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SPACE NUCLEAR POWER AND MAN'S EXTRATERRESTRIAL CIVILIZATION

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ABSTRACT

Operational flights of the Space Shuttle have initiated an exciting new era of space utilization and habitation. In fact, the start of the Third Millennium will be highlighted by the establishment of man's extraterrestrial civilization. There are three technical cornerstones upon which human expansion into space will depend:

1) compact energy systems, especially power and propulsion modules;
2) the ability to process extraterrestrial materials anywhere in heliocentric space; and
3) the development of permanent human habitats in space.

The manned and unmanned space missions of the future will demand first kilowatt, then megawatt, and eventually even gigawatt levels of power. Energy, especially nuclear energy, will be a most critical technical factor in the development of man's extraterrestrial civilization.

This paper examines leading space nuclear power technology candidates. Particular emphasis is given the heat-pipe reactor technology currently under development at the Los Alamos National Laboratory. This program is aimed at developing a 10-100 kWe, 7-year lifetime space nuclear power plant. As the demand for space-based power reaches megawatt levels, other nuclear reactor designs including: solid core, fluidized bed, and gaseous core, are considered.

INTRODUCTION

The highly successful test flights of the Space Shuttle mark the start of a new era of space exploitation--an era characterized by routine manned access into cislunar space. Human technical development at the start of the next millennium will be highlighted by the creation of man's extraterrestrial civilization. There are several foundational technical steps involved in the off-planet expansion of the human resource base. These include the development of reusable space transportation systems; the establishment of permanently manned space stations and bases (initially in low-Earth-orbit and, eventually, throughout cislunar space); the development of space-based industries; the creation of lunar bases and settlements; and finally the utilization of extraterrestrial resources--as may be found on the Moon and the Earth-approaching Apollo/Amor asteroids.

The Space Shuttle represents the United States' commitment to the first step in this extraterrestrial expansion process, since operational Space Shuttle supports routine manned access to near-Earth space. This technical step will be followed by the creation of permanently manned space habitats--first in low-Earth-orbit (LEO) and then in other advantageous regions of cislunar space, such as geosynchronous orbit. Although the early space stations in low-Earth-orbit would most likely depend on solar arrays for their initial power supplies, nuclear reactors could eventually be incorporated as such stations grow in size and complexity--as for example, to satisfy increased power demands for materials processing. Large space platforms at geosynchronous-Earth-orbit (GEO) could also effectively use nuclear reactors. In this application, the reactors would not only support the initial movement of massive platforms from LEO to GEO through the use of nuclear electric propulsion systems (NEPS), but would also serve as the platform's prime power source once operational altitude is achieved. Thus, in the 1990s and beyond, advanced-design nuclear reactors could represent a major energy source for both space power and propulsion systems. Some of the sophisticated space missions of tomorrow will require first kilowatt and then megawatt levels of power. This paper explores man's extraterrestrial civilization, and the role energy, particularly nuclear, can play in the development of that civilization.

THE HUMANIZATION OF SPACE

Human progress is based upon challenge and continued technical growth. As mankind enters the next millennium, expansion of the human resource base into space provides the pathway for continued material development. In fact, the overall development of civilization in the future depends on an ever-expanding outlook--an "open world" philosophy.[1,2,3] Its counterpart, a "closed-world" philosophy for human civilization, leads eventually to evolutionary stagnation. As demonstrated by the law of natural selection, once a life form has become fully adapted, it achieves an intimate balance with its environment. No further evolutionary changes occur, unless the nature and characteristics of the environment itself change. Exploitation of space, the ultimate frontier, however, provides mankind with an infinite environment in which to continue to develop and grow.

Human civilization, forged and molded in the crucible of challenge and adversity, must have new frontiers, both physical and psychological, in order to flourish.[1,3] For without sufficient stimuli, individuals as well as entire societies would eventually degenerate and experience an ever-decreasing quality of life. Physical frontiers provide the living spaces and new materials with which to continue human progress. Psychological frontiers supply the challenge, variety, adventure, and outlet for creative energies that make intelligent life interesting. Unfortunately, this age is the first period in human history in which there are no new land or sea frontiers to be explored and conquered on Earth. Only the space frontier with its infinite potential and extent can provide the challenge and opportunity necessary for continued, constructive development of the human race. In a closed-world civilization--that is, one restricted to just a single planet--no truly new ideas, technologies, or cultures can develop once all planetary frontiers have been crossed; only variations of old familiar themes can arise.

The operational Space Transportation System, or Space Shuttle, has now initiated an exciting new era of space exploitation. Over the next few decades, humanity will experience a subtle techno-social transformation in which the physical conditions (e.g., high vacuum, weightlessness), resources (e.g., lunar and asteroid), and properties of outer space (e.g., view of the Earth, biological isolation from Earth) are effectively used to better the quality of life for all on Earth. This process has been called the "humanization of space."[4,5] As part of this process, man (only a selected few at first) will also learn to live in space.

The humanization of space is a complex development, which identifies the start of the second phase of the Earth's planetary civilization--expansion of the human resource base into the Solar System.[1,6] The first phase of planetary civilization began with the origins of intelligent life on Earth and will culminate with the full use of the terrestrial resource base. The third, and perhaps ultimate, phase of planetary civilization involve migration to the stars. Figure 1 displays some of the potential technical steps that might occur during the second phase of the Earth's planetary civilization.[7,8] In this projected sequence of technical achievements, man first learns how to permanently occupy near-Earth space and then expands throughout cislunar space. As space-based industrialization grows, a subtle but very significant transition point is reached. Man eventually becomes fully self-sufficient in cislunar space--that is, those human beings living in space habitats will no longer depend on the Earth for the materials necessary for their survival. Thus, from that time forward, humanity will have two distinct cultural subsets: terran and nonterran or "extraterrestrial."

The final stage of this phase of planetary civilization will be highlighted by the permanent occupancy of heliocentric or interplanetary space. Human settlements will appear on Mars, in the asteroid belt, and on selected moons of the giant outer planets. Finally, as humanity--or at least its extraterrestrial subset--starts to fill the ecosphere of our native star with manmade "planetoids"--a cosmic wanderlust will also begin attracting selected citizens of the Solar System to the stars. With the first interstellar missions, the human race will indeed become a galactic explorer--perhaps as the first intelligent species to sweep through the Galaxy or perhaps destined to meet other starfaring civilizations!

THE NEED FOR ENERGY

Human development at the start of the Third Millennium will be highlighted by the establishment of a new extraterrestrial civilization. Three critical technical cornerstones that support this exciting development are currently perceived. These are: (1) the availability of compact energy sources for power and propulsion; (2) the ability to process materials anywhere in the Solar System; and (3) the creation of permanent human habitats in outer space.[2,5]

Energy--reliable, abundant and portable--is a critical factor in developing and sustaining man's permanent presence in outer space. Space nuclear power systems, in turn, represent a key enabling technology that must be effectively incorporated in future space programs, if imaginative and ambitious space applications and utilization programs are actually to occur in the next few decades.[8] For example, the movement of large quantities of cargo from low-Earth-orbit (LEO) to high-Earth-orbit (HEO) or lunar destinations, the operation of very large space platforms throughout cislunar space, and the start-up and successful operation of lunar bases and settlements can all benefit from the creative application of advanced space nuclear power technology. Very imaginative future space activities, such as asteroid movement and mining, planetary engineering and climate control, and human visitations to Mars and the celestrial bodies beyond, cannot even begin to be credibly considered without the availability of compact, pulsed and steady-state, energy supplies in the megawatt and, eventually, gigawatt regime.

