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REACTORS FOR NUCLEAR ELECTRIC PROPULSION*

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Abstract

Propulsion is the key to space exploitation and power is the key to propulsion. This paper examines the role of nuclear fission reactors as the primary power source for high specific impulse electric propulsion systems for space missions of the 1980s and 1990s. Particular mission applications include transfer to and a reusable orbital transfer vehicle from low-Earth orbit to geosynchronous orbit, outer planet exploration and reconnaissance missions, and as a versatile space tug supporting lunar resource development. Nuclear electric propulsion is examined as an indispensable component in space activities of the next two decades.

I. Background

Of the two principal energy source options available for electric propulsion, nuclear and solar, nuclear has some distinctive advantages. Nuclear electric propulsion systems (NEPS) have potentially higher power densities than solar and their performance is independent of the distance from the Sun. In addition, NEPS will not degrade in passing through the Earth's radiation belts--a factor severely limiting the use of solar electric propulsion as a reusable orbital transfer system from low-Earth orbit (LEO) to geosynchronous orbit (GEO) and vice versa.

The necessary quantity of power for future space missions can be divided into two classes--hundreds of kilowatt electric and tens of megawatts electric. The former class is one in which the Space Power Advanced Reactor (SPAR) fits and whose components are under development at the Los Alamos National Laboratory. The size of the reactor, shield, converter, and radiator makes for a compatible system that can be launched in a deployed mode by the Space Shuttle. The latter class leads to new development problems because of the quantity of reject waste heat necessarily involved. The radiator will become quite large and require a deployable configuration. Reject heat temperatures will need to be raised to keep the radiator size within reasonable bounds. Higher-efficiency converters with higher reject heat temperature will need to be developed. This will require major advancements in converter technologies. A desirable goal is a converter of 20% efficiency and a reject temperature over 1000 K. Subsequently, this places great stress on the reactor core design with fuel swelling a major potential problem. A reactor concept that might support this power requirement in space is discussed.

*This paper represents the views of the authors and does not necessarily reflect the official opinion of the US Department of Energy, the Los Alamos National Laboratory, or the Department of Defense. Work performed under the auspices of the US Department of Energy.

II. Missions

Human progress depends on challenge and growth. As we enter the next millennium, expansion into space offers a virgin resource base for human progress.¹ Despite contemporary doomsday predictions that exaggerate the Earth's finite resource base and increasing population density, technical progress can continue through use of extraterrestrial resources.² The key here is the skillful exploitation and "humanization" of space. This humanization is an evolutionary process in which mankind learns to use cislunar and translunar space to improve life on Earth after first learning to live in space (see Fig. 1). The dynamic growth of mankind depends on an ever expanding outlook--a closed-world environment leads to evolutionary stagnation.^{3,4} Exploitation of the extraterrestrial frontier provides mankind with a limitless environment to continue our development and growth.⁵

We have the technical expertise for initiating the next phase of space development--extension of the human resource base throughout the solar system.⁶ This extraterrestrial expansion will create an "open world" philosophy for human civilization. Key steps involved in off-planet expansion are: the development of reusable space transportation systems; the establishment of manned space stations in low-Earth orbit and eventually in geosynchronous orbit; and the establishment of space-based industries, lunar settlements, and tapping of lunar and asteroid resources. The Space Shuttle represents the US commitment to the first step in extraterrestrial expansion.

There are three cornerstones on which the extraterrestrial portion of an "open world" will depend.⁷ These are: (1) energy conversion systems--especially power and propulsion modules; (2) the ability to process extraterrestrial materials anywhere in the solar system; and (3) the space station as a habitat for man's permanent occupancy of space. Initially, we can get by with solar arrays for power and with chemicals for propulsion; but as our needs expand, nuclear reactors will become the prime energy source. This use of nuclear energy will not only power the space-based manufacturing facilities, but will also be the energy source for transporting large volumes of material in cislunar and translunar space. In fact, without a nearly limitless portable energy base, space development will be severely truncated and finally crippled.

Therefore, a key enabling technology in man's extraterrestrial expansion is the development and effective utilization of NEP systems. Such systems not only support the creation of a cislunar industrialization process^{8,9} but also enable the detail reconnaissance and eventual exploitation of the outer planets¹⁰ of this solar system and can serve as a technical prelude to interstellar flight.¹¹

<u>1980 - 1990:</u>	<u>DIRECT SERVICES AND NEW PRODUCTS FROM SPACE</u> (near-earth orbits)
	<ul style="list-style-type: none"> - Electronic Public Services - New Products & Goods - Space Construction & Space Power Experiments/Tests (R&D)
<u>1990 - 2000:</u>	<u>PROVING OUT THE ENERGY OPTIONS FROM SPACE</u> (near-earth & geosync)
	<ul style="list-style-type: none"> - Energy Technology and Initial Operations - Illumination from Space (small-scale Lunettas) - Products/Profits "made in Space" - Return to the Moon - First Private Orbital Travellers/Tourists
<u>2000 -</u>	<u>SPACE FLIGHT REACHES MATURITY</u> (near-earth, geosync, lunar, beyond)
	<ul style="list-style-type: none"> - Abundant clean Energy throughout 21st Century (solar/nuclear) - Major Industry in Space - Materials from the Moon - Local Climate Control - Space Sciences Center in Orbit - Space Tourism & Space Therapeutics - Permanent Habitats with Increasing Autarky

Fig. 1. Toward the huminization of space.

