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AUTHOR(S): David Buden

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los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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STATUS REPORT ON NUCLEAR REACTORS FOR SPACE ELECTRIC POWER

David Buden

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

ABSTRACT

The Los Alamos Scientific Laboratory is studying reactor power plants for space applications in the late 1980s and 1990s. The study is concentrating on high-temperature, compact, fast reactors that can be coupled with various radiation shielding systems and thermoelectric, dynamic, or thermionic electric power conversion systems, depending on the mission.

Increased questions have been raised about safety since the COSMOS 954 incident. High orbits (above 400-500 nautical miles) have sufficient lifetimes to allow radioactive elements to decay to safe levels. The major proposed applications for satellites with reactors in Earth orbit are in geosynchronous orbit (19,400 nautical miles). In missions at geosynchronous orbit where orbital lifetimes are practically indefinite, the safety considerations are negligible.

The potential missions, why reactors are being considered as a prime power candidate, reactor features, and safety considerations will be discussed.

A VIGOROUS PROGRAM for use of reactors in space existed from the mid 1950s until the early 1970s. This included the U.S. nuclear-powered rocket program whose prime objective was to provide a propulsion unit for taking men to Mars and an array of space electric power systems for powering sensors and ion propulsion units. As mission emphasis changed, the various propulsion and space electric power systems being developed no longer were needed to support the revised program plans and by 1973 the development of reactors for space were largely discontinued.

The major factor warranting a fresh look at the need for higher power levels, and thus possibly considering nuclear reactors again for space, is the space transportation system (STS) or space shuttle. The space shuttle provides a reusable system that can be considered a true transportation system. As such, it opens a new space era leading to larger satellites and generating new power requirements.

MISSION REQUIREMENTS

A nuclear power plant should be designed with the intent of meeting a range of potential power requirements. Because of development times involved, continually evolving definitions of potential missions, uncertainties during payload integration, and uncertainties with schedules and budgets, it is not desirable to concentrate reactor power plant development on a single mission. Both Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) future missions are being analyzed as a basis for establishing power plant requirements.

A number of potential DoD missions have been identified in communications and electro-optical and radar surveillance requiring electric power in the 10-100 kW_e range. A plot of peak projected power requirements (Fig. 1) indicates that electric power requirements would grow continuously from a few kilowatts currently to maybe 50 kW_e in the late 1980s and over 100 kW in the early 1990s.

Fig. 1 - Maximum single-spacecraft power requirements by year

NASA's potential missions for nuclear reactors center on large satellites in geosynchronous Earth-orbits and planetary exploration. I. Bekey, H. I. Mayer, and M. G. Wolfe[1] did a comprehensive study which categorized various potential space applications as to the function, weight, size, power, orbit, time frame, initial operational cost, and risk. Potential missions in geosynchronous orbit requiring 15-220 kW_e are plotted in Fig. 2. The space shuttle[2] is estimated to provide about 29,000 kg capacity in low Earth orbit; however in geosynchronous orbit, the payload estimate is 3180 kg. The low Earth orbit requirements can usually be handled with a solar arrays plus batteries power supply. However, the weight limitations at geosynchronous orbit imply the need for compact, low-weight power supplies, and thus this orbit is a potential application for nuclear power sources.

Table I provides a summary of power plant requirements to be used as a basis for making various technology decisions.

WHY REACTORS BECOME A PRIME POWER SOURCE?

Projected 1985 power technologies (the technologies that would be used in 1990 missions) indicate that solar arrays with batteries are

Fig. 2 - Potential NASA applications in geosynchronous orbit. Source: "Advanced Space System Concepts and Their Orbital Support Needs (1980-2000)," Aerospace report AIR-76(7365)-1

expected to be heavier than reactors above 10-20 kW_e (Table II). At 50 kW_e, nuclear system mass is about 60% of the solar system mass, and at 100 kW_e, it is 40%.

Reactors will be less costly than solar power systems. Table II shows a cost comparison including a factor for launch mass differences. At 10 kW_e, the cost of delivery to geosynchronous orbit is estimated to be almost equal, but at 50 kW_e, the reactor cost is one-fourth of the solar cost and at 100 kW_e, it is one-fifth.

Table I - Power Plant Requirements for Geosynchronous Orbit Missions

	Geosynchronous
Power output (kW_e)	10-200
Lifetimes (yr)	7
Reliability	0.95
Mass	
Single shuttle (kg)	955
Dual shuttle (kg)	1910
Configuration	Minimize packaging volume in shuttle bay
Radiation attenuation	
Neutrons (nvt)	10^{13}
Gamma (rad)	10^7
Maneuverability	Mission dependent
Safety	STS requirements

The space shuttle is expected to be the main launch vehicle. Considering that the practical limits of most missions around 1990 are two shuttle trips per spacecraft, about 1910 kg would probably be the most that can be devoted to the power supply for geosynchronous orbit missions. This implies that solar arrays will have difficulty in providing 50 kW_e power and will be much too heavy at 100 kW_e. Reactor systems can span the whole range.

