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SPACE NUCLEAR POWER - A STRATEGY FOR TOMORROW*

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Abstract

Energy: reliable, portable, abundant and low cost will be a most critical factor, perhaps the *sine qua non*, for the unfolding of man's permanent presence in space. Space-based nuclear power, in turn, is a key technology for developing such space platforms and the transportation systems necessary to service them.

A strategy for meeting space power requirements is the development of a 100-kW_e nuclear reactor system for high earth orbit missions, transportation from Shuttle orbits to geosynchronous orbit, and for outer planet exploration. The component technology for this nuclear power plant is now underway at the Los Alamos National Laboratory. As permanent settlements are established on the Moon and in space, multimegawatt power plants will be needed. This would involve different technology similar to terrestrial nuclear power plants.

I. Background

Human progress depends on challenge and growth. As we enter the Third Millennium, Space offers human development an expanding resource base for human progress.¹ Despite contemporary doomsday predictions which highlight the Earth's finite resource base and diminishing living area, technical progress can continue.² The key is the skillful exploitation and "humanization" of space.^{3,4} This humanization of space is the evolutionary process in which mankind learns to use cislunar space to improve life on Earth, and also learns (a selective few people at first) to live in space.

Space, man's ultimate frontier, will be exploited--the question is who will be the pioneers and reap the benefits. The whole dynamic growth of mankind depends on ever expanding our outlook--a closed environment leads to evolutionary stagnation.^{1,2} Exploitation of the extraterrestrial frontier provides mankind an infinite, limitless environment to continue our development and growth.

We now have the technical foundations for initiating the next phase of global development--expansion of the human resource base to encompass

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the solar system.⁵ This extraterrestrial expansion creates an "open world" approach to human civilization. Several key steps will mark our off-planet expansion starting with the development of reusable space transportation systems, the establishment of manned space stations in low-Earth orbit and eventually in geosynchronous orbit, 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 into extraterrestrial expansion.

There are three cornerstones on which the extraterrestrial portion of an open-world will depend.⁶ 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 on solar arrays for power and chemicals for propulsion; but as the 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 materials in cislunar space. In fact, without a nearly limitless energy base, space development will be severely limited and crippled.

Like nuclear energy, the space station is a critical tool in man's exploitation of Space. Nuclear energy--reliable, portable, and compact--makes a truly open-world civilization possible; while the space station--supporting man's permanent presence in the extraterrestrial environment--provides a renewed sense of cosmic purpose for human civilization and growth. Properly designed and powered, future space stations will integrate unique human abilities with sophisticated capabilities of fully automated and cybernetic systems. The space station, or more precisely, a series of space station designs, will perform a variety of functions, see Fig. 1.⁷ In time, space stations will not only remain captive to Earth in low or geosynchronous orbits, but will also provide habitats far from Earth in lunar space, in orbits around other planets, and in the vast interplanetary regions of the solar system (e.g., heliocentric orbits in the asteroid belt). These orbiting stations will open up the solar system to human exploration and meaningful exploitation. As the size of such manned space platforms grows from the "captive" Spacelab, to a "free flying" version of Spacelab, to our early, perhaps mini-modular space station in LEO, to large modular space habitats--the nuclear power plants will be recognized as the key to higher productive capacity; the key to successful human expansion into cislunar space--and beyond.

Fig. 1. Typical space station functions.

Figure 2 depicts a typical 60-person nuclear-powered space station. The station could consist of 6 large, manned modules and 5 telescoping, connecting booms. Two nuclear reactors are present to provide a redundant, continuous power source. The station features such characteristics as zero and artificial gravity environments and a shirt-sleeves habitat.

Future lunar settlements may at first be semi-permanent and then grow to permanent occupancy. A 12-man lunar base would require 20-100 kW_e of continuous power. As the base expands to 200 persons, power requirements have been estimated to increase to multimegawatt range. An advanced lunar base could require several hundred megawatts of power especially if mass drivers are used (see Table I) or large quantities of heat are needed to process lunar materials.

TABLE I
ADVANCED LUNAR BASE

Facility	Power Requirements (MW)
Habitat (300 persons)	2
Farm	9
Oxygen plant	1
Material bagging plant	2
Mass drivers	186
Total	200 MW

Now let us turn our discussion to current space reactor development and investigate possible forms of future developments. Current reactor development centers on the Space Power Advanced Reactor (SPAR) program.

