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Title: Nuclear Design Analysis of Low-Power (1-30 KWe) Space Nuclear Reactor Systems

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Abstract Approved: ______________________
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Preliminary nuclear design studies have been completed on ten configurations of nuclear reactors for low power (1-30 kWe) space applications utilizing thermionic energy conversion. Additional design studies have been conducted on the TRICE multimegawatt in-core thermionic reactor configuration. In each of the cases, a reactor configuration has been determined which has the potential for operating 7 years with sufficient reactivity margin. Additional safety evaluations have been conducted on these configurations including the determination of sufficient shutdown reactivity, and consideration of water immersion, water flooding, sand burial, and reactor compaction accident scenarios. It has been found, within the analysis conducted using the MCNP Monte Carlo neutron transport code, that there are configurations which are feasible and deserve further analysis. It has also been found that solid core reactors which rely solely on conduction for heat removal as well as pin type cores immersed in a liquid metal bath have merit. The solid cores look attractive when flooding and

compaction accident scenarios are considered as there is little chance for water to enter the core and cause significant neutron moderation. A fuel volume fraction effect has also been found in the consideration of the sand burial cases for the SP-100 derived configurations.

Nuclear Design Analysis of Low-Power (1-30 KWe) Space Nuclear Reactor Systems

by

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Nuclear Design Analysis
of Low-Power (1-30 KWe)
Space Nuclear Reactor Systems

1.0 Introduction

As man progresses into space, the need for compact reliable sources of electrical energy becomes more pressing. When considering the various methods available, the options are rather limited. Chemical processes are capable of high power levels, but only at high rates of fuel usage. Even at more modest power levels, fuel consumption eliminates chemical processes for any mission whose duration is more than a few months. At first glance solar power seems very attractive, but it is obviously inappropriate for deep space. Additionally, a very practical consideration limits the size of the solar array: that array also behaves as a sail in the solar wind, and at power levels above at most a few tens of kilowatts, fuel expenditure to counteract that sail become prohibitive. Radioisotope thermoelectric generators are not affected by fuel or solar wind considerations but they tend to be heavy. RTG systems designed for more than a few kilowatts are prohibitively massive.

Only power sources centered around a nuclear reactor appear capable of high power levels, compact size, relatively low mass, long operating life and still be technologically feasible.

The potential application of in-core thermionic power conversion to a variety of nuclear reactor core arrangements are presented in this report. Considerable mass reduction for multimegawatt space power systems using in-core thermionics for power conversion has been shown previously in the TRICE (Thermionic Reactor with Inductively Coupled Elements) configuration (Rasor 1987, Huey 1988). The objective of this work was to investigate the use of in-core thermionic fuel elements and both in-core and out-of-core thermionic convertors in low power applications (tens of kilowatts). Additionally, an alternative fuel element arrangement for the TRICE design was examined. I have focused my efforts on the nuclear design and safety of these reactors.

A brief discussion of thermionic power conversion is given in Chapter 2. The technique by which each concept was modelled is described in Chapter 3, while Chapter 4 details the scenarios and the desired design goals. In essence, each concept was evaluated based on Monte Carlo model calculations of the effective multiplication factor, k_{eff}, using the MCNP neutron transport code, version 3 (Breismeister 1985). Calculations were performed primarily on the OSU Nuclear Engineering Department's Apollo Domain Series DN3000 engineering work station. Some of the out-of-core convertor reactor calculations were performed on the NASA Lewis Research Center CRAY X-MP computer, using the same code version and cross-section set. First order criticality results are obtained for the proposed reactor concepts utilizing homogeneous, three-dimensional models of each reactor. I feel that greater detail for this preliminary design study is not warranted at this time as it would have greatly increased the computational time required. The cross-section set being utilized is the ENDF/B-IV data set supplied by the Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee with the MCNP code (2).

The fifth chapter of this thesis details the models which were used to evaluate the feasibility and safety analysis. The majority of the effort was expended in developing the maximum reactivity cases with interest in designing critical reactor configurations. Once a reasonable design was achieved, the shutdown and the various accident cases were considered. The fifth chapter also describes the various reactor configurations considered in both low power (1-30 kWe) and TRICE multimegawatt designs. The low power concepts include: a solid core configuration using UO_2 in a tungsten matrix which relies solely on conduction for heat removal to the thermionic elements on the outside of the cylindrical core; an annular core design which uses conduction to both the outside of the reactor as well as to an annular region in the center of the core for heat removal; and a core which utilizes the fuel and technology of SP-100 and utilizes liquid lithium as a conduction path to the thermionic elements of the outside of the core. A variation of this last case was also considered in which SP-100 technology is used; however, the fuel pins are taken to be 20% larger than the original design.

A multimegawatt configuration is described in Chapter 6. This design is a variation of the TRICE multimegawatt reactor concept.

The seventh chapter of the report covers the results of the calculations which were performed on each of the reactor concepts, and the final section describes future studies which need to be considered for these reactor designs.

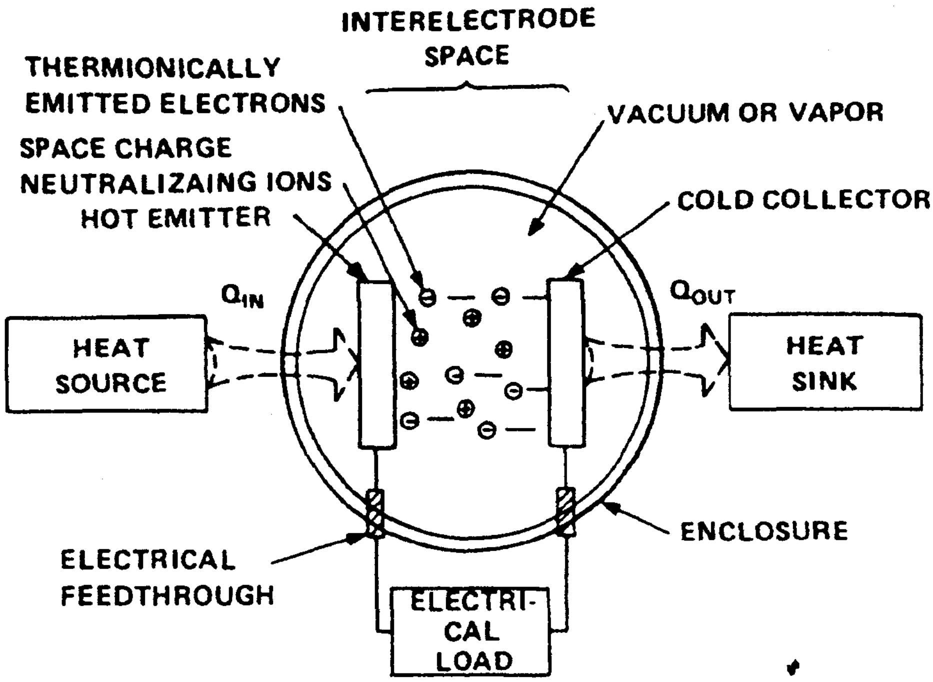
2.0 Thermionic Power Conversion

Thermionic conversion is a method of directly transforming heat energy into electrical energy. In its simplest form, a thermionic converter consists of one electrode (the emitter) connected to a heat source, a second electrode (the collector) connected to a heat sink and separated from the first by an intervening gap; the appropriate electrical leads and load, and an enclosure. The space in the enclosure may be either a vacuum or filled with an ionized gas, as illustrated in Figure 1 (Rasor, 1982).

When sufficient heat is applied to the emitter, electrons, because of thermal agitation, will boil off and cross through the intervening space to the collector. With the two electrodes connected externally, the electrons will flow in the circuit from the collector to the emitter.

This process is analogous to the process by which solar energy is converted into mechanical energy. Seas and lakes represent the electrodes, the atmosphere corresponds to the intervening space, the gravitational potential (or altitude) for an electrical potential, and water flow through rivers and turbines represent electron flow through a load. Solar heat vaporizes water from the sea. The water vapor moves inland to cooler regions, where it condenses into lakes at high altitude. Water returning to the sea through the turbine completes the cycle, generating mechanical energy.

THERMIONIC CONVERTERS



TYPICAL OPERATING REGIME

EMITTER TEMPERATURE:	1600–2000 K (2420–3140°F)
COLLECTOR TEMPERATURE:	800–1100 K (980–1520°F)
ELECTRODE EFFICIENCY:	UP TO 20%
POWER DENSITY:	1–10 W/cm^2

MATERIALS

EMITTER MATERIALS:	W, Re, Mo
COLLECTOR MATERIALS:	Nb, Mo
INSULATOR MATERIALS:	Al_2O_3, Al_2O_3/Nb CERMET
ELECTRODE ATMOSPHERE:	Cs AT 1 Torr

Figure 1. Components of Thermionic Converters

Thus, it can be seen that in a thermodynamic sense, the thermionic converter is a heat engine using electrons as the working fluid. It operates in a cycle, receiving heat at high temperature, rejecting heat at low temperature and generating electrical work in the process.

Typical present day thermionic converters have electrodes made of either refractory metals with adsorbed cesium or of metals impregnated with high-emission materials. Typical emitter temperatures range from 1400 to 2200K; the collectors operate from 500 to 1200K. Under optimum conditions, the energy conversion efficiency is of the order of 5 to 25%, the electrical power densities range from 1 to 100 watts/cm^2 and current densities are of the order of 5 to 100 amp/cm^2. Output of the individual converter cell is usually 0.3 to 1.2 volts, and is typically rated at 10 to 500 watts. Higher emitter temperatures are generally required to get efficiency, power and current densities in the high end of these bands.

Thermionic power conversion offers many features that are attractive to a space nuclear power program. The process entails the use of many convertors that are essentially independent of each other: failure of one should have little or no effect on any other. This, coupled with the non-existence of moving parts, promises high system reliability. Additionally, many independent cells allow designing for a multitude of power levels by simply adding or subtracting converter cells until the desired output is achieved. Since the amount of energy a space heat rejection system can handle varies as the fourth power of the rejection temperature, the inherently high rejection temperature of the thermionic conversion process promises low system specific weight (lb/kW(e)).

