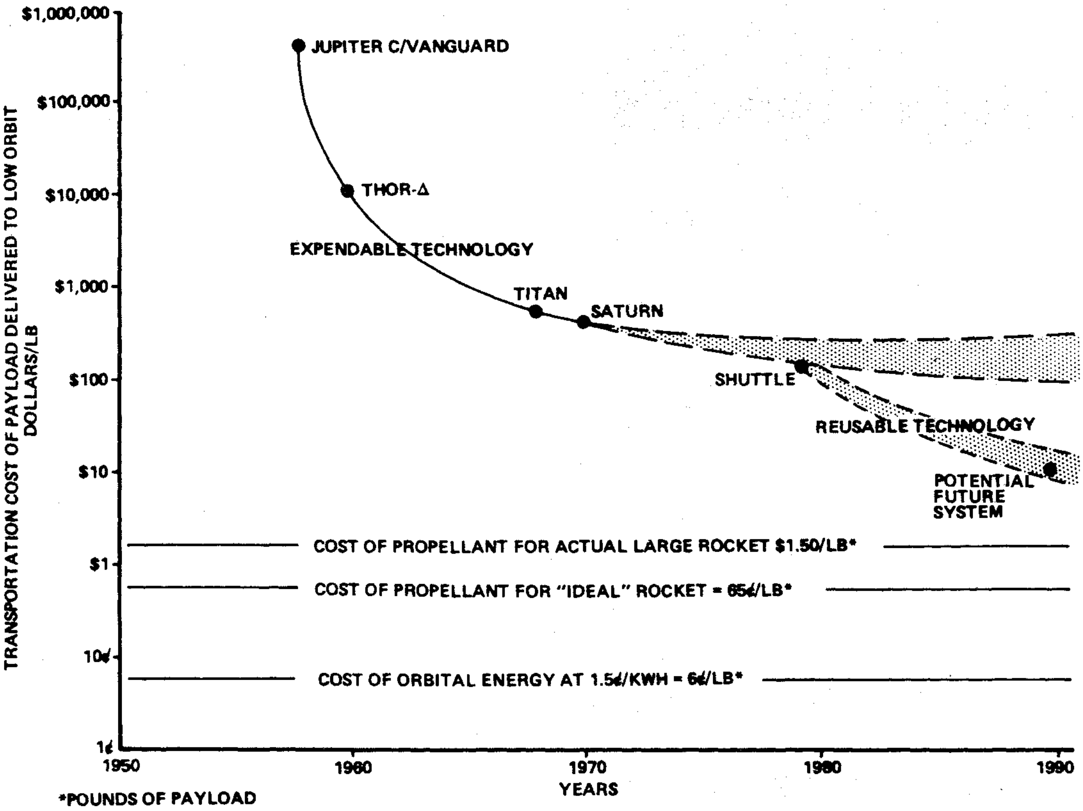


Fig. 5 Space transportation cost trends.

weighs over 100 million lb. Stated as 50,000 tons, the mass is not quite so startling. This is recognizable as a typical gross weight for a large ship. We may, however, be assured in asserting that the plant will require orbital assembly, and many flights will be necessary to support the task.

The cost of the many flights is a key factor in the total system cost. If we examine historical trends of the cost of placing mass in orbit (Fig. 5) we find expendable launch system technology leveling off between $500 and $1000 per lb. Significant further reductions through expendable space launch systems technology are unlikely.

The NASA Shuttle is presently projected at about $160 per lb. Perhaps more significant in the context of this discussion is that the Shuttle is the first of a new generation of technology not limited in economic potential by the cost of expending sophisticated aerospace machinery on every flight. Limits are presumably found in the cost of propellant and flight operations. Figure 5 suggests that costs ultimately attainable by reusable transportation technology may be as low as $5–$10 per lb in low Earth orbit.

Reusable technology (i.e., the space tug) has also been extensively analyzed for transportation from low orbits to geosynchronous orbit. Although the cost of operating a resuable tug is low, it can place in the high orbit only about 10% of the gross mass delivered to low orbit, resulting in costs per lb about ten times those discussed. It seems natural, therefore, to plan to use the electric output of the plant (transporting one module at a time) to drive an electric propulsion system. Because these solar power modules have a high power-to-weight ratio, electric propulsion can place roughly 90% of the low orbit mass in high orbit, requiring a few weeks for the transit.

