NASA Technical Memorandum 83690

Space Power Technology into the 21st Century

Karl A. Faymon and J. Stuart Fordyce
Lewis Research Center
Cleveland, Ohio

Prepared for the
Space Power Systems Technology
sponsored by the American Institute of Aeronautics and Astronautics
Costa Mesa, California, June 5-7, 1984

NASA

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Karl A. Faymon and J. Stuart Fordyce
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-2144

SUMMARY

This paper discusses the space power systems of the early 21st century. The focus is on those capabilities which are anticipated to evolve from today's state-of-the-art and the technology development programs presently in place or planned for the remainder of the century. The power system technologies considered include solar thermal, nuclear, radioisotope, photovoltaic, thermionic, thermoelectric, and dynamic conversion systems such as the Brayton and Stirling cycles. Energy storage technologies considered include nickel hydrogen biopolar batteries, advanced high energy rechargeable batteries, regenerative fuel cells, and advanced primary batteries. The present state-of-the-art of these space power and energy technologies is discussed along with their projections, trends and goals. A speculative future mission model is postulated which includes manned orbiting space stations, manned lunar bases, unmanned earth orbital and interplanetary spacecraft, manned interplanetary missions, military applications, and earth to space and space to space transportation systems. The various space power/energy system technologies anticipated to be operational by the early 21st century are matched to these missions.

INTRODUCTION

The continued exploration and exploitation of space will require the development of high efficiency-cost effective space power and energy systems. As on earth, realitization of the promises of space depend largely on the availability of abundant, relatively low cost energy. Large increases over today's spacecraft power levels - by orders of magnitude - will be necessary to meet the perceived mission requirements over the next several decades. These missions of the 21st century will include, large earth orbit manned space stations, manned lunar bases, large manned space transportation systems for earth space, high power geostationary communications and solar power transmitting platforms, multiple purposehigh power-earth resource satellites, large multi-purpose interplanetary probes, and even manned interplanetary exploration spacecraft. In addition, national defense needs will also continue to dictate high power needs for military space systems.

Present and future programs for space power systems development will provide the technology to meet these needs. To progress from today's low voltage - kW sized space power systems to the hundreds-of-kilowatts and multi-megawatt systems of the 21st century will require aggressive development programs to bring these systems to the required technology readiness.

This paper discusses the present state-of-the-art of the various space power systems and energy storage technologies and their projected trends to the end of the century. These trends are then projected to future possible missions of the 21st century to sketch the space power systems of the early

21st century. The discussion will be limited to steady state power requirements. Power systems to meet the very high repetitive or pulsed power requirements characteristic of some military space missions will not be addressed. Figure 1 shows the future space energy demands for some projected space missions. The cross hatched area indicates the historical region, i.e., the energy spectrum of all past missions. Orders of magnitude increases in energy and power over these missions of the past will be required.

PRESENT STATE OF THE ART AND TECHNOLOGY TRENDS

Photovoltaic Cells and Arrays

Most U.S. spacecraft have used low voltage solar arrays. The highest voltage level flown to date on a U.S. spacecraft was that flown on Skylab which has an array voltage of 70 to 115 V and generated 16 kW of power. This planar silicon cell array had a specific power of approximately 6 W/kg.

Present silicon solar cell technology has reached efficiencies of 14 percent for production units and shows some promise for higher efficiencies with further development. Solar cell technology for advanced systems will address the issues of decreased specific weight by means of thin film, (50 μm) cells in light weight flexible arrays, increased efficiency by means of new materials and physical processes, decreased degradation of beginning of life power, and reduced costs.

Figure 2 indicates the projected trends in space photovoltaic cell and array technology. By the mid to late 80's GaAs photovoltaic cells are projected to yield 18 percent efficiencies for planar cells and 20 percent for concentration cells. Present dual multibandgap cells are expected to yield 22 percent efficiencies which should increase to 25 percent by the late 80's with improved fabrication techniques. Beyond this point triple junction bandgap cells will ultimately approach 30 percent efficiencies and advanced photovoltaic concepts such as those based on surface plasmon effects and superlattices are optimistically predicted to yield 50 percent efficiencies. These advanced concepts are presently in the research stage. They are expected to be operational by the early part of the next century.

The cells themselves must be mounted in array assemblies and the current state-of-the-art of arrays is approximately 36 W/kg (specific power), but specific power levels of 66 W/kg have already been demonstrated using flexible arrays of thin silicon solar cells. Improvements in thin cells (50 μm silicon and GaAs), efficiency and radiation resistance, coupled with advancements in the design of durable lightweight support structures will yield 100 W/kg or greater by 1990. Technology advancements in 5 μm thin GaAs and advanced concept cells now in the research stage along with advances in concentrations and array structures should increase capabilities to 200 W/kg by the mid 90's. Additional advances in thin high efficiency III-V cells may show 23 percent efficiencies with specific powers of 350 W/kg. Thin cascade GaAsSilicon, (2 mill cells), with efficiencies of 27 percent (planar) and 30 percent (Concentrator), are expected to reach 400 W/kg specific power for use in PV space power systems of the early 21st century. Figure 3 shows the impact of cell efficiency on concentrator arrays in which the array is transparent to the cell technology.

