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MISSIONS AND PLANNING FOR NUCLEAR SPACE POWER*

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ABSTRACT

Requirements for electrical and propulsion power for space are expected to increase dramatically in the 1980s. Nuclear power is probably the only source for some deep space missions and a major competitor for many orbital missions, especially those at geosynchronous orbit. Because of the potential requirements, a technology program on reactor components has been initiated by the Department of Energy. The missions that are foreseen, the current reactor concept, and the technology program plan are described.

POTENTIAL MISSION REQUIREMENTS

When the Space Transportation System (STS) becomes operational, we will enter a new era in space exploration and exploitation. Many of the great advances in space we have seen to date will be like the early biplanes compared to today's 747 jet liners. There are a number of key technologies emerging that will make this new era feasible, including new approaches of meeting vastly increased demands for power. Large quantities of electrical power will be needed for both sensors and propulsion. Since I will be discussing the potential use of nuclear power, I will concentrate on the areas that appear most attractive for nuclear power, i.e., high power satellites in geosynchronous orbit and electric propulsion systems for both orbital transfer and planetary exploration missions.

Mission requirements can be categorized by user agencies, mainly the Department of Defense (DoD) and National Aeronautical and Space Agency (NASA).

Potential DoD Missions - The Department of Defense is continuously seeking more effective means of defending our country. With our global commitments and international involvement, improved surveillance and communications systems are increasingly important. Furthermore, with the political instability associated with depending on foreign bases, the US must look to basing these systems where they will be less vulnerable. It is also true that observation from space is the only practical way of monitoring activities in certain areas of the world.

Let us take a look at one possible application - a radar in geosynchronous orbit. The radar could use, perhaps, a Cassegranian parabolic antenna or planar array antenna. The size of the antenna would depend on such factors as the size of the object to be detected, the power available, and the radar wavelength. Possible arrangements for phase array radars using a solar array with batteries and a nuclear system are shown in Fig. 1 and Fig. 2, respectively. Using projected 1985 technology, the nuclear system would weigh about half the weight of a solar system. This reduced weight of the nuclear power plant allows the number of antenna modules to be increased and thus leads to a better radar for a given weight satellite, i.e., the scans per second for detecting targets with 1-m^2 radar cross-section and the number of target traces with 5-min revisit are increased about 80%. Point studies by two industrial contractors concluded that the nuclear power system is superior to the solar system at the 50-kW_e level when one considers mission performance, weight, and cost effectiveness.

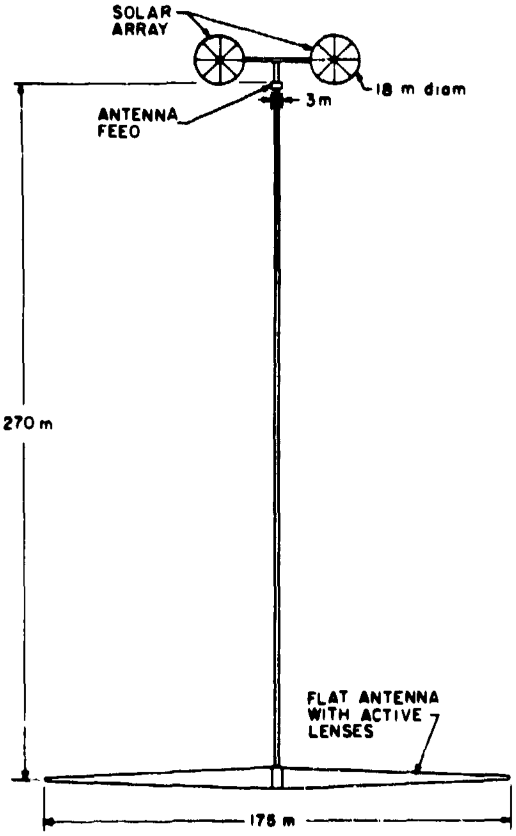


Fig. 1. Space based radar with solar power.

Large optical systems are also being studied as possible surveillance devices. These too would require a large quantity of electric power to cool the optical components and for tracking the targets. Nuclear power systems offer a compact power plant that should reduce the vibrational problems to which optical systems are sensitive.

