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Final Project Report for NASA Lewis Research Center
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AN ASSESSMENT AND VALIDATION STUDY
OF NUCLEAR REACTORS FOR
LOW POWER SPACE APPLICATIONS

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**An Assessment and Validation Study
of Nuclear Reactors for Low Power
Space Applications**

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ABSTRACT

The feasibility and safety of six conceptual small, low power nuclear reactor designs was evaluated. Feasibility evaluations included the determination of sufficient reactivity margins for seven years of full power operation and safe shutdown as well as handling during pre-launch assembly phases. Safety evaluations were concerned with the potential for maintaining subcritical conditions in the event of launch or transportation accidents. These included water immersion accident scenarios both with and without water flooding the core. Results show that most of the concepts can potentially meet the feasibility and safety requirements; however, due to the preliminary nature of the designs considered, more detailed designs will be necessary to enable these concepts to fully meet the safety requirements.

1.0 INTRODUCTION

This report documents the results of a preliminary small reactor concepts feasibility and safety evaluation study performed by the Oregon State University Department of Nuclear Engineering, Dr. Andrew C. Klein, principal investigator. The study was carried out over a seven-month period from November 1986 to May 1987 and is fully compliant with the grant objectives set forth by the NASA Lewis Research Center, Harvey S. Bloomfield, Technical Officer. It was designed to provide a first-order validation of the nuclear feasibility and criticality safety assessment of six small reactor concepts provided by five U.S. corporations with interest and expertise in space nuclear power systems. Each concept proposed by industry included an appropriate power conversion and heat rejection subsystem. This study, however, addresses only the proposed reactor subsystems and includes power conversion elements only to the extent that they form an integral part of the reactor design concept. For proprietary and other reasons the six concepts have been disassociated from their industry advocates.

Validation of nuclear feasibility and criticality safety assessments of each concept was based on Monte Carlo three-dimensional model calculations of the effective multiplication factor, k_{eff} , for four configurations of each reactor concept. Each configuration represented a specific geometry case to evaluate startup and operational life capability, launch pad and ascent shutdown capability and water immersion criticality and safety for both a normal launch configuration with all shutdown subsystems in place and a post-impact launch abort configuration with all exterior control and shutdown systems removed. Optional concept variations in core poison materials, reflector and control rod/drum geometries, core

core poison materials, reflector and control rod/drum geometries, core fuel distribution and partial water flooding geometries have also been included where necessary for concept evaluation.

The small reactor concepts evaluated in this study have potential space applications for missions in the nominal 1 to 20 kWe power output range. These electrical power outputs correspond to reactor thermal power levels of from about 5 to 300 kWt depending on power conversion subsystem type and efficiency.

Many small reactor concepts have been proposed for applications in this power range. These include the well known U.S. SNAP series of reactors [1-5] as well as U.S.S.R. reactors [7].

The launch abort water immersion safety philosophy that was acceptable for U.S. space reactors in the 1960's allowed for a supercritical excursion. Current safety standards will require subcriticality under all water immersion and credible flooding situations. Therefore, low power reactor design concepts that incorporate additional poison control schemes without sacrificing operating reactivity need to be evaluated.

2.0 DESCRIPTION OF MODELING TECHNIQUES USED

2.1 Nuclear Models

The nuclear feasibility and criticality safety evaluations were performed using the MCNP Monte Carlo neutron transport code, version 3 [8]. All calculations were performed on the NASA Lewis Research Center's CRAY-XMP computer. First order criticality results are obtained for the proposed reactor concepts utilizing homogeneous, three-dimensional models of each reactor and its associated sub-systems and components as described below. It is felt that greater detail for such scoping studies is unnecessary and would not be warranted considering the level of design detail available. 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. 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 [9]. The following sections give detailed descriptions of the operational and accident scenarios modeled, and the compositional and geometrical models used for each of the six conceptual designs.

2.2 Case Descriptions and Desirable Limits

2.2.1 Maximum Reactivity

In these configurations, the maximum operating reactivity is determined to evaluate the initial criticality of each of the reactor concepts. For this analysis, all control rods are fully withdrawn, all control drums are rotated so that their absorber surfaces are faced away from the core and their reflector surfaces face inward toward the core. For concepts with sliding reflectors which are removed to allow sub-criticality, these reflectors are positioned in such a way as to provide for the maximum amount of neutron reflection. In these cases, fixed poisons are assumed to remain in the core and the objective is to estimate the maximum amount of excess reactivity available for normal operation.

The target values for 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.

2.2.2 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, control drums are rotated so that their absorber sections are facing 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 the safety of the concept after it is loaded into the launch vehicle. They also give some measure of the capability to shut-down 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 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.

2.2.3 Water Immersion

In 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, or during the loading of the reactor system into the launch vehicle. 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 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.

2.2.4 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 and any control drums. 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, heat pipes, reflector cooling tubes, etc. This includes the assumption that all coolant volume fractions in those concepts which utilize a liquid coolant (even if it is frozen solid for launch) are replaced with water and that any core heat pipes are filled with water. In addition, the resulting configuration is then submersed at the center of a 5 meter sphere of water as in the water immersion cases. No allowances for the compaction of the reactor core and reflectors are made in this modeling effort, however, since such an accident scenario would be highly design and impact dependent.

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 was possible.

2.3 Concept Models

2.3.1 Conceptual Design #1

This first reactor concept is an SP-100 derivative reactor system with uranium nitride fuel (90% enriched in U^{235}). The fuel pin cladding is the refractory metal alloy Nb-1Zr, and the reactor coolant is lithium. This coolant is assumed to be enriched to 100% in the Li^7 isotope to eliminate parasitic thermal captures by Li^6 and to reduce the formation of tritium during operation. Another feature of the reactor core is that the fuel elements are arranged in a close packed arrangement with a pitch to diameter ratio of 1.0. The lithium coolant is pumped through the core by a thermoelectric electromagnetic (TEM) pump and through an annulus outside of the radial reflector where the thermal energy is converted to electricity by an array of thermo electric (TE) conversion elements located on the outside of the reactor vessel.

The neutron economy of the reactor system is enhanced by radial and axial beryllium oxide reflectors, and reactivity control is obtained through the use of a central, fine motion control rod containing boron carbide. This rod is fully inserted for shutdown, and the drive mechanism is to be designed to provide sufficient accuracy to allow for operational reactivity control.

Figure 2-1 shows the nominal 10 kWe model used for the reactivity and safety calculations, including the dimensions of all components. Each region is homogenized for simplicity and the compositions for each region are shown in Table 2-1. Note that both the coolant plena and the TE elements are not modeled in extensive detail; however, this should not have any effect on the calculations. For the maximum reactivity

case, the control rod channel is assumed to be filled with a fuel region follower; Figure 2-1 represents the shutdown configuration. For the water flooding case, it was assumed that the entire reactor remains intact, including the control rod and the reflectors and all of the lithium coolant was replaced with water. This assumption neglects the fact that lithium will burn when exposed to air/water, and the resulting fire would likely cause damage to the reactor core and reflectors. However, for criticality calculations, it was assumed that the straightforward replacement of lithium with water on a volumetric basis would comprise a worst case accident condition.