II. SPAR Power Plant and Its Potential Role in Support of Space Platforms and in Establishing Lunar Bases

A. SPAR Technology

At the present time, the Los Alamos National Laboratory is developing components for a 100 kW_e (1200 kW_t) space power plant. This power plant, SPAR, is being designed for a 7-yr-lifetime without provisions for maintenance or refueling. It is being designed to fit within the confinements of the Space Shuttle. The mass goal is 1910 kg including a radiation shadow shield. The technology concentrates on a heat pipe, solid core, fast reactor design.

Fig. 2. 60-person space base.

A space reactor electric power plant has four major subassemblies: the nuclear reactor that generates thermal energy (heat), the radiation shield that protects other parts of the spacecraft from reactor radiation, the converter that produces electricity from the thermal energy created in the reactor, and the radiator that discharges waste heat. The SPAR reactor uses uranium dioxide as a fuel and is designed to operation around 1400 K. Heat pipes are used to extract the thermal energy from the core and to transport it to the electrical conversion equipment. The heat pipe is a tube with a working fluid that is vaporized in the heated end (the reactor) and is condensed back to a liquid in the heat extraction end (the electrical converter). A wick in the flow path along the tube wall returns the liquid by capillary action to the reactor. The electric conversion system makes use of thermoelectrics mounted on the end of the core heat pipes. Heat pipes are also used to extract the heat rejected from the electrical conversion process and form a radiating surface-to-space. The general features of the SPAR system are illustrated in Fig. 3.

Fig. 3. General features of the SPAR system.

The reactor design features a beryllium reflector except where the heat pipes exit the core, the reflector becomes beryllium oxide. The core features a laminated configuration with sheets of molybdenum extending across the full diameter of the core and interspersed between layers of UO_2 . Reactor heat is transferred by the sheets from the UO_2 to an array of some 90 Mo/Na heat pipes. The heat is then transported by the heat pipes around the LiH shield to a ring of high power density thermoelectric modules constructed from modified SiGe alloys using GaP. Conversion takes place over a temperature gradient of 1400-775 K with an efficiency of 9%. Residual heat is rejected by a radiator that is constructed using titanium heat pipes.

Avoidance of single point failures and propagating failure chains has constituted the main design emphasis for the SPAR system. Currently, no single failure points are known to exist in the power plant. Thus, the core contains 90 separate thermally-coupled heat transfer loops, each with an associated power conversion module. Connecting modules in a series-parallel network makes it possible to tolerate the loss of several of these

units while still maintaining operational capability for the system as a whole. Interconnecting the heat pipes in the waste heat removal system yields a network that is highly tolerant of heat pipe failures.

The current SPAR system is designed to generate 1200 kW_t 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 thermoelectric converters and could result in increased SPAR performance to 150-200 kW_e. Also, dynamic converters, such as potassium 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.

B. Use of SPAR to Establish Space Stations and Lunar Bases

The use of nuclear reactors on a low orbit manned platform was studied by Grumman⁸ and McDonnell-Douglas⁹ in 1977. The base was assumed to require 150 kW_e. Various potential power plants were analyzed including Si and GaAlAs photovoltaic systems, solar-thermal systems with Brayton or thermionic electric power converters and nuclear reactors with either Brayton, thermionics, or thermoelectric converters. The study concluded that photovoltaic, solar thermal, or nuclear power plants (with manned rated shielding) could satisfy the power requirements. New technology is not needed for a low-Earth orbit space station. However, nuclear power offers certain advantages, including:

- 1) ease of station keeping and less use of propellant,
- 2) less restrictions of docking ($\pm 6^\circ$ with a 4π radiation attenuation shield vs $\pm 60^\circ$ with photovoltaics), and
- 3) sun-oriented experiments more easily performed.

Another major advantage not considered in these previous studies is the experience gained for the movement to more ambitious space bases further from the Earth, where nuclear will most likely be a necessity.

With a reactor present, personnel must be protected from the radiation emitted by the power plant. The shield mass to protect space station personnel depends on power level, location, and biological requirements. We have considered a short boom (10-m), a long boom (100-m), a tethered cable (1000-m), or a separate satellite where the electric energy is microwaved back to the Space Station (5000-m). For the boom configuration, it may be acceptable to have a higher radiation level away from the Space Station because of the rigid

arrangement. The tethered and separate power satellite may need equal shielding on all sides of the reactor (4π) because of orientation uncertainties.

