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The Potential Impact of New Power System Technology on the Design of a Manned Space Station

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THE POTENTIAL IMPACT OF NEW POWER SYSTEM TECHNOLOGY ON THE DESIGN OF A MANNED SPACE STATION

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SUMMARY

Larger, more complex spacecraft of the future such as a manned Space Station will require electric power systems of 100 kW and more, orders of magnitude greater than the present state of the art. Power systems at this level will have a significant impact on the spacecraft design. Historically, long-lived spacecraft have relied on silicon solar cell arrays, a nickel-cadmium storage battery and operation at 28 V dc. These technologies lead to large array areas and heavy batteries for a Space Station application. This, in turn, presents orbit altitude maintenance, attitude control, energy management and launch weight and volume constraints. Size (area) and weight of such a power system can be reduced if new higher efficiency conversion and lighter weight storage technologies are used. Several promising technology options including concentrator solar photovoltaic arrays, solar thermal dynamic and ultimately nuclear dynamic systems to reduce area are discussed. Also higher energy storage systems such as nickel-hydrogen and the regenerative fuel cell (RFC) and higher voltage power distribution which add system flexibility, simplicity and reduce weight are examined. Emphasis is placed on the attributes and development status of emerging technologies that are sufficiently developed that they could be available for flight use in the early to mid 1990's.

INTRODUCTION

The continued exploration and exploitation of space will require the development of high efficiency, cost effective space power systems. As on earth the realization of the promises of man's movement into space depends largely on the availability of abundant, relatively low-cost energy. This becomes clear on examining the history of man in space contrasted with the presently evolving requirements of a manned Space Station now in the planning stages in the U.S. for initial operation in the early 1990's. Project Mercury (1961-1963) used 0.4 kW, Gemini (1965-1966) and Apollo/ASTP (1968-1972/75) used 1.0 to 1.5 kW. Skylab (1973-1974) was a bold step to 20 kW (design), 11 kW (as flown). The Space Shuttle (1981- ?) operates with 21 kW. The U.S. Space Station anticipates 75 kW or more initially growing within a few years to more than 150 kW and much higher over a 10-yr period. It is being planned as a permanent facility with all that entails in terms of reliability and life cycle cost; a "research and development center" in orbit requiring an electric utility type of power system. It has to be capable of meeting growing loads by on-orbit replication or technological transparency. This technological challenge is great and because of its size and weight the electric power system has an important impact on the Space Station design.

Long lived spacecraft historically have depended upon silicon solar cell arrays, nickel cadmium storage batteries and operation at 28 V dc. These technologies supporting 75 kW bus power would require 2500 m^2 of arrays and a battery weight of 11 000 kg. Large arrays in low earth orbit can require significant orbit maintenance propulsion (fuel) and present formidable attitude control and stabilization problems. High battery weight adds Shuttle launch and resupply constraints and costs and the technology itself limits the system in other ways. The size (area) and weight of such a large space power system can be significantly reduced if new power technologies are employed.

A number of promising new technologies exist which offer significant advantages. Reduction in size can only be accomplished either by converting sunlight to electricity more efficiently, or by using a nonsolar energy source. One approach to increasing efficiency is to substitute a more efficient semiconductor material, such as gallium arsenide, or a multi-bandgap (cascade) structure for silicon. A second approach is to use a more efficient conversion process, such as a solar dynamic heat engine operating on the Stirling, Brayton or Rankine cycles. The ultimate approach may be to eliminate the solar array altogether by employing a nuclear heat source. The weight of the storage system can be reduced by substituting more energetic electrochemical systems such as the hydrogen-oxygen regenerative fuel cell or nickel-hydrogen battery. In addition the weight of the power management and distribution system can be reduced if the system voltage level is increased from 28 to 100 V or more. Each of the technologies and their Space Station implications are presented below.

