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Abstract. Several different reactivity control schemes are considered for future space nuclear reactor power systems. Each of these control schemes uses a combination of boron carbide absorbers and/or beryllium oxide reflectors to achieve sufficient reactivity swing to keep the reactor subcritical during launch and to provide sufficient excess reactivity to operate the reactor over its expected 7-15 year lifetime. The size and shape of the control system directly impacts the size and mass of the space reactor's reflector and shadow shield, leading to a tradeoff between reactivity swing and total system mass. This paper presents a trade study of drum, shutter, and petal control schemes based on reactivity swing and mass effects for a representative fast-spectrum, gas-cooled reactor. For each control scheme, the dimensions and composition of the core are constant, and the reflector is sized to provide $5 of cold-clean excess reactivity with each configuration in its most reactive state. The advantages and disadvantages of each configuration are discussed, along with optimization techniques and novel geometric approaches for each scheme.

Keywords: Space reactor, reactivity control, control drums, control shutters, control petals.
PACS: 28, 28.41-i, 28.41.Ak, 28.41.My.

INTRODUCTION

Nuclear reactors are a steady and reliable source of energy that may provide the foothold required for man's ascent into space. Space nuclear reactors are highly reliable, compact and relatively lightweight. They can operate virtually anywhere in space and have long operating lifetimes (7-15 years). They can offer higher power than solar panels or batteries and can operate regardless of their proximity to the sun. Space nuclear reactors contain minimal amounts of radioactive material at launch and are not made critical until they reach a safe operating trajectory.

Typical terrestrial nuclear reactors use control rods and chemical shimming for reactivity control (Lamarsh and Baratta, 2001). In space, chemical shimming is impractical and control of space reactors is usually accomplished by manipulation of the reactors' reflectors (Angelo and Buden, 1985). Manipulating the reactor's reflector to control reactivity keeps the reactor's core compact and reduces the number of core penetrations, which decreases the chance of a loss of coolant accident leading to premature reactor shutdown.

Figure 1 shows a typical layout of a space nuclear reactor power system. The core is surrounded by a reflector, which improves neutron economy and reduces the mass of uranium needed to achieve criticality. The shadow shield creates a 15° shadow cone inside which the payload and power conversion components are protected from the neutron and gamma radiation produced by the reactor core. The current philosophy is that the shadow shield diameter must be sufficient that all components on the core side of the shadow shield are within the shadow cone. Thus, increasing the diameter or length of the reflector can greatly increase the size and mass of the shadow shield. To allow space for the heat removal piping, there is usually a gap between the reflector and the shadow shield. The heat removal piping is routed around (or through) the shadow shield to a power conversion system, which is then connected by more piping to a radiator. The rest of the payload lies beyond the radiator.

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A space reactor's control scheme must allow for enough excess reactivity for the reactor to operate for a 7-15 year lifetime and provide sufficient shutdown margin to keep the reactor subcritical during launch. Several different approaches have been proposed and are examined in this research.

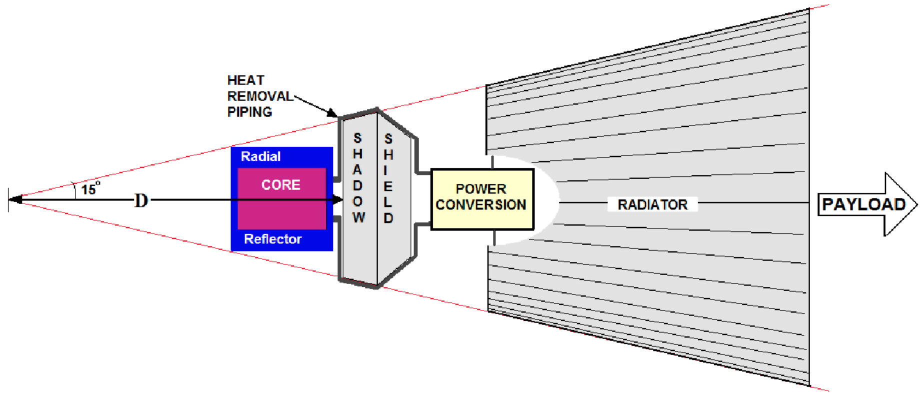


FIGURE 1. Example Space Nuclear Reactor System Layout.

Control drums are the most commonly used methods of reactivity control (Angelo and Buden, 1985). In this scheme, cylindrical beryllium oxide (BeO) drums with a thin boron carbide (B_4C) absorber segment covering a portion of the outer radius of the drum are located within the reflector around the outside of the core. This scheme controls the reactivity of the core by rotating the drums, thus changing the proximity of the absorber to the core and altering the amount of neutron reflection. A six drum control scheme is proposed in a recent metal-fueled design proposed by Poston et al (2007). The low-mass Sectored Compact Reactor (SCoRe-S) (Hatton and El-Genk, 2007), the Heatpipe Power System (HPS) for Mars outpost and manned Mars missions (Poston et. al., 2000), and the Heatpipe-Operated Mars Exploration Reactor (HOMER) (Poston, 2001) designs also use six-drum control schemes.

Interestingly, both the HPS (Poston et. al., 2000) and HOMER (Poston, 2001) designs suggest that a sliding reflector would be lighter than control drums. In this arrangement, the radial BeO reflector is segmented into shutters, which are moved axially along the core, exposing the core to more or less reflector, and thus changing the rate of neutron leakage from the core. Other proposed designs that use shutters are a gas-cooled reactor proposed by Lipinski et al. (1999), which used three beryllium metal shutters for reactivity control, and a gas-cooled reactor for nuclear-electric propulsion proposed by Wright and Lipinski (2003).

Control petals are another available reactivity control scheme. In this scheme, the radial BeO reflector is segmented into petals, which are hinged at their outer radial edge located furthest from the shadow shield. The petals are rotated toward or away from the core, exposing the core to more or less reflector, which controls neutron leakage from the core. A petal control scheme was incorporated in one of the SP-100 design variants (Deane et. al., 1989).