Space industrialization may be defined as a new wave in man's socio-technological development in which the special environmental conditions and properties of outer space are employed for the economic and social benefit of people on Earth.^{1,8,9} Some interesting properties of space include hard vacuum, zero-g, low vibration, a wide-view angle of Earth and the heavens, and complete isolation from the terrestrial biosphere.

Recent studies^{8,9} have attempted to look some fifty years into the future and to correlate anticipated human needs with growing space opportunities. These space industrial opportunities can be conveniently broken down into four basic categories: (1) information services; (2) products; (3) energy; and (4) human activities (see Fig. 2). In the full-scale exploitation of cislunar space, NEP systems will serve a critical enabling role in the efficient transport of massive, non-priority cargoes between LEO, low-lunar orbit (LLO), high-Earth orbit (HEO), and GEO. In many cases, the NEP system will serve not only as the propulsive means of placing a massive payload (e.g., large information platform) in HEO, but

once the operational station has been reached, the nuclear reactor will then serve as the prime power supply for many years of continuous, profit-making operation. The geosynchronous information platform that so uses a NEP system will be described shortly. Another critical application of a NEP system is in reusable orbital transfer vehicles (OTVs) or tugs. These propulsive workhorses of tomorrow will gently lift massive cargoes, resupply materials, large and fragile payloads to be assembled on-orbit, and even entire (unoccupied) habitats, carrying them effectively to their final cislunar destinations. Return trips from LLO, HEO, or GEO to LEO would see these same OTVs carrying lunar or space-manufactured products back to terrestrial markets.

In a real sense, the information service area of space industrialization already exists. In recent years, space platforms have provided valuable communication, navigation, meteorological, and environmental services to people around the globe. Further expansion of such services involves more massive platforms in orbit (especially at GEO) and much higher power levels. The NEP system is the key to such development.

1. INFORMATION SERVICES	● INFORMATION TRANSMISSION (Education, medical aid, mail, news services, teleconferences, communications, telemonitoring and teleoperation, time, navigation, search/rescue, etc.) ● DATA ACQUISITION (Earth resources, crop measurement, food production, water resources, weather and climate, oceans, oil/mineral location, environment, mapping and inventory, etc.)
2. PRODUCTS	● ORGANIC (Biochemicals: Isozymes, urokinase, insulin, etc.) ● INORGANIC (Semiconductors, large single crystals, high-strength fibers, perfect glasses, new alloys, high-strength magnets, etc.)
3. ENERGY	● POWER FROM SPACE (Nuclear or solar) ● FUSION RESEARCH IN SPACE ● ILLUMINATION FROM SPACE ● CONSERVATION
4. HUMAN ACTIVITIES	● MEDICAL AND GENETIC RESEARCH ● SPACE SCIENCES AND SPACE-BORN EDUCATION ● SPACE THERAPEUTICS (Hospital, Sanatorium) ● SPACE TOURISM (Hotel) ● ENTERTAINMENT AND ARTS

Fig. 2. Space industrialization.

For example, current aerospace industry evaluations^{8,9} indicate that greatly expanded information transmission services from space represent some of the most beneficial (industrialization) activities that could be accomplished in the next decade or so. What is needed is a multifunction platform of major capability at GEO--one capable of continued reliable operation. A baseline geosynchronous platform would weigh some 30,000 kg and require some 500 kW_e of total power (see Fig. 3). This platform would provide five new nationwide information services to the American people: direct-broadcast TV (5 nationwide channels, 16 hours per day); pocket telephones (45,000 private channels linked to the current telephone system); national information services (utilizing pocket telephone hardware); electronic teleconferencing (150 two-way video, voice, and facsimile channels); and electronic mail (40 million pages transferred among 800 sorting centers overnight). A smaller version of the baseline 500-kW_e geosynchronous platform has also been examined. Its power level is 100 kW_e, providing one direct broadcast television channel and 15,000 simultaneous pocket telephone conversations. In addition, its electronic mail services are restricted to off-peak hours when other services need less electrical power.

- EXPANDED INFORMATION SERVICES

- DIRECT BROADCAST TV
- POCKET TELEPHONES -
- NATIONAL INFORMATION SERVICES
- ELECTRONIC TELECONFERENCING
- ELECTRONIC MAIL

- BASELINE SYSTEM

- 30,000 kg MASS
- 500 kW_e POWER LEVEL -
- CONSTRUCTION IN LEO
- NEP TO GEO

Fig. 3. Geosynchronous platform.

Obviously, space reactor power is the only choice for such geosynchronous platforms in the 100-500 kW_e regime. The other categories of space opportunities, namely products, energy, and even human activities are equally impacted by the development and operation of NEP systems.