Table II provides a list of requirements as defined by NASA in the Space Transportation Payload Safety Guidelines Handbook. Thirty-five rem/quarter from Table II corresponds to 16 mrem/h. Natural radiation at 370 km (200 nmi), 28-1/2° inclination orbit with a 300-mil aluminum shield is 3.5 mrem/hr allowing 12.7 mrem/hr for induced radiation. The use of 3 mrem/h as a base seems very reasonable at this time. Radiation attenuation varies as the distance squared and linearly with power level. Sufficient studies have not been performed on manned shielding to provide optimized designs. However, information was available from a study by Oak Ridge National Laboratory reported in "Optimization of a Shield for a Heat-Pipe Cooled Fast Reactor Designed as a Nuclear Electric Space Power Plant," ORNL-YM-3449, June 15, 1971, to provide a good base for initial power plant studies. The study considered two core angles--45° and 90° for the shield. If the power plant is located in the middle of one side of the space station, the short boom (10-m) would require a 90° shield while with the long boom a 45° shield should be adequate. If the power plant is located at one end of the space station, a 45° shield (or less) would suffice for either boom. Projected shield masses are given in Table III. A 4π shield can easily be delivered to low Earth orbit in a single Shuttle flight as part of the SPAR power plant for a long boom or further separation configuration.

Since early low orbit manned space stations can be expected to have a lifetime of tens of years by continuous expansion and maintenance, consideration must be given to how to maintain the

power systems. Two major philosophies are considered feasible for maintainability. The first is based on replacement of the power module except for the major biological shield in case of a malfunction; the second would replace major subassemblies or components that are readily accessible and do not have high levels of induced radiation. Maintenance at the component level is considered undesirable in the near-term because of the cost of setting up specialized facilities in space that would have little demand.

Replacement of Power Module. The power plant is designed for operation for a selected time period such as 10 years without maintenance. Because of the need for continuous power, dual power modules or an emergency power unit (each independent) will be needed in case a failure should occur at some time. 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 (see Fig. 4).

Major Subassembly Replacement. The reactor actuators, converters, and sections of radiators are considered potential subassemblies that might be replaced. It is assumed that only limited access would be permitted in the immediate vicinity of these components and then only when the reactor is not operating and sufficient time has passed to

TABLE II

RADIATION EXPOSURE LIMITS AND EXPOSURE RATE CONSTRAINTS FOR UNIT REFERENCE RISK*

From Space Transportation System Payload Safety Guidelines Handbook, NASA Lyndon B. Johnson Space Center, Houston, TX, July 1976, Table 3.14-III.

Constraints	REM**		
	Bone Marrow (5 cm)	Skin (0.01 mm)	Eye (3 cm)
1-year average daily rate	0.2	0.6	0.3
30-day maximum	25	75	37
Quarterly maximum	35	105	52
Yearly maximum	75	225	112
Career	400	1200	600

*For details, see "Radiation Protection Guides and Constraints for Space Missions and Vehicle Design Studies Involving Nuclear Systems, Report of the Radiobiological Advisory Panel of the Committee on Space Medicine, Space Science Board, National Academy of Science, 1970."

**REM (Roentgen equivalent man) REM is a unit of radiation dose equivalent. For details, see "International Commission on Radiation Protection," Publication No. 9, 1966.

TABLE III
MANNED SHIELD MASS, kg

		45° Shield		
		Power, kW(t)		
Distance, m		200	600	1000
Short boom	10	8,590	11,330	11,840
Long boom	100	3,620	4,370	4,510
Tethered cable	1000	930	1,750	1,900
Power satellite	5000	560	830	930

		90° Shield		
	10	14,950	19,730	20,610
	100	6,310	7,610	7,840
	1000	1,610	3,050	3,310
	5000	980	1,450	1,610

		4 π Shield		
	10	18,670	24,620	25,720
	100	7,870	9,500	9,790
	1000	2,010	3,810	4,130
	5000	1,220	1,810	2,010

Fig. 4. Power-model replacement and power model separated from shield.

eliminate fast fission decay products (about two days). The amount of maintenance time would be limited to perhaps 8 hours for a person to disconnect and replace a failed subassembly. Biological radiation standards would be strictly adhered to. Replacing major subassemblies has the advantage that the most probable failures will occur in the conversion units and as such, a power plant could possibly give many more years of useful life. The major arguments against subassembly replacement are:

- Locating the exact failed unit may be difficult.
- Making provisions for replacing subassemblies may lead to a higher probability of failure.
- The cost of developing special disconnect and connection equipment may exceed the cost of replacing the complete power

module. Only a few such operations are anticipated over the life of the space station.

