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TITLE: SPACE REACTORS - PAST, PRESENT, AND FUTURE

AUTHOR(S): David Buden, DAD/NP
Joseph Angelo, Florida Institute of Technology

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SPACE REACTORS - PAST, PRESENT, AND FUTURE

David Buden and Joseph A. Angelo

Los Alamos National Laboratory
Los Alamos, NM 87545

Florida Institute of Technology
Melbourne, FL 32901

ABSTRACT

The successful test flights of the Space Shuttle mark the start of a new era--an era of routine manned access into cislunar space. Human technical development at the start of the next Millenium will be highlighted by the creation of Man's extraterrestrial civilization with off-planet expansion of the human resource base. In the 1990s and beyond, advanced-design nuclear reactors could represent the prime source of both space power and propulsion. Many sophisticated military and civilian space missions of the future will require first kilowatt and then megawatt levels of power.

This paper reviews key technology developments that accompanied past US space nuclear power development efforts, describes on-going programs, and then explores reactor technologies that will satisfy megawatt power level needs and beyond.

PAST POWER PLANT DEVELOPMENTS

The interest in space reactors from 1955-1973 was primarily for propulsion of manned Mars missions and to satisfy electric generation needs anticipated for communication satellites, manned space stations and lunar bases.

To support this interest, the US engaged in an extensive space reactors development program. Table I summarizes programs that included materials and component development. High power, hundreds-to-thousands megawatt reactors, were being developed for propulsion while technology for from 0.5 W to hundreds of kilowatts was being developed to meet electric power needs. These reactors incorporated a variety of coolants, including liquid-metal cooled reactors using NaK in SNAP-2, 10A and 8, advanced hydride reactor and in-core thermionics, lithium coolant in SNAP-50 and the advanced metal-cooled reactors, gas-cooled using hydrogen in ROVER and neon in 710, heat-pipe reactors cooled in NEP and SPAR/SP-100, fluidized bed reactors using hydrogen, and gaseous core reactors also using hydrogen.

Reactor Core Development

The most extensive fuel development efforts took place during the years 1965-1973 (Fig. 1). The two areas receiving greatest focus were uranium-zirconium hydride fuel for the Space Nuclear Auxiliary Power (SNAP) program and coated uranium carbide fuel elements for the nuclear rocket (Rover) program. The former qualified fuel elements for 10 000 h at a 975-K operating temperature using the liquid metal NaK as the core coolant. The latter operated for 2 h with hydrogen gas coolant at 2450 K. Both were demonstrated in full reactor core tests.

Coatings for fuel elements act both as a chemical barrier between the fuel and the coolant and as a physical erosion barrier. A good coating material, besides being chemically compatible with the fuel and coolant, should have good high-temperature stability and match the thermal coefficient of fuel expansion. (See Table II).

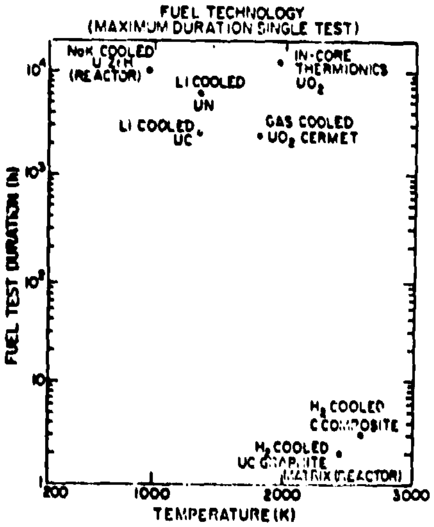

Fig. 1. Fuel Technology (Maximum Duration Single Test)