The technologies for large space-based surveillance systems are still being developed. However, it appears that the amount of power required will be

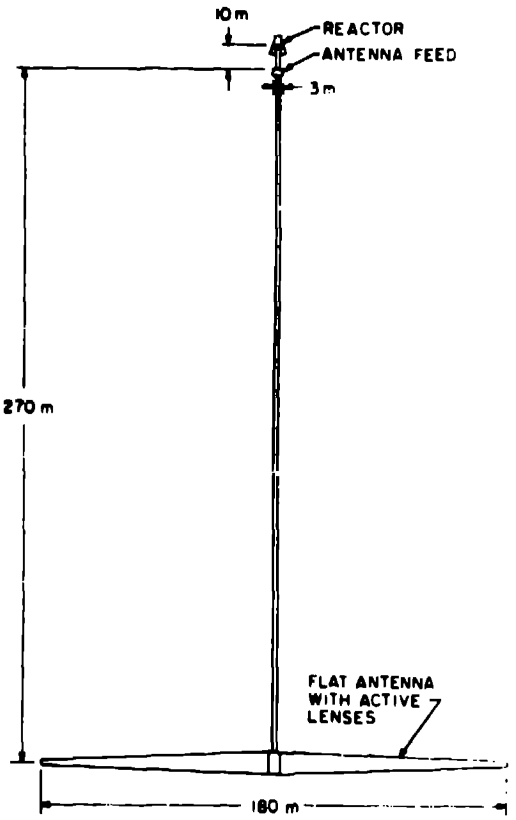


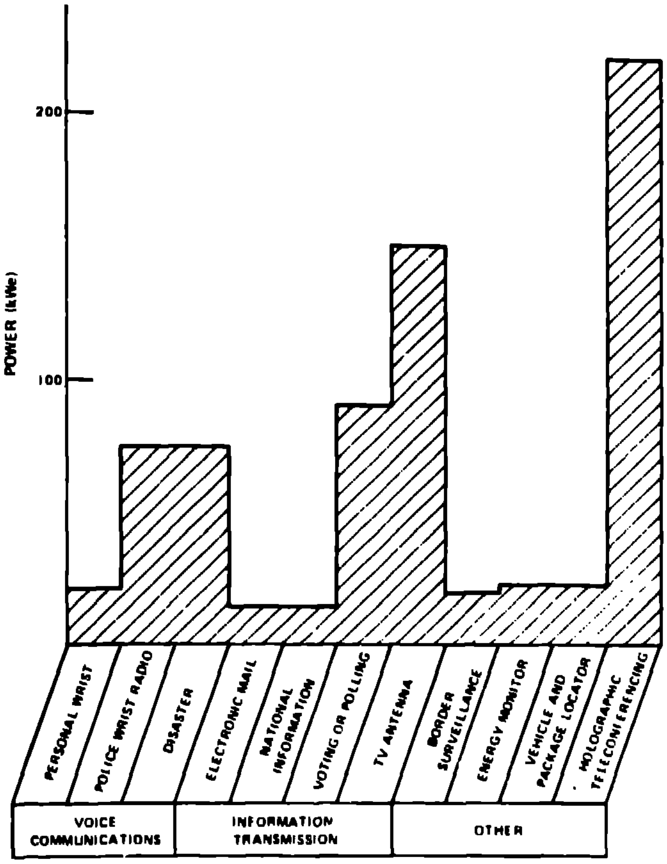
Fig. 2. Space base radar with nuclear power.

in the tens to maybe a hundred kilowatts of electricity. This is many times the power needed in present day systems.

Large communication systems with compact earthbound receivers and transmitters are also of interest to the military. These types of satellites will also require tens of kilowatts of power.