The reactivity effects and the masses of various components vary significantly for each control scheme, leading to a tradeoff between reactivity control and system mass. Since the optimum space reactor control scheme is not intuitively obvious, there is need for an in-depth study of the various schemes in terms of both mass and reactivity effects. This paper examines the reactivity swing and total system mass effects for both previous and novel control schemes, including a discussion of each scheme's advantages and disadvantages. The conceptual models used in this research are described in the next section.

REACTOR MODEL DESCRIPTION

Since the present research is focused on control schemes external to the reactor core, a representative gas-cooled, fast spectrum core was used for all schemes. The core composition and dimensions are based on the Submersion Subcritical Safe Space (S^4) reactor (King and El-Genk, 2006). The S^4 reactor is a fast spectrum, He(28%)-Xe gas cooled reactor that uses uranium nitride fuel and a Mo-Re structure. The hexagonal core has a 4 cm thick BeO reflector cap on both the axial sides of the core. The core is modeled as a homogeneous hexagonal block with the composition and dimensions presented in Table 1 in order to focus on the details of the external control scheme. Homogeneity is usually an acceptable assumption for small, fast spectrum reactors (Lamarsh, 2002). The reflector material in each configuration is beryllium oxide (BeO) and the absorber material, if used, is fully enriched boron carbide (B_4C).

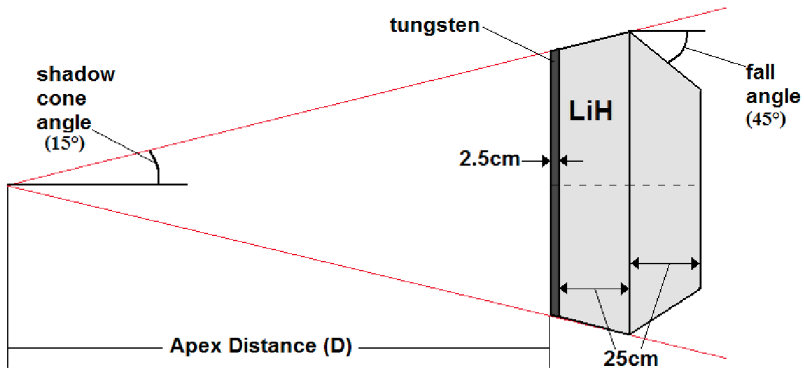


FIGURE 2. Shadow Shield Model Used in Current Research.

TABLE 1. Core Parameters.

Parameter	Value
Core Height (cm)	48.65
Front and Rear BeO Cap Thickness (cm)	4.0
Total Reactor Height (cm)	56.65
Core Layout	hexagonal
Flat-to-Flat (cm)	27.7
Core Mass (kg)	333.590
Composition (wt%)	
U235	40.0828945
U238	3.6783023
N	2.6050532
Mo	29.7584557
Re	23.8544017
He	0.0027806
Xe	0.0181120

MCNP5 (X-5 Monte Carlo Team, 2005) is used to calculate the reactor's reactivity for each configuration. The MCNP model used 10 inactive and 200 active cycles with 20,000 particles per cycle. Standard deviations for the calculated k_{eff} are ~0.00035 ($0.05). The ENDF66b (.66c) libraries included with MCNP were used for the materials in the model (X-5 Monte Carlo Team, 2005). The shadow shield was not included in the MCNP models, as it is expected to have a negligible effect on reactivity. Reactivity values are based on an assumed delayed neutron fraction of 0.007.

The shadow shield mass model, shown in Figure 2, is based on the shadow shield proposed in the Scalable AMTEC Integrated Reactor Space (SAIRS) design (El-Genk and Tournier, 2004) and is used for all control schemes. The shadow angle is held at 15°. A 2.5 cm thick tungsten plate is the first shielding layer between the core and the payload and provides gamma shielding. The gamma shield is followed by a 50 cm thick lithium hydride (LiH) layer to provide neutron shielding. The shield is conical with a 15° shadow angle up the halfway point of the LiH layer, after which the shield closes conically at a fall angle of 45°. MA-ODS steel cladding (0.5 mm thick) surrounds the shadow shield. The apex distance (D in figure 2) is the distance between shadow shield and the apex of the shadow cone.

Without a reflector, the calculated reactivity of the bare core is -$42.47 (k = 0.70268). The reflector in each control scheme was adjusted to provide $5.00 of cold, clean excess reactivity in the most reactive state, representing a maximum possible reflector worth of $47.47.

For each configuration, the total system mass is calculated as a function of the amount of reactivity swing provided by the control system. A larger reactivity swing will generally require a larger reflector/shadow shield, and thus the reactivity swing provided by any given control scheme effects the size (and mass) of the resulting reactor system. Reactivity swing is defined as the difference between the least reactive (shutdown) state and the most reactive (excess reactivity) case. Total system mass is the sum of the mass of the core, the specific reflector for each control scheme, and the shadow shield. Control shutters are considered in the next section, followed by control drums, and then control petals.

CONTROL SHUTTERS

Shutter control schemes provide reactivity control by moving parts of the reflector (shutters) axially away from the core (Figure 3). Some proposed designs with shutter controls are a gas-cooled reactor proposed by Lipinski et al. (1999), which used three beryllium metal shutters for reactivity control; and, a gas-cooled reactor for nuclear-electric propulsion proposed by Wright and Lipinski (2003). At shutdown, the shutters are positioned away from the reactor and are moved toward the core to provide positive reactivity. Because of this motion, the shutters require space to be withdrawn/inserted. This space must be within the area covered by the shadow shield, increasing its mass, which is a possible disadvantage to this control scheme. Both the reflector shape and direction of travel are considered in the following subsections.