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TABLE I

PRINCIPAL US SPACE NUCLEAR REACTOR PROGRAMS

Power Plant	Purpose	Power Level	Operating Temp (K)	Period	Type Reactor	Fuel	Converter	Development Level
Rover	Propulsion	365-5000 MW_t	2450	1955-1973	Epithermal	UC		Twenty reactors tested. Demonstrated all components of flight engine >2 hr. Ready for flight engine development.
Fluidized Bed Reactor	Propulsion	1000 MW_t	3000	1958-1973	Thermal	UC-ZrC		Cold flow, bed dynamics experiments successful.
Gaseous Core Reactors	Propulsion and Electricity	4600 MW_t	10,000 1500	1959-1978	Fast	Uranium plasma, UF_6	Brayton	Successful critical assembly of UF_6.
SNAP-2	Electricity	3 kW_e	920	1957-1963	Thermal	Uranium zirconium hydride	Mercury Rankine	Development level. Tested two reactors with longest test reactor operated 10,500 hrs. Precursor for SNAP-8 and -10A.
SNAP-10A	Electricity	0.5 kW_e	810	1960-1966	Thermal	Uranium zirconium hydride	Thermoelectric	Flight tested reactor 43 days. Tested reactor with thermoelectrics in 417-day ground test.
SNAP-8	Electricity	30-60 kW_e	975	1960-1970	Thermal	Uranium zirconium hydride	Mercury Rankine	Tested two reactors. Demonstrated 1-yr operation. Nonnuclear components operated 10,000 hr and breadboard 8700 hr.
Advanced Hydride Reactors	Electricity	5 kW_e	920	1970-1973	Thermal	Uranium zirconium hydride	Thermoelectric and Brayton	PbTe thermoelectrics tested to 42,000 hrs.
SNAP-50	Electricity	300-1200 kW_e	1365	1962-1965	Fast	UN, UC	Potassium Rankine	Fuels tested to 6000 hr.
Advanced Metal-Cooled Reactor	Electricity	300 kW_e	1480	1965-1973	Fast	Uranium nitride	Brayton and potassium Rankine	Nonnuclear potassium Rankine cycle components demonstrated to 10,000 hr. Ready for breadboard loop.
710 Gas Reactor	Electricity and propulsion	200 kW_e	1445	1962-1968	Fast	UO_2	Brayton	Fuel element tested to 7000 hr.
In-Core Thermionic Reactor	Electricity	5-250 kW_e	2000	1959-1973	Fast or thermal driver	UO_2 UC-ZrC	In-core thermionics	Integral fuel element, thermionic diode demonstrated >1 yr operation.

TABLE II

FUEL ELEMENT COATINGS

Fuel	Reactor	Coolant	Coating	Maximum Fuel Temperature (K)
U-ZrH	SNAP	NaK	Hastelloy N	1035
UC_2	Rover	H_2	NbC, ZrC	2700
UO_2	SPAR/SP-100	Li, Na	Mo-13% Re*	2200
UO_2	710	Neon	T-111 W-30-Re-30-Mo	1800
UN	SNAP-50	Li	Cb-1 Zr-0.090C	1350-1500
UO_2, UC	In-core thermionics		W	2200

*Heat pipe wall separates fuel from heat transport fluid.

Core components such as the core support, periphery, and enclosures are difficult to generalize, being more or less unique to a particular design. Gas-cooled reactors usually operate at relatively high pressures and require more massive support systems. Liquid-metal cooled reactors usually operate at low pressure, but corrosion and erosion are more of a concern. Heat-pipe-cooled reactors require a fluid containment structure within each heat pipe and avoid the thermal-hydraulic interaction problems.

Reflector and Control Assemblies Development

Beryllium has been selected as the reflector material for a number of space reactors. Various arrangements of moveable elements have been used in the reflector for reactivity control. These vary from sliding blocks, to rotatable half cylinders, to rotatable drums with poison segments. All of these use some form of actuator for movement of the reactivity control element and require bearings in the moveable member.