Thermionic reactor designs can be grouped into two general categories: Out-of-Core designs, where the converters are mounted external to the reactor core and are coupled to the core by some conductive and/or convective heat removal path; and In-Core designs, where the converters are integral parts of the nuclear fuel elements and are emplaced throughout the core.

The Out-of-Core design category can be further sub-divided into conduction designs, forced-convection designs and heatpipe designs. Conduction designs typically place the thermionic converter cells around the periphery of and in physical contact with the reactor core. Heat is transferred from the core to the emitters by conduction. Forced convection designs use a circulating fluid, usually a liquid metal, to carry heat from the core to the converters. Heatpipe designs utilize heatpipes to transfer heat energy from the core to the converter emitters. The feature these designs all share is the fact that the thermionic converters are outside the core, making the system much easier to design and construct. This simplicity of design has a price, however. These systems tend to be heavier and bulkier because of the additional mass and volume taken up by the heat transfer mechanisms--heatpipes, working fluid, pumps--that are not present with In-Core designs.

The In-Core design category can also be subdivided into three groups: flashlight, pancake and externally fueled designs. The flashlight and pancake designs both use a thermionic diode similar to that shown in Figure 2 as the basic unit around which the rest of the reactor is built. The fuel is fashioned as a pellet and enclosed within the emitter, which in turn is surrounded by a tubular collector. The collector is covered by a ceramic tube for electrical insulation; everything is enclosed by a metallic sheath for hermetic containment and structural integrity.

The thermionic fuel element in the flashlight-style reactor is made by stacking several (typically six) of these diodes, analogous to a flashlight with its batteries in series. Many fuel elements are then assembled into a critical reactor. Heat removal is typically by axial flow forced convection around the outside of the collector.

In the pancake design, the thermionic diodes are placed in a one-layer thick cylindrical array. These arrays, or pancakes, are then stacked to achieve a critical reactor. Cooling is usually by cross-flow forced convection. Series-parallel electrical connections of the converters in one layer are made in the space between the layers.

An example of an In-Core thermionic reactor concept with externally fueled diodes is illustrated in Figure 3. Here coolant passes through a tube in the center of the module (heatpipes could also be used). The outer surface of the coolant tube acts as the thermionic diode collector. The emitter surrounds the collector and also acts as the inner container of the fuel.

The main advantage of this concept is the high fuel volume fraction, which generally results in smaller core sizes than with the pancake or flashlight designs. The main disadvantage stems from the fact that the converters extend the length of the core. It is difficult

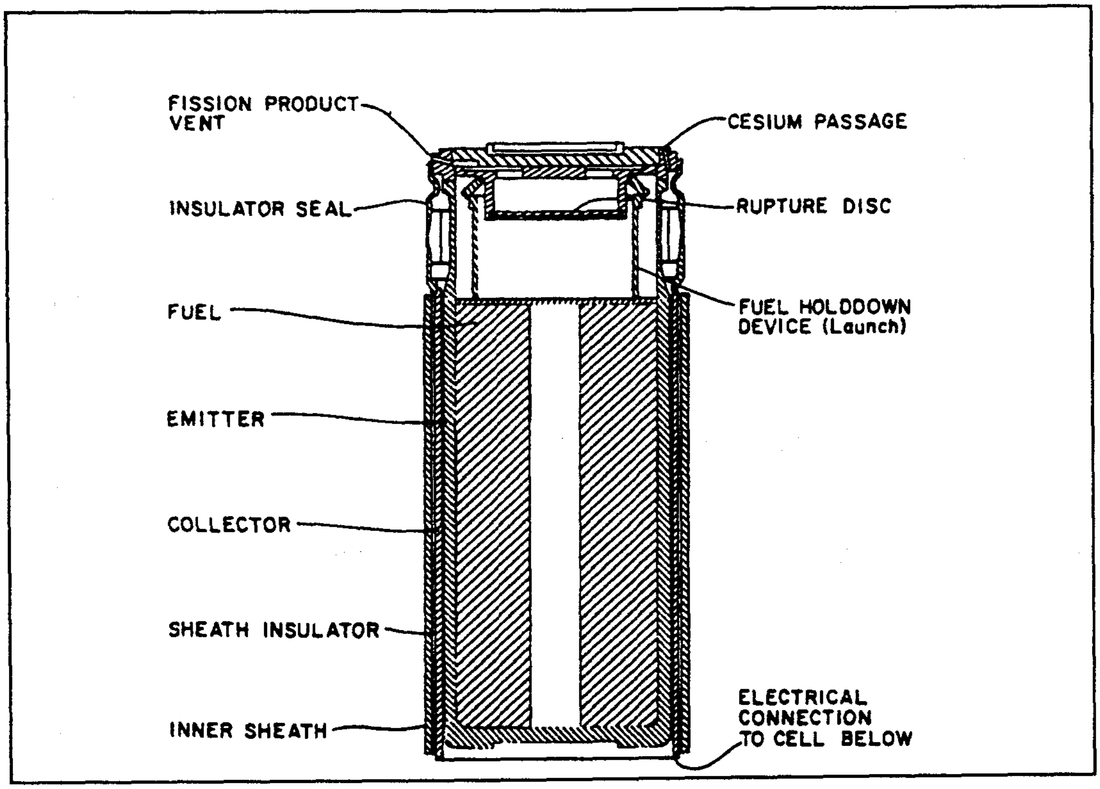


Figure 2. Thermionic Diode

to maintain interelectrode spacing over a long distance, and at power levels above approximately 300 KWe, full-length converters are extremely difficult to manufacture. (Angelo 1985, pp217-219; Hatsopoulos 1979, pp639-642)

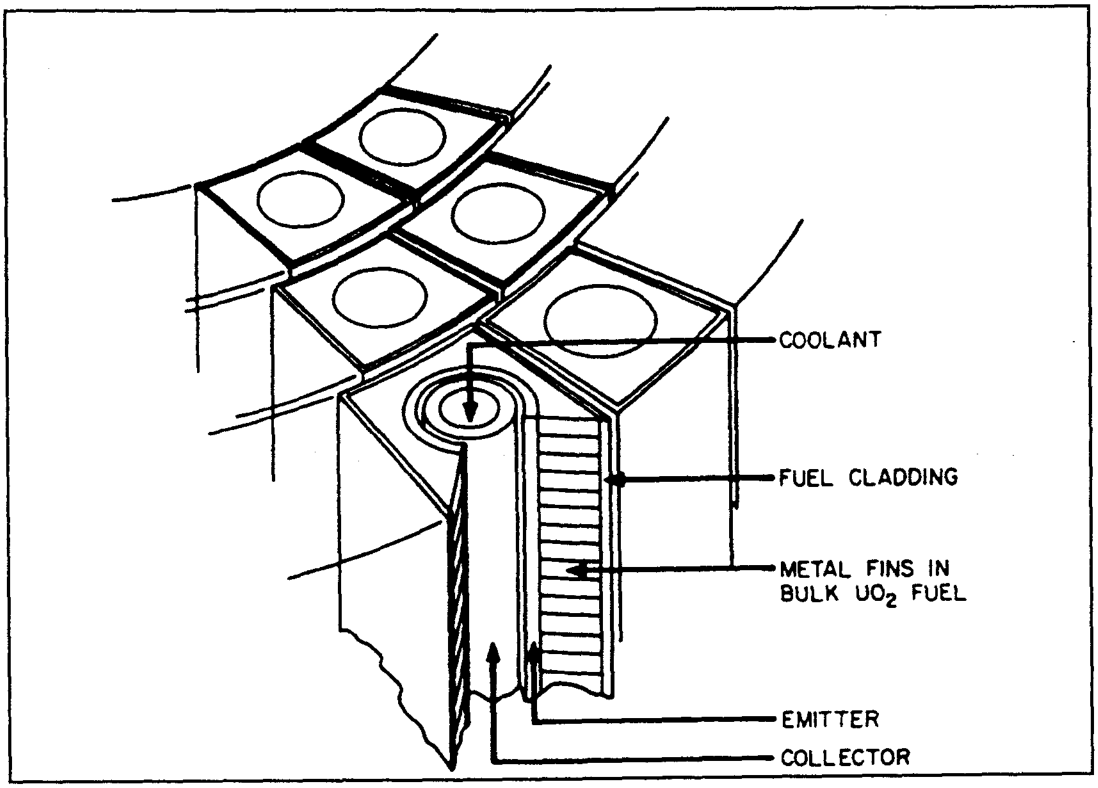


Figure 3. Externally Fueled Full Length Thermionic Diode Modules

3.0 Description of Modeling Techniques

Nuclear feasibility and criticality safety evaluations were performed using the Monte Carlo Neutron/Photon (MCNP) transport code, version 3 (Briesmeister, 1985). MCNP is a general purpose Monte Carlo code that can be used for neutron, photon or coupled neutron-photon transport. It was used in this analysis to calculate eigenvalues for critical systems. The majority of the calculations were performed on the OSU Nuclear Engineering Department Apollo engineering workstation; some earlier work was performed on the NASA-Lewis Research Center Cray X-MP Computer. Both machines used the same source code and cross section sets. First order criticality results were obtained for the proposed reactor concepts utilizing homogeneous, three-dimensional models of each reactor and its associated sub-systems and components as described further below. In those cases where more accurate geometrical representations were available, more detail was included. A three dimensional model, such as is available by using MCNP, allows the models to more accurately treat non-symmetric reactor components, such as reflectors, than a one- or two-dimensional model. By homogenizing the reactor components, some details of the system, such as self shielding effects, are lost. However, it is felt that greater detail for such scoping studies is unnecessary and would not be warranted considering the level of design detail available.

The cross section set utilized for these calculations was the ENDF/B-IV data set supplied by the Radiation Shielding Information

Center, Oak Ridge National Laboratory, Oak Ridge Tennessee with the MCNP code.

