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NUCLEAR POWER: KEY TO MAN'S EXTRATERRESTRIAL CIVILIZATION

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ABSTRACT

The start of the Third Millennium will be highlighted by the establishment of man's extraterrestrial civilization with three technical cornerstones leading to the off-planet expansion of the human resource base. These are (1) the availability of compact energy sources for power and propulsion, (2) the creation of permanent manned habitats in space, and (3) the ability to process materials anywhere in the Solar System. In the 1990s and beyond, nuclear reactors could represent the prime source of both space power and propulsion. The manned and unmanned space missions of tomorrow will demand first kilowatt and then megawatt levels of power. Various nuclear power plant technologies will be discussed, with emphasis on derivatives from the nuclear rocket technology.

APPLICATIONS

Operational flights of the reusable Space Transportation System, or Space Shuttle, will initiate an exciting new era of space utilization and habitation. In time, humanity will also witness a subtle socio-technical transformation in which the physical conditions, resources, and properties existing beyond the Earth's atmosphere are effectively utilized to better the quality of life on Earth. At first, only a few selected persons will participate in the early phases of the permanent occupancy of space.

This overall process, called the "humanization of space," (1,2) marks the initiation of the second phase of planetary development--expansion of civilization into the Solar System. The first phase of planetary development began with the origination of life on Earth and will culminate with the full use of the terrestrial resource base. The third, and perhaps ultimate phase of planetary development will involves migration to the stars.

Human progress depends on challenge and continued technical growth. As mankind enters the next millennium, expansion into space offers an essentially limitless resource base for continued material development. The dynamic growth of humanity depends on an ever-expanding outlook--an "open world" philosophy (2,3). A "closed world" philosophy for human civilization, on the other hand, leads to evolutionary stagnation (4).

There are three technical cornerstones upon which the extraterrestrial component of an open world civilization will depend (3,5). These are: (1) compact energy systems, especially power and propulsion modules; (2) the ability to process (extraterrestrial) materials anywhere in the Solar System; and (3) the creation of permanent human habitats in space.

Figure 1 depicts some near-term activities in the humanization of space (1,5). In the 1990s and beyond, nuclear reactors could represent the prime source of both space electric power and propulsion. The manned and unmanned space missions of tomorrow will demand first kilowatt, then megawatt, and eventually even gigawatt levels of power. Figure 2 presents an "infinite horizon" view of manned space activities at the start of the next millennium (6). The term "infinite horizon" refers to long-range planning processes unconstrained by schedules, budgets, or dates.

TOWARD THE HUMANIZATION OF SPACE
DIRECT SERVICES AND NEW PRODUCTS FROM SPACE
(1985-2000)

- Information service platforms
- New products and goods
- Space construction
- Illumination from space
- Products "made in space" (profit flow back to Earth)
- Return to the Moon
- First private space travellers and "tourists"

MATURATION OF SPACE INDUSTRIALIZATION
CISLUNAR SPACE (2000-)

- Major space-based industries
- Use of materials from Moon
- Local climate control
- Orbiting space science center
- Space tourism
- Permanent habitats with increasing autarky

Fig. 1. Humanization of space.

PHASE 1. Permanent Occupancy of Near-Earth Space
- Space operations center (6-12 persons)
- Space case (50-200 persons)
- Propellant depot and service station
- Earth-orbital launch facility

PHASE 2. Permanent Occupancy of Cislunar Space
- Large (nuclear) power plants at GEO (megawatt-range)
- Manned GEO platform
- Orbiting lunar station
- Lunar-orbit launch facility
- Initial lunar base (6-20 persons)
- Permanent lunar base (200-300 persons)
- Cislunar OTVs and shuttles

PHASE 3. Full Self-Sufficiency in Cislunar Space
- Space communities in Earth orbit
- Space cities (e.g., Kraft Ehricke's "astropolis")
- Extensive lunar settlements
- Settlements throughout cislunar space
- Utilization of Apollo/Amor asteroids

PHASE 4. Permanent Occupation of Heliocentric Space (Interplanetary)
- Mars orbiting station
- Initial Martian base (6-20 persons)
- Permanent Martian settlement
- Asteroid belt exploration
- Asteroid belt base (bases on M-J belt)
- Outer planet satellites (Titan, Ganymede)
- Planetary engineering programs (including climate modification, domed habitats, etc...)
- Manmade "planetoids" in heliocentric space
- Interstellar expeditions

Fig. 2. Manned space activities--infinite horizons.