Figure 4 presents an unofficial version of NASA's current plan for interplanetary exploration.¹² (It is unofficial primarily because of uncertainty surrounding the development and availability of the Shuttle and Inertial Upper Stages (IUS) as a launch vehicle for these missions.) Presently there are five missions that are being pursued, with the Venus Orbiting Imaging Radar (also known as VOIR) and the Halley Intercept seeking Program New Starts in FY-82. The other missions listed in the Plan are all in various stages of development and will become New Start candidates before the end of this decade. Just over the horizon is an additional set of missions for which there is interest and support in the scientific community. Among these are the Far Outer Planets missions which are presently

being studied by the Office of Space Science. The Far Outer Planets mission set and the Saturn Orbiter mission are possible using chemical propulsion and gravity assist trajectories, but useful spacecraft mass in orbit is 1500 kg and mission duration is 15 to 20 years. For desirable spacecraft mass 1500 kg and attractive mission durations of 4 to 12 years, the NEP system is required.

The types of missions and the transportation requirements for outer planetary missions are indicated in Fig. 5. In the early days of space exploration, missions were characterized as reconnaissance flights and typically utilized relatively small spacecraft with masses in the range between 200 and 800 kg. As the exploration of space continued and owing to its great success, a more sophisticated and ambitious class of spacecraft became necessary to achieve the expanded mission objectives. These were the orbiter-class spacecraft which have masses in the range between 750 and 1500 kg. Orbiter-class spacecraft are appropriate to the exploration-class missions previously noted in the NASA exploration plan and are consistent with the predicted level of fiscal support expected to occur over the next decade and all the way to the end of this century. However, if NEP was available, NASA could expand its horizon and pursue the next step in this progression: the so-called Intensive Investigation and/or Sample Return Class of missions.

As an example of the value of NEPS for outer planet exploration, Fig. 6 provides a performance comparison for the Neptune orbiter mission where nuclear electric propulsion is compared with solar electric propulsion and the ballistic trajectory mode.¹² Performance is characterized by mass in orbit as a function of flight time. From the figure it is apparent that NEP systems consistent with technology projections can deliver more mass in less time than any competing propulsion technology or trajectory scheme. The slight spread in performance for the NEP mission mode is a consequence of considering two different NEP systems at different ends of the power range defined by the achievable technologies. The nearly imperceptible difference in performance further underscores the insensitivity of the NEPS to variations in the power rating or technology. Herein lies a principal advantage of using NEP for missions to the Outer Planets; namely, nuclear propulsion offers the prospect of executing explorations at these planets in 10 years or less with technology resiliency.

Finally, although interstellar missions may still lie in the minds of only the most far-thinking dreamers, an interstellar precursor mission could soon become a reality. A recent study by Jaffe and Norton¹¹ examined such an interstellar precursor mission. According to these investigators it would take over 10,000 years to reach the nearest star, Proxima Centauri (which is some 4.3 light-years, 4×10^{13} km, or 270,000 AU away) if a spacecraft would be given a hyperbolic velocity for solar system escape of 100 km/s. Of course, creating a functioning spacecraft with such a mission lifetime appears well beyond the technology levels of the year 2000. However, an interstellar precursor mission to a distance of 400 to 1000 AU appears most

TEN YEAR PLAN	NEW START	LAUNCH DATE	REMARKS
VENUS ORBITING IMAGING RADAR	FY '82	JULY '86	CHEMICAL PROPULSION OR AEROBRACING
HALLEY INTERCEPT	FY '82	JULY '85	SIMPLE, BALLISTIC FLYBY
COMET RENDEZVOUS	TBD	TBD	REQUIRES SOLAR ELECTRIC PROPULSION SYSTEM (SEPS)
STAR PROBE	FY '85	SEPT '88	JUPITER GRAVITY ASSIST TRAJECTORY
SATURN ORBITER DUAL PROBE	TBD	TBD	REQUIRES SEPS OR GRAVITY ASSIST TRAJECTORY
POSSIBLE ADDITIONS			
FAR OUTER PLANETS	FY '86		JUPITER GRAVITY ASSIST TRAJECTORIES WITH LONG FLIGHT TIMES, e.g., 15 TO 20 yr. AND SMALL PAYLOADS < 1500 kg REQUIRES NEP FOR PAYLOADS < 1500 kg AND MISSION TIMES < 12 years
PLUTO		OCT. '89	
URANUS		NOV. '91	
NEPTUNE		DEC. '92	
CLOSE SOLAR ORBITER	FY '91	TBD	JUPITER GRAVITY ASSIST
ASTEROID RENDEZVOUS	TBD	TBD	MAIN BELT ASTEROIDS REQUIRE SEPS
MARS SAMPLE RETURN	TBD	TBD	REQUIRES MAJOR COMMITMENT

Fig. 4. NASA interplanetary exploration plan.

RECONNAISSANCE MISSIONS

- FLYBY CLASS SPACECRAFT OF 200 - 800 kg NOT INCLUDING PROPULSION

EXPLORATION MISSIONS (PLANETARY ORBITERS AND/OR SMALL BODY RENDEZVOUS)

- ORBITER CLASS SPACECRAFT OF 750 - 2000 kg, NOT INCLUDING PROPULSION

INTENSIVE INVESTIGATION AND SAMPLE RETURN MISSIONS

- MULTIPLE VEHICLES, MULTIPLE SPACECRAFT OF ≥ 2000 kg NOT INCLUDING PROPULSION

Fig. 5. Planetary transportation needs.

