Safety Considerations in a Nuclear Electric Propulsion Spacecraft

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Some nuclear safety aspects of a 3.2-MWt heat-pipe-cooled fast reactor with out-of-core thermionic converters are discussed. Safety-related characteristics of the design, including a thin layer of B_4C surrounding the core, the use of heat pipes and BeO reflector assembly, the elimination of fuel element bowing, etc., are highlighted. Potential supercriticality hazards and countermeasures are considered. Impacts of some safety guidelines of the space transportation system are also discussed briefly, since the currently developing space shuttle would be used as the primary launch vehicle for the nuclear electric propulsion spacecraft.

Introduction

THE power system of the nuclear electric propulsion (NEP) spacecraft being studied is composed of a fast reactor, reactor controls, multiple heat pipes, a thermionic converter matrix, and an associated heat-rejection subsystem. Safety to the general public and operating personnel is an important consideration in the design of the nuclear reactor. Failure modes having a potential for releasing dangerous levels of radiation must be identified and analyzed. Appropriate safety measures must be incorporated in the system design and in all operating procedures to minimize nuclear accidents. Precautions must be taken in the manufacturing process, assembly, transportation, launch, orbit injection, system start-up, and in the final disposal of the spent reactor. However, this must not impose excessive penalties on system weight, on mission reliability, and on component development costs.

The NEP spacecraft is to be launched from the space shuttle as a single payload. Space transportation system (STS) safety guidelines[1] require that the payload design should ensure safe payload operation with minimum reliance on the STS crew. The STS provides only a limited capability for displaying and commanding of the payload parameters. Therefore, safety provisions must be carefully incorporated in the design of the propulsion system.

The heat-pipe nuclear reactor with out-of-core thermionic converters is designed to be launched cold and for remote start-up in a stable orbit after successful launch and orbit injection by the space shuttle. No significant amount of radioactive material is present in the core until the reactor has been started and brought up to power, at several hundred kilometers above the surface of the Earth. After launch, the incremental background radioactive level on the ground due to neutron and gamma emission from the operating reactor is negligibly small, owing to large separation distance and atmospheric attenuation. Hence the operation of the nuclear electric propulsion system in Earth orbit would not cause any discernible nuclear hazard to the population.

So long as the electric propulsion system is operating properly, re-entry could not credibly occur. However, if propulsion failure occurs, further action is required unless the spacecraft is in a "safe" orbit (usually specified as an altitude $\geq 30,000$ km). One action possibly required is to separate the nuclear power source from the spacecraft. This will remove high-drag components from the reactor and greatly extend the orbital lifetime of the radioactive material. Removal and disposal from unsafe orbit would subsequently be accomplished. Also, possible occurrence of some accidents during ground handling of the reactor, shuttle launch, orbit injection, disposal of the spent reactor (if used for geocentric missions), etc., which could constitute nuclear hazards, must be considered carefully.

At this stage of NEP power system development, one major concern of nuclear safety is to ensure that the reactor assembly can be kept subcritical under all circumstances, including credible accidents, until the orbit injection is successfully achieved with the space shuttle. Upon NEP separation from the shuttle, the reactor is activated and brought up to power. Stable reactor start-up and operation are prerequisite for both mission success and reduction of nuclear hazards. An essential requirement of a stable reactor is to have an adequate magnitude of negative reactivity feedback during power transients. In this paper, some of the features of an inherently safe design approach are identified. Mechanisms that could lead to unfavorable reactivity variations are studied. Impacts of nuclear safety considerations and a few STS safety guidelines on the conceptual design of the space reactor are also discussed.

NEP Spacecraft Power System

A sketch of the NEP spacecraft is shown in Fig. 1. In the power system, the heat pipes transport thermal power from the reactor to the out-of-core thermionic converter array, where dc power is generated. The dc power is transmitted via low-voltage bus bars to a power processor, where it is conditioned to suit thruster and other spacecraft housekeeping functions. Liquid-metal coolant dumps the waste heat from the thermionic converters to the primary heat-pipe radiator. A shadow shield for neutron and gamma radiation is located between the reactor and the spacecraft electronics. More detailed descriptions of the power system have been published elsewhere.[2,3]

The basic concept of the out-of-core thermionic reactor, with one section removed, is shown in Fig. 2. The fast spectrum reactor is designed to provide 3.2 MW thermal power to the thermionic converter matrix outside of the core. Mo-40v/oUO_2 nuclear fuel is bonded to the evaporation