Energy, reliable, abundant and portable, is a most critical factor for establishing man's permanent presence in space. Space-based nuclear power, in turn, is a key enabling technology that must return to the national space program if such ambitious space utilization programs are actually to occur in the next few decades. For example, the movement of large quantities of cargo from low Earth orbit to high Earth orbit or lunar destinations, the operation of very large space platforms throughout cislunar space, and start-up and successful operation of lunar settlements can all benefit from the creative use of advanced space nuclear reactor technology. Future space activities such as asteroid movement and mining, climate control, and planetary engineering cannot even be legitimately considered without the availability of compact, pulsed and steady-state energy supplies in the megawatt and, ultimately, gigawatt class.

NUCLEAR POWER PLANT TECHNOLOGY

Table I lists desirable power plant characteristics and how they change with power level. Whether a particular technology best meets the requirements of a given mission depends on a number of factors. We have attempted to roughly classify the leading technology candidates based on reactor type, conversion system, and heat rejection system as a function of power level, as shown in Fig. 3. As power levels increase, the reject-heat system becomes the dominant weight and size element. As a power source, heat pipe reactor technology is a prime candidate into the megawatt range. However, at higher power levels, the size and mass of the core increases rapidly because of the large void space introduced by the heat pipes. Solid core reactors are a well-developed technology above this range. Converter technology on the low-power end favors thermoelectrics, but their low efficiency limits their useful operating power range. Increased efficiency and high reject heat temperature that can be achieved in a Rankine cycle are desirable, because this tends to minimize radiator size and weight. In ranges where open-loop systems are satisfactory, Brayton cycles have desirable attributes.

Papers by D. Koenig and W. Ranken, "Design Options for the SP-100 Thermoelectric Nuclear Power Plant," and T. E. Botts, J. Powell, J. Usher and F. Horn, "Nuclear Reactors Using Fine Particulate Fuel for Primary Power in Space," will discuss heat pipe reactors and fluidized bed reactors, so we will concentrate our discussion on gas-cooled solid core power plants, which were extensively developed as part of the Rover nuclear rocket program.

Figure 4 shows the major Rover tests. The KIWI test objectives established the basic reactor technology and developed sound design concepts. Accomplishments of the KIWI program included the demonstration of high-temperature fuels; identification of vibrational problems and demonstrated solutions; operation with liquid H_2; and automatic reactor control using reactivity control by

TABLE I
DESIRABLE POWER PLANT CHARACTERISTICS

Reliability	High-reliability components No single-failure points
Weight	Single shuttle or less • 100 kW_e range <20 kg/kW_e • 1 MW_e range <10 kg/kW_e • 10 MW_e range < 3 kg/kW_e* • 100 MW_e range < 0.3 kg/kW_e*
Volume	Single-shuttle compatible
Shielding	10^{12} - 10^{13} nvt 10^{6} - 10^{7} Rad

*Assumes use of nuclear electric propulsion to higher orbits.

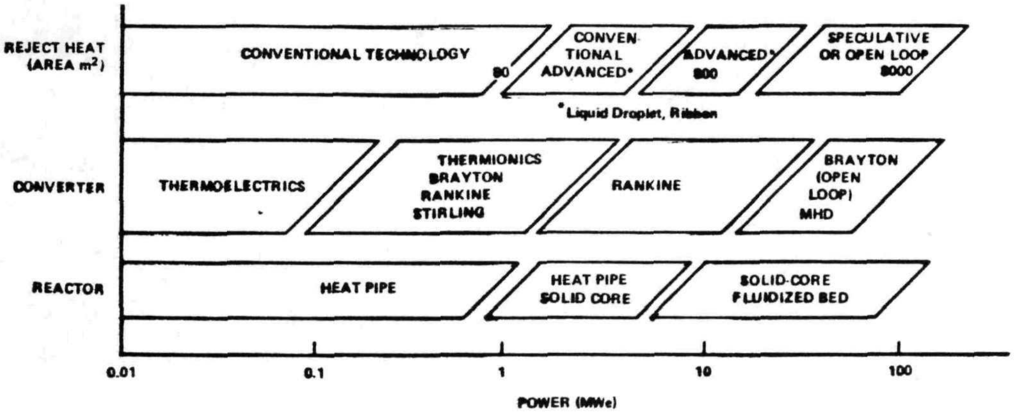

Fig. 3. Power plant technologies as a function of power level.