Potential NASA Earth-Orbit Missions - A number of potential geosynchronous-orbit NASA missions are described in the literature. I. Bekey, A. I. Mayer, and M. G. Wolfe[1] categorized a number of these by function, weight, size, power, orbit, time frame, initial operating cost, and risk. A plot of the high power geosynchronous potential missions is shown in Fig. 3. The missions included:

- Personal communications wrist radio (mobile telephones worn on the wrist) to serve 2.5 million people.
- Police wrist radio communications to provide real-time, secure, anti-jam, high-coverage, wide-area personal communications for policemen.
- Disaster communications to provide command and control to area emergency personnel.
- Electronic mail to transmit facsimilies of letters at reduced cost.
- National information services to provide small users rapid access to information.
- Voting or polling wrist set to provide convenient, rapid determination of the electorate's stand on candidates and issues.
- Advanced television antenna systems to provide improved television coverage especially to mountainous, rural, and remote areas.
- Border surveillance to detect illegal aliens, drug traffickers, and others who are attempting overt or covert crossings of the border using small sensitive, seismic sensors planted along the border and monitored from space.
- Energy monitor to fine tune energy distribution by monitoring current, voltage, or power readings on the network.
- Vehicle and package locators to be used to monitor shipments throughout the US continuously and thereby minimize thefts, hijackings, and lost shipments.
- Three-dimensional holographic teleconferencing to reduce the need for travel and thereby save considerable time and money. Laser illuminators and stereo sound would give the impression that all participants are present and active at the meeting.



SOURCE ADVANCED SPACE SYSTEM CONCEPTS AND THEIR ORBITAL SUPPORT NEEDS (1980 2000), AEROSPACE REPORT AIR-78(7365) 1

Fig. 3. Potential NASA applications in geosynchronous orbit.

It is seen that the power range of these potential missions overlaps the DoD potential missions.

Planetary Exploration - Solar system exploration missions are being performed at greater distances from the earth and in ever increasing detail. Exploration progresses from reconnaissance probes of bodies in the solar system to the exploration of these bodies with orbiting sensors and landers followed by intensive studies using rovers and surface sample and return techniques, and may finally lead to establishing semipermanent or permanent bases.

Figure 4 depicts expected growth for planetary missions with the capability expected from various propulsion systems. Chemical power has been the major propulsion source to date, but the limits of its capability will be reached in missions during the 1980s. Solar electric propulsion with ion thrusts will extend the ability to perform planetary missions and meet requirements for the late 1980s and early 1990s, but its limit will be reached in the reconnaissance mission to Uranus and exploration mission to Saturn. Nuclear electric propulsion with ion thrusters extends the capability to investigate the outer planets and to perform solar escape missions. The nuclear electric propulsion power supply envisioned here uses a 400-kW_e power plant. A significant advantage is obvious for nuclear electric propulsion, especially as the distance from the sun increases.

Transportation to Geosynchronous Orbit - A number of candidate systems exist to move satellites from low to geosynchronous orbit. Some of these are one-time only systems and others are based on reusable vehicles. The characteristic of the transfer will determine the type of propulsion desirable. Chemical systems tend to perform the transfer in a matter of hours at high acceleration levels. Electrical propulsion with ion thrusters take hundreds of days to perform a similar transfer. However, the stage weights are considerably less with ion thrusters. Chemical rockets can be characterized as high thrust but limited specific impulse systems, while electrical propulsion are limited thrust but high specific impulse systems. A number of potential orbital transfer vehicles are compared in Fig. 5.

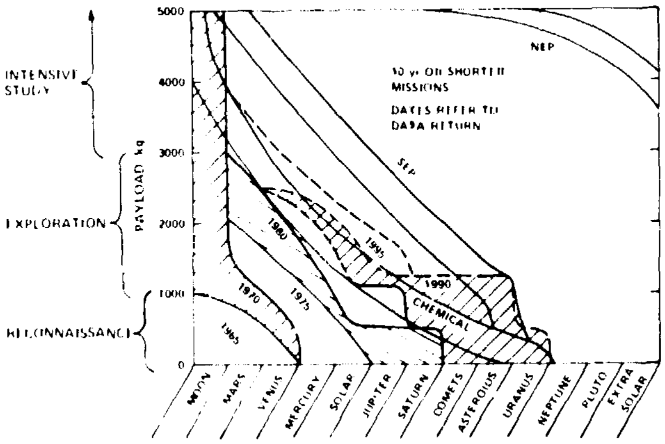
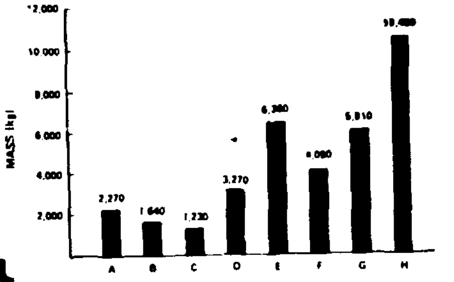