Energy Storage Systems

Most earth orbital missions using solar derived power will require onboard energy storage to provide spacecraft power during the earth shadow periods. Energy storage can be accomplished for these missions by means of secondary rechargeable batteries, regenerative fuel cells, or possibly inertial energy storage using flywheel systems. Secondary space battery systems are presently undergoing transition from the traditional nickel cadmium systems to nickel hydrogen systems and ultimately to high energy density rechargeable batteries, (HEDBR) of the Li/X and the Na/X types. Significant gains in specific weight reductions will be realized using the proposed HEDRB technology. Present NiCd technology is at a level of 10 to 15 W hr/kg, depending upon the application (Leo or Geo) with some gains possible in the future. NiH_2 battery systems presently are at 20 W hr/kg with expected improvements to 30 W hr/kg for the NiH_2 bipolar concept. The bipolar approach permits high capacity, high voltage storage system modules, avoiding the multitude of cell to cell interconnects, and presents the opportunity for active cooling. Design life is related to orbit, (cycling), operating temperature and depth-of-discharge (DOD). Projected lifetimes to well beyond 10 years are possible. Aggressive development of lithium and sodium based battery systems is expected to yield energy densities on the order of 80 W hr/kg or greater. However, much more development effort is needed to overcome the limited cycling capabilities.

An energy storage system which shows great potential is the regenerative fuel cell, (RFC). An RFC is one that operates in both the conventional power producing mode, and also in the reverse, (power consuming) mode to regenerate the reactants which are stored for future use. An advanced H_2O_2 biopolar battery now at the breadboard level of development for large low earth orbit application is being explored for synchronous orbit application and has a potential for specific energies in excess of 100 W hr/kg. H_2/halogen based regenerative fuel cell systems offer the potential for very high efficiency storage systems and are also being investigated. Figure 4 shows the projected trends in electrochemical storage systems.

Flywheels as energy storage devices are also under consideration. Inertial devices have been used in the past for attitude control, (Control Moment Gyros), but not as direct energy storage for space systems. Recent studies indicate that advanced flywheel systems will be competitive with other storage technologies but these conclusions are very preliminary at this time. Attractive features of flywheels are high level of discharge, (75 percent), high response rates, high overall efficiencies, and possible long life. Projections of composite material flywheel energy densities up to 40 W hr/kg, (for the overall system), have been made. Problems in the areas of materials, structural integrity, and system design remain to be overcome.

Figure 5 shows the impact of the various energy storage technologies on the power system mass for a given solar power system.

Thermal Power Systems

Thermal power systems consist of a heat source, (solar, chemical, nuclear, etc.) and a thermal energy conversion system. (For steady state systems, no chemical or open cycle systems will be considered.) The heat source provides the energy to the conversion system which could be either dynamic (Rankine, Brayton, Stirling, etc.) or static (Thermoelectric, thermionic). Only thermoelectric systems powered by radioisotope heat sources have been routinely operated in space by the U.S. The dynamic Brayton system has been extensively developed and tested in a flight type system, and significant effort has also been carried out on liquid metal Rankine systems. Only ground system testing has been carried out on these systems. The Stirling cycle energy conversion system has been extensively developed for terrestrial power applications and shows significant potential for application to space power systems in the form of the free piston-linear alternator configuration.

Heat Sources

Radioisotope heat sources have been used extensively for low power space applications, both earth orbit and interplanetary missions. PU 238 has been the dominant isotope. These systems show negligible delay over a 10 year life at temperatures up to 1400 K. High cost, limited fuel availability, and questions of safety will limit these isotope systems for larger powers (Multikilowatt). For space power applications, the fuel capsule must be designed to withstand intact reentry should there be a mission failure or abort. An RTG system of 400 W (electrical) will be flown on the upcoming Galileo mission in 1986.

The only U.S. flight of a nclear reactor was the low power SNAP 10A reactor. This reactor experienced a shutdown after 47 days in orbit due to a nonnuclear component failure (voltage regulator). This was a small (less than 1 kWe) U-ZrH reactor with a Si-Ge thermoelectric energy conversion unit.

The SNAP technology of the 1960's was limited to reactor outlet temperatures of less than 1000 K, but the potential, based on LMFBR technology, exists for reactor outlet temperatures in excess of 1500 K by substitution of a high temperature material for stainless steel in the reactor design. A substantial data base for these advanced materials exists. A potential reactor design has evolved, from the Los Alamos National Laboratories which is a departure from conventional design. This concept uses unclad fuel wafers with heat pipe cooling for the reactor. Reactor outlet temperatures up to 1500 K are projected for this design.

The major issues with respect to reactor design are related to fuel type, fuel irradiation data base, clad material, material data base and selection, safety, failure tolerances, and reliability. These issues are presently being addressed by the SP-100 and Multi-Megawatt Systems projects of NASA, DOE, and DARPA. A schematic showing the cross section of a typical conventional reactor is given in figure 6.

This particular reactor was a liquid cooled fast-spectrum type which was investigated in the past at the Lewis Research Center of NASA. This was a low temperature, 950° C 2 MW (thermal) unit with a temperature capability growth to about 1230° C. It was designed for a lifetime of 50 000 hr. The fuel selected for this reactor was uranium mononitride.

An attractive nonnuclear alternative exists for solar photovoltaic systems, namely, solar thermal dynamic power systems. Compared to present day solar photovoltaic cell/array technology, these systems will show substantial decreases in solar collection area, due to the increased efficiency (over solar cells with battery storage), of the dynamic (Brayton, Rankine, Stirling), energy conversion systems. Figure 7 shows the relative sizes of the solar thermal system concentrator relative to candidate solar PV arrays. This decreased size can have significant effects of the drag, (in low Earth orbits), and on controllability due to decreased moment of inertia about the spacecraft controls axis. Also structural dynamic interactions with the spacecraft can be minimized.

Figure 8 indicates the expected trends in specific weights of solar dynamic systems (kg/kW) to the end of the century.