SOLAR PHOTOVOLTAIC ARRAYS

Flight quality solar cell technology has displayed steady growth in efficiency over the past 30 yr almost to the 20 percent level with silicon and gallium arsenide cell technology. The highest efficiencies have been reached with miniature concentrator gallium arsenide cells at 100 suns, 80° C (ref. 1) These cells are being developed for use in the miniature Cassegranian concentrator, an approach that potentially can reduce costs because each cell is only 5x5 mm. An erectable composite hexagonal modular array structure, 1.25 cm thick, (1500 to 3000 W per module unit) mounted on an erectable strut assembly is being studied (fig. 1). A 37.5 kW suitably stiff array (> 1 Hz) can be assembled in about 48 man-hr from the Shuttle bay using a "mobile work station." The idea is shown in figure 2. The significant area reduction with this technology is summarized schematically with various lifetime assumptions in figure 3. An important benefit of this approach to station evolution is its cell technology transparency. Technology efforts are being directed at higher efficiency miniature cell concepts e.g., cascade cells at ~30 percent, and possibly surface plasmon cells at up to 50 percent efficiencies. These can easily be incorporated in the identical array structure leading to smaller area for a given power level for future needs as depicted in figure 4.

ELECTRICAL ENERGY STORAGE

There are two new system level approaches to spacecraft energy storage suitable for the high capacity requirements of a Space Station. The hydrogen-oxygen fuel cell - electrolysis system (RFC) (ref. 2) in which hydrogen and oxygen are generated and stored during the sunlit portion of the orbit for use in the fuel cell during eclipse is particularly attractive since it can be integrated with propulsion and life support subsystems. Because storage capacity is determined by gas volume in light tanks, it has emergency reserve benefits. The bipolar nickel-hydrogen battery (ref. 3) is a recent innovation which incorporates active cooling and electrolyte management. It faces nickel electrode cycle life challenges. These storage options are shown schematically in figure 5. Table 1 compares a nickel cadmium battery with these options in a 37.5 kW Space Station module point design. It should be noted that the bipolar approach in the RFC and $Ni\text{-}H_2$ battery reduces the number of units that must be controlled electrically to insure maintenance of storage capacity with cycling. The higher operating temperature of the RFC assists heat rejection. Now approaching breadboard verification, a substantial engineering data base at the cell and small stack level has been accumulated for the RFC. Less than 1 μV/hr decay rates have been attained and endurance tests beyond 25 000 hr are continuing (ref. 4).

THERMAL POWER SYSTEMS

Thermal power systems consist of a heat source, solar or nuclear, and a thermal energy conversion system. The heat source provides the energy to the conversion system which could be either static (thermoelectric or thermionic) or dynamic (Rankine, Brayton, Stirling). The dynamic options are most attractive for Space Station applications because of the 25 to 30 percent conversion efficiencies that can be attained, not penalized by the electrical storage cycle that seldom exceeds 80 percent. Complete Brayton power conversion subsystems have been extensively tested by NASA (2 to 15 kWe). A total of 40 000 hr of testing have been carried out at temperatures of 1100 K. There are no significant technology issues barring the application of Brayton technology in the range of 1100 to 1500 K. A component technology base for the potassium-Rankine cycle exists for temperatures up to 1100 K. Organic-Rankine systems have been extensively developed for terrestrial application. In space the Rankine cycle presents the problem of two phase flow in zero gravity. The Stirling cycle has been extensively developed for terrestrial applications. The free piston version has potential for space application. Small 3 kWe engines have been ground tested with reliable long-life operation. Critical technology issues, present at preferred operating temperatures of 1100 K to achieve highest efficiency, are currently being addressed in a NASA, DOE, DARPA program (ref. 5).

The non-nuclear heat source for these dynamic options consists of a concentrator mirror collector and a heat receiver with thermal storage. This is coupled to the dynamic heat engine/alternator and waste heat rejected with a space radiator behind the mirror. This is depicted in figure 6. The mirror can be erected and pointed with suitable precision. The performance potential is 10 to 75 kWe continuous to user with a single Shuttle launch, ac regulated output, single or multiphase 100 to 300 V, low to high frequency. System specific area and power are 175 to 300 W/m^2 and 40 to 120 kg/kWe respectively. The technology base for collectors and receivers for space is limited to prototype 6 ft and 20 ft rigid concentrators tested on the ground and experimental verification of a heavy receiver at 1100 K. Critical technology work on the receivers and large lightweight deployable concentrators will commence soon. The profound impact of solar dynamic systems on Space Station is shown in figure 7 where two 50 ft diameter or three 40 ft diameter mirror systems can meet the 75 kW load. It is an important option for the power growth of the Station (ref. 6).