The longest operational times for beryllium reflectors were experienced in uranium-zirconium hydride fueled reactors. These reflectors were cooled by NaK liquid metal. The SNAP-8 Demonstration Reactor (S8DR) reached neutron dose of 1×10^{20} nvt and a gamma dose of 1×10^{11} rad. During steady-state operation, the reflector operated at around 600 K. The beryllium was anodized to provide oxidation protection and emittance enhancement. In a one-year vacuum test, the reflector drive operated satisfactorily with no signs of self-welding or sticking of any component. Bearings of a solid carbon-graphite ball operated successfully 7000 h in the S8DR reactor test. Four individual bearing sets completed 12 000 h of vacuum testing at 895 K and 1.3×10^{-3} Pa or lower and altogether accumulated in excess of 100 000 test hours.

Space qualified, long-life control actuators were most highly developed in the SNAP program. Successful operation of actuators were demonstrated in reactor systems (Donelan, 1973):

SNAP 10A Ground Test	2 Actuators	10 000 h
SNAP 10A Flight	2 Actuators	46 days
S8DR	6 Actuators	6 400 h

The SNAP-10A actuators were designed to provide 8.5 N-cm torque at 615 K; S8DR 26.1 N-cm of torque with a position of 0.41 deg at 810 K. In development testing, one of the S8DR units was tested for over 20 000 h without malfunction.

Shielding Technology

The longest-life demonstration of space shielding technology is associated with the SNAP program. Similar technology can be applied to any space reactor within the operational constraints of the materials. For SNAP-10A, five cold-pressed (LiH) shields were fabricated. One shield was used in the SNAP-10A flight and another in the FS-3 ground test. The latter successfully operated some 10 000 h as part of the reactor test assembly. Dimensional measurements of the LiH block revealed that it had not changed in size within the accuracy of the measurement ($\pm 1.2\%$). Also, the lattice parameter and density of LiH samples removed from the block were found to agree with the unirradiated LiH values. Activation analysis of the stainless steel vessel indicated fast neutron fluence of 2.6×10^{18} nvt for the top of the vessel and 8.9×10^{15} nvt at the bottom of the shield. Thermal neutron fluences of 4.9×10^{17} and 3.8×10^{16} were measured for the top and bottom of the shield, respectively. It was concluded that a cold-pressed LiH block withstood the rigors of the reactor experiment without noticeable damage, but improved support was needed to avoid damage on launch.

Evaluation of the methods for fabricating LiH shield shapes led to a melting and casting process instead of the cold-pressing and machining method. This was a faster, cheaper, and more versatile process with more structurally reliable shields because the LiH could be solidified in the shield vessel intimately surrounding all internal structural members, penetrations, etc. Also, in SNAP-8, the substitution of lithium enriched with the ^{7}Li isotope reduced the nuclear heating in the shield. In the 7000 h SNAP-8 test, the LiH shield was exposed to a maximum fluency of approximately 10^{19} nvt and to temperatures ranging from 365 to 500 K. Post-test evaluation showed the shield vessel to be clean and the emissivity coating to be intact, except for some spalling where the top head and the side wall met. The top of the vessel was estimated to have bulged about 1.6 cm, but no bulging was noted on the side walls. Examination of the LiH under the wafer showed the material to be hard and crystalline as typical of cast LiH.

Electrical Conversion Technology Status

Thermoelectric converters are the most extensively demonstrated electrical conversion device having successfully operated certain units in space for over 10 years, such as on the Pioneer missions. All US space nuclear power systems have used thermoelectric converters including radioisotopes and the one-flight reactor. Silicon germanium is now the mainstay of operational systems, having successfully demonstrated in space missions 50 000 hr. These converters use silicon germanium with a nitride sublimation coating and operate between 1275 K hot-junction temperature and 573 K cold-junction. The efficiency of these devices is 6.7%. Improved technology is proceeding with development work on silicon-germanium alloys to reduce its thermal conductivity and better sublimation coatings to permit operation at higher temperatures. The goal is to improve efficiency about 40%. Research into rare-earth sulfides and boron carbides is also underway with a goal to double the efficiency over plain silicon germanium.