Solar arrays have been flight demonstrated in a 16 kW_e system. Because of weight limitations imposed by the shuttle and the mass of a solar array plus battery system, it is doubtful that 50 kW_e power systems can be demonstrated by the mid 1980s. The SNAP 10A is the only flight-demonstrated space reactor, and it operated at 500 W.[3,4] Today's technology would permit flight testing a fast, compact reactor system in the mid to late 1980s at 100 kW_e.

Solar arrays have to be oriented sunward. Reactors require no orientation mechanism, power transfer slip rings, array deployment, or mechanism to compensate for tracking disturbances. However, both systems have location limitations. Because of their size and the need to focus on the sun, solar arrays must be arranged to avoid shadowing by large antennas and other spacecraft components. Reactors must be positioned to minimize radiation shielding.

Solar arrays restrict maneuverability. Unless a mechanism for retracting and deploying the arrays is included, the spacecraft will have to

Table II - Solar Array vs Reactors Based on Projected Technology, 1985

	10 kW_e		50 kW_e		100 kW_e	
	Solar	Nuclear	Solar	Nuclear	Solar	Nuclear
W/kg	24	14	24	40	22	55
Cost, delivered to geosynchronous orbit (Million $)	8	7	32	10	63	14
Shuttle Compatible (~1810 kg)	Yes	Yes	Difficult	Yes	No	Yes
Space Flight	Demonstrated	Possible	Possible	Possible	Doubtful	Possible

be moved slowly to minimize acceleration loads. Reactors are compact, making maneuverability feasible.

Natural radiation affects solar array life, but has no effect on nuclear reactors. However, solar arrays do not introduce radiation, which is a major consideration with reactors. Shielding must be provided to attenuate radiation emitted from the reactor. Radiation rates affect component life by both instantaneous intensity (which ionizes sensitive electronic systems) and integral effects (which cause semipermanent lattice defects that create physical and chemical property changes in materials). The amount of shielding depends on the power level, the distance of radiation-sensitive components from the reactor, and their radiation tolerance. Each individual mission's best reactor location must be determined. Judicious location will usually permit unmanned shieldings of less than a few hundred kilograms.

Solar arrays create a minimum of safety handling and disposal problems. The reactor safety considerations were demonstrated solvable in the SNAP 10A reactor flight test. More concerning reactor safety will be discussed later.

In summary, 5- to 25-kW_e solar arrays power systems have been demonstrated, but solar arrays with batteries become quite heavy at 50 kW_e. They introduce a minimum of radiation, safety, handling, or disposal problems. Reactor power plants tend to weigh less, have lower unit cost, and are compatible with the shuttle loads at 10 to 100 kW_e. Space reactors are compact and independent of spacecraft orientation. Furthermore, the space reactor power plant is unaffected by natural radiation, can be made highly reliable and allows the spacecraft to be maneuverable.

POWER PLANT DESCRIPTION

The power plant includes the reactor, radiation shield, electrical converter, and waste-heat radiator.

REACTOR-A typical 1000 kW_t reactor described herein could satisfy the 10 to 220 kW_e power demands.

The reactor core contains 90 hexagonal fuel elements made of 90% UC and 10% ZrC (Fig. 3) Each element is 27.9 mm across the hexagonal flats and 280 mm long and is contained in a thin-walled molybdenum can. Each is cooled by a centrally located molybdenum heat pipe, an efficient means of transporting heat from the core. The heat pipe is a self-contained structure that achieves very high thermal conductances by means of two-phase flow with capillary circulation. Heat is transferred within the heat pipe's contained envelope by evaporating a liquid (sodium), transporting the vapor to another part of the container, condensing it, and returning the condensate to the evaporator through a wick of suitable capillary structure. The fuel is segmented to allow for swelling, minimize fabrication problems, prevent bowing, enhance heat transfer, permit variations in uranium loading, and allow for thermal expansion.

The core is enclosed and is kept compressed by a series of rings. Multi-foil insulation minimizes heat transfer from the core to the reflector. The core, with its 90 heat pipes, essentially provides 90 independent loops for removing heat. Loss of one heat pipe causes elevated, but acceptable temperature increase in the surrounding pipes. The core could sustain several failures with no major degradation of performance.

The core is surrounded by a neutron reflector of beryllium on the sides and aft end and beryllium oxide at the forward end. Beryllium oxide is required at the end that the heat pipes penetrate because of higher operating temperatures there. The reactor is controlled by changing the position of neutron-absorbing material within the reflector. Twelve drums are used in the reflector, each containing a boron-carbide sector that is rotated for power control. The control surfaces are rotated in discrete steps by actuators placed behind the shield to reduce the incident nuclear and thermal radiation that reaches them. The reactor power will be controlled to maintain a constant outlet voltage from the power conversion units so as to minimize thermal cycling of the reactor. Redundant instrumentation and control electronics are provided to increase reliability and eliminate single-point failures.

Fig. 3 - Reactor core assembly

Table III shows typical design parameters for the 1000 kW_t reactor.