Fig. 4. Solar system exploration.

Currently, an Interim Upper Stage (IUS) is under development for use as a standard module with the STS. The basic IUS consists of a two-stage vehicle 4.5 m in length, and is capable of transporting a payload of 2270 kg to geosynchronous orbit. There is also a three-stage version of the IUS. The three-stage vehicle is formed by adding another large motor as a lower stage to the two-stage vehicle. It is 6.4 m in length and can deliver 3180 kg to geosynchronous orbit.

Transtage, Agena, and Centaur, current upper stage chemical rockets, provide limited payloads to geosynchronous orbit. A number of advanced chemical stages, Low Thrust Liquid (LTL), All Propulsion Orbit Transfer Vehicle (APOTV), and Aeromaneuvering Orbit Transfer Vehicle (AMOTV) are being investigated. The LTL can deliver twice the payload to geosynchronous orbit as a three-stage IUS. Also shown in Fig. 5 is the nuclear electric propulsion stage (NEPS). The delivery capacity is three times that of the three-stage IUS. NEPS can deliver large payloads compared to chemical stages, but at a cost in delivery time (150-225 days compared to one day or less).



	A	B	C	D	E	F	G	H
	IUS TWO STAGE	TRANSTAGE	AGENA	CENTAUR	LTL	APOTV	AMOTV	NEPS
TRANSFER MODE	1 BURN/ STAGE	2 BURN	2 BURN	2 BURN	MULTIPLE PERIGEE BURN	2 BURN	2 BURN W/AEROBRAKE (reusable)	CONTINUOUS THRUST SPIRAL (reusable)
TRANSFER TIME	~6 h	~6 h	~6 h	~6 h	~24 h	~6 h	~6 h	~150 TO 225 DAYS

LTL - LOW THRUST LIQUID
AMOTV - AEROMANUVERING ORBIT TRANSFER VEHICLE
APOTV - ALL PROPULSION ORBIT TRANSFER VEHICLE

Fig. 5. Orbit transfer system performance comparison (low earth orbit to geosynchronous orbit).

If solar arrays are incorporated into the spacecraft, then these can be used as a power source for ion thrusters. Because of higher mass and larger volume, solar arrays can deliver about half the mass and require twice the time compared to nuclear electric propulsion. One reason for their poorer performace is that about one-third of the solar array power is lost from degradation in the Van Allen Belt.

Nuclear power appears to offer an interesting option for one-way transfer of spacecraft to geosynchronous orbit or possibly as a space tug (depending on safety aspects) where transfer times close to a year are acceptable. The competitive weight with chemical stages or solar arrays and the ability to endure long time periods in the Van Allen belts are definite advantages. In addition, experience will be gained for planetary missions in the 1990s.

Power Plant Requirements -

1. POWER OUTPUT. Nuclear power requirements in geosynchronous orbit cover the range from 10-100 kW_e for potential DoD missions and 15-220 kW_e for potential NASA applications. For planetary missions, 400 kW_e is required.

2. LIFETIMES. Lifetimes are established by anticipated developments of other components in the spacecraft. Goals of 7-10 yr have been established for spacecraft in geosynchronous orbit and 10 yr for planetary missions.

3. RELIABILITY. Power subassembly reliability of 0.95 is the design goal for geosynchronous orbit and as high as possible for planetary missions. Designs that avoid single-point failures and degrade gradually are favored.

4. MASS. A general rule-of-thumb is that the power subassembly will require up to 30% of total spacecraft mass. For a dual-Shuttle launched spacecraft, the goal is 1910 kg.