Since the beginning of the Space Age in the late 1950s, a range of nuclear power supply options has been developed by the United States to support civilian and military space activities. Tomorrow's space program, keyed more heavily perhaps to applications and exploitation objectives, will require even larger quantities of reliable, long-lived power. Nuclear energy judiciously applied in future space missions offers several distinctive advantages over traditional solar and chemical space-power systems. These advantages include: compact size, light-to-moderate mass, long-operating lifetimes, operation in hostile environments (e.g., trapped radiation belts, surface of Mars, moons of outer planets, etc...), operation independent of the system's distance from or orientation to the Sun, and increased space system reliability and autonomy.[9,10,11] In fact, as power requirements approach the hundreds of kilowatts and megawatt electric regime, nuclear energy appears to be the only realistic space power supply option. (See Figure 2).

Space nuclear power technology involves the use of the thermal energy liberated by nuclear reactions. These reactions include: the spontaneous, yet predictable, decay of radioisotopes; the controlled fission or splitting of heavy nuclei (such as Uranium-235, symbol $^{235}_{92}$U in a sustained neutron chain reaction; and the fusion or joining together of light nuclei (such as deuterium and tritium, symbols $^{2}_{1}$D and $^{3}_{1}$T respectively) in a controlled thermonuclear reaction. The thermal energy so liberated may then be used directly in space system processes demanding large quantities of heat, or it may be converted directly into electrical power. Until controlled thermonuclear fusion is actually achieved, nuclear energy applications will be based on radioisotope decay or nuclear fission.

A generic space nuclear power system is depicted in Figure 3. Here, the primary system output is electrical energy, which is created by converting radioisotope decay heat or the thermal energy released in nuclear fission into electrical energy, using static conversion (e.g., thermoelectrics and thermionics) or dynamic conversion (e.g., the Rankine, Brayton, or Stirling thermodynamic cycles) principles. Contemporary options for nuclear energy heat sources and companion power-conversion subsystems are shown in Figure 4. While these options are, of course, not all inclusive, they nevertheless form the basis for intelligent planning of nuclear-power sources application for space missions in the next decade and beyond. Radioisotope and nuclear reactor power systems--up to a few hundred kilowatts electric--are further classified in matrix format in Figure 5. For space-power applications in the megawatt regime and beyond, there are a number of possible advanced nuclear reactor technology options. These designs include the solid-core nuclear reactor (a derivative of the Rover program nuclear rocket technology), the fluidized bed reactor, and the gaseous core nuclear reactor.

US SPACE NUCLEAR PROGRAM

Since 1961, the United States has launched over 20 NASA and military space systems that derived all or at least part of their power requirements from nuclear energy sources. These systems and missions are summarized in Table I. As can be seen in this table, all but one of the previous missions used radioisotope thermoelectric generators (RTGs) fueled by Plutonium-238 (symbol $^{238}_{94}$Pu). The SNAP-10A system was a compact nuclear reactor that used fully enriched Uranium-235 as the fuel. The acronym "SNAP" stands for "Systems for Nuclear Auxiliary Power." Odd numbers designate radioisotope systems, while even number designate nuclear reactor systems.

From the very beginning of the US space nuclear power program, great emphasis has been placed on safety. Contemporary policy and practices for all space nuclear power sources promote designs that ensure that the levels of radioactivity and the probability of nuclear fuel release will not provide any significant risk to the Earth's population or to the terrestrial environment. For radioisotope heat sources, this aerospace nuclear safety policy essentially consists of providing containment that is not prejudiced under any circumstances, including launch accidents, re-entry or impact on land or water. For nuclear reactors, the safety mechanism consists of maintaining subcriticality under all conditions, normal and otherwise, in the Earth's atmosphere or on the Earth's surface. After the reactor has experienced power operation in space, the reactor will be prevented from re-entering the terrestrial biosphere. This is achieved by ensuring that the reactor achieves a final orbit that has a sufficient lifetime to permit the decay of fission products and other radioactive materials to levels that no longer represent a radiological risk. Orbital lifetimes in excess of 300 years support this aerospace nuclear safety philosophy.

A typical space nuclear reactor power plant, such as pictured in Figure 6 consists of a nuclear reactor as a heat source, a radiation attenuation shield to protect the payload, the electric power conversion equipment, and a heat rejection system to eliminate waste heat.

Figure 7 roughly classifies the leading technology candidates based on reactor type, conversion system, and heat-rejection system. Heat-pipe reactor technology is currently under development in the SP-100 program. This program has a goal of developing a 10-100 kWe, 7-year-lifetime nuclear reactor power plant. This same reactor technology can be used for thermal power levels of 10-40 MW.

The reactor pictured in Figure 8 has a centrally fueled core region made up of 120 fuel modules. These modules consist of a heat pipe with circumferential fins attached and fuel wafers arranged in layers between the fins. The heat pipes are used to transport the reactor thermal energy to electric power converters, and consist of a cylindrical tube, lined with a metal screen wick. Lithium, the working fluid, is evaporated in the reactor-fuel-module section of the heat pipe. The vapor travels up the heat pipe until the heat is given up to the electrical converter. The lithium then condenses, and is returned to the evaporator end of the heat pipe by the capillary action of the wick. No pumps or compressors are used for heat transport. The fins around the heat pipes enhance heat transfer from the UO_2 fuel to the heat pipes, reducing the temperatures in the UO_2. Surrounding the core is a containment barrel, which provides support to the fuel modules, but is not a pressure vessel. The container also provides a noncompressive support for the multifoil insulation. Multiple reflective insulation layers reduce the core heat loss to an acceptable level. The reflector surrounds the core and reflects neutrons back into the fueled region. Located within the reflector are drums that are rotated by electomechanical actuators. On part of these drums is a neutron-absorption material; the positions of this material are used to establish the reactor power level.

Power conversion in the SP-100 system is by the direct thermoelectric conversion of heat to electricity. Thermal energy is radiated from the heat pipes to panels containing thermoelectric material. Hot-shoe thermal collectors concentrate the radiant energy from the core heat pipes. The heat is conducted through the thermoelectric material, producing electrical energy. Insulation is used around the thermoelectric material to reduce the thermal losses. Heat that is not used is radiated from the outside surface to space; this is the cold shoe component of the thermoelectric elements. By distributing the thermoelectric elements over a wide area with a sufficient number of elements, the cold shoe becomes the heat rejection radiator. Table II gives the characteristics of a 100-kWe power plant. The power plant weighs 2625 kg if improved silicon-germainium thermoelectric materials are used, and less than 2000 kg with carbide or sulfide materials. The overall length is 8.5 m for the earlier system.

As depicted in Figure 7, thermoelectric converters are limited to the power-production region below 200 kWe because of the numberr of small modules involved and their low efficiency. From 200 kWe to the megawatt level, a choice of converters is possible between Rankine, Brayton, and Stirling cycles, which would not require any increase in reactor temperatures. Thermionic converters are another possibility, but would require reactor temperatures several hundred degrees Kelvin higher. Higher temperature reactors increase fuel swelling and material problems. Converter efficiencies of 15 to 30% are possible, but the higher efficiencies lead to lower heat rejection temperatures. Because heat radiated to space follows a fourth-power relationship in temperature (T^4), high reject temperatures tend to have much reduced radiator areas. As power levels increase, higher heat rejection temperatures usually dominate the choice of converters. Although work has been performed on all these converters in the past, activity on space systems is no longer ongoing. There appear to be no technology barriers to power plants up to a few megawatts, but active development is needed if any of the power options above a few hundred kilowatts are to be available to space mission planners of the 1990s.