drums in the reflectors. In addition, KIWI-B4E ran at over 1890 K for 11.3 min and 2005 K and 937 MW for 95 s. The NRX development reactors objectives were to demonstrate a specific impulse of 760 s operating at 1100 MW for 60 min. These objectives were exceeded when the NRX-A6 reactor was tested for 62 min at 2220 K and 1100 MW. The Phoebus test objectives were to increase the specific impulse to 825 s, increase power density 50%, and increase power to 4000-5000 MW. These capabilities were demonstrated in Phoebus-2A, which operated 12 min above 4000 MW. The Pewee and Nuclear Furnace test objectives were to demonstrate higher temperature and longer life fuel elements. Pewee-1 ran at 2555 K and 514 MW for 40 min, and the Nuclear Furnaces, NF-1, ran at 2450 K and 54 MW for 109 min.

Engine tests are also shown in Fig. 4. The experimental engine objectives were to determine system characteristics during startup, full power, and shutdown conditions; evaluate control concepts; and qualify engine test stand operation. These objectives were accomplished in NRX/EST and XE test programs, including 28 XE' engine downward-firing prototype engine tests; and demonstration of prototype nonnuclear components. Flight engine systems were being designed with the full-flow-topping cycle selected to maximize specific impulse.

The major development emphasis in the Rover program was to increase temperature and operating duration of the reactor core. Success is shown in Fig. 5.

Significant historical events are listed in Table II. Active program development took place from 1955-1973.

The Rover reactor design features a graphite-moderated, hydrogen-cooled core (Fig. 6). The enriched 93.15% ^{235}U fuel was arranged in hexagonal-shaped fuel elements, with 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. Power flattening was achieved by varying the fuel loading in the core and controlling flow distribution by orifices in the core support plate. The core periphery contained an outer insulation layer, a cooled inboard slat section, a metal wrapper, a cooled outboard slat section, and an expansion gap. The core was surrounded by a reflector barrel of beryllium, with 12 reactivity control drums containing a neutron absorbing material. The reactor was enclosed in an aluminum pressure vessel.

Table III provides actual data of a number of tests. The highest power achieved was Phoebus-2A at 4080 MW_t, with a thrust of $\sim$930 000 N and a flow rate of 120 kg/s. The minimum reactor-specific mass was also Phoebus-2A at 2.3 kg/MW_t. Pewee-1 had an equivalent specific impulse of 845 s at an average exit temperature of 2550 K and a peak fuel temperature of 2750 K.

Fuel in the KIWI-A and KIWI-B through KIWI-B4D was a highly enriched UO_2 extruded in carbon. Particle size was $\sim$4 μm, with particle density of $\sim$10.9 mg/m^3. The demonstrated performance was 20 s at 2127 K. The major problem encountered was that UO_2 reacts with carbon and the fuel melts at 2683 K. Because of this, the KIWI-B4E, Phoebus, Pewee, and NRX-A used beaded UC_2 particles with a pyrolytic graphite coating to protect against oxidation. The fuel element-graphite matrix was coated with NbC (later ZrC) to protect against H_2 corrosion. The demonstrated operating limit was 1 h at 2400 to 2600 K. A limiting factor in performance was the large difference in thermal expansion coefficients between the graphite matrix and NbC coating, which led to excessive carbon loss after 1 h at 2375-2575 K. In the Nuclear Furnace, composite uncoated (U,Zr)C particles coated with ZrC were tested. Demonstrated operating limits were 109 min at 2450 K at a peak power density of $\sim$4500 MW/m^3. Lifetime projection was 4 to 6 h at 2500-2800 K with matched thermal conductivity. Here, the major problem encountered was cracks in the cladding from radiation damage.