Present-day electric propulsion machinery of the ion thruster type, delivering 5000 to 10,000 sec Isp. has demonstrated high efficiency and long life. Power conditioning equipment plus thrusters are expected to weigh roughly 5 lb per kW in large sizes. This is a significant penalty to the plant, which is projected in the 10 lb/kW range without electric propulsion, but much less than that for chemical propulsion orbit transfer. The penalty can be minimized by using some of the plant modules in a shuttle mode, returning the electric propulsion equipment to low orbit for reuse.

If we presume payload capability in the shuttle class—65,000 lb—some 1500 to 2500 flights will be required to place enough hardware in low orbit to assemble one 10,000 mW plant. This certainly suggests a major fabrication and assembly operation in orbit—by no means a matter of just docking a few modules. Further, since something like 10 such plants per year will be needed to meet the projected rate of increase in new world capacity demand around the year 2000, we must imagine an operation involving on the order of fifty transport vehicles, each flying once every day. This is staggering to those used to thinking in terms of Shuttle traffic models of 30 to 60 flights per year, but by no means impossible.

Technology Demonstration

The technology can be available by 1980 to carry out a pilot plant demonstration to validate this concept. Key technical areas which will require a flight pilot plant demonstration are: 1) solar collector efficiency and life; 2) efficiency of large high gain phased array antenna; 3) orbital assembly of large lightweight structures; and 4) avoidance of communications interference by the power beam.

Design Assumptions and Requirements

Requirements

The world energy requirements will double in approximately 13 yr.[3] The above requirement and the increasing cost of conventional electrical energy is a basic motivation for developing solar energy. Fundamental to the arguments that conventional electrical power cost will increase by a factor of approximately 3[14] is the rising cost of fuel as shown in Fig. 6.[15]

Economic requirements for the system are set by cost of competing power sources. The scale of the system is set by world energy requirements. 10^6 megawatts is a reasonable working design number for the total system of power plants.[16]

Basic orbital thermal solar power system parameters and assumptions

Basic parameters and assumptions utilized in the system preliminary design are shown in Table 1. The parameters and

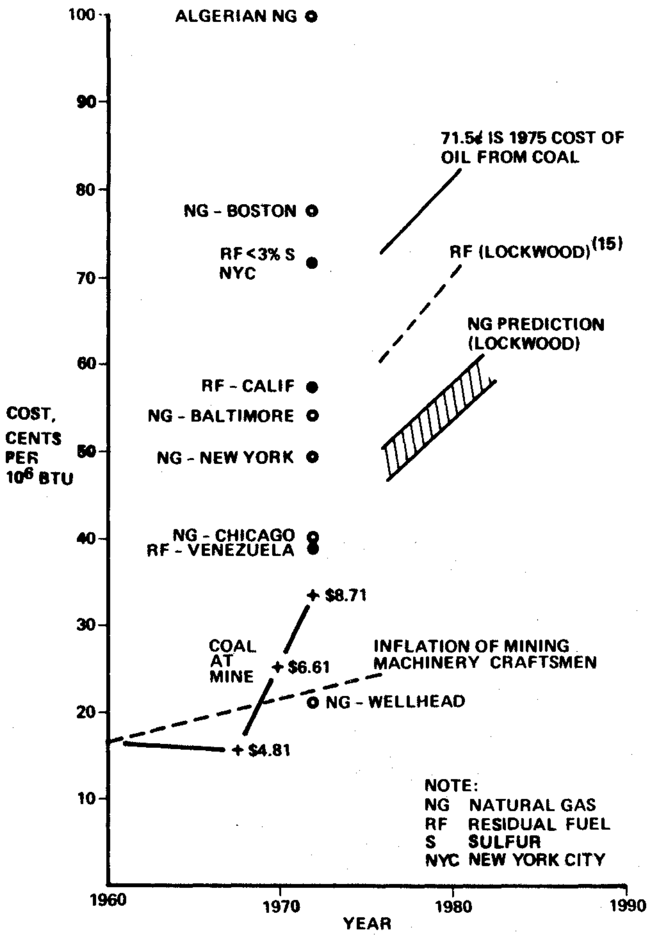


Fig. 6 Cost of fuel.