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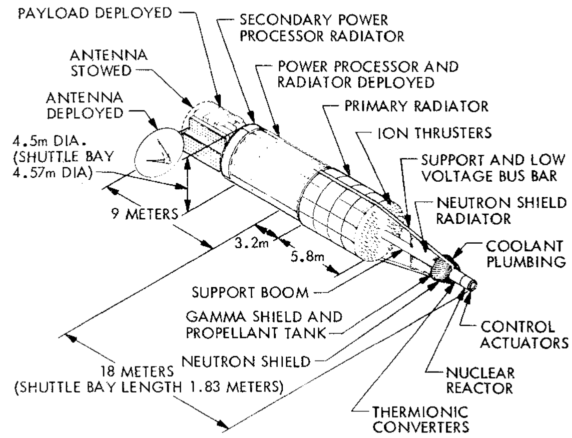

Fig. 1 NEP spacecraft configuration.

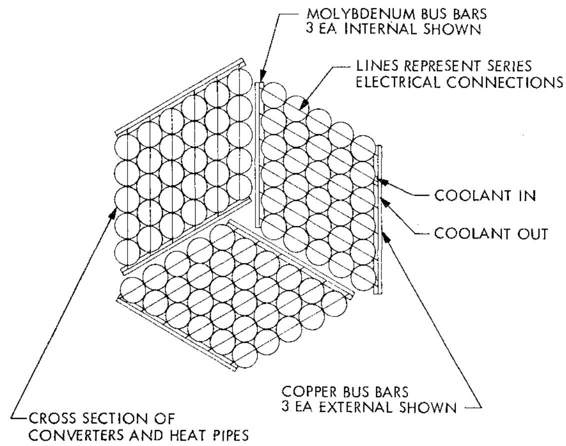

Fig. 3 Power system cross section.

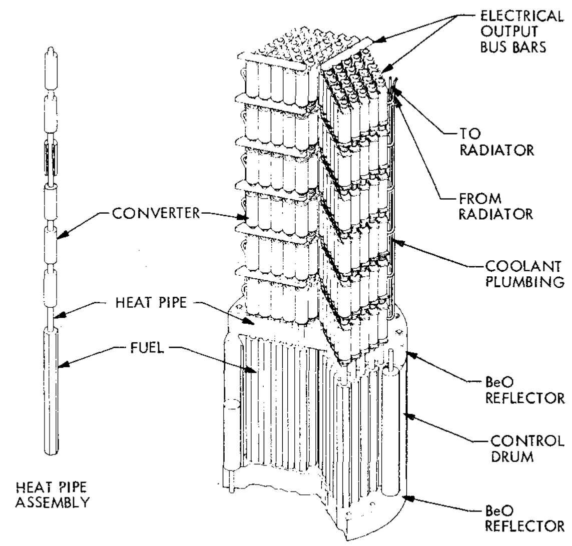

Fig. 2 Out-of-core thermionic reactor concept.

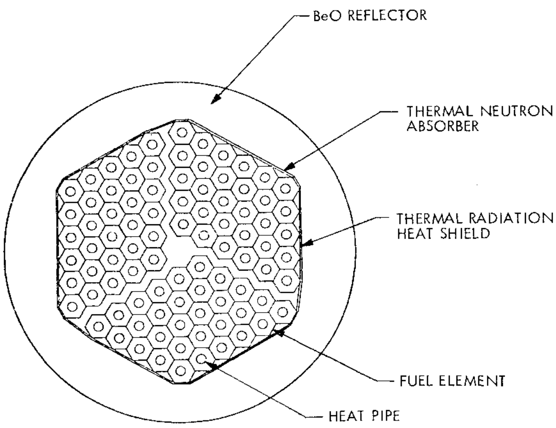

Fig. 4 Reactor cross section.

section of the molybdenum heat pipe, whereas six thermionic converters (approximately 1 kWe each) are attached to the condenser section. A total of 90 heat pipes together with 540 thermionic converters comprise the power system, based on considerations such as the proper length-to-diameter ratio of the whole assembly, reasonable I^2R losses in converter electrodes, etc.[2] Nominal thrust power requirement for the spacecraft is 400 kWe. Under constraints of the current space shuttle payload capacity, the spacecraft with this power level appears to be optimal with respect to its overall weight and size.