The technology for solar thermal heat receivers and thermal storage components is not very extensive and requires much additional development. Experimental verification for systems of 1100 K have been carried out but no flight experience exists. Questions of the thermal storage medium (especially for high temperature systems), materials compatibility, and receiver design will be addressed under a new solar thermal initiative being proposed by several NASA centers led by the Lewis Research Center of NASA. Solar concentrator technology must be developed along with solar thermal heat storage technology. Prototype 6 ft and 20 ft rigid concentrations have been fabricated and ground tested at NASA Lewis Research Center, but no flight testing of these components has been carried out. A limited technology base on concentrators does exist, in part stemming from advanced space antenna concepts. Key technology issues, as of today, are related to the development of lightweight deployable concentrators with good surface accuracy. These issues will also be addressed under the NASA initiative.

Energy Conversion Technology

Static conversion of thermal energy to electricity includes thermoelectric and thermionic devices. Thermoelectric power conversion systems have been extensively developed over the last 25 years. These conversion devices (thermoelectric), are the only units so far routinely used with nuclear heat sources by the U.S. The thermoelectric units were Si-Ge and were in the multi-hundred watt (MHW) range. These were relatively low efficiency units and the present upper temperature limit for Si-Ge is approximately 1250° F with some improvement possible. New classes of thermoelectric materials may raise both the efficiency and peak temperatures, but actual demonstration of these requires an additional technology program. Figure 9 shows thermoelectric technologies which are applicable for advanced thermoelectric systems.

Another possible thermoelectric technology which may show some promise for space power applications is that of AMTEC (Alkalai Metal ThermoElectric Conversion). This system consists of a sodium thermal electric battery which has been assessed and determined to be a viable technology for application to space power systems. No extensive development of this technology is now in progress.

Performance of thermionic converters is directly related to temperature, both efficiency and power density increasing with increasing temperature. For temperatures of 1500 K the performance of thermionic systems is not competitive with other technologies.

Test results of various thermionic converter units are given in table I. The converters were tested with varying geometries, fuels, and heat sources. The converters, LC-9, LC-11, and LC-3, were electrically heated and the first LC-9 gave stable performance, with LC-3 shorting out. The other converters were tested in a nuclear reactor. The units 6F-2 and 6F-3 were configured with 6 converters in a stack much like the batteries in a flashlight. Of these reactor tested converters, two of the units operated successfully for up to 11 084 hr, the others failing for various reasons. Fuel temperature and converter lifetime are thus the outstanding problems in thermionic converter technology (ref. 7).

Dynamic conversion systems based on the Brayton, Rankine, and Stirling cycle are viable candidates for space power systems. Complete Brayton power conversion subsystems have been extensively ground tested by NASA (2 to 15 kW_e). A total of 40 000 hr of testing have been carried out on Brayton systems at temperatures of 1100 K. The turbo-alternator consisted of an axial flow turbine and a synchronous alternator with gas bearings. This energy conversion system showed a net efficiency of 20 percent. Structural materials for 1100 K, substitution of tantalum based alloys can provide performance gains. There are no significant technology issues barring the application of Brayton cycle technology to space power system using heat source temperatures in the range 1100 to 1500 K.

The principal technology which was evolved in the past Rankine space power program was that for the potasium-Rankine cycle. Although a complete power plant of this type was never built and tested, a large amount of enabling technology has been evolved. Turbines were built and tested for 5000 hr at 1100 K. Condensers were built and tested for coolant temperatures up to 1000 K, and electromagnetic pumps were tested for 10 000 hr at fluid temperatures up to 1035 K. This technology base is directly applicable to space power applications. Critical issues for the Rankine cycle are associated with potential "Zero G" problems of two phase flow which exists in both the boiler and condenser systems reliability is also an issue since these are relatively complex machines.

The Stirling cycle has been extensively developed for terrestrial applications. The free piston Stirling-linear alternator version of this technology is believed to have potential for space power applications. Small, 3 kW_e, free piston Stirling engines have been ground tested and this concept appears to offer reliable long life operation. Critical technologies are in the areas of high heater temperatures and long life piston seals. Temperatures of at least 1100 K are desirable and heat rejection temperatures must be such as to minimize system specific weight. These technology issues and the overall applicability of the free piston Stirling technology to space applications are being addressed by the SP-100 program of NASA, DOE, and DARPA.

Space Power Systems Architecture

An operational space power system consists of: (1) an energy or heat source, (2) an energy conversion system, (3) a heat rejection/thermal management system, and (4) a power management and distribution system which includes controls. The choice of a particular power system and its particular architecture will be determined by the individual application; type of earth orbit or interplanetary trajectory, peak and average power requirements, etc.

For the thermal power systems, the output temperature of the heat source must be matched to the input temperature of the energy conversion component. In addition, because of the large heat rejection requirement, the radiator temperature must be chosen so as to meet some "optimization" requirements, possibly minimum overall system weight. The actual power system configuration and operating characteristics will be determined by the particular mission or function to which it will be applied.

The missions of the future will require large increases in power over today's missions in order to carry out their function. This will drive the power systems toward higher voltages compared to today's systems because of the inefficiencies and weight penalties associated with low voltage systems. Also, the dc systems of today will yield to ac or hybrid ac-dc systems for the same reasons and also to meet a diversity of power needs on future spacecraft/ space stations. Technology programs presently under way will address the development of the required components for these power management and distribution systems. In addition, spacecraft design guidelines and techniques are being developed to address what may be significant problems of interactons of high voltage systems with the space environment.

High power spacecraft/space stations must also contend with large heat rejection and thermal management problems. Space radiators for these power systems will be large and massive to accommodate the large heat loads, which must be rejected to space. Technology programs for advanced thermal management systems are also under way at this time. Some advanced concepts, such as the liquid droplet radiator, show promise for application to the high power systems of the future.