A liquid metal cooled nuclear reactor heat source operating at a modest 900 K with a Stirling conversion system, shielded for man rating, complete with radiator can provide a 250 kW power system to low earth orbit in a single Shuttle launch. It requires no sun-pointing. Thus the potential of the nuclear option with very small drag area must be seriously considered for the future (refs. 7 and 8). However, full discussion is beyond the scope of this paper.

POWER MANAGEMENT AND DISTRIBUTION

At high power levels, operation at higher voltage levels becomes a necessity unless exorbitant busbar weights can be tolerated. Typically, the mass of a solar array bus for 100 kW system (300 kW array) exceeds 1500 kg at 100 V. Operation at 300 V would reduce this to about 550 kg. Unfortunately, the space environment contains plasma and interacts with exposed conductors. Relative ion and electron mobilities lead to solar arrays floating primarily at negative potential. Under these conditions, arcing can occur at critical voltages determined by the plasma density and other factors. This arcing can be catastrophic or not depending on circumstances. Solar array design and operating voltage is constrained by this phenomenon. Unfortunately, though much is now known about the high altitude spacecraft charging situation, the low earth orbit region is poorly understood and hard to simulate. A program of theoretical modeling ground experiments and flight experiments are underway to address these critical issues which can impact design (refs. 9 and 10).

Power distribution requires efficient power electronic devices and switchgear. Technology now exists for high power, high speed diodes and transistors, capacitors, and magnetics and much has been accomplished in high frequency (up to 20 kHz) ac components (ref. 11). These various components will enable the construction of large space power distribution systems either high frequency, high voltage ac or high voltage dc. High frequency ac represents a potentially "user friendly" and safe option.

CONCLUSIONS

To place all of the foregoing discussion into perspective the major photovoltaic, solar and nuclear dynamic system options are compared for specific area and power in figure 8. The gallium arsenide erectable concentrator array has a smaller area and is lighter than rigid planar silicon, but requires pointing within 1 to 2°. Arrays can be of modular construction for future system growth and repair or replacement. For storage the regenerative fuel cell is lighter than nickel cadmium, has integration, peak load and emergency power advantages and can be packaged in interchangeable modular containers (orbital replacement units). Bipolar nickel hydrogen cycle life problems may not be solved in time for initial station. Solar dynamic systems have a much smaller area and are lighter than photovoltaic options. They can be made in appropriate launchable modules and may have operational benefits.

High pointing accuracy is required ~0.1 degree, unless the heat receiver aperture can be controlled. Because spacetype collector/receiver technology is immature, a major commitment would be needed to provide the option for initial station. The nuclear option is heavy but compact and has many attributes for high power. It requires considerable hardware development that may not be ready until the mid to late 1990's. Nuclear safety and public concerns are significant issues. Many power management and distribution options are viable, but voltage levels and specific designs must carefully consider space plasma environment interaction phenomena not yet fully understood in low earth orbit.

It is important to emphasize that many more detailed studies, optimizations and system verifications must be completed before reasoned decisions can be made. Between now and 1987 an intensive program of system design studies and advanced development work will be pursued in NASA and the aerospace community to quantify performance, cost and risk before flight system engineering and construction begins.

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TABLE I. - 37.5 kW POINT DESIGN RESULTS

Requirements: 3 modules (any 2 able to provide full power)
120 V
58.8/35.7 min Charge/Discharge cycle

Characteristics	NiCd	Bipolar NiH_2	RFC
Effective energy density, Wh/kG	3.9	13.9	13.2
Electrical efficiency, percent	70	70	58.2
Weight[a], kg	5618	1603	1691
Volume[b], ft^3	57	63	115
No. replacements in 30 yr	6	7	5
Heat rejection, kW	12.9	15	21.6
temperature, °C	10	30	60
Number of controllable units	2289	3	6 FC & 3 EU

[a]Excludes heat rejection equipment external to the module.
[b]Algebraic sum of component volumes - no allowance for packaging.