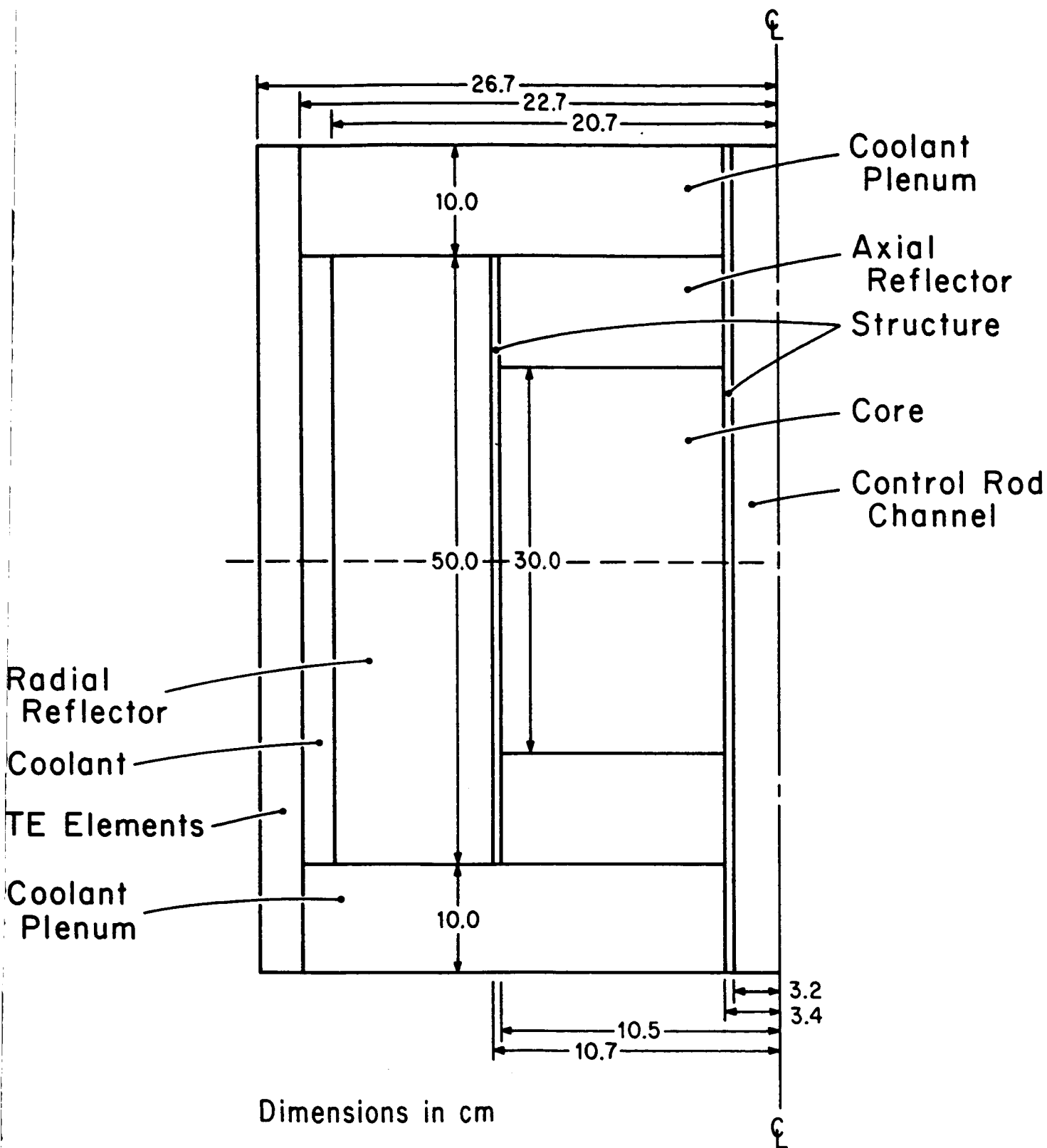


Figure 2-1. Schematic diagram of conceptual design #1.

Table 2-1. Region compositions modeled for conceptual design #1.

<u>Region</u>	<u>Composition (volume fraction)</u>
Core	UN (90.521), Nb (0.308), Li (0.093)
Control rod channel	Boron carbide (shutdown); UN (operating)
Structure	Nb
Radial reflector	BeO
Axial reflector	BeO (0.521), Nb (0.308), Li (0.093)
Coolant plenum	Li
TE elements	Si

2.3.2 Conceptual Design #2

This reactor concept is a SNAP derivative system utilizing uranium-zirconium-hydride fuel clad with stainless steel. Heat transfer from the core is provided by the forced convection of sodium-potassium (NaK), and thermal to electrical power conversion is provided by an organic Rankine cycle (ORC) heat engine using a NaK-to-organic fluid boiler.

This reactor is controlled by the motion of the radial reflector made of beryllium metal and by the incorporation of a gadolinium burnable poison coating on the fuel pin cladding. The stationary axial reflectors are also constructed of beryllium, and there is a fairly sizable region of the core designed to allow for fuel expansion. This region is constructed of stainless steel springs or collapsible expansion buttons.

The nominal 5 kWe model used for these calculations is shown in Figure 2-2, and the compositions of the respective regions are given in Table 2-2. Only the upper portion of the radial reflector is movable for reactivity control, and there is a designed shutter opening of 10.16 cm which is required for the shutdown of this reactor. The shutdown configuration is modeled in Figure 2-2, and for maximum reactivity cases this gap is completely closed. For the flooded cases, the movable radial reflectors were considered to be dislodged from the outside of the reactor with water filling these regions. Additionally, water replaces the NaK throughout the reactor core on a volumetric basis.