In place of the current SPAR design which has the thermoelectrics directly mounted to the core heat pipes, one might want to consider a radiative coupling approach between the reactor and the power conversion equipment. The power conversion equipment could still be thermoelectrics or consideration might be to thermionics or a dynamic converter. By proper configuration and shielding, this would allow the converter and radiator to be maintained or replaced separate from the reactor. The reactor reactivity power control drum actuators can also be redesigned to be replaced as part of a maintenance procedure. However, the core itself, including the heat pipes cannot readily be designed for maintenance or refueling in the current configuration. For the reactor, the subassembly should be replaced as a unit: thus, the reactor can be arranged as a plug-in module that can be separated from the major part of the radiator, shield, and converters. The reactor with a shield plug can then be removed as a unit and disposed of in high-orbit, while a new reactor unit is installed in the power plant. This scheme requires removal and disposal of only a small part of the power plant mass, as represented by the plug in Fig. 5.

Fig. 5. Replacement of SPAR reactor for refueling or maintenance.

The low orbit space platform can reasonably be serviced by the Space Shuttle and will represent the first stage in the permanent occupancy of space. However, manned stations at geosynchronous orbit, orbiting lunar stations, and settlements on the lunar surface can follow several technology paths and will represent a giant step beyond the low orbit stations. To put the problem in perspective, the payload-to-geosynchronous orbit from a Space Shuttle flight using chemical propulsion is less than one-tenth that of low orbits. For lunar orbits or the lunar surface, the payload is further reduced. Nuclear electric propulsion can expand the payload-to-geosynchronous orbit (Fig. 6) by factors of 4-6 times, and thus, forms a basis for high orbit stations. Time periods to move cargo to these high orbits may approach one year and, to minimize shielding, will be unmanned. A chemical tug will be needed for the manned part of the operations and to move priority cargo. The nuclear power plant used in the transportation of cargo can then be tied into a utility for the space station. The major problem is shielding. If the lunar base is established first, this can

be the source of material for shields against natural and reactor produced radiations. Lunar materials represent a shielding material resource that is frequently not considered. Otherwise, long power transmission tethers may be best for initial operation. Optimization studies are needed on this point. An important point here is that without nuclear electric propulsion, manned occupancy of high orbits or lunar bases is probably not feasible--there is only so much energy in a kilogram of propellant. Thus, without nuclear electric propulsion, we will reach a plateau in space development established by the limitations of the transportation system.

Source: M. H. Kaplan, R. M. Tan, D. Buden, "A Nuclear Electric Orbital Transfer Vehicle for the Shuttle Era," Paper 79-2109, Princeton/AIAA/DGLR 14th International Propulsion Conference, Princeton, NJ, Oct. 30-Nov. 1, 1979.

Fig. 6. Maximum payload vs mission time.

III. Nuclear Power in Support of Expanding Space Settlements

A. Desirable Features of Lunar or Manned Space Reactors

As we move to permanent occupancy of the lunar surface and to space stations, desirable power plant features approach those of terrestrial utility systems. However, we are constrained by isolation and mass restrictions. We may witness an interesting phenomena where nuclear power for Earth applications gets a new impetus for advancement as a result of developments for space applications. We postulate power requirements as follows:

(1) Power level - a thermal power level on the order of a hundred megawatts appears desirable. This could power mass drivers or chemical processes on the Moon. On space stations, it would power manufacturing processes.

(2) Reliability - an uninterrupted power source for life support equipment and a minimum interruption for experiments is required. Certain manufacturing and fabrication tasks can accept interruptions, but for limited periods of time. This implies at least two independent power plants that may or may not be identical or an arrangement of substitutable redundant assemblies.

(3) Lifetimes - lifetimes of 30-40 years will be required because of the large capital investment. Space stations and lunar settlements will be expected to be permanently manned.

(4) Safety - the power plants should be designed to avoid single failure points and catastrophic failures, such as core melt downs. Personnel must be protected from radiation. Isolation from the general terrestrial population already exists, so this is not a problem.