SHIELD-Shield design and technology make extensive use of work on space reactor shields for SNAP 2, 8, and 10A, and of ROVER experience. These reactors have certain features in common with current designs, namely, small physical size, unmanned space application with comparable allowance of neutron and gamma doses, and comparable radiation flux levels. Only shadow shielding is required. The shield can be considered as follows: neutron attenuation is provided by lithium hydride (LiH) in the shape of a frustum, and a heavy metal gamma shield is added at the reactor end of the shield if needed.

To minimize single-point failures, the LiH is to be encapsulated in a number of pancake-shaped cans, so that pressure containment failure from meteoroid penetration or a weld failure, for ex-

Table III - Design Parameters for 1000-kWt Reactor (1400 K Heat pipe Temperature)

Temperatures (K)			
Max fuel delta t	155	Burn fraction of ^{238}U	0.0272
Av delta t across heat pipe wall	17.5	Fuel swelling, vol%	8.0
Av fuel temperature	1469		
Max fuel temperature	1581		
Reactor Dimensions (m)		**Fuel Element Dimensions (mm)**	
Core diam	0.28	Width across hex flats	27.9
Core height	0.28	Equiv fuel element diam	28.3
Reactor diam	0.51	Equiv fuel region o.d.	28.6
Reactor height	0.49	Heat pipe o.d.	15.3
Reflector thickness	0.10	Vapor diam	11.9
Pipe length outside reactor	1.00	Vapor area (mm^2)	110.4
Total heat pipe length	1.38		
Overall reactor and heat pipe length	1.49		
Reactor Mass (kg)			
Fuel	127 (includes 108 kg of ^{235}U)		
Reflector	133		
Heat pipes	94		
Control system	33		
Support Structure	27		
Total	414		

ample, will deplete the hydrogen in only a small part of the shield. The shield is also a structural member that connects to the reactor on one end and by a boom to the payload on the other. The load can be carried by the outer conical shield shell.

ELECTRIC POWER CONVERTERS-A number of technologies for electric power converter systems are being developed. The principal near-term ones are thermoelectrics and dynamic converters, such as the Brayton cycle.

THERMOELECTRICS-Thermoelectrics (TE) have been used in many space missions as the power conversion elements of radioisotope power supplies with demonstrated high reliability. The heat removed by each reactor heat pipe becomes the heat source of a TE module. The TE operates at about 1275 K.

The cold side of the TE module will be cooled by heat pipes that are an integral part of the heat rejection radiator. The cold-side temperature is a compromise between that required for optimal TE efficiency and that required for optimal radiator size and weight. About 775 K TE heat sink temperature seems nearly optimum and is in the range already tested with potassium-filled heat pipes.

A number of semiconductor TE materials have been developed. Silicon-germanium is well known and has the potential for operating at as high as 1400 K with 6.5% efficiency. The reference design is based on a "compression" module that was built and tested several years ago; other designs have also been made with high-performance TE modules. Figure 4 is a conceptual drawing of the module and shows projected converter efficiencies.

DYNAMIC CONVERTERS-The Brayton cycle is used to illustrate dynamic converter systems. Mounted on the end of the reactor heat pipes are heat exchangers to feed redundant Brayton loops. The Brayton loop consists of a rotating group (compressor, turbine, and alternator on a single shaft supported on foil gas bearings) and heat exchangers from the reactor, the recuperator, and

Fig. 4 - Thermoelectric design concept and projected converter efficiencies

to the radiator. An inert gas, xenon and helium, is used as working fluid in the closed-loop system. Typical temperatures and pressures are shown in Fig. 5.

Fig. 5 – Brayton cycle power system

A single-unit Brayton converter has operated over 30,000 h in tests by NASA-Lewis Research Center[7] at a turbine inlet temperature of 1145 K. The demonstrated efficiencies were 30-33% at 7-8 kW_e.

RADIATORS-The radiator is being designed for 99% reliability and 7-yr lifetime. Radiator area depends on such factors as the converter efficiency, electric power level, heat rejection temperature, and probability of component failure mainly from meteoroids. The present concept is based on stringer heat pipe arrangement transporting the heat from a thermoelectric cold-junction ring. Circumferential heat pipes surround the stringers to distribute the heat and act as a bumper and as fins. Calculations of meteoroid penetration were based on NASA space shuttle user guidelines for payloads in geosynchronous orbit.[5,6] To ensure that the heat pipe radiator survives meteoroid penetration throughout the mission, the radiator can be overdesigned and penetration armor can be added. Beryllium and titanium seem the most promising space radiator materials; others are appreciably heavier.

SYSTEM MASS-Figure 6 shows a thermoelectric system. The core and shield are separated to provide space to bend the core heat pipes around the shield to the thermoelectric converters. The converters are located in a ring of good thermal conductive material. The radiator extracts the heat from the cold junction of the converter ring.

A representative power plant layout for the Brayton cycle is shown in Fig. 7. As a compromise between converter efficiency and radiator mass, we use 25% efficiency in analyzing Brayton converter weights. To avoid single-point failures, duplicate loops each capable of full-power operation have been included in the system mass totals. This redundancy achieved at some weight penalty appears feasible within the total weight constraints.