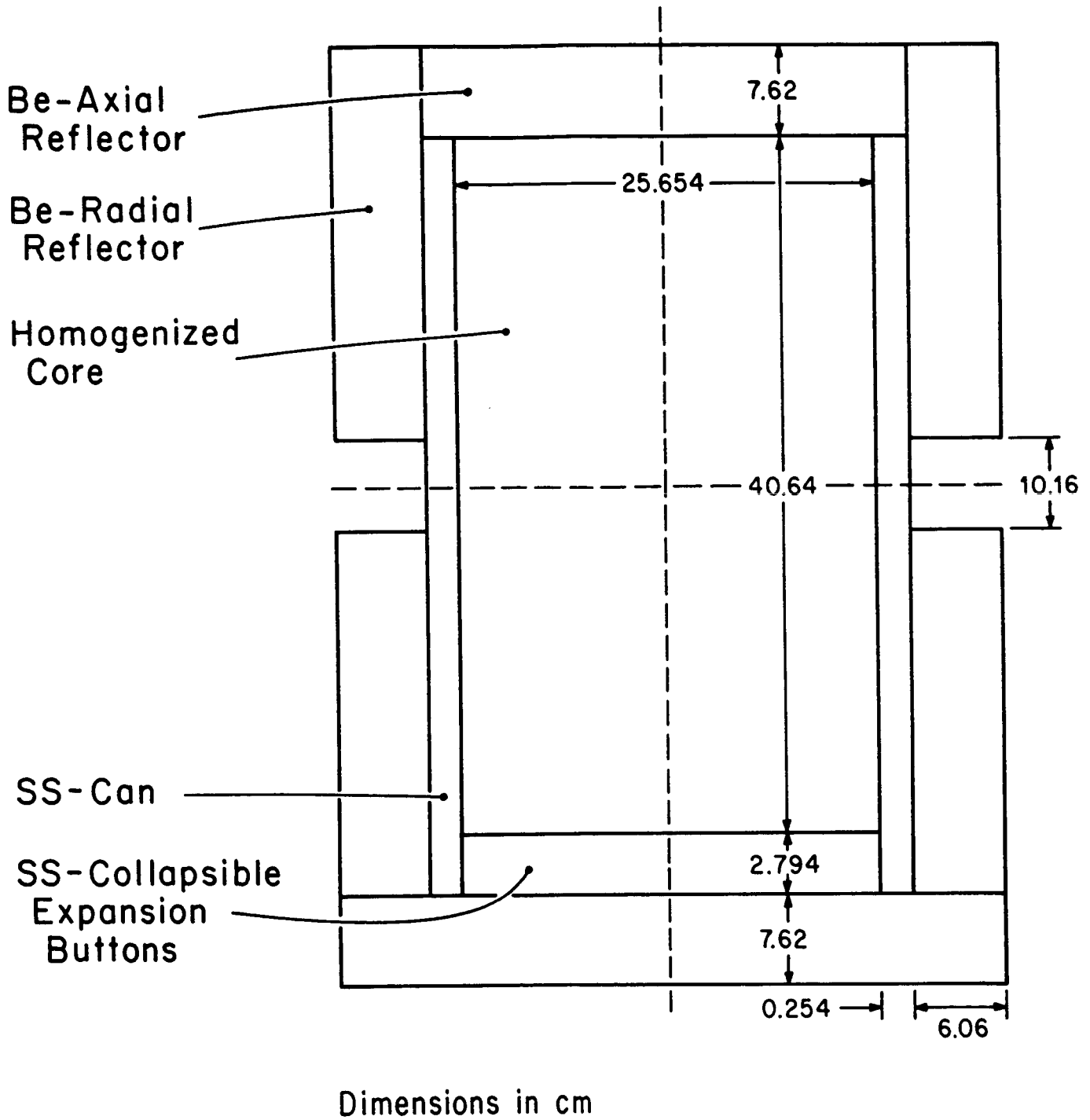


Figure 2-2. Schematic diagram of conceptual design #2.

Table 2-2. Region compositions modeled for conceptual design #2 (shutdown)

<u>Region</u>	<u>Composition (volume fraction)</u>
Core	U10Zr (U-Zr-H fuel) 0.694, Zr (0.076), NaK (0.117), SS 316 (0.088)
Can	SS 316
Axial reflector	Be
Radial reflector	Be
Collapsible expansion buttons	SS 316

2.3.3 Conceptual Design #3

This concept is based on a solid core reactor configuration. In this design, uranium carbide fueled microspheres coated with pyrolytic graphite and zirconium carbide are embedded into graphite matrix fuel disks. These fuel disks are then bonded into poco graphite fuel trays for support. There is no liquid coolant for this concept, and all of the fission heat generated must be conducted to the outside edges of the reactor through the fuel disks and graphite trays. Power conversion is by thermionic convertors fixed into the beryllium metal radial reflector.

Control of this reactor concept is by the use of movable beryllium metal axial reflectors. To obtain sufficient shutdown margin it was proposed that boron carbide plates should be placed on the top and bottom surfaces of the core, underneath the axial reflectors. These shutdown plates must then be removed for operation once the reactor is in space and in position for startup.

Figure 2-3 shows a schematic representation of the nominal 6 kWe configuration modeled during these studies. This core is modeled in considerably greater detail than most of the other reactor concepts, primarily because of its relatively simple and heterogeneous design. The core has not been homogenized; rather, ten fuel tray/disk assemblies have been modeled. Table 2-3 gives the representative compositions of the various regions modeled. The configuration shown in Figure 2-3 is the maximum achievable, normal operation reactivity case. The launch configuration is quite similar, with the axial reflectors completely removed to provide sufficient shutdown margin. For the water immersion cases, the shutdown configuration is placed as is into a 5 m sphere

of water, and for the water flooding cases, it is assumed that the axial reflectors are displaced and removed on impact, and water fills this region. Since the core itself has no coolant channels, no water is assumed to enter the core during a flooding accident.

A second basic configuration was also modeled to assess the effects of placing boron carbide in close proximity to the core exterior to attempt to reduce the thermalization and reflection of neutrons back to the core in the water immersion and flooding cases. These configurations resulted in the placement of a 0.5 cm thick B_4C annulus around the outside of the radial reflectors, outside of the thermionic elements, and a 3 cm thick disk of B_4C being placed on the top and bottom surfaces of the core. In addition, a very small hole (on the order of a few millimeters in diameter) is included in the central column of graphite for fission gas collection and removal. In the maximum reactivity case, the B_4C disks are removed and the axial reflectors are replaced on the top and bottom of the core. For the shutdown configuration, the disks are placed underneath the axial reflectors and for the water immersion case, this configuration is maintained during immersion. For the flooding case, it is assumed that the axial reflectors are displaced and removed on impact, that the boron carbide shutdown plates are dislodged from their positions, and water fills each of these regions. In all cases, however, the radial annulus of boron carbide remains intact.