Full Shutter Insertion

In the full-reflector insertion scheme, the entire radial reflector is moved away from the shadow shield at shutdown and is moved to cover the reactor to provide positive reactivity during operation. A cross section of this configuration is shown in Figure 3. This scheme results in a relatively heavy reactor system, as full removal away from the shadow shield increases D, requiring a considerably larger shadow shield. This scheme does, however, provide the largest reactivity swing of any control scheme examined in this research. Figure 4 shows the total system mass as a function of reactivity swing, with a total system mass of 1603 kg at full withdrawal.

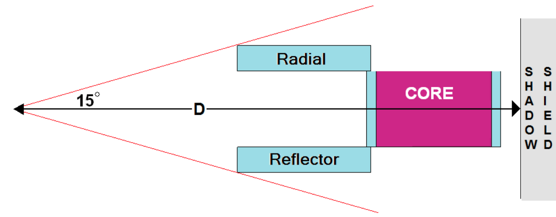


FIGURE 3. Axial View Showing the Shutters Fully Withdrawn From the Core.

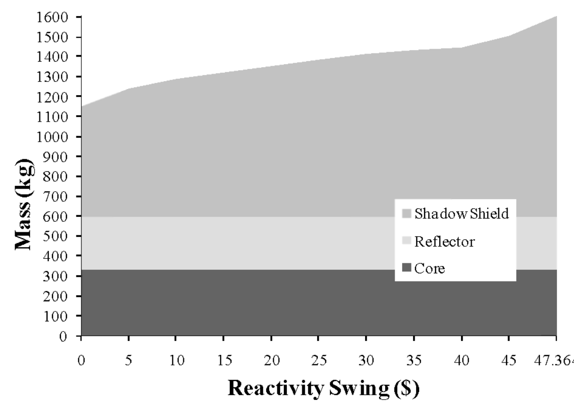


FIGURE 4. System Mass vs. Reactivity Swing for the Full Shutter Insertion Scheme.

Both the core and reflector masses are constant for all values of reactivity swing; the shadow shield mass, however, increases dramatically at higher values of reactivity swing and is the largest contributor to the total system mass. Figure 5 shows reactivity swing as a function of the distance the shutters are removed away from the shadow shield. Most of the reactivity swing is gained when the reflector is removed from the centerline of the core, while removal of reflector from the periphery of the core provides less reactivity swing for the mass gained. Because of this, particular attention should be paid to manipulating the reflector near the center of the core to provide reactivity control, which will be examined in detail in the following subsections.

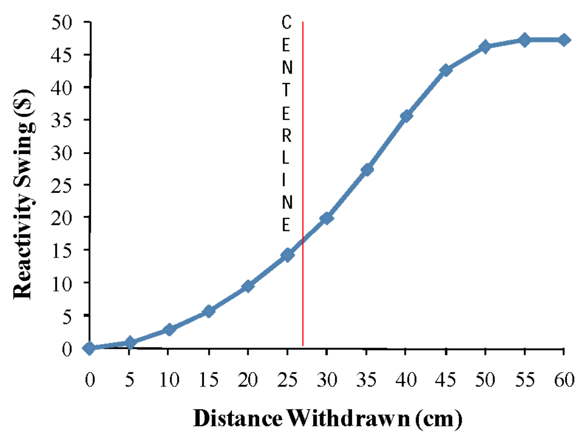


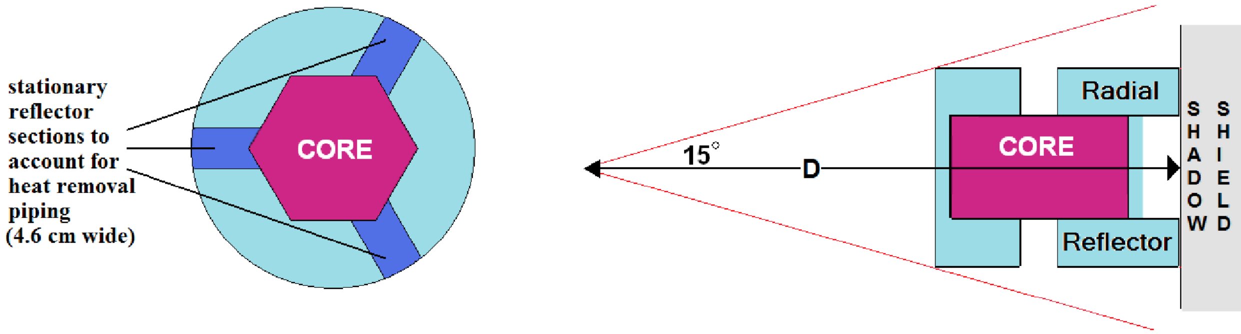
FIGURE 5. Reactivity Swing vs. Withdrawal of Shutters for the Full Shutter Insertion Scheme.

Partial Withdrawl Toward the Shadow Shield

Instead of withdrawing the shutters away from the shadow shield, the shutters can be drawn toward the shadow shield into the 10 cm gap between the axial reflector and the shadow shield. This scheme is desireable because it does not increase the size of the shadow shield to account for movement of the shutters; however, only 10 cm of insertion is available, limiting the total amount of reactivity swing. Cross sections of this configuration are shown in Figure 6.

Based on the results of the previous subsection, the reflector is split 5 cm from the center of the core, allowing a 10 cm gap centered on the midplane of the core (Figure 6b). This scheme achieves a maximum reactivity swing of $16.58 with a total system mass of 1143 kg; the core weighs 334 kg, the reflector weighs 263 kg and the shadow shield weighs 546 kg. This scheme does not, however, take into account the area required for the heat removal piping. In reality, some reflector must be held stationary in this scheme, as space for piping is needed (Figure 1). Taking this into account, with three pieces of 4.6 cm wide stationary reflector (Figure 6a), this scheme achieves a maximum reactivity swing of $14.27 with the same mass (1143 kg). The 4.6 cm width of the three sections was calculated as the diameter of piping and insulation that would be required for the heat removal piping from the S^4 reactor (King and El-Genk, 2006). This change decreases the maximum reactivity swing by $2.31 (approximately 14%).