Space Power Systems of the 21st Century

The definitions and descriptions of space missions for the first part of the 21st century are obviously meager. However, with some trepidation we can indulge in speculation and for the sake of illustration postulate the following types of missions and space systems for that era.

(1) Large manned earth orbiting stations (LEO)

(2) Smaller manned and unmanned orbiting platform (LEO)

(3) Geosynchronous manned and unmanned utility and communications platforms

(4) Unmanned earth resource/physics/environment satellite

(5) Unmanned interplanetary spacecraft (planetary exploration)

(6) Manned lunar base/colonization

(7) Manned planetary orbiters/landers

(8) Military earth orbit missions

(9) Space transporation systems

Each of these classes of missions has unique requirements of on-board power and energy. No one single technology is the most optimum or cost effective for such a wide spectrum of applications. The actual requirements will be determined by the individual mission specifications. We will, however, speculate on these missions and assign to each mission the power system which we feel best suits that mission requirement.

CONCLUDING REMARKS

These missions are listed in table 2 with the matching power systems technologies. If more than one power or storage system technology is applicable, this is also shown on table 2 with the primary choice indicated by o, and other possible candidates shown with an .

The manned and unmanned space transportation missions will be of short durations compared to the other missions listed here. Thus they will be, in most cases, powered by primary power systems. These include advanced fuel cells, dynamic APU's (auxiliary power units), and advanced primary batteries of the $Li/SOCL_2$ type.

In designing a spacecraft or space station, additional considerations arise which were not explicitly considered here. In selecting a subsystem or component, the consideration of how that particular item can be "integrated" with the remainder of the on-board systems arises. For instance, H_2/O_2 regenerative fuel cells could be chosen over another type of storage system since they could be integrated, (in a manned system), with the life support system, and the reaction control system by providing make up oxygen for the cabin, and hydrogen propellent for the attitude control system the space shuttle resupply being H_2O for this case. Flywheels may be chosen for energy storage, since it may be possible to use them in an integrated energy storage-attitude control configuration. For orbital processing functions, nuclear and solar thermal system could be used to provide "direct process heat" at high temperatures rather than providing this heat by resistance heating at a lower efficiency. A problem arises in that nuclear systems must be either shielded or "isolated" and this complicates the integration problem into a manned station that must be compatible with space shuttle operations. In addition, the manned stations or vehicles will be required to have on board some form of back-up power to protect the personnel in case of a mission emergency until help is available. These will in all probability be some form of excess battery or fuel cell capability, or could take the form of an open cycle on-board dynamic auxiliary power unit, (APU), using stored propellants.

Finally, human ingenuity and unpredictable new technologies may arise in the next decade which could significantly alter these projections which are based reasonable extrapolations from the technology development programs presently in progress and those foreseen for the future. Many things could come about which would significantly alter the future opportunities presented here. But it is a certainty that many diverse challenges lie ahead for space power technologies, an enabling factor in man's ever expanding horizons.

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TABLE I. - SUMMARY OF THERMONIC TESTS

Device	In pile or out	Fuel	Temperature, K	Power, W/cm	Duration, hr	Result
LC-9	Out	None	1970	8.0	46 647	Operable
LC-11	Out	UC-ZrC	1870	6.5	18 569	Operable
LC-3	Out	W-UO_2	2000	8.9	10 406	Short
I-4	In	UC-ZrC	1840	6.0	8 754	Leak
C11		UO_2	1840	3.4	7 811	Crack
2E-1		UO_2	1820	4.0	12 534	Swelling
2E-2		UO_2	1820	5.6	11 084	Operable
1F-1		UC-ZrC	1780	4.0	8 560	Swelling
6F-2		UO_2	1780 to 1950	2.3	7 685	Cracks
6F-3		UO_2	1740 to 1820	3.0	8 062	Operable

TABLE 2

	Large Manned Earth Orbiting Stations	Manned/Unmanned Orbiting Platforms	Geo Manned/ Unmanned Utility and Comm Platforms	Unmanned Earth Resource Satellites	Unmanned Interplanetary Spacecraft	Manned Lunar Base	Manned Planetary Orbiters/ Landers	Military Earth Orbit Missions	Space Transportation System
Heat Source									
Nuclear	●				●	●	●	●	
Radioisotope								○(3)	
Solar		●(1)	●						
Energy Conversion									
Photovoltaic		◇	○(2)	●					
Thermoelectric									
Thermionic					◇				
Dynamic-Alternator	●	●	●		●	●	●	●	
APU									●(4)
Energy Storage									
Fuel Cells		●		●				◇	
Batteries		◇		◇				●	●
Flywheels		◇		◇					
Thermal			●						
Power Requirements									
High Voltage	●	●	●		●	●	●	●	
D.C.					●				
A.C.			○(2)						
AC-DC	●	●	●	●	●	●	●	●	●
System Integration									
W. Life Support		●							
W. Attitude Control		◇		◇					
W. Process Heat	●					●	●		

Notes:

● Prime choice
◇ Possible choice - depending on mission requirements.
(1) Larger systems may go with prime choice - smaller, 1-10K systems may best be served by ◇ systems.
(2) For the large (GW) size space power - actual conversion system to be determined - storage to be on ground (advanced Redox system).
(3) The military missions will have many specialized requirements which will dictate choice.
(4) The space transportation systems will use primary batteries - an on-board APU is also possible.

Remark: The manned systems will also require emergency - back up power - These requirements can be met by excess secondary systems capacity - or by providing primary systems capacity.