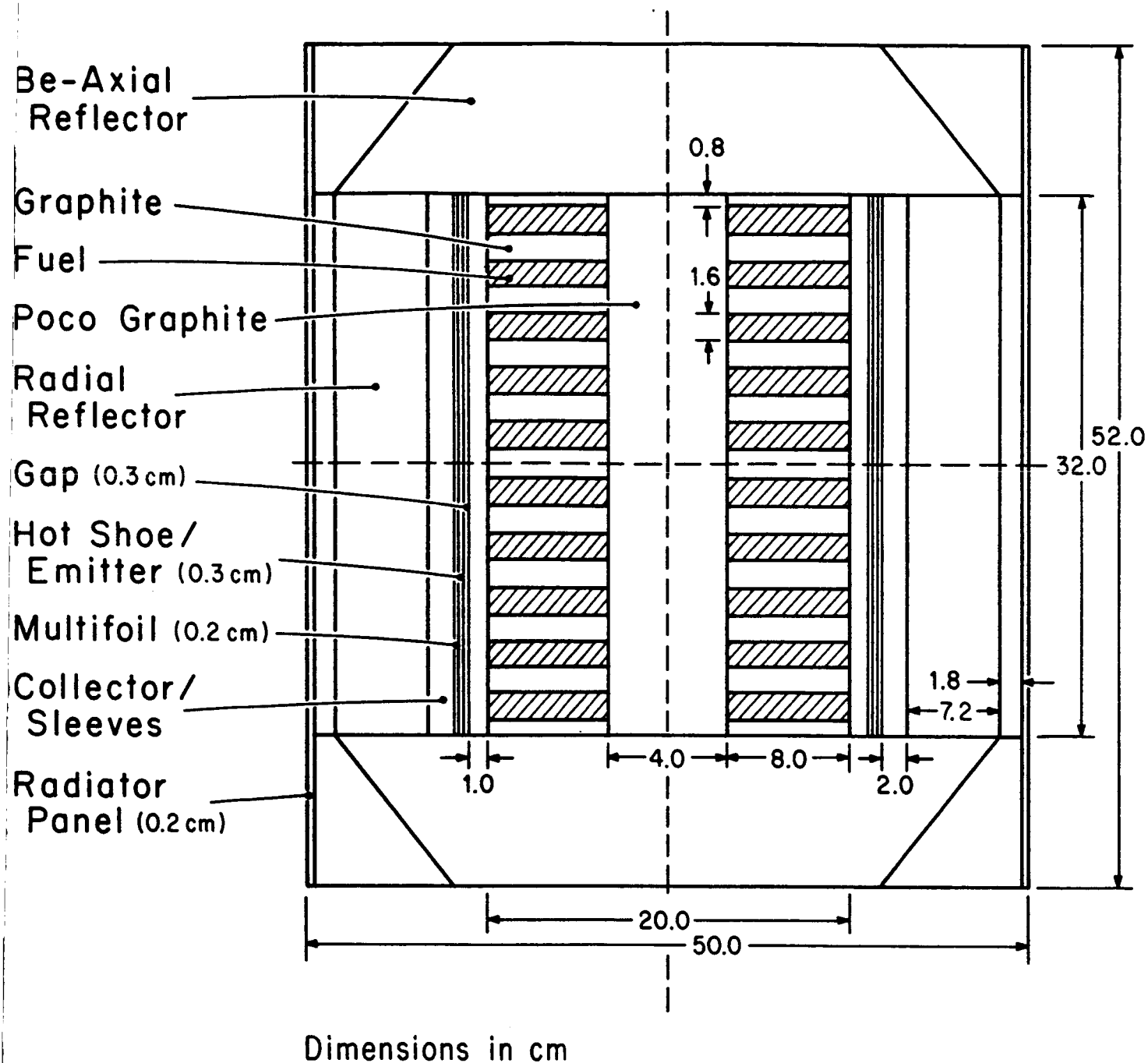


Figure 2-3. Schematic diagram of conceptual design #3.

Table 2-3. Region compositions modeled for conceptual design #3 (operating)

<u>Region</u>	<u>Composition (volume fraction)</u>
Core	UC (0.438), Graphite (0.562)
Hot shoe/emitter	W
Multifoil insulation	Nb-Ta
Collector/sleves	Be-Nb-W
Radiator panel	Nb
Axial reflector	Be
Radial reflector	Be-Nb-Al ₂ O ₃ mixture

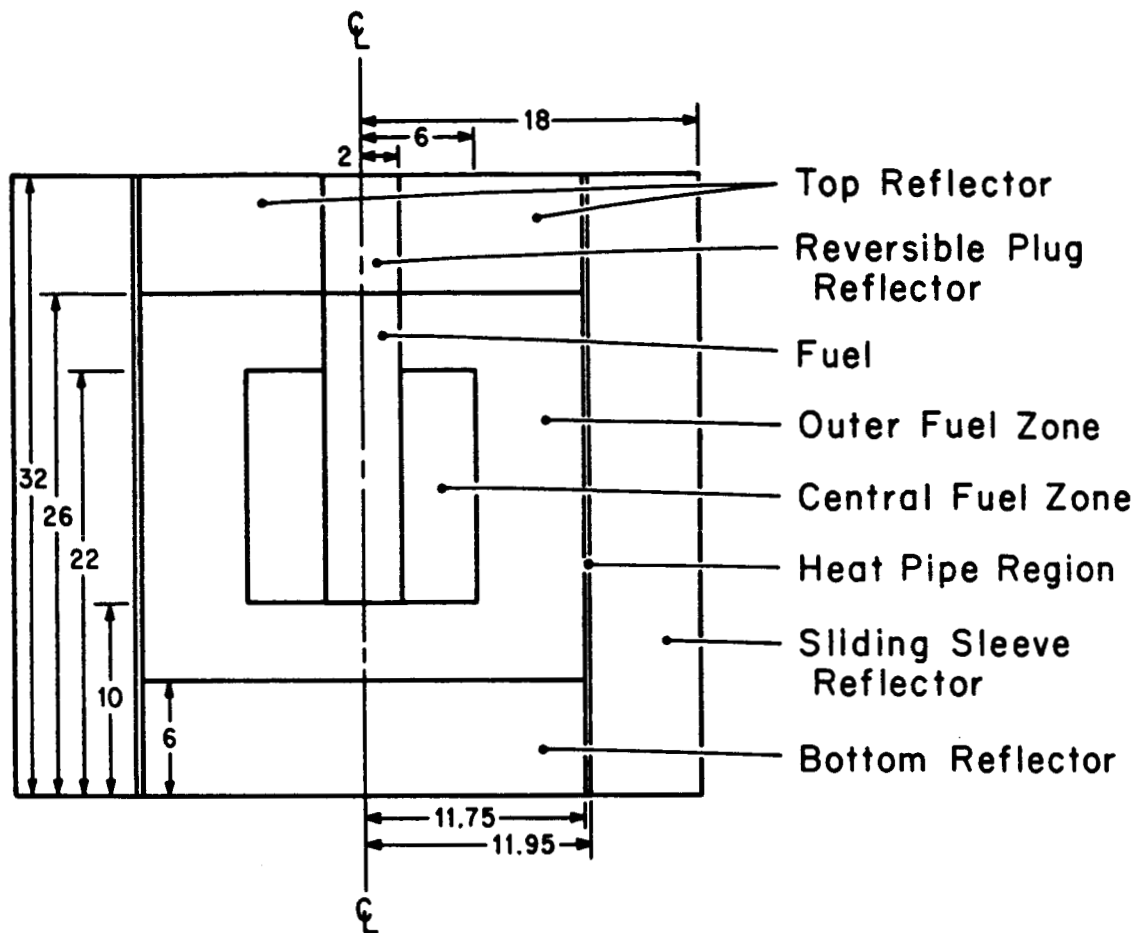
2.3.4 Conceptual Design #4

This reactor conceptual design utilizes a uranium-yttrium-hydride (U-Y-H) fuel fabricated into plates and clad with stainless steel. The uranium enrichment is 92%. It is primarily a SNAP derivative concept, except that the zirconium used in the SNAP program is replaced with yttrium for the purpose of extending the high temperature range of operation for the reactor. This fuel type may be useful at temperatures up to 1000 K, rather than the 800 K limit for U-Zr-H based fuels, due to its better high temperature retention of hydrogen [10]. Heat is removed from the core by means of disk shaped heat pipe fuel elements, and power conversion is by thermoelectric convertors attached to the outside surface of the core. Heat pipes are then used on the cold side of the thermoelectrics to radiate the waste heat into space.

Figure 2-4 shows the nominal 1.0 kWe model used for this reactor configuration. The reflector regions are in general treated as homogenized sections, but three core zones are included. There are two fuel zones represented by the plate-type heat pipes. These are shown as the "Central Fuel Zone" and the "Outer Fuel Zone." The third fuel region is part of a reversible fuel plug, made of uranium oxide clad with stainless steel. This fuel plug can be removed, reversed, and replaced for shutdown and launch configurations. The reversed, or shutdown, section of the fuel plug contains boron carbide. Thus, the model shown in Figure 2-4 is the maximum reactivity case. Reactivity is to be controlled during operation through the use of a sliding sleeve radial reflector arrangement. The compositions of the various regions are seen in Table 2-4. Note also that, due to the lack of nuclear data for yttrium, zirconium has

been substituted for yttrium throughout the core. This could greatly affect the results obtained for this concept since yttrium has a significantly higher thermal absorption cross section than does zirconium.