Fig. 6 – Thermoelectric power plant

Fig. 7 – Brayton cycle space electric power supply

Table IV shows the mass parameters of major components at 10, 50, and 100 kW_e.

SAFETY

Recently, questions have been raised as to whether nuclear reactors can be used safely as electric power plants in Earth orbit and whether such power sources are indeed needed.

Safety has been and continues to be a major concern of U.S. scientists involved in using reactors in space. Before operation, the reactor and its uranium fuel are perfectly safe to handle. There is absolutely no possibility that a nuclear electric power plant can explode.

The key to safe operation before and during launch is to keep the reactor in a nonoperative mode. This is accomplished by adding built-in safety features, such as redundant control elements, where only one element is allowed to be unlocked at a time; brakes on the control element actuating mechanisms to prevent movement without two independent signals; and a reactor designed to remain nonoperative even with environment changes, such as immersion in water.

Most applications considered for nuclear reactors are in high orbits, such as geosyn-

Table IV - Mass Parameters for Nuclear Space Electric Power (7-yr lifetime)

	$10 kW_e$		$50 kW_e$		$100 kW_e$	
	TE	Brayton	TE	Brayton	TE[c]	Brayton
Reactor power (kW_t)	156	40	781	200	1111	400
Efficiency (%)	6.4	25	6.4	25	9.0	25
Radiator power (kW_t)	146	30	731	150	1011	300
Radiator temp (K)	775	475	775	475	775	475
Mass (kg)						
Core	415	415	415	415	525	415
Shield[a]	165	110	215	130	250	145
Converter	45	250[b]	235	460[b]	335	710[b]
Radiator	35	30	255	200	380	400
Structure	65	80	110	120	150	165
Total	725	885	1230	1325	1640	1835
W/kg	14	11	41	38	61	54

[a] Assume 12° cone half-angle at 25 m.
[b] Dual converter systems.
[c] Improved TE material and larger reactor (1500 kW_t).

chronous. The higher the orbit, the longer a satellite will remain in orbit. Long orbit times provide time for radioactive elements to decay. An orbit altitude of about 400-500 n mi will provide for over a 1000 y life and thus could provide a margin of conservatism in meeting safety criterion. Doubling the orbit increases the orbital lifetime to about a million years. Satellites in geosynchronous orbit (19,400 nautical miles), the proposed location of most reactor-powered U.S. satellites, will, for all practical purposes, never reenter the earth's atmosphere.

PROGRAM STATUS

At the time this report was prepared, screening studies were under way at the Los Alamos Scientific Laboratory to determine the design approach to be followed in developing future electrical systems. The heat pipe reactors described here are only one approach under consideration, but are heavily favored because of longevity requirements and to avoid single failure points that could result in a significant loss in power.

An experimental program is planned to start in Fiscal-1979 to resolve key technology feasibility questions. The experimental program will be performed in areas where sufficient data are not available to make a system selection for a ground demonstration power plant.