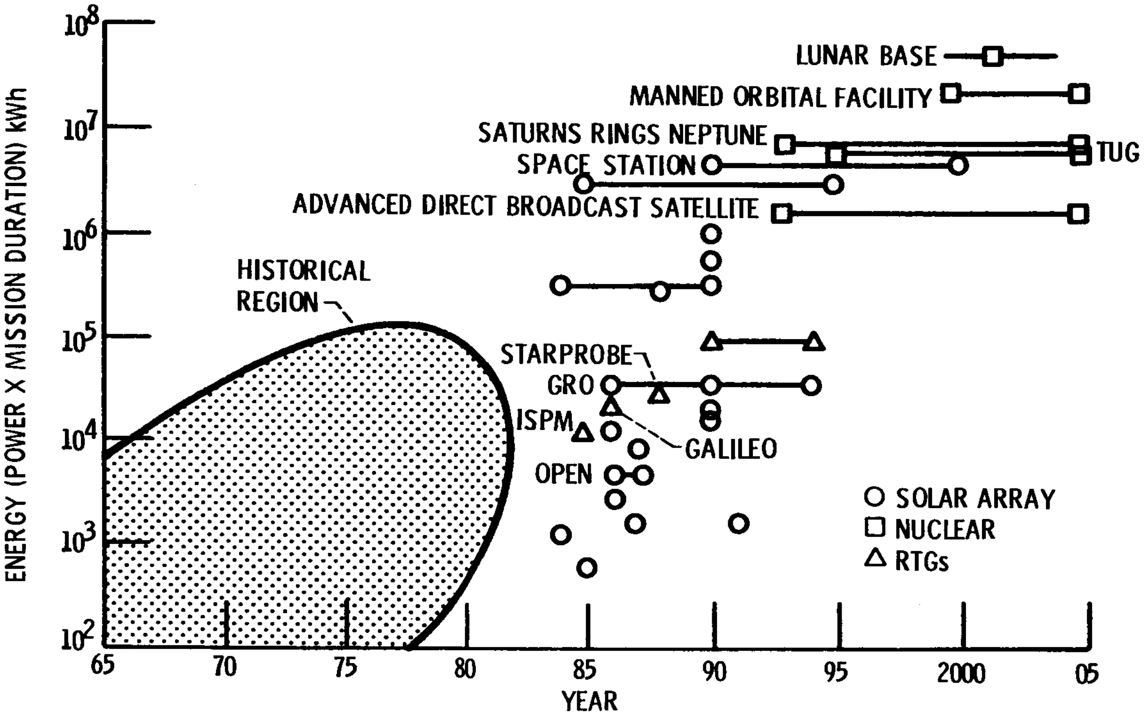

Figure 1. - Future space energy demands (ref. JPL).

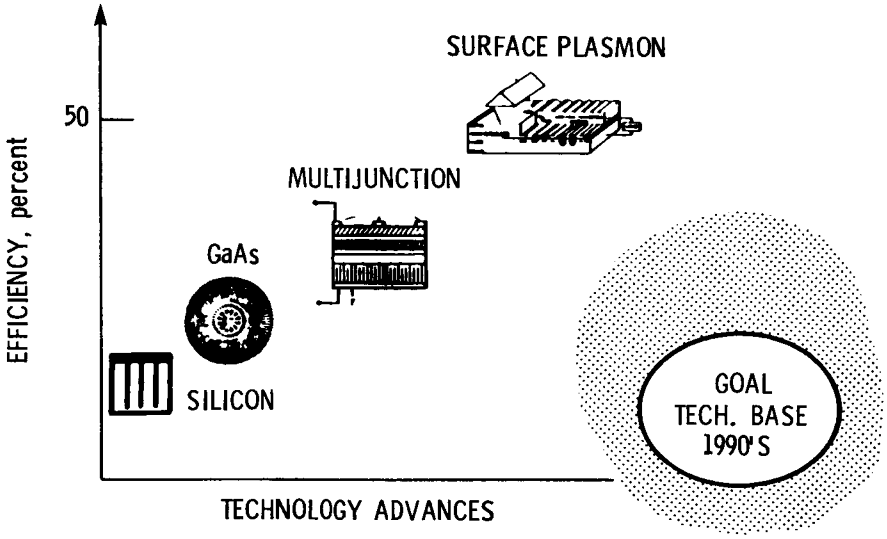

Figure 2. - Advanced photovoltaic device R&T.