The 15% conversion efficiency of the power system will require that 2.7 MWt of waste heat be radiated to space. Approximately 500 kg of NaK-78 is required for the heat removal from the thermionic collectors. The outside diameters of five converters are enclosed by a common cooling sheath. A total of 30 converters are connected as one coolant loop, and there are 18 coolant loops. Electromagnetic pumps are used to circulate NaK-78 in the coolant ducts. Several hundred stainless-steel heat pipes with beryllium micrometeoroid shielding are assembled to form a 4.5-m-o.d. cylindrical primary radiator. No rotating machinery is involved in the power operation of the spacecraft.

The individual thermionic converter is a high-current, low-voltage (less than 1 V) device. Each section of the assembly has six rows of five heat pipes with converters stacked six layers high. Each layer of the section consists of 30 thermionic converters that are series/parallel connected (each row of five in series, and the six rows in parallel). The entire assembly contains 18 modules of such series/parallel connection arrangement. The power system cross section is shown in Fig. 3. To increase the voltage to a level suitable for input to the power processor, all 18 modules are connected in series. Redundancy is achieved by the many parallel paths within each of the 18 one-third-layer modules. These paths provide adequate protection against an open-circuit failure mode, since nuclear fuel fission products do not contaminate readily, and swelling cannot damage the converter electrodes.

Room needed for converter electrical connections necessitates a void (or equivalently, a blank fuel element) in the center of the core and three 2-cm wide gaps between each core section, as shown in Fig. 4. These void and gaps in the core are needed to accommodate the electrical bus bars and could have a significant bearing on nuclear safety. Therefore, bending of the heat pipes is currently being examined as an avenue for eliminating these gaps.

The reactor is designed to provide 75,000 hours operation at full-power, which would result in a reactivity loss of 2.3% due to fuel burnup. The Mo-40v/oUO_2 fuel volume swelling accompanying this burnup is only about 1% or an equivalent reactivity loss of 0.55%. However, the porosity of the fuel, occupying 6% of the core volume, will probably absorb the irradiation swelling completely, and no reactivity loss would actually result. Thermal expansion of the core represents the only remaining major reactivity loss mechanism. The reactivity (ΔK) requirement of the reactor is listed in Table 1.

Included in the contingency are allowances for uncertainties in nuclear data, mathematical modeling, and numerical methods; for losses due to fission products, power defects, etc.; and for control drum redundancy and reactor safe shutdown margin. The control of the reactor reactivity is done by means of 18 BeO-B_4C control drums. Contribution to the

Table 1 Reactivity requirement

Item	ΔK, %
Fuel burnup	2.3
Thermal expansion	1.1
Contingency	1.6
Total	5.0

effective multiplication factor (K_{eff}) of the cold, clean reactor can be distributed as in Table 2.

Reflector worth calculations indicate: 1) the control drums with a 1-cm layer of B_4C moved from the inner region of the reflector to the outer region would be sufficient to yield the required reactivity swing; and 2) if one increases the thickness of the B_4C layer from 1 cm to 3 cm, ΔK would increase to 8.5%. Some nuclear safety considerations, to be discussed later, may require a reactivity swing of more than 5%. A possible alteration of K_{eff} distribution to account for the higher reactivity swing requirement is shown in Table 2 for later reference.

Safety-Related Features of the Reactor Design

A cross-sectional view showing a third of the reactor is presented in Fig. 5. The hexagonal core is surrounded by a cylindrical reflector and control-drum structure. As discussed previously, a central blank fuel element and gaps between the three sections of the core are needed to accommodate electrical bus bars in the converter matrix. Suitable material will be used to fill these gaps solidly.

Bowing of fuel rods, which could introduce an appreciable, prompt, positive reactivity effect, has been a great concern in previous fast reactor designs.[4,5] A positive power coefficient of reactivity could have an autocatalytic effect and lead to reactor power excursion. In the present design, the use of heat-pipe fuel elements eliminates the need for providing clearances between fuel rods. The core is power-flattened radially (by varying the fuel loading) and thermally shielded since, by nature of the operation, the heat pipes all operate at essentially the same temperature. It is unlikely that a large radial temperature gradient can develop across the core. Segmented molybdenum load rings, surrounding the core at three elevation positions, allow thermal expansion of the core. Spring-loaded plungers between the load rings and the support structure located outside the reflector hold the core together radially. Furthermore, the fuel elements are free to expand in the axial direction. Thus, bowing of the fuel elements, if it occurs at all, cannot possibly yield a more compact core configuration. This effect is one of the nuclear safety features of the heat-pipe reactor design.