(5) Maintenance - all parts of the power plant should be maintainable or replaceable. No large shutdown times will probably be acceptable because of the limited redundancy that can be provided to the power grid. Therefore, power plants that can be refueled while operating would be favored. No massive maintenance equipment can be tolerated.

(6) Waste disposal - because the reactors are located in space or on the lunar surface, waste should be accumulated in a form that allows easy isolation (on the Moon) or transport to a safe orbit (from a space station). No plans should be made for returning radioactive material to Earth for terrestrial reprocessing or disposal.

(7) Mass - because the reactor will probably be manufactured on Earth, mass restrictions are still significant. Lunar settlements can furnish shielding by mounding lunar material around the reactor--large containment vessels will not be needed. Space stations will need sufficient shielding or separation to protect the residents. A minimum of support equipment should be considered because of mass restrictions.

(8) Interference with other operations - a minimum of restrictions to operations such as docking, scientific observations, etc., should be tolerated.

B. Potential Multimegawatt Power Plants

With the above goals in mind, one can begin to configure potential power plants for lunar or manned space stations. Because transportation costs will continue to be a dominant factor, the mass and volume restrictions are very significant, as well as the deployment strategy. It appears reasonable that one would start a lunar settlement with small reactors, such as SPAR, to provide an initial source of power and to be available as an emergency back-up system in case of planned or unplanned power outage. Solar arrays do not appear reasonable when one considers a 14-day period out of 28 on the lunar equatorial region without sunlight. A 20 MW_e solar array (20% efficiency) would cover an area on the order of 40 football fields on the lunar surface. Small reactors could provide a power source for site preparation leading to the installation of one or several hundred megawatt reactor power plants. Site preparation might include preparation of a lunar soil shielded igloo for installation of the power plant, preparation of pads for power conversion equipment, and a power distribution system (thermal or electrical). The power grid may include two reactors, three or more power conversion units, process heat distribution system,

and an intertied, modularized heat rejection system. Figure 7 shows the affect on reliability of different module arrangements. The reactors and power conversion equipment would be delivered as units. The radiator modules and heat distribution system could be delivered in parts and assembled at the lunar base.

For a manned space station, a similar implementation strategy is possible. In fact, it is highly desirable to standardize on power plant assemblies for both applications. Space stations would need to incorporate a more concentrated shield. The source of the shielding material might depend on the station location and what resources are available. For instances, a low orbit space station would probably use shields built on Earth. Geosynchronous Space Station (GSS) or Orbiting Lunar Station (OLS) stations might use material from the lunar surface, if the lunar surface base is in existence first.

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. Also, heat for thermal processing and for thermal conditioning of the station or settlement needs to be considered. If one selects a radiator temperature of 1000 K, we need 20 m²/MW for reject heat. If one considers the energy will be used in the form of electrical power and if the conversion efficiency is 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). On the lunar surface, this would be one-third the size of a football field but still quite a bit smaller than the 40-football field area for solar arrays. 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. Figure 8 plots potential radiator materials. Impact tests indicate beryllium is quite brittle and would not be a good choice for a radiator. At 800 K, a titanium alloy might be feasible. Above this temperature, stainless steel appears to be the better choice. For now, because of volume restraints in the Shuttle, we will use a reject temperature goal of 1000 K.

After reviewing various potential reactor configurations, conceptual choices selected center on the pebble bed solid fuel reactor, fluid core reactor, and the gas core reactor. All of these concepts allow continuous refueling for maintenance. Remember, mass and volume restrictions still dictate keeping refueling and maintenance equipment to a minimum in volume and mass. The hot side operating temperatures are established by reactor materials that provide long lifetimes in conjunction with power conversion equipment limitations. Power conversion equipment selection centers around thermionics, dynamic rotating machinery, and magnetohydrodynamics. The former systems will probably have efficiencies around 20% (remembering the reject heat restrictions), while the latter could extend this to 35% in efficiency.

TABLE IV
PEBBLE BED REACTOR TECHNOLOGY BASE SUMMARY

Plant	Thermal Power (MWt)	Location	Experience Type	Primary	Startup Date	Fuel Type
Dragon	20	U.K.	Construction & Operation	Helium	1965	Rods
Peach Bottom	115	USA	Construction & Operation	Helium	1967	Rods
AVR	46	FRG	Construction & Operation	Helium	1967	Pebble Bed
Fort St. Vrain	842	USA	Construction & Startup	Helium	1976	Prismatic
THTR	750	FRG	Construction	Helium	1981	Pebble Bed
AGRs	135-1690	U.K.	Construction & Operation	CO ₂	1956-1979	Rods
GCRs	105-1450	France	Construction & Operation	CO ₂	1959-1972	Rods
HTGR Studies	2000-3000	USA	Licensing & Studies	Helium	-	Prismatic

Sources: "Gas Reactor International Cooperative Program Interim Report," COO-4057-6, General Electric Co., Sunnyvale, CA, SEpt. 1978.