Fig. 6. Neptune orbiter performance comparison.

interesting from both a scientific and engineering viewpoint in that time frame. (It should be noted that Pluto will be about 30 AU from the Sun in the year 2000.) NEPS was chosen for the baseline extraplanetary spacecraft and its mission. Some of the spacecraft performance goals included a 20-year design lifetime and a 50-year extended lifetime, a heliocentric excess velocity of approximately 100 km/s, a telecommunications system adequate for data transmission and command reception to a distance of 1000 AU, and appropriate scientific instrumentation and pointing apparatus.¹¹ (See Table I.)

According to the authors,¹¹ the NEP would be a 500-kW_e system with 20% conversion efficiency. Mercury was chosen as the propellant because of its high liquid density (13,600 kg/m³) and its effectiveness as a gamma ray shield. The NEP booster would employ two of these 500-kW_e reactor units. The nuclear reactor itself would be designed for a fuel burnup equivalent to 200,000 hours at full power.

The basic mission profile for this extraplanetary mission involves placement at LEO, NEP

TARIF I

For single- and two-NEP-stage versions, including the optional Pluto Orbiter; I_{sp} and propellant loading not yet optimized.

<u>Allocation</u>	<u>Mass (kg)</u>	
Spacecraft (without power and propulsion)	1200	
Pluto orbiter	1500	
Propulsion, dry (NEP, 500 kW _e)	8500	
Propellant (Hg): spiral from Earth orbit	2100	
heliocentric trajectory	18100	
Propellant tankage	600	
Total mass in Earth orbit, 1 stage	<u>32000</u>	
Booster stage (2 x 500 kW _e NEP)		58000
Total mass in Earth orbit, 2 stages		<u>90000</u>
 <u>Performance</u>	 <u>1 Stage</u>	 <u>2 Stages</u>
Distance at booster burnout (AU)	---	8
V _∞ at booster burnout (km/s)	---	25
Time from launch to booster burnout (yr)	---	4
Distance at spacecraft NEP burnout (AU)	65	155
V _∞ at spacecraft NEP burnout (km/s)	105	150
Time from launch to spacecraft NEP burnout (yr)	8	12
Spacecraft distance in 20 yr (AU)	370	410
Spacecraft distance in 50 yr (AU)	1030	1350

thrusting through an Earth-escape spiral which continues as the spacecraft flies along a heliocentric-orbit trajectory. It would take a long NEP "burn" to attain $V_{\infty} = 100$ km/s. The thrusters would be shut off during the Pluto fly-by and during other mission times when propellant exhaust would interfere with scientific measurements.

The motive for such an extraplanetary mission about the year 2000 is man's ultimate reaching for the stars. Two critical technology requirements for such precursor interstellar probes are a 50-year spacecraft lifetime and a long-life NEP.¹¹

III. Reactor Technology

A. Early Space Reactor Programs

From the mid-1950s until the early 1970s, the United States (US) pursued a vigorous program to develop space nuclear reactors. This ambitious effort included a nuclear-powered rocket program whose primary objective was to serve as the propulsive unit for a US manned Mars mission and an array of space electric power systems to support remote sensing instruments and ion propulsive units. Then, as part of a national retrenchment concerning space activities, US space mission emphasis changed, and these advanced nuclear propulsion and power systems were not considered necessary. In fact, by 1973, the development of space nuclear reactors was for the most part discontinued.

The US space reactor power plant program through 1973 is summarized in Fig. 7.¹³ The US flew one space reactor (SNAP-10A) in 1965. The objective of the SNAP-10A program was to develop a nuclear reactor power unit capable of producing a minimum of 500 watts (electric) for a period of one year in the space environment. SNAP-10A was the first and only space nuclear reactor flight tested in Earth-orbit by the US. Built by

Atomics International, the SNAP-10A was a zirconium hydride (ZrH) thermal reactor fueled by ^{235}U . The SNAP-10A test was successful though terminated prematurely by a failure outside the reactor.

B. Current Space Nuclear Reactor Systems

At the present time, the major US space reactor effort is at the Los Alamos National Laboratory where development work is underway on components for a 100-kw_e class space reactor. This power plant, called SPAR, is being designed for a 7-yr lifetime without need for maintenance or refueling. Its imaginative features center around the heat-pipe, solid-core fast reactor design with a mass of less than 1910 kg, including radiation attenuation shadow shield. The system is being designed to be fully compatible for safe launch into LEO by the Space Transportation System (STS).

A space reactor electric power plant has four major subassemblies (Fig. 8): the nuclear reactor that generates thermal energy (heat), the radiation shield that protects other parts of the spacecraft from the reactor's nuclear radiations, the converter that produces electricity from the thermal energy created in the reactor, and the radiator that rejects waste heat to space.

C. Reference SPAR Power System Description

The SPAR reactor shown in Fig. 9 (upper right) uses uranium dioxide (UO_2) as a fuel and is being designed to operate at 1500 K. Heat pipes are used to extract the thermal energy from the core and to transport it to the energy conversion subsystem. The heat pipe is a sealed thermal conduction device that contains a working fluid which is vaporized in the heated end (the reactor) and is condensed back to a liquid in the heat extraction end (the energy converter). A wick in the flow path along the tube wall returns the liquid via capillary action to the reactor.