The BeO reflector assembly, including 18 reactor control drums, is separated from the core by an annular gap. Each control drum is made of BeO loaded with a fractional layer of B_4C. Thus, control of the reactor is achieved by rotating the drums, which changes the extent of neutron leakage and reflection across the core boundary.

A multifoil thermal insulation and a thin layer of B_4C surround the core. The main function of the B_4C layer is to reduce power peaking at the core periphery by keeping reflected low-energy neutrons out of the core. This thin layer of B_4C, if intact, will guarantee the subcriticality of the core, regardless of the survival of the reflector, if the reactor is accidentally immersed in water. This is because, for this fast reactor, BeO proves to be a better reflector than water. However, the multiplication factor does increase slightly if the core is immersed in water with the protective B_4C layer removed. Unlike the SNAP 8 or 10 reactor, no special void-poison sleeve device is required for safe reactor transportation.[6]

Table 2 K_{eff} distribution of the reactor

Component	Percent: Current design	Percent: Possible alteration
Bare core	81	83
Reflector assembly (including all control drums at "in" position)[a]	19	13.5
Control drums (from all "in" to all "out")	5	8.5

[a] Here "in" or "out" is referring to the B_4C position in the drums.

The use of heat pipes for heat removal from the core requires a very small amount of coolant. About 2.5 kg of lithium is required for the 90 heat pipes. Operation of a heat pipe is characterized by latent heat transfer, small temperature drop, and self-regulation. Reactivity variations that are coupled with power transients are inherently smaller than those of conventional liquid-metal-cooled reactors. Since Li^6 isotope, a strong neutron absorber, is to be excluded, the power coefficient of reactivity of the heat pipes would not be positive. A negative reactivity coefficient is expected, since, in addition to thermal expansion of the heat pipes, fewer Li^7 molecules, a relatively strong moderator, will be available in the evaporator section to slow down neutrons as the heat flux increases. Because there is so little lithium in the core, the reactivity worth of all lithium is only a small fraction of 1%. Also the heat pipes provide highly redundant, closed-loop core cooling channels. Risks of loss-of-coolant, cold coolant addition, plugging of coolant channels, etc., are either greatly reduced or completely eliminated by this modular approach.

Smooth reactor start-up and stable power operation, which are essential to mission success and minimized nuclear hazards, require an inherent mechanism for the rapid insertion of negative reactivity. This is particularly important in a fast reactor because of its much shorter neutron lifetime. The large negative coefficient with fuel thermal expansion (of the order of 10^{-5}/K) plays the major role of guaranteeing the rapid response needed for safety of the reactor. Doppler broadening of neutron capture resonances for all material present in the core will decrease the reactivity and provide an additional negative prompt power coefficient. However, the effect is small, since the reactor is small and has a hard spectrum. On the other hand, Doppler broadening of fission

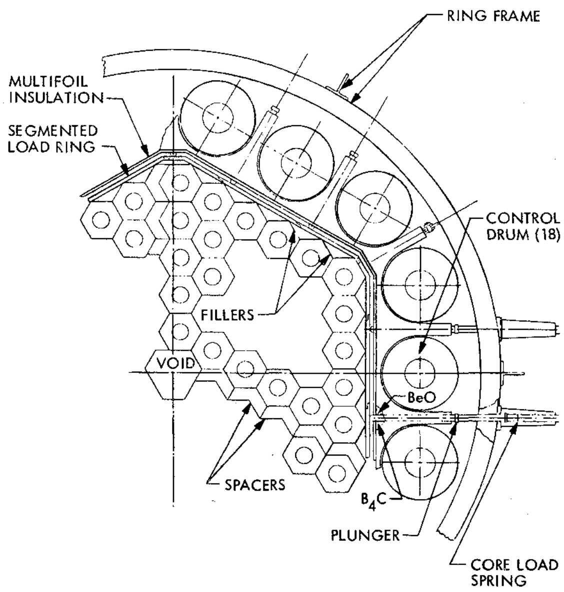

Fig. 5 Heat-pipe out-of-core thermionic reactor.