4.0 Case Descriptions and Desirable Limits

The nuclear feasibility and criticality safety assessments of each reactor concept were based on Monte Carlo three-dimensional model calculations of the effective multiplication factor, k_{eff}. Each case represents a specific scenario: startup and operational life capability; launch pad and ascent shutdown capability; water immersion criticality and safety, both for normal launch configuration with all shutdown subsystems in place and a post-impact launch abort configuration with all exterior control and shutdown systems removed; sand burial criticality for the post-impact launch abort configuration; and finally, a compaction scenario of the launch abort configuration with all exterior control systems removed, and immersed in water.

4.1 Maximum Reactivity

In this configuration, the maximum operating reactivity is determined in order to evaluate the initial criticality of each of the reactor concepts. For this analysis, all control rods are fully withdrawn and all movable reflectors used for reactivity control are positioned in such a way as to provide for the maximum amount of neutron reflection. In these cases, any fixed poisons are assumed to remain in the core and the objective is to estimate the maximum amount of excess reactivity available for normal startup.

The target values of k_{eff} for these cases was required to fall between 1.05 and 1.09. These limits were chosen to allow for statistical variances in the calculational techniques, cross section inaccuracies and temperature effects on startup, and to ensure sufficient reactivity margins to provide for reactor operation for a seven year period due to burnup. It is felt for these initial feasibility calculations that if a concept falls within this range, the results should provide sufficient confidence in the startup capability of the reactor. In all cases examined, the statistical variance of the results was found to be less than ±2%. This has been accomplished by a combination of variance reduction techniques and running sufficient histories.

4.2 Launch Configuration

In the launch configuration, all movable poisons are placed in such a manner that a subcritical assembly is maintained prior to and during launch. Control rods are fully inserted into the core and any movable reflectors used for control are removed and stored in their launch positions. These cases are designed to test the amount of shutdown margin available to the reactor during the fabrication of the concept and its safety after being loaded into the launch vehicle. They also give some measure of the capability to shutdown the reactor system after initial criticality in space should a problem develop.

The ideal values for k_{eff} for these cases would be as low as possible; however, a value of less than 0.9 would be more than acceptable from an initial feasibility standpoint. This would provide sufficient shutdown margin for these concepts and allow for statistical variations, inaccuracies of nuclear data, and other effects.

4.3 Water Immersion

For the water immersion cases, an accident in which the reactor system is dropped into water is simulated. This could occur during a launch which is unable to place the reactor into orbit, or during the transportation of the completed reactor system to the launch site. In these cases it is assumed that the launch configuration described above is maintained, no water is allowed to enter the reactor system, and the entire reactor system is placed at the center of a 5 meter radius sphere of water. Here, the water only acts as an additional reflector and external neutron moderator. No neutron moderation, other than from designed core materials, is included within the reactor system. Also, it is assumed that no physical damage to the reactor core occurs and that there is no redistribution of core or reflector materials (i.e., no compaction).

For water immersion accident scenarios, an acceptable upper limit for k_{eff} was chosen to be 0.95. This value includes allowances for statistical and data uncertainties, and possible small amounts of re-distribution of reactor components due to impact damage.

4.4 Water Flooding

Water flooding cases model the water immersion accident with no allowances for active shutdown systems external to the core. In these cases, all movable components exterior to the core are assumed to have been removed on impact. This includes any movable reflectors. It is further assumed that the core itself and any fixed reflector sections will remain intact on impact. Also, for these cases, water is allowed to fill any and all of the voids within the reactor system, including coolant flow channels inside the core, and the void spaces in the thermionics and heat pipes. Additionally it is assumed that all coolant volume fractions in those concepts which utilize a liquid coolant are replaced with water and that any core heat pipes are filled with water. In addition, the resulting configuration is then submerged at the center of a 5 meter radius sphere of water as in the water immersion cases. No allowances for the compaction of the reactor core and reflectors are made in this scenario.

Acceptable levels of subcriticality could be assumed for such cases if k_{eff} is found to be less than 0.95. Again, this includes a margin to allow for statistical and data accuracy, but does not leave very much margin in the cases where compaction of the core is possible.

4.5 Sand Burial

Sand burial cases simulate the flooded reactor buried in water saturated sand. Again, all movable components exterior to the core are assumed to have been removed by the impact, and water fills all the voids, coolant channels, etc. No sand is assumed to seep in to the reactor, and no compaction is assumed to occur.

The porosity of the sand is assumed to be 50% -- i.e. the sand/water mixture consists of 50% by volume sand, and 50% by volume water. Additionally, in an attempt to more fully approach actual conditions, two types of sands were modeled. One type was assumed to be

100% silicon dioxide, and the other was assumed to be 100 % calcium carbonate, as some Florida beaches are made up almost exclusively of crushed coral.

Acceptable levels of subcriticality could again be assumed if k_{eff} is found to be less than 0.95.

4.6 Compaction

These configurations are an attempt to simulate a more catastrophic event. As in the previous two scenarios, all movable components exterior to the core are assumed to have been removed on impact. It is assumed that the core itself and any fixed reflectors remain intact. However, the impact "squeezes" the core, so that the density of the fuel region increases by ten percent. Water is allowed to fill all voids within the reactor system, and replaces any coolant in the system. The resulting configuration is then submerged in a 5 meter radius sphere of water.

As in the previous cases, a target value of less than 0.95 for k_{eff} is considered acceptable.

5.0 Low Power Thermionic Reactor Configurations

Ten small, low-power reactor designs were proposed for space applications. These "milliMW" designs were analyzed with MCNP to determine the dimensions necessary to achieve $k_{eff} = 1.05$. As this is a preliminary investigation, the following assumptions were used:

a) all reactor configurations are without any reactivity control, approximating a cold clean startup for the determination of the maximum amount of positive reactivity.

b) an attempt is made to maintain the overall core height/diameter ratio close to unity.

c) cylindrical geometry.

d) 7 cm reflector thickness on top, bottom and sides.

e) each reactor region is treated as a homogeneous mixture of the appropriate materials.

f) 95% enriched uranium used in the fuel.

g) reactivity control is accomplished by louvered radial reflectors. To model the shutdown scenarios, it is assumed that the radial reflector density is 10% of the value used in the maximum reactivity cases.

Two different geometries are analyzed for each of the following low power concepts. The "internal reflector" geometries have the 7 cm thick radial reflector inside the thermionics and heat pipes; the "external reflector" geometries place the reflector as the outer-most layer of the system (that is, outside the heat pipes).

These reactors were originally conceived with the internal reflector geometry. Upon analysis, it appeared that the best way to control reactivity was through use of a movable reflector of some sort. However, a movable reflector interferes with the heat conduction path between the core and the thermionic elements, hence the need for the external configurations.

5.1 Case 1 Solid Core Reactor Configuration

This design uses a solid core and heat removal is solely through conduction. The nominal power for this reactor system is 1-10 kWe. The fuel region is uranium dioxide (60 volume percent) in a tungsten matrix (40 volume percent), with a uranium enrichment of 95 percent. The core is surrounded by a 7 cm thick reflector of BeO. The thermionics are assumed to be 40 volume percent tungsten, 40 volume percent niobium and 20 volume percent void. Waste heat removal is accomplished by heat pipes using potassium as the working fluid. They are modeled as 20 volume percent potassium, 20 volume percent tungsten and 60 volume percent void. An additional 23 cm of BeO is placed on top of the reactor as a shield. Reactivity control is accomplished by a louvered radial reflector. Positive shutdown in the launch configuration is obtained by the use of a single boron carbide control rod (with fuel follower) through the center of the core.

Figures 4 and 5 schematically show the core materials arrangement for this reactor configuration. Please note that these and other figures which follow are <u>not</u> to scale. Table 1 gives the compositions of the various regions; Table 2 lists the dimensions and region masses of the critical configurations.

REGION	COMPOSITION	VOLUME FRACTION
FUEL	UO_2 W	0.6 0.4
REFLECTOR	BeO	1.0
THERMIONICS	W Nb void	0.4 0.4 0.2
HEAT PIPES	W K void	0.2 0.2 0.6
SHIELD	BeO	1.0

Table 1. Solid Core and Annular Core Region Compositions

1. Solid Core (UO_2) With Internal Reflector		
Dimensions	Radius Height Length Diameter	13.4 cm 26.8 cm 40.8 cm 43.8 cm
Mass	Fuel Region (UO_2	207.42 kg 90.71 kg)
	Reflector Region Thermionics Region Heat Pipe Region	115.63 kg 45.57 kg 34.37 kg
2. Solid Core (UO_2) With External Reflector		
Dimensions	Radius Height Length Diameter	13.9 cm 27.8 cm 44.8 cm 41.8 cm
Mass	Fuel Region (UO_2	231.51 kg 101.25 kg)
	Reflector Region Thermionics Region Heat Pipe Region	134.68 kg 13.69 kg 13.69 kg