If more than $14.27 of reactivity swing is required, the shutters would have to be removed further than the present gap would allow. In the next subsection, the shutters are withdrawn away from the reactor in both directions,



(a) radial cross-section **(b)** axial cross-section

FIGURE 6. Axial and Radial Views Showing the Shutters Partially Withdrawn Towards the Shadow Shield.

creating a larger gap in the middle of the core and increasing the reactivity swing, but at the penalty of increasing the size and mass of the shadow shield.

Partial Withdrawl in Both Directions

In some system designs, more reactivity swing may be required than can be provided by having the shutters withdrawn only toward the shadow shield. A larger gap in the reflector (and thus a larger reactivity swing) could be accomplished by having the shutters withdrawn in both directions. While the maximum reactivity swing would increase, so would the size and mass of the shadow shield. In this case half the reflector is withdrawn 10 cm toward the shadow shield and the other half is withdrawn away from the shadow shield. Assuming equal travel for both segments, the maximum central gap is 20 cm. A cross section of this configuration is shown in Figure 7. The shutters would then be inserted from both directions to provide positive reactivity.

The forward movement of the shutters increases the apex distance, D (Figures 1 and 7), thereby increasing the shadow shield mass. Figure 8 shows the system mass vs. reactivity swing for this configuration. Since the mass of the core and the reflector are not changing, the only mass effect is from the shadow shield. As the shutters are withdrawn further from the shadow shield, the shadow shield becomes larger. The 10cm increase in the apex distance, D, results in a 67 kg increase in the mass of the shadow shield. Though the mass of the system increased from 1143 kg to 1210 kg, the maximum reactivity swing ($28.23) was significantly larger than for the previous case with only a 10 cm gap ($16.58).

While this scheme achieves a larger reactivity swing than just moving the reflector toward the shadow shield, making the segment of the reflector furthest from the shadow shield conical could further reduce the mass of the reflector and shadow shield. This would allow this section of the reflector to be withdrawn further without increasing D. This approach is discussed in the next subsection.

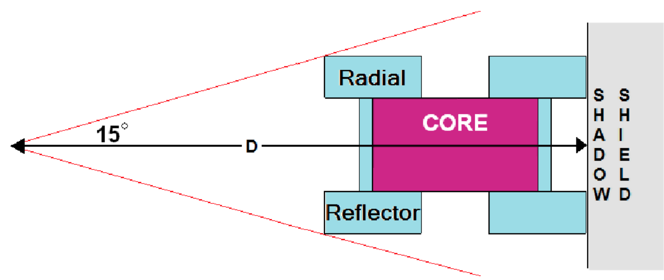


FIGURE 7. Axial View of the Shutters Partially Withdrawn in Both Directions.

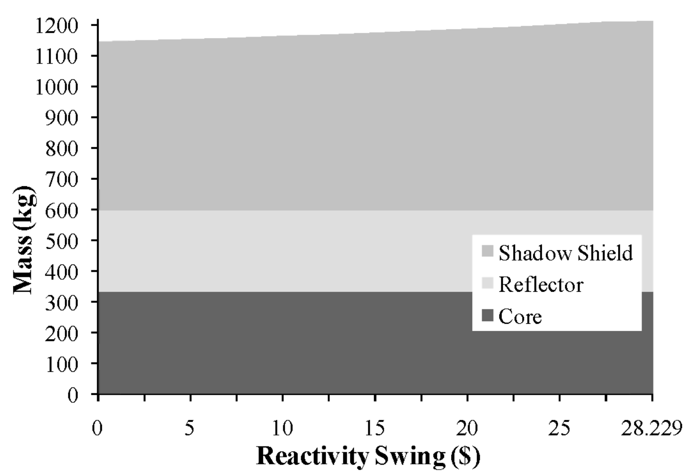


FIGURE 8. System Mass vs. Reactivity Swing for Control Shutters Withdrawn in Both Directions.

Conical Shutters

The results of the previous subsection indicate that the reflector material nearer the center of the core has a higher reactivity worth than the reflector material at the periphery of the core. With this in mind, the total reflector mass can be reduced by removing material from the edge of the reflector and adding less than what was removed nearer to the center of the core. In addition, by removing material from the reflector away from the shadow shield, the size of the shadow cone in which the reflector must fit can be significantly reduced. Figure 9 illustrates this configuration. The reflector segment furthest from the shadow shield is now conical, reducing D, and thus reducing the size and mass of the required shadow shield.

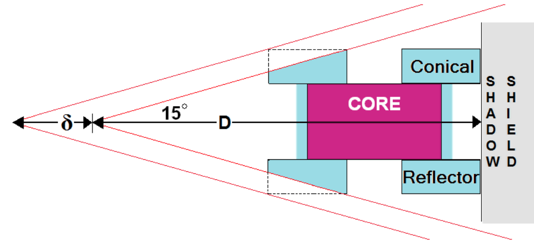


FIGURE 9. Axial View of the Conical Shutters Configuration.

The distance (D) between the apex of the shadow cone and the shadow shield greatly affects the mass of the shadow shield, which tends to be the most massive component of a space reactor system. Decreasing D, making the reflector more conical and the shadow shield smaller, decreases the total system mass significantly. The distance between the apex of a strictly cylindrical reflector and a partially conical reflector is designated as δ in Figure 9. This value is adjusted and the resulting changes to the system mass and reactivity are shown in Figure 10. In the figure, the maximum central gap is 30 cm, 10 cm drawn towards the shadow shield and 20 cm drawn towards away from the shadow shield (for a 2:1 movement ratio). The reflector mass decreases at first and then increases as the reflector becomes increasingly conical in shape. The resulting reflector is sized to provide a cold-clean excess reactivity of \$5. Above δ=20 cm, the mass of the reflector begins to increase as mass is being removed from the center of the reflector where it has the greatest reactivity worth. Above δ=25 cm, the total system mass begins to increase as reflector mass is being added to the periphery of the reflector where its reactivity worth is the lowest. At δ=26.025 cm the reflector becomes completely conical.