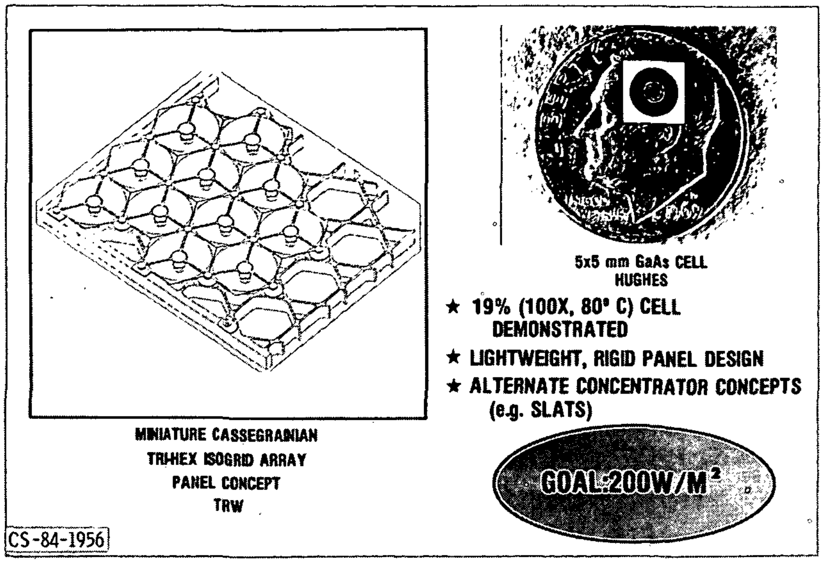

Figure 1. - Concentrator array technology.

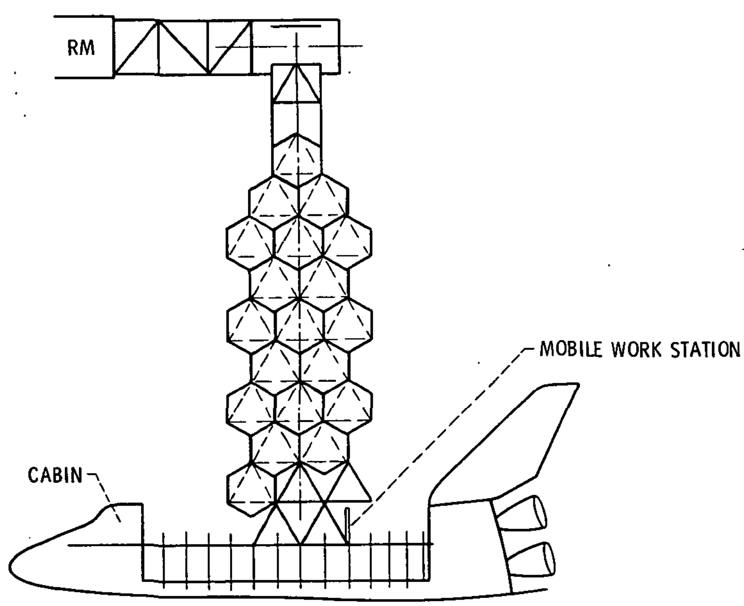

Figure 2. - Assembly of erectable solar array.