resonances of the fuel will increase the reactivity. It is known that, in a fast reactor where highly enriched U^{235} is present, the net Doppler effect of the fuel will give a positive power coefficient.[7] It is also known that the magnitude of the coefficient is proportional to $T^{-2/3}$.[8] The operating fuel temperature of the reactor is fairly high (1650 to 2000 K). A rough estimate indicates that the magnitude of the temperature coefficient due to Doppler effect of the fuel, albeit positive, is less than 1% of that due to thermal expansion. The absence of any appreciably positive reactivity coefficient and the presence of a reliable, negative prompt thermal expansion effect of sufficient magnitude all help to demonstrate the inherent safety of the reactor design.

Finally, the propellant and its feeding system for the NEP spacecraft is decoupled from the reactor cooling subsystem. Propellant, such as mecury, will be used for electric propulsion. It is completely confined in the thrust system. Hence, the hazard of propellant leakage to the core and induced criticality, which existed for the NERVA reactor, is eliminated completely.

Reactor Supercriticality Hazards and Countermeasures

A compact space nuclear reactor can be rendered supercritical under certain accidental conditions through the following four major mechanisms: 1) roll-out of control drums, 2) core compaction, 3) neutron reflection, and 4) neutron moderation. In this section, we shall discuss these four mechanisms and possible countermeasures to minimize the risk.

Roll-Out of Control Drums

The 18 boron-loaded beryllium oxide control drums can provide a reactivity swing ΔK from 5 to 8.5% (corresponding to the B_4C layer thickness of 1 to 3 cm). Inadvertant roll-out of the control drums can be prevented by mechanical locking devices together with a redundant lockout circuit. Key-operated locking arms and squib-operated locking pins were used in the SNAP 10 reactor to prevent control drum rotation.[9] A nuclear safety and diagnostic system was proposed for the NERVA reactor which provides means to electrically disconnect each individual control drum drive actuator in order to assure against criticality during nonoperating periods.[10] With similar safety devices incorporated, the nuclear power system can be handled safely on the ground, eliminating any credible danger of supercriticality.

Core Compaction

The electric layout requirements of the thermionic converters result in a central void and three 2-cm-wide gaps in the core. These voids constitute a core volume fraction of 7.7%. Complete compaction of these voids, under accidental conditions such as fuel explosion, impact on launch pad, or impact in the ocean after launch failure, would introduce a reactivity gain of about 4%. It is mandatory to fill up the voids with suitable solid material. A good neutron moderator material can be considered, making available a large negative moderator temperature coefficient of reactivity[11] to compensate the positive reactivity coefficient due to core compression. However, the possible penalty of the introduction of moderating material into the core is to increase the critical size of the core. Further study is required to ensure that the penalty does not exceed the amount allowed for the K_{eff} alteration of the core (see Table 2). A thermal neutron absorber, if inserted in the voids, would have less impact on the neutronic properties of the reactor. The advantages, in addition to reducing core compaction hazard, are twofold: 1) it can serve as a burnable poison for the fast-spectrum reactor to compensate normal reactivity losses; and 2) it further guarantees the inherent subcriticality of the core, on top of the function of the thin B_4C layer.

The vapor volume of the heat pipes in the core occupies a volume fraction of 17%. Complete compaction of the heat pipes would cause a reactivity increase of about 9%, and a supercritical core would become inevitable. Since the required impact force to compact the fuel elements is expected to be very large, a broken-up and dispersed core more likely would result.

Neutron Reflection

As mentioned previously, there is a stationary 2-mm B_4C layer surrounding the core. This B_4C layer not only reduces the power peaking at the boundary of the core, but also minimizes the supercriticality hazards due to thermal neutron reflection if the reactor is accidentally immersed in water.