Dynamic converters, using Brayton, Rankine, or Stirling cycles have also been considered for space reactor systems because of their higher efficiency. In the 1960s and 1970s, compact Brayton equipment was tested for some 38 000 h and Rankine equipment for almost 10 000 h.

Radiator Development Status

Flight experience with radiators has been at relatively low temperatures and power levels compared with what will be needed with many space reactor power plants. This experience has mostly been around 300 K. A plot of radiator development is shown in Fig. 2. Conventional radiators generally employ thin, solid fins as extended surfaces between fluid-carrying tubes. The fluid tubes must be protected against possible meteoroid damage. These systems tend to be heavy but have proven to be highly reliable and satisfactory for satellites flown to date. An isothermal fin can be used to improve performance in the form of a heat pipe but meteoroid protection limits the performance gain.

The most significant high-temperature hardware program was a 50 kWt radiator weighing 7.7 kg including a 2.0 kg section of pumped loop. The operating temperature was 1044 K. The radiator contained 100 stainless steel heat pipes using sodium as the working fluid. Heat-pipe radiator components were also under development for the SPAR and NEP programs. For SPAR, titanium heat pipes using potassium as the working fluid as long as 5.5-m were tested.

PRESENT PROGRAMS

A national program is going forward under an agreement between the DoD, Defense Advanced

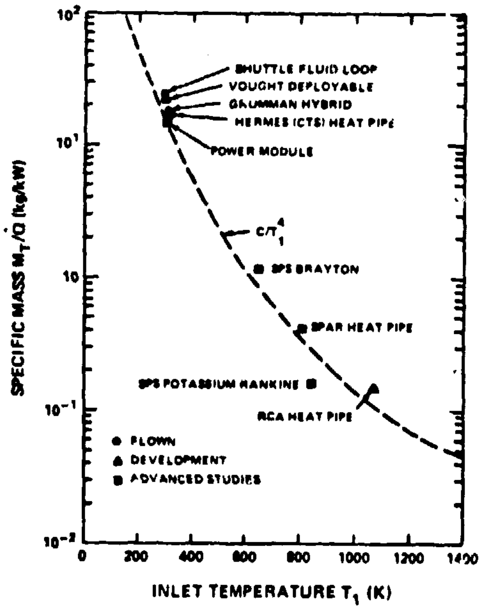

Fig. 2. Radiator Technology

Research Projects Agency; NASA, Office of Aeronautics and Space Technology; and DOE, the Office of Nuclear Energy to jointly develop technology necessary for space nuclear reactor power systems. The major emphasis is on 100-kWe technology, though multimegawatt technology also will be pursued if needs warrant it. Though many forms of reactors are being evaluated, the primary experimental work at this time is on the heat-pipe reactor concept. The SP-100 is being designed for 7-10 times the lifetime at one-third the weight of a SNAP-8 power plant and yet with an objective to have no single-failure points.

The SP-100 nuclear subsystem, shown in Fig. 3 consists of: 1) the nuclear reactor as the thermal power source, 2) core heat pipes to transport the thermal power from the nuclear reactor to the conversion/radiator syubsystem, 3) the radiation shield to attenuate nuclear radiation to the payload, and 4) the reactor controller to regulate the nuclear reactor.

The reactor, pictured in Fig. 4, 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 compressers 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 electromechanical 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 systems is by the direct thermoelectric conversion of heat to electricity (Fig. 5). 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 III provides characteristics of a 100-KWe power plant. The power plant weighs 2625 kg if improved silicon-germanium 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.

Another contemporary program involves the study of fluidized bed reactors. Two reactor concepts are being investigated--a Rotating Bed Reactor (RBR) and Fixed Bed Reactor (FBR).

The first of these reactors, the RBR, is an externally-moderate cavity reactor. The core is a rotating fluidized bed of UC/Zr-coated particles very similar to particles currently used in high-temperature, gas-cooled reactors (HTGR). Coolant gas enters the bed through a porous metal frit after cooling the reflector/moderator and the cavity exit nozzle. This configuration allows the heated coolant, which can be as hot as 3000 K, to come into contact with an absolute minimum amount of structural material.