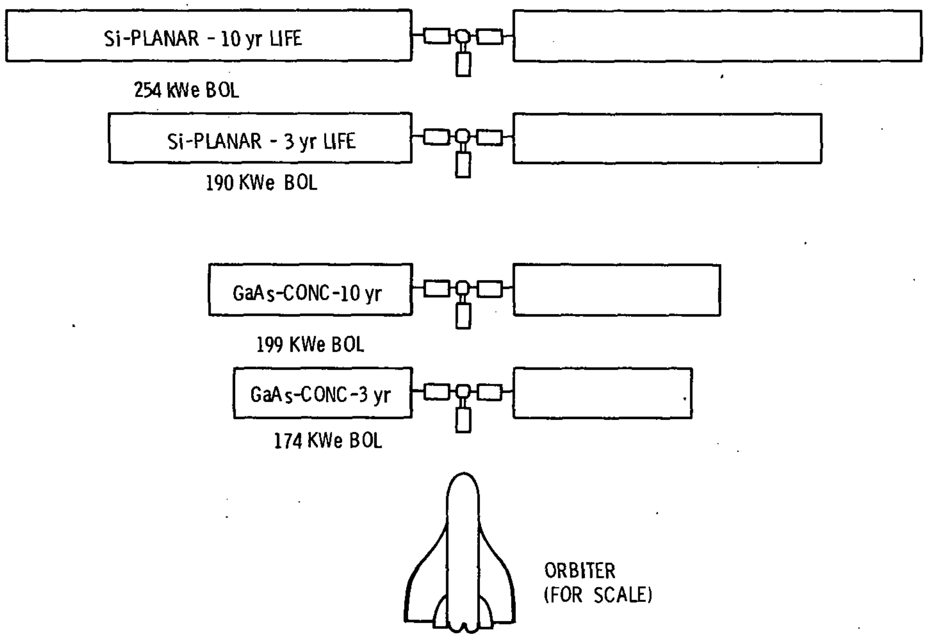

Figure 3. - Space station 75 KWe (EOL) net to bus bar.

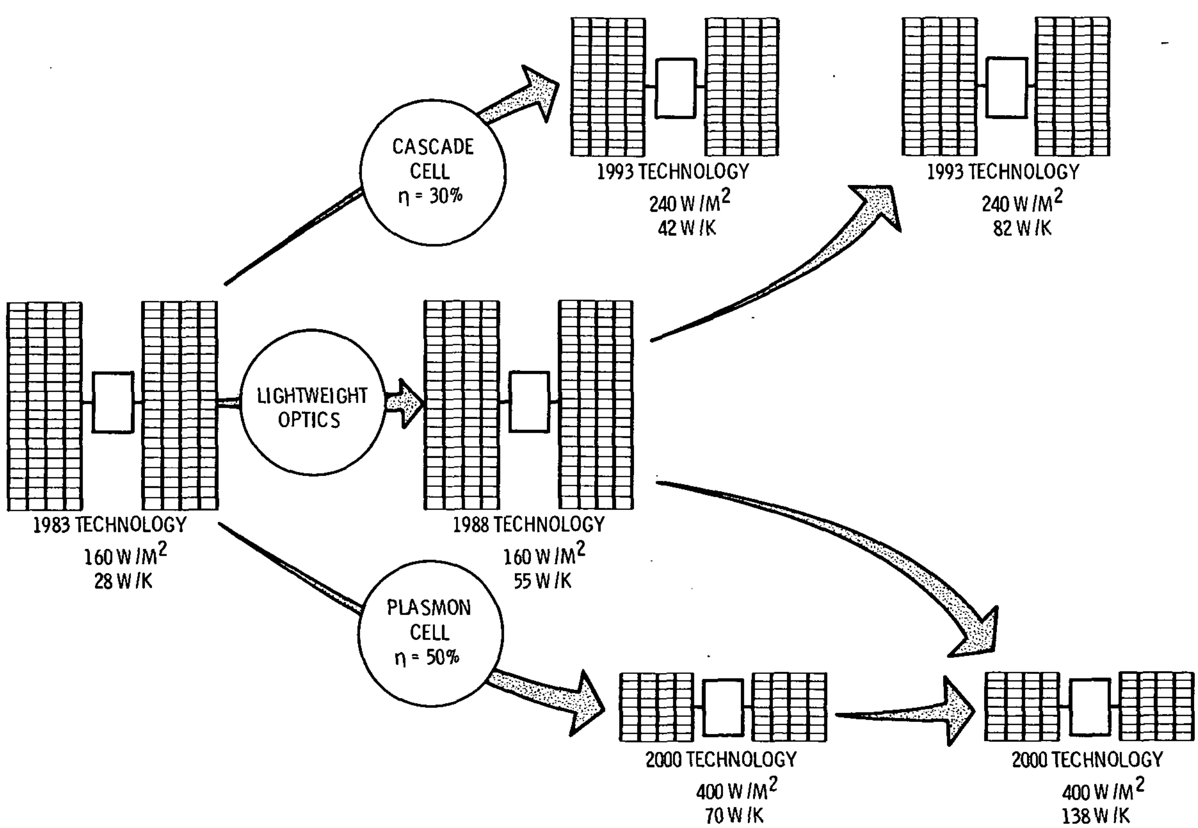

Figure 4. - Impact on concentrator arrays.