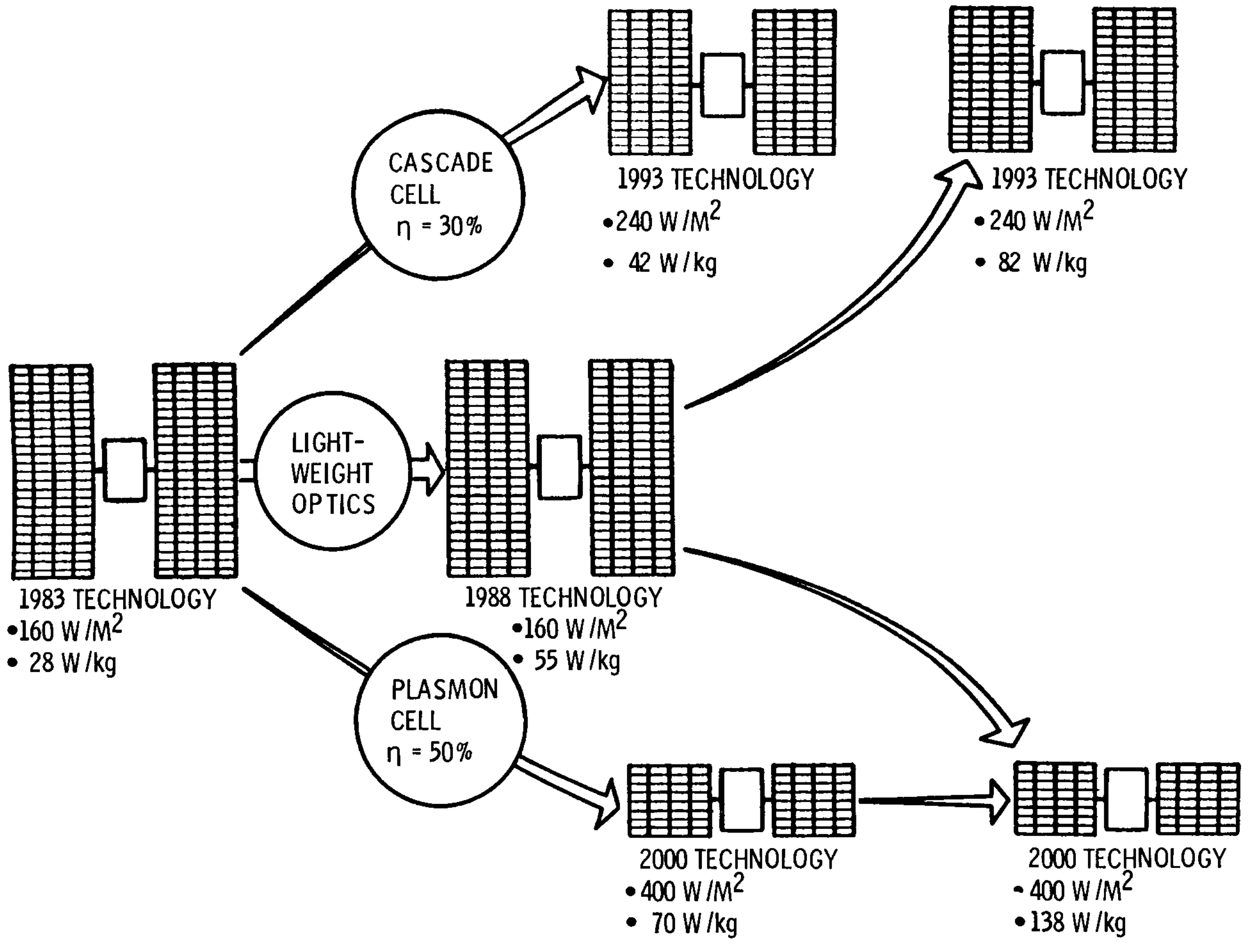

Figure 3. - Impact on concentrator arrays.

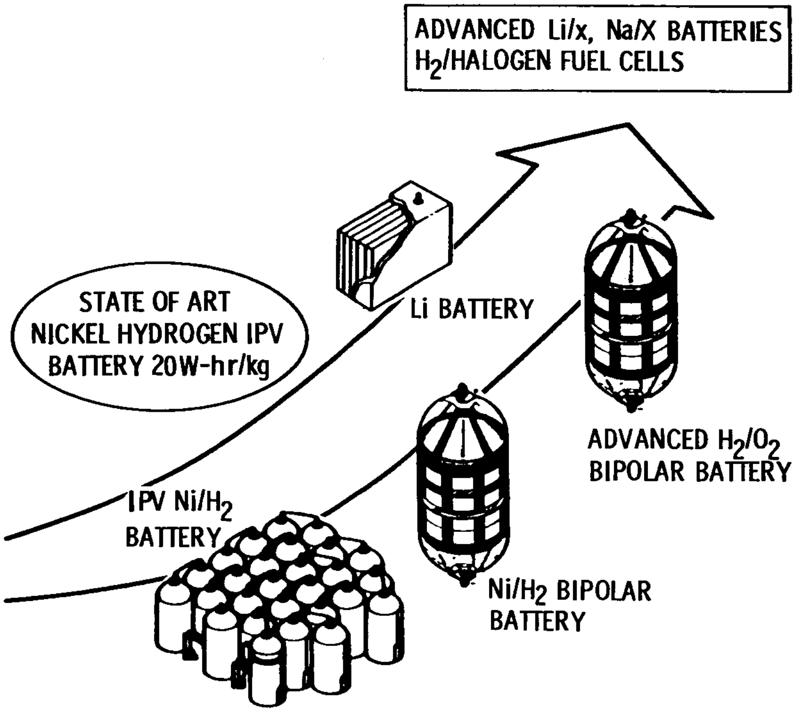

Figure 4. - High-density energy storage for spacecraft R&T advances.