**SNAP
EXPERIMENTAL
REACTOR (SER)**

**SNAP
DEVELOPMENTAL
REACTOR (SDR)**

**SNAP 8
EXPERIMENTAL
REACTOR (S8ER)**

**SNAP 10A
FLIGHT SYSTEM
(FS-3)**

**SNAP 8
DEVELOPMENTAL
REACTOR (S8DR)**

CRITICAL	SEPTEMBER 1959	APRIL 1961	MAY 1963	JANUARY 1965	APRIL 1965	JUNE 1968
SHUTDOWN	DECEMBER 1960	DECEMBER 1962	APRIL 1965	MARCH 1966	MAY 1965	DECEMBER 1969
THERMAL POWER	50 kw	65 kw	600 kw	38 kw	43 kw	600-1000 kw
THERMAL ENERGY	225,000 kw-hr	273,000 kw-hr	5.1×10^6 kw-hr	382,944 kw-hr	41,000 kw-hr	4.3×10^6 kw-hr
ELECTRIC POWER	-	-	-	402 watts	560 watts	-
ELECTRIC ENERGY	-	-	-	4028 kw-hr	574 kw-hr	-
TIME AT POWER AND TEMPERATURE	1800 hr AT 1200°F 3500 hr ABOVE 900°F	2800 hr AT 1200°F 7700 hr ABOVE 900°F	1 yr AT 1300°F 400 TO 600 kw	10,005 hr (417 days)	1000 hr	7023 hr 1100-1300°F

Fig. 7. Early US space reactor programs.

Fig. 8. SPAR power plant.

The SPAR reactor features a beryllium reflector and a laminated core configuration with sheets of molybdenum (Mo) extending across the full diameter of the core and interspersed between layers of UO_2 . Reactor heat is transferred by the Mo sheets from the UO_2 to an array of some 90 Mo/Na heat pipes. Ninety of these pipes are used

in the reactor to provide many independent alternative paths for removing the thermal energy from the reactor. The heat is then transported by the heat pipes around the LiH shield to a ring of high-power density thermoelectric modules using improved SiGe alloys (Fig. 9 lower left). The reactor heat is converted to electricity by the SiGe thermoelectric alloy with a temperature gradient of 600 K and an efficiency of 9%. Waste heat is rejected by a radiator that is constructed using heat pipes (Fig. 9 lower right). These heat pipes are arranged in panels made of titanium and provide redundancy to compensate for meteoroid damage. Avoidance of single point failures and propagating failures has constituted the main design emphasis for the SPAR system. Currently, no single failure points are known to exist in the power system.

Experimental and analytical work is being performed simultaneously on the reactor design (Fig. 10). The neutronics are experimentally checked using a critical assembly (Fig. 10 upper left) which contains core and reflector materials that match the reactor neutronics design. Thermal conduction experiments (Fig. 10 upper right) are used to verify contact resistance between the molybdenum fins and the core heat pipes. Core assembly procedures are being developed (Fig. 10 lower left) including attachment of the core support plate and

Fig. 9. Power plant subassemblies.

molybdenum fins. UO_2 wafer (Fig. 10 lower right) similar in thickness and density to the final UO_2 fuel form have been produced. Engineering design and testing of assembly procedures on scale models is on-going.

However, controls and shielding technologies are not actively being pursued because of lack of funds. Much of the technology in these areas was well developed from the SNAP program and that technology would be used on this reactor program as needed.

Table II is a typical design point for a 100-kW_e power plant.

TABLE II
TYPICAL 100 kW_e PARAMETERS

Power (kW _e)	1110
System efficiency (%)	9
Heat pipe temperature (K)	1450
Radiator temperature (K)	775
Fuel swelling (%)	4.4
Mass (kg)	1785
Reactor	400
Shield (25° half-angle)	540
Converter	290
Radiator	395
Structure	160

Fuel capsules for in-core fuel testing of the fuel wafer configuration to verify UO_2 fuel technology and heat transfer through the molybdenum fins are being fabricated.

The reactor thermal structural analyses and potential experimental tests required to demonstrate that the structural design of the reactor is acceptable will be conducted as part of the Advanced Development Phase.

Fig. 10. Reactor design.

The reactor heat pipes are currently made with molybdenum, although a more ductile at room temperature molybdenum-rhenium alloy is being investigated to better accept the ground handling and launch loads (Fig. 11). Two wick designs, the screen tube annulus (upper left) and the artery configuration are being developed. Both are composite wicks that provide relatively low-loss channels for the liquid phase working fluid while generating high pumping capability because of the fine porosity of the screen walls which contain liquid. The nonavailability of molybdenum screen with fine enough mesh (400) to give the desired capillary pore diameter ($\sim 30 \mu\text{m}$) has made it necessary to develop a compression screen from 150 mesh. Several 1-to-2-m-long heat pipes have been fabricated (Fig. 11 upper right) and tested (Fig. 11 lower left) in a vacuum test facility. The heat pipes will need to be bent to traverse the shield without radiation streaming. A stainless steel pipe was fabricated and tested (Fig. 10 lower right) successfully. An on-going long-term test of a molybdenum heat pipe at 1700 K has reached almost 18,000 hr, as of January 1981.

Fig. 11. Core heat pipe development.

Current activities include acquiring Mo-Re material for heat pipes, developing means to construct improved wicks, and developing bending technology. Plans are to develop a prototype artery heat pipe using Mo-Re including two bends and proceed to long-term demonstration tests. The basic technology appears in hand, but heat pipe fabrication procedures, performance predictability, performance reproducibility, behavior with an adiabatic section, the effects of bends, etc., is part of the on-going program.