For the launch configuration, the sliding sleeve radial reflector is removed, and the reversible fuel plug is arranged so that the boron carbide end of the plug is inserted into the core region. This configuration was also used for the water immersion cases. For the flooding cases it is assumed that the sliding sleeve reflector is removed and water fills this region as well as all of the void spaces in the plate type heat pipes. It is also assumed that the central reversible fuel plug is dislodged on impact and water fills this region.



Dimensions in cm

Figure 2-4. Schematic diagram of conceptual design #4.

Table 2-4. Region compositions modeled for conceptual design #4

<u>Region</u>	<u>Composition (volume fraction)</u>
Reversible fuel plug	Uranium oxide (operating), B ₄ C (shutdown)
Central fuel zone	U-Y-H alloy
Outer fuel zone	U-Y-H alloy
Reflectors	Be metal
Heat pipes	Fe

2.3.5 Conceptual Design #5

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 enrichment is 100% and Pu²⁴⁰ is the only plutonium isotope used in the fuel. (Note: Cases were also run with 100% enriched uranium replacing the Pu²⁴⁰ on an atom per atom basis. These cases will be designated as Conceptual Design #5/URANIUM). Heat removal is accomplished by the use of lithium heat pipes constructed from a tungsten/rhenium rhenium alloy, and power conversion is by out of core thermionic convertors.

Control is achieved by boron carbide poison drums integrated with radial reflectors made of beryllium oxide. A central channel is provided for a shutdown control rod of boron carbide. Figure 2-5 shows a nominal 6 kWe reactor configuration for the maximum reactivity cases, and Table 2-5 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 accident scenario 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 allowed to fill their inside volumes.

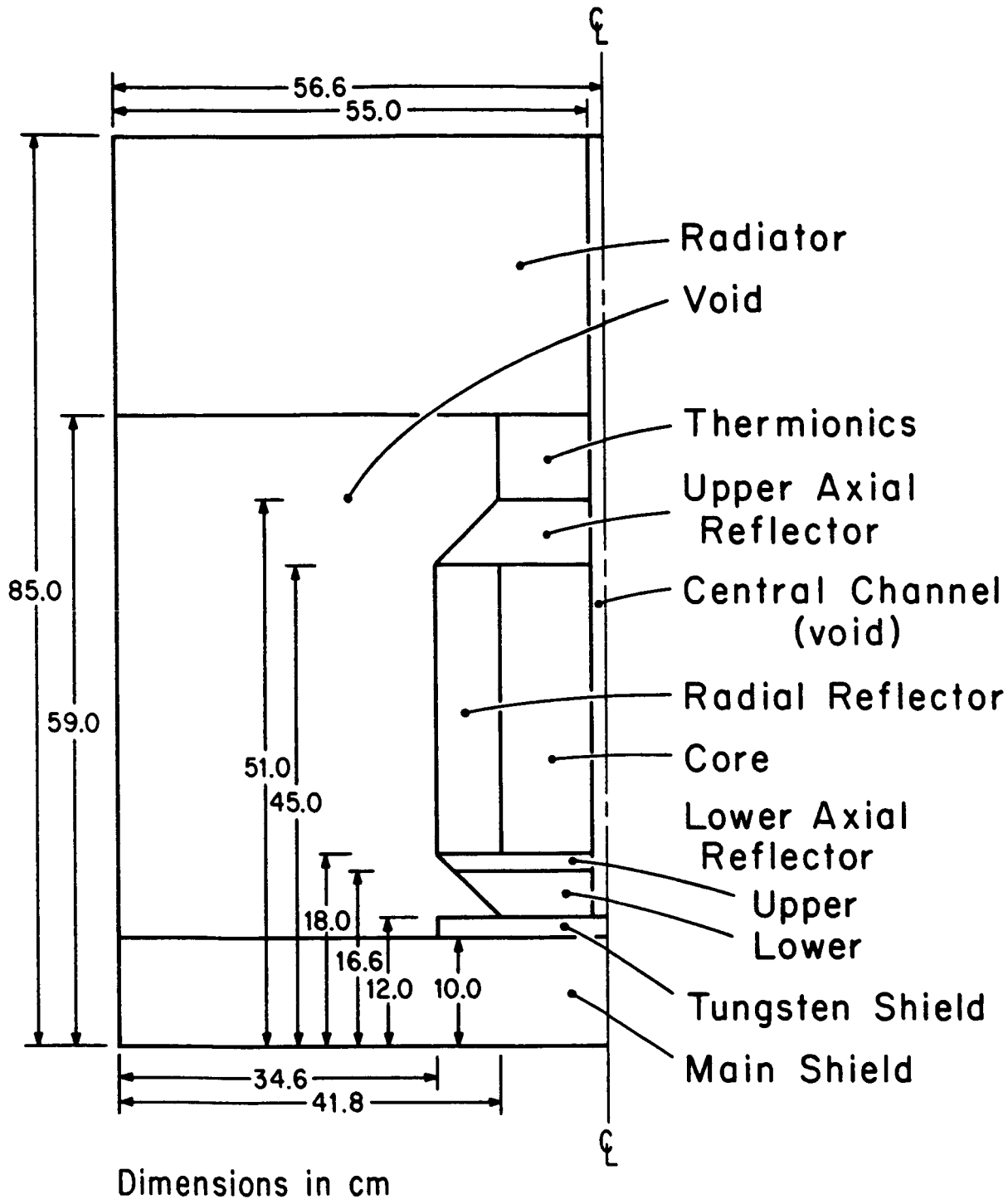


Figure 2-5. Schematic diagram of conceptual design #5.

Table 2-5. Region composition modeled for conceptual design #5

<u>Region</u>	<u>Composition (volume fraction)</u>
Central channel	Void (operating); B ₄ C (shutdown)
Core	U-Pu oxide (0.86), W (0.14)
Upper reflector	BeO (0.86), W (0.14)
Lower reflector top portion	W (0.05), BeO (0.95)
bottom portion	BeO
Radial reflector	BeO (0.5), B ₄ C (0.5)
Tungsten shield	W
Main shield	LiH
Thermionics	W, Mo
Radiator	Mo

2.3.6 Conceptual Design #6

This concept is a thermal fission, heat pipe, solid core reactor system. The fueled region consists of uranium carbide microspheres coated with pyrolytic graphite and zirconium carbide uniformly embedded into a beryllium metal matrix. Beryllium metal is utilized for both the axial and radial reflectors. Inert gas controlled, lithium heat pipes constructed of Nb-1Zr are placed within the core to remove the heat which is generated during operation. Heat is transferred through the fuel to the heat pipes by conduction and then to an AMTEC energy conversion system. The nominal power of the reactor modeled was 1 kWe.

This reactor is controlled by two independent control systems as seen in Figure 2-6. The first control mechanism is achieved through the use of shutdown control rods which penetrate the core, and the second consists of rotating control drums embedded into the radial reflector. The compositions of the regions modeled is shown in Table 2-5. Figure 2-6 represents a maximum reactivity case in which the internal control rods are fully removed and the control drums are rotated outwardly. For shutdown and launch configurations, the control drums are rotated inward and the shutdown rods are inserted. The water immersion cases also utilize this configuration. For the flooding cases the control drums are removed, the central control rod is assumed to remain intact, and all of the heat pipes are filled with water.