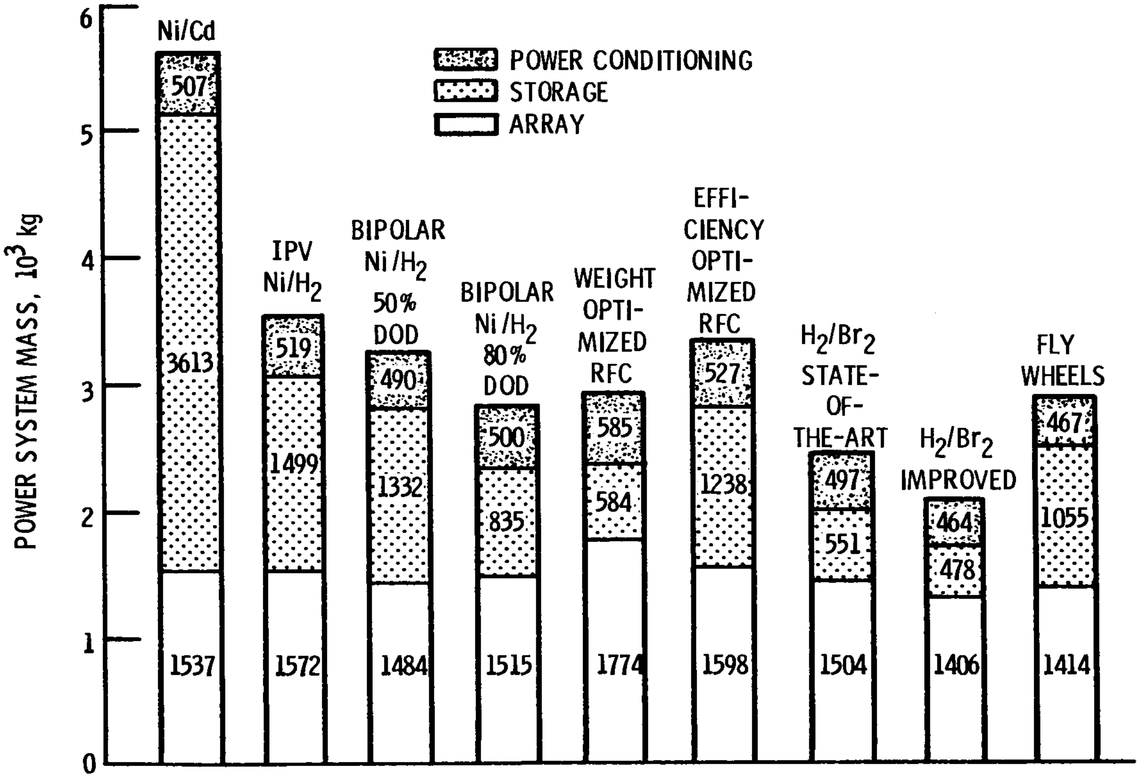

Figure 5. - Power system mass breakdown by major subsystem, 35 kW to load, SEP array 200 n mi, 28-1/2° orbit.

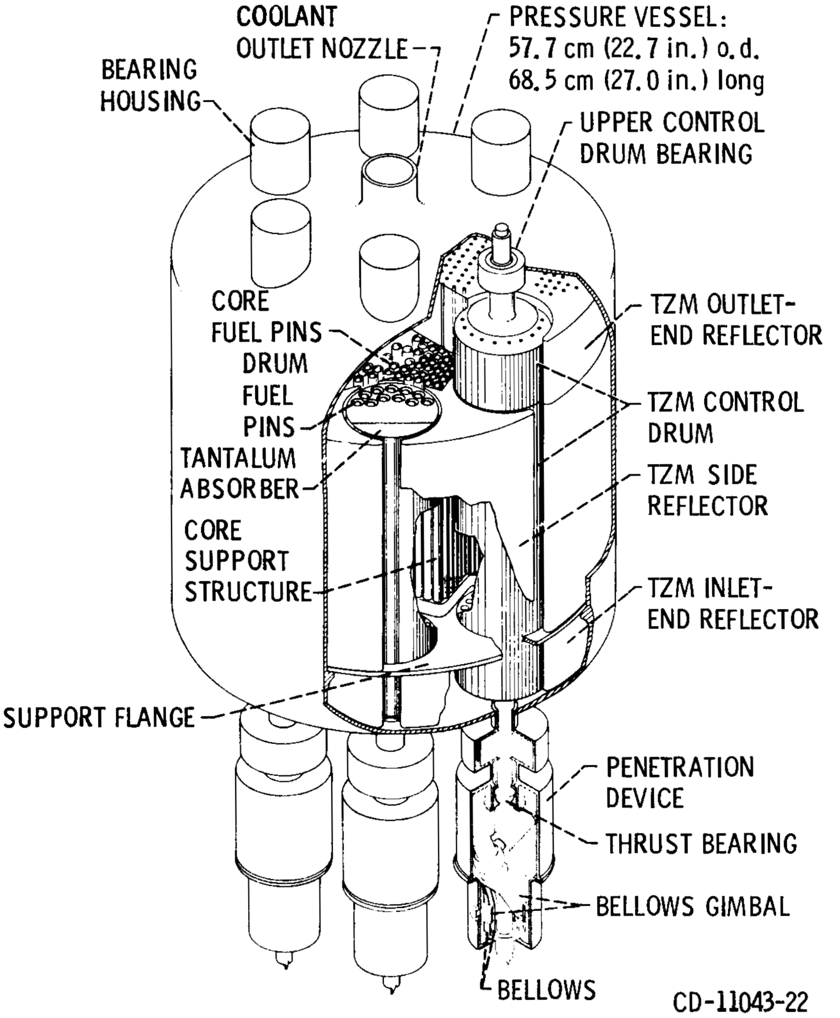

Figure 6. - Compact fast reactor reference design.

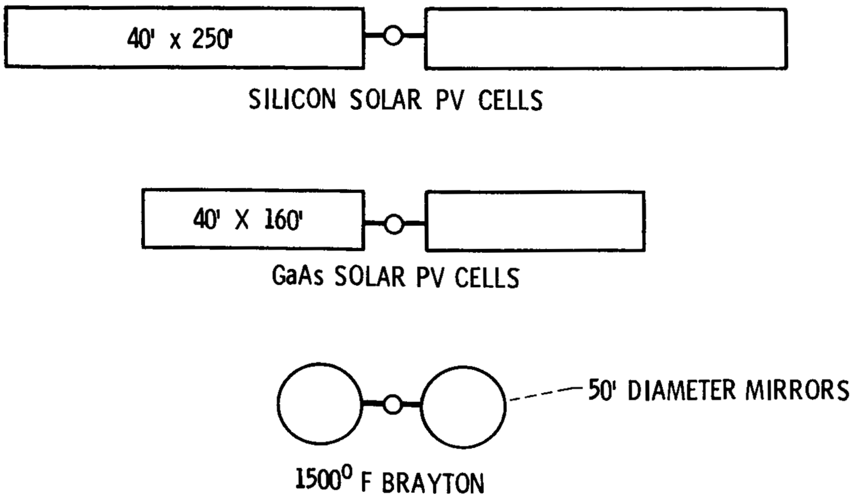

Figure 7. - Solar thermal power systems technology.