Fig. 9. Diagram of pebble bed reactor.

a swirl flow of buffer gas, and in a coaxial-flow device, by the propellant stream. The reactor vessel has a few cubic meter volume and is filled with enriched UF₆ at a typical pressure of 40 atm. The critical mass is in the range of 10 to 50 kg. The part of the kinetic energy of the fission fragments that is randomized, heats the UF₆ gaseous fuel to a temperature of 1500 K. This heat is removed from the reactor by a heat exchanger and is fed into a thermodynamic cycle for power generation in a conventional fashion.

It appears that pebble bed, molten-salt or gaseous reactors can be designed to operate in the vicinity of 1600-1700 K. The gaseous core as a plasma might be capable of much higher temperatures.

Table V provides estimates for 100 MWt power plants for pebble bed, fluid, and gas reactors. The size of the reactor and, consequently the mass, is determined by power density. The low

power density of the pebble bed reactor is due to the safety features built into the design where sufficient heat capacity exists to take care of a loss of coolant accident. The fluid reactor has the highest power density and therefore, is the most reasonable mass. All systems assumed a reflector thickness of 15-cm surrounded by a B₄C thermal shield to reduce the neutron fluence to the pressure vessel (2.5-cm thick) and a steel pressure vessel (2.5-cm thick).

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. Magneto-hydrodynamics 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.

Fig. 10. Fluid core reactor.

Fig. 11. Gas core reactor.

Since we are not ready to do a detailed evaluation of all possible converters, let us assume the potassium Rankine cycle in our discussions. Rankine cycles using mercury, potassium, and organic working fluids have been studied for potential space power systems. The SNAP-8 mercury cycle was studied extensively by NASA for use with a NaK-cooled U-ZrH reactor operating at 933 K. The potassium cycle was studied for a high-temperature (1400 K turbine inlet) system. Component tests were conducted to demonstrate material compatibility and performance. The potassium Rankine cycle was investigated by the NASA-Lewis Research Center as part of NASA's advanced space power technology research program during the 1960s. Unfortunately, this work was terminated in the early seventies. An experimental program was conducted on materials and components, and systems studies were made. A reference 300- to 375-kW_e Rankine cycle power system, incorporating the results of the experimental test programs and studies, was prepared and presented by J. A. Heller, et al., (Ref. 14).

The basic Rankine cycle is shown schematically in Fig. 12. This system uses a heat-pipe reactor, whereas the NASA system used a liquid-metal (lithium) reactor. Potassium working fluid is vaporized and superheated in a heat-pipe heated boiler. The potassium vapor expands through the turbine, driving the alternator to produce both net electric power and current to drive the liquid-metal EMPs. At low-pressure, the potassium working fluid is condensed. The major components of the conversion system are the heat-pipe to potassium boiler, multistage turbine with potassium reheat and condensate removal, alternator, potassium to liquid-metal (NaK) condenser, NaK space radiator, and electromagnetic pumps (EMP) for liquid potassium and NaK circulation. Small secondary loops are needed for cooling the potassium turbine bearing coolant, the potassium alternator bearing lubricant, and an organic coolant for electronics.

SUMMARY

This Nation is now ready for a new long-range commitment to the creation of the extraterrestrial phase of human civilization.¹⁵ Space

TABLE V

ESTIMATED REACTOR CHARACTERISTICS FOR 100 MW_t

	<u>Pebble Bed</u>	<u>Fluid</u>	<u>Gas</u>
Core power density (MW _t)	510	220 ¹¹	90 ¹³
Fuel	Coated UO ₂ (void fraction = 0.4)	UCl ₃ , PuCl ₃	UF ₆ , U metal
Core Size (m)	H, D = 1.85	H, D = 0.5	H = 3.0, D = 0.7
Reflector	Be, BeO	BeO or NiO	Be
Mass (kg)	36,000	2200	7800
Fuel Residence Time	4.5 yrs	1 S	3 S