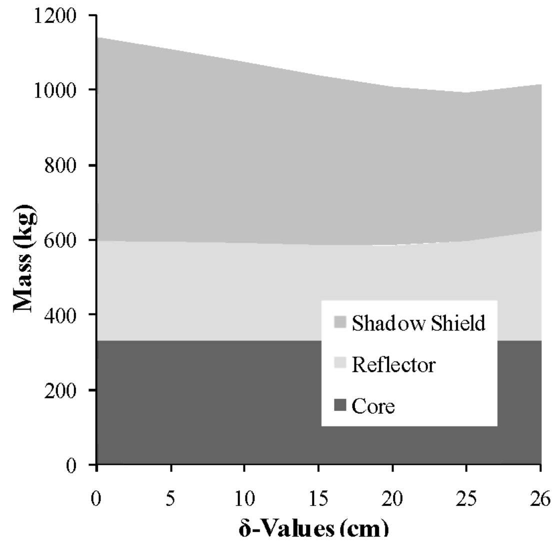


FIGURE 10. Component Mass vs. δ for Conical Shutters with a Gap of 30 cm and \$5 of Cold-Clean Excess Reactivity.

Figure 11 shows the total system mass vs. max reactivity swing for δ–values from 0 cm to 26.025 cm, with the reflector sized to provide \$5 of cold-clean excess reactivity. In this figure, the maximum central gap is variable with a 1:2 movement ratio withdrawal towards and away from the shadow shield, respectively. The maximum reactivity swing is almost the same for all δ -values at ~\$30, corresponding to a gap of 30 cm. The case at δ=25 cm results in the lightest of the conical reflectors, with a maximum reactivity swing of ~\$30 and a total system mass of 1111 kg.

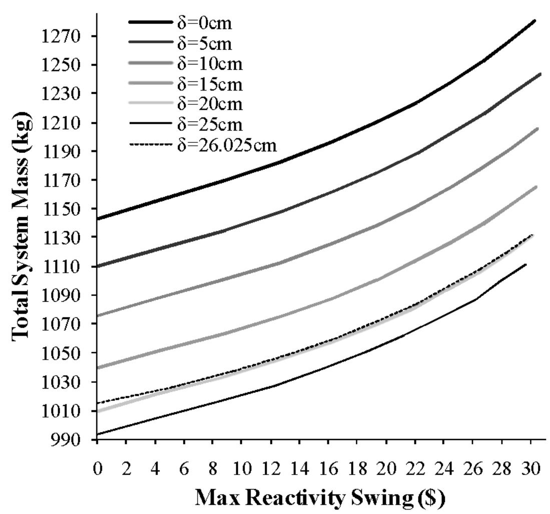


FIGURE 11. Total System Mass vs. Max Reactivity Swing for Conical Shutters.

Shutters provide a large reactivity swing by the withdrawal and insertion of the beryllium oxide reflector. Full withdrawal of the shutters provides the most reactivity swing of any scheme discussed in this research, but at a high mass penalty. Withdrawing the shutters only toward the shadow shield achieves a reactivity swing of \$14.27 without any mass penalty. Partially conical shutters can provide large reactivity swing (~\$30) for significantly less mass than other schemes. As an alternative to removing part of the reflector, reactivity swing can be achieved by changing the position of a boron carbide absorber segment within the reflector. This is discussed in detail in the next section.

CONTROL DRUMS

Control drums have been proposed in many previous space reactor designs, including the Heatpipe Power System (HPS) (Poston et. al., 2000), the low-mass Sectored Compact Reactor (SCoRe-S) (Hatton and El-Genk, 2007), and the Heatpipe-Operated Mars Exploration Reactor (HOMER) (Poston, 2001). SNAP-10A, the only American space nuclear reactor to have flown in space, also used control drums (Angelo and Buden, 1985). Control drums typically consist of a rotating cylinder inserted within the radial reflector. The control drum is made of reflector material (typically BeO), with a layer of a neutron absorber material (typically B_4C) covering an arc on the outer radius of the control drum. Figure 12 depicts a radial cross section of a control drum configuration with six drums having 1 cm thick, 120° absorber segments.

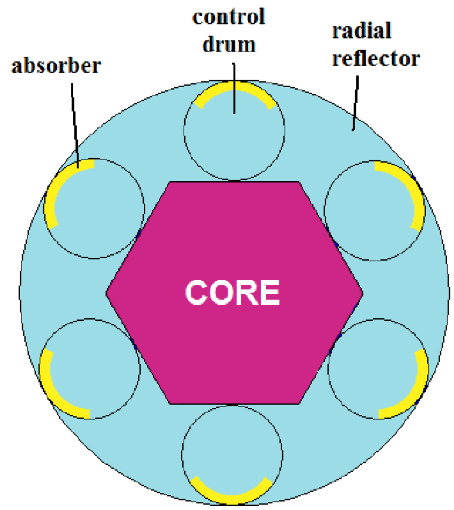
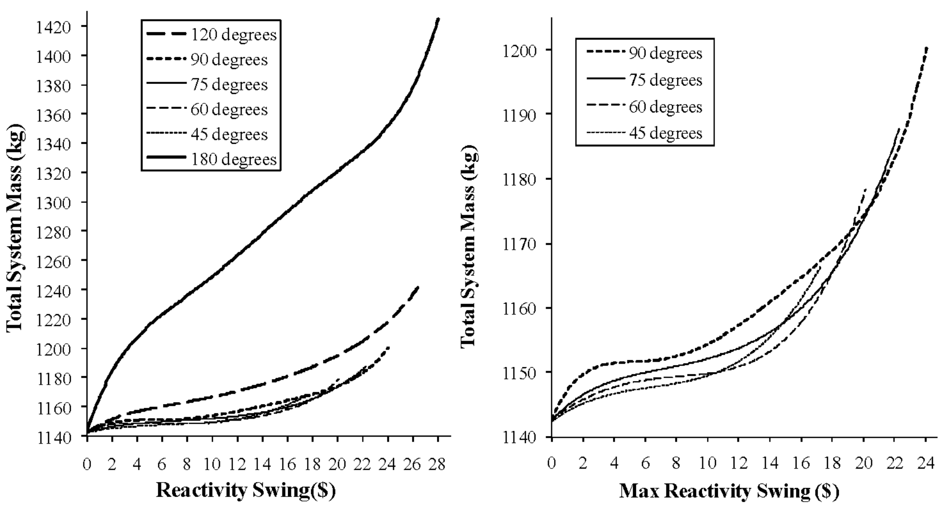