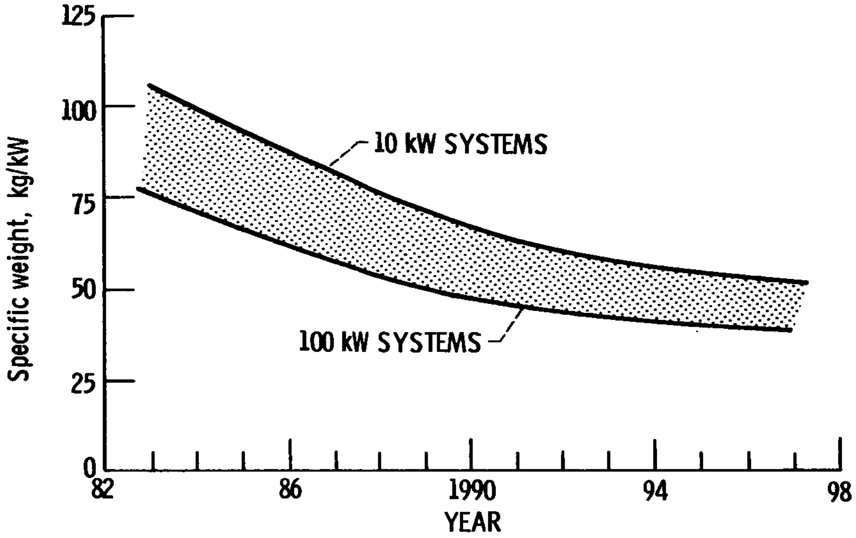

Figure 8. - Solar thermal power systems technology.

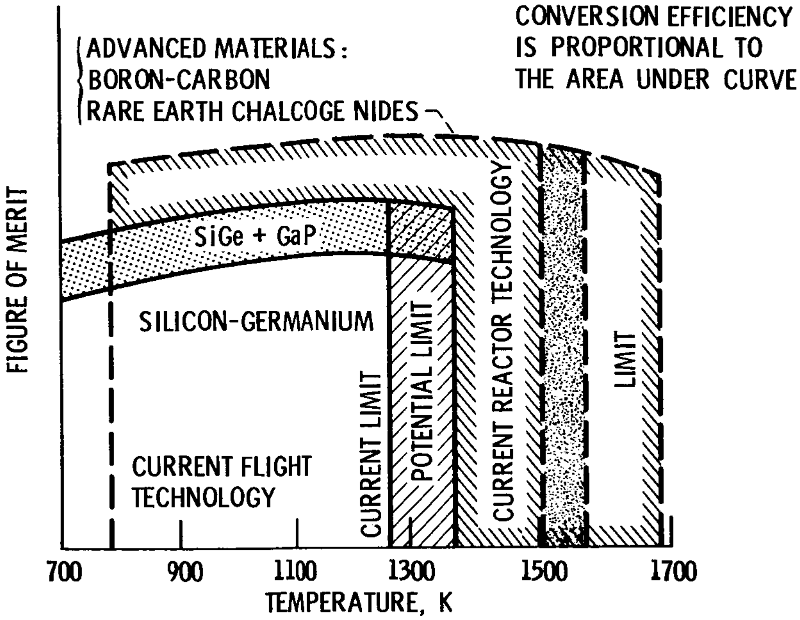

Figure 9. - Thermoelectric conversion technology (from ref. 8).

1. Report No. NASA TM-83690	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Space Power Technology into the 21st Century	5. Report Date 6. Performing Organization Code 506-55-42
7. Author(s) Karl A. Faymon and J. Stuart Fordyce	8. Performing Organization Report No. E-2144 10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Space Power Systems Technology Conference sponsored by the American Institute of Aeronautics and Astronautics, Costa Mesa, California, June 5-7, 1984.

16. Abstract

This paper discusses the space power systems of the early 21st century. The focus is on those capabilities which are anticipated to evolve from today's state-of-the-art and the technology development programs presently in place or planned for the remainder of the century. The power system technologies considered include solar thermal, nuclear, radioisotope, photovoltaic, thermionic, thermoelectric, and dynamic conversion systems such as the Brayton and Stirling cycles. Energy storage technologies considered include nickel hydrogen biopolar batteries, advanced high energy rechargeable batteries, regenerative fuel cells, and advanced primary batteries. The present state-of-the-art of these space power and energy technologies is discussed along with their projections, trends and goals. A speculative future mission model is postulated which includes manned orbiting space stations, manned lunar bases, unmanned earth orbital and interplanetary spacecraft, manned interplanetary missions, military applications, and earth to space and space to space transportation systems. The various space power/energy system technologies anticipated to be operational by the early 21st century are matched to these missions.

17. Key Words (Suggested by Author(s)) Space power; Photovoltaics; Batteries; Fuel cells; Nuclear reactors; Solar thermal; Thermionics; Thermoelectric	18. Distribution Statement Unclassified - unlimited STAR Category 20

19. Security Classif. (of this report) Unclassifed	20. Security Classif. (of this page) Unclassified	21. No. of pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161