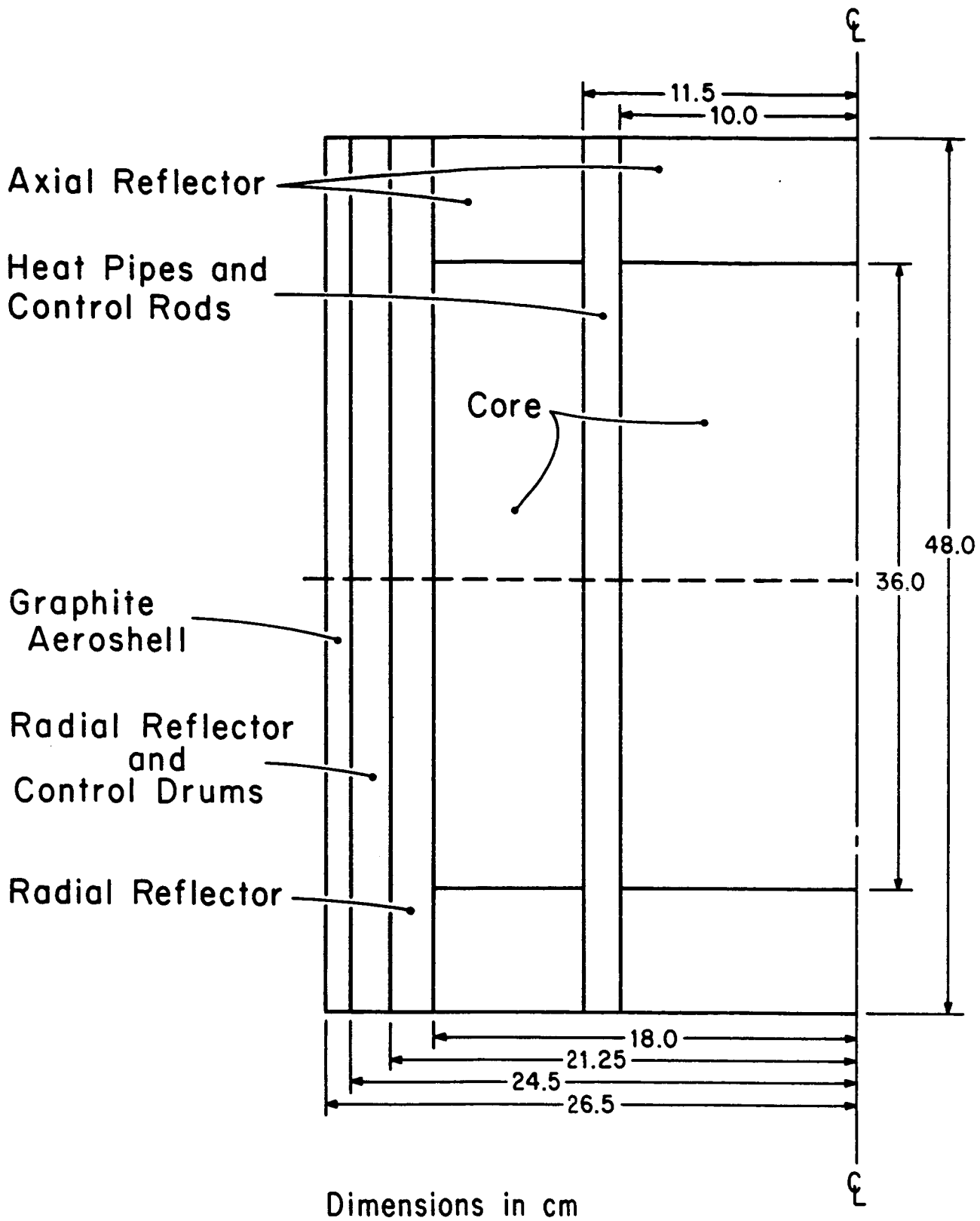


Figure 2-6. Schematic diagram of conceptual design #6.

Table 2-6. Region compositions modeled for conceptual design #6

<u>Region</u>	<u>Composition (volume fraction)</u>
Core	Uranium carbide (0.24), ZrC (0.08), C (0.08), Be (0.60)
Heat pipes and control rods	Uranium carbide (0.223), ZrC (0.074), C (0.074), Nb (0.156), Li (0.158), Boron carbide (0.314) (shutdown), without B ₄ C for operating case
Radial reflector*	Be
Radial reflector and control drums*	Boron carbide (0.36), Be (0.64)
Axial reflector	Be
Graphite aeroshell	Graphite

* Operating case shown; for shutdown case the radial reflector and control drums region is reversed with the radial reflector region.

3.0 CRITICALITY FEASIBILITY AND SAFETY EVALUATION

3.1 Conceptual Design #1

The initial feasibility results for this reactor concept are quite encouraging. In the first three cases shown in Table 3-1 (maximum reactivity, launch configuration, and water immersion) this reactor concept nearly meets the criticality objectives. The launch configuration case only slightly exceeds the objective of 0.90, and the addition of a small amount of boron carbide would easily help reach that goal. The one case which significantly fails to meet the goal is the water flooding case. This occurred because water was assumed to completely replace the lithium coolant while the reactor core configuration was maintained. Since the exposure of lithium to water or air causes a violent fire, it is unlikely that this core configuration could be maintained during such an accident. Also, the addition of extra control rods in the core could be utilized; additional parasitic absorbers, U^{238} for example, could be incorporated directly into the fuel material, or a small fraction of Li^6 could be included in the coolant to reduce this k_{eff} value. The last two adjustments are particularly interesting in that small amounts of these materials would serve to insure the launch configuration subcriticality requirement and could then be burned up in the reactor in a rather short time. The U^{238} addition would be especially helpful in that Pu^{239} which would be produced could be utilized to reduce the amount of U^{235} necessary at launch to ensure a 7 year reactor lifetime.

Table 3-1. Criticality feasibility and safety evaluation
(k_{eff}) results for conceptual design #1

MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
1.08	0.91	0.95	1.02

3.2 Conceptual Design #2

The results for the second reactor conceptual design are shown in Table 3-2. Due to the homogeneous nature of the calculations, a range of gadolinium burnable poison values, from 0.00 to 0.02 weight percent, are shown. As can be seen, a considerable amount of fine tuning of this burnable poison is still required; however, the optimal value should fall close to 0.01 weight percent. It is obvious that at gadolinium levels less than 0.01 weight percent it is difficult to show that the reactor has sufficient shutdown margin, yet at much above this level it will be difficult to get the reactor to reach criticality. It is also obvious that this reactor concept has a problem for both the water immersion and flooding cases. This can be explained largely by the fact that this concept is based on the old SNAP safety criteria which placed a different emphasis on the direction of reactor criticality during water immersion accidents than is required today. The philosophy at that time was to allow the reactor to go supercritical during such an accident and disperse itself rapidly, thereby creating few fission products and little environmental concern. Thus, in order for a SNAP based reactor system to meet the requirement for subcriticality under these accident conditions a core re-design is needed.

It is interesting to note that the k_{eff} values for the water immersion accident scenarios are higher than those for the water flooding cases. This results because the sliding beryllium radial reflector is allowed to fall off during the water flooding accident, and it stays attached for the water immersion case. This shows that the beryllium reflector is a more efficient neutron reflector for this reactor configuration than water.