FIGURE 12. Radial View of a Six-Drum Control Scheme Configuration with 1 cm Thick, 120° Absorber Segments.

The thickness of the absorber and the angle of the drum that the absorber covers directly impact the reflector size and resulting reactivity swing. A 0.5-1.0 cm thick absorber covering 120° is generally standard in many proposed designs (Hatton and El-Genk, 2007; King and El-Genk, 2006; Poston et. al., 2000; Poston, 2001). In order to bracket the range of possible designs, the current study considers a six-drum system with absorber thicknesses from 0.05 cm to 2.0 cm and absorber angles from 45° to 180°. The resulting systems are compared in terms of total mass and reactivity swing.

Control drums schemes using more than six drums are also possible. The Pratt & Whitney ESCORT reactor, designed for propulsion and use on the Martian surface, uses 8 control drums (Feller, 1999). The Heat Pipe Segmented Thermoelectric Module Converters (HP-STMCs) Space Reactor Power System (SRPS) reactor uses an 18-drum scheme with 120°, 1.5 cm thick absorber segments (King and El-Genk, 2004). The current research, however, only considers six-drum configurations, as additional drums would not fit within the reflector, given the compact size of the S^4 core.

Figure 13 presents the total system mass vs. reactivity swing as a function of absorber angle. In this figure, the absorber thickness is varied from 0.05 cm to 2 cm to provide the calculated amount of reactivity swing between the least and most reactive states, with a cold-clean excess reactivity of $5. As the thickness of the absorber increases, the maximum possible reactivity swing increases along with the thickness of reflector required to produce $5 of cold clean excess reactivity. Not only does this increase the mass of the reflector, but the shadow shield mass significantly increases as well. Since the worth of the reflector material decreases as it is placed further from the reactor core, the reflector must increase in size at an increasing rate as the thickness of the absorber is increased. This is the reason for the concave-up section of the curve for reactivity swings above ~$8 (Figure 13b).



(a) all drum angles **(b)** angles between 45°-90°

FIGURE 13. System Mass vs. Reactivity Swing for Control Drums as a Function of Absorber Angle.

Figure 13 shows that configurations using a

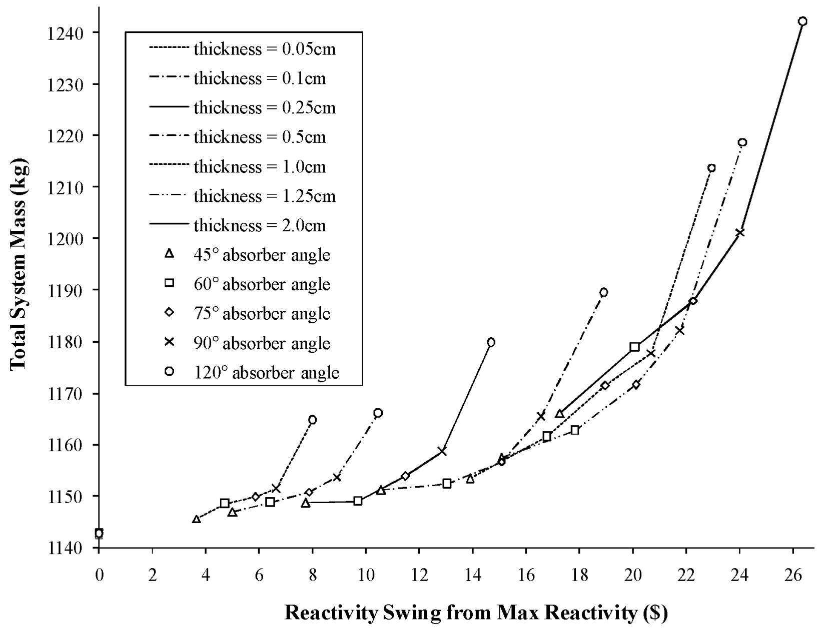


FIGURE 14. System Mass vs. Reactivity Swing for Control Drums as a Function of Absorber Thickness.

180° absorber angle are very inefficient, requiring a large amount of mass for a given reactivity swing. Though less massive than 180° absorber angle schemes, the 120° absorber angle schemes are not the most effective absorber configuration for smaller reactivity swings; however, they may be required if a large reactivity swing (>$25) is desired.

For a given amount of reactivity swing, there is an optimum absorber angle that increases with the desired amount of reactivity swing. A system with an absorber angle of 45° is the least massive choice for up to ~$11 of reactivity swing, then a system with an absorber angle 60° up to ~$18 of reactivity swing, followed by 75° up to ~$22 of reactivity swing, and 90° up to ~$24 of reactivity swing (see figure 13b). Control drums with a 90° absorber angle and 1.5 cm absorber thickness offer ~$23 of reactivity swing for 25 kg less mass (1188 kg vs. 1213 kg) than control drums with 120° of 1 cm thick absorber (Figure 13a). However, control drums with 120° of greater than 1.5 cm thick absorber are the most mass efficient configurations for reactivity swings between ~$25 and $27. At the maximum reactivity swing of ~$27, the 120° control system has a total mass of 1242 kg.