As the power-level demand expands to the tens-of-megawatt levels, solid core, fluidized bed, or even gaseous core reactors might be considered. For space, solid-core reactors were most extensively developed as part of the nuclear rocket program. The Rover design featured a graphite-moderated, hydrogen-cooled core (Figure 9). The 93.15% ^{235}U fuel was in the form of UC_2 particles, coated with a pyrolytic graphite. The fuel was arranged in hexagonal-shaped fuel elements, coated with ZrC; each element had 19 coolant channels. The fuel elements were supported by a tie-tube structural support system, which transmitted core axial pressure load from the hot end of the fuel elements to the core inlet support plate. Surrounding the core was a neutron reflective barrel of beryllium, with 12 reactivity control drums containing a neutron-absorbing material. The reactor was enclosed in an aluminum pressure vessel. Electric power up to 100 MW could be generated by replacing the rocket thrust nozzle with power conversion equipment. This is a limited-life system, however. A low-power electric, long-life mode could be achieved by exracting energy through the tie-tube support system. The Rover technology is ready for flight development, having been tested in some 20 reactors. Peak performances are shown in Table III.

High-power requirements might also be met by fluidized bed reactors, in either the rotating or fixed-bed forms. The former was investigated as a rocket propulsion concept, and the latter has been proposed for space electrical power. A modest research effort in fluidized bed reactors was carried out from 1960 until 1973.

Another candidate for megawatt-power reactors is a gaseous core reactor system. The central component of such a gaseous core reactor is a cavity where the nuclear fuel is in the gaseous state. The reactor concept shown schematically in Figure 10 is an externally moderated cavity assembly that contains the uranium fuel in the gaseous phase. For temperature requirements less than a few thousand degrees Kelvin, the appropriate nuclear fuel would be uranium hexafluoride, UF_6. Above about 5000 K, uranium metal would be vaporized and ionized with the fuel as a fissioning plasma. At lower temperatures it is desirable, and at higher temperatures it is necessary to keep the gaseous fuel separate from the cavity walls. This is accomplished through fluid dynamics by using a higher velocity buffer gas along the wall. Power is extracted by convection or optical radiation, depending on temperature. Gaseous core reactors offer simple core structures and certain safety and maintainability advantages. The basic research development was completed prior to program termination, including the demonstration of fluid mechanical vortex confinement of UF_6 at densities sufficient to sustain nuclear criticality.

SPACE INDUSTRIALIZATION

Sapce industrialization may be defined as a new wave in man's technical development in which the special environmental conditions and properties of outer space are harnessed for the economic and social benefit of people on Earth. Some interesting properties of space include: hard vacuum, weightlessness or "zero-gravity" effects, low vibration levels, a wide-angle view of Earth and the Universe, and complete isolation from the terrestrial biosphere.[5,12,13]

Recent aerospace studies[12,13] 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 divided into four basic categories: (1) information services, (2) products, (3) energy, and (4) human activities. (See Figure 11.)

In the full-scale exploitation of cislunar space, nuclear electric propulsion systems (NEPS) will serve a critical enabling role in the efficient transport of massive, nonpriority cargoes throughout cislunar space. In many missions, the NEPS will serve not only as the propulsive means of placing a massive payload in an appropriate operating orbit, but once the operational location is reached, the nuclear reactor would then service as the prime power supply for many years of continuous, profit-making operation of the payload. Nuclear electric propulsion systems could also be used as reusable orbital transfer vehicles (OTVs) or "space tugs." These propulsive workhorses of tomorrow would gently lift massive cargoes, supplies and materials, large and fragile payloads that had been assembled in low-Earth-orbit, or even entire (unoccupied) habitats, and ferry these cargoes to their final destinations in cislunar spce. Return voyages from lunar or geosynchronous orbit would witness these same nuclear electric vehicles carrying space-manufactured or selenian products back to the terrestrial markets. Finally, the continued, more sophisticated scientific exploration of the Solar System will also require nuclear electric propulsion systems as ambitious, advanced exploration missions are undertaken to both the inner planets and the outer planets.

In a real sense, the information service area of space industrialization already exists. Space platforms are now providing valuable communication, navigation, meteorological and environmental services to people around the globe. Further expansion of such services involves more massive platforms in orbit and much higher power levels. For example, current aerospace industry evaluations[12,13] 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. A multifunction information services platform of the major capability is needed at geosynchronous-Earth-orbit. A baseline GEO platform would require some 500 kilowatts (electric) of power.[8,12] This unmanned platform would provide five new nationwide information services: (1) direct-broadcast TV (five nationwide channels, 16 hours per day); (2) pocket telephones (45,000 private channels linked to the current telephone system); (3) national information services (using pocket telephone hardware); (4) electronic teleconferencing (150 two-way video, voice and facsimile channels); and (5) electronic mail (40 million pages transferred overnight among 800 sorting centers.)

Another space industrialization opportunity involves a Space Processing Facility in near-Earth-orbit. Designed mainly for zone refining and crystal growth,[12] this facility has fifteen furnaces capable of producing 750 boules of finished product every 60 days. The Space Shuttle would service raw material magazines and return finished "space-manufactured" products to markets on Earth. The conceptual facility would be capable of producing 4500 boules (weighing some 21,000 kilograms) of finished products annually. A continuous power level of 300 kilowatts with a peak power requirement of some 550 kilowatts is projected.

Geosynchronous-Earth-orbit is also the favored location for a number of other Earth-oriented applications and scientific platforms--both manned and unmanned. Power requirements for these systems would range from hundreds of kilowatts (electric) to several megawatts.

THE MOON-KEY TO CISLUNAR SPACE

The Moon is Earth's only natural satellite and closest celestial neighbor. Relative to its primary, it is extremely large. In fact, the Earth-Moon system might be regarded as a "double planet" system. Not too long ago, the Moon was only an inaccessible celestial object--but today, through the technology of the Space Age, it has become a "planet" to explore, exploit, and inhabit.[14]

To initiate the further exploration of the Moon, we can first send sophisticated machines in place of men. For example, an unmanned lunar orbiter could circle the Moon from pole-to-pole remotely measuring its chemical composition, gravity, magnetism, and radioactivity. This Lunar Polar Orbiter mission would continue the scientific tasks started by the Apollo Program and would produce extensive maps of the entire lunar surface. Automated lunar surface rovers would be used to make detailed lunar surface surveys, determining physical and chemical characteristics as well as searching for potential mineral resources. These automated rovers, powered by radioisotopes (most probably $^{238}_{94}$Pu) will be operated near the poles, on the far side of the Moon and in other interesting but previously unvisited lunar regions. Then, when man himself returns to the Moon, it will not be for a brief moment of scientific inquiry as occurred in the Apollo Program, but rather as a permanent inhabitant--building bases from which to explore the lunar surface, establishing science and technology laboratories, and exploiting the lunar resource base in support of humanity's extraterrestrial civilization.

Table IV suggests several stages of lunar development and companion nuclear power requirements. It is anticipated that the first stage will involve site preparation prior to the establishment of the permanently inhabited lunar base. Robotic surface equipment controlled by orbiting spacecraft would prepare a suitable lunar site for a permanently inhabited base of operations. One of the areas prepared would be the site for the nuclear power reactors needed in Stage 2 of lunar development. These remotely controlled robotic devices would be powered by radioisotopes (probably ^{238}Pu) enabling continuous operation throughout the full lunar day night cycle (some 28 earth days). Radioisotope thermalelectric generators (RTG), like the GPHS-RTG with a specific power 5/3 Wkg, have proven to be rugged, highly reliable, and capable of operating in hostile environments for years at hundreds of watts levels of power. With the creative use of dynamic power-conversion equipment, as, for example, an organic rankine cycle, the GPHS could also be capable of supplying kilowatts of power in support of lunar-development activities.

The initial permanently manned lunar base is projected to have a habitat for 6-12 persons. To meet their power needs, a 100-kW electric nuclear reactors (of the SP-100 heat pipe and core design) would support the initial lunar base (see Figure 11). By the time man returns to the moon as a permanent inhabitant, these nuclear reactor units will have a well-established engineering performance on unmanned spacecraft and manned space-station operations througnout cislunar space. Of course, minor modifications of the basic reactor system will be needed to support manned lunar activities. For example, a 4 [illegible] radiation shield could easily be implemented using lunar soil material.