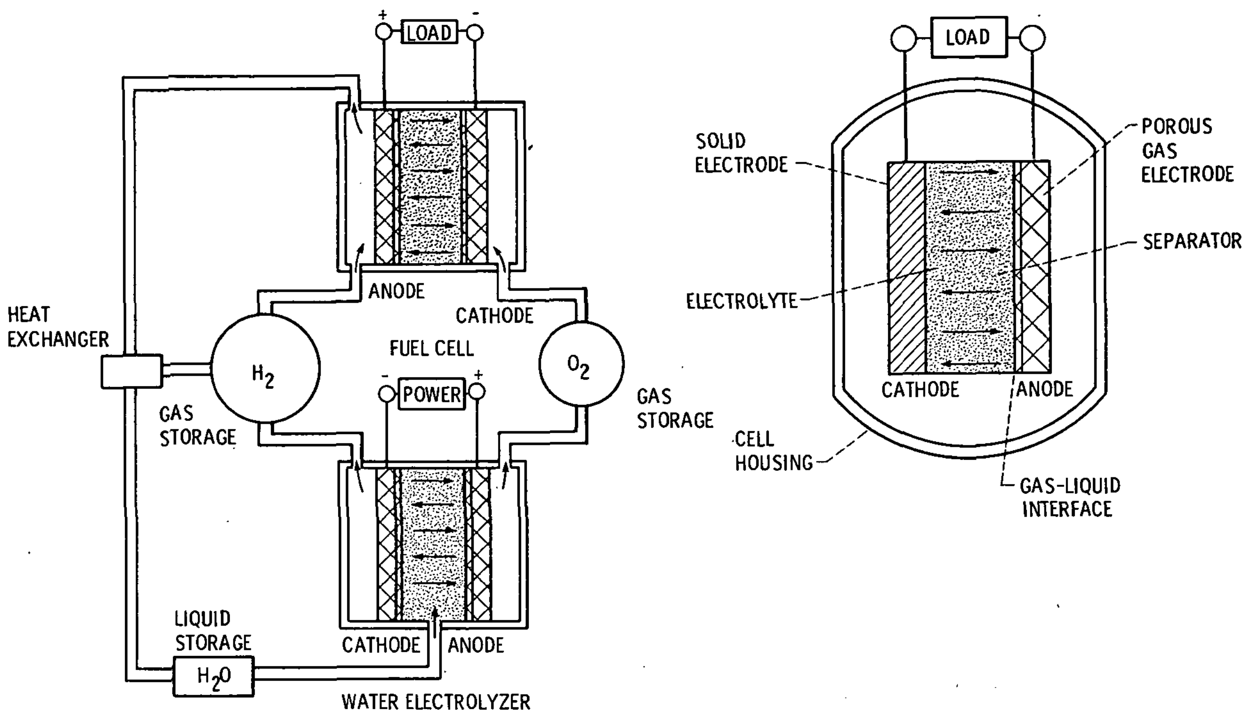

Figure 5. - New approaches to spacecraft energy storage.

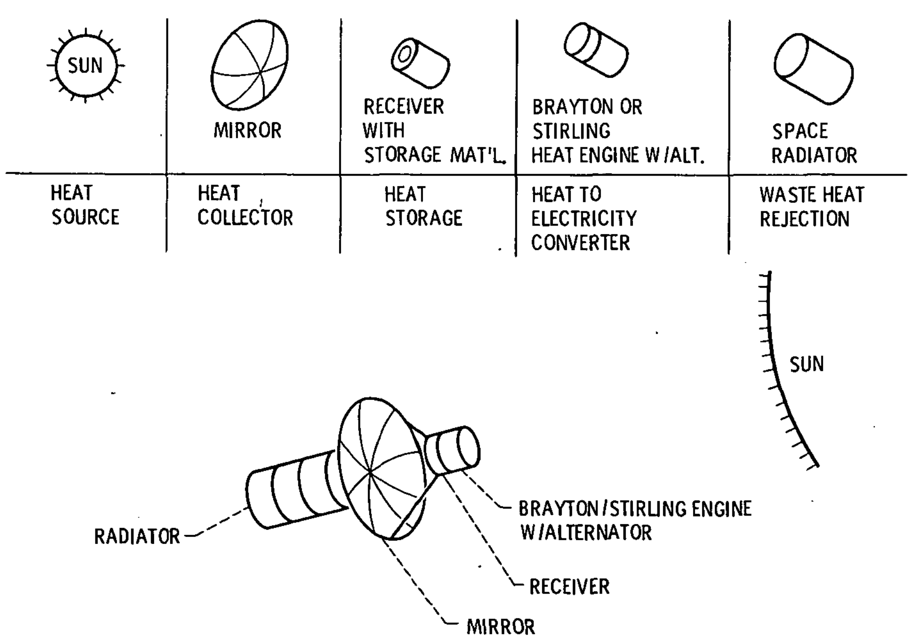

Figure 6. - System concept.