5. CONFIGURATION CONSTRAINTS. The Space Shuttle dimensions of 18.3 m length and 4.5 m diameter limit the volume of the power source. The

individual spacecraft will determine how much of this can actually be used by the power source.

6. RADIATION. The spacecraft must be able to operate in natural radiation fields. Induced radiation created by nuclear power systems must be reduced to an acceptable radiation level determined by spacecraft components. For present electronic components, it is 10^{13} nvt and 10^7 rad over the mission life.

7. SAFETY FEATURES. The power subassembly must meet all regulations of NASA, DoD, DOF, and the National Range Commanders. All payloads using the STS are subject to a uniform set of basic safety and interface verification requirements. The safety requirements are tailored to identify the hazard potential of the payload. The Payload Safety Guidelines Handbook (JSC-11123) provides a basis for selecting design options to eliminate hazards. The STS safety policy requires that the basic payload design assure the elimination or control of any hazard to the Orbiter, crew, or other payloads.

Table I provides a summary of power plant requirements.

POWER PLANT DESCRIPTION

Our studies considered various types of reactors, power conversion equipment, and heat rejection systems. We selected a heat-pipe reactor design because of its high reliability, avoidance of single point failure mechanisms, higher tolerance to fuel swelling and radiation damage, elimination of pressure vessel and mechanical pumps, and lower development costs. Electric power conversion will use thermoelectrics because of achievable mass goal, inherent redundancy, modularity for different power levels, and relatively low development costs. The radiator will use a heat pipe design for light weight, high reliability, redundancy, and elimination of pumps. Figure 6 shows the relative arrangement and size of the power plant elements.

A 1200-kW_t heat pipe reactor is being designed. The current design concept is pictured in Fig. 7 with parameters listed in Table II. The core consists of layers of UO_2 and molybdenum which surround the heat pipes that are used to extract heat and transport it to the thermoelectric converters. The fuel consists of UO_2-20 vol% Mo. The heat pipes, self-contained structures that achieve very high thermal conductances by means of two-phase flow with capillary circulation, are made of molybdenum and provide an efficient means of transporting heat from the core to the power conversion equipment. With 90 heat pipes, redundant heat removal paths are provided. The core is surrounded by multi-foil insulation to minimize heat transfer to the reflector. The reflector is beryllium on the sides and one end and BeO on the reactor end, traversed by the heat pipes. Drums are placed around the reactor for reactivity control.

The radiation attenuation shield protects the payload using LiH for neutron attenuation and tungsten (if needed) for gamma attenuation.

Power conversion will use an improved SiGe thermoelectric material, the improvement being alloying with GaP for lower thermal conductivity. System efficiencies of 9-10% appear obtainable.

The radiator will use heat pipes called stringers to extract reject heat from the thermoelectrics and distribute it to the radiating surfaces. The radiating surfaces are also heat pipes that act as a radiating area and bumper for micrometeoroid protection of the stringer heat pipes.

PROGRAM PLAN FOR 10-100 kW_e POWER PLANT

Program Description - Components for a 10-100 kW_e space nuclear reactor electrical power plant will be designed, fabricated, and tested. At the completion of this phase, the power plant technology

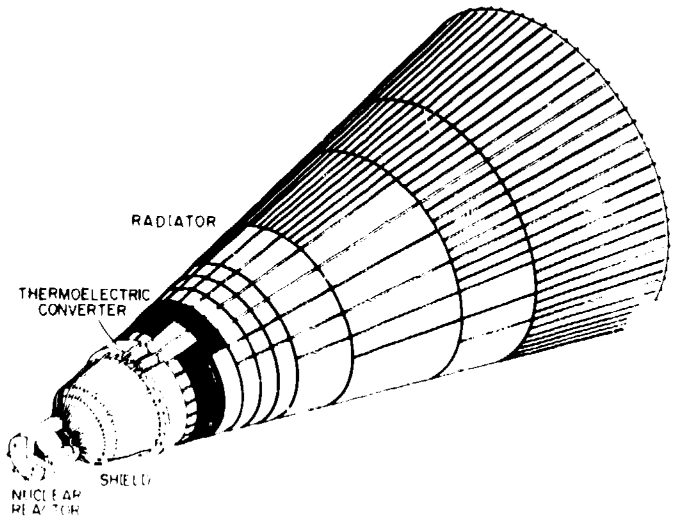


Fig. 6. Nuclear space power plant configuration.