The initial lunar base, focusing on detailed exploration in resource identification, will then evolve into a multihundred-person early settlement. One of the main objectives of this early settlement will be to conduct basic research and development, which takes advantage of the lunar environment. Another key objective will be the engineering demonstration of prototype processes upon which a viable lunar economy might eventually be based. Expanded versions of the SP-100 heat-pipe reactor, coupled to more efficient power-conversion systems such as Brayton, Stirling, or Rankine cycles, would provide megawatt levels of electric power to the early lunar settlement.

In Stage 4, the early lunar settlement matures and economically exploits processes developled in Stage 3. Lunar products feed the the growth of lunar expansion, finds markets throughout cislunar space, and may even export products to selected terrestrial markets. Power levels on the order of a few hundred megawatts electric would be needed to support the processing of lunar materials and the operation of advanced transportation systems (such as surface electric monorails and mass-driver systems). An advanced design nuclear reactor system is envisioned with 30 year or more useful lifetime, online refueling, and robotic maintainability features. Another characteristic of this new generation of lunar nuclear reactors would be "walk-away safety"--that is, if a malfunction should occur in any part of the power plant, it is so designed that no operator action or even mechanical automatic control mechanism is needed to achieve a safe condition.

Finally, as the lunar settlement expands and grows economically, a point will be reached when the lunar civilization, for all practical purposes, becomes autonomous of Earth. Lunar products would be widely used throughout cislunar space--the lunar economy, being driven by the abundance of nuclear electric power, making full lunar-cycle productivity a technical and economic reality. As part of the full self-sufficiency experience in Stage 5, a lunar nuclear fuel cycle will also evolve, taking advantage of native Uranium and Thorium minerals, as well as the classic breeding reactions involving fertile ^{232}Th and ^{238}U.

SUMMARY

If man is to expand beyond his terrestrial womb and assume his proper role in the cosmic scheme of things, he must have abundant, compact, and reliable energy supplies to accompany him on his journey beyond the Earth's atmosphere. Nuclear energy, properly developed and used, is the sini qua non for manned extraterrestrial civilization.

TABLE I

SUMMARY OF SPACE NUCLEAR POWER SYSTEMS LAUNCHED BY THE U.S.A. (1961-1982)

POWER SOURCE	SPACECRAFT	MISSION TYPE	LAUNCH DATE	STATUS
SNAP-3A	TRANSIT 4A	NAVIGATIONAL	JUNE 29, 1961	SUCCESSFULLY ACHIEVED ORBIT
SNAP-3A	TRANSIT 4B	NAVIGATIONAL	NOVEMBER 15, 1961	SUCCESSFULLY ACHIEVED ORBIT
SNAP-9A	TRANSIT-5BN-1	NAVIGATIONAL	SEPTEMBER 28, 1963	SUCCESSFULLY ACHIEVED ORBIT
SNAP-9A	TRANSIT-5BN-2	NAVIGATIONAL	DECEMBER 5, 1963	SUCCESSFULLY ACHIEVED ORBIT
SNAP-9A	TRANSIT-5BN-3	NAVIGATIONAL	APRIL 21, 1964	MISSION ABORTED: BURNED UP ON REENTRY
SNAP-10A (REACTOR)	SNAPSHOT	EXPERIMENTAL	APRIL 3, 1965	SUCCESSFULLY ACHIEVED ORBIT
SNAP-19B2	NIMBUS-B-1	METEOROLOGICAL	MAY 18, 1968	MISSION ABORTED: HEAT SOURCE RETRIEVED
SNAP-19B3	NIMBUS III	METEOROLOGICAL	APRIL 14, 1969	SUCCESSFULLY ACHIEVED ORBIT
SNAP-27	APOLLO 12	LUNAR	NOVEMBER 14, 1969	SUCCESSFULLY PLACED ON LUNAR SURFACE
SNAP-27	APOLLO 13	LUNAR	APRIL 11, 1970	MISSION ABORTED ON WAY TO MOON. HEAT SOURCE RETURNED TO SOUTH PACIFIC OCEAN.
SNAP-27	APOLLO 14	LUNAR	JANUARY 31, 1971	SUCCESSFULLY PLACED ON LUNAR SURFACE
SNAP-27	APOLLO 15	LUNAR	JULY 26, 1971	SUCCESSFULLY PLACED ON LUNAR SURFACE
SNAP-19	PIONEER 10	PLANETARY	MARCH 2, 1972	SUCCESSFULLY OPERATED TO JUPITER AND BEYOND
SNAP-27	APOLLO 16	LUNAR	APRIL 16, 1972	SUCCESSFULLY PLACED ON LUNAR SURFACE
TRANSIT-RTG	"TRANSIT" (TRIAD-01-1X)	NAVIGATIONAL	SEPTEMBER 2, 1972	SUCCESSFULLY ACHIEVED ORBIT
SNAP-27	APOLLO 17	LUNAR	DECEMBER 7, 1972	SUCCESSFULLY PLACED ON LUNAR SURFACE
SNAP-19	PIONEER 11	PLANETARY	APRIL 5, 1973	SUCCESSFULLY OPERATED TO JUPITER, SATURN, AND BEYOND
SNAP-19	VIKING 1	MARS	AUGUST 20, 1975	SUCCESSFULLY LANDED ON MARS
SNAP-19	VIKING 2	MARS	SEPTEMBER 9, 1975	SUCCESSFULLY LANDED ON MARS
MHW	LES 8/9	COMMUNICATIONS	MARCH 14, 1976	SUCCESSFULLY ACHIEVED ORBIT
MHW	VOYAGER 2	PLANETARY	AUGUST 20, 1977	SUCCESSFULLY OPERATED TO JUPITER AND SATURN
MHW	VOYAGER 1	PLANETARY	SEPTEMBER 5, 1977	SUCCESSFULLY OPERATED TO JUPITER AND SATURN

TABLE II

SP-100 PERFORMANCE AND MASS SUMMARY

	Late 1980s	Early 1990s
Output Power (kWe)		
Range	10 - 100	10 - 100
Nominal	100	100
Reactor Thermal Power (kWt)		
Range	200 - 1600	
Reference Design	1480	950
Design Life (yr)		
Design Power	7	7
Total	10	10
Overall Dimensions		
Length (m)	8.5	7.0
Diameter (max)(m)	4.3	4.3
Radiator area (m^2)	70	43
System Mass (at Reference Design)(kg)		
Reactor	405	370
Shield	790	670
Heat Pipes	450	215
TE Conversion	375	155
Thermal Insulation (including end panels)	285	195
Radiator	80	35
Structure (10%)	240	165
Total System Mass	2625	1805
Specific Power (W/kg)	38	55

TABLE III

REACTOR SYSTEMS TESTS PERFORMANCE

	KIWI-4BE	NRX-A6	Phoebus-2A	Pewee-1
Reactor Power (MW)	950	1167	4080	507
Flow Rate (kg/s)	31.8	32.7	119.2	18.6
Fuel Exit Average Temperature (K)	2230	2472	2283	2556
Chamber Temperature (K)	1980	2342	2256	1837
Chamber Pressure (MPa)	3.49	4.13	3.83	4.28
Core Inlet Temperature (K)	104	128	137	128
Core Inlet Pressure (MPa)	4.02	4.96	4.73	5.56
Reflector Inlet Temperature (K)	72	84	68	79
Reflector Inlet Pressure (MPa)	4.32	5.19	5.39	5.79
Periphery and Structural Flow (kg/s)	2.0	0.4	2.3	6.48

TABLE IV

STAGES OF LUNAR DEVELOPMENT AND POWER REQUIREMENTS (1992-2092)