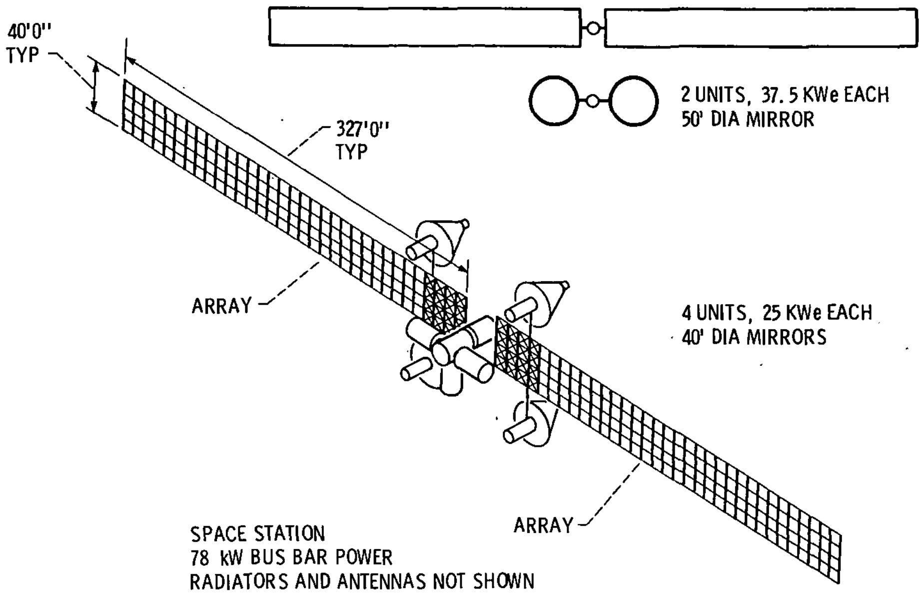

Figure 7. - Impact of solar dynamic technology. Basis: 1500° F Brayton system.

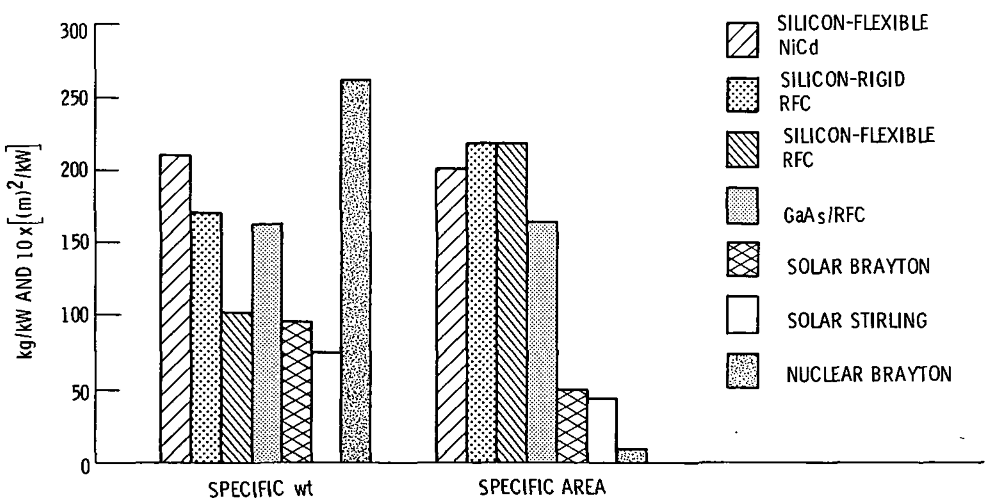

Figure 8. - Specific weight and area of several space station power systems net power output = 75 kWe.

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16. Abstract

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