Table 2. Solid Core Dimensions

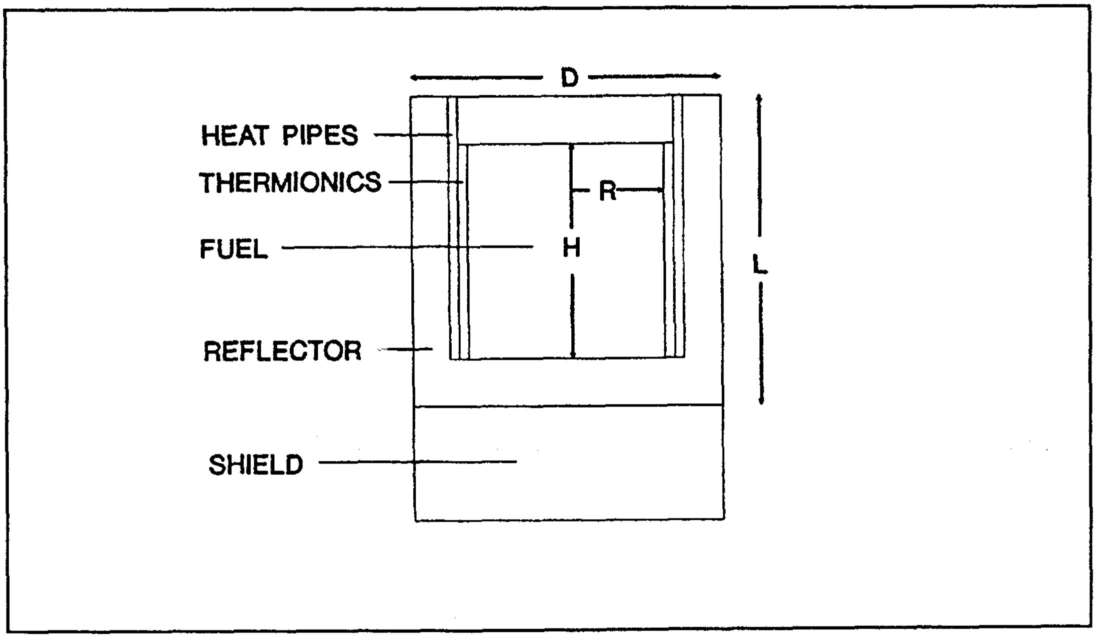


Figure 4. Solid Core (UO_2) with Internal Reflector

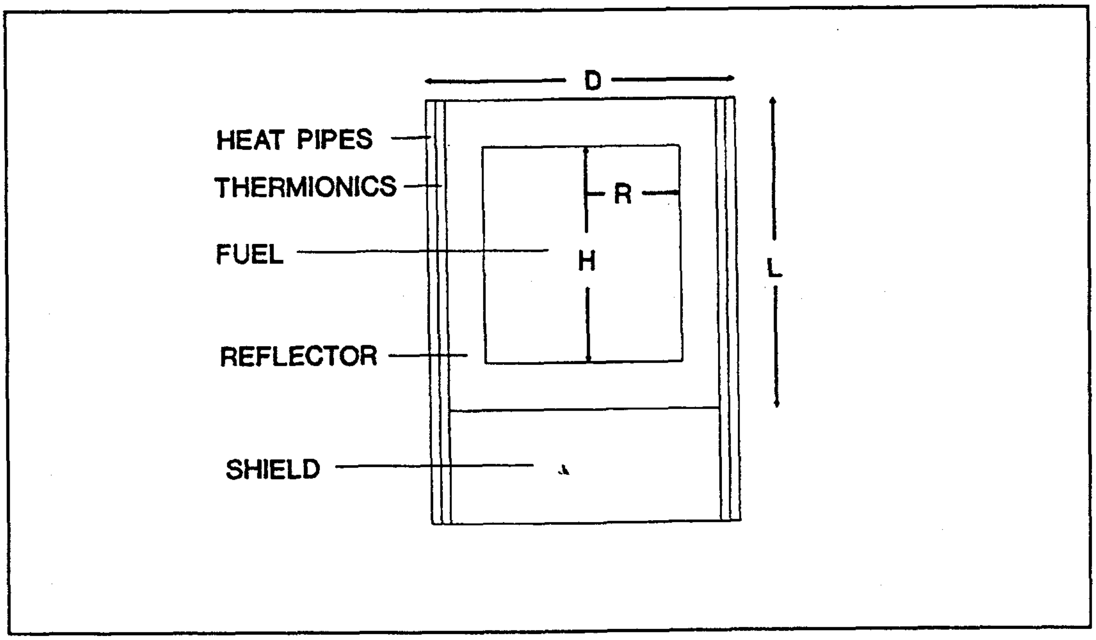


Figure 5. Solid Core (UO_2) with External Reflector

5.2 Case 2 Annular Core (UO_2)

This reactor also use a solid UO_2 core with heat removal solely through conduction. The fuel region is identical to the Case 1 reactor except for the addition of a central annular region. This region consists of heat pipes, thermionics and a small central void. The additional thermionics give a total nominal power of 1-15 kWe. Reactivity control is accomplished by using both a boron carbide poison rod in the central void and a louvered radial reflector. Figures 6 and 7 demonstrate the inclusion of the annular region, and the compositions for the various regions are given by Table 1. Dimensions and masses for the maximum reactivity configuration are given by Table 3.

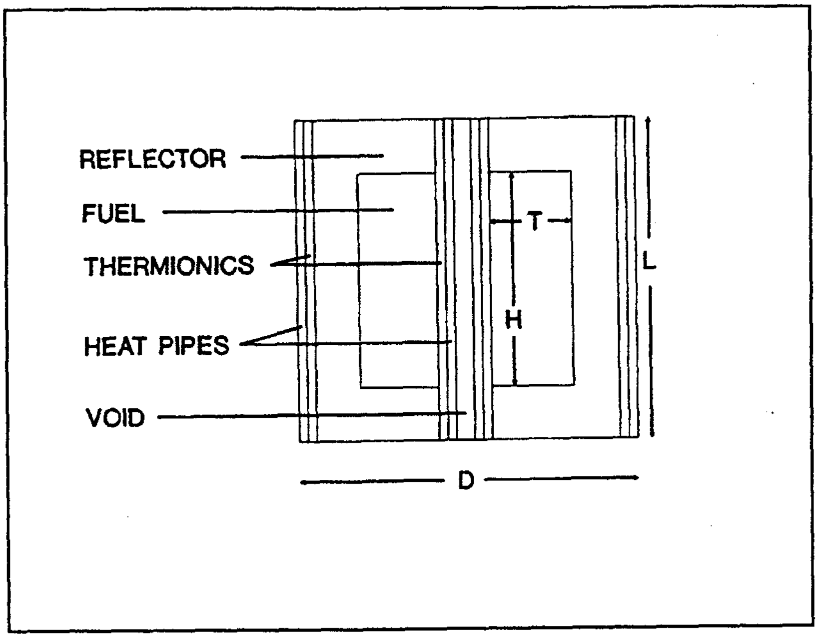


Figure 6. Annular Core (UO_2) with Internal Reflector

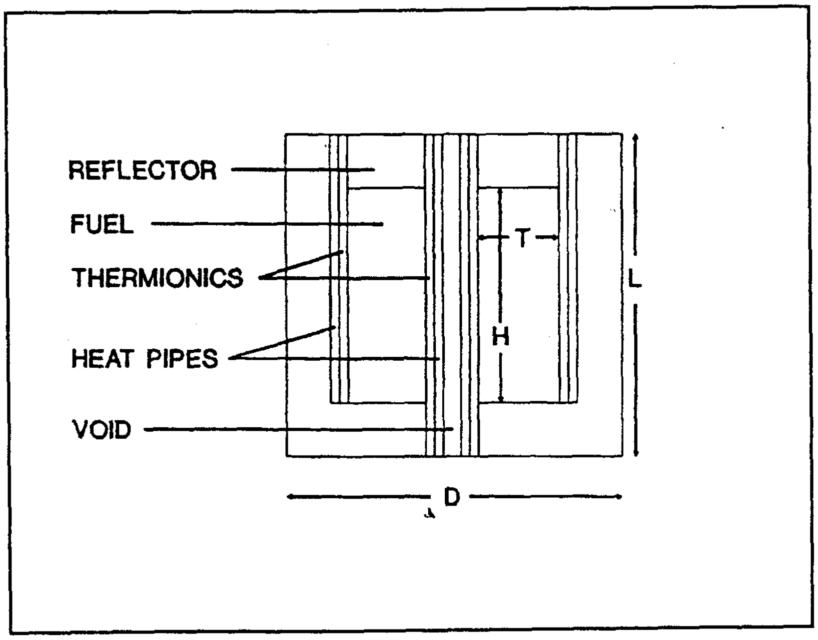


Figure 7. Annular Core (UO_2) with External Reflector

1.	Annular Core (UO_2) With Internal Reflector	
Dimensions	Thickness Height Length Diameter	12.0 cm 31.0 cm 45.0 cm 48.0 cm
Mass	Fuel Region (UO_2	304.65 kg 133.23 kg)
	Reflector Region Thermionics Region Heat Pipe Region	96.46 kg 40.73 kg 29.64 kg
2.	Annular Core (UO_2) With External Reflector	
Dimensions	Thickness Height Length Diameter	12.8 cm 32.6 cm 49.6 cm 46.6 cm
Mass	Fuel Region (UO_2	356.12 kg 155.74 kg)
	Reflector Region Thermionics Region Heat Pipe Region	169.18 kg 28.08 kg 20.31 kg

Table 3. Annular Core Dimensions

5.3 Case 3 Uranium Nitride Core (SP-100)

In general, the overall geometry of this case (as modelled) is identical to that of Case 1 and is depicted in Figures 4 and 5. The difference lies in the composition of the fuel region. The core consists of uranium nitride fuel pins (with a rhenium liner and niobium-1 percent zirconium clad) in a hexagonal array. These fuel pins are identical to those planned for the SP-100 GES program. However due to the unavailability of rhenium cross sections, tungsten has been substituted in this analysis. The pitch-to-diameter ratio is 1.1 and the interstitial volume is filled with static liquid lithium. This lithium is used to conduct the heat generated in the fuel rods to the outside of the reactor vessel where it is converted to electricity. Heat pipes are again used to reject the waste heat to space. The fuel is 95% enriched. Actual dimensions of the fuel pins used in these calculations are:

fuel pellet diameter	1.021 cm
liner thickness	0.013 cm
gap	0.006 cm
clad thickness	0.038 cm
overall fuel pin diameter	1.135 cm

The nominal power for this reactor is 1-30 kWe. Table 4 shows the compositions of the material regions used in modeling this concept. Final dimensions and masses of the reactor system are shown in Table 5.

Note these results are consistent with the GE/LANL results for a downsized SP-100 as shown in Figure 8 (Pluta 1987).

5.4 Case 4 Uranium Nitride Core (SP-100) with Large Fuel Pin

This case is identical to case 3 except the fuel pellet diameter is increased by 20% to 1.2252 cm, giving an overall fuel pin diameter of 1.3392 cm. The reactor composition is given in Table 6, dimensions and masses are given in Table 7. Nominal power for this design is 1-40 kWe.