Stage	Activity	Power Level	Probable Nuclear Power Supply
1	Automated Site Preparation	few KWe	Radioisotopes (RTGs)
2	Initial Lunar Base (6-12 persons)	~100 kWe	Nuclear Reactor (SP-100)
3	Early Lunar Settlements (10^3-10^4 persons)	~1 MWe	Expanded SP-100 (Advanced Design)
4	Mature Lunar Settlement (10^2-10^4 persons)	~100 MWe	Nuclear Reactor (Advance Design)
5	Autonomous Lunar Civilization (Self-Sufficient Lunar Economy: >10^5 persons)	Hundreds of Megawatts Electric	Nuclear Reactors (Advance Design, Complete Lunar Nuclear Fuel Cycle

STEP 1: Permanent Occupancy of Near-Earth Space

- Space Station/Space Operations Center [6-12 persons]
- Space Base [50-200 persons]
- Orbiting Propellant and Service Depot
- Near-Earth Orbital Launch Facility

STEP 2: Permanent Occupancy of Cislunar Space

- Large Power Plants (nuclear) at GEO [megawatt range]
- Manned Space Platform at GEO [6-12 persons]
- Orbiting Lunar Station [6-12 persons]
- Initial Lunar Base [6-12 persons]
- Cislunar Orbital Transfer Vehicles
- Permanent Lunar Settlements [200-300 persons]

STEP 3: Full Self-Sufficiency in Cislunar Space

- Space Communities in Earth Orbit
- Space Cities [e.g. Krafft Ehricke's "Astropolis"]
- Extensive Lunar Settlements
- Settlements Throughout Cislunar Space
- Utilization of the Apollo/Amor Asteroids

STEP 4: Permanent Occupancy of Heliocentric Space

- Mars Orbiting Station
- Initial Martian Base
- Permanent Martian Settlements
- Asteroid Belt Exploration
- Manned Bases in Asteroid Belt
- Bases on Selected Outer Planet Moons [e.g., Titan, Ganymede]
- Planetary Engineering Programs [e.g., climate modification]
- Manmade "Planetoids" in Heliocentric Space
- First Interstellar Missions