Table 3-2. Criticality feasibility and safety evaluation (k_{eff}) results for conceptual design #2

MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
1.09 ¹	1.02	1.15	1.12
1.06 ²	0.97	1.10	1.06
1.03 ³	0.92	1.03	1.01

1. No gadolinium internal poison.
2. Internal gadolinium poison in fuel zone, 0.01 weight percent.
3. Internal gadolinium poison in fuel zone, 0.02 weight percent.

3.3 Conceptual Design #3

Table 3-3 shows the criticality results for the third reactor concept. The initial data input for this concept resulted in the k_{eff} values given on the first line of the table. The maximum reactivity case is close to the required value and the launch configuration, without the shutdown disk and with the axial reflectors (which are to be used for control) completely removed, lies slightly above the target value of 0.90. The original configuration for the water immersion case is only slightly subcritical and greatly exceeds the limiting criterion. This occurs because of the reflection and moderation of neutrons escaping through the ends of the reactor. In order to exclude water from the core/reflector regions in the water immersion case, a void region is assumed in this case where the axial reflectors would be placed for normal operation. This accident scenario assumes that there is a solid container around the reactor, acting as a water barrier. In the flooding case, water is allowed to fill all of these spaces, and, due to its proximity to the core, acts as a significantly better neutron moderator and reflector than in the immersion case, causing an increase in k_{eff} to 1.07.

The second line of Table 3-3 contains the k_{eff} values for a modified configuration of conceptual design #3. In this configuration, 3 cm thick disks of B_4C are provided on the top and bottom of the core during launch to reduce the possibility of a criticality accident due to water immersion. In addition, a 0.5 cm thick annulus of B_4C surrounding the radial reflectors is provided. A small increase in the maximum reactivity is observed over the original configuration. This is apparently due

to the imperfect absorption of the B₄C radial strips and a slight amount of reflection from these strips. In the original case, any neutron leaking into this region is assumed to have escaped from the system, but the inclusion of any material, even a very good absorber like B₄C slightly increases the possibility of reflection. This conclusion can also be reached in comparing the two launch configuration results. In the original configuration, any neutron which crosses the top or bottom surfaces of the core is assumed to be removed. In the modified configuration, a small amount of reflection is possible from the combined shutdown disk and axial reflector.

The addition of the B₄C to this configuration shows its benefit in the water immersion and flooding cases. There is very little increase in the amount of reflection achieved by adding a 5 m sphere of water around the shutdown configuration. This shows how effective the boron carbide is in cutting off the return of neutrons to the core once they have leaked out of the reactor vessel. Any neutron which escapes the reactor and enters the water has very little possibility of becoming thermalized and being reflected into the core. The B₄C is very useful in absorbing these returning neutrons, especially in the water immersion case. The effect is also important in the flooding case in reducing the value of k_{eff} from 1.07 to 1.03. However, this is still an unacceptable result since it allows supercriticality. A reactor re-design that prevents removal of the 3 cm B₄C shutdown disks, or prevents water flooding is required.

Table 3-3. Criticality feasibility and safety evaluation (k_{eff}) results for conceptual design #3.

	MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
ORIGINAL CONFIGURATION	1.04	0.93 ¹	0.99	1.07
MODIFIED CONFIGURATION	1.05 ²	0.95 ³	0.95	1.03 ⁴

1. Boron carbide launch shutdown disk removed from proposer's configuration. Axial reflectors removed completely for launch.
2. Small central hole for fission gas collection and B₄C radial strips (1.5 cm).
3. Axial shutdown disks (B₄C) on top and bottom and axial reflectors placed on top of shutdown disks.
4. Axial reflectors and B₄C axial shutdown disks removed prior to flooding. Radial B₄C strips remain intact.

3.4 Conceptual Design #4

A large number of cases were required for conceptual design #4, since this reactor could not achieve initial criticality as shown in the first line of Table 3-4. A variety of design changes were attempted in order to achieve the desirable range of criticality values for maximum reactivity. The initial changes which were made involved adjusting the location of the uranium fuel within the inner and outer fuel zones of the heat pipe plates. It was found that varying the location of the fuel had an effect on the k_{eff} values, and that criticality was approached when only 1/4 to 1/3 of the uranium was placed in the inner fuel plate region and 2/3 to 3/4 in the outer region. The initially proposed concept had 2/3 of the uranium in the inner fuel region. However, this adjustment by itself was insufficient to provide enough available reactivity for reactor start up, and in order to achieve criticality, the core was made larger as shown on the bottom line on Table 3-4. In all of the cases on this line, the inner core region shown in Figure 2-4 was increased by 3.75 cm in radius and 4 cm in height. The inner fuel region was increased from 6 cm to 9.75 cm in radius, the outer fuel region increased from 11.75 cm in radius to 13.75 cm, and the overall radius of the reactor system was increased from 18 cm to 20 cm. Also, the overall height of the reactor was increased from 32 cm to 36 cm, and the central fuel zone height was changed from 12 cm to 16 cm. The resulting configuration shows quite satisfactory results for the maximum reactivity, launch configuration (achieved by inserting the boron carbide end of the reversible fuel plug and removing the sliding radial reflector

sleeve), and the water immersion cases. This is due to the large amount of negative reactivity from the reversible fuel/shutdown plug and from the effectiveness of the sliding radial reflector. (Note: The use of such a reversible fuel/shutdown plug requires an in-space operation that would allow for the removal, rotation, and replacement of this fuel plug. This concept feature needs further study.)

A significant problem exists for the water flooding case which results in supercriticality. This occurs for two reasons. The first is that on impact, the reversible fuel/shutdown plug is assumed to be dislodged. However, should the shutdown plug remain in place, the k_{eff} value would more closely approach the 0.93 value for the water immersion case. The second reason is that water is assumed to enter the shutdown plug region, the sliding radial reflector spaces, and displace the coolant in the heat pipe plates. This considerable amount of water provides a significant amount of neutron moderation, thus increasing k_{eff} . A re-design of the shutdown plug hold-down scheme to assure intact re-entry and impact is required.

Table 3-4. Criticality feasibility and safety evaluation
(k_{eff}) results for conceptual design #4

MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
0.87 ¹	0.57	0.83	
0.98 ²			
0.99 ³			
0.95 ⁴			
0.84 ⁵			
1.07 ⁶	0.75 ⁶	0.93 ⁶	1.07 ⁶

1. Cases run as received from proposer.
2. 1/4 of the uranium in the inner fuel region, remainder in outer region.
3. 1/3 of the uranium in the inner fuel region, remainder in outer region.
4. 1/2 of the uranium in the inner fuel region, remainder in outer region.
5. 3/4 of the uranium in the inner fuel region, remainder in outer region.
6. 1/4 of the uranium in the inner fuel region, remainder in outer region, and core inner region increased in radius by 2 cm and 4 cm in height. Thickness of all other regions maintained.

3.5 Conceptual Design #5

A variety of cases were also considered for conceptual design #5. Table 3-5 and the accompanying footnotes present the results for two slightly different reactor concepts. As stated earlier, the difference between the two is the replacement of the Pu²⁴⁰ in the conceptual design #5 with U²³⁵ on an atom per atom basis for the uranium cases in the lower half of the table. The top line of the table contains the results of the calculations using the detailed geometry provided by the concept's proposer. However, a flaw was found in the data describing the geometry of the concept, and when corrected, the result was a small increase in k_{eff} for the maximum reactivity cases. The third line of the table (footnote 3) contains an even more appropriate reactor configuration in which the control drums are more adequately treated. This configuration then is utilized as the "base case" for the subsequent calculations.