Another aspect of interest is the thickness of the absorber. Figure 14 shows the total system mass vs. reactivity swing for varying thicknesses of absorber at several absorber angles. Absorber thicknesses between 0.5 cm and 1.25 cm generally result in the least massive reactors. Absorber thicknesses below 0.5 cm do not provide as much reactivity swing as a 0.5 cm thick absorber for the same mass (see Figure 14). Total system mass increases dramatically for control drums with absorber thicknesses above 1.25 cm, without a significant increase in maximum reactivity swing.

Control schemes that do not result in unused portions of the shadow shield cone are desirable, as the shadow shield is usually the heaviest component of a space nuclear reactor system. Shutter control schemes require a larger shadow cone to accommodate the geometric manipulation of the reflector but result in larger reactivity swings. While control drum schemes do not change the geometry of the reflector during operation, they are generally limited in their maximum amount of reactivity swing.

Control petals are another available control method and were proposed in one version of the SP-100 design (Deane et. al., 1989). Petals achieve reactivity swing by rotating reflector sections away from the core like flower petals, while keeping the petals within the cone angle of the shadow shield. This scheme is the topic of the next section.

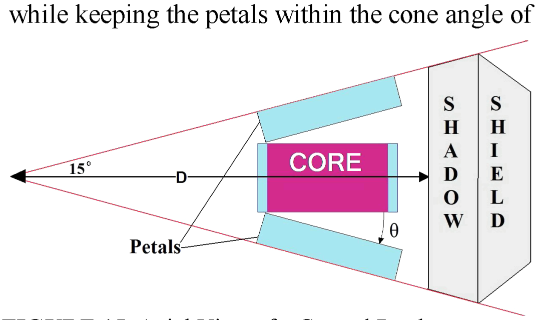


FIGURE 15. Axial View of a Control Petal Configuration.

CONTROL PETALS

Control petals are similar to shutters in that they do not use absorber material to produce a reactivity swing. This improves the neutron economy of the reactor, resulting in lighter reflector configurations. Like shutters, they require shielded space for operation. Unlike shutters, however, the reflector is moved at an angle to the central axis of the core, keeping the reflector within the shadow cone. Figure 15 shows this configuration with the

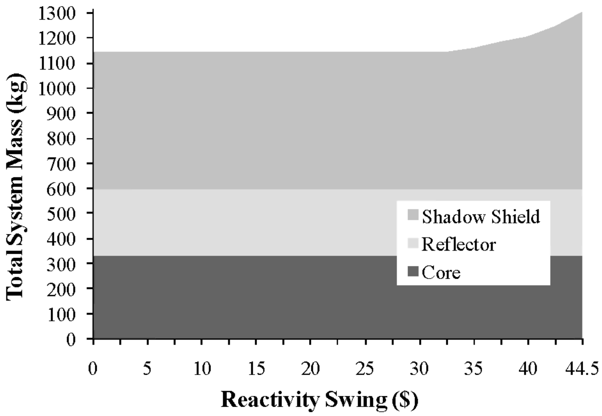


FIGURE 16. Total System Mass vs. Reactivity Swing for Control Petals.

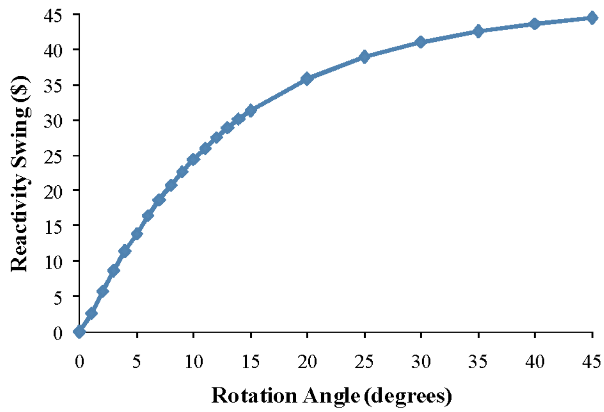


FIGURE 17. Reactivity Swing vs. Petal Rotation Angle.

petals rotated 15°, which is the maximum rotation possible without increasing the size of the shadow shield. The petals are rotated to 15° from the core central axis in the least reactive state and are rotated inward to achieve positive reactivity swing. In the present study, six petals are rotated away from the core with the pivot point on their edge furthest from the shadow shield.

Figure 16 shows the total system mass vs. reactivity swing for the six-petal scheme. Petals can achieve up to $31.33 of reactivity swing at 15° rotation without increasing the required shadow shield mass, resulting in a total system mass of 1143 kg. Beyond 15° rotation, the shadow shield size significantly increases, thereby increasing the total system mass. Figure 17 shows the reactivity swing vs. petal rotation angle for the six-petal scheme. Above $5, the reactivity swing asymptotically approaches a maximum value of $45. Rotated out at 45°, petals achieve a reactivity swing ($44.5) only $3 less than the core with no reflector at all, with a total system mass of 1303 kg.

COMPARISON BETWEEN CONTROL SCHEMES

Figure 18 shows reactivity swing vs. total system mass for several of the reactivity control schemes considered in this research. The most mass efficient variations are presented for each control scheme. While several schemes are comparable to each other (some drum and shutter schemes), other schemes can provide more reactivity swing for significantly less mass (control petals and conical shutters).

Shutter schemes can achieve virtually free reactivity swing by utilizing the 10 cm gap between the core and the shadow shield. Shutter schemes that withdraw the shutters away from the shadow shield achieve larger reactivity swings but dramatically increase the size of the shadow shield, which increases the total system mass. By removing mass in low importance regions, conical shutters can keep the shadow shield compact, making them 100 kg less massive than any other option for reactivity swings up to ~$30.

Control shutter schemes require a shielded space in which to withdraw the shutters. If this were not an issue, such as in a buried lunar reactor where a shadow shield is not required, shutters would be the best option in terms of both mass and reactivity swing.