Power conversion uses thermoelectric (TE) technology for high reliability. Silicon-germanium (SiGe) alloys possess attractive thermoelectric performance characteristics as well as mechanical and physical attributes that make them highly desirable candidates for space power applications. This material was used on the recent successful Voyager fly-by flights of Jupiter and Saturn. Most important of these qualities is their stable high-temperature operating capability, which allows high heat rejection temperatures and, hence, reduces the radiator area and weight of a space power system. Too high a thermal conductivity has been the main limitation of the SiGe alloys. However, work preformed initially for NASA and now for DOE has demonstrated

that significant reduction in thermal conductivity and consequent increase in efficiency can be obtained by adding 5 to 7% GaP to Si 20 at% Ge alloy. A cylindrical TE module using SiGe with GaP is under development. Figure 12, upper left, shows a compression-coupled SiGe TE module design on a heat pipe being prepared for test. Fig. 12, upper right, depicts part of the material fabrication facilities, while Fig. 12, lower left, shows a vacuum test chamber and lower right shows some of the compression module details.

Fig. 12. Thermoelectric module development.

Our immediate goal is to develop a higher efficiency module, all-bonded TE flight prototype, using improved materials and higher temperatures (1400 K). There are two basic approaches to developing a TE module. One approach is to develop individual modules compatible with each heat pipe and the other is to develop a panel-type TE module that is a portion of the TE generator which receives heat from all the reactor heat pipes. The compact cylindrical module is now receiving the most attention.

Titanium heat pipes are being developed to provide light-weight, reliable heat rejection devices for the radiator. The radiator design includes 270 heat pipes, each of which is approximately 5 m long and dissipates 4 kW of power at 775 K. The radiator heat pipes are potassium filled, have two screen arteries for fluid return, and a roughened surface distributive wicking system. As part of the development program leading toward a 5-m heat pipe, shorter heat pipes in 0.3- and 2-m-lengths were fabricated (Fig. 13, upper left). These heat pipes have a "D" shaped cross section (Fig. 13 upper right). They are operated isothermally at 775 K and dissipated up to 1.5 kW. A 5.3-m-long heat pipe is now being fabricated by welding three shorter sections together. Figure 13, lower left, shows the forming operation, lower middle a potassium/titanium compatibility test apparatus, and lower right installation of a heat pipe into a vacuum test chamber. Meteoroid impact tests have verified the use of titanium as an acceptable radiator material.

Currently, work has slowed on the radiator because of lack of funds. Titanium fabrication

Fig. 13. Radiator heat pipe development.

facilities need to be established for manufacturing radiator panels. The 5-m-long heat pipes need to be tested at temperatures for long times. Also, higher temperature tests are needed to define the upper operating temperature limits and the effect of heat pipe length on performance.

Another area that needs to be developed is the method of coupling the radiator heat pipes to the TE cold junction with as small a temperature drop as possible.

Safety is a key consideration in reactor design and operation (Fig. 14). The reactor is launched without any operating history to avoid fission product inventory and thus is not radiologically hazardous on launch. Safety precautions include multi-redundant control elements that are locked during launch and ascent to orbit and reactor designs that are subcritical in water in case of a launch abort. Also, no thermal cooling is required prior to reactor operation.

After 300 yr following operation (allowing time for fission product decay) reactors are again considered radiologically safe. The missions currently contemplated call for an initial operation of the reactor at orbits with lifetimes that exceed 300 yr. Lower orbits could be considered with a satellite boost capability at the end-of-life and an operational Space Shuttle to deliver a back-up boost capability.

In the final analysis, reactor power systems can be designed so there is no added perceptible risk to the STS operation.

We also need to consider some of the operational features in using NEP. In a one-way transfer from LEO to GEO, the nuclear power plant would continue to be used as the spacecraft power source. For outer planet exploration, there is no maintainability or future manned activities to be considered. In a reusable orbital tug, however, one might consider refurbishment of the power source, ion thruster subsystem, or other parts of the stage in LEO. A possible philosophy for this would be to replace the entire power module when degradation is sufficient to warrant it.

Fig. 14. Reactors provide a safe power source.

The power plant is designed for operation for a selected time period, such as 10 yr without maintenance. With the expected high design reliability, failures should be separated by years of successful operation. When a failure does occur, the life of the remaining components and subassemblies will have been reduced from use and thus the mean time between failures in the future of the remaining subassemblies is less. Replacing the power module instead of a subassembly avoids lower mean times between failures. Also, new technology can be introduced into the power subassemblies and additional requirements met. The cost of a power subassembly is sufficiently low to justify replacing the module. To replace a module would be relatively straightforward, following a procedure such as:

1. Shutdown reactor and allow a few days for fast decay product decay.
2. Secure drums in shutdown position.
3. Disconnect cables to spacecraft.
4. Attach removal rocket and disconnect power module.
5. Activate thrusters for removal from spacecraft to a safe distance.
6. Activate Sun-disposal thrusters.
7. Bring in new module.