The FBR (Fig. 6) is neutronicaly similar to the RBR. Fuel is held in place with an inner porous frit, rather than a rotationally induced gravity field. Maximum outlet temperature from this reactor is lower than with a RBR, on the order of 1500 K.

TABLE III

SP-100 PERFORMANCE AND MASS SUMMARY

	Late 1980's	Early 1990's
Output Power (kW_e)		
Range	10-100	10-100
Nominal	100	100
Reactor Thermal Power (kW_t)		
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

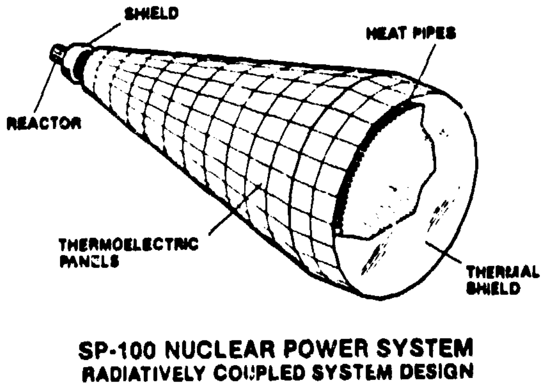

Fig. 3. SP-100 Nuclear Power System, Radiatively Coupled Design

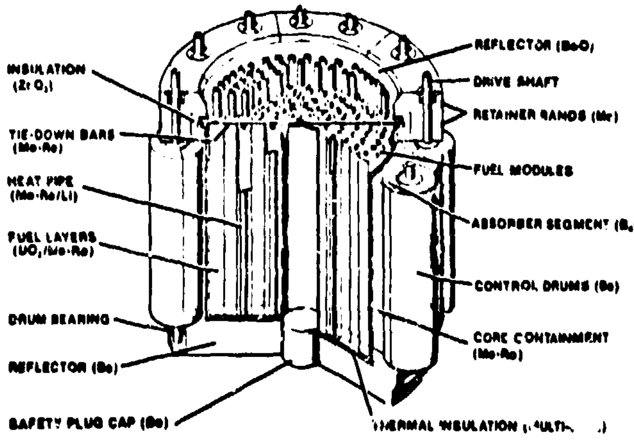

Fig. 4. Heat-Pipe Reactor Schematic

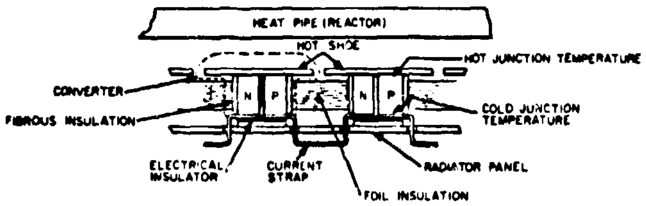

Fig. 5. SP-100 Thermoelectric Arrangement

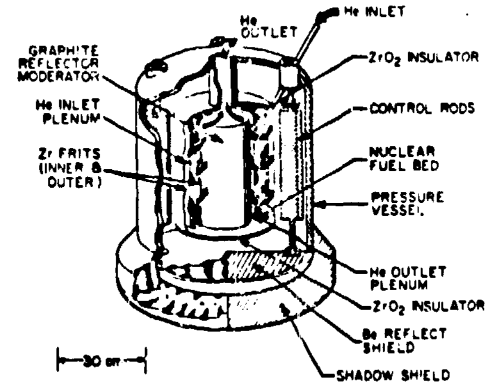

Fig. 6. Fluidized Bed Reactor

Both reactors are controlled via rotating drums in the outer reflector/moderator region. The reactors are thermalized and very sluggish in response to reactivity insertions. Because of the small size (~600 to 800 μm) of the fuel particles, the fuel is highly insensitive to thermal shock. It is possible, from the point of view of neutronics, to bring the reactor from 0.1% power to full power in a few seconds.