Region	Composition	Volume Fraction
Fuel	UN W Nb Li void	0.61 0.03 0.10 0.25 0.01
Reflector	BeO	1.00
Thermionics	W Nb void	0.40 0.40 0.20
Heat Pipes	W K void	0.20 0.20 0.60

Table 4. Uranium Nitride Core (SP-100) Region Compositions

1. Uranium Nitride Core (SP-100) With Internal Reflector		
Dimensions	Radius Height Length Diameter	9.35 cm 18.7 cm 35.7 cm 32.7 cm
Mass	Fuel Region (UN	52.44 kg 44.80 kg)
	Reflector Region Thermionics Region Heat Pipe Region	67.54 kg 32.18 kg 24.48 kg
2. Uranium Nitride Core (SP-100) With External Reflector		
Dimensions	Radius Height Length Diameter	10.35 cm 20.7 cm 37.7 cm 34.7 cm
Mass	Fuel Region (UN	71.13 kg 60.77 kg)
	Reflector Region Thermionics Region Heat Pipe Region	88.04 kg 7.64 kg 7.96 kg

Table 5. Uranium Nitride Core (SP-100) Dimensions

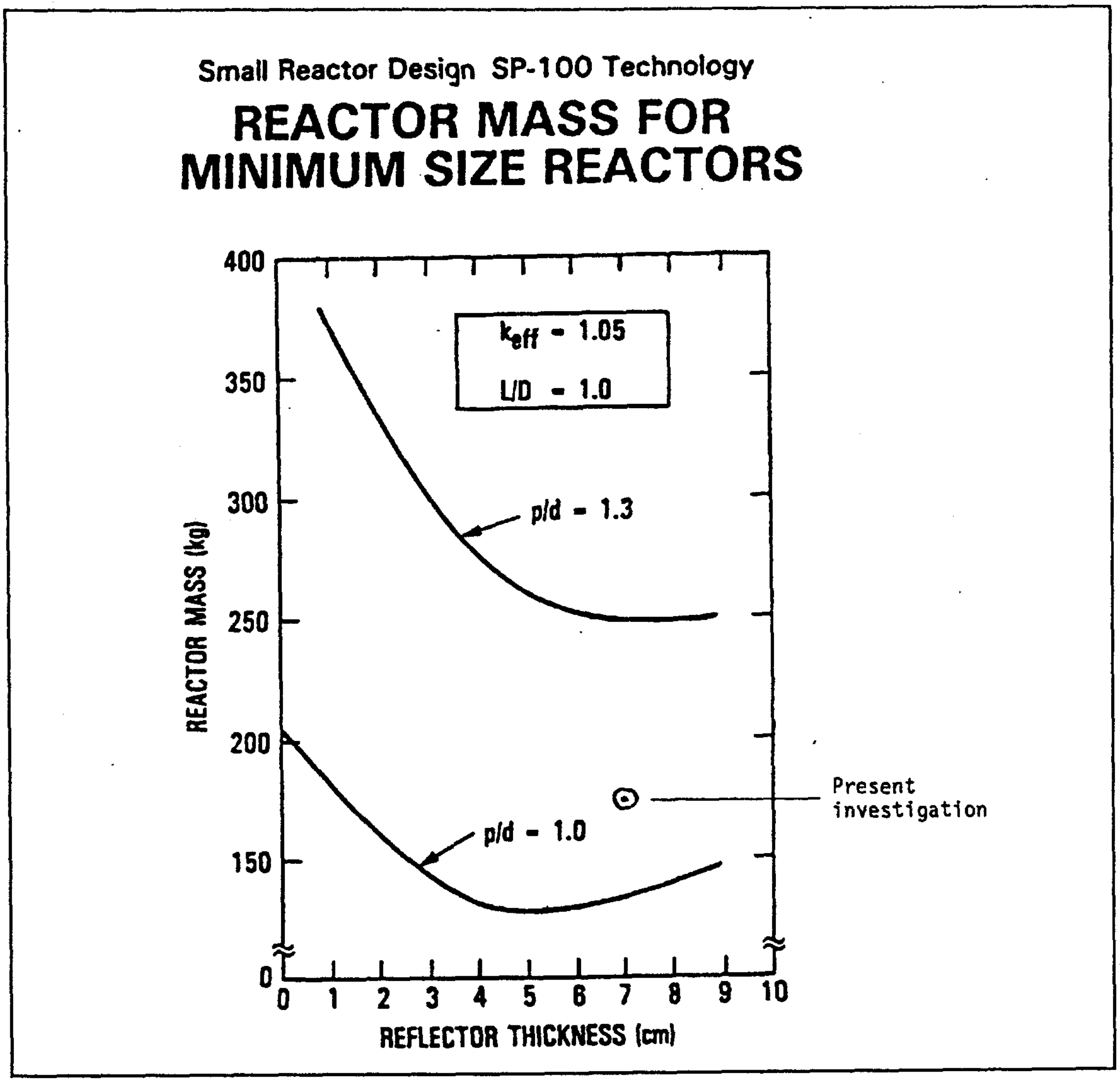


Figure 8. Comparison with GE/LANL Results

Region	Composition	Volume Fraction
Fuel	UN W Nb Li void	0.63 0.03 0.08 0.25 0.01
Reflector	BeO	1.00
Thermionics	W Nb void	0.4 0.4 0.2
Heat Pipes	W Nb void	0.2 0.2 0.6

Table 6. Uranium Nitride Core (SP-100, with Large Pin) Region Compositions.

1. Uranium Nitride Core (SP-100, with Large Pins) With Internal Reflector		
Dimensions	Radius Height Length Diameter	9.00 cm 18.0 cm 35.0 cm 32.0 cm
Mass	Fuel Region (UN	46.77 kg 41.27 kg)
	Reflector Region Thermionics Region Heat Pipe Region	64.00 kg 31.11 kg 23.69 kg
2. Uranium Nitride Core (SP-100, with Large Pins) With External Reflector		
Dimensions	Radius Height Length Diameter	10.4 cm 20.8 cm 37.8 cm 34.8 cm
Mass	Fuel Region (UN	72.16 kg 63.67 kg)
	Reflector Region Thermionics Region Heat Pipe Region	88.63 kg 7.71 kg 8.03 kg

Table 7. Uranium Nitride Core (SP-100, with Large Fuel Pins) Dimensions

5.5 Out of Core Convertor Design

This design is radically different from the reactor concepts analyzed to this point. Electric power in Cases 1 through 4 was produced from heat energy by thermionic convertors that were integral parts of the fuel elements. This concept places the thermionics outside the core, using conventional mixed oxide pellets inside a metal clad as the fuel elements.

This reactor concept is a fast fission, heat pipe cooled core fueled with uranium/plutonium mixed oxide fuel and clad with a molybdenum/rhenium alloy. The uranium in the fuel is enriched to 100% ^{235}U; ^{240}Pu, the only plutonium isotope used, is added for reasons of non-proliferation. (Note: Cases were also run with 100% enriched uranium replacing the ^{240}Pu on an atom per atom basis. These cases are designated below as Out-of-Core/Uranium). Heat removal is accomplished by the use of lithium heat pipes constructed from a tungsten/rhenium alloy, and power conversion is by out of core thermionic convertors.

Control of this concept is achieved by boron carbide poison drums integrated with the radial reflectors, which are made of beryllium oxide. A central channel is also provided for a shutdown control rod of boron carbide. Figure 9 shows a nominal 6 kWe reactor configuration for the maximum reactivity cases, and Table 8 shows the represented region compositions. For shutdown and launch, the control drums are rotated in order to face their boron carbide surfaces toward the core and the central control rod is inserted. This configuration is then maintained for the water immersion cases. For the flooding and sand burial accident scenarios it is assumed that the control drums remain intact and in their shutdown configuration due to their integration into the radial reflector. It is also assumed that the central control rod remains in place and that all of the heat pipes are sheared off and water is allowed to fill their inside volumes.