Table 1 Basic parameters and assumptions. Orbital solar/thermal power system (1980 technology)

- 8.2%* RETURN ON INVESTMENT, 3.0% OPERATION & MAINTENANCE△, 3.25%* DEPRECIATION } % OF TOTAL SYSTEM CAPITAL COST
- WEIGHT OF MYLAR, 1/2 MIL: 0.0037 LB/FT^2; COST = .778¢/FT^2
- COST OF FABRICATED ALUMINIZED MYLAR = 21.¢/FT^2 ‡
- AVERAGE SOLAR DENSITY AT EARTH: 130 WATTS/FT^2
- MICROWAVE SYSTEM
  - MICROWAVE GENERATOR
  - ANTENNA
  - MICROWAVE GENERATOR COOLING } 1.5 LB/KW †
- TOTAL SYSTEM EFFICIENCY: 10.7%△
- SYSTEM OUTPUT AT BUS BAR: 10 X 10^6 KW
- TOTAL SYSTEM COLLECTION AREA: 720 X 10^6 FT^2 (25.8 MI^2)△
- 30-YEAR LIFE*
- TRANSPORTATION COST: $160/LB □
- WHOLESALE VALUE OF ELECTRICAL ENERGY: 1¢/KW HR ◇
- SOLAR COLLECTOR PER MODULE { RIM ANGLE: 40 DEGREES; FOCAL LENGTH: .7 MI△; DIAMETER: .9 MI△; SOLAR CONCENTRATION RATIO: 2000 ‡; MAXIMUM TEMPERATURE: 3812°F ‡
- GENERATOR TURBINE { 0.2 LB/HP; INLET TEMPERATURE: 2952°F; BLADE COOLING

* TYPICAL FOR PRIVATE UTILITY
** G.T. SCHJEDAHL CO. (PRELIMINARY ESTIMATES)
*** BASED ON TURBINE ENGINE DATA FROM UNITED AIRCRAFT RESEARCH LABORATORIES [12]
† W.C. BROWN (RAYTHEON) [2]
‡ PRELIMINARY CALCULATIONS, R.M. ENGELBRECHT CONSULTANT [10]
‡ PROJECTED ESTIMATE BASED ON CURRENT TECHNOLOGY AND PRELIMINARY ANALYSIS
△ PRELIMINARY CALCULATIONS
□ ESTIMATED SPACE SHUTTLE TRANSPORTATION COST
◇ ESTIMATED NATIONAL AVERAGE BASED ON FEDERAL POWER COMMISSION [14] AND TASK FORCE ON ENERGY STUDY [17]

assumptions are related to 1980 technology and were obtained from the sources indicated.

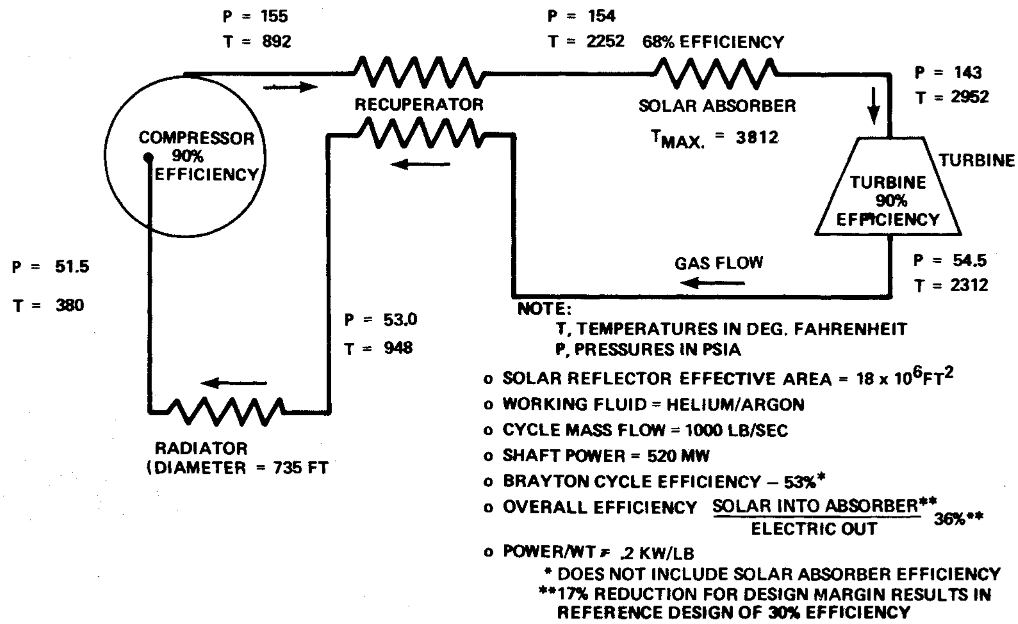
Reference system conceptual design

A preliminary design analysis was carried out with system parameters based on practical engineering and manufacturing capabilities of today and judged appropriate for the post-1980 time frame. An exception is the preliminary design of the expandable structure proposed for the large scale solar collector described in this paper. This design was carried out based on today's technology with the aid of Robert Margin Engelbrecht, Chairman of the International Conference on Air Structures.[10]