Table 3 Reactor supercriticality hazards

Hazard mechanism	Component	Maximum reactivity insertion, %	Countermeasure
Roll-out of control drums	...	8.5	Mechanical locking devices, redundant lockout circuit, nuclear safety and diagnostic system
Core compaction	1) 3 gaps, central void	4	Fill up the gaps and void
	2) Heat pipes	9	Disassembly of the core
Neutron reflection	1) B_4C layer and reflector assembly both intact	0.1	Not required
	2) B_4C layer intact; reflector assembly lost	−10	Not required
	3) B_4C layer and reflector assembly both lost	2	Higher shut down margin, insertion of thermal neutron absorber or other slightly modified core composition
Neutron moderation (internally flooded core)	Water enters the core through damaged heat pipes	−11	Not required

Results from several neutron-reflection calculations indicate that: 1) with an intact reflector, the K_{eff} of the reactor increases only 0.1% when the reactor is surrounded by water; 2) if the entire BeO reflector assembly is lost during an accident and the B_4C layer is intact, K_{eff} of the core surrounded by water is about 0.9; and 3) if the 2-mm B_4C layer and the BeO reflector assembly are completely lost, the K_{eff} of the flooded bare core increases by 2% above the shutdown condition. Thus, if the shutdown margin is less than 2%, then supercriticality can result. However, this could be offset by the thermal neutron absorber filling the three gaps and the central void in the core, as discussed earlier, or by having a large enough shutdown reactivity margin so that the K_{eff} distribution of the reactor is close to the one under "possible alteration" of Table 2.

Neutron reflection imposed a potential hazard for early SNAP reactors. A special external safeguard device was required. In the present fast-reactor design, however, intrinsic subcriticality of the heat-pipe reactor described here can probably be achieved.

Neutron Moderation

The propellant for the electric propulsion is decoupled from the reactor cooling subsystem. The criticality hazards due to propellant leakage in the core do not exist. However, accidents such as launch abort during ascent could result in spacecraft impact in the ocean, with subsequent water entry into the core through damaged heat pipes.

Calculations of the infinite multiplication factor K_∞ performed on a single fuel element indicate that filling the heat pipe with water produces a decrease in reactivity ($\Delta K/K_\infty$) in excess of 10%. This means that a similar decrease would occur to the K_{eff} of the reactor. In other words, the flooded reactor would be less critical than the normal reactor. It appears that this reactor can be made inherently safe to both water immersion and flooding. The preceding safety analysis on the reactor supercriticality hazards is summarized in Table 3.

Impacts of Safety Considerations on Design

As noted previously, we have outlined some impacts of safety considerations on the reactor design. These include the following: 1) the central void and the gaps in the core must be filled solidly to avoid core compaction; 2) the control drums reactivity swing ΔK greater than 5% is desirable and can be achieved with a thicker B_4C layer in the drums and/or a thicker reflector assembly; and 3) core disassembly may be desired if the impact force has a tendency to compress the heat pipes.

Since the NEP spacecraft is to be launched from the space shuttle, the STS policy on its payload safety could also have some impact. In the following paragraphs, we shall discuss a few STS payload safety guidelines.[1]

1) Double-walled containment of the liquid metal should be provided throughout the coolant loop (guideline 3.14.1.1.a-[2]). The thermionic converters are to be cooled by NaK. Fire or explosion hazard does exist for this liquid metal. One safety precaution would be to isolate leaking coolant from moist air and water. The weight penalty of the double-walled containment was estimated to be less than 5% of the total weight of the coolant subsystem (excluding EM pumps). Alternatively, a separate NaK reservoir, in which the coolant is stored until the time for spacecraft separation, can be considered. This would eliminate the weight penalty on the NEP spacecraft.

2) A positive and permanent shutdown would be provided for malfunctioning reactors and for reactors that have completed their missions (guideline 3.14.1.1.i). As discussed previously, the 18 control drums with a B_4C layer of thickness from 1 to 3 cm can provide a reactivity ΔK swing of 5% to 8.5%. There is ample margin for shutting down the reactor positively and permanently. The NEP spacecraft is intended primarily for exploration of the outer planets. Shutdown of the spent reactor is not essential. If the NEP spacecraft is used for geocentric missions, shutdown of a reactor that has completed its mission is important. Obviously, the higher value of reactivity swing is desired, along with other aforementioned safety considerations. Geocentric mission completion must include safe disposal of the spent reactor. High-Earth orbits, solar orbits, and solar system escape are possible destinations for the reactor disposal.