Recent experimental work has been performed on the resistance of packed particle beds, helium-cooled packed beds using electrical heating and helium-cooled rotating beds. These indicate stable operation up to 1675 K with fast ramps to power (2 to 3 sec to 1475 K) without fuel particle damage by thermal cycling.

THE FUTURE

Tens-to-Hundreds of Kilowatts

Advanced civilian and military missions will require tens-to-hundreds of kilowatts of power continuously for up to 10 years to satisfy requirements in communications, surveillance, deep-space exploration, and electrical propulsion. These missions are the focus of the SP-100 space nuclear reactor power system technology goals. An assessment is underway as to whether the heat-pipe reactor or some other concept should be the final selection for a ground engineering demonstration. Other possible configurations such as liquid-metal, gas-cooled, or thermionic reactors are under consideration

Low-Megawatt Power Plants

Possible future missions that could utilize one to several megawatts of power are mature space stations, orbital transfer vehicles, larger radars and surveillance satellites, and electronic jammers. These missions may require continuous power for maybe 10 years for materials processing on an advanced space station or periods of power for a few years for an electric propulsion orbital transfer vehicle. It is envisioned that the reactor technology developed for the tens to hundreds of kilowatts will be used in this regime. For instance, Fig. 7 shows the scaling of the heat-pipe reactor concept. In the megawatt range, a more efficient converter will be needed to replace the thermoelectrics in the baseline SP-100 design. Brayton, Rankine, and Stirling are logical choices because they operate at similar reactor exit temperatures. The Brayton cycle is limited by a tendency to have a low-heat rejection temperature, which results in a relatively large radiator. The Rankine cycle is not necessarily as efficient as a Brayton cycle but the heat-rejection temperature is higher, leading to lower overall power plant size and mass. Difficulties exist in demonstrating the jet condenser in a ground demonstration compared to zero gravity space environment. For the Stirling cycle, an improved version must be demonstrated for the power levels of interest.

Table IV provides estimated performance for a 1-MWe power plant. If the power plant is used not only to supply energy for the spacecraft but also as a power source for electric propulsion, payload from low-earth orbit to geosynchronize orbit is increased by a factor of four over a Centaur transfer stage.

TABLE IV

1 MWe POWER PLANT

	1 MWe
Power Level (MWt)	3
Efficiency (%)	33
Converter Inlet Temperature (K)	1500
Reject Heat Temperature (K)	1000
Radiator Area (m^2)	42
Power Plant Deployed Length (m)	7
MASS (kg)	
Reactor	570
Primary Loop	300
Shield	880[1]
Converter (Stirling)	1500
Radiator	345[2]
Structure (10%)	360
Total	3955

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[1] Assumes 15° half-angle, payload 7-year dose levels 10^{12} nvt and 10^6 rad, 25-m separation from core.