The fabricated weight of the solar concentrators is equivalent to a 27 ply (1/2 mil mylar per ply) construction and is appropriate for present state-of-the-art. However, this may be too conservative for 1980 technology and vigorous research and development in this single area could provide a major system improvement.

The more important design parameters and their sources are shown in Table 1. These parameters are the starting point for the reference system design analysis. Each major subsystem was sized, a weight calculation performed, and a preliminary cost estimate made. Considerable effort was made to select realistic

Fig. 7 Typical solar Brayton cycle state points.



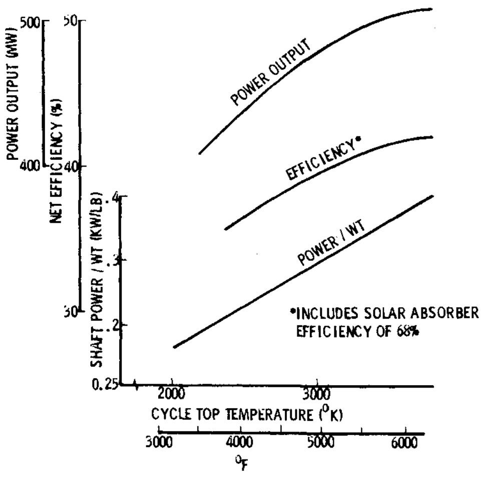


Fig. 8 Solar-Brayton cycle optimization results.

numbers for the calculations and "orders of magnitude" advancements in the state-of-the-art were avoided.

Typical solar Brayton cycle state points

Figure 7 shows Brayton cycle state points and design parameters determined for an optimized cycle with maximum temperature of 3800°F. A single loop is assumed, with the inert gas working fluid passing directly through radiator and collector heat exchangers. Heat transfers and pressure drops were determined by standard engineering methods.

Solar Brayton cycle optimization results

The performance of a Brayton cycle system tends to be very sensitive to a variety of design condition assumptions. Therefore, optimization of the cycle was conducted as a function of allowable cycle upper limit temperature. A steepest descent computer program was developed and utilized to investigate optimum system design parameters. Foreseeable materials technology will presumably limit the maximum temperature (high temperature heat exchanger wall) to the range 3000°F–4000°F assuming an inert gas atmosphere. The results of the optimization study are shown in Fig. 8.

Quasi-idealized Brayton cycle efficiency (ideal recuperator, no pressure drop)

Figure 9 illustrates the efficiency advantage of a recuperator cycle showing that high compression ratios are not required for high efficiency. Data shown were based on a simplified analysis assuming an ideal recuperator (no delta p, no delta t) and ideal heat exchangers with no pressure drop. Inert gas properties were used. Cycle efficiencies with pressure drop, as shown on previous charts, are less.

Solar Brayton power system concept

Figure 10 illustrates the design concept for a Brayton cycle power plant used as a basis for economics analysis. The power plant is sized to deliver 10,000 mW of electricity to the Earth. Roughly 100 such plants would be required to supply projected U.S. energy needs in the year 2000. The plant is modularized to allow development of rotating machinery on a reasonable scale. Modularization also allows much relaxation of meteoroid impact design criteria.