ACKNOWLEDGMENTS

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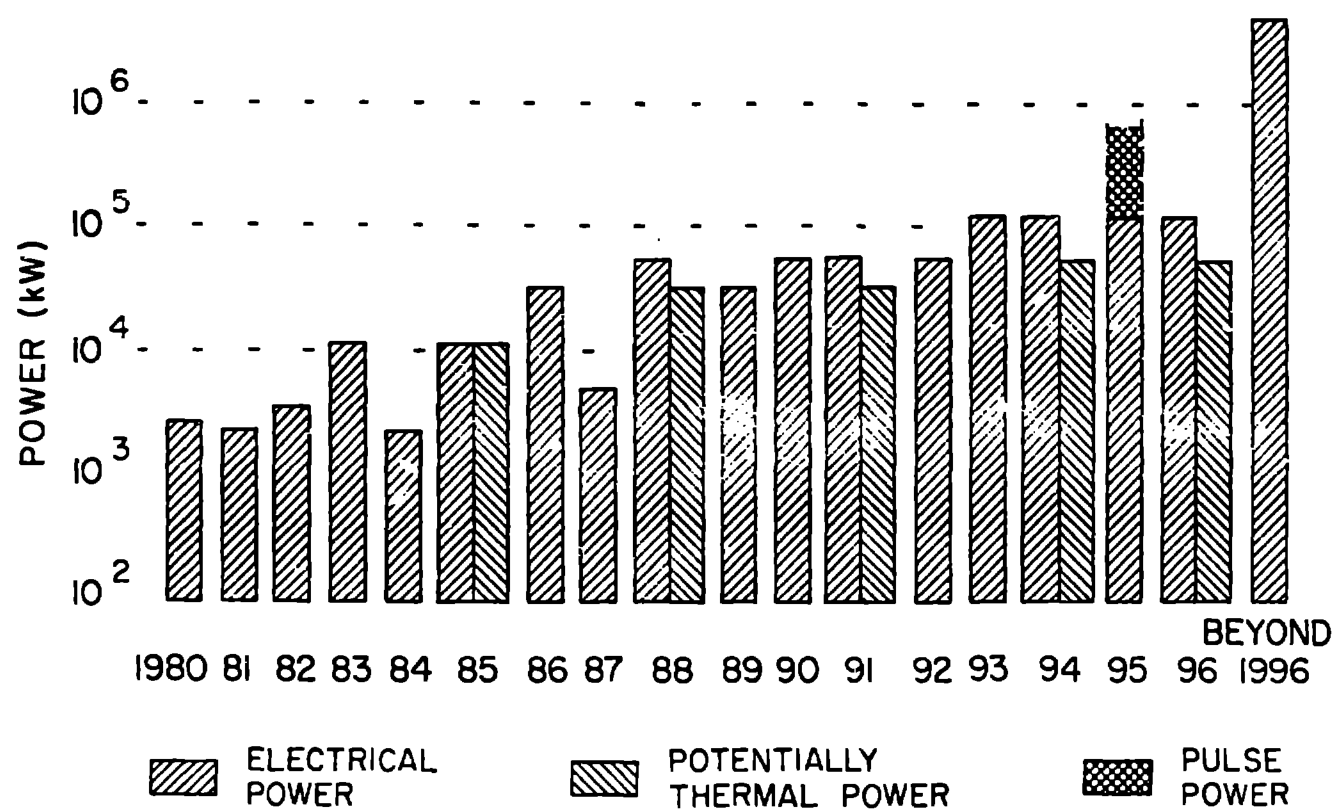
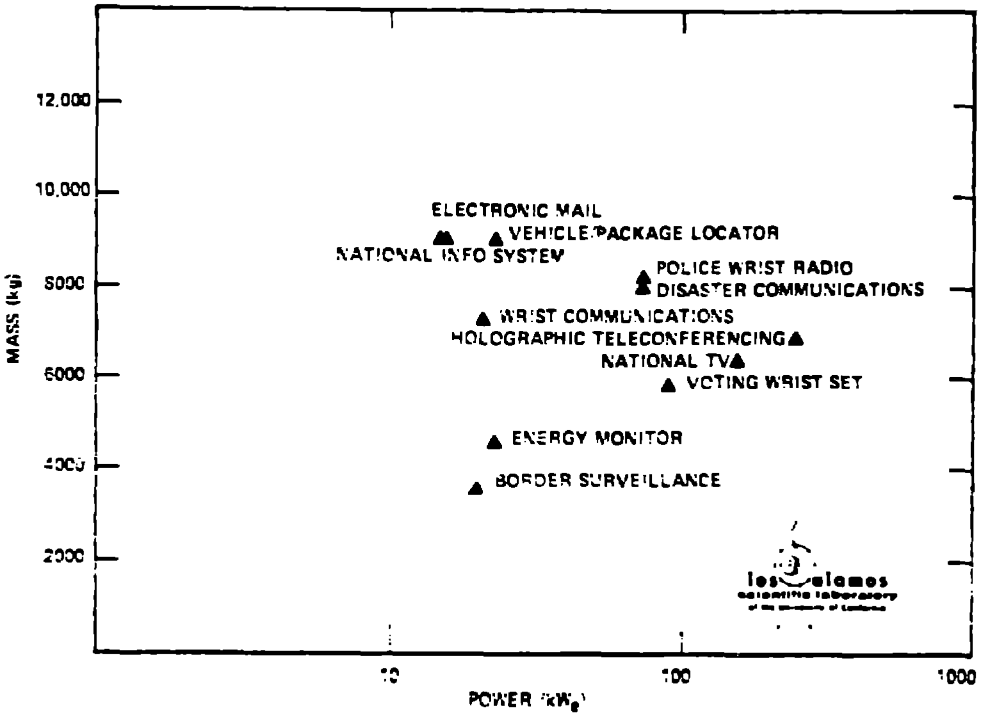

POWER (kW)
10 6
10 5
10 4
10 3
10 2
1980 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96
BEYOND 1996
ELECTRICAL POWER
POTENTIALLY THERMAL POWER
PULSE POWER