[2] Stainless steel based on RCA heat pipe design

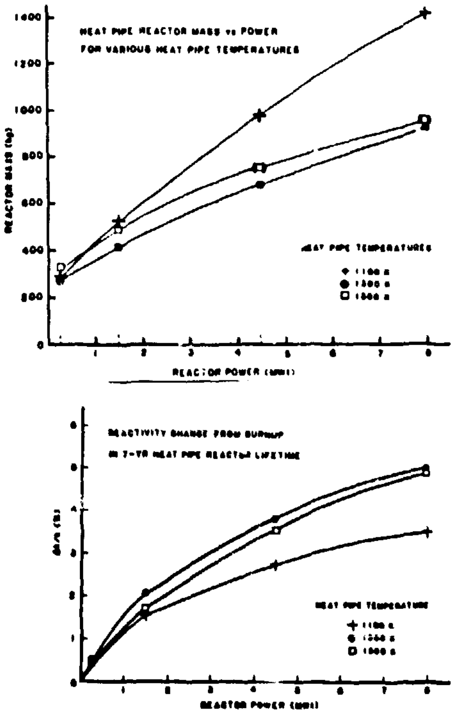


Fig. 7. Heat-Pipe Reactor Scaling

Multimegawatt Burst Power Plants

A number of missions that might use large quantities of power for short durations of time have been identified, such as weather modification and directed energy weapons. Power levels in the hundred megawatt or higher range have been mentioned. In addition, these satellites probably will need other power ranges--a power level in the low megawatts for maneuvering and orbital transfer and in the tens to hundred kilowatts for station keeping, sensors, etc. Whether all power ranges should be met by a single power plant still needs further studies, especially, if the highest range is for limited time periods. Power systems can be configured for the highest power level using chemical or nuclear open-loop systems. However, when one examines the use of expandables, spacecraft stability, long-term operations, etc., then a closed-loop system may be found to be desirable. For an open-loop system, the solid core nuclear rocket (ROVER) has already demonstrated 2 h operation at temperatures 2450 K and is ready for flight development. Also, the fluidized bed reactors are being investigated for these missions. A closed-loop system, especially at the higher power levels, will require some significant improvements in technology for practical-size power plants. The major improvements will be for converters and heat rejection. For heat rejection, at least an order of magnitude improvement using a system that does not require armoring will be necessary for practical closed-loop multimegawatt power plants. The best studied of these to date is the liquid droplet radiator.

Micron-size dust particles or liquid droplets are heated in a direct contact heat exchanger. The particles are then ejected from a "pitcher" and collected in a "catcher." The distance between the pitcher and catcher is proportional to the heat rejected by radiation. The technique of generating droplets has been demonstrated with the development of high-speed printers in the computing industry. Because of the zero-g environment, the collector must employ a collection scheme such as a spinning drum with a pump to recirculate the radiator working fluid. The droplets have a relatively low emissivity. Typical specific mass is 0.02 kg/kW--almost a decade better than a solid material radiator. Table V shows that at 100-MWe, the power plant mass is reduced to less than half with a liquid droplet radiator compared to conventional technology.

TABLE V

MULTIMEGAWATT POWER PLANT

	20 MWe	100 MWe
Power Level (MWt)	61	303
Efficiency (%)	33	33
Converter Inlet Temperature (K)	1500	1500
Reject Heat Temperature (K)	1000	1000
Radiator Area (m^2)	850-3620[1]	4210-17000[1]
Power Plant Deployed Length (m)	26-55	60-123
MASS (kg)		
Reactor	2200	2500
Primary Loop	500	1000
Shield	3200-2480[2]	3360-2760[2]
Converter (Stirling)	5000-2200	11 000
Radiator	6150-700	30450-3450
Structure (10%)	1705-810	4830-2070
Total	18755-8890	53140-22780

[1] Left hand number is conventional radiator (emissivity 0.85); right hand number is liquid droplet radiator (emissivity 0.2)

[2] Shield half angle 30°, payload 7 year dose levels 10^{12} nvt and 10^6 rad, 10-m beyond radiator

Multimegawatt Long-Duration Power

Long-duration power in years in the multimegawatt levels will be needed for lunar settlements. This introduces a new factor because the moon can be used as a source of shielding material and possibly a place to fabricate the heat-rejection system. The reactor would probably need to be a refuelable system, which would favor a fluidized core or gaseous core configuration. We would like to introduce to you a new concept, pellet reactor, which could also be a candidate. It has the advantages of being more compact than the other concepts and could be a desirable approach for all the high-power missions. In this concept, the fuel is envisioned to be in the form of pellets.