System weight analysis

Table 2 shows a summary of the system weight analysis for each major subsystem. It is noted the solar collector and the waste heat radiators are the major weight contributors. The concentrator has 4 ply mylar per wall (1/2 mil mylar per ply) and fabricated with an equivalent 3 wall construction throughout the total area. Ten per cent of the above total weight is added

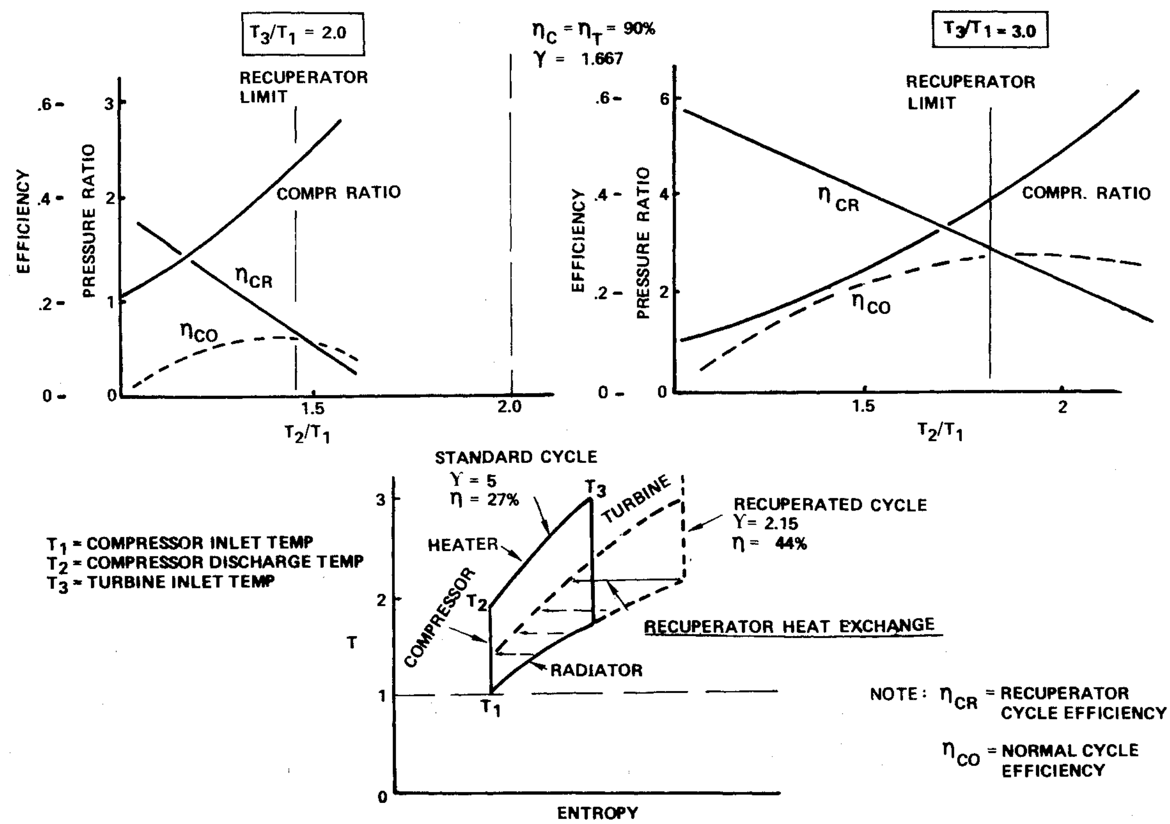


Fig. 9 Quasi-idealized Brayton cycle efficiency (ideal recuperator, no pressure drop).