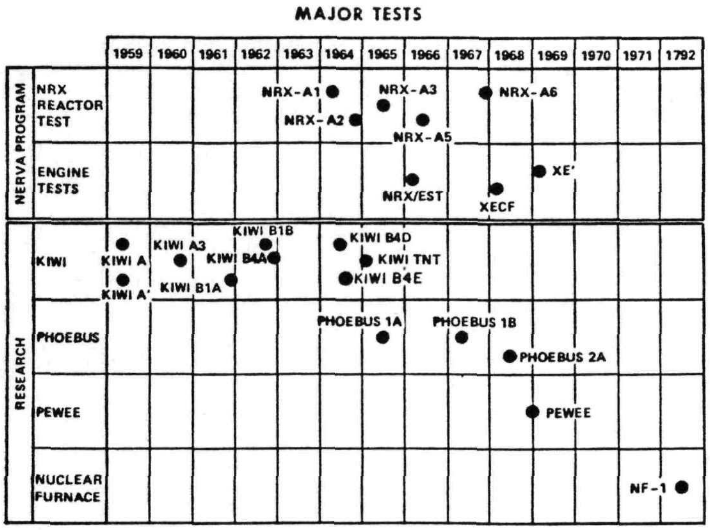

Fig. 4. Major systems tests in the Nuclear rocket program.

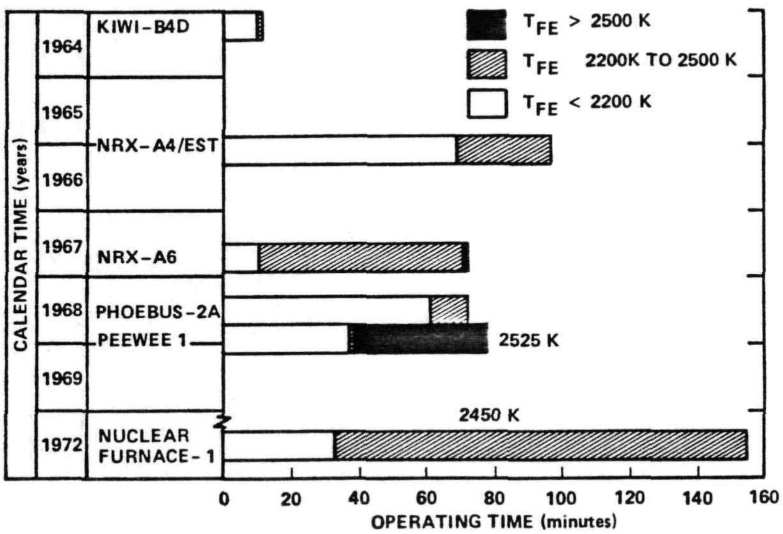

Fig. 5. Operating times and temperature levels in major reactor tests.

Limited tests were also done with pure carbide (U,Zr)C fuels. The projected fuels performance is summarized in Fig. 7.

A dual-mode nuclear rocket was also studied. Valves could be installed to isolate the tie tubes. Heat through the tie tubes is used to drive an electrical converter, such as a Rankine cycle.

Rover nuclear rocket technology could be adapted to electrical power production for single-mode, limited-life missions. Reactors have demonstrated the capability of operating at 2450 K, and technology exists to extend this to 2700 K. The technology exists for the propellant feed system if the converter is run in an open-loop mode. The nozzle would need to be replaced with the power conversion system. For closed-looped systems, helium could replace hydrogen greatly increasing the operating life.

A dual-mode electrical system could also be designed. This would, in addition to replacing the nozzle, incorporate a long-life tie tube power mode.