POTENTIAL NASA APPLICATIONS IN GEOSYNCHRONOUS ORBIT



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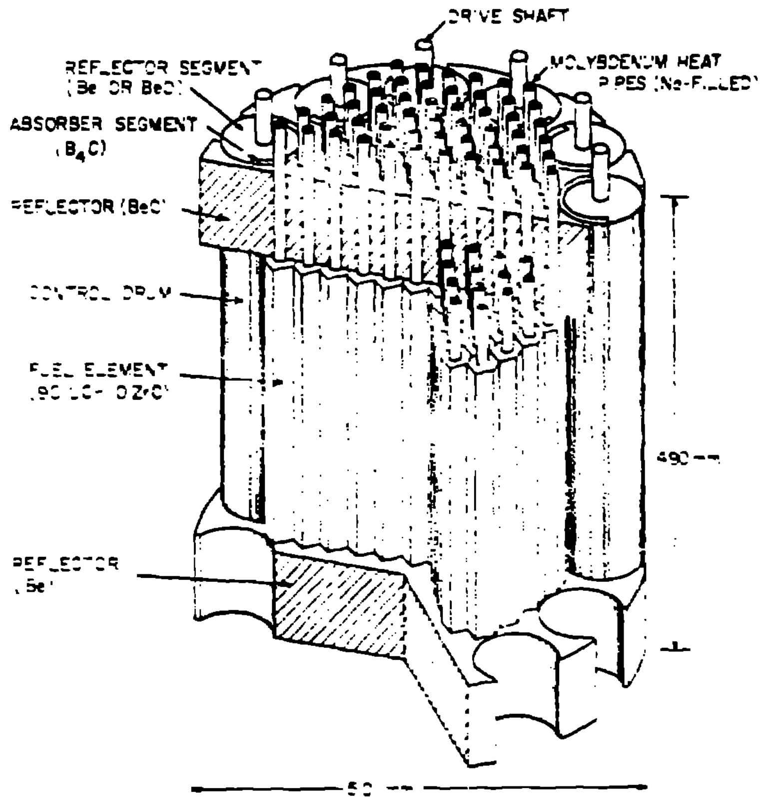
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