TABLE I
POWER PLANT REQUIREMENTS

	Requirement	
	Geosynchronous	Planetary
Power output (kW_e)	10-100*	400
Lifetimes (y)	7	10
Reliability	0.95	High as possible; no single point failures
Mass (kg)	1910	8000 (includes power conditioning and larger shield)
Configuration constraints	Minimize packaging volume in shuttle bay	Minimize packaging volume in shuttle bay
Radiation attenuation		
Neutrons (nvt)	10^{13}	10^{12}
Gamma (rad)	10^7	10^6
Maneuverability	Mission dependent	Ion thrusters
Safety	STS requirements	STS requirements

*NASA requirements could extend this to 220 kW_e.

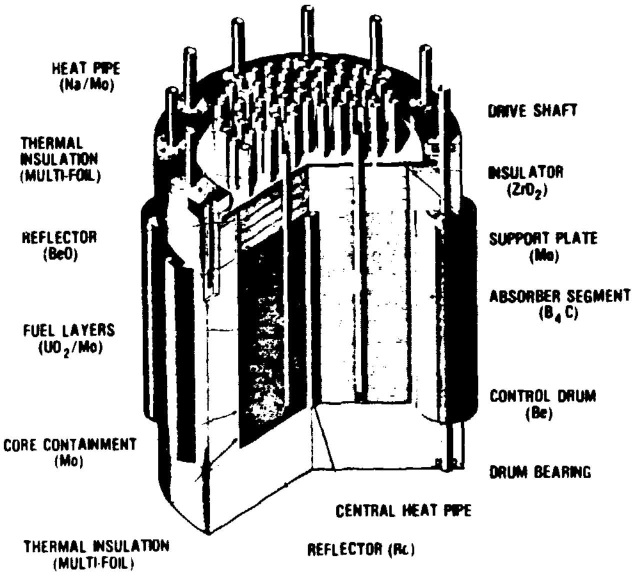


Fig. 7. Space power reactor (1200 kW_t).

will be sufficiently mature to initiate a ground demonstration system program with low technical risk. The information necessary to proceed to the ground demonstration power plant includes: understanding the basic physics; knowledge of basic material properties; demonstration of our ability to fabricate the components of the power plant; demonstration that these components will behave as specified; understanding of power plant assembly; and demonstration of our ability to meet safety requirements.

TABLE II
TYPICAL DESIGN PARAMETERS FOR 100 kW_e POWER PLANT

Reactor power (kW_t)		1100
Core heat pipe temperature (K)		1400
Number of core heat pipes		90
Fuel swelling (%)		2
Burn fraction of ^{235}U (%)		3
Radiator power (kW_t)		1000
Thermoelectric efficiency (%)		9
Reactor diameter (mm)		550
Radiator length (mm)		530
Radiator area (m^2)		70
Overall power plant length (m)		9.4
Reactor, shield and TE	1.6	
Radiator height	7.8	
Power Plant Mass (kg)		
Reactor		440
Fuel region	165	
Reflector	150	
Heat pipes	60	
Control system	35	
Support structure	30	
Shield		255
Thermoelectric converters		200
Radiator intertie		85
Radiator		380
Structure		135
Total		1495

The basic physics of the power plant and its components are straightforward for today's technology. Reactor neutronic and kinetic calculations, radiation shielding, converter technology, and radiator technology are all well established. The particular configurations being adopted for this power plant will be experimentally verified with mockups, such as critical assemblies.

The basic material properties for a system designed for a 7 yr lifetime implies a degree of knowledge of material that exceeds normally available data for time dependent properties. A low risk design is still possible with this lifetime by incorporating a degree of conservatism to cover uncertainties. Available material data will be collected and essential material data not available will be experimentally determined.