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 was 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 criterion. The final 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 uranium results are seen in the lower half of the table. Similar results and trends are seen as just presented for the Pu^{240} 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. It is obvious that a considerable amount of re-design is necessary, especially for control and launch safety, if the Pu^{240} is to be replaced by U^{235} .

Table 3-5. Criticality feasibility and safety evaluation (k_{eff}) results for conceptual design #5 and conceptual design #5/uranium.

	MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
CONCEPTUAL DESIGN #5	1.04 ¹	0.94	0.99	1.13
	1.05 ²			
	1.04 ³	0.94 ⁴	0.94	1.00 ⁶
		0.93 ⁵		0.98 ⁷
				1.00 ⁸
CONCEPTUAL DESIGN #5/URANIUM ¹⁰	1.06 ²			0.96 ⁹
	1.07 ¹¹	0.96 ¹²	0.97	1.09 ¹⁴
		0.93 ¹³		1.04 ¹⁵
				1.06 ¹⁶
				1.02 ¹⁷

1. Cases run as received from proposer.
2. Corrected symmetrical geometry--upper reflector and upper core 3 cm higher.
3. Footnote 2 with control drums simulated in operational configuration.
4. Footnote 2 with control drums simulated in shutdown configuration and without shutdown rod.
5. Additional shutdown margin provided by insertion of shutdown rod.
6. Heat pipes flooded, core flooded, and without control rod inserted.
7. Heat pipes flooded, core flooded, and control rod inserted.
8. Heat pipes not flooded, core flooded, and without control rod inserted.
9. Heat pipes not flooded, core flooded, and control rod inserted.
10. Replace Pu²⁴⁰ with U²³⁵ on an atom per atom basis.
11. Footnote 3 with control drums in operational configuration.
12. Footnote 7 with control drums in shutdown configuration.
13. Additional shutdown margin provided by insertion of shutdown rod.
14. Heat pipes flooded, core flooded, and without control rod inserted.
15. Heat pipes flooded, core flooded, and control rod inserted.
16. Heat pipes not flooded, core flooded, and without control rod inserted.
17. Heat pipes not flooded, core flooded, and control rod inserted.

3.6 Conceptual Design #6

The final reactor concept considered shows the most favorable criticality feasibility and safety results. As seen in Table 3-6 for the primary cases, all of the reactivity values fall within the desirable limits. The maximum reactivity of 1.07 is in the middle of the acceptable range. The launch configuration and water immersion cases show a considerable amount of available negative reactivity for shutdown and immersion accident considerations. Even with the removal of the control drums on impact and the flooding of the core heat pipes, the k_{eff} value for the water flooding case is less than 0.95.

A few extra cases were run to determine the relative shutdown capabilities of the control rods and drums. As can be seen in Table 3-6, the rotation of the control drums to their operational configuration while the control rods are inserted has only a small effect on k_{eff} . The reverse situation is not true, however. If the control drums are placed in their shutdown configuration and the control rods are removed, then criticality will be approached. Thus, a small re-design of the effectiveness of the control drums is suggested in order that by themselves they are capable of providing sufficient negative reactivity to maintain subcriticality.

A highly unlikely water flooding accident was also considered in which the core remains intact, all the control rods and control drums are removed, and the reactor is filled with water. In this case the reactor would go super critical.

Table 3-6. Criticality feasibility and safety evaluation (k_{eff}) results for conceptual design #6

MAXIMUM REACTIVITY	LAUNCH CONFIGURATION	WATER IMMERSION	WATER FLOODING
1.07	0.78 ¹	0.78	0.93 ⁴
	0.83 ²		1.16 ⁵
	1.00 ³		

1. Control rods inserted and drums turned to shutdown configuration.
2. Control rods inserted and drums turned to operational configuration.
3. Control rods removed and drums turned to shutdown configuration.
4. Control rods remain in core and control drums removed during flooding.
5. All control rods and drums removed during flooding.

4.0 SUMMARY AND CONCLUSIONS

There are two general conclusions reached by this study concerning small space reactors and also specific conclusions concerning each of the six small reactor conceptual designs.

1. Small reactor concepts are available from the U.S. nuclear industry which have the potential to meet both the operational and launch safety missions requirements.
2. Each of the concepts studied has the potential for useful space application; however, each design has its uncertainties and failures. All of the design concepts studied require further efforts to enable a more positive conclusion to be reached.

Specific conclusions on the six conceptual designs studied are:

Conceptual Design #1

This design appears to be quite satisfactory for all cases considered, except for the water flooding case. Considerable re-design will be necessary to ensure subcriticality during such an accident scenario. Small amounts of burnable poisons for launch, or increasing the number and worth of the internal control rods are two possible adjustments. However, the unlikely possibility of replacing the lithium in the core with water without seriously dispersing the fuel into a sub-critical configuration needs to be considered.

Conceptual Design #2

This design, because it is based on the SNAP10A launch criticality philosophy, fails both the water immersion and water flooding tests. A re-design of this reactor is necessary to incorporate more negative

reactivity. The inclusion of poison control rods may be sufficient to provide the necessary negative reactivity.

Conceptual Design #3

This concept includes a number of interesting features. Unfortunately, control of this reactor will be a significant problem since it utilizes only the end surfaces of the cylindrical core for reflector control. This greatly limits the amounts of positive and negative reactivity available, especially during water immersion and flooding. A proposed solution to this problem, i.e., the inclusion of boron carbide shutdown disks on the top and bottom surfaces of the core, helps matters only slightly. This is because (1) these disks must be removed in space for reactor operation, (2) even though they are very good absorbers, they still reflect a small fraction of neutrons back into the core, and (3) the disks are not likely to remain on the top and bottom core surfaces on impact during a launch accident.

Conceptual Design #4

This concept required quite a bit of effort even to reach a critical configuration. This design also fails to meet the water flooding criteria, primarily because it is not clear how the central fuel shutdown plug can remain in place on impact in a launch accident. During such an accident a significant amount of water enters the core causing neutron thermalization and supercriticality. Considerable re-design is necessary to ensure that this cannot happen.

Conceptual Design #5

This design also had trouble meeting the accident criteria; however, there were instances in which subcriticality was achieved, but not below

the requirements stated. In this case, only a small amount of re-design may be needed to reach the objectives. Suggested improvements include burnable poisons in the core, and/or increased worth of the reactor shutdown and control rods. One problem associated with this design is the use of Pu^{240} as a fuel in the core. Switching fuel from Pu^{240} to U^{235} will require a considerable amount of core re-design since this modified concept cannot meet the safety requirements.

Conceptual Design #6

This reactor conceptual design, as modeled, is the only concept to meet all of the requirements. It has sufficient negative reactivity included to enable it to remain subcritical during all of the accident cases modeled. Since the reactor modeled was based on an output power of only 1 kWe, scale-up to higher power levels must include the consideration that more control rods will be needed to ensure subcriticality for the water flooding case since a greater amount of water will have access to the center of the core if all of the heat pipes become flooded.

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