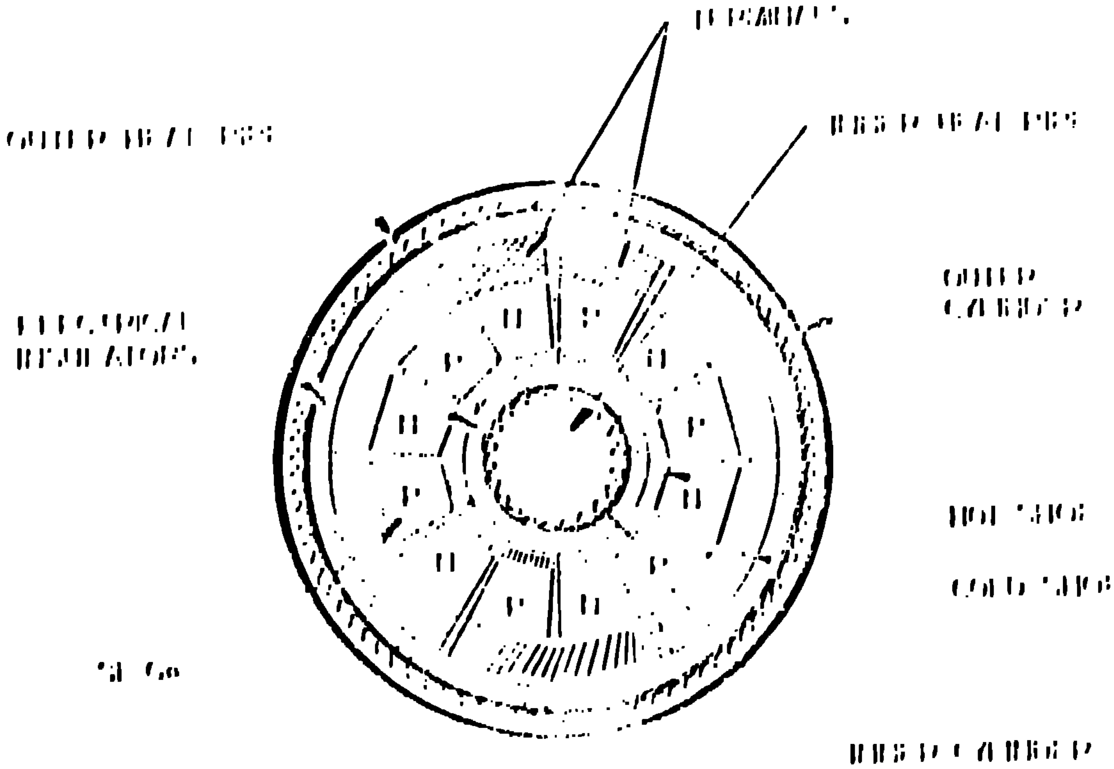
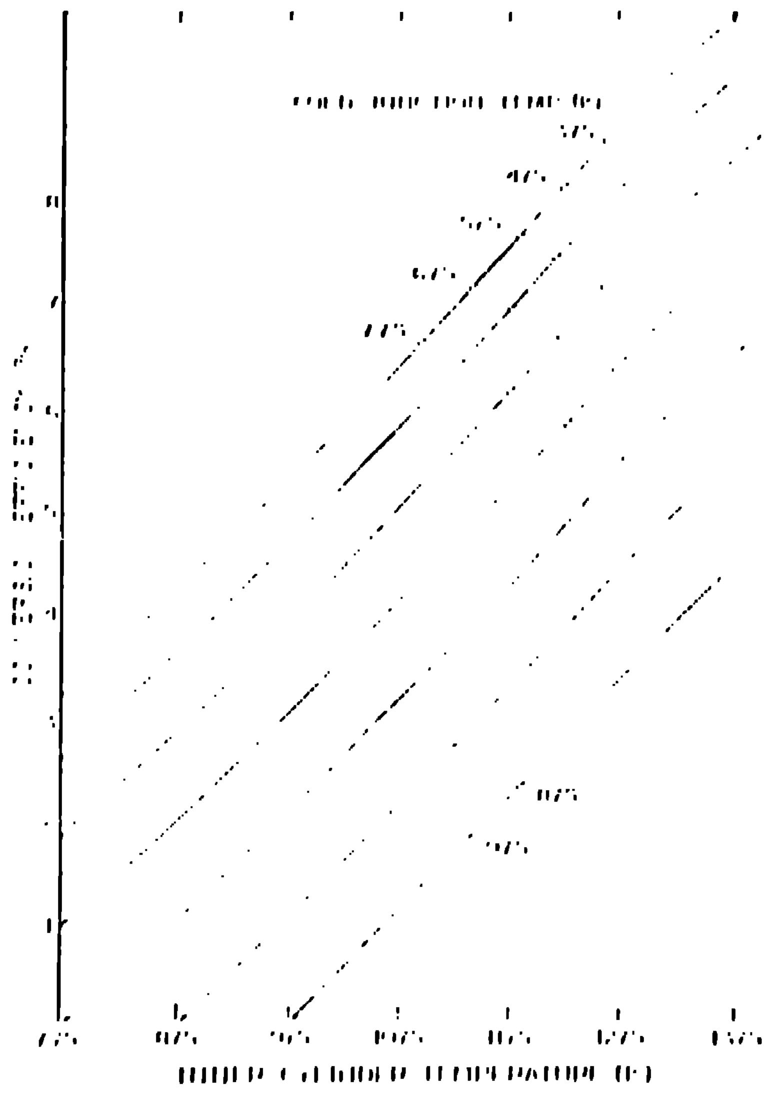
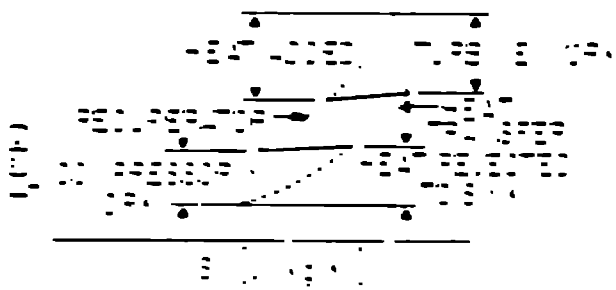
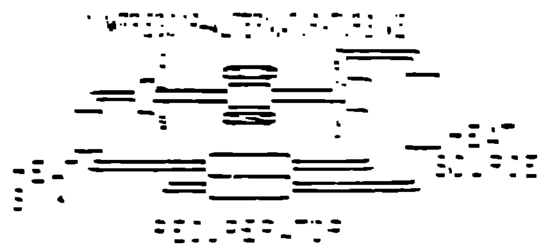
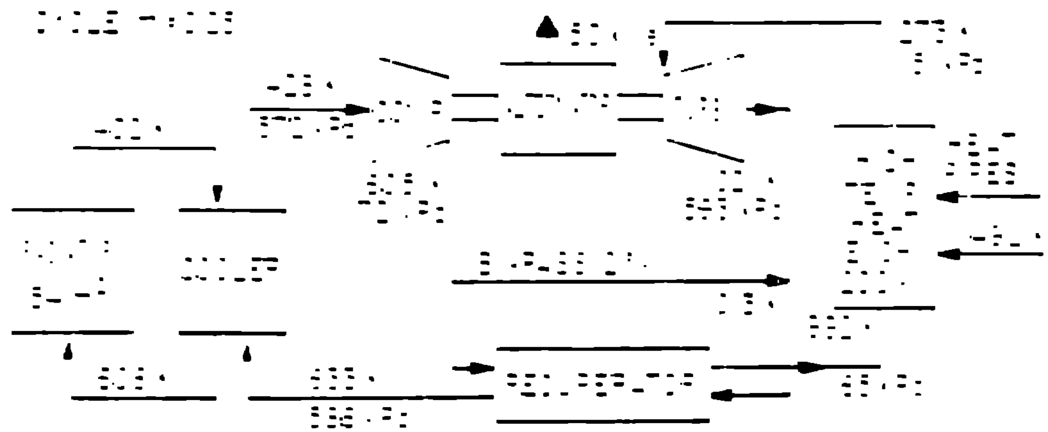
REFLECTOR