SUMMARY

Solid-core nuclear rocket technology has completed the development phase and is ready for flight demonstration. This technology can be used to meet short term electrical power requirements in the tens of megawatts, and may also be

TABLE II
HISTORY (1955-1964)

1955	Following several years of nuclear rocket studies, nuclear rocket program initiated as project Rover at Los Alamos National Laboratory. Concept to be pursued as solid core, H_2 cooled, reactor expanding gas through a rocket nozzle.
July 1959	First reactor test, KIWI-A, tested at 70 MW for five min.
Oct. 1960	Proof-of-principle tests (KIWI-A series of three reactors) completed.
July 1969	Industrial contractors (Aerojet-General for rocket engine and Westinghouse Electric Corporation for reactor) selected to perform rocket development phase. Reactor in-flight tests (Rift) program initiated.
1963	RIFT program canceled.
1961-1964	KIWI-B series of 1000 MW reactors tests included five reactors plus several cold-flow unfueled reactors to resolve vibration problems and demonstrate design power.
May-Sept. 1964	First full power test, KIWI-B4D, at design power with no indications of core vibrations. Also demonstrated restart capability.
Sept. 1964	NRX-A2, first test of the Nerva reactor, reached full power of 1100 MW for about 5 min.
Jan. 1965	KIWI-B type reactor deliverately placed on fast transient to destroy itselt as part of safety program.
June 1965	The prototype of a new class of reactors, Phoebus-1A, was run at full power for 10.5 min.
Dec. 1967	The fifth fueled reactor in the Nerva engine series, NRX-A6, exceeded the design goal of 60 min at 1100 MW.
June 1968	The Phoebus 2A--the most powerful nuclear rocket reactor ever built--ran for 12 min above 4000 MW.
Dec. 1968	Pewee set records in power density and temperature operating at 503 MW for 40 min at 2550 K, and core power density of 2340 MW/m^3.
Mar. 1969	The first down-firing prototype nuclear rocket engine, XE-prime, was successfully operated at 1100 MW.
1969	Saturn V production suspended--prime launch vehicle for Nerva.
June 1972	In the 44 MW nuclear furnace (NF-1), fuel was demonstrated at peak power densities of $\sim$4500 MW/m^3 and temperatures up to 2500 K for 109 min.
Jan. 1973	Nuclear rocket program terminated. Judged a technical success but changing national priorities resulted in cancellation decision.

used to satisfy long-term kilowatt mission requirements. This technology could be extremely useful in meeting pulse mode missions such as climate control.

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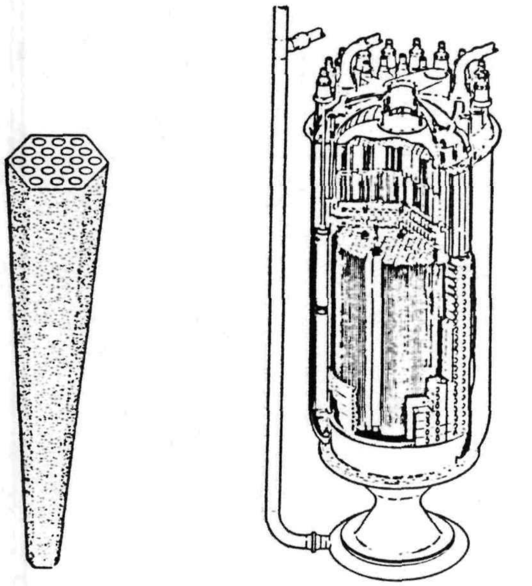

Fig. 6. Cutaway of reactor and fuel element.

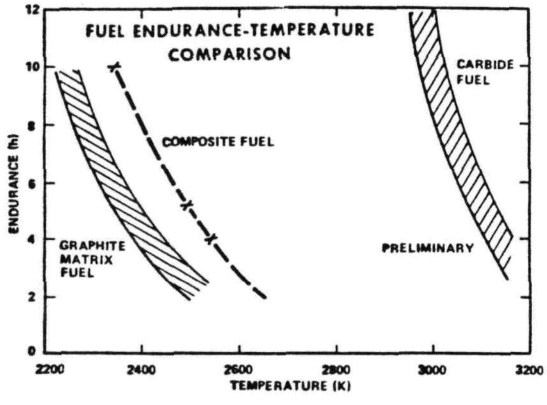

Fig. 7. Fuel endurance-temperature comparisons.

TABLE III
REACTOR SYSTEMS TESTS PERFORMANCE

	KIWI-4BE	NRX-A6	Phoebus-2A	Pewee I
Reactor power (kW)	950	1167	4080	507
Flow rate (kg/s)	31.8	32.7	119.2	18.6
Fuel exit average temperature (K)	2330	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