Figure 1. POTENTIAL STEPS IN PHASE TWO OF THE EARTH'S PLANETARY CIVILIZATION

REGIMES OF POSSIBLE SPACE POWER APPLICABILITY

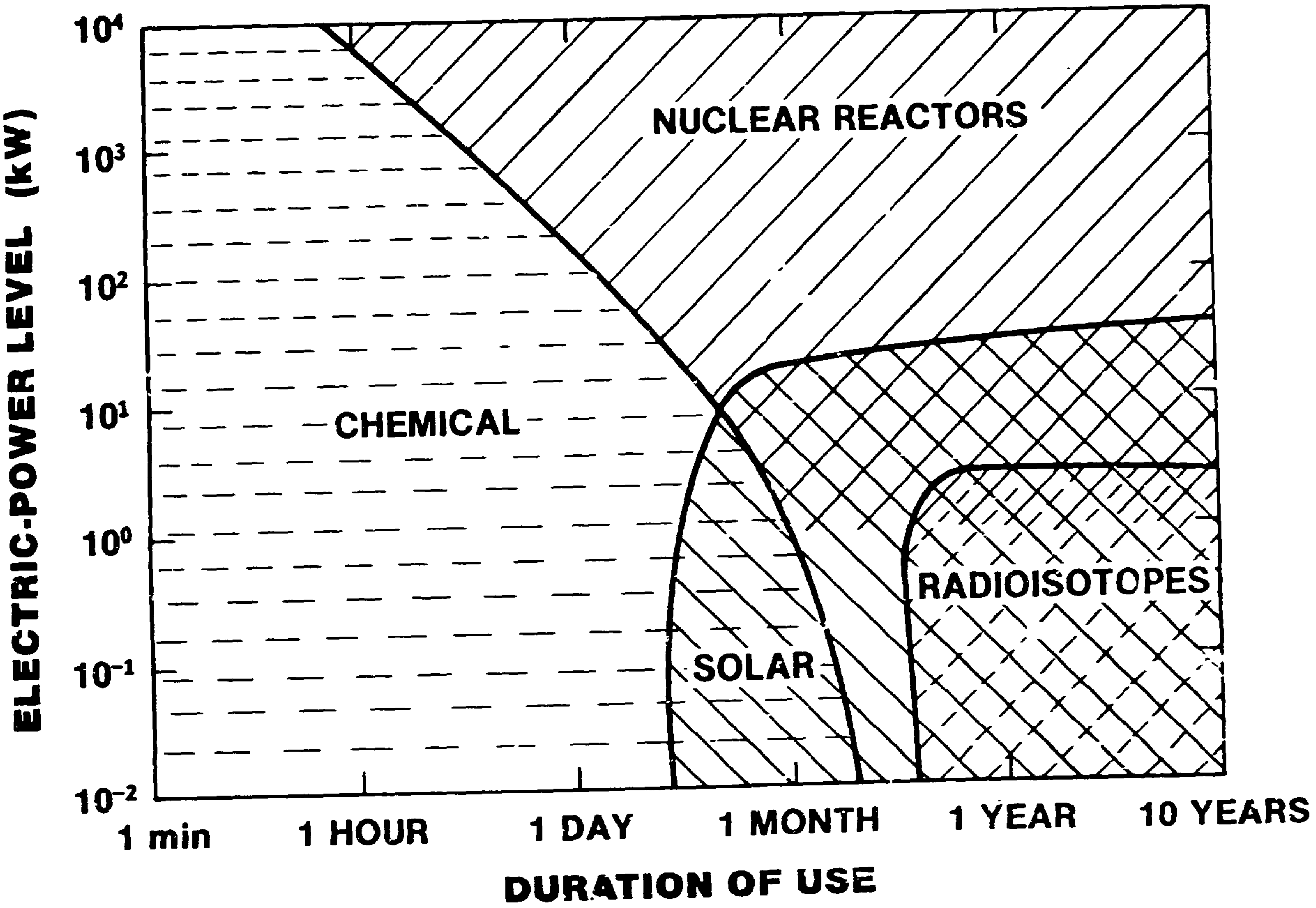


Figure 2

GENERIC SPACE NUCLEAR POWER SYSTEM

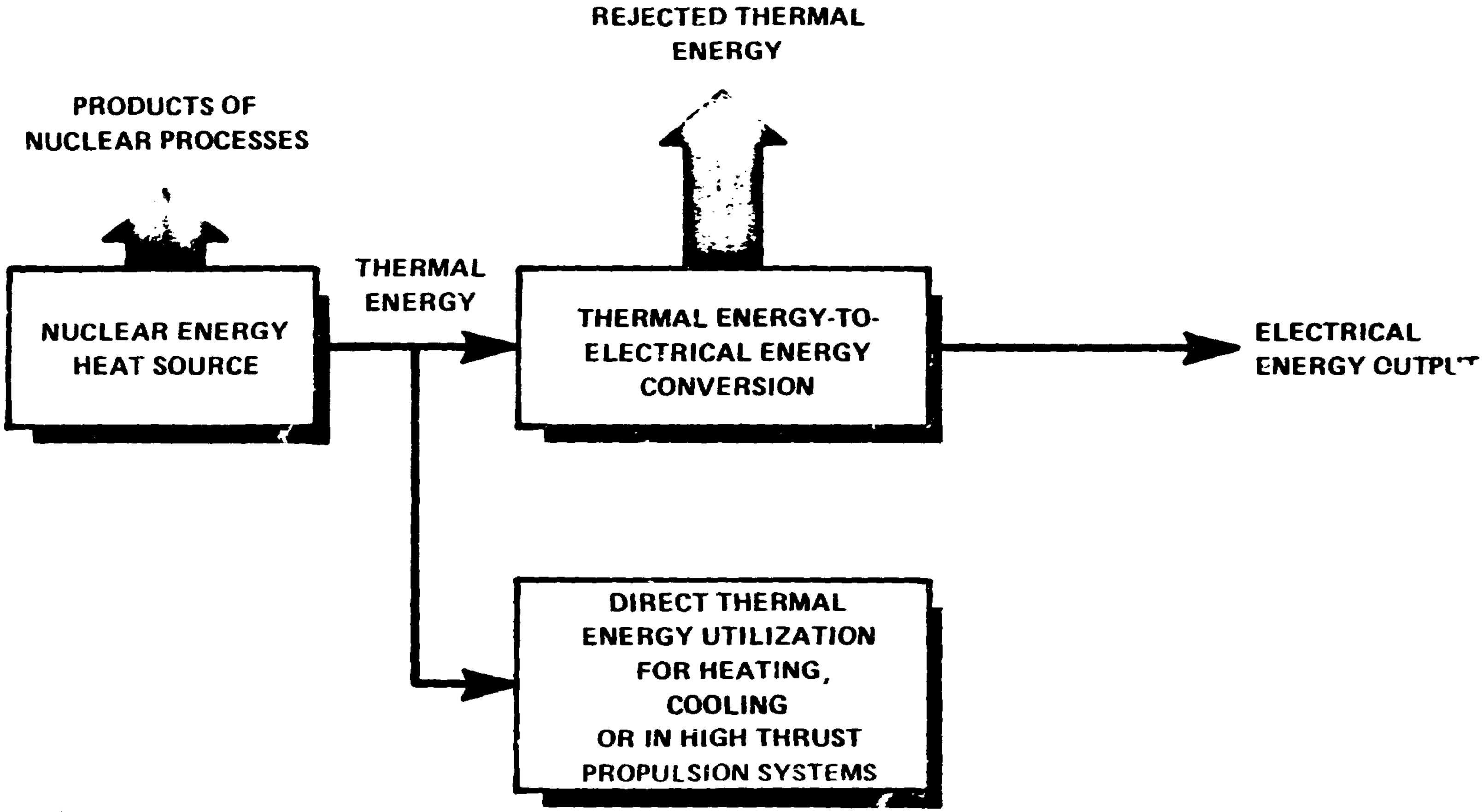
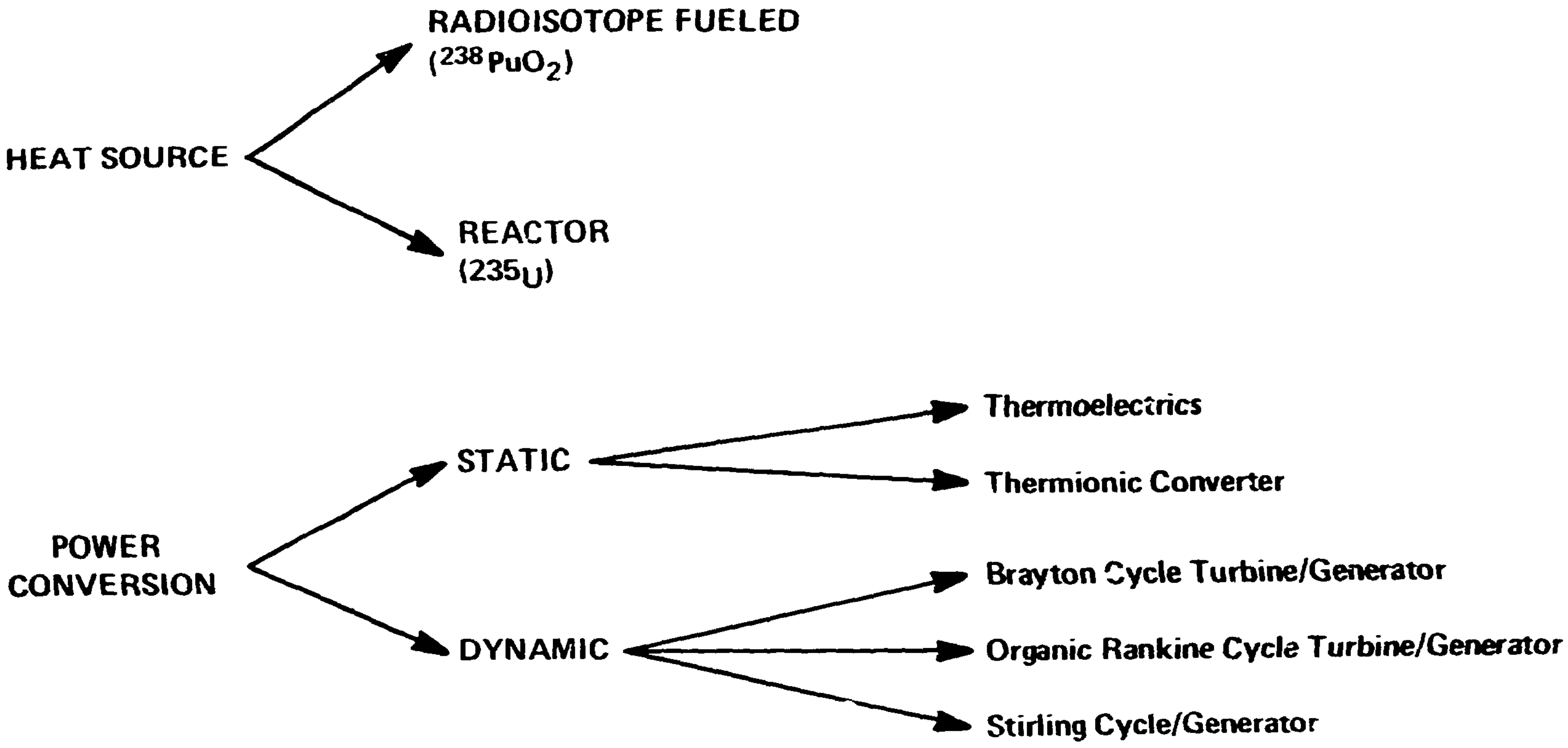


Figure 3

OPTIONS COVERED IN SPACE NUCLEAR PROGRAM



HEAT SOURCE

RADIOISOTOPE FUELED ($^{238}PuO_2$)

REACTOR (^{235}U)