D. Possible SPAR Derivatives

The current SPAR system is designed to generate 1200 kW power. The use of sodium in the heat pipes limits the design to about 1550 K. Higher temperatures to maybe 1700 K are possible by substituting lithium in the heat pipes and making the reflector all BeO. Fuel swelling--of which there is the need for more in-pile testing--appears to limit long-term reactor operation to less than 1700 K heat pipe temperature. This potential higher temperature can be used as a thermal energy source for thermionic or advanced TE converter and could result in increased SPAR performance to 150-200 kW_e. Also, dynamic conversion schemes, such as Rankine or Brayton

cycles, could provide several hundred kilowatts of power. These cycles would not require the advancements in reactor technology in the high temperature regime, but tend to require very large radiators.

Heat pipe reactor designs appear to be a feasible concept up to maybe 1 MW_e. An alternate SPAR core that might be desirable to investigate is a fluid core. Heat pipes could still be used.

E. Multimegawatt Technology

We will use 20 MW_e as our design goal for a multimegawatt power source. The operating temperature for the power plants is a compromise between the desire to keep reactor temperatures low to minimize fuel swelling and material problems, keeping the radiator temperatures high to minimize size and mass, and selecting temperatures compatible with electric power conversion equipment. If one selects a radiator temperature of 1000 K, we need 20 m²/MW for reject heat. Assuming conversion efficiency of 20%, this implies a heat rejection area of 1600 m²--one-sixth the size of a football field (assuming heat rejection from both sides of a flat radiator). This would be quite a bit smaller than the 40-football field area for solar arrays. Assembly or deployable radiators in space would be required. If the radiator temperatures are decreased to 900 K, this area increases 50% and if decreased to 800 K, the area increases by a factor of 2.4. At 800 K, a titanium alloy might be feasible. Above this temperature, stainless steel appears to be the better choice. Because of volume restraints in the Shuttle, a reject temperature goal of 1000 K appears desirable.

As a candidate for the multimegawatt power plant, we might want to consider a fluid reactor. Fluid-fuel reactors probably in the form of molten salt offer the potential of high temperatures, avoidance of fuel element fabrication, rapid and inexpensive reprocessing, on-line refueling, a good neutron economy. The major problem is possible corrosive interactions between the molten salt and the core structural and heat transfer materials. Molten plutonium or uranium chloride for fuel with molybdenum as the structural material may be candidates. Figure 15 shows a possible arrangement of the core.⁵ Liquid 16% PuCl₃/84% NaCl has a liquidus temperature of 960 K and boiling point of 1775 K; liquid 65% UCl₃/35% NaCl has a liquidus temperature of 985 K and boiling point of 1975 K. The core can be designed with a very strong negative temperature coefficient of reactivity; arising out of any power excursion we get an increase of fuel temperature, causing a decrease in density and an ejection of part of the fuel material from the core region through specially arranged tubes. The molten salt can be removed from the core continuously or periodically to remove undesirable fission products. The reactor size is expected to be quite compact and fit into the Shuttle bay with ease. Estimated reactor characteristics are given in Table III.

Fig. 15. Fluid core reactor.

TABLE III
ESTIMATED REACTOR CHARACTERISTICS FOR FLUID
100 MW_t

Core power density (MW _t /m ³)	200
Fuel	UCl ₃ , PuCl ₃
Core size (m)	
Height	0.5
Diameter	0.5
Reflector	BeO or NiO
Mass (kg)	2200
Fuel residence time	1 s

Turning to electrical converters compatible with hot side temperatures of 1600-1700 K and a reject temperature of 1000 K, we have thermionics or advanced dynamic turbomachinery. Magnetohydrodynamics is a potential candidate as a topping cycle for a gas core reactor. The former systems have the potential of about 20% efficiency, while the latter could increase efficiency up to 35%. The confidence level in achieving 20% is much higher.

IV. Concluding Remarks

Nuclear power is a logical energy source for ion propulsion because of its independence of solar fluence and its insensitivity to space radiation. With it, all manner of opportunities open for the humanization of space especially when one considers the transportation of large masses of materials and the exploitation of materials from the lunar surface. Outer planetary exploration depends on nuclear electric propulsion.

Currently, the major space reactor power plant development effort is concentrated on developing components for a fast-spectrum, heat pipe reactor. This power plant when fully developed can provide the power for nuclear electric propulsion. The technology also provides a base for power levels up to 1 MW_e. Above this level, alternative approaches to reactor power plants will need to be pursued.