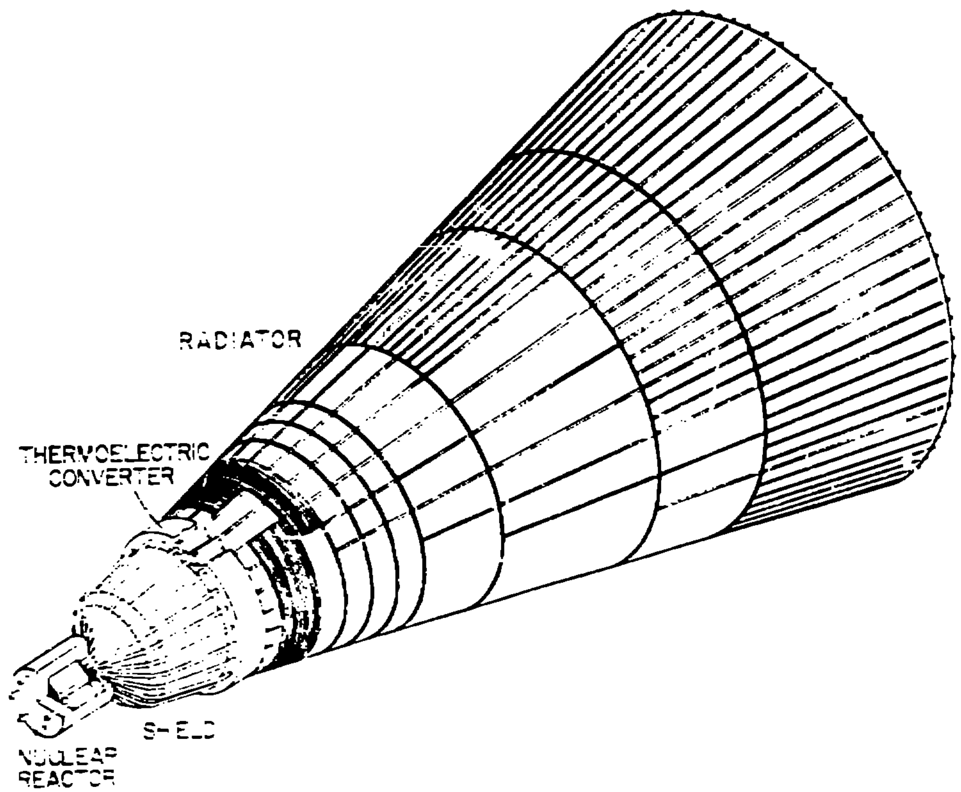


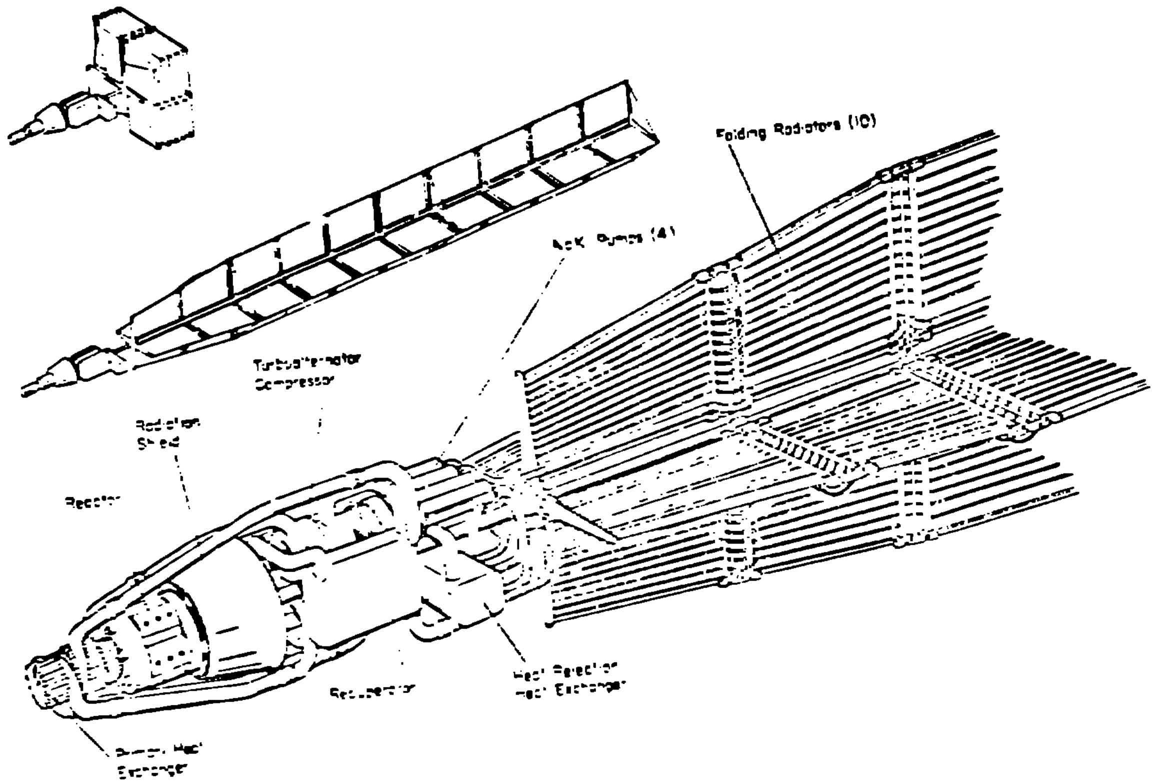









RADIATOR
THERMOELECTRIC
CONVERTER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Shield
Reactor
Recuperator
Heat Rejection
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