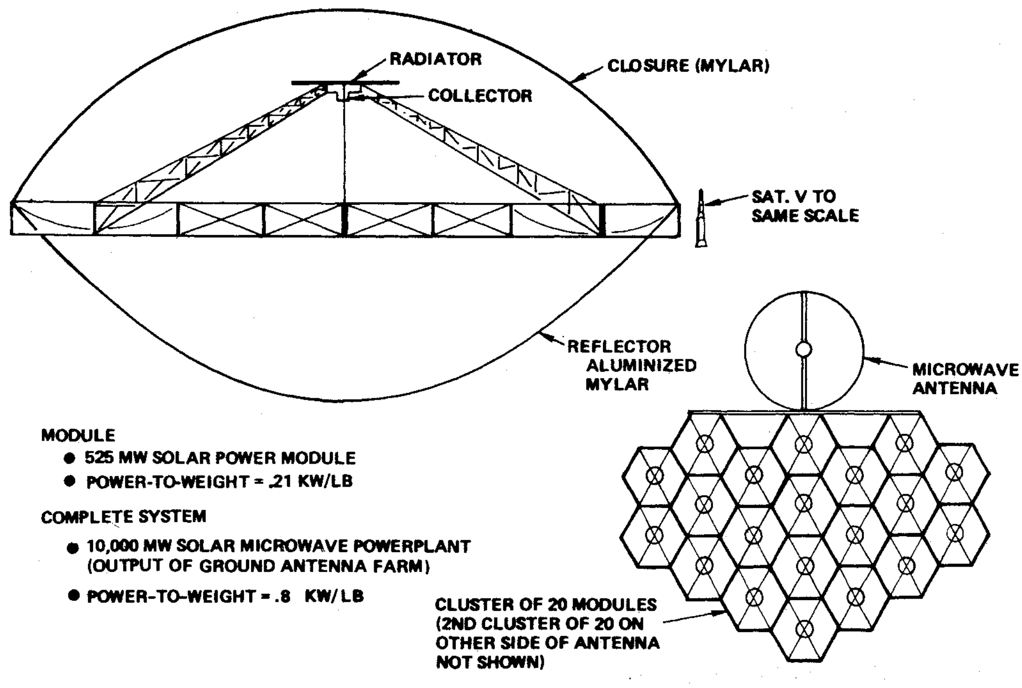


Fig. 10 Solar-Brayton power system concept.

Table 2 Orbital solar thermal power system weight (10×10^6 kW plant)

SOLAR COLLECTOR	72.0
BRAYTON CYCLE SYSTEM	5.7
MICROWAVE ANTENNA	10.8
MICROWAVE GENERATOR	5.4
MICROWAVE GENERATOR COOLING	5.4
WASTE HEAT RADIATORS	20.8
MISCELLANEOUS*	5.6
	125.7 X 10^6 LBS

WEIGHT PER SQ. FT. OF TOTAL SYSTEM = 0.175 LB/FT^2

*INCLUDES: CREW QUARTERS' ELECTRICAL TRANSMISSION LINES, ELECTRICAL PROPULSION SYSTEM TO TRANSPORT SYSTEM FROM LOW EARTH TO SYNCHRONOUS ORBIT, CONTROL THRUSTERS AND CONSUMABLES.

for joining of material. The aluminum framing was weighed by standard aircraft design techniques.

The gas turbine generators weights are based on 1973 technology. Development must be carried out in this area to extend the present turbine life. Turbine life extension is somewhat enhanced by the "weightless" space condition and the use of inert gas working fluid. Air bearings for large rotating machinery may become practical in the "weightless" environment.

The microwave equipment weights are based on Refs. 1, 2, and 13 which are derived from analysis and laboratory development.

System Cost Analysis

The transportation costs to low Earth orbit are computed from the system weights analysis. The system is self-propelling from low Earth orbit to synchronous orbit. Preliminary analysis shows the final transfer should be accomplished two modules at a time to minimize gravity gradient, air drag effects in low Earth orbit, and system cost.

The solar collector costs are based on preliminary calculations with the aid of R. M. Engelbrecht, Consultant[11] and basic mylar cost data from the G. T. Schjedahl Co. A review of Goodyear inflatable structure technology was also carried out.[18]

The modules will be assembled in low Earth orbit and self-propelled to synchronous orbit for final assembly. Gravity gradients at synchronous orbit altitude will produce torques which must be counteracted. Analysis indicates an inertia wheel system to be a satisfactory solution. The reference system transportation cost to low Earth orbit was chosen at $160/lb.

The microwave equipment costs are based on near term microwave cost projections:[1,13] 1) $10/kW for microwave generators and $40/kW for the cooling system and waste heat radiators; 2) microwave antenna cost are based on projected manufacturing cost ($50/kW); and 3) the Earth receiving antenna cost is based on the already achieved rectification of microwaves with three pounds of solid-state rectifiers/kW and a reasonable cost projection.

A summary of the cost analysis is shown in Table 3. The total cost per kilowatt hour for the baseline system is 0.97¢/kW hr assuming a 30-year life. The capital cost of the system is $2540/kW, a factor of approximately 5 higher than the allowable investment cost of $485/kW. This appears discouraging but should not lead to a premature conclusion that the system is not feasible. A parametric sensitivity study was carried out to identify economic leverages and the associated technical challenges.