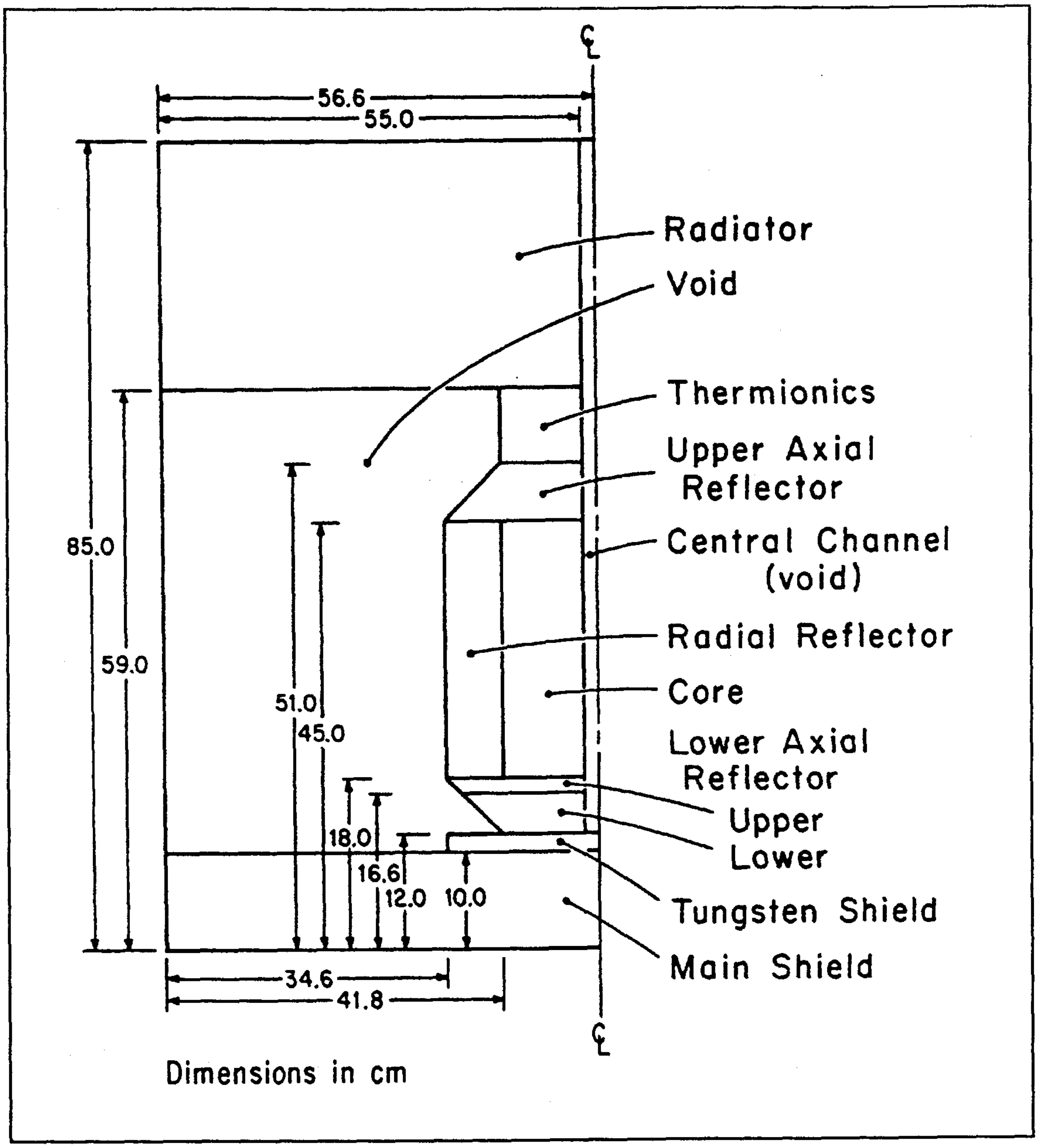


Figure 9. Out-of-Core Converter/Uranium-Fueled Reactor

Region	Composition	Volume Fraction	Mass (kg)
Central Channel	Void (operating) B_4C (shutdown)	1.00	0.46
Core	U-Pu Oxide W	0.86 0.14	110 38
Upper Reflector	BeO W	0.86 0.14	18
Lower Reflector top portion	BeO W	0.95 0.05	4.2 1.5
lower portion	BeO	1.00	10
Radial Reflector	BeO B_4C	0.50 0.50	23 23
Tungsten Shield	W	1.00	48
Main Shield	LiH	1.00	11
Thermionics	W Mo	0.95 0.05	31 5
Radiator	Mo	1.00	430

Table 8. Out of Core Convertor Design Region Compositions.

6.0 TRICE Multimegawatt Reactor

This concept is a modification of the TRICE in-core thermionic multimegawatt reactor using 95% enriched fuel (Rasor 1987). The primary modification to the design which is analyzed here is in the arrangement of the fuel pins in identically numbered rings in order to maintain the same output voltage in each ring (Figure 10). In this design the emitter also functions as the fuel rod liner, the collector acts as the cladding, and heat is removed from the outside of the cladding/collector by flowing lithium. Heat is then rejected to space outside the reactor vessel by means of heat pipes or other radiators.

The use of in-core thermionics imposes a limit on the length of the fuel pin at approximately 25 cm. To achieve criticality while maintaining reasonable mass and geometry, the modules are to be stacked on top of each other in an attempt at maintaining the length-to-diameter ratio close to unity.

Again, MCNP was used to analyze the criticality feasibility and safety of this concept. The following assumptions apply:

a) cylindrical geometry,

b) core height fixed,

c) no reactivity control present,

d) 7 cm radial reflector, no axial reflectors,

e) each reactor region was treated as a homogeneous mixture of the appropriate materials, and

f) fuel region was split into three parts to model the change in fuel pin density as radial distance increased.

The actual geometry modeled is shown in Figure 11, and region compositions are given in Table 9. Dimensions and masses of a potential configuration are reported the results.

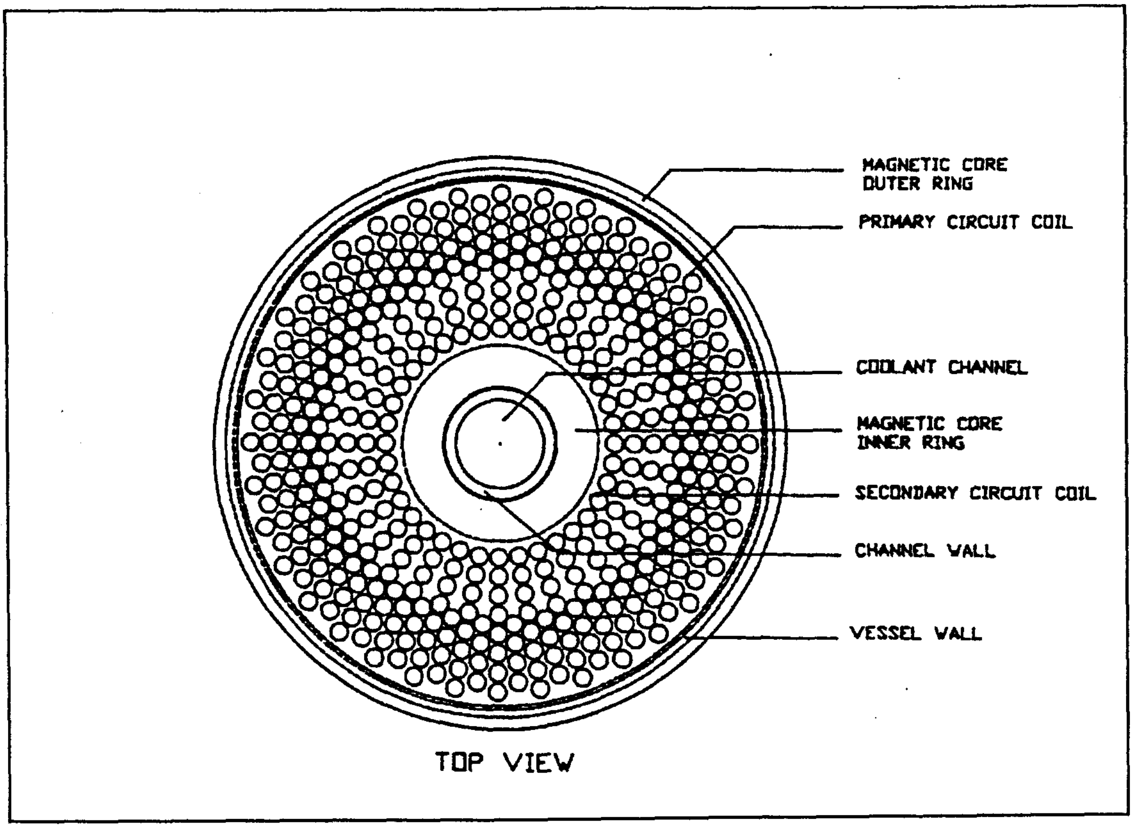


Figure 10. TRICE Multimegawatt Reactor Fuel Pin Arrangement

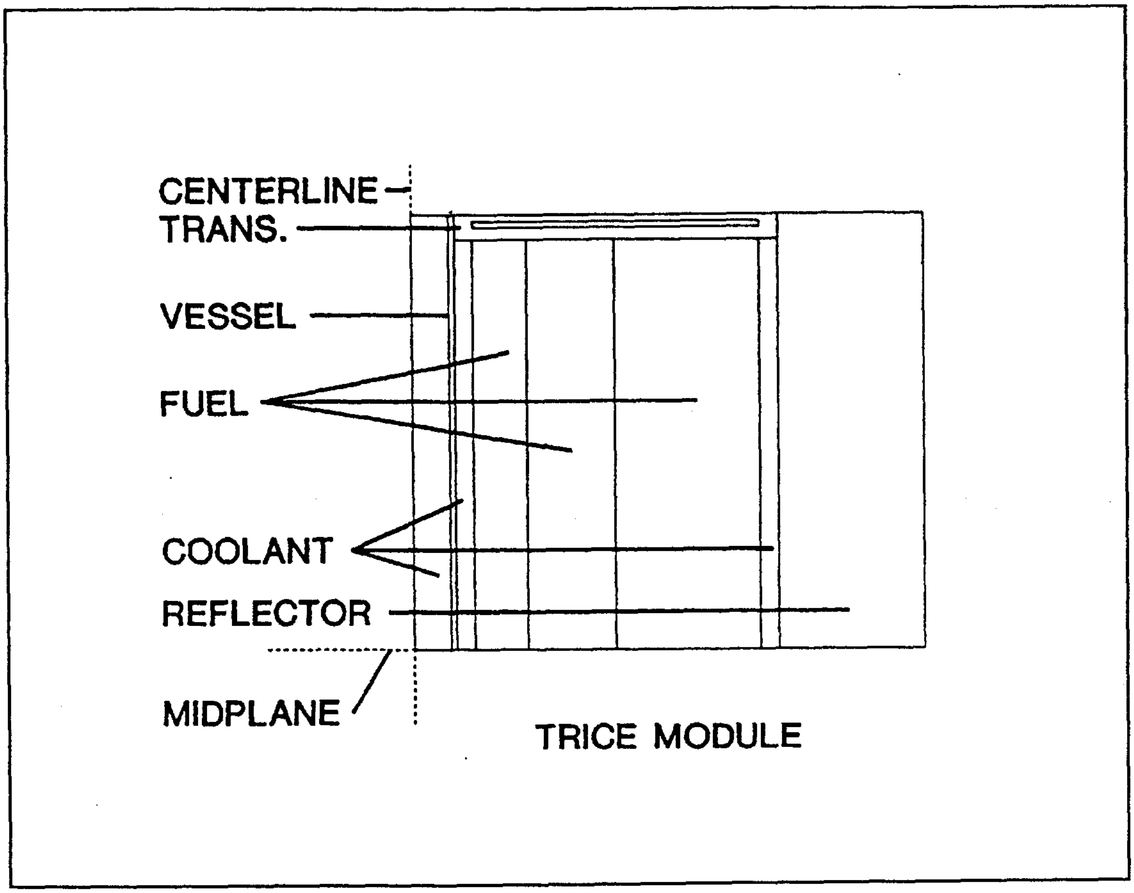


Figure 11. TRICE Module (Cutaway View of Right Side)

Region	Composition	Volume Fraction		
Fuel	UO_2 Li W void	0.19 0.45 0.30 0.06	0.24 0.30 0.38 0.08	0.20 0.42 0.31 0.07
Coolant	Li	1.0		
Reflector	BeO	1.0		
Vessel	Nb-1Zr	1.0		
Transformer	Fe	1.0		

Table 9. TRICE Core Region Compositions

7.0 Criticality Feasibility and Safety Evaluation

7.1 Solid Core

The initial feasibility results for this reactor appear to be quite encouraging. Looking at the internal reflector geometry first, Table 10 shows that this reactor nearly meets all the criticality objectives except the last one--compaction. It is felt that failure to meet the compaction objective of 0.95 is not a serious problem. This scenario was simulated by increasing the fuel region density by 10%, and since the solid core configuration here is a solid piece of metal, a 10% compaction is probably not very reasonable. The water flooding case only slightly exceeds the objective of 0.95, and the addition of a small amount of boron carbide (perhaps as a burnable poison mixed with the fuel) could easily help reach that goal.