Material compatibility with its environment is very important in nuclear power plants. Accelerated material and components tests are planned in a simulated environment comparable in stress to flight power plant conditions. Emphasis will be on testing those components that may degrade with time, such as the core and radiator heat pipes and thermoelectric modules, and those components for which limited knowledge now exists.

Safety testing that can be performed on components or materials will be done. This will include simulating such conditions as propellant fires that may result from a Shuttle accident and the accidental immersion of the reactor in water.

Components will be fabricated as part of the technical feasibility phase to develop the necessary processes and procedures and to demonstrate the ability to manufacture the parts needed in a power plant. Also, sections of the power plant will be assembled to demonstrate that the ground demonstration system can be built as designed. Some of these components will be used for accelerated life testing and irradiation testing. In addition to demonstration of acceptable components, an effort will be made to develop improved components in selected areas where new ideas and concepts may lead to significantly better power plant performance.

Risk Assessment - The program goals are believed to be technically feasible with low risk.

The prime candidate for fuel is UO_2-20 vol% Mo. UO_2 has been extensively used in other reactors. The major new development is in the core configuration. The probability of successfully designing the core with this fuel is considered high.

Core heat pipe development depends on learning to bend high temperature heat pipes without loss of wick attachment and manufacturing fine mesh molybdenum screen material. Straight molybdenum heat pipes have a good history of operating at the temperatures of interest. The degree of bending required depends on whether the core heat pipes are routed to the thermoelectric converters through the shield or around the shield. We believe that either grooved or artery type heat pipe development will lead to a satisfactory design.

Thermoelectric risks are minimized by starting with an established thermoelectric material, SiGe. This is being alloyed with GaP to reduce thermal conductivity and increase converter efficiency. Sufficient samples have been made to provide encouraging results. The question of long-term stability must still be answered. An engineering assessment of the module design also appears encouraging; the design appears to be considerably more straightforward than that used on thermoelectric isotope power sources.

The radiator design uncertainties center around the use of beryllium; will it react with potassium, what is the impact resistance, how much will it diffuse with nickel? If the answer to these questions indicate that beryllium is a satisfactory radiator material, the heat pipe development effort appears to be a reasonable risk. If not, a heavier material will be substituted at some weight penalty.

Developing confidence that components will meet the lifetime of interest presents a major challenge. Accelerated component demonstration testing will be performed on the reactor heat pipes, thermoelectrics, and radiator heat pipes. During the development phase, accelerated testing relationships must be found to verify this approach.

Irradiation tests of fuel segments will measure the interactions between the fuel and heat pipes in a simulated power plant environment. The effects of radiation and fission product formation on core heat pipe structure and operation will be determined. These effects are expected to be small, but experimental verification is needed to develop the confidence to proceed to a demonstration power plant. The effect of radiation on core specimens will verify the baseline core design.

Mechanical actuators for SNAP have been individually tested for over 3 years. However, the effect of going from 3-yr to 7-yr periods on the durability of mechanical devices is hard to project. A thorough examination of previous actuator performance data and accelerated testing of actuators will be used to verify technical readiness.

Overall, we believe that the risks involved in the nuclear power plant are reasonable and that a high degree of confidence exists in demonstrating technical feasibility. Sufficient experimental data should be available by the end of FY-1983 to proceed to a ground demonstration power plant if potential mission requirements warrant. The activities in the present program will result in a relatively modest investment before commitment to the full-scale ground demonstration of a 10-100-kW_e nuclear power plant.

Cost - Currently, the component technology program is funded by the DOE at $2 million per year. The level-of-funding started in FY-79 and is expected to continue for 5 years. Depending on mission requirements, the next phase would be to build a ground demonstration of the power plant. The funding for this would be on the order of $15-20M per year.

ACKNOWLEDGEMENT

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REFERENCES

1. I. Bekey, A. I, Mayer, and M. G. Wolfe, "Advanced Space Systems Concepts and Their Orbital Support Needs (1980-2000)," Vols. I-IV, Aerospace report ATR-76 (7365)-1, April 1976.