POWER CONVERSION

STATIC

Thermoelectrics

Thermionic Converter

DYNAMIC

Brayton Cycle Turbine/Generator

Organic Rankine Cycle Turbine/Generator

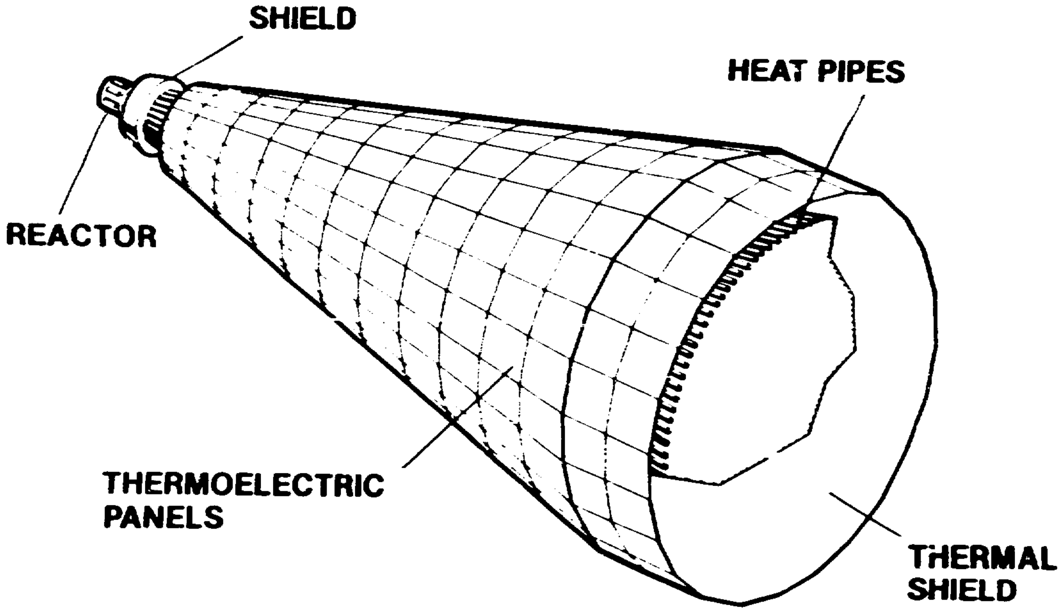
Stirling Cycle/Generator

Figure 4

CLASSIFICATION OF NUCLEAR POWER SYSTEM TYPES BEING CONSIDERED FOR SPACE APPLICATION

NUCLEAR POWER SYSTEM TYPE	ELECTRIC POWER RANGE (MODULE SIZE)	POWER CONVERSION
RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)	Up to 200 We	STATIC: THERMOELECTRIC
RADIOISOTOPE DYNAMIC CONVERSION GENERATOR	0.5 kWe – 2 kWe	DYNAMIC; BRAYTON OR ORGANIC RANKINE CYCLES
REACTOR SYSTEMS (HEAT PIPE)	10 kWe – 100 kWe	STATIC: THERMOELECTRIC
REACTOR SYSTEM HEAT PIPE SOLID CORE	1 – 10 MWe	BRAYTON CYCLE RANKINE CYCLE STIRLING CYCLE
REACTOR SOLID CORE FLUIDIZED BED GASEOUS CORE	10 – 100 MWe	BRAYTON CYCLE (OPEN LOOP) STIRLING MHD

Figure 5



SP-100 NUCLEAR POWER SYSTEM
RADIATIVELY COUPLED SYSTEM DESIGN

Figure 6

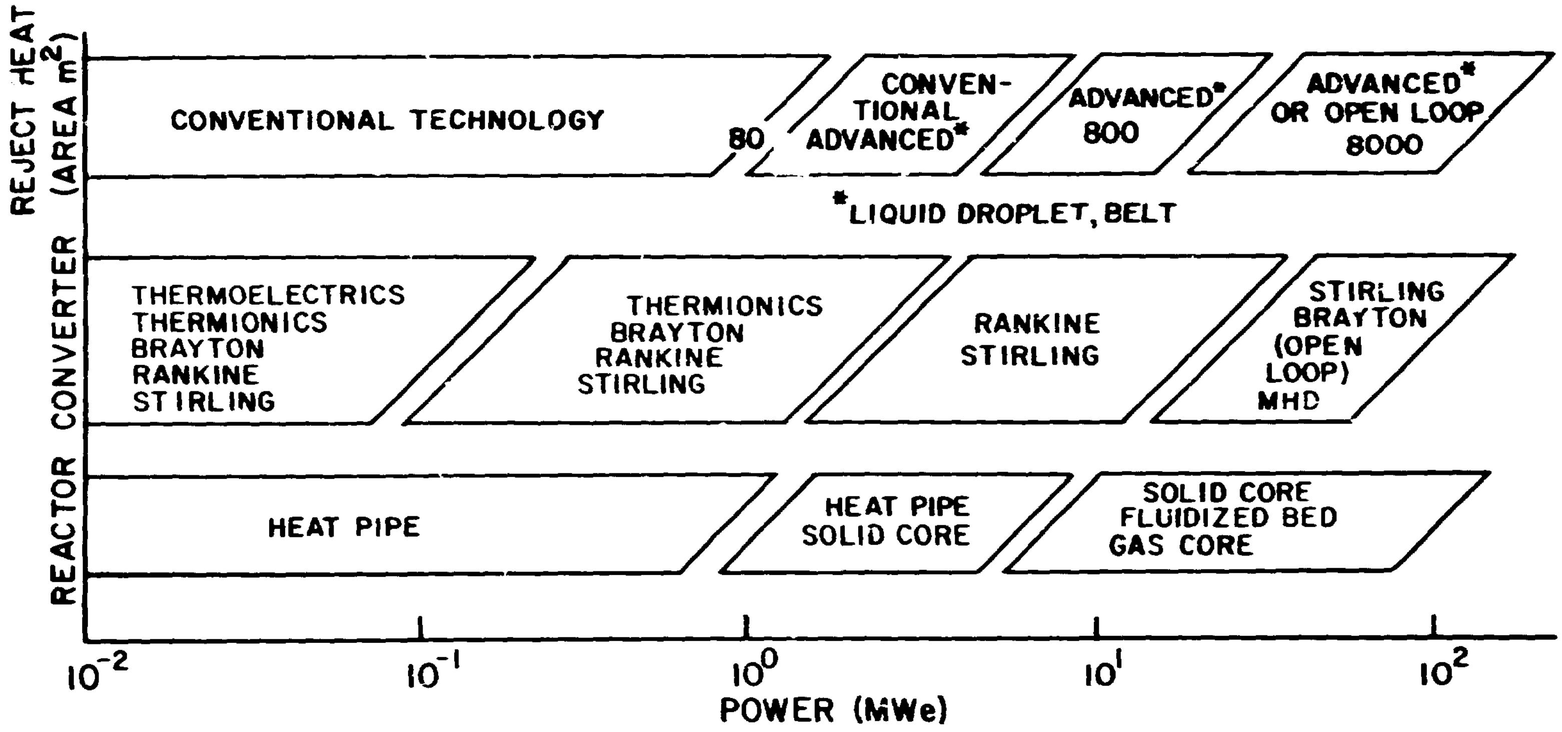


Figure 7. Leading Technology Candidates

HEAT PIPE SPACE REACTOR

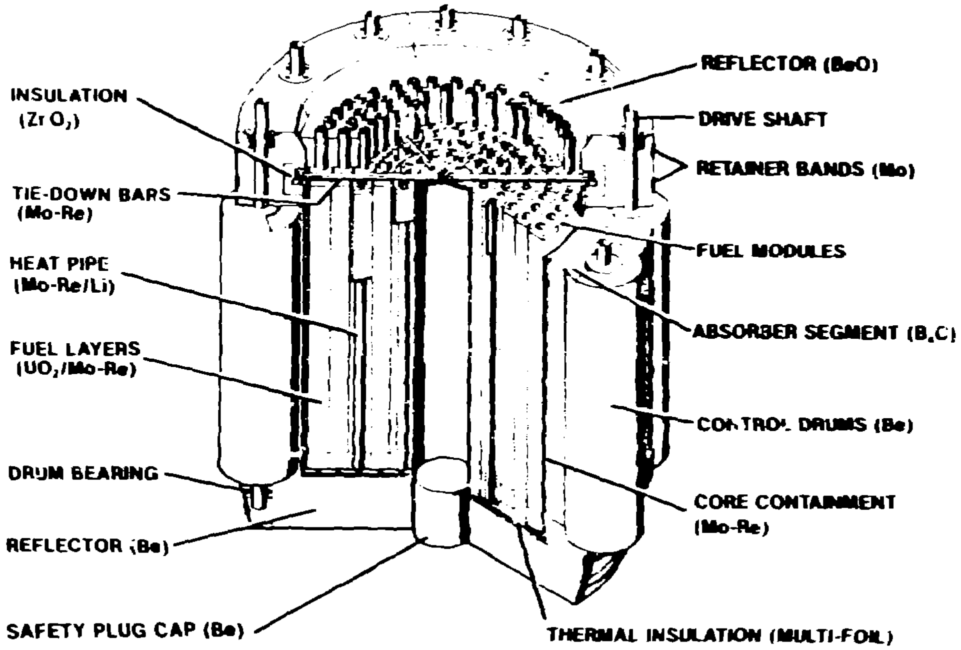
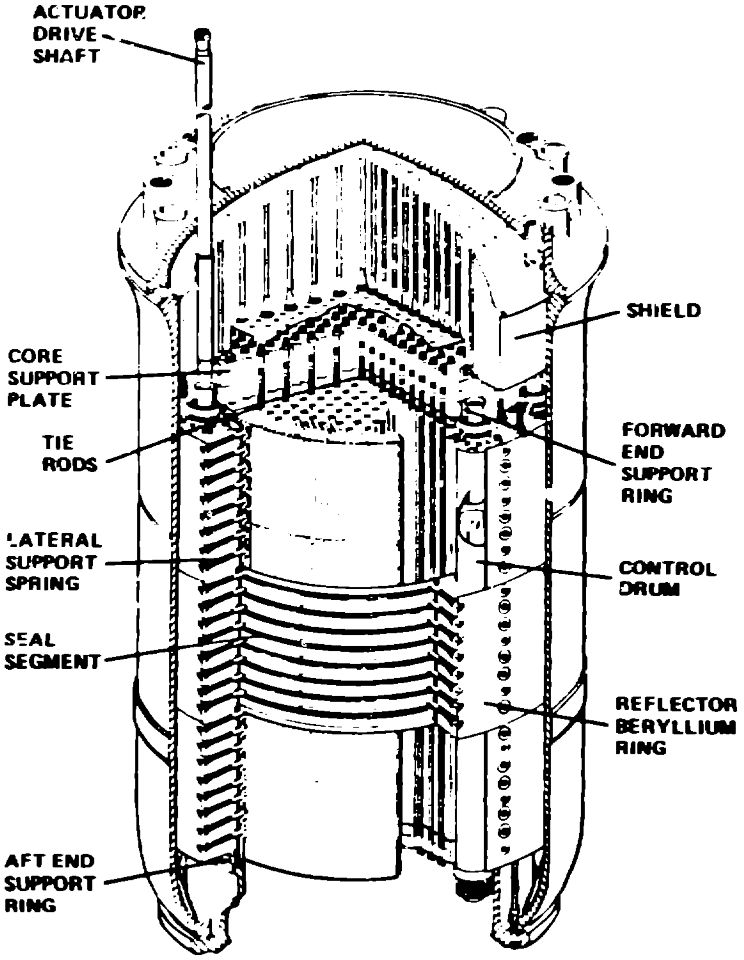