System Trades and Sensitivity Data

The reference system was used as a starting point design, about which parametric trades were carried out. The parameters that

Table 3 Cost of solar/thermal 10×10^6 kW generation plant

	¢/KW HR
INSERTION INTO SYNCHRONOUS ORBIT	.77
SOLAR COLLECTOR	.01
BRAYTON CYCLE GENERATOR	.10
MICROWAVE GENERATOR	.04
MICROWAVE ANTENNA	.03
EARTH RECEIVING ANTENNA	.02
TOTAL	.97 ¢/KW HR

CONVERTING THE ABOVE TO COST PER KILOWATT RESULTS IN:

$$\text{BASELINE SYSTEM COST} = 2624 \frac{\$\text{HR}}{¢}(.97 \frac{¢}{\text{KW HR}}) = 2540 \frac{\$}{\text{KW}}$$

$$\text{ASSUMED BUSBAR VALUE OF ELECT. POWER} = \frac{1¢}{\text{KW HR}}$$

BASED ON BUSBAR VALUE, THE MAXIMUM ALLOWABLE INVESTMENT WITH 14.45% TOTAL ANNUAL OVERHEAD COST AND 80% UTILIZATION IS: 485. $/KW.

NOTE:

CAPITAL COST OF CONVENTIONAL SYSTEMS:

FOSSIL – $150-200/KW
NUCLEAR – $250-500/KW

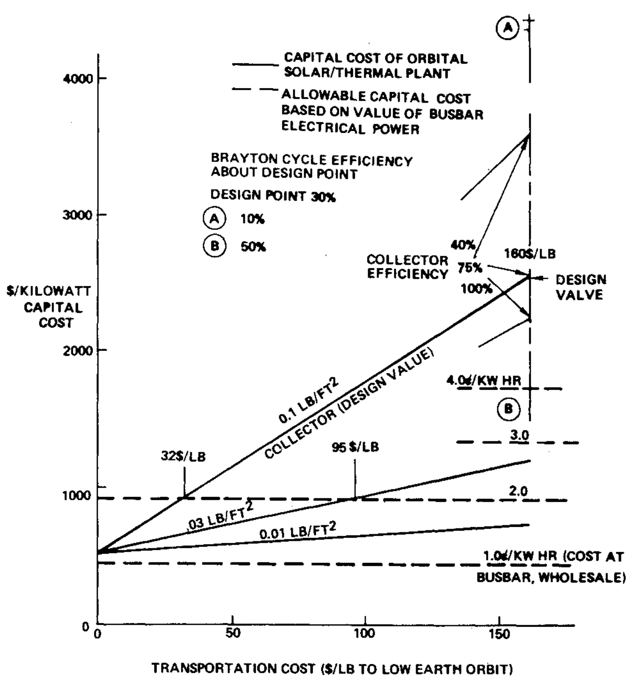


Fig. 11 Orbital solar/thermal power generation is potentially feasible in the 1980s.

most drive the system cost are shown in Fig. 11. These are: low-Earth-orbit transportation cost, solar concentrator weight per square foot and efficiency; and thermal cycle efficiency. The main conclusions to be drawn from Fig. 11 are that the system will not become feasible unless: the cost of electrical power increases; transportation cost decreases; or the solar collector design weight can be reduced; or an improvement in system efficiency; or a combination of the above.

The Federal Power Commission has stated that the nation's present generating capacity of 340 million kW must nearly quadruple by 1990. The price of electricity will double (to 3.5¢ per kW hour retail) reflecting higher fuel prices plus the cost of raising some $500 billion to build new power plants.[14] There are many potential avenues for improving the baseline system design. Some of these improvements will be brought about naturally by the advancements in the state-of-the-art in the more conventional areas, e.g. turbine plant efficiency and space transportation cost. Research and development of inflatable solar concentrators for large scale space applications could bring about large factors of improvement because this technology has not been pursued as vigorously as for example, fuel cells or solar cells. This is understandable, because for relatively low power requirements the economic comparison between systems is relatively unimportant. However, for large scale systems the economic environment is entirely different.

The potential possible improvement in inflatable concentrator weight falls within the range of 0.03 to 0.1 lb/ft^2. The potential possible improvement in inflatable concentrator calorimetric efficiency fall within the approximate range of 30 to 90%.[4]

If 1¢/kWh is used as today's electrical cost at the busbar, then the reference design as shown in Fig. 11 is a factor of five away from being an economical system. However, each of the above critical technical areas appear to be amenable to standard engineering research and development optimization techniques which might produce the required system improvements.