The fuel pellets, which are envisioned to be about 0.5-2 cm in diameter, would be confined in a cylindrical liner with end plates that contain holes to allow the coolant to circulate through the core. The pellets would probably be circular in shape with 93% ^{235}U enriched uranium in the form of an oxide, carbide or nitride encapsulated to minimize erosion, corrosion, and to avoid materials interaction problems. Gaseous fission products could probably be allowed to circulate in the primary loop as long as plate out in the primary to secondary loop heat exchanger is not a problem. Surrounding the core is a reflector layer with control elements. The reflector can be cooled by the reactor inlet coolant or radiation to space. The coolant flow paths will determine the arrangement of the thermal barrier between the core and reflector and how the pressure or confinement vessel will be cooled.

Typical materials might be UC coated with 1-2 mils of pyrographite for helium-cooled cores or UC_2 coated with Mo or W for Li-cooled cores for fuel, a refractory metal for the cylindrical core confinement or core periphery components, Be or BeO for the reflector, and B_4C for the control reactivity neutron absorber. The pressure vessel would be cooled or isolated from the high-temperature core region, probably allowing the use of an aluminum or steel alloy.

Depending on the particular lifetime requirements and the method selected to meet certain safety standards, the pellets can either remain relatively fixed in the core or slowly removed. With removal of the pellets, new pellets could be used to provide a long lifetime system with low built-in excess reactor reactivity, or the used pellets could be reinserted into the core in order to provide relatively uniform burnup. In the weightlessness of space, the forces of the flowing coolant can be used to move the pellets forward.

Figure 8 shows schematics for various possible configurations of pellet reactor concepts. Figure 8-A shows a noncirculating fuel configuration. The pellets are located inside a pressure containment vessel that is cooled by the inlet fluid. A baffle arrangement is used to distribute the flow before entering the core through the end plate. Flow distribution can be controlled by the end-plate hole arrangement. The coolant is then heated by the fuel pellets. The fluid exits through the top end plate. The reflector is shown located outside the pressure vessel to reduce the pressure vessel size and weight. It is cooled by conduction of heat to the outer surface and radiation of the heat to space. The control elements are located within the reflector.

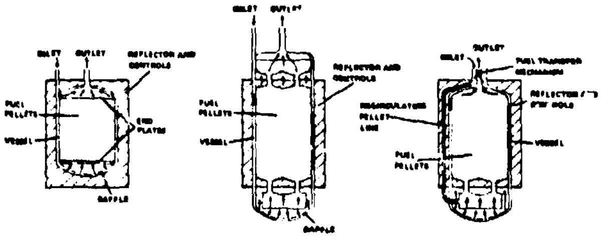
Figure 8-B is a schematic of a once-through-then-out pellet fuel configuration. Extra storage volumes are located at the top and bottom of the reactor. The fuel would be slowly moved through the reactor by hydraulic forces. New fuel is located at the bottom of the reactor and used at the top. Longer lifetimes are expected from such a configuration over a noncirculating fuel, plus safety advantages from not having as much excess reactivity built into the reactor.

Figure 8-C incorporates a circulating fuel to provide for uniform burnup. It can also include a reserve of fuel pellets for longer lifetimes. The pellets are transferred from the relatively lower pressure outlet stream to the higher pressure inlet stream without significant bypassing coolant. For very high powers and long lifetimes, this type of concept has many advantages. For a reactor that runs one year at 40 MWt (10 MWe), approximately 15 kg of ^{235}U will be consumed. At 5% burnup, this implies a need for 290 kg of fuel. The ability to add new fuel solves both criticality, safety, and overall mass limitation problems.

Water immersion criticality and criticality from impact during a launch abort might be handled by having the fuel stored outside the core during launch. It could then be stored in an arrangement that precluded any chance of accidental criticality.

SUMMARY

As man permanently occupies space, he must have abundant supplies of power. Nuclear reactors will become a prime energy source for advanced space stations, lunar bases, sophisticated orbital transfer vehicles, and a host of other exciting possibilities.



(A) NON-CIRCULATING PELLET REACTOR

(B) ONCE THROUGH THEN OUT

(C) CIRCULATING FUEL

Fig. 8. Pellet Reactor Configurations