Figure 8

REACTOR DESIGN FEATURES



- EPI-THERMAL, GRAPHITE-MODERATED, HYDROGEN-COOLED REACTOR
- USED ENRICHED 93.15% URANIUM-235 AS FUEL
- POWER FLATTENING BY VARYING FUEL LOADING AND FLOW DISTRIBUTION
- CORE INLET ORIFICES CONTROL FLOW DISTRIBUTION
- CORE SUPPORTED BY COLD END SUPPORT PLATE AND STRUCTURAL TUBE ARRANGEMENT
- REACTIVITY CONTROL BY ROTATING DRUMS IN REFLECTOR CONTAINING NEUTRON ABSORBER

Figure 9. Nuclear Rocket Reactor Design Features

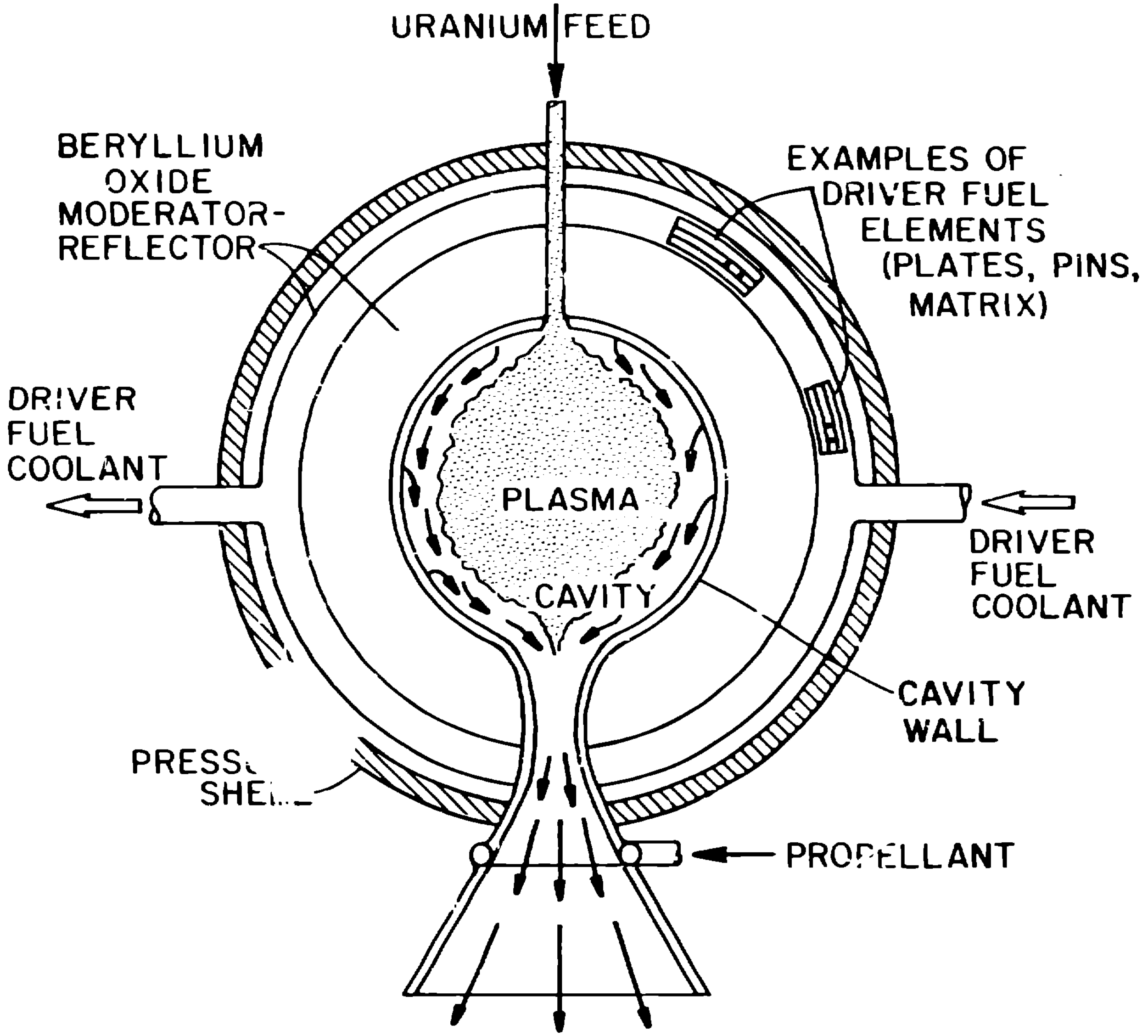


Figure 10. Gaseous Core Reactor Concept

O INFORMATION SERVICES

- Information Transmission
  [education, medical aid, electronic mail, news services, teleconferences, telemonitoring and teleoperation, time, navigation, search and rescue, ...]

- Data Acquisition
  [Earth resources, crop and forest management, water resources, weather and climate, ocean resources, mineral resources, environmental monitoring, land use surveys, ...]

O PRODUCTS

- Organic
  [biochemicals: isozymes, urokinase, ...]

- Inorganic
  [large single crystals, high-strength fibers, perfect glasses, new alloys, high-strength magnets, ...]

O ENERGY

- Power From Space
  [nuclear or solar]

- Nuclear Fusion Research in Space

- Illumination from Space

O HUMAN ACTIVITIES

- Medical and Genetic Research

- Orbiting Scientific Laboratories

- Space-Based Education [i.e., "The University of Space"]

- Space Therapeutics
  [e.g., "zero-gravity" hospital, sanitarium ...]

- Space Tourism

- Entertainment and the Arts

Figure 11. MAJOR AREAS OF SPACE INDUSTRIALIZATION

Figure 12. Lunar Base With
Nuclear Power