References

1. J. Angelo, "The Space Shuttle - A Cosmic Perspective," XXXth International Astronautical Federation Congress, Munich, FRG, September 1979.
2. A. Berry, The Next Ten Thousand Years, The New American Library, Inc., New York (1975).
3. A. C. Clarke, Profiles of the Future, Popular Library, revised edition (1977).
4. J. von Puttkamer, "Humanization beyond earth: the new age of space industrialization." Symposium on Prospects for Life in the Universe: Ultimate Limits to Growth, Washington, DC (1978).
5. J. Angelo and D. Buden, "Space Nuclear Power-A Strategy for Tomorrow," AIAA Conference on Large Space Platforms: "Toward Permanent Manned Occupancy in Space," San Diego, CA, 2-4 February 1981.
6. N. S. Kardashev, "Transmission of Information by Extraterrestrial Civilization," Soviet Astronomy, Vol. 8, 217 (1964).
7. K. A. Ehricke, "Space Stations - Tools of New Growth in an Open World," Proceedings of the XXVth International Astronautical Congress, Amsterdam, The Netherlands (1974).
8. Rockwell International "Space Industrialization," (Final Report) SD-78-AP-0055-1, 1978.
9. Science Applications, Inc., "Space Industrialization Study," (Final Report) SAI-79-602-HU, 1979.
10. R. Nagorski, "Advanced Power and Propulsion Study, Phase 1: Nuclear Electric Applications," (Final Report) Jet Propulsion Laboratory 7-5-99, December 1980.
11. L. Jaffe and H. N. Norton, "A Prelude to Interstellar Flight," AIAA Astronautics and Aeronautics, January, 1980, p. 38.
12. DoD/NASA/DOE Space Reactor Power System Working Group (DRAFT) Briefing on Applications, Technology Status, and Development Plan, 20 February 1981.
13. "ZrH Reactor-Thermoelectric Space Power System Program Review," Atomics International, Canoga Park, CA, Sept. 11, 1973.

REACTORS FOR NUCLEAR ELECTRIC PROPULSION*

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Abstract

Propulsion is the key to space exploitation and power is the key to propulsion. This paper examines the role of nuclear fission reactors as the primary power source for high specific impulse electric propulsion systems for space missions of the 1980s and 1990s. Particular mission applications include transfer to and a reusable orbital transfer vehicle from low-Earth orbit to geosynchronous orbit, outer planet exploration and reconnaissance missions, and as a versatile space tug supporting lunar resource development. Nuclear electric propulsion is examined as an indispensable component in space activities of the next two decades.

I. Background

Of the two principal energy source options available for electric propulsion, nuclear and solar, nuclear has some distinctive advantages. Nuclear electric propulsion systems (NEPS) have potentially higher power densities than solar and their performance is independent of the distance from the Sun. In addition, NEPS will not degrade in passing through the Earth's radiation belts--a factor severely limiting the use of solar electric propulsion as a reusable orbital transfer system from low-Earth orbit (LEO) to geosynchronous orbit (GEO) and vice versa.

The necessary quantity of power for future space missions can be divided into two classes--hundreds of kilowatt electric and tens of megawatts electric. The former class is one in which the Space Power Advanced Reactor (SPAR) fits and whose components are under development at the Los Alamos National Laboratory. The size of the reactor, shield, converter, and radiator makes for a compatible system that can be launched in a deployed mode by the Space Shuttle. The latter class leads to new development problems because of the quantity of reject waste heat necessarily involved. The radiator will become quite large and require a deployable configuration. Reject heat temperatures will need to be raised to keep the radiator size within reasonable bounds. Higher-efficiency converters with higher reject heat temperature will need to be developed. This will require major advancements in converter technologies. A desirable goal is a converter of 20% efficiency and a reject temperature over 1000 K. Subsequently, this places great stress on the reactor core design with fuel swelling a major potential problem. A reactor concept that might support this power requirement in space is discussed.

*This paper represents the views of the authors and does not necessarily reflect the official opinion of the US Department of Energy, the Los Alamos National Laboratory, or the Department of Defense. Work performed under the auspices of the US Department of Energy.

II. Missions

Human progress depends on challenge and growth. As we enter the next millennium, expansion into space offers a virgin resource base for human progress.¹ Despite contemporary doomsday predictions that exaggerate the Earth's finite resource base and increasing population density, technical progress can continue through use of extraterrestrial resources.² The key here is the skillful exploitation and "humanization" of space. This humanization is an evolutionary process in which mankind learns to use cislunar and translunar space to improve life on Earth after first learning to live in space (see Fig. 1). The dynamic growth of mankind depends on an ever expanding outlook--a closed-world environment leads to evolutionary stagnation.^{3,4} Exploitation of the extraterrestrial frontier provides mankind with a limitless environment to continue our development and growth.⁵

We have the technical expertise for initiating the next phase of space development--extension of the human resource base throughout the solar system.⁶ This extraterrestrial expansion will create an "open world" philosophy for human civilization. Key steps involved in off-planet expansion are: the development of reusable space transportation systems; the establishment of manned space stations in low-Earth orbit and eventually in geosynchronous orbit; and the establishment of space-based industries, lunar settlements, and tapping of lunar and asteroid resources. The Space Shuttle represents the US commitment to the first step in extraterrestrial expansion.

There are three cornerstones on which the extraterrestrial portion of an "open world" will depend. These are: (1) energy conversion systems--especially power and propulsion modules; (2) the ability to process extraterrestrial materials anywhere in the solar system; and (3) the space station as a habitat for man's permanent occupancy of space. Initially, we can get by with solar arrays for power and with chemicals for propulsion; but as our needs expand, nuclear reactors will become the prime energy source. This use of nuclear energy will not only power the space-based manufacturing facilities, but will also be the energy source for transporting large volumes of material in cislunar and translunar space. In fact, without a nearly limitless portable energy base, space development will be severely truncated and finally crippled.

Therefore, a key enabling technology in man's extraterrestrial expansion is the development and effective utilization of NEPS systems. Such systems not only support the creation of a cislunar industrialization process^{8,9} but also enable the detail reconnaissance and eventual exploitation of the outer planets¹⁰ of this solar system and can serve as a technical prelude to interstellar flight.¹¹