Table 11 shows the results for the external reflector geometry. As the radial reflector is now much farther away from the core, it is less efficient and the thermionics and heat pipes act as control materials by parasitically absorbing neutrons; therefore, a slightly larger reactor core region is necessary. However, the external reflector geometry comes very close to meeting the criticality objectives. Only the compaction objective is exceeded, and that not by much. Again, since this is a solid core, a 10% compaction may not be a reasonable scenario.

Scenario	k_{eff}	Comments
Maximum Reactivity	0.983 1.071	R = 12.0 cm. R = 13.4 cm.
Launch Configuration	1.004 0.953 0.821	1.5 cm (radius) Shutdown Rod. 2.5 cm (radius) Shutdown Rod. 1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Immersion	0.876	1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Flooding	0.968	1.5 cm (radius) Shutdown Rod, no reflector.
Sand Burial	0.922 0.936	1.5 cm Shutdown Rod, no reflector, SiO_2. 1.5 cm Shutdown Rod, no reflector, $CaCO_3$.
Compaction	1.016	10% fuel region density increase, flooded.

Table 10. Results--Solid Core (UO_2) With Internal Reflector.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.060 1.030	R = 13.9 cm. R = 13.4 cm.
Launch Configuration	0.842	1.5 cm (radius) Shutdown Rod.
Water Immersion	0.905	1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Flooding	0.926	1.5 cm (radius) Shutdown Rod, no reflector.
Sand Burial	0.935 0.932	1.5 cm Shutdown Rod, no reflector, SiO_2. 1.5 cm Shutdown Rod, no reflector, $CaCO_3$.
Compaction	0.979	10% fuel region density increase, flooded.

Table 11. Results--Solid Core (UO_2) With External Reflector.

7.2 Annular Core (UO_2)

The results for the next reactor configuration are shown in Tables 12 and 13. Although the internal reflector concept does not meet the desired maximum reactivity objective, it seems reasonable to expect that a small increase in fuel mass (a few kg) will be sufficient to achieve the goal. As it is, it easily meets the launch and water immersion criteria and nearly meets the flooding and sand burial criteria. The external reflector design (Table 13) meets the maximum reactivity and launch configuration goals, but exceeds the water immersion objective.

Both designs exceed the compaction objective by a significant amount. It is possible that this problem can be minimized by including additional fixed or burnable poison.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.018	12 cm thick fuel region.
Launch Configuration	0.998 0.842	1.5 cm (radius) Shutdown Rod. 1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Immersion	0.910	1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Flooding	0.960	1.5 cm (radius) Shutdown Rod, no reflector.
Sand Burial	0.972 0.945	1.5 cm Shutdown Rod, no reflector, SiO_2. 1.5 cm Shutdown Rod, no reflector, $CaCO_3$.
Compaction	1.015	10% fuel region density increase, flooded.

Table 12. Results--Annular Core (UO_2) With Internal Reflector.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.049 1.005 1.070	12.8 cm thick fuel region. 12.0 cm thick fuel region. 13.0 cm thick fuel region.
Launch Configuration	0.886	1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Immersion	0.970	1.5 cm (radius) Shutdown Rod and Thin Reflector.
Water Flooding	0.956	1.5 cm (radius) Shutdown Rod, no reflector.
Sand Burial	0.964 0.967	1.5 cm Shutdown Rod, no reflector, SiO_2. 1.5 cm Shutdown Rod, no reflector, $CaCO_3$.
Compaction	1.013	10% fuel region density increase, flooded.

Table 13. Results--Annular Core (UO_2) With External Reflector.

7.3 Uranium Nitride Core (SP-100)

The results for the internal and external reflector geometries of this concept are shown in Tables 14 and 15, respectively. Both systems easily meet the first three objectives (maximum reactivity, launch configuration, water immersion); however, both have a significant amount of trouble with the water flooding criteria -- the internal reflector concept marginally, the external reflector more seriously. This is a consequence of replacing the static lithium bath with water. Surprisingly, both concepts have significant excess reactivity in the sand burial cases, exceeding the water flooding cases. General Electric has reported a similar result in the design of the SP-100 space reactor (Pluta, 1987). This problem is evidently dependent on the fuel region composition as it was shown above that the Solid Core (UO_2) systems are geometrically identical to the Uranium Nitride systems; yet for the UO_2 systems, water flooding is definitely the more limiting scenario. The compaction criteria is failed in both the external and internal reflector cases by a large amount, and substantial design work will be needed to overcome the deficiencies in both compaction and burial situations.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.053 0.951	R = 9.35 cm. R = 8.35 cm.
Launch Configuration	0.998 0.960 0.750	1 Pin per Quarter Shutdown Rod. 2 Pins per Quarter Shutdown Rods. 1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Immersion	0.801	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Flooding	0.958	1 Pin per Quarter Shutdown Rod, no reflector.
Sand Burial	 1.016 1.015	1 Pin\Quarter Shutdown Rod, no reflector, in SiO_2. in $CaCO_3$.
Compaction	1.052	10% fuel region density increase, flooded.

Table 14. Results--Uranium Nitride Core (SP-100) With Internal Reflector.

Scenario	k_{eff}	Comments
Maximum Reactivity	0.975 1.050	R = 9.35 cm. R = 10.35 cm.
Launch Configuration	0.809	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Immersion	0.878	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Flooding	0.994	1 Pin per Quarter Shutdown Rod, no reflector.
Sand Burial	 1.027 1.007	1 Pin\Quarter Shutdown Rod, no reflector, in SiO_2. in $CaCO_3$.
Compaction	1.050	10% fuel region density increase, flooded.

Table 15. Results--Uranium Nitride Core (SP-100) With External Reflector.

7.4 Uranium Nitride Core (SP-100) with Large Pin

Tables 16 and 17 contain the criticality results for the large pin SP-100 system. As with the smaller fuel pins, both reflector geometries of the large fuel pin system easily satisfy the maximum reactivity, launch configuration and water immersion objectives. Both geometries exceed the desired water flooding reactivity, again as a result of water replacing lithium in the fuel region. Interestingly, the sand burial scenarios turn out to be less limiting for the internal reflector design, and more limiting for the external reflector. Also, it is seen that the sand burial cases appear to be less of a problem for the larger fuel pin design than for the nominal SP-100 design. Further studies are recommended to determine the cause of this effect. Again, both reflector geometries fail to remain subcritical upon undergoing compaction. This system requires a substantial redesign effort if it is to remain viable.

Scenario	k_{eff}	Comments
Maximum Reactivity	0.940 1.079 1.013	R = 8.0 cm. R = 9.0 cm. R = 8.9 cm.
Launch Configuration	0.980 0.953 0.733	1 Pin per Quarter Shutdown Rod. 2 Pins per Quarter Shutdown Rod. 1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Immersion	0.792	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Flooding	1.010	1 Pin per Quarter Shutdown Rod, no reflector.
Sand Burial	 0.971 0.956	1 Pin\Quarter Shutdown Rod, no reflector, in SiO_2. in $CaCO_3$.
Compaction	1.029	10% fuel region density increase, flooded.

Table 16. Results--Uranium Nitride Core (SP-100, With Large Pins) With Internal Reflector.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.050	R = 10.4 cm.
Launch Configuration	0.835	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Immersion	0.887	1 Pin per Quarter Shutdown Rod and Thin Reflector.
Water Flooding	1.000	1 Pin per Quarter Shutdown Rod, no reflector.
Sand Burial	 1.027 1.012	1 Pin\Quarter Shutdown Rod, no reflector, in SiO_2. in $CaCO_3$.
Compaction	1.095	10% fuel region density increase, flooded.

Table 17. Results--Uranium Nitride Core (SP-100, with Large Pins) With External Reflector.

7.5 Out-of-Core Convertor Design

A variety of cases were run for this design. Tables 18 and 19 present the results for two slightly different reactor concepts. As stated earlier, the difference between the two is the replacement of the ^{240}Pu in the original design with ^{235}U on an atom per atom basis.

The launch configuration result (k_{eff} = 0.94) shows that additional negative reactivity is needed in this concept to provide adequate (0.90) shutdown prior to launch. The addition of the central control rod is insufficient (k_{eff} = 0.93) to accomplish this and some other method is required. The water immersion case, however, does meet the requirements. This is caused by the already efficient reflectors which were used in this design.

A variety of accident scenarios were modeled for the water flooding cases. In all of these cases the control drums remain intact and in their shutdown configuration. The first case assumed that the heat pipes and core void spaces were flooded with water and the central control rod removed. In this case, as well as for all of these cases, k_{eff} exceeds the limit of 0.95. The second configuration shows the effects of adding the central control rod, and while k_{eff} is less than 1.00 it does not meet the 0.95 criteria. The next two cases show the effects of flooding the heat pipes. In the first case it is seen that not flooding these spaces with water has very little effect on k_{eff}. There is a larger control rod effect in the final case without the water inside the heat pipes. The final two accident scenarios considered were burial and compaction. This design grossly exceeds the criteria for both scenarios.