A comparison analysis was carried out between the heat engine system and a solar photovoltaic (solar cell) system. Comparison of costs between the thermal concept discussed here and the more popular solar cell concept is difficult because of the larger uncertainty in costs of the latter. Solar arrays have been used for spacecraft since the earliest days of space exploration. Rather little progress has been made in cost reduction, no doubt in part because of today's cost of over $100,000/kW the solar array represents only a small part of the cost of a typical spacecraft. $100,000/kW is clearly much too high to consider for commercial applications. However, those who advocate commercial use (e.g. Glaser[1]) have projected array costs in the $500/kW

SYSTEM CONCEPT / COMPARATIVE EVALUATION	SOLAR CELL SYSTEM (YR 1980)	BRAYTON SOLAR THERMAL SYSTEM (YR 1980)
CYCLE DEFINITION & EFFICIENCIES	SOLAR CELLS 15% → CONVERSION TO MICRO WAVE 85% → TRANS-MISSION 80% → RECEIVING 70% (DENOTES EFFICIENCY) TOTAL SYSTEM EFFICIENCY = 7.1%	SOLAR CONCEN-TRATOR 75% → BRAYTON CYCLE 30% → CONVERSION TO MICRO-WAVE 85% → TRANS-MISSION 80% → RECEIVING 70% TOTAL SYSTEM EFFICIENCY = 10.7%
SYSTEM CAPITAL COST (BASED ON 30 YEAR LIFE)	$118,000 $\frac{\$*}{KW}$ (2950 $/KW)***	2540 $\frac{\$**}{KW}$
MAXIMUM ALLOWABLE INVESTMENT	485 $\frac{\$}{KW}$	485 $\frac{\$}{KW}$

NOTE: ASSUMED TRANSPORTATION COST TO LOW EARTH ORBIT IS 160 $/LB

*BASED ON: SOLAR CELL COST OF $1000/FT²
(PRESENT SOLAR CELL COST ≈ $2600/FT² (21))
SOLAR CELL WT. OF .5=/FT²
TOTAL SYSTEM WT. = 570 X 10⁶ LBS
**SEE REFERENCE SYSTEM DESCRIPTION

***BASED ON: SOLAR CELL COST OF $6/FT²
SOLAR CELL WT. OF .05 LB/FT²
SOLAR CELL EFFICIENCY OF 10%
TOTAL SYSTEM WEIGHT = 108 X 10⁶ LBS

Fig. 12 Comparison between solar cell and solar/thermal systems.

range as well as weights in the 2–3 lb/kW range. Rappaport[19] projects an array cost of $1000/kW. It is not entirely clear to what degree the very low costs and very low weights go together. Paul Berman of JPL states[20]

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

A comparison between solar cell and solar thermal systems is shown in Fig. 12. If both systems are analyzed with equal conservatism the solar cell system is computed to cost $118,000/kW and $2540/kW for the thermal system (a factor of 45). The major contributor of cost for the solar cell system is dollars per ft^2 and for the thermal system is orbital transportation cost. If the solar cell system is based on optimistic parameters the cost is reduced to $2950/kW. This reduction results in a cost that is approximately the same as the conservative solar thermal approach.

Only at the low end of the range of solar array cost projections, i.e. $500/kW, does the photovoltaic system appear economically feasible. It is not prudent to discount the advocate's projections since the raw material (silicon) for solar cells is plentiful. Process and fabrication costs are subject to substantial reduction. However, the future development of space solar power is not dependent on solar array cost reduction. The solar thermal approach is a promising alternative.

Conclusions

The space solar power system concept will require major engineering development strides in several areas, notably space transportation and operations, large scale microwave power transmission, and lightweight, efficient low cost solar collectors, whether of the photovoltaic or concentrator/heat engine type. These strides, however, represent plausible extrapolations of known technology.

Based on the present investigations carried out the conclusion is that the solar/thermal approach is the preferred orbital power generation concept.

It is not clear whether photovoltaic or heat engine solar energy conversion will ultimately be the preferred approach. Both should be pursued in the present early conceptical analysis phase of investigation. At some later date, sufficient reason may be found to eliminate one or the other.

Some of the system feasibility issues will require a subscale pilot plant demonstrator (not necessarily in synchronous orbit) for resolution. Such a demonstration should be considered as a candidate shuttle payload.

At the present the orbital solar/thermal approach appears to have approximately the same level of economic feasibility as large-scale solar terrestrial power systems. Future technology developments will play a major role in this comparison.

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