Petal control schemes are the most mass efficient control scheme for reactivity swings above ~$30, and can achieve reactivity swings up to ~$44.5, nearly equal to that achieved by complete removal of the reflector ($47.47). Both petals

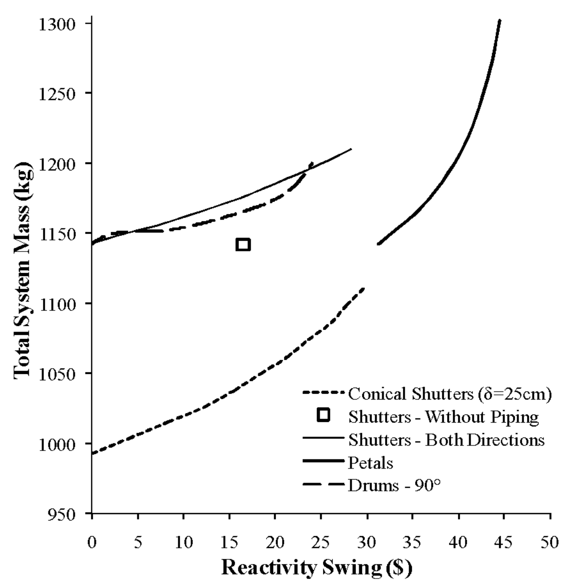


FIGURE 18. Compiled Total System Mass vs. Reactivity Swing.

and conical shutters require shielded space during operation for the withdrawal/rotation of reflector sections; however, conical shutters require additional space that would increase the size of the shadow cone as the shutters are moved away from the shadow shield. Petals can achieve reactivity swings up to ~$31.33 without increasing the size of the shadow cone as they are rotated up to 15° away from the core.

Control drum schemes have the advantage that they do not require additional shielded space for operation. Unfortunately, the maximum reactivity swings possible with drums is lower than that of shutters and petals. Absorber thickness between 0.5 cm and 1.25 cm are generally the most mass efficient configurations. Absorber angles above 120° are not competitive with other control schemes. A 90° absorber angle is most mass efficient for reactivity swings between $19 and $24; 60° absorber angle is the most efficient for reactivity swings between $11 and $18; 45° absorber angle is most efficient for swings below $11 (Figure 13b). Absorber thicknesses below 0.5 cm or greater than 1.5 cm are not desirable.

SUMMARY & CONCLUSIONS

Control shutters, control drums and control petals are considered for the reactivity control of future space nuclear reactor power systems. Control shutters and control petals change the configuration of the reactor's beryllium oxide reflector in order to control the amount of neutron leakage, and thus the reactivity of the core. Control drums achieve the same result by changing the position of a number of boron carbide absorbers relative to the reactor core, which decreases the number of neutrons returning from the reflector. Each scheme is designed to provide sufficient reactivity swing to keep the reactor subcritical during launch and to provide sufficient excess reactivity to operate the reactor over its expected 7-15 year lifetime.

The size and shape of the control system directly impacts the size and mass of the reactor's reflector and shadow shield, leading to a tradeoff between reactivity swing and total system mass. In the analysis of each control scheme, the dimensions and composition of the reactor core are kept constant based on a representative fast-spectrum, gas-cooled reactor configuration. The reflector is then sized to provide $5 of cold-clean excess reactivity with each control configuration in its most reactive state. The mass of the resulting reactor system is then calculated as a function of the amount of reactivity swing provided by each control system.

Control shutters can provide the largest amount of reactivity swing, with the full withdrawal of the radial reflector away from the shadow shield resulting in a reactivity swing of more than $47. However, this large reactivity swing comes at a significant mass penalty, as the diameter of the shadow shield must be significantly increased to account for the travel of the reflector segments. With full withdrawal, the total system mass is 1603 kg. Splitting the radial reflector and withdrawing the reflector segment nearest the shadow shield 10 cm towards the shadow shield can provide a reactivity swing of up to $14.27 with a total system mass of 1143 kg, without increasing the size of shadow shield and still providing space for the reactor's heat removal piping. If additional reactivity swing is required, both halves of the radial reflector may be withdrawn in opposite directions, resulting in a reactivity swing of up $28.23, at the penalty of increasing the system mass 67 kg to 1210 kg. When the section of the reflector furthest from the shadow shield becomes conical, the total system mass is significantly reduced. Conical reflectors provide a maximum reactivity swing of ~$30, with a system mass of 1111 kg.

Control drums can provide up to $27 of reactivity swing at a total system mass of 1240 kg. The optimum choice of absorber angle is function of the amount of desired reactivity swing. A 45° absorber angle is optimum for reactivity swings of less than $11, with the optimum angle increasing as a function of the desired reactivity swing (from 60° for $11-$18 of reactivity swing to 90° for $20-$24 of reactivity swing and 120° above $24). Absorber thicknesses between 0.5 cm and 1.25 cm generally result in the least massive reactor systems.

Control petals achieve large reactivity swings by pivoting the radial reflector away from the reactor core, while keeping the reflector segments within the cone of the shadow shield. Control petals can provide up to $31.33 of reactivity swing without increasing the required size of the shadow shield and keeping the system mass constant at 1143 kg. Above $31.33 of reactivity swing, the mass of the shadow shield increases, with a maximum system mass of 1303 kg for $44.5 of reactivity swing.

In general, conical control shutters will result in the smallest and lightest reactor systems for reactivity swings of up to ~\$30. Above ~\$30, control petals are preferred. Control drums are limited in the total amount of reactivity swing they can provide (<~\$27), and are generally heavier than either conical shutters or control petals.

NOMENCLATURE

D = distance between the shadow shield and the apex of the shadow cone
δ = distance between the shadow cone apex of a strictly cylindrical reflector and that of a partially conical reflector
θ = angle of rotation from the central axis for control petals

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