3) Design of nuclear hardware should include intact re-entry and impact to protect the general public from potentially dangerous radiation (guideline 3.14.1.1.m). The space shuttle has the capability of intact abort.[12] Until the NEP spacecraft is successfully injected into orbit, the reactor is not activated. No significant amount of radioactive material is present in the core. Intact re-entry of the clean reactor is a possibility. However, uncontrolled re-entry of the reactor, whether it is cold or hot, should be avoided. Under uncontrolled condition, intact impact of the reactor may not be safer than a disintegrated core because of the supercriticality hazards due to possible core compaction. A reactor that operates at full power for some time should not be allowed to return to the Earth. Nevertheless, Ref. 6 concluded that re-entry burnup, as a backup to orbit boost or controlled re-entry, may provide a two-order-of-magnitude improvement (in terms of the number of overexposures) over the disposal mode of controlled re-entry with intact impact. An effective destruct device for the reactor might be considered as an additional safety precaution.

Conclusion

The heat-pipe-cooled out-of-core thermionic reactor design exhibits a large, negative, prompt-acting reactivity effect, primarily from fuel expansion. Doppler effects of all core materials except U^{235} are negative and small. Although the net Doppler effect of the highly enriched fuel is positive, it is negligibly small compared to the effect of thermal expansion. Bowing of fuel elements and cold coolant injection are essentially eliminated in the design. The rapid shutoff coefficient with fuel expansion, and the absence of any appreciably positive reactivity coefficient, assure a reactor with safe stable operation.

Voids in the core should be filled in solidly to avoid core compaction. A spacer of thermal neutron absorber material is helpful in the aspect of intrinsic subcriticality of the core, whereas a neutron moderator can increase the magnitude of the negative power coefficient appreciably. The thin layer of B_4C surrounding the core assures the safety of the reactor during transportation, storage, or accidental immersion in water. The control drum reactivity ΔK swing of 8.5% is preferred over 5%, when the subcriticality of the core and the shutdown of the spent reactor are to be assured.

An effective destruct device should be considered for the reactor to safeguard against possible hazards resulting from compressed heat pipes on impact, although the reactor appears to be inherently safe to water immersion and flooding. Double-walled containment of the coolant loops would further reduce the risk of fire or explosion in the space shuttle payload area, with only slight weight penalty on the spacecraft. To avoid the weight penalty completely, alternatives such as a separate NaK reservoir should be considered.

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References

[1] *Space Transportation System Payload Safety Guidelines Handbook,* NASA Lyndon B. Johnson Space Center, July 1976.

[2]Phillips, W.M., Estabrook, W.C., and Hsieh, T.M., "Nuclear Thermionic Power System for Spacecraft," *Proceedings of the 11th Intersociety Energy Conversion Engineering Conference,* Stateline, Nev., Sept. 1976, Vol. II, p. 1487.

[3]Koenig, D.R., "Heat Pipe Nuclear Reactor for Space Power," *Proceedings of the 11th Intersociety Energy Conversion Engineering Conference,* Stateline, Nev., Sept. 1976, Vol. II, p. 1139.

[4]Gronroos, H. and Davis, J.P., "Reactivity Effects from Fuel Displacement in a Small Thermionic Reactor," Jet Propulsion Lab., Space Programs Summary 37-45, Vol. IV, June 1967, pp. 136-141.

[5]Sullivan, R.E., "Reactivity Insertions in Compact Reactor Cores Due to Fuel Movement," NASA TMX-1587, March 1969.

[6]Otter, J.M., Buttrey, K.E., and Johnson, R.P., "Aerospace Safety Program Summary Report," Atomics International Div., Rockwell International, AI-AEC-13100, July 1973.

[7]Scott, C.C., "Plant Instrumentation and Control," *Fast Reactor Technology-Plant Design,* edited by J.G. Yevick, The MIT Press, Cambridge Mass., 1966, Chap. 9.

[8]Nordheim, L.W., "The Doppler Coefficient," *The Technology of Nuclear Reactor Safety,* Vol. 1 edited by T.J. Thompson and J.G. Beckerley, The MIT Press, Cambridge, Mass., 1964, Chap. 4.

[9]"Guidebook for the Application of Space Nuclear Power Systems," Atomic Industrial Forum, Jan. 1969.

[10]"NSS Anticriticality Requirements for Space and Mission Operations," Westinghouse Astronuclear Lab., TID/SNW-107, 1970.

[11]Mayo, W., "Neutronic Effects of Moderator Insertion in Fast-Spectrum Reactors," NASA TMX-1614, Aug. 1968.

[12]"Space Shuttle Final Technical Report, Vol. VIII: Mission/Payload and Safety/Abort Analysis," General Dynamics, Oct. 1969.