The uranium results are seen in Table 19. Similar results and trends are seen as just presented for the ^{240}Pu cases. The one major difference is the increase in all of the k_{eff} values across the table. While the maximum reactivity values now fall within the acceptable range, all of the other results either now move out of the acceptable range or move farther outside the range.

This concept will obviously require a considerable amount of re-design, especially for control and launch safety. If the ^{240}Pu is replaced by ^{235}U, the need for changes is even more pressing.

Scenario	k_{eff}	Comments
Maximum Reactivity	1.051 1.042	Original case. Control drums simulated in operational configuration.
Launch Configuration	0.942 0.929	Control drums shutdown, no shutdown rod. Control drums shutdown, shutdown rod added to design.
Water Immersion	0.938	Control drums simulated in operational configuration.
Water Flooding	1.001 0.984 1.002 0.958	Heat pipes flooded, core flooded, without control rod. Heat pipes flooded, core flooded, with control rod. Heat pipes not flooded, core flooded, without control rod. Heat pipes not flooded, core flooded, with control rod.
Sand Burial	1.119 1.103	Sand burial, water in internal voids. Coral burial, water in internal voids.
Compaction	1.160	Water in internal voids.

Table 18. Results--Out-of-Core Convertor Design with Mixed Oxide Fuel

Scenario	k_{eff}	Comments
Maximum Reactivity	1.06 1.07	Original case. Control drums simulated in operational configuration.
Launch Configuration	0.96 0.93	Control drums shutdown, no shutdown rod. Control drums shutdown, shutdown rod added to design.
Water Immersion	0.97	Control drums simulated in operational configuration.
Water Flooding	1.09 1.04 1.06 1.02	Heat pipes flooded, core flooded, without control rod. Heat pipes flooded, core flooded, with control rod. Heat pipes not flooded, core flooded, without control rod. Heat pipes not flooded, core flooded, with control rod.
Sand Burial	1.151 1.145	Sand burial, water in internal voids. Coral burial, water in internal voids.
Compaction	1.221	Water in internal voids.

Table 19. Results--Out of Core Convertor Design with ^{235}U Fuel.

7.6 TRICE Multimegawatt Reactor

Considerable effort was expended in analyzing this system in order to obtain a reasonable, critical configuration. The results are summarized in Table 20. Initially, one TRICE module was considered. As mentioned previously, the height of a module is limited to 25 cm; thus in order to maintain the optimum L/D ratio of unity a fuel region radius of approximately 13 cm is needed. However, for this size reactor, k_{eff} for a single module was found to be extremely low (0.4), and increased very slowly as the fuel radius was increased, so that at a radius of 26 cm, k_{eff} was still only 0.5. As an alternative configuration, an infinite stack of these modules was analyzed, resulting in a k_{eff} value of 1.05 for a fuel zone radius of 32 cm.

Next, a stack of two modules was considered with a fuel region radius of 95 cm. This configuration yields a k_{eff} of 1.04. In this configuration, small changes in radius do not give significant changes in k_{eff}: for example, 90 cm yields k_{eff} = 1.037. The approximate mass of such a system is given in Table 21.

A three module configuration was then analyzed. A value of k_{eff} of 1.05 was achieved at a much more reasonable fuel radius of 46 cm with 65% less UO_2. This system mass is also shown in Table 21.

As a check to the calculations, the three module configuration was run with twice the number of histories per cycle used in the above analysis (1500 vs 750). This run gave k_{eff} = 1.063 as opposed to 1.056; variance was 0.0048 compared to 0.0096. However, it took roughly two and a half times longer to run--12 hours instead of 5. At this stage of the investigation, the increase in accuracy is not needed and does not justify the increased computer time. After a maximum reactivity geometry was determined, the three module TRICE reactor was subjected to the other criteria of the safety analysis. This reactor showed that it had significant excess positive reactivity for the immersion and flooding scenarios. The best way to reduce the excess reactivity is through the use of a burnable poison and gadolinium was chosen for this study. It was found that with 3.5 weight percent gadolinium added to the fuel region that there is enough positive reactivity to assure startup, yet more than enough shutdown reactivity for all four of the accident scenarios as can be seen in Table 20.

Scenario	k_{eff}	Comments
Maximum Reactivity	0.500	Single, R = 26 cm.
	0.989	Double, R = 70 cm.
	1.037	Double, R = 90 cm.
	1.041	Double, R = 95 cm.
	1.016	Triple, R = 40 cm.
	1.063	Triple, R = 46 cm, case used below.
	1.083	Triple, R = 50 cm.
	1.049	1.0 weight percent Gd.
	1.066	1.5 weight percent Gd.
	1.021	2.5 weight percent Gd.
	1.017	3.5 weight percent Gd.
Launch Configuration	1.026	100 volume percent poison rod in center.
	1.016	80 volume % poison rod, 20% Lithium.
	0.919	100 volume % poison rod, thin reflector.
Water Immersion	0.984	100 volume % poison rod, thin reflector.
	0.928	100 volume % poison rod, thin reflector, 3.5 weight % Gd.
Water Flooding	1.068	No reflector.
	0.899	No reflector, 3.5 wt% Gd.
Sand Burial		No reflector, 3.5 wt% Gd, in:
	0.897	SiO_2.
	0.899	$CaCO_3$.
Compaction	0.899	10% fuel region density increase, flooded, 3.5 wt% Gd.

Table 20. Results--TRICE Multi-megawatt Reactor.

	Dual Module Configuration	Triple Module Configuration
Fuel: Radius Height	95 cm 50 cm	46 cm 75 cm
Fuel (UO_2) Thermionics Reflector Coolant Vessel Transformer	1412 kg 3961 kg 384 kg 145 kg 2.7 kg 699 kg	330 kg 922 kg 195 kg 36 kg 2.7 kg 319 kg
Module Mass System Mass	6609 kg 13219 kg	1804 kg 5413 kg

Table 21. TRICE Reactor System Mass

8.0 Conclusions

It has been found during this study that each of the concepts studied has the potential for useful space application. However, there are uncertainties in this analysis and failures to meet the objectives in all of the reactor systems modeled. All of the concepts merit further study, however some require substantial redesign before they could receive a higher level of recommendation.

I feel that, because of mass considerations, some kind of movable reflector is the most efficient means of reactivity control. If this is accepted, then all the low power internal reflector geometry cases analyzed here are mechanically unworkable. These concepts all depend on conduction as the primary method of heat transfer from the core to the thermionics. If the reflector is inside the ring of thermionics, as it is for the internal reflector geometries, then the conduction path will obviously include the reflector. If that reflector is also used for reactivity control, then voids will be introduced into the heat conduction path, seriously degrading its heat transfer capability . For this reason, I believe that heat conduction and reactivity control are incompatible functions for the same piece of reflector material. Not explored is the possibility of using the axial reflectors for reactivity control. However, this poses possible shielding difficulties and limitations on the amount of reactivity available for control and shutdown.

The Solid Core (UO_2) reactor very nearly meets all of the design criteria, and shows real promise of being a simple, robust system ideal for low power applications. This concept has difficulty only with the compaction criterion, and there is question just how applicable this criterion is to this concept.

The Annular Core (UO_2) reactor marginally fails the flooding and burial criteria, and could be helped by the addition of burnable poisons. This concept has somewhat more trouble with the compaction scenario, and some redesign may be necessary.

The Uranium Nitride cores, both the standard fuel pin and the enlarged fuel pin cases, are attractive in that they offer considerable mass savings over the UO_2 fueled cores. However, these concepts both have significant difficulties meeting the flooding, burial and compaction criteria. Substantial effort will be required to resolve these issues. Additionally, further study is merited to investigate the possible fuel fraction effect that is evident in the sand burial cases.

The Out of Core Convertor reactor also has significant difficulties meeting the accident criteria. While variations were devised in which subcriticality was achieved, it was not below the stated goals of this study. These concepts need further refinement--suggested improvements include burnable poisons in the core, and/or increased worth of the reactor shutdown and control rods. Another concern is the use of ^{240}Pu in the fuel matrix. One of the initial "ground rules" of the design competition was no plutonium in the system (to simplify the safety analysis). Simple replacement of ^{240}Pu with ^{235}U results in a system with far too much positive reactivity. Replacement with ^{238}U may be a better option.

The TRICE multimegawatt reactor clearly benefitted from the addition of burnable poisons. In its final configuration it meets all the criteria of this study, and at this point TRICE shows great promise of being a viable system. I highly recommend more detailed study of this system to further refine it and examine the thermalhydraulic aspects of the concept.

9.0 Recommendations for Future Efforts

From the above analysis, it is evident that additional concentration is warranted on a few areas in the future. The analysis performed to date has been limited to first order, global effects, and the amount of design detail incorporated into the models has been restricted. Thus, it is strongly suggested that future efforts incorporate significantly greater design analysis, including detailed parametric design studies of the neutronic capabilities, as well as the thermal-hydraulic characteristics, of each of the concepts. This includes, but is not limited to:

--running MCNP for more histories to reduce statistical errors and including additional variance reduction techniques to increase the confidence in the results,

--more detailed geometrical modeling to include individual pin effects such as self-shielding,

--extensive sensitivity analysis on the effects of perturbations to the basic concept, data, and other uncertainties,

--extended parametric analysis of the compaction and sand burial cases including more realistic sand/water materials combinations, and

--thermal-hydraulic analysis of the various design concepts to determine their feasibility and robustness to off normal operation.

Specific additional studies include:

--more detailed analysis of all TRICE cases including more accurate analysis of the individual fuel elements and pin orientations, with emphasis on the addition of parasitic absorbers to minimize the strong reactivity insertion evident under the water flooding and sand burial cases,

--further analysis concerning the apparent pin diameter effect on the sand burial cases which were seen in the SP-100 reactor configurations.

10.0 References

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