4/18/91
E5835

NASA Technical Memorandum 103649

Power Technologies and the Space Future

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April 1991

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E-5835

SUMMARY

Human society is inexorably advancing into space - the new frontier of the 21st century. Advancements in space power and energy technologies are critical to serve space development needs and help solve problems on earth. The availability of low cost power and energy in space will be the hallmark of this advance.

Space power will undergo a dramatic change for future space missions. The power systems which have served the U.S. space program so well in the past will not suffice for the missions of the future. This is especially true if the commercialization of space is to become a reality. New technologies, and new and different space power architectures and topologies will replace the lower power, low-voltage systems of the past. Efficiencies will be markedly improved, specific powers will be greatly increased, and system lifetimes will be markedly extended.

This report discusses space power technology: its past, its current status, and predictions about where it will go in the future. A key problem for power and energy (not unique to space) is its cost or "affordability." Power must be affordable, or it will not serve future needs adequately. This aspect of space power is also specifically addressed.

INTRODUCTION

Energy and power are crucial commodities in today's highly industrialized society. Throughout the ages, the ability to harness resources and to augment human capabilities with external power and energy has been the key to continued progress. The availability of low-cost, plentiful power and energy will also be the key to humankind's future advancement, both on the terrestrial sphere and in space.

Human society is inexorably advancing into space - the new frontier of the 21st century. Advancements in space power and energy technologies are critical to serving space development needs and to helping solve problems on Earth. The 21st century will truly be "the Century of the Global Economy," "the Century of Space." Space technology will expand our horizons and will serve all on Earth. The availability of low cost power and energy in space will be the hallmark of the advance.

This chapter discusses space power technology: its past, its current status, and predictions about where it will go in the future. A key problem for power and energy (not unique to space) is its cost or "affordability." Power must be affordable or it will not serve future needs adequately. This aspect of space power will be specifially addressed.

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[*] To be published as chapter 7 in "Space Power: A 21st Century Option for Energy Supply on Earth," Eds. Dr. Peter Glaser and Prof. F. Davidson, Ellis Horwood Limited, Chichester, England.

HISTORY: SPACE POWER TECHNOLOGY IN THE EARLY DAYS OF THE SPACE ERA

Satellite space power systems which were flown in the 1960's and 1970's consisted of photovoltaic solar cell energy conversion systems backed up by batteries for Earth orbital missions where energy storage was required. These early systems were of low power, less than 1 kW - usually a few hundred watts at most. They were low-voltage, direct current systems, an inheritance from aircraft power system practice of the day. The one exception, a major advance at its time, was the Skylab, which had a 12-kW power system of approximately 56 V. In general, the space power systems of that time period were silicon-based photovoltaic systems with power densities of 16 W/kg and efficiencies of 10 to 12 percent. Energy storage systems were nickel cadmium batteries with 7 W-hr/kg energy densities and power system lifetimes of 7 years with a performance degradation of 25 percent over their lifetimes. These were high-cost systems - $1.0 to $1.5 million/kW (in dollars of those years). Low-power radioisotope thermoelectric generators to augment the solar power conversion system for Earth orbit and outer planet missions were used extensively. Thermal dynamic and nuclear power systems development was started, and a small nuclear reactor was flown by the United States. Further development of these technologies was halted because of an absence of specific applications. Significantly, turbo-alternator Brayton energy conversion systems were developed and extensively tested on the ground. Organic Rankine energy conversion systems were also developed, but no flight test data on any of the dynamic energy conversion systems or their components were obtained. Some unique applications of space and space power were conceived. One such concept was that of the Satellite Solar Power System (ref. 1), which addressed a concern about the terrestrial environment and energy limitations on Earth and used the space domain to help overcome these limitations.

During this period, the total cumulative power that was launched by the United States for civil mission applications was less than 150 kW. The major part of this was launched in fractional kilowatt increments.

SPACE POWER TECHNOLOGY DURING THE DECADE OF THE 80'S

Considerable progress was made in advancing space power technologies in the period leading up to the 80's. However, in general, the satellite space power systems of this decade were still relatively heavy and had low power - less than 10 kW. They were, as a rule, still low-voltage systems (28 V). The more efficient, and more costly, gallium arsenide photovoltaic cells were available, but the well established silicon cells - which had been developed to be 14 to 18 percent efficient - were still the mainstay of the space power program.

Work was begun during this decade on more efficient radiation-resistant cells - indium phosphide, for example. Nickel-hydrogen batteries, with their more flexible mode of operation and increased energy density, were developed and were beginning to replace the nickel cadmium batteries, which were the mainstay of the past decades. Sodium-sulfur batteries with higher energy densities were under extensive development. In general the power systems of the 80's were characterized by photovoltaic systems of 30 to 60 W/kg, 14 to 15 percent cell efficiency - dominantly silicon technology. Battery energy densities had been increased to 20 W-hr/kg, and power system lifetimes were 7 years with performance degradation over their lifetime reduced to 15 percent. Costs were still in the $1.5 to $2.0 million/kW range (in 1980's dollars). Hydrogen-oxygen fuel cells were well established and were used on the Space Transportation System (STS, or shuttle). High-power radioisotope systems (hundreds of watts) were used on outer planet missions.

Thermal dynamic (fig. 1) and space nuclear power systems were again under active development for future missions - both civil and military. Brayton and free-piston Stirling energy conversion systems and passive thermoelectric systems were being developed to support the space ventures of the 1990's and the 21st century. Solar dynamic systems were actively considered as a candidate for the space power system (ref. 1). Space missions undertaken in this period included Earth resource; weather and navigation; and communication satellites, Spacelab, and other STS missions. Interplanetary probes were sent to Venus and Jupiter.

SPACE POWER SYSTEMS OF THE COMING DECADE - THE 90'S

There will be dramatic changes in the power system architectures for the space programs of the 21st century. The 1990's will see the beginning of this change. The power system technologies to support the future space missions will be developed during the 90's decade - advanced technologies to support the ambitious space ventures envisioned for the future.

There will still be many missions requiring low power - on the order of 10 kW or less - but in general the power requirements per mission to support the future space program will be vastly greater than in the past. The power requirements growth will be exponential - just as the initial power growth on Earth went through an exponential expansion phase. The start of this exponential growth, a breakpoint in space power technology, will be the international Space Station Freedom (ref. 2), which will have the characteristics of a "utility power system." For the initial stage, this station will require at least an order of magnitude greater power than previous systems, as will its supporting platforms.

Initial growth versions of Space Station Freedom will require hundreds of kilowatts of power. Longer range evolutionary and growth versions of Space Station Freedom will require megawatts of power. The initial Space Station Freedom will have a conventional silicon solar photovoltaic system for primary power with nickel-hydrogen batteries for energy storage. For evolutionary versions of Space Station Freedom, solar dynamic power generation (fig. 2) is being considered, at first in conjunction with solar cells, with later versions depending solely on solar dynamic power systems. The reduced size of the solar dynamic concentrators, over that of the photovoltaic arrays, will reduce orbital drag, and thus orbit decay, and will result in less orbit make-up propellants required over the lifetime of the station.

These requirements, by themselves, will dictate significant changes in power system technologies, such as supplementing the solar photovoltaic system of Space Station Freedom with a solar thermal system to increase its output. Another significant change will be the manner of operating the power system in space.

The space power systems will operate like utilities on Earth and will provide a distinct number of service classes (ac, dc, etc.) to satisfy specific needs. Equipment to provide power other than that supplied directly from the spacecraft bus will be the responsibility of the user: just as it is for utilities operated on Earth.

The power systems of the 90's will be the forerunners of new space power architectures; the high-power, high-voltage ac and dc they supply to their users will be their hallmark. Very high frequencies (ac to 20 kHz, for example) show considerable promise for space applications. The high cost of delivering and moving mass about in space will be a significant driver for reducing power system masses - by at least a factor of two.

The characteristics of the power systems for the last decade of the 20th century will be increased power levels - higher voltage ac and dc supplied to users - based on much higher frequency ac distribution than on systems of the past. Nuclear power systems are under development during this decade as are dynamic energy conversion systems based on Brayton and free-piston Stirling engine cycles. Power systems will become much more efficient and will have longer lifetimes: 10 to 30 years with in-space servicing and maintenance greatly contributing to increased power system utilization. Power system costs will be greatly reduced. These improvements along with development of more efficient space transportation (launch vehicles) will lead to significantly reduced power and energy costs in space - making space ventures more affordable. This will be addressed in a later section.

Photovoltaic systems of 300+ W/kg and batteries with energy densities of 100+ W-hr/kg are in the development stage and will be put into use in the 90's. Solar dynamic systems approaching 20 W/kg and nuclear systems with power densities of 50 W/kg will continue to be developed during the 90's. There will be continued use of high-power radioisotope thermoelectric generators to power outer planet missions where solar energy is not available.

POWER REQUIREMENTS FOR MISSIONS OF THE FUTURE

The technologies required to support the power systems of the future will, to a large extent, depend on the specific mission requirements for power. It is difficult to estimate what levels of power will be required to support various space ventures. We can however, postulate a scenario by making an analogy with the history of terrestrial power growth to support human activities on Earth.

The technological progress of humanity and its standard of living, is directly linked with the availability and use of power and energy. Highly developed societies have more "power in place" per inhabitant and use more energy on a per capita basis than do less developed societies. Data from the United Nations Energy Statistic Handbook for 1985 (ref. 3) indicates that survival-level primitive societies subsist on power levels of approximately 200 to 300 W per inhabitant. The more self-sufficient societies require on the order of 1 to 2 kW per inhabitant, while the highly developed technological societies utilize on the order of 2 to 10 kW per inhabitant. Each step to the next higher level of social development appears to represent an approximate ten-fold increase in power usage.

Although this is a terrestrial scenario, it is reasonable to expect a similar scenario for space (fig. 3). Today's manned spacecraft are at the "survival level" in comparison with previous and present day survival level terrestrial societies. There is some logic to this line of reasoning since today's long-term Soviet spacecraft have limited capability and are completely dependent on resupply from Earth for life-sustaining stores. Sustained space operations will, to a large extent, be determined by their independence of the mission from Earth resources, especially the life support and the stores to maintain a livable environment. The U.S. Skylab mission and the Soviet Mir space station have "open" life support facilities and require approximately 1 kW per crew member. Space Station Freedom will require about 2 to 5 kW per crew member with a partially closed life support system. It is estimated that a closed life support system for Space Station Freedom would require on the order of 10+ kW per crew member. We can project that the power need for the next space development stage (a self-sufficient space station with a defined mission) would be 50 to 100 kW per crew member. Progressing to the next step, we postulate that commercialized space ventures will require anywhere from hundreds of kilowatts to megawatts per crew member depending on what the commercial venture is. The use of electric propulsion to shorten trip times for the Mars mission will require power levels in the tens of megawatts.

Also, in addition to the manned space program there will still be an unmanned program requiring spacecraft with power levels of 5 to 10 kW and beyond. Development of advanced power and energy system technologies to support that class of missions is also underway. The space missions planned at these power levels are those that are essential for space-based studies of global change and comprehensive scientific missions.

NASA and the Department of Defense (DOD) studied the space power technology requirements for future missions (refs. 4 and 5). Necessary developments in space power technology were also assessed (ref. 6) and future mission scenarios were analyzed. This was done to define the technology development programs that will bring future power systems to the desired states of readiness for the missions of the 21st century.

TECHNOLOGY GOALS FOR ADVANCED SPACE POWER AND ENERGY SYSTEMS

The technology programs in effect today and those of the future will dramatically change and improve space power systems and related subsystems. The U.S. long-range plan for power technology development calls for progression from one stage to another. Those programs now in the research stage will require anywhere from 10 to 15 years before they will be ready for implementation on a flight-ready space system, and this stage will pace the other stages. Because of the high cost of delivering and moving mass about in space, the reduction of space power system mass is one of the major goals of the development programs. Component development, improved fabrication techniques, systems checkout cost reductions, and reductions in system maintenance requirements are also prime goals with high payoffs. This is true of any onboard space system, but the power system is a major portion of both the mass and cost. Major improvements in power and energy will have significant benefits. Goals for the various space power and energy technologies have been set, and the present and future planned technology development programs are a step towards those goals.

The status and future applications of photovoltaic technology are given in (ref. 7). Goals in this area include high-efficiency radiation-tolerant cells, thin film amorphous silicon, and other classes of arrays at 500+ W/kg. Indium phosphide cells with improved radiation resistance and multijunction cells at 30+ percent efficiency are visualized. They will be miniature cells with concentrators and/or thin film devices. Copper-indium-diselenide (CIS-$CuInSe_2$) cells also show potential for improved radiation resistance and performance and are being investigated. Both high-performance planar and concentrator arrays are being developed to support future missions.

Energy storage, for those missions that operate during orbital eclipse periods or other times when sunlight is not available, is one of the most voluminous and massive subsystems on board a spacecraft. Expected improvements in energy storage with respect to energy density, efficiency, and other factors should result in significant benefits. Development programs (refs. 8 and 9) are directed towards improving both energy density and lifetimes of these storage systems. Goals include energy densities of 200+ W-hr/kg for low-Earth orbit applications. Continued development of advanced nickel-hydrogen, sodium-sulfur batteries and high energy density, rechargeable lithium batteries is under way. Regenerative H_2-O_2 fuel cells with energy densities on the order of 1000+ W-hr/kg for long-term storage for planetary applications and in which designing for power and designing for total energy required are independent of each other are also under active development. Other forms of energy storage such as flywheels and capacitors are also being pursued. Superconducting magnetic energy storage may also show considerable advantages for specific applications.

Solar dynamic systems will be further developed for larger scale power systems. At the present time the evolutionary space station is envisioned to grow to the hundreds of kilowatts by adding solar dynamic modules. Brayton systems have been extensively tested on the ground, and subsystems and components have been designed and tested for these systems. No flight experience has been accumulated on any of these dynamic systems, but plans to conduct space experiments on components for these systems and accumulate a design data base are presently in place. One energy conversion system with considerable potential for solar dynamic and nuclear systems is based on the Stirling cycle, and its development is being aggressively pursued (ref. 10). Brayton cycle and Stirling cycle systems can be adapted to either solar or nuclear heat sources.

Goals of these programs are to develop Stirling energy conversion systems with specific power densities of 5 kg/kW. Two critical components for solar dynamic systems that require further development are the heat receivers and the concentrator. Energy storage for solar dynamic systems incorporating thermal phase change materials are being developed. Alternate forms of energy storage for solar dynamic systems are also being developed. The use of the lunar regolith for thermal energy storage for lunar applications is being studied.

Goals for high-precision concentrators for solar dynamic systems are 1 to 2 kg/m^2 with surface accuracies of 0.5 mrad and high durability in LEO. The specific power goal for the complete advanced solar dynamic system is 20 W/kg with further possible increases in the long-term future.

Radioisotope thermoelectric generators (RTG'S) are being developed to support outer planet missions where reliance on solar power is not possible (ref. 11). Nuclear heat source systems are also being developed at this time by both NASA (ref. 12) and DOD. Goals of the nuclear program are to develop high-capacity power systems with 5 to 20 times the specific powers of existing nuclear systems - on the order of approximately 100 to 150 W/kg for the total system at high power levels. Systems for low and medium power levels are also being investigated.

Considerable challenges exist in supporting technologies such as thermal management and control and power management. Development efforts in these areas are also being aggressively pursued. These technologies are very specific to the particular application, but they make up a sizable portion of the total power system mass (ref. 13). Increasing the efficiency of the power management, distribution, and control electronics; developing higher temperature electronic components; and improving thermal management and heat rejection components are all under way. The goals of this program are to increase the efficiency and operating temperatures of the electronic components and to reach a level of approximately 1 to 2 kg/kW for the support and power-conditioning electronics. Advanced heat rejection systems are being developed with a goal of 1 to 2 kg/kW of power output (from the radiator) with additional mass decreases possible in the longer term future.

Extended lifetimes for space power systems of 30+ years with on-orbit servicing and onboard maintenance are major long-range goals of the advanced power systems development program. Reduction in the cost of electricity in space by at least one order of magnitude in the near future, and possibly more in the far-off future, is a prime objective. Making space ventures more affordable for both government and private enterprise is mandatory if the rewards of space are to be realized.

The goals for the primary space power technologies are summarized in table I. The technology development goals are given for the year 2000 and also for the longer range, the year 2015 and beyond.

In addition to the more conventional technologies, there are some technologies in the early research stage which have tremendous potential (though unproven at this time) for enhancing, and in many cases, enabling future missions. Studies are now under way to ascertain applications and the resulting benefits for these technologies. Some of these are discussed in the following paragraphs.

Microwave beam power shows some promise for supporting the planetary exploration program in a number of applications. Space-to-surface beamed power for planetary bases and rovers, space-to-space central power stations to beam power to co-orbiting satellites, surface-to-space beamed power for orbit raising, and surface-to-surface central beamed power stations on planetary surfaces are possible applications of beam power. Either microwave or laser power beams may satisfy these needs, and studies are under way to see which technology best fits a given application. A number of applications of beamed power have been investigated (ref. 14). These studies indicate that beamed power can be beneficial because less mass is delivered to a surface or in orbit. Also, isolating a nuclear power system in orbit and beaming power to a manned surface base can alleviate shielding problems in addition to keeping the planetary surface "nuclear free."

Superconductivity applications to NASA power systems are also being considered. Power transmission lines, microwave beam power components, and superconducting magnetic energy storage (ref. 15 and K.A. Faymon, Superconducting Magnetic Energy Storage for Future NASA Missions. Presented at the 2nd World Congress on Superconductivity, Houston, TX, Sept. 9-13, 1990. Proceedings to be published) are candidates for NASA missions. The NASA Lewis Research Center in a cooperative agreement with the Department of Energy's Argonne National Laboratory is investigating superconductivity technologies for space power systems applications; preliminary results appear to be promising. High-temperature superconductivity (liquid nitrogen temperatures) shows considerable promise for space applications since cooling requirements will be greatly reduced over those required for conventional superconductivity (liquid helium temperatures).

In today's world, operational support (both on the ground and in space) is a major cost factor affecting any space mission. Reducing this factor by means of expert systems and artificial intelligence technologies to effect spacecraft autonomous operation is a means of reducing mission support costs. These technologies are currently being investigated for autonomous operation in the areas of system fault detection, isolation, and recovery for space power systems (ref. 16). Power system health monitoring and system trend prediction are possible applications of this class of technology. Onboard real time event planning and replanning for anomalous situations is another possible application of expert systems and artificial intelligence for manned and unmanned space vehicles. All of these applications have significant potential for reducing mission support costs, which at the present time are a significant part of the "total" mission cost structure.

These technologies will be applied first as "advisors" to the operations team and crew. Once these systems are understood and proven, actual control may be effected through expert systems and artificial intelligence with decreases in human support both in space and on Earth.

Generation of electrical power by "dragging" a conducting tether through the Earth's magnetic field by a spacecraft is a possibility. Reducing orbital velocity by means of the resulting electrodynamic drag, or reversing the process - charging the tether with a electric current - to produce a propulsive force to make orbit adjustments is being investigated.

The use of tethers to achieve safe separation distances of a nuclear power system (fig. 4) from inhabited or radiation-sensitive space modules or spacecraft, may offer considerable benefits by reducing the shielding masses required by a nuclear system - reducing radiation to acceptable levels by increasing the separation distance. In this case the tether is the transmission line.

We must, however, be cautious in evaluating these and other technologies. The specific technology must be evaluated as an integral part of the "total space system" in its operating environment. Simple "bench parameters" such as specific power or energy density are not true indicators of subsystem and component performance or of how they will contribute to the "optimum system." Interactions between systems, subsystems, and components can result in "cascading benefits." Cascading benefits are those that occur in another subsystem and which can more than offset unattractive bench parameters in one system. The reverse is also true - cascading benefits can be negative, offsetting attractive bench parameters in some systems or subsystems. Initial studies on many of these power system technologies indicate that such interactive effects can be significant. A "total systems" approach to technology evaluation of space power systems is mandatory for all future technology evaluation analyses. Total systems analyses are being conducted to guide technology development programs and select those technologies for development which show the greatest payoff for a given application.

POWER TECHNOLOGIES AND THE SPACE EXPLORATION ACTIVITIES OF THE 21ST CENTURY

In his July 20, 1989, remarks commemorating the 20th anniversary of the Apollo 11 Moon landing, President George Bush outlined a long-term program for human exploration of space: First for the coming decade, for the 90's - Space Station Freedom - the critical next step in all our endeavors. And next, for the new century - back to the Moon. Back to the future, and this time to stay, and then a journey into tomorrow - a journey to another planet - a manned mission to Mars. Each mission shall, and will, lay the groundwork for the next. This program is compatible with the NASA proposed Space Exploration Initiative (SEI), a focused multidecade civil space applications program whose goals are to expand human presence and activity into the solar system, to extend the frontiers of human knowledge of the solar system, and to bring the benefits of space to all Americans (ref. 4).

Therefore power systems requirements for lunar exploration will evolve as the activities on the lunar surface grow from an initial outpost to a self-sufficient base. To meet these requirements, a variety of power systems will be developed (ref. 17).

The architectures for lunar applications will evolve from solar-based systems for the initial phase to nuclear-based systems as the power needs grow. Figure 5 shows an artist's concept of a lunar base powered by a photovoltaic-regenerative fuel cell system.

However, the power and energy storage systems developed for the space station are not suitable for the Moon: they are too massive because of the storage requirement for the long lunar night. Thus, for the initial phase of the lunar buildup it will be necessary to use photovoltaic power systems with regenerative fuel cells (RFC) for energy storage. The development of RFC energy storage systems will result in a twenty- to forty-fold increase in specific energy over the nickel hydrogen batteries. Advanced photovoltaic arrays (PVA) in the 300+ W kg range will make possible solar-based lunar power systems in the 25-kWe range in this exploration phase.

Figure 6 shows an advanced lunar base that has evolved from the initial habitat to a fully operational, self-sufficient base powered by a nuclear reactor.

Centralized systems will supply power for habitation, laboratory modules, science experiments, in situ resource utilization, manufacturing, and construction. In addition, remote power systems for far-side observatories and communications outposts; mobile power systems for pressurized and unpressurized rovers, transportation systems, and construction and hauling vehicles; and a multitude of other support systems will be required. The power systems for the next step in the President's exploration program - the habitation and exploration of Mars - will build on the experience and technologies gained from the lunar program.

These power system technologies and their respective technology development programs are designed to support all aspects and future phases of the Space Exploration Initiative (SEI).

NASA already has the initial program elements in place for the development of the key power systems needed for the President's space exploration program. The nuclear systems and their development programs are discussed in detail in reference 18. In this report the initial power system requirements for Moon and Mars exploration have been identified. Advancements in the present state of the art in both solar and nuclear space power systems are necessary to meet these requirements.

AFFORDABILITY OF ELECTRICITY IN SPACE

The "affordability" of power and energy is crucial to the advancement of any society. This is also true in space: advancements in the utilization of space are directly related to the affordability of power and energy in space. At present, costs are high and must be reduced. On Earth, low energy rates encourage development, and the same will be true in space. The cost elasticity for endeavors in space is not well understood, and the markets are not defined at this point. However, the "affordability" of energy and power will be crucial to any attempt to utilize the space environment. We address this issue next.

Many elements enter into the "cost equation" for space power and energy: recurring costs (spacecraft hardware); cost of transportation (launch and orbital positioning); Design, Development, Test, and Engineering (DDT&E) of the flight hardware; operational (ground) support; maintenance; capacity factor (what fraction of usable power and energy is actually utilized); and - for commercial operations - insurance, interest rate on borrowed money, and rate of return on investment. Technology advances in both power system and support system technologies will significantly affect the future cost of energy in space. In many cases the technology advances which reduce the cost of power and energy in space will be the enabling factor for future ventures.

Significant advances have already taken place in power (and support) systems technologies since the Space Power Platform study (ref. 1), and these advances must have some effect on the conclusions reached in that study. The effects of advanced technologies (power and propulsion) for commercial space business ventures have been addressed in reference 18. The study showed that advanced power and propulsion technologies can have a significant effect on space venture revenues for commercial communication satellites - mainly from the decreased masses of the advanced systems. For scientific (and government) missions, increases in payload per vehicle will also result from advanced technologies - for example, reducing the mass of the power system and thus releasing mass for additional payload. In the case of commercial ventures, this additional payload will be revenue-producing payload.

Transportation costs, delivery to orbit, and orbital placement represent a significant portion of the costs of a space mission and are directly reflected in the "cost of electricity in space." For Earth orbit missions these costs can be anywhere from 25 to 50 percent of the mission costs. For geosynchronous orbit (GEO), lunar, and interplanetary missions, the costs are an order of magnitude, or more, greater than for low-Earth orbit (LEO) missions. As an illustrative example, we present the cost of energy, in terms of 1989 dollars and technology status, for typical Earth orbit missions - a LEO (scientific) and a GEO (communications) mission.

Assuming a spacecraft with a 3-kW power system (usable) and typical operational parameters (lifetime, capacity factors, and other factors), we find the cost of energy in space to be on the order of $500- to $800-kW/hr depending on the assumptions made. This figure does not change appreciably between the LEO scientific satellite and the GEO orbit communication satellite. Compare this with the terrestrial-utility-generated energy costs of approximately 10¢/kW-hr. For the above example, the DDT&E costs for the LEO scientific spacecraft were amortized over a single spacecraft, whereas the GEO commercial communications satellite DDT&E costs were distributed over five spacecraft (this is a typical scenario). To arrive at the cost figures, capacity factors of 50 and 80 percent were used for the GEO and the LEO missions respectively, and the cost of money was 12 percent - to be paid back in 15 years. Insurance costs at 10 percent of the recurring (hardware) costs were included; however, no tax liability or return on investment was included in these figures.

For advanced technologies now in the planning stage, major improvements in specific power and useful life for technologies such as large-scale nuclear power systems will significantly reduce these cost-of-electricity figures in the near future. Additional technology advances (which include advanced launch systems with decreased orbit delivery costs per unit payload, further reductions in power systems costs, and other factors) will result in additional decreases in the cost of energy in space in the more distant future. These projections are considered to be realistic.

We have projected costs of space power and energy and associated technology for the next two decades. Table II lists those parameters which affect power and energy system costs. The figures in this table represent average estimates for the various entries. The cost-of-electricity numbers given here represent optimistic and pessimistic limits for these items. For present purposes we will restrict these projections to LEO missions. Space Station Freedom will be used as the baseline.

The first column in table I includes relevant cost parameters based on the assumption that Space Station Freedom will be launched in 1995 and consist of present-day technology for both the power system (PV, or photovoltaic) and the supporting entities. A Space Station Freedom version utilizing solar dynamic power systems could be ready by the year 2000, and the cost parameters are presented for this case in column two. By the year 2010 the SP-100 nuclear power system should be ready, and its cost parameters are given in the last column on table II.

It was assumed that the Freedom power systems would have extended lifetimes with on-orbit maintenance and replacements when required. The power system components would be subject to replacement every 10 years. Design, Development, Test, and Engineering costs for the Space Station Freedom systems were taken to be $\$1\frac{1}{2}$ billion. These cost projections are for a "man-rated" space system.

Supporting technologies are also assumed to advance in the next two decades. Operation costs for the initial Space Station Freedom power system were assumed to be $2 million/yr. However, advancements in expert systems and artificial intelligence technologies will result in increased automation on board Freedom, thus reducing operations and maintenance costs over the next two decades. These advancements will also improve scheduling and planning aboard Freedom, and thus the power system capacity factor (the percent of available energy actually used) will increase. In the year 2010 the capacity factor is expected to be close to 100 percent because of the ability to do more accurate planning and scheduling of the use of the power and energy resources aboard Space Station Freedom.

By the year 2010, improvements in launch vehicles are also expected. On the basis of historical data, present day launch costs are in the neighborhood of $8000/kg for LEO missions. This value, which was used for the Earth science satellite previously discussed, is not expected to change appreciably by the year 2000. By the year 2010, we project this to be reduced to approximately one-half of the present day costs. Figure 7 shows the energy costs in space on the basis of these projections.

Additional cost reductions will be possible once these technologies have matured. Inheritance and experience gained from the initial installation of a given system can result in significant reductions in the DDT&E costs for subsequent installations thereby reducing the cost of energy in space to less than projections shown here.

The costing was done on an economic venture basis. Cost of money is assumed to be 12 percent to be recovered in the 30-year lifetime of Space Station Freedom. No insurance costs, taxes, or rate of return on investment was included since these missions were assumed to be government missions. The upper and lower bounds of the crosshatched region represent optimistic and pessimistic estimates. These were arrived at by perturbing the values in table I to account for uncertainties in the cost projections of the various entities shown.

CONCLUDING REMARKS

Space power will undergo a dramatic change for future space missions. The power systems which have served the U.S. space program so well in the past will not suffice for the missions of the future. This is especially true if the commercialization of space is to become a reality. These systems are, however, the building blocks from which the power systems of the future will evolve. New technologies, new and different space power architectures and topologies, some already in the planning stage, will replace the lower power, low-voltage, direct current systems of the past. Thus greatly enhanced and enabled operations will be possible in the future. Efficiencies will be markedly improved, specific powers will be greatly increased, and system lifetimes will be greatly extended. Along with this, advances in associated technologies and launch systems will reduce the cost of placing mass in orbit or on a planetary surface for the President's space exploration program and the NASA Space Exploration Initiative.

Energy and power in space will become more affordable with the cost of energy reduced by an order of magnitude or more over today's costs, thus making space itself affordable. This is an absolute necessity in order to make the full development and utilization of space a reality. The space power technologies now in place and those planned for the future will be the instruments for achieving this reality.

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TABLE I. - TECHNOLOGY GOALS FOR ADVANCED SPACE POWER AND ENERGY SYSTEMS

System	Readiness date	
	Year 2000	Long range[a]
Photovoltaic arrays		
Power output, W/kg	300	500
Efficiency, percent	20+	30+
Energy storage capacity, W-hr/kg		
Batteries (orbital)	100+	200+
Fuel cells[b]	----	1000+
Dynamic energy conversion system - Stirling cycle density, kg/kW	7	<5
Solar dynamic system power output, W/kg	20	25+
Nuclear power systems power output, W/kg	30+	100 to 150+
Supporting technology space radiators density, kg/kW	1 to 2	<1

[a] Year 2015 and beyond.

[b] Long-term planetary surface storage.

TABLE II. - PROJECTED POWER SYSTEM COST PARAMETERS FOR 10-YR LIFETIMES[a]

[Orbit applications.]

Type of expense	1995 Space Station Freedom (photovoltaic)	2000 Space Station Freedom (solar dynamic)	2010 [b]SP-100 nuclear reactor
Power level, kW	75	75	100
Recurring costs, $ million	600	300	80
Delivery costs, $ million	100	100	60
DDT&E costs, $ billion	1.5	1.5	1.0
Operations support, $ million/yr	2	[c]1.5	[c]0.75
Capacity factor, percent	75	[c]85	[c]95
Maintenance and system replacement cost, $ million	1400	800	280
Cost of electricity, $/kW-hr	350 to 550	200 to 350	75 to 125

[a] Assumes on-orbit maintenance with total replacement of system after 10 and 20 years - includes delivery-to-orbit costs.

[b] Assumes nuclear-safe orbit.

[c] Reflects increased automation on the space vehicle.

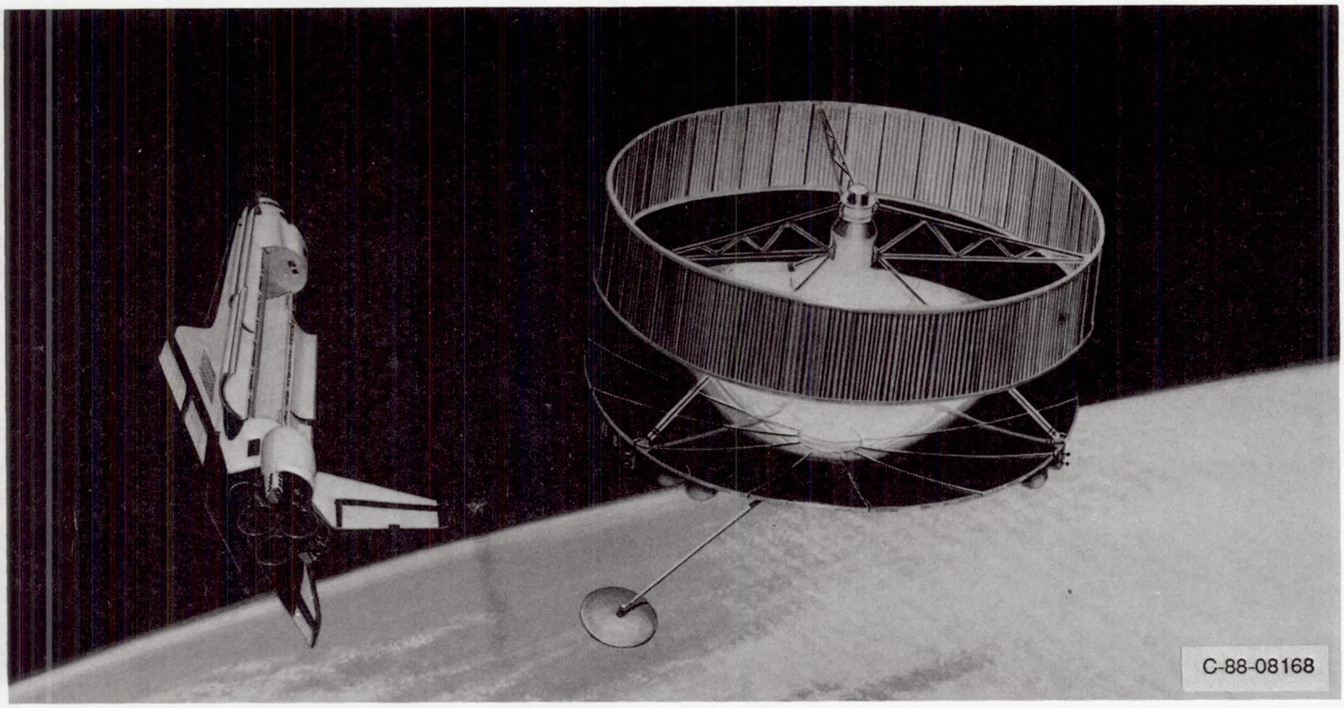

Figure 1.—Artist's concept of a solar dynamic space power system. The concentrator collects the Sun's energy and focuses it on a heat receiver. Here the heat is transferred to a working fluid which drives a heat engine - either a Brayton, Stirling, or Rankine cycle engine - which drives a generator-alternator producing electricity. For operation in the orbital eclipse period (the Earth's shadow), stored thermal energy collected during the solar phase of the orbit by the concentrator is used to drive the heat engine. A system capable of supplying 25 kW to the user would have a concentrator with a diameter of approximately 45 ft.

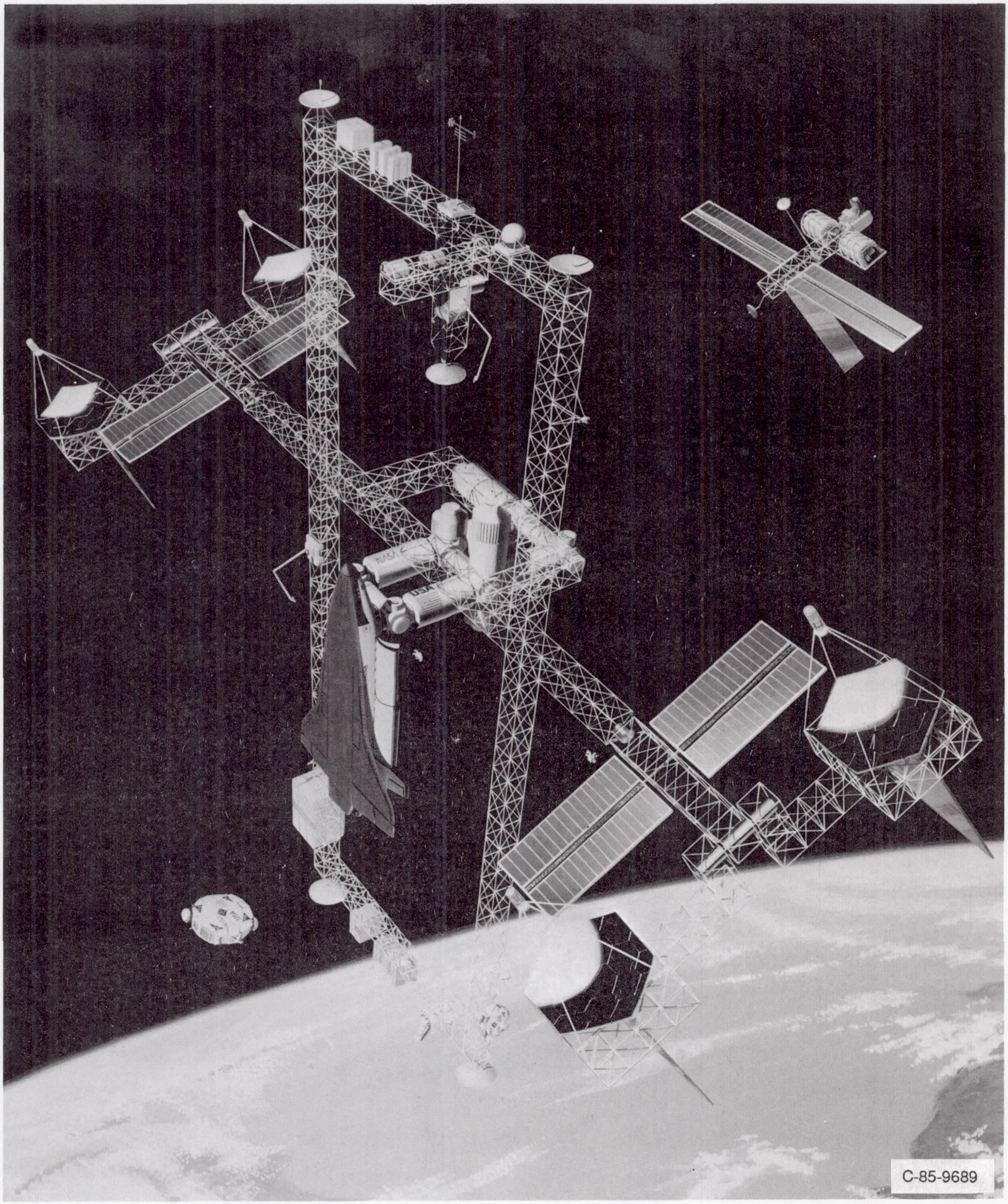

Figure 2.—Artist's concept of the "evolutionary" Space Station Freedom. Freedom's power - in the hundreds of kilowatts - is furnished by a hybrid power system, made up partially of photovoltaic cells and partially of solar thermal dynamic power units. Energy for the Earth shadow phase of the orbit is furnished by batteries for the photovoltaic portion and thermal energy storage for the solar power units. As Freedom evolves to require still more power, the solar photovoltaic system may be completely replaced by solar thermal dynamics systems.

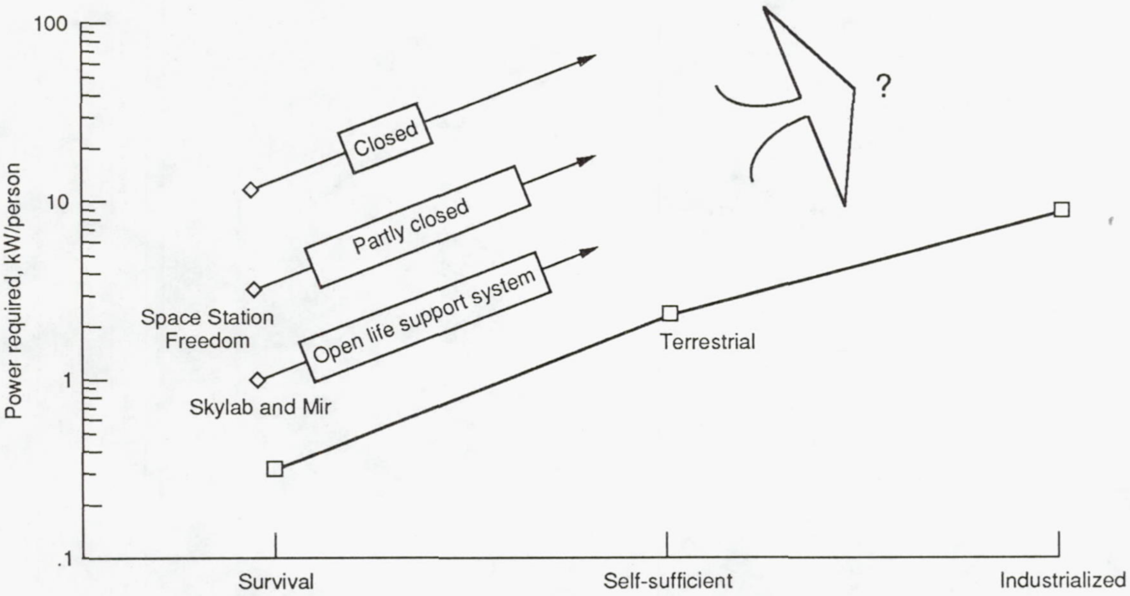

Figure 3.—Inhabitant power requirements (not including transportation energy). It is difficult to predict power requirements for future manned space missions. However, it is not unreasonable to draw a parallel with terrestrial power requirements. The bottom curve indicates power levels for various stages of terrestrial development. In space, the power requirements will, to a large extent, be dictated by the life support systems requirements and the function of the space station. (From reference 3.)

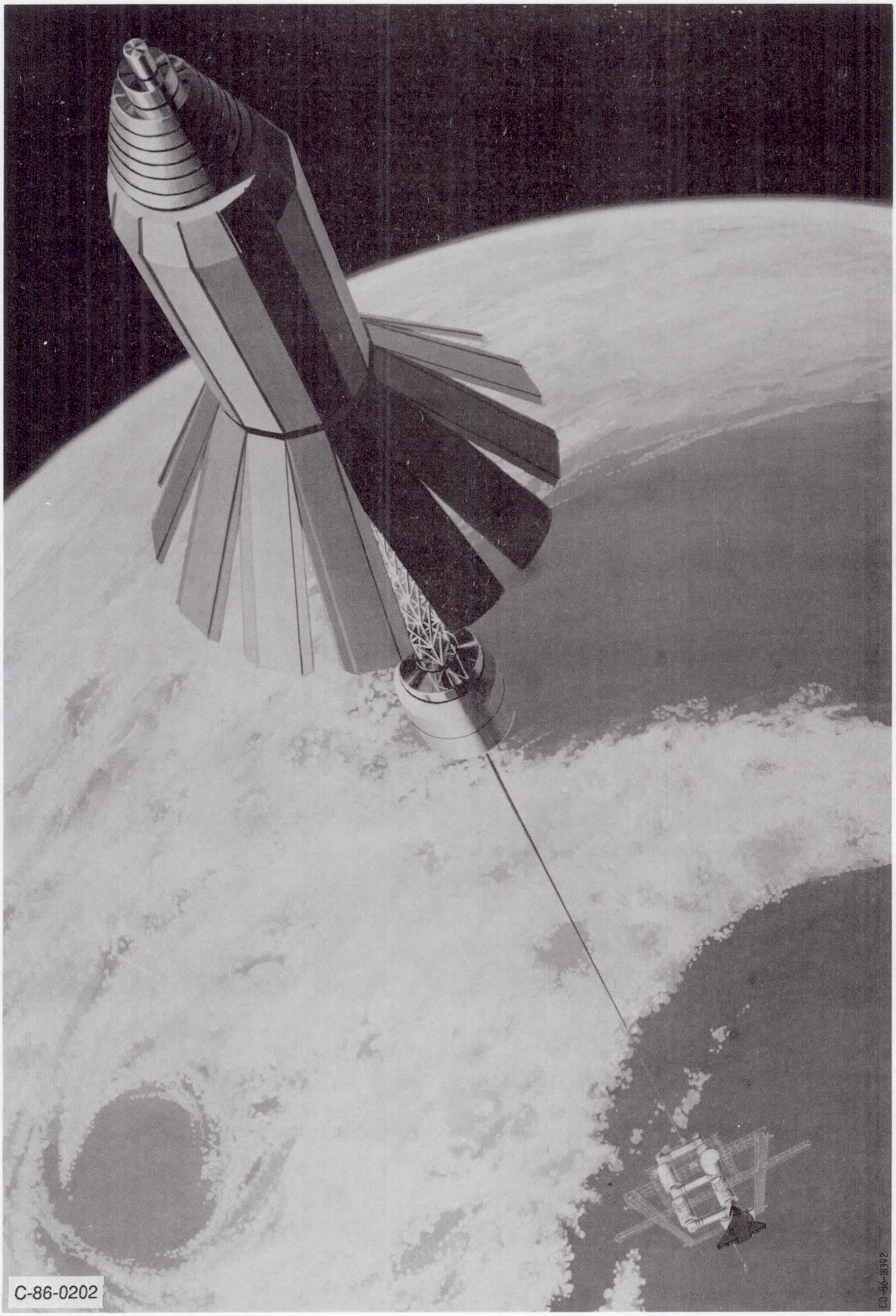

Figure 4.—Artist's concept of a tethered nuclear power system. The tether provides separation distance to reduce radiation to safe levels for the human inhabitants (or for instruments that are radiation sensitive). At the same time it is the transmission line that brings power to the inhabited spacecraft.

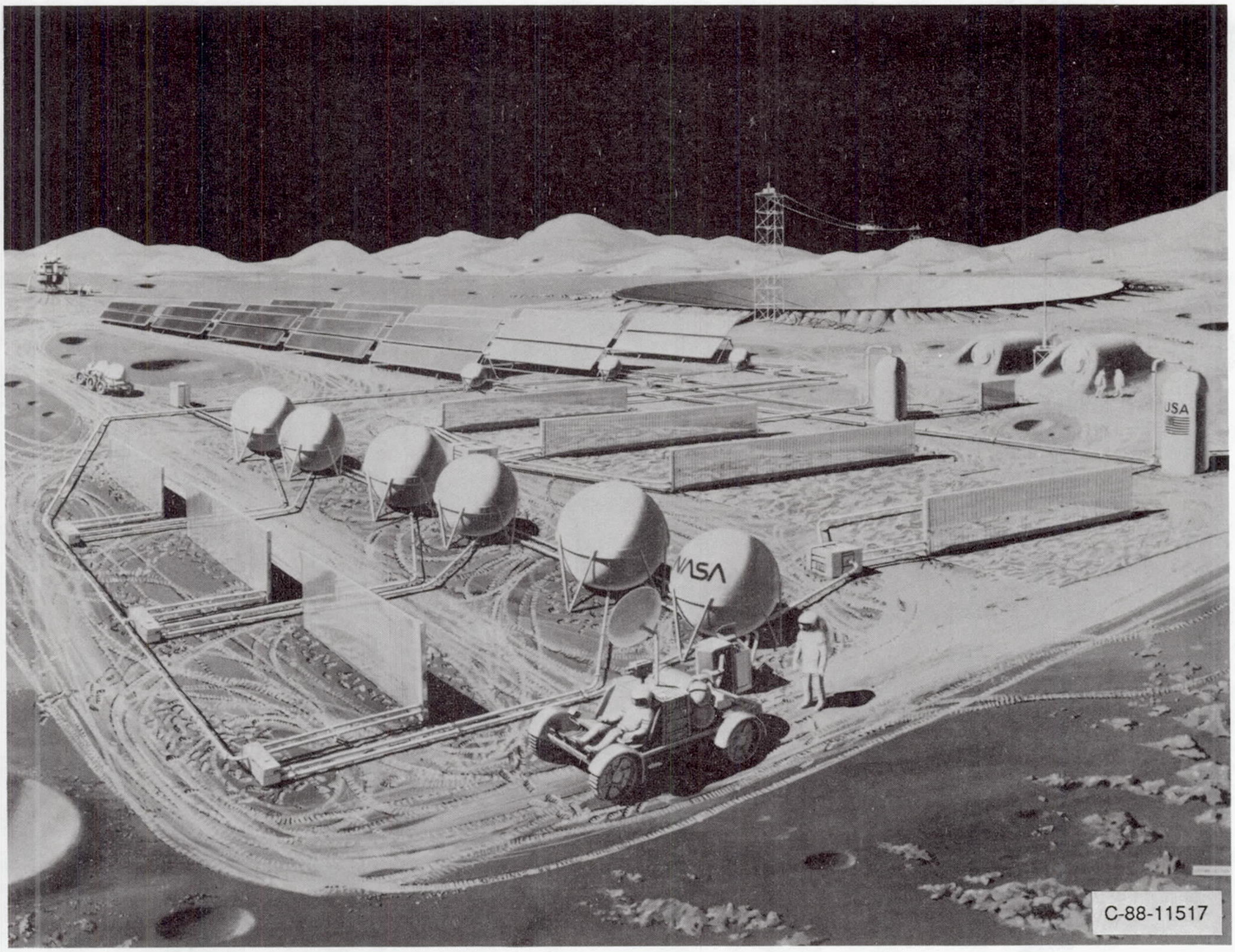

Figure 5.—Photovoltaic array and regenerative fuel cell centralized lunar power system. The large tanks shown here store the oxygen and hydrogen that power the fuel cell. The solar arrays in the background provide the power during the lunar day to power Space Station Freedom and to "regenerate" the hydrogen and oxygen (by electrolysis of water) in order that the fuel cells can power Freedom throughout the lunar night.

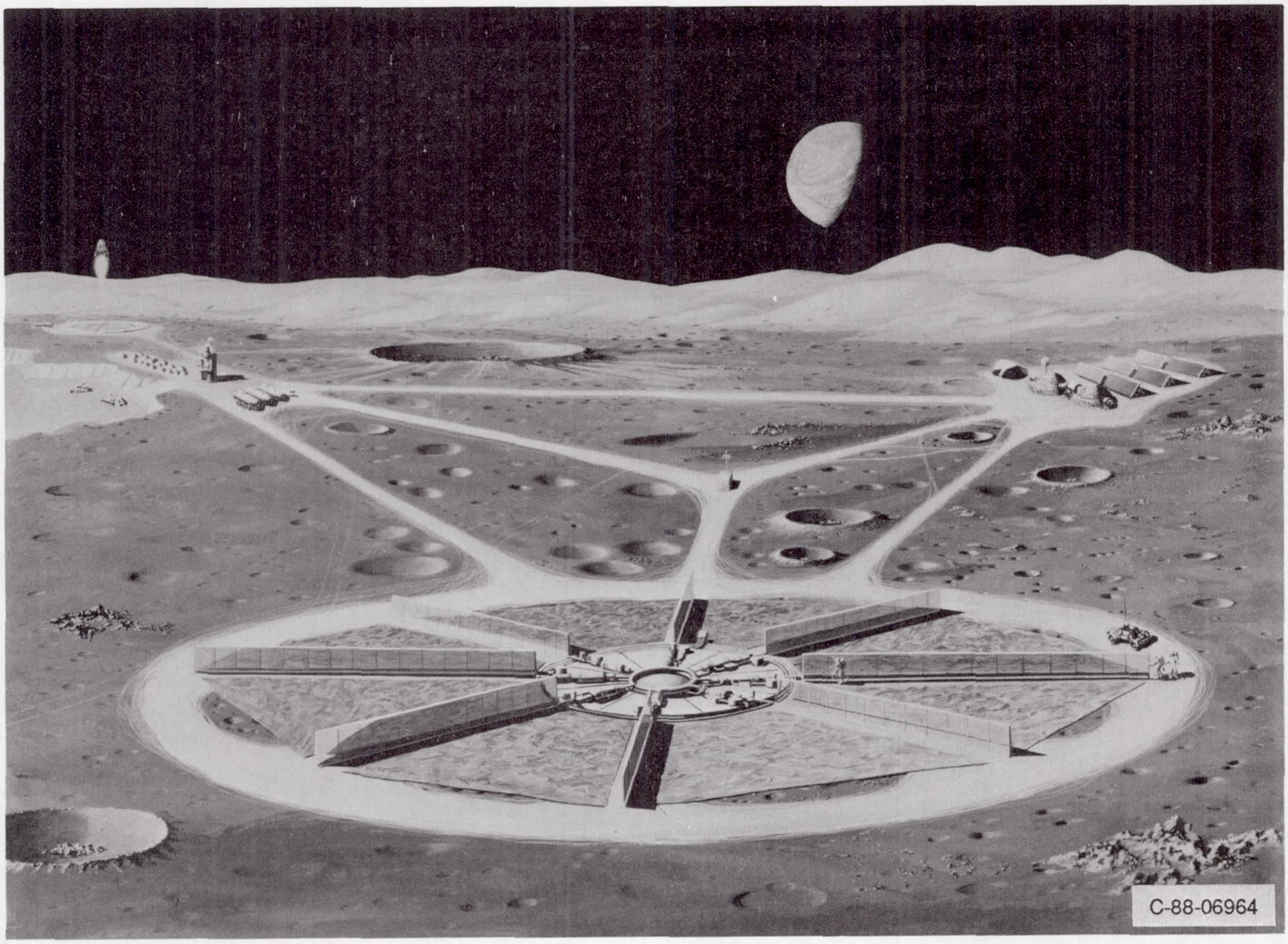

Figure 6.—Nuclear reactor central power station for a lunar base. This artist's concept shows one of the initial designs for an 825-kWe reactor space power system. This system is based on the SP-100 reactor and free-piston Stirling engine energy converter. The reactor is located in a hole at the center of the power system. A dominant feature of this system is the heat pipe radiator panels shown radiating out from the reactor site.

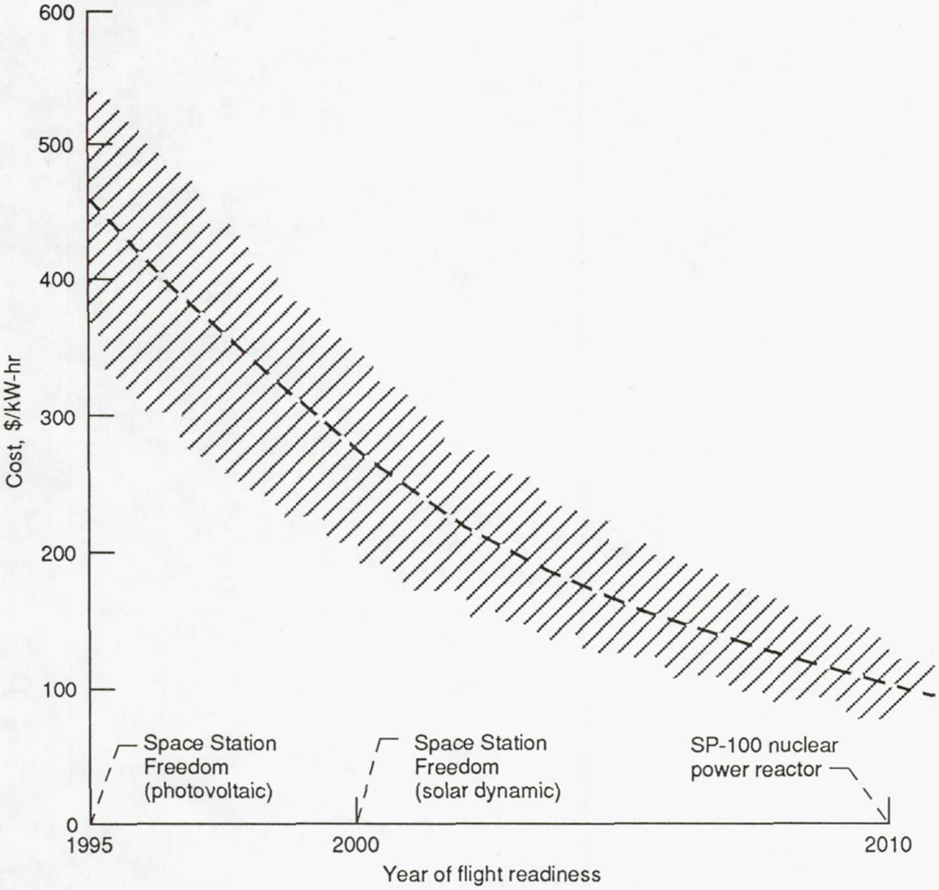

Figure 7.—Projected costs of energy in space as a function of technology advances. From present day costs which are in the range of hundreds of dollars per kilowatt hour, we project cost reductions as advanced technology comes on line. Gains in power system weight reduction, improved efficiencies, reduced manufacturing, and reduced checkout costs, along with advanced launch systems to reduce launch costs will, in the distant future, reduce the cost of energy in space. This reduction can be an order of magnitude or more over today's space energy costs.

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Report Documentation Page

1. Report No. NASA TM-103649	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Power Technologies and the Space Future		5. Report Date April 1991
		6. Performing Organization Code
7. Author(s) Karl A. Faymon, J. Stuart Fordyce, and Henry W. Brandhorst, Jr.		8. Performing Organization Report No. E-5835
		10. Work Unit No. 506-49-21
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		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. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

To be published as Chapter 7 in "Space Power: A 21st Century Option for Energy Supply on Earth," Eds. Dr. Peter Glaser and Prof. F. Davidson, Ellis Horwood Limited, Chichester, England.

16. Abstract

Human society is inexorably advancing into space—the new frontier of the 21st century. Advancements in space power and energy technologies are critical to serve space development needs and help solve problems on Earth. The availability of low cost power and energy in space will be the hallmark of this advance. Space power will undergo a dramatic change for future space missions. The power systems which have served the U.S. space program so well in the past will not suffice for the missions of the future. This is especially true if the commercialization of space is to become a reality. New technologies, and new and different space power architectures and topologies will replace the lower power, low-voltage systems of the past. Efficiencies will be markedly improved, specific powers will be greatly increased, and system lifetimes will be markedly extended. This report discusses space power technology—its past, its current status,and predictions about where it will go in the future. A key problem for power and energy (not unique to space) is its cost of "affordability." Power must be affordable or it will not serve future needs adequately. This aspect of space power is also specifically addressed.

17. Key Words (Suggested by Author(s)) Space power Energy costs Technology projections	18. Distribution Statement Unclassified – Unlimited Subject Categories 20 and 44

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 24	22. Price* A03

NASA